European Technology Platform for Communications Networks and Services

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5G: Challenges, Research Priorities, and Recommendations

Joint White Paper

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List of Contributors

Contributors	Company/institute	e.mail
Dirk Trossen (Editor)	InterDigital Europe, UK	Dirk.trossen@interdigital.com
David Soldani	Huawei, Germany	David.soldani@huawei.com
Rahim Tafazolli	Surrey University, UK	r.tafazolli@surrey.ac.uk
Werner Mohr	NSN, Germany	Werner.mohr@nsn.com
Valerio Frascolla	Intel Mobile Communications	Valerio.frascolla@intel.com
Barry Evans	Surrey University, UK	b.evans@surrey.ac.uk
Andreas Georgakopoulos	University of Piraeus, Greece	andgeorg@unipi.gr
Nicola Ciulli	Nextworks s.r.l.	n.ciulli@nextworks.it
Amela Karahasanovic	SINTEF IKT	Amela.Karahasanovic@sintef.no
Philippe Boutry	Airbus Defence and Space	Philippe.boutry@astrium.eads.net
Agnès Salvatori	Airbus Defence and Space	Agnes.salvatori@astrium.eads.net
Homer Papadopoulos	NCSR Demokritos, Greece	homerpap@dat.demokritos.gr
Christos J. Bouras	University of Patras, Greece	bouras@cti.gr
Sergio Beker	Huawei, Germany	Sergio.Beker@huawei.com
Jean-Sebastien Bedo	Orange, France	jeansebastien.bedo@orange.com
Rui L. Aguiar	University of Aveiro, Portugal	ruilaa@ua.pt
Andrea Zanella	University of Padova, Italy	zanella@dei.unipd.it
Antonio Lotito	Inst. Sup. Mario Boella, Italy	lotito@ismb.it
Artur Krukowski	Intracom, Greece	krukowa@intracom-telecom.com
Carla-Fabiana Chiasserini	Politecnico de Torino, Italy	chiasserini@polito.it
Daniel Saez Domingos	ITI, Spain	dsaez@iti.es
David Lund	HW Communications	dlund@hwcomms.com
Enrico Del Re	University of Firenze and CNIT, Italy	enrico.delre@unifi.it
Eran Raichstein	IBM Haifa Research Lab, Israel	ERANRA@il.ibm.com
Felipe Gil	University of Vigo, Spain	malvarez@gradiant.org
Franco Davoli	CNIT, Italy	franco.davoli@cnit.it
Graham Peters	Avanti Communications, Ireland	xil@det.uvigo.es
Hamed Al-Raweshidy	University of Brunel, U.K.	Hamed.Al-Raweshidy@brunel.ac.uk
Josep Manges-Bafalluy	CTTC, Spain	josep.mangues@cttc.es
Marius Corici	Fraunhofer FOKUS, Germany	marius-iulian.corici@fokus.fraunhofer.de
Marcos Alvarez-Diaz	Gradiant, Spain	malvarez@gradiant.org
Michele Zorzi	University of Ferrara, Italy	zorzi@ing.unife.it
Nicola Blefari Melazzi	University of Rome, Italy	blefari@uniroma2.it
Nicolas Chuberre	Thales AleniaSpace, France	nicolas.chuberre@thalesaleniaspace.com
Panagiotis Demestichas	Uni. of Piraeus, Greece	pdemest@unipi.gr
Paolo Dini	CTTC, Spain	paolo.dini@cttc.es
Roberto Verdone	University of Bologne, Italy	roberto.verdone@unibo.it

Thomas Magedanz	Fraunhofer FOKUS/TU Berlin	magedanz@ieee.org
Emilio Calvanese Strinati	CEA-LETI	Emilio.calvanese-strinati@cea.fr
Matti Latva-aho	OULU	matla@ee.oulu.fi
Howard Benn	Samsung	howard.benn@samsung.com
Michael Faerber	INTEL	michael.faerber@intel.com
Louagie Filip	IMEC	Filip.Louagie@imec.be
Dimitri Ktenas	CEA-LETI	Dimitri.ktenas@cea.fr
Oliver Blume	Alcatel-Lucent	Oliver.Blume@alcatel-lucent.com
Raffaele D'Errico	CEA-LETI	Raffaele.derrico@cea.fr
Luís Correia	INOV	luis.correia@inov.pt
J Wang	Kent University	j.z.wang@kent.ac.uk
Maziar Nekovee	Samsung	m.nekovee@samsung.com
Mehdi Bennis	OULU	bennis@ee.oulu.fi
Thomas Haustein	Fraunhofer HHI	thomas.haustein@hhi.fraunhofer.de
Armyn Dekorsy	Univ. of Bremen	dekorsy@ant.uni-bremen.de
Chiara Petrioli	Univ. of Rome	petrioli@di.uniroma1.it
Harald Haas	Univ. Edinburg	h.haas@ed.ac.uk
Miguel Egido	GOWEX	megido@gowex.com
Jochen Mezger	IRT	mezger@irt.de
Symeon Chatzinotas	Univ. of Luxembourg	Symeon.chatzinotas@uni.lu
Ana Garcia Armada	U. Carlos III of Madrid	agarcia@tsc.uc3m.es
Dimitrios Karvounas	Univ. Of Piraeus	dkarvoyn@unipi.gr
Francesco Delli Priscoli	Univ. of Rome "La Sapienza"	dellipriscoli@dis.uniroma1.it
Guido Oddi	Univ. of Rome "La Sapienza"	oddi@dis.uniroma1.it
Vincenzo Suraci	Univ. of Rome "La Sapienza"	suraci@dis.uniroma1.it
Sharadha Kariyawasam	HW Communications Ltd	sharadha@hwcomms.com
Felipe Gómez Cuba	Univ. Vigo	fgomez@gti.uvigo.es
Ray Sperber	SES	ray.sperber@ses.com
Víctor Sempere	ITI	vsempere@iti.es
Mikhail Popov	Acreo Swedish ICT	mikhail.popov@acreo.se
Arturo Azcorra	IMDEA Networks and U. Carlos III, Spain	arturo.azcorra@imdea.org
Carlos Jesús Bernardos	IMDEA Networks, Spain	cjbc@it.uc3m.es
Antonio de la Oliva	U. Carlos III de Madrid, Spain	aoliva@it.uc3m.es
Xavier Perez-Costa	NEC Europe	Xavier.Perez-Costa@neclab.eu
Noel Crespi	Institut Telecom, Telecom SudParis, France	Noel.crespi@institut-telecom.fr
Holger Karl	U. Paderborn, Germany	holger.karl@upb.de
Diego Lopez	Telefonica, Spain	diego@tid.es
Eduard Escalona	i2cat, Spain	Eduard.escalona@i2cat.net
Joan Antoni Garcia	i2cat, Spain	joan.antoni.garcia@i2cat.net
Artur Hecker	Huawei, Germany	Artur.Hecker@huawei.com

Mayur Channegowda	University of Bristol, UK	Mayur.Channegowda@bristol.ac.uk
Dimitra Simeonidou	University of Bristol, UK	dimitra.simeonidou@bristol.ac.uk
Geir Millstein	Telenor, Norway	geir.millstein@telenor.com

List of Acronyms

2G	2^{nd} Generation
3G	3^{rd} Generation
4G	4^{Th} Generation
5G	5^{th} Generation
ABC	Always Best Connected
API	Application Programming Interface
BSD	Berkeley Software Distribution
BYOD	Bring Your Own Device
CAPEX	Capital Expenditure
CDN	Content Delivery Network
C-RAN	Cloud-Radio Access Network
D2D	Device to Device
E2E	End to End
EU	European Union
GEO	Geostationary Orbits
ICN	Information Centric Networking
ICT	Information and Communication Technologies
IoT	Internet of Things
IP	Internet Protocol
ISP	Internet Service Provider
IT	Information Technology
KPI	Key Performance Indicator
L2	Layer 2 of Protocol Stack
LTE	Long Term Evolution
M2M	Machine to Machine
MAC	Media Access Control
NFV	Network Function Virtualisation
OPEX	Operational Expenditure
OTT	Over The Top
PPP	Public Private Partnership
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
SatCom	Satellite Communication
SDN	Software Defined Network
SLA	Service Level Agreement
UNI	User Network Interface
V2V	Vehicle to Vehicle
V2X	Vehicle to Infrastructure
WiFi	Wireless Fidelity

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Executive Summary

The Advanced 5G Infrastructure, defined as the ubiquitous ultra-broadband network that will carry the Future Internet, is not only an ***evolution*** of current generations, but a ***revolution*** in the ICT field that will enable highly efficient, ultra reliable, dependable, secure, privacy preserving and delay critical services to everyone and everything. Fully immersive experience, enriched by context information and realized as a "All as a Service", will be the main drivers for a massive adoption of the new technology components and market uptake. This calls for a complete redesign of the architecture, services and service capabilities of the new infrastructures, and a re-thinking of interfaces, access and non-access protocols and related procedures, functions, and advanced algorithms, for authorization, authentication, establishment, maintenance and reconfiguration of ICT services and any type of resource among cyber-physical entities, especially at the edge. Several challenges still need to be addressed to meet and exceed the expected key performance indicators, in terms of throughput (1000x more in aggregate and 10x more at link level), service-level latency (1ms for tactile Internet and below 5ms for 2-8**K** change in view, at 30-50Mb/s), energy efficiency (90% less consumption for the same service compared to 2010 levels), coverage (global and seamless experience), battery lifetime (10x longer), QoS, manageability, etc. Moreover, the advanced 5G infrastructure needs to be highly ***flexible*** in order to meet foreseen as well as unknown requirements, in alignment with current and future stakeholders' expectations, while optimising the total cost of ownership in various deployment contexts in Europe and beyond. This calls for the integration of various access technologies. Most of the research and innovation efforts need to be in place well before 2016; intensive standardization activities and large field test trials and testing will take place globally before 2020; beyond that, commercial products will be most probably available in the market. Europe can make this vision happen through crucial investments in 5G technologies and related measures to focus and strengthen its knowledge in the new ICT fields. Ultimately, we believe the EU 5G Infrastructure Public Private Partnership (5G PPP) to be a viable initiative for the EU ICT industry achieve a competitive advantage in the global marketplace by contributing to the research and investigations of the new technologies that will characterize 5G.

This whitepaper represents the joint efforts of the NetWorld2020 expert community, initially developed within five distinct whitepapers on requirements and challenges, wireless, satellite, converged connectivity, and virtualization, presented here as a first consolidated view on 5G.

1 Rationale

The call for the next generation of (mobile) networks is founded on a changing set of societal challenges and reflected in the establishment of the 5GPPP as a collaborate initiative between industry, academia and public funding agencies. The following section sheds light on this changing society with an attempt to present a (broad) vision of what the future 5G system will be, eventually leading to defining the rationale behind this very document.

1.1 Changing User Needs, Driven by a Changing Society

Today, for the first time, especially thanks to the deployment of LTE (4G), we are witnessing the convergence of “Cloud Computing”, “Computing Power” and “Connectivity at High Speed”, all realized over the bitpipe model of the current Internet[1]. It is now time to go beyond this model and design 5G, i.e. the next generation of ubiquitous ultra-high broadband infrastructure that will support the future Internet, and provide delay-critical and ultra-reliable, secure and dependable services to billions of smart objects and cyber physical systems, such as cars, robots and drones. With 5G, the Information and Communication Technologies will generate new services at low cost not only focusing on providing a seamless and efficient communication capability as in the past, but also trying to really improve the way we interact among ourselves, with the final target of improving our lives. Communication services will be free for the end user in many cases, and will monetize all those applications, machines and things, that will be offered as a service, thus allowing the shift, and that really matters, towards a more and more real Information-oriented Society.

One of the key drivers for the development of a future 5G infrastructure will be the growing **ecosystem of things** around the end user, acting as a producer and consumer (*prosumer*) of data, as new terminals will retrieve and generate information through ephemeral networks of cognitive objects and cyber physical systems in their proximity, independently from the network infrastructure availability. It is the latter distributed intelligence in future smart phones, drones, robots, and any smart objects – with or without network assistance – that will provide the ultra-reliable, secure and privacy preserving, dependable, and performing connectivity services with extreme low latency, when necessary. The distributed intelligence in pervasive local actuators will be one of the fundamental catalysts in the interest of today’s operators, creating enablers for business model changes that could allow operators to recover a central role in the data management. Operators could then add value to services offered by OTTs, instead of OTTs developing all the functionality and the value outside the network[2].

5G will see the integration of new mobile and wireless access systems (very broadband systems and IoT) with legacy networks in order to use deployed investment like LTE, 3G, 2G, WiFi, satellite etc. as long as such systems will be still in operation. All these systems should cooperate and interwork seamlessly. 5G services will place very stringent requirements in terms of achievable coverage, data rates, latency, reliability and energy consumption. In most of the cases, not all of these requirements need to be simultaneously met. However, the advanced 5G infrastructures need to be flexible and adaptable to diverse use cases and scenarios, moving away from a ‘*one architecture fits all*’ nature towards a ‘*multiple architectures adapted to each service*’ concept.

For instance, for seamless integration of smart objects, we expect 5G networks to provide measurable and provable security, as well as a service-level delay below 5ms when needed, with 99.999% transmission reliability and approximately 100% availability. For reproducing three-dimensional scenarios, like big events and professional transmissions, where an immersive “dreaming” experience is achieved through capturing and rendering signals coming from a large number of sensors and multi-directional transmitters, we expect any future 5G infrastructure to cope with 30-50 Mb/s, for a single video transmission, and perform most of the light field and sound field processing in the network, as terminals are likely to receive only a portion of

[1] See Eric Smith, “Google keynote speech”, MWC 2010, Barcelona, Spain

[2] See Antonio Manzalini, et al., “Software-Defined Networks for Future Networks and Services: Main Technical Challenges and Business Implications,” White Paper, January 2014.

the full set of views/channels available. This will require the network to adapt the data stream with (close to) "zero latency" for some applications, according to decoder characteristics. In order to support applications like the "tactile Internet", service-level latency should be reduced to about 1ms. The full collaborative and immersive experience is expected at home, in cinemas, theatres, public arenas, vehicles, vessels, aircrafts and especially using the next generation of devices without needing to wear glasses or binaural receivers[3].

1.2 What is 5G?

None of the arising user needs that we outlined before can be met by any of the wireless technologies within the scope of the current standardization and network evolution frameworks. Satellite offers the wide broadcast coverage and high bandwidth but is challenged by latency for some applications, expense and saturation in areas with high user density, whereas terrestrial mobile achieves the connectivity to indoor and ground-mobile users but is economically challenged when user density is sparse or intermittent. It is thus necessary to research and develop new architecture concepts and technologies for accessing and delivering ultra-reliable, fast, ubiquitous, dependable and secure wireless services, as well as rethinking network services and their capabilities, in terms of identity, mobility, trace preventing and connection management, while taking advantage of the faster-than-Moore's law affordability growth of storage for end user media caching with suitable content management.

*In order to funnel the manifold efforts of the wider research community into a coherent vision for a future infrastructure, we also call for a **pan-EU 5G infrastructure**, catalyzing innovation across the community towards a next generation of the connected society*. In this, the member states may play an important role in defining their relevant scenarios looking at an EU information-oriented society, where anyone will have the possibility of communicating and contributing to the good of our networked society, in terms of:

(1) High speed ubiquitous mobile access to global Internet and high bandwidth services, including the creation of an environment where miniaturized smart systems (with in-built "intelligence") are able to provide more intelligent services anytime anywhere

(2) High level of democracy as a fast medium for the population of high diversity cultural groups to access to information related to candidates and parties standing for election at national and European level.

(3) Higher individual and societal wellbeing by allowing for mobile health and wellness services anytime anywhere

(4) Booming generation of jobs in a diverse pool of activities and business models as well as across many sectors, created by the information highway network.

(5) Generation of high level of cooperative and collaborative works by different businesses around Europe and intercontinental commercial entities.

(6) Creation of an environment in which risks of criminal actions and attacks are minimized, and effective solutions to disaster and recovery areas are easily and rapidly implemented.

(7) Automation of many tasks, during our daily activities, that could be offloaded to machine, robots and drones, following the "Smart Factories", "Smart Energy" and "Smart City" paradigms.

(8) Increased privacy control for European citizens through pan-European data management technology, transferring data ownership back to prosumers, while only keeping its management in the network

In other words, we see the role of 5G as that of providing a universal communication environment that enables to address the wider societal challenges such as in transport, automotive, societal safety, employment, health, environment, energy, manufacturing and food production. This will be achieved

[3] See John Thomson, et al., "5G Wireless Communication Systems: Prospects and Challenges," IEEE Communications Magazine, February 2014.

through flexibly aligning stakeholder incentives by virtue of being truly programmable, secure, dependable, privacy preserving, ubiquitous, and flexible, while minimizing the costs per bit by efficiently harnessing all available communication capabilities and reducing the system power consumption, e.g. by harvesting accessible energy from the environment and other means.

This wider diffusion of wireless communication and its enabling networks will allow for addressing the societal challenges at an unforeseen economy of scale, moving away from vertical silos and truly enabling cross-value chain collaborations across the many sectors that utilize the common 5G technologies. Hence, 5G will enable the development of an ecosystem that have been so far dispersed across vertical solutions with high barriers of entry for new market players, including ISPs and application developers, as well as prohibitive costs and energy per bits in the existing solutions. The effect of a common information and communication substrate will be the introduction of a much wider range of stakeholders into the 5G ecosystem, compared to any existing single ICT-based solution, ranging from individual people and digital asset owners over vertical sectors such as transport, energy, health, manufacturing, food production, broadcast to public bodies like municipalities and public safety organisations. Such widening of the stakeholder community will require an openly accessible communication environment in which solution providers as well as network owners can strive towards addressing the specific societal challenges that are addressed in every solution in conjunction with the policy challenges in security, privacy and energy footprint that will lie ahead. Furthermore, with many more people expecting to have the same coverage when travelling (on cruise liners, passenger aircraft, high-speed trains and in holiday villas), it is key to allow for seamless extension of 5G services anywhere anytime, e.g., through satellite technology.

This vision of a deeply penetrating common information and communication substrate will require a re-thinking of how we design the overall ICT system, allowing reconfiguration of value chains (and therefore the underlying provisioning of the communication substrate) in real-time, while providing an evolutionary path for integrating the advances in radio and network technologies. Such endeavour has to address the well-known set of specific technological challenges, e.g., providing 1000x more bandwidth to end users while reducing the end-to-end latency to about 1ms when needed, as already mentioned above. This re-thinking requires an orchestrated effort of collaboration across Europe that takes the individual technological advances and embeds them into a system that we can truly call 5G.

1.3 Rationale for this Document

Europe can make this vision happen through crucial investments in 5G technologies and related measures as well as actions to strengthen the know-how and ensure the EU leadership in the field of ubiquitous ultrafast broadband, ultimately re-enforcing European data protection and supporting the most plausible scenarios and valuable use cases for all (not only urban areas) expected in 2020 and beyond.

The 5G Public Private Partnership (5G PPP) is the manifestation of the orchestrated effort for the EU ICT industry to achieve a competitive advantage in the global marketplace by contributing to the research and investigations of the new technologies that will characterize the next generation of ICT infrastructures.

This document discusses the challenges for a future 5G infrastructure, leading the way to define clear research priorities that will need to align within a roadmap of orchestrated efforts within the 5GPPP and its surrounding research and development efforts. Although this document reflects on the input from a wide research community, it is only a starting point to consolidate the many views of the wider stakeholder community into a coherent understanding as to what 5G is and how it will eventually come about.

2 Challenges & Key Performance Indicators

The aforementioned vision 5G reveals a plethora of challenges that we can outline:
5G strives to provide a universal ICT infrastructure that addresses wider societal challenges through a flexible alignment of stakeholder incentives by virtue of being truly programmable, secure, dependable, privacy preserving, and flexible, while minimizing the costs per bit by efficiently harnessing all communication capabilities and reducing the system power consumption by harvesting any kind of accessible energy from the environment.

First, this vision points towards a significantly increased (in comparison to earlier generations) set of stakeholders that 5G needs to accommodate when providing communication solutions. Examples of stakeholders are:

- Individual and communities of people.
- SMEs, corporations, not-for-profit and social organizations.
- Digital asset owners, such as public transport and utilities authorities and organisations.
- Vertical sectors like energy, health, manufacturing, robotics, environment, broadcast, content and creative industries, transport, smart cities.
- Municipalities and public administrations.
- Public safety organisations and defence bodies.

Providing communication solutions for this large set of stakeholders with current communication solutions is intrinsically difficult due to the large set of requirements that needs addressing at any point in time of deployment. Following our vision, it seems clear that 5G will be able to provide broadband location-independent access to places like planes, high-speed trains and ships. 5G networks will **optimally explore** the underlying L2, and will **use the existing context** to provide **energy efficient** communications. This means that 5G will be **multi-technology** – not in the sense that resorts to **different physical layers**, but that they can resort to **different networks** as well, either from the point of view of technology or of administrative ownership. In this, we consider the future 5G network a "*not always all-IP network*", bringing the advantages of other network architectures to the forefront where they may provide value over IP-only systems (e.g. ICN, Zigbee, etc…). The network will also be inherently **multi-tenant**, in order to be able to explore the technology diversity that will exist. Driven by Moore's Law, the networks (or some network nodes) will need to be seen as intelligent "**computing & storage**" entities, bringing different features into the network realm, where some concepts that resided until now at the service layer are integrated, enabling the **synergetic development of network functions** based on software engineering principles (thus lowering the product development costs). The 5G network thus brings to users not only **better performance**, but also **new functionality**. Its scope is not limited to the radio access, but encompasses the whole network, including aspects as subscriber management, core network and transport features.

This view on 5G leads to a number of **key performance challenges** that 5G technologies will need to address for meeting expected **key performance indicators** (KPIs):

- **Throughput**: provide 1000x more available throughput in aggregate, as well as 10x more speed to individual end users, in order to enable fully immersive experiences. This may require the integration of new forms of broadcast services.
- **Latency**: provide service-level latency down to about 1ms (when needed) for tactile Internet, interactive and immersive experiences as well as standard Internet services.
- **Energy efficiency**: Wireless/mobile broadband infrastructures account for more than 50% of the energy consumption of telecommunication operator networks, while the amount of global energy consumption of ICT approaches 4.5% with a rising trend[4]. It is important that future 5G networks

[4] See Project EINS (Network of Excellence on Internet Science), "Overview of ICT energy consumption", Deliverable 8.1, Feb. 2013, available online at: http://www.internet-science.eu/sites/internet-science.eu/files/biblio/EINS_D8%201_final.pdf

meet requirements and challenges in an energy efficient manner (by achieving 90% of energy efficiency compared to 2010 levels).
- **Service creation time**: enable the creation of user experiences from the application over the individual service components down to the individually participating network(s) in a matter of seconds or less.
- **Battery lifetime**: provide 10x better battery lifetime for low throughput solutions such as sensors.
- **Coverage**: with many more people expecting to have the same coverage when travelling (on cruise liners, passenger aircraft, high-speed trains and in holiday villas), it is key to provide seamless extension of 5G services anywhere anytime. IoT coverage to wide areas involving sensors and M2M connections are ideal services to make use of satellite wide area coverage.

In addition to the key performance challenges, we also outline **system-level challenges** that arise from the changing ecosystem in which 5G is expected to operate:

- **Privacy by design challenge**: provide accountability within the communication substrate and enable truly private communication when needed, aligned with policy constraints in terms of data management and ownership, ensured by the infrastructure operators that realize the overall service.
- **Quality of Service challenge**: in order to allow for optimizing the **Quality of Experience**[5] **(QoE)** for the end user, 5G should provide differentiated services across various dimensions such as throughput, latency, resilience and costs per bit as much as possible independent of users' location with respect to the antennas deployment geography. This includes increased security, availability, resilience and delivery assurance for *mission critical* applications such as health-related or emergency applications, but also ultra-low cost solutions for emerging countries with less stringent QoE requirements.
- **Simplicity challenge**: provide to 5G users the best network services seamlessly without complex customer journeys (e.g. for inter RAT switching).
- **Density challenge:** increased number of diverse devices connected in proximity, e.g., challenging the current architecture for mobility management.
- **Multi-tenancy challenge**: provide service solutions across different infrastructure ownerships, with the different networks (not necessarily IP-based) co-existing and providing and providing an integrated as well as efficient interaction between the wireless domain and the backhaul.
- **Diversity challenge**: Beyond the aforementioned diversity of stakeholders, 5G must support the increasing diversity of optimized wireless solutions (to different application domains, e.g., M2M) and the increasing diversity and number of connected devices, and associated diversity of traffic types.
- **Harnessing challenge**: exploit any communication capability, including device-to-device (D2D), for providing the most appropriate communication means at the appropriate time.
- **Harvesting challenge**: devise radically new approaches to provide devices with power, which not only has to come from batteries, but also harvests existing environmental energy.
- **Mobility challenge**: support for unlimited seamless mobility across all networks/technologies
- **Location and context information challenge**: provide positioning and context capabilities in the sub-metre range in order to enable the Internet of everything, e.g., through the integration of cellular and satellite positioning systems**.**
- **Open environment challenge**: enable horizontal business models by opening the right business interfaces within the system in order to enable flexible operator models in a multi-tenancy fashion.
- **Manageability**: Improve manageability of networks in order to reduce the need for manual management and reduce the human involvement.

[5] **QoE** is the degree of delight or annoyance of the user of an application or service. It results from the fulfillment of his or her expectations with respect to the utility and / or enjoyment of the application or service in the light of the user's personality and current state.

- **Hardening challenge**: deploy a communication system through a combination of bearer techniques such as cellular and satellite that is intrinsically robust to attacks from malicious entities as well as to natural disasters; a resilience without which the smart-grid/smart-city paradigm will never be achieved.
- **Resource management challenge**: provide access agnostic control, policy and charging mechanisms and protocols for dynamic establishment, configuration, reconfiguration and release of any type of resource (Bandwidth, Computation, Memory, Storage), for any type of devices (e.g. terminal, car, robot, drone, etc.) and services (e.g. Network, Security, Data, Knowledge, Machine, and Thing as a Service), including in E2E fashion when necessary.
- **Flexibility challenge**: devise truly flexible control mechanisms and protocols for relocating functions, protocol entities and corresponding states in a truly end-to-end manner, leveraging programmable network technologies such as SDN and NFV.
- **Identity challenge**: provide identity management solutions for any type of device (terminal, car, robot, drone, etc.) with access agnostic authentication mechanisms that are available on any type of device, device to device and network to device, independent from specific technologies of communication entities and of their current location.
- **Flexible pricing challenge**: provide methods for flexible pricing mechanisms across and between different parts of the future 5G value chain in order to enable pricing regimes that are common across the industries that will utilise the future 5G infrastructure. Furthermore, new business models could consider the underlying technology (e.g., wireless or mobile, legacy or later one) as well as other aspects like the contribution of a privately owned small cell to the operator's infrastructure through its open access.
- **Evolution challenge**: provide the ability for evolution and adaptation, allowing a transparent migration from current networks and permitting future development

From a system level perspective, our vision outlines one particular challenge that overarches all technology-focussed research priorities; this challenge is that of **flexibility**. Given the wide range of stakeholder incentives and requirements, future 5G system must provide an enormous degree of flexibility. This challenge drives 5G away from the rather rigid pre-5G designs with limited service classes available to its users and few assumed deployment models at the communication substrate level. Specialized network components provided as specialized hardware boxes, based on commonly agreed standards, reflect this rigidity in design. In order to achieve the necessary flexibility of 5G systems, we foresee a high degree of **programmability** of otherwise standard network-enabled hardware components, such as reflected in the current network function virtualization (NFV) efforts. This programmability pushes the resolution of incentive conflicts from the early standards phase to the later deployment phase where network emulation as well as validation of software components paves the way to significantly reducing the service deployment time from several days to minutes or even seconds. The programmability also provides the ability to account for the usage of resources across the network, enabling the envisioned flexible incentive alignment across several stakeholders. Furthermore, with resources interpreted as that of computing, storage, volatile memory and bandwidth, the envisioned programmability of the network will also facilitate solutions for the aforementioned guarantee challenge at the system level by allowing for optimizing across all these resource dimensions towards a single deployed solution. Combining flexibility and programmability in future 5G systems should also allow to build complex, mission-critical services with specific requirements in terms of service quality, where a dedicated physical infrastructure would be normally required. Harnessing the true benefits of programmability is only achieved by **openness** of key APIs to network services across different domains. Furthermore, the future 5G system needs to perform in an **energy-efficient manner**, by meeting at the same time all the necessary 5G KPIs in line with the 5G vision. This trend will result in the design of energy-efficient hardware that ultimately reduces the energy consumed per bit.

Beyond these identified technology challenges, we also identify research priorities needed in economic and policy research that investigate the impact of this new flexibility on business and standards processes as well as on policy-making processes. We believe that this research will be transformative to today’s processes. For instance, we need to investigate the role of standards as a way to agree on technological and business interfaces within the system in the light of upcoming virtualization solutions. We will also need to investigate the impact of new spectrum management approaches on spectrum policy, possibly integrating the technological solution (e.g., the exchanged information for spectrum sensing) into the policy approach itself. Last but not least, the flexible alignment of incentives, as envisioned by our 5G vision, will truly enable fluid information-driven markets through our 5G platform. We will need to study the potentially transformative changes within the many industries that 5G intends to provide solutions for in the light of this new economic market fluidity. For instance, we can already see today that the 'app economy' of smartphone-based applications has had an impact on areas such as public transport as well as health. Quantifying this impact, identifying new business models as well as fostering emerging stakeholders in these future markets are the priorities of this economic research in the 5G context.

3 Research Priorities

While Section 1 described the overall 5G vision and the expected ecosystem, Section addressed the requirements in terms of KPIs as well as main challenges to be addressed. From this, we derive the main 5G Technology Areas, depicted in Figure 1 below, that Section 3 will now address in terms of research priorities, including, but not limited to, research into new radio waveforms, new joint access/backhaul designs, integration of satellite into the wireless subsystem, new routing solutions for backhaul and core networks, new caching solutions for reducing service-level latency, new low throughput solutions for sensor deployments and many more.

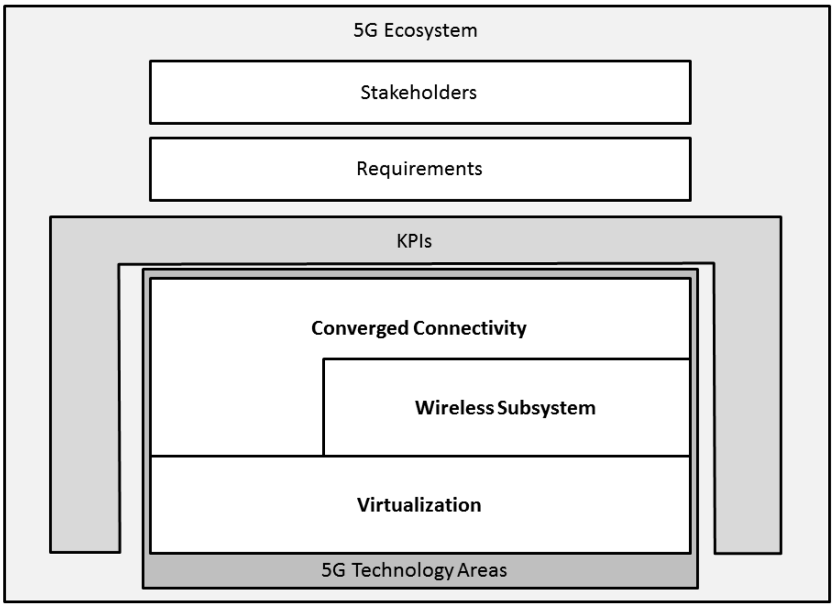

Figure 1: Keys Areas of 5G Investigation

3.1 *Converged Connectivity*

The space diversity strategy (with heterogeneous networks) is now an expected evolution for increasing wireless capability, often associated with ideas of centralized solutions (C-RAN) for handling the increase complexity and interference issues (see Fig. 2).

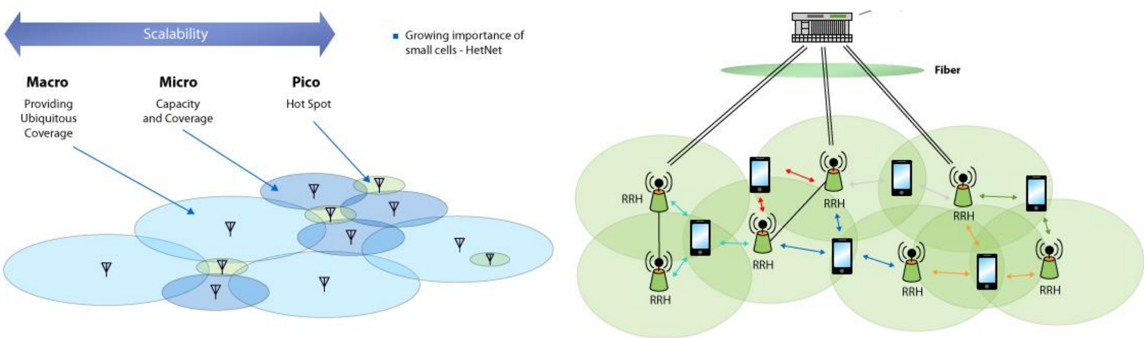

Figure 2: Changes to the wireless cell concept

This brings significant challenges on how mobility, and connectivity in general, is addressed. Heterogeneity is currently achieved through: i) multi-tier architectures (a mix of macrocells and smaller cells), and (ii) the coexistence of different wireless technologies, e.g., 2G/3G/4G, WiFi. As a further aspect of this heterogeneity, a User Equipment is expected to be able to communicate in a device-to-device (D2D) fashion (or in an edge-path approach). Such D2D links could be established on license-exempt bands but under the control of the cellular infrastructure (or not). As a result, users will soon have several and different connectivity opportunities to exploit. The heterogeneity dimensions will be further enhanced by the expected increase in the simultaneous usage of different control platforms, with users dynamically switching/simultaneously accessing different connectivity control platforms.

Many traditional research areas remain as priorities and need to continue in the future. Nevertheless, we specifically highlight a few important and strategic aspects to consider.

3.1.1 Novel Views on Network Architecture

To meet these technical requirements, the 5G network needs to adopt a name-oriented architectural framework in which communication takes place among entities identified by names, without a static binding to their current location. Names must be used to identify all entities involved in communication: content, users, devices, logical as well as physical points involved in the communication, and services. With the ability to communicate between names, the communication path can be dynamically bound to any of a number of end-points, and the end-points (both source and destination) themselves could change as needed. Note that this is a challenge that must be extended across multiple types of technologies from IP to other Future Internet approaches, from systems web-oriented to systems relying on L2 switching.

The separation of identifiers (names) and locators (addresses) provides well known advantages. Current technology already allows for the deployment of a cleaner architecture that decouples the internetworking layer from the service layers, but research is needed on how to perform migration from current architectures to more efficient technical solutions.

Such solutions would allow named entities to be mobile; should enable them to be reached by any number of communication primitives; should allow the pushing of information to a specific set of receivers based on name; should allow choice of the return path independent from the forward path; should support source/initiator mobility and choosing the path at the time the data is sent rather than at the time when a subscription was made (without needing to maintain state in the network for the reverse path); should allow communication to span (simultaneously) networks with different technologies (e.g., exploiting multipath protocols) and allow for disconnected operation. Furthermore, the communication path must be able to be dynamically bound to any number of endpoints, and the endpoints themselves can change as needed. In this sense, the whole network will rely on views very akin to opportunistic routing: instead of choosing known routes, mechanisms that decide the next hop dynamically upon link emergence will be common.

3.1.2 Highly Flexible Connectivity

The current heterogeneity of networks and technologies implies that new protocols and layers should be devised or adapted from existing standards in order to ensure a transparent and seamless end-to-end connectivity between services (sensors, user terminals, cloud services...), including defining the communication model to use (unicast, broadcast, multicast, D2D) .

Network functionalities for dynamically handling network connectivity in a flexible manner as operational conditions vary (e.g., propagation conditions, user positions) need to be developed. Of particular importance will be device and link discovering and pairing. For on-need connectivity, the current pairing times need to be substantially reduced and devices need to have fast mechanisms for device discovery.

Novel connectivity algorithms to determine the best connection opportunities (including multiple access aggregation schemes) for users based on the requested service will need to be developed, along with the mechanisms to realize and to dynamically adapt the connectivity in an efficient manner and without affecting the end-to-end communication, especially considering that some of the interfaces involved may not be running IP-protocols. The intelligence required on such algorithms (and the information required for their proper operation) will increase substantially compared with current day standards.

3.1.3 Smart Orchestration and Use of Network Analytics

The expected complexity of 5G networks demands some "intelligence" in the network. A logically centralized process can analyse the network context so as to, for example, route the data according to the current status or even depending on expected/predicted future events. Additionally, this process can also have self-awareness and learning capabilities for learning from the consequences of its past actions. Cognitive Networking in 5G should be an inherent characteristic of future networks. The process will provide automatic adaptation policies to the different network areas.

However, current "network monitoring" techniques are limited, as they focus on just portions of information, without taking a look at the whole "network picture", across domain boundaries even into capillary networks. These limitations can be overcome using network analytics tools as an additional source of "network monitoring" information, by exploiting advanced big data analysis techniques. Rather than just providing status updates the monitoring analytics will customize measurements according to the need e.g. if device X utilization is beyond 80% for more than T time in a particular user network then apply load balancing policy based on user profile.

Since the instantiated and released functions are believed to become very general in the future, the orchestration should be dynamic enough to be able to *a)* keep track of all available and used resources, *b)* determine the best available resource containers for any required function within delays adapted to the function semantics, *c)* implement different scheduling strategies to best adapt to the different context and different natures of resources (storage is different than computing, etc), *d)* deallocate unused functions and release resources at the end of the execution/lifecycle, *e)* dynamically uphold the required SLA by elastically adapting the allocated functions through additions, re-allocations, etc. Additionally, intelligent orchestration can have objectives like increasing the infrastructure utilization ratio or the number of simultaneously fulfilled user reality instantiations, etc. The orchestration mechanisms per se can be centralized or distributed, depending on the precise requirements on the orchestration. Centralized mechanisms will be able to achieve higher accuracy at the expense of higher requirements on the orchestration platforms or lower overall performs (in terms of request throughput or delay); distributed approaches will suffer from temporarily incoherent views, therefore requiring operations on partial, local views.

3.1.4 Local Wireless and Wired Wireless

Energy considerations and resource optimization will be two important features that 5G networks must comply with – and the diversity of transmission modes, to be expected, require intelligent perception of the localised communication domain. Integrated localisation schemes will be key enablers to communication management and for many new services in 5G. Localisation (and specially neighbouring) can be used to for example relocate video service provision server in the backhaul; or to select the best interface for communication, resorting to cellular or D2D as adequate; or to perform multi-domain network breakout operations. This will become increasingly important with the increasing number (and diversity) of cells.

(There is a need for D2D proximity capability where terminals can communicate directly and without support of a backhaul network. This can be in terms of specific need, range extension or temporarily in a time of outage or adverse conditions.)

However, for such approaches to be efficient, highly improved interactions between the wireless segment and the backhaul network are required, both in terms of performance, complexity (e.g. selecting which traffic to steer, and when) and administrative flexibility (crossing operators). Harmonization of processes is essential here (harmonization of authentication and authorization, harmonization of QoS, harmonization of network views: local data path, short data path, core data path).

3.1.5 The Software Network: Interface Abstractions and Layering

In a multi-technology, multi-connected, multi-tenancy network such as is being envisaged for 5G, flexibility, programmability, dynamic reconfiguration and dynamic resource allocation (spectrum, bandwidth, networking technologies, …) should play a central role. A major goal should be to improve – with respect to the existing situation - control capability on the part of infrastructure and service providers, context- (and, in some cases, content-) awareness in carrying out the actions required by a service, users' Quality of Experience (QoE) and, last but not least, time-to-market service offerings and their deployment. The last point requires easier and uniform interaction (through more powerful and content-rich APIs) of developers with the network and with providers of networking services.

Achieving flexibility and programmability can be fostered by different architectural choices: i) a more aggressive use of virtualization to implement network functionalities; ii) improved control capability, by decoupling the control and data plane and acting on flows at different granularity levels; and iii) usage of software engineering paradigms for simplifying the development of features as network function placement, load balancing, high availability and exception cases handling.

Thus, the diversity of networking scenarios inside 5G networks are such that serious attention should be paid to architecture design interfaces. For full exploitation of flexibility, it is essential that different parts of the communication path can be redesigned and repositioned. It is clear that relying on the often misunderstood "All-IP" concept is not enough to address the complex challenges for deployment of scalable and reliable networks. Interface abstractions, from the user (e.g. metadata to signal application requirements, or some other improved UNI that is able to supersede the basic BSD Socket Interface), network control and service development side, are essential for such dynamic environment. The diversity of situations for M2M communications (continuous connection? Intermittent network? Low bandwidth reliable? Health safety monitoring?) clearly illustrates the radical changes we need on our visions of device-network signalling. On a different view of the same issue, 5G networks will need to develop a clear view of network layering, in order to foster the complex ecosystem we expect. As IP increasingly loses its claim as universal data and control protocol, a new layering structure will need to be found.

Furthermore, such decoupling strategies significantly increase the chances of developing an environment that fosters quick and efficient contributions from various members and obviously from very, and many different networking areas. It will promote evolutionary approaches to network deployment, and will potentiate the usage of virtualization techniques to network deployment, and facilitate federation of networks and services. Deployment of novel network features is an area that will need to be globally researched, and which can be facilitated by proper interface design.

The developments in C-RAN also bring similar problems. The basic concept of cloud-RAN is to separate the digital baseband processing units (BBUs) of conventional cell sites, and move the BBUs to the "cloud" (BBU pool or BBU hostelling) for centralized signal processing and management. For different scenarios of the C-RAN architectures, what is the optimum position of the base band pool and where can be placed? Is it near the central office, or close to cell sites? And what are the interfaces (and which functional decomposition) that should be imposed in these different scenarios? And how can CRAN impact mobility management?

Research is needed to understand what should be the best interfaces and protocols for internetwork and service control and management. (e.g. an API for the application for transmitting their requirements hiding all items which are to be processed under an "intelligent adaptation" of the network?).

3.1.6 Social as a network element

We expect an explosion in the number of user-centred devices in the next years, with increasingly connected human-owned devices. As a result, their traffic will inherit social behaviours. Things will move or generate data according to "social" patterns (i.e. space-time correlation of data generated by things). Exploiting the knowledge about this social behaviour can bring many benefits from the technological viewpoint, such as:

- Interference prediction and coordination techniques at PHY and MAC layers

- Traffic pattern prediction useful at MAC scheduling and RRC level
- Content sharing techniques applied to D2D concepts
- Opportunistic routing in multi-hop networks
- Customization based on the QoE requirements (i.e. not to give more network resources than needed but also not less).

These advantages in terms of better exploitation of network resources provide an opportunity for novel views on network design and control. Tailored QoE should be a usual ability for the system management, potentially context-aware (in function of the user/social aspects/application/service).

3.1.7 Personalized "follow me" Context-aware Networks

Advanced network and service virtualization techniques will allow to dynamically create and move personal networks, that can "follow" the user with minimal or no impact on its network access experience. These virtual networks can be built on top of a variety of network elements at the edge, for example on base stations owned by an operator, WiFi access points owned by the user or even different types of user devices. Such personalized networks can adapt their characteristics to the user profile, location and general context. They also allow providing a homogeneous and customized network access environment to users, regardless of their location and adapting to the end-user device capabilities. By doing this, the users or their devices are no longer concerned with different access networks, access-specific authentication mechanisms, etc. While a similar connectivity experience could be achieved by adding intelligence to the end-user device, the use of context-aware personalized virtual networks removes any dependencies on the user terminal, thus leading to faster deployments.

This faster deployment of new network services on demand will likely benefit from software orchestration mechanisms (e.g., SDN), as they improve the manageability and adaptability of the network, by separating the user and control plane functions and centralizing the latter beyond what can be done today. With approaches such SDN, low level control and management functions can be more easily centralized.

The concept of personalized networks is not limited to the edge, since it can be applied in a more general use case to serve different heterogeneous services on top of the same physical infrastructure. For example, IoT/M2M type of traffic is quite different from high-definition video streaming. Different virtual networks/domains across the whole network might be set up and configured to provide connectivity to different services. Future 5G networks are expected to handle a large variety of traffic with disparate requirements. Therefore, the orchestration of the network resources adapted to both the context and the requirements of the service is an important topic for research.

3.1.8 Integrating Satellite for Increased Convergence

Mobile satellites today provide services to air, sea and remote land areas via GEO operators (e.g., Inmarsat, Thuraya) and non GEO operators (e.g. Iridium, Globalstar,O3b). These operate in L, S, and recently Ka bands, to both handheld and vehicle mounted as well as some fixed terminals. Air interfaces and network functions have tended to be proprietary although some integration with MSS and 3GPP network interfaces exists. Fixed satellites today provide backhaul services to cellular in C, Ku and Ka bands. Satellite has been an overlay, rather than integrated system except in S band where an integrated satellite and terrestrial MSS standard has been adopted.

3GPP like services exist via satellite to individual users, but as yet these have not been extended to 4G. Services to ships, aircraft and fast trains using FSS satellites provide a full range of mobile and broadcast services to passenger vehicles. A growing area of interest is in the transport sector where safety services and V2V are seen as ideal for satellite delivery. Satellite is also used extensively for low rate SCADA applications to/from pipelines, oil and gas remote installations etc. Satellite is also used in cases of failure in the cellular system due to natural or made-made disasters. Increased data requirements for applications such as oil and other mineral exploration and security via UAV's has spurred the need for more spectrum and the use of higher frequencies, e.g., Ka band.

Looking towards the future to 2020/5 there will be a trend to larger and more powerful GEO satellites taking capacities from 100's Gbps to over a Terabit/s. Several hundreds of spotbeams will, via higher order frequency reuse increase the capacity in limited spectrum. Higher frequency bands will also be used—Q/V/W and also optical for gateway connections. Advances in satellite payload technology via new materials and optimised designs will enable up to 30m deployable antennas at L/S bands and increased payload powers from 20 to 30KW. On board signal processing will enable improved connectivity and flexibility to meet changing traffic patterns and demands e.g. adaptive beam forming and hopping and interference management to increase capacity. Alternative architectures involving clusters of GEO's and possibly fragmentation of link functions between the connected (possibly with ISL's) clustered satellites could evolve. Following the innovations of using different orbits by O3b, new non GEO systems are likely to appear possibly using all optical technology—between satellites and from satellite to ground and possibly using constellations of smaller and cheaper satellites.

Satellite and terrestrial system integration is already a trend and this will continue with the development of integrated and interoperable standards to allow the two sectors to interconnect efficiently both at network level and at IP levels. In addition mobility management integration will evolve across the larger satellite and smaller terrestrial cells. Satellite communications systems encompass a wide range of solutions providing communication services via satellite(s) as illustrated in Figure 3.

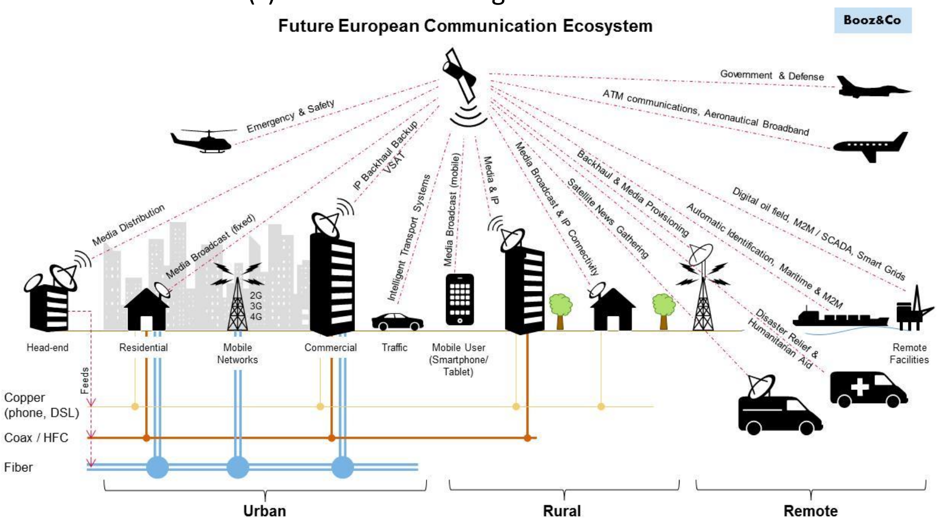

Figure 3: Sketch of satellite role in future communication systems[6]

The integration of network standards is seen to be crucial in these architectures. In particular how the satellite gateway interconnects into the 5G network interfaces. There are various scenarios of interconnection between the network entities that separate the control plane from the data plane that will determine the performance and the signalling load on the networks that needs to be minimised.

A major contribution that satellite can make to 5G is to off-load traffic from terrestrial networks and in particular for video based traffic which is the largest contributor to spectrum demands. This can be achieved by traffic classification and intelligent routing and will thus reduce the demands on the terrestrial spectrum. Satellites have been traditionally used for broadcast purposes but as CDNs become common, the ability of satellites to download high data that can be cached for onward delivery becomes an attractive feature. The interplay with new (inter)network architectures, such as CDN is important to consider for SatCom/cellular

[6] From Booz&Co, "Why satellites matter", http://www.esoa.net/news-info-30.htm

integration. Pervasive caching and naming of information and content transferred over the networks would more easily allow the inclusion of SatCom into an integrated Satellite-Terrestrial network by exploiting the broadcast/multicast and broadband capabilities and masking the longer propagation delay, improving overall performance with caches at the edges. QoE is becoming the byword for service provision and a major differentiator, but it is little understood at the moment. It is clear that peak and average bit rates are not the determining factor but sustainable bit rate links more to the QoE. Intelligent delivery of services using the systems that best suite the QoE to the user is another area in which satellite can play a part.

Integrated localisation schemes are key enablers to many new services in 5G. The notion of per-user integrated location and service management in cellular/satellite systems should be investigated either to help in spectrum sharing or to improve trunking systems. A Per-user service proxy can be created to serve as a gateway between the user and all client-server applications engaged by the user. The aim is that whenever the user's location database moves during a location handoff, a service handoff also ensues collocation of the service proxy with the location database. This allows the proxy to know the location of the mobile user to reduce the network communication cost for service delivery. Different users with vastly different mobility and service patterns can adopt different integrated location and service management methods to optimize system performance.

The integration of satellite (GEO and non-GEO) and terrestrial can be used to extend the 5G network to ubiquitous coverage. For example to sea—cruise liners and yachts, to passenger aircraft, trains and even to remote locations such as holiday villas. A simple example is via backhauling but this can be done in an intelligent manner by routing traffic either over the satellite or terrestrially depending on the content and the required QoE. IoT coverage to wide areas involving sensors and M2M connections are ideal services to make use of satellite wide area coverage. The challenge is to design efficient low data rate communications in large numbers via the satellite. Transport services including V2V are again ideal for satellite with its wide coverage. In the safety market all new vehicles are likely to be mandated to include safety packages and given the need for ubiquitous coverage systems that follow on from the EU SAFETRIP system demonstration will play a key role. Furthermore, we foresee the provisioning of a robust, virtually infrastructure-less network for safety and emergency networks, highly distributed enterprise networks and backhaul alternative for isolated and remote areas.

Localisation and positioning is key to many different 5G services. The integration of cellular and satellite positioning systems is a key challenge to enabling this vast range of services. Satellites are already used for earth resource data, which is in itself used as an input to many new services. Coupling this with integrated satellite and cellular communications will provide a powerful new fusion enabling the innovation of services. Future 5G system will include the integrated provision of communication, localization and sensing on a global and very accurate scale.

Security services require high resilience and thus the use of satellite together with cellular delivery will help provide the availability required. Most countries have fallback disaster and emergency networks, which can benefit from an integrated satellite and cellular approach. There is increased use of surveillance using UAV's and the necessity for real time high definition video, which is best delivered by satellite.

3.1.9 Security, Privacy and Trust

Security is a crosscutting topic that needs to be carefully considered by design from the start. Secure mechanisms must be developed that allows access to only authorized parties (both in human form or through agents) in creating/configuring a virtual network. It must be flexible enough to accommodate the increased and multi-dimensional dynamics introduced by fine-grained virtualisation. Additionally, isolation between virtualized networks has to be guaranteed as well as providing trust for the virtual infrastructure users on the virtual service enablement.

Security solutions for assuring integrity, privacy and access to information are challenged by emerging data protection legislation and simply the human desire to produce, own, share and control information. Often, data exchanged is expected to include information from several critical services such as emergency or medical information that must have full network availability as well as security and confidentiality protection measures. These vectors are transversal across areas, and need to be supported in all research aspects. It is worth to note that the diversity of scenarios considered will unavoidable imply that the trust guarantees of future network providers will vary greatly, presenting network designers with a completely different scenario for trust establishment. Countering anomalous dysfunctional and/or malicious activity is of key importance for assuring the protected operation of the network and maturity of the components from which it is constructed.

Current networks are comprised of secure pipes that terminate in insecure endpoints. Virtualised endpoints, agents or network functions will become more granular, increasing the number of secure pipes and the complexities of trust, overcomplicating modern day public key schemes. New techniques such as Identity Based Encryption (IBE), Attribute Based Encryption (ABE), functional encryption and fully homomorphic encryption offer new solutions, which should be addressed from the start. New key management techniques are of primary importance.

Furthermore, BYOD and mobile sensing based on common smartphones brings new possibilities for using mobile devices to gather data about users and, as consequence, about the world or some specific circumstance. The usage of mobile phones as means to collect and analyse behaviour patterns of individuals and environment in order to understand how events affect their behaviours and, consequently, how potential events can be automatically detected starting from data collected by a number of users, poses specific challenges as open and big data issues may improve network and service delivery, but user privacy needs to be balanced in this process.

Trust establishment is currently rigidly defined, and largely centralised. As networks become more capable to operate at the speed and agility of a person embedded within their online virtual and pervasive world, It is required to have trust relationships to largely map the changing trust environment of the people and enterprise using that network. This begins to move away from secure network transactions and more towards the information itself being implicitly secure, hence supporting the changing sensitivities of the information and the impact that information has on those making decisions based upon that information and the effect on the real physical environment. New techniques such as Identity Based Encryption (IBE), Attribute Based Encryption (ABE), functional encryption and fully homomorphic encryption offer new solutions, which should be addressed from the start. New key management techniques are of primary importance here.

3.1.10 Effective Service Development and Deployment

5G networks call for successful handling of many and demanding requirements. This has a major impact on service development and deployment, bringing specific challenges to proper application provisioning. It is important to stress on the following requirements:

***Rapid, easy and dependable application/service deployment*:** Rapid service deployment is needed in order to follow the rapid pace of changes of services and applications. Aspects as faster conformity testing, and automatic seamless handover to an updated system are essential in this context.

Intelligent adaptability to varying conditions: The guarantee of high QoS/QoE levels that will be relevant to the deployed applications/services (corresponding to a certain level of service availability, performance, reliability, and usability) will need novel and intelligent approaches to lead with extremely varying networks.

Support scalabilit: We will need to support proper application provisioning in very demanding and changing contexts of operation, e.g., 1000x capacity increase in 10 years with billions of users and trillions of machines/things. System consolidation is also an issue, as extreme diversity may lead to unmanageable service requirements (provisioning 1000 devices with the same firmware is much less complex than provisioning 50 devices with 20 types of firmware).

3.1.11 Agile Management Frameworks

In the future, often virtualized, networks, advanced management techniques are required to manage the deployment and to follow the dynamic nature of the network and their integration into the end-to-end communication infrastructure. Following the path initiated by the virtualization platforms in the computer world, mechanisms for the group management of network appliances, the dynamic creation and setup of network functions and their associated entities are important research issues. Management and orchestration also requires awareness of the underlying resource availability, while pure processing and storage tasks for network functions can be shifted to parts of the network where sufficient resources are available, the actual underlying link capacity will be limited by the physical boundaries of the transport medium. Management functionality needs to be resource aware and to consider not only the most opportune location to execute virtualised network functions but also the availability of the underlying resources (e.g., honouring the difference between moving virtual functions for execution into capillary networks or into a cellular access network).

A powerful (self-)management framework is necessary in order to achieve optimality in 5G systems and meet strict usage and development requirements (e.g., acceleration of deployment, high QoS/QoE, proper application provisioning in demanding environments, lower cost of the infrastructure, cost and energy efficiency). Such a system may rely on traditional components of management frameworks: (i) data and context acquisition; (ii) fast immediate automatic adaptation, to maintain system operation; (iii) analysis and learning, to guarantee continuous optimum performance, and (iv) decision making, to select the most important aspect at a given time. Nevertheless, higher degrees of intelligence, adaptability and self-management are expected. A problem that will be compounded by the need for multiple management systems, including multiple Radio Access Technologies management platforms, to negotiate and agree in stable operation points.

This approach requires network architecture capable to enable network-wide observation and sensing (beyond spectrum occupancy, and including quantities such as protocol parameters and state variables, traffic, channel statistics, transmission and error events, interference, human behaviour, and so on) as well as data collection from various layers of the protocol stack. In this architecture, communication nodes shall perform sensing and data collection, as well as dissemination of appropriate information, in order to achieve situational awareness through sensing, model building from new data and situations, and exploitation of past experience to plan, decide and act. Furthermore, all these actions may have to be performed with strong energy efficiency considerations in place. Future 5G network should be highly energy efficient without compromising the expected user quality of experience, and the above aspects of self-network management, covering variable topologies, device reconfiguration and intelligent setup functions have to be enabled in the network.

For instance, context acquisition can target the monitoring of contextual situations as soon as they are created. Contextual information includes the traffic, mobility and radio conditions. The output can describe the contexts encountered with respect to the aforementioned parameters, as well as the likelihood of encountering similar contexts in the future. Learning mechanisms can then target the development of knowledge regarding the handling done to encountered contexts (e.g., system configuration applied), the potential alternative handlings, and the respective efficiency of each handling. It can rely on reinforcement learning techniques. Finally, decision making will be responsible for the designation and execution of optimal solutions in order to handle specific situations (e.g., which cells are capable of providing extra capacity when needed etc.) according to the specific contexts encountered, in conjunction with the knowledge built from previous, similar handlings.

As another example, the network shall be able to recognise a data flow generated by a user that is watching a video streaming while commuting by train from office to home. By exploiting the context information, the network management system proactively distributes video chunks to the servers along the path followed by the train, in order to guarantee that the required video sequence is readily available from the closest server as the train passes by. Furthermore, the network management system may temporarily increase the data transfer rate before predictable connectivity holes (e.g., when the train enters a tunnel), in order to buffer enough data for overcoming the outage period. Furthermore, recognizing the type of video content, the network is capable of determining the source encoding that guarantees the best QoE to the final user depending on the current conditions of the connection, and to selectively drop the enhancement layers that cannot be delivered.

Due to the new business possibilities that network virtualization offers, an efficient service delivery management has to be carefully implemented. Relations between resources, services, providers and users can bring a complexity that virtualization may hinder. Different service provider roles may involve hierarchy of virtualized infrastructure increasing the complexity of service deployment. Therefore, a proper service management should consider the required information (e.g., ownership, access rights, delegation, context, SLAs) to allow a multi-level management while keeping consistency among the different layers.

3.2 Wireless Subsystem

5G wireless research happens in different regions in the world. In the EU the H2020 program sets a strong position for ICT 5G research. However, for the aim of consensus building in later standardization activities, an early collaboration with other regions is important. The competitive element of research in different regions foster the innovation, but finally a global standard has to emerge. The EU already started joint programs in FP7, and in call 1 of H2020 we find a wider range of global collaboration possibilities.

The 5G collaborative research, as conducted in the framework of EU funded research programs, starts in an environment and with a timeline where companies not yet competing with products. This allows collaborative research and focus on certain scientific topics, by organisations, which are usually competing in their markets. The collaborative research is an excellent way for early consensus building about the gains and pains related to potential new technical concepts. Further, the phase of collaborative research allows as well the provision of fundamental needs for later standardisation work, like the design of channel models and reference scenarios.

H2020 call 1 projects can influence work in standards and ITU and provide input to ITU WRC 18. In bodies like 3GPP it is always difficult to predict the duration of actual and planned releases, and therefore it is difficult to predict how the H2020 project cycles and the 3GPP releases will synchronize. However, the call 1 ICT projects have a clear potential to impact the release 14 and 15 work in 3 GPP. ICT projects in later calls can than potentially refer to existing study and work item activities, which have its roots in call 1 results, and can help to drive the future feature evolution.

3.2.1 Novel RAN Architectures

Macrocellular centricity has dominated cellular network architectures until now. In order to greatly improve mobile networks capacity, several new architectural components can be foreseen:

3.2.1.1 Heterogeneous Networking & Ultra-dense Small Cells Deployment

Future networks will need to be deployed much more densely than today's networks and will become significantly more heterogeneous than today. They will become more heterogeneous in terms of: transmit power, antenna configuration, supported frequency bands, transmission bandwidths, directional blindness, multi-hop architecture, and duplex arrangements. The radio-network architectures of the nodes will vary from stand-alone base stations to systems with different degrees of centralized processing, depending on the available backhaul technology. One major venue in 5G networks is dense deployment of small cells coexisting with micro and macrocells as well as other systems such as WiFi, LTE/A and HSPA, comprising a Heterogeneous Network (HetNet). Interference and cell densification is beneficial already at frequencies below 6GHz at current and possible new frequency allocations. New methods for spectrum sharing are of particular interest in small cells domain. Some of the foreseen developments imply drastic changes to operator roles – new business models need to be justified. Providing ubiquitous communications in mobility and enabling continuous evolution from legacy to future systems will require seamless integration of all available technologies, where the concepts of seamless vertical handover, multi-technology data load balancing and multi-operator roaming must be generalized. At the same time, ultra dense small cells deployment will not happen without the appropriate means to reduce site acquisition and installation costs (such as using relays not owned by the operator, self-backhauling techniques…).

3.2.1.2 Efficient Wireless Backhauling

Due to novel network architectural components and explosion of such network nodes, single and multi-hop wireless backhauling will become very important in the future. Thus, more efficient transmission mechanisms need to be developed. Inclusion of mobile network nodes requires intelligent and self-adaptive backhauling techniques, for example using intelligent Routing of services between satellite and fixed links to off load traffic. For small cells, a number of wireless backhauling options can be implemented including Line Of Sight (LOS) technologies such as microwave, millimetre wave, and non LOS technologies, such as WiFi and cellular radios. Since most small cells will be deployed at non-conventional locations, including street furniture or sides of buildings, where fibre availability will be limited, the wireless options may be preferred. In case of millimetre wave technologies, dynamic beam-forming is a key technique to enhance robustness and to enable reconfiguration of the backhaul topology.

Another backhaul and fronthaul option may include sharing/using the available fibre-to-the-home/building (FTTH/FTTB or more generally FTTx) with fixed optical access. From the energy efficiency perspective, one should remember that backhauling/fronthauling itself also consumes energy and cannot be neglected for a larger amount of smaller cells.

3.2.1.3 Self-Organising Networks

The increasing network heterogeneity and dynamicity lead to increasing complexity and efforts of the Operation, Administration and Maintenance (OAM) of mobile networks. Self-organising Networks (SON) are the first step towards the automation of OAM tasks, introducing closed control loop functions dedicated to self-configuration, self-optimisation, and self-healing. Extremely automated systems have to follow high-level operator goals regarding network performance and reliability. Cognitive Radio Networking principles are used to achieve end-to-end operator goals and many existing results can be used to greatly improve OAM functions. Synergies between SON and Software Defined Networking (SDN) architectures and protocols should be studied.

3.2.1.4 Context Awareness and Dynamic Caching

By harnessing recent advances in storage and computing/processing, dynamic caching can help alleviate backhaul congestion, reduce loads at peak times and minimize latency, by pre-caching contents at strategic network edge locations. If smartly coupled with meta-data analytics, network operators can further exploit the vast amount of users' context information (location, speed, etc.) for a better predictability of future demands, to proactively cache popular contents before users actually request them. Contents can be cached at small cell base stations, user terminals or intermediate network locations such as gateways and home set-top boxes. Moreover, content caching lends itself to proximity-based services and D2D communication, where users can turn into "prosumers" to help disseminate contents. Making dynamic content caching a reality hinges on addressing a number of key challenges such as what/where/when to cache? Bit-wise versus content-wise caching, joint routing with caching among multi-ISPs, scalability issues, as well as changes to the current architecture.

3.2.1.5 Quality of Experience (QoE) & user-oriented wireless resources management

Quality of Experience (QoE) is a complex concept which is related to subjective user perception, while using a given service/application. A key innovative target that future networks should provide, is the ability to minimize the difference between the personalized QoE level perceived by a given user while using a given service/application, and the QoE level expected by such user while using the service/application in question.

3.2.2 Intelligent Radio Resource Management

The use of various spectral resources in HetNets and especially the exploitation of mmWave bands that have not been used previously in cellular networks impose the need for intelligence on the management of the radio resources. First, a management framework should be developed that will coordinate and optimize the access of the users to the mmWave ultra-dense networks. Furthermore, due to the utilization of wireless backhaul the joint management of the resources in the wireless access and the backhaul shall be introduced.

In order to estimate high quality solutions to the radio resource management problem a knowledge-based approach should be followed. Specifically, the algorithms that will provide the solution shall take into account the capabilities of the network entities (e.g. possible operational RATs and spectrum bands, transmission power levels, etc.), the network context (e.g. current operating RAT, spectrum, transmission power, interference, battery level, etc.), as well as previous solutions in order to estimate better solutions (in terms of quality and runtime).

3.2.3 New Air Interface

The air interface is the foundation on which any wireless-communication infrastructure is based. The properties of the different air-interface protocol layers (physical layer, MAC layer, retransmission protocols, etc.), and how these operate together, are thus critical for the quality-of-service (QoS), spectral and energy efficiency, resilience, and flexibility of the entire wireless system. One of the key drivers for the evolution of the air interface is the paradigm shift from larger coverage cells to smaller and smaller, less and less regularly deployed cells dominating network architectures; hence, this viable change has to be carefully studied as an enabler for novel technical solutions to provide the expected services despite the fact that the available spectrum does not increase in the same proportion.

3.2.3.1 Novel transmission technologies

Different means to further enhance spectral efficiency and flexibility/robustness, e.g., improved spectral containment allowing better coexistence with services in adjacent bands, and thus efficient implementation of Cognitive Radios (CRs), beyond that of conventional OFDM, should be pursued. This includes more general multi-carrier transmission schemes, as well as other transmission approaches that may not be based on the multi-carrier principle, such as full duplex transmission (realizing the merge between FDD and TDD). An example candidate is the FBMC (Filter Bank Multi Carrier) technique, and its variations, white space techniques. Radio resource allocation technologies based on non-orthogonal multiple access and removing the synchronicity assumption must be investigated in the near future, along with advanced interference handling, e.g. including interference classification and alignment for both mobile and satellite.

3.2.3.2 Advanced Multi Antenna Transmission Reception (including 3D MIMO beam-forming)

Although today multi-antenna transmission/reception is an established technology component in state-of-the-art mobile-broadband technologies, such as HSPA and LTE, much can still be done to fully exploit all its potential, on both link and system levels. This includes more robust multi-antenna transmission schemes (e.g., in terms of limited channel knowledge), as well as extending their capabilities to provide efficient and flexible multi-user multiplexing. A more radical technology step is to extend current multi-antenna schemes, typically consisting of just a few antenna ports at each transmitter/receiver node, towards massive multi-antenna configurations, in the extreme case consisting of several hundred antenna ports per site and even more remote antennas provided by remote radio heads (RRH), cooperative multi-point base stations (CoMP) and user-assisted cooperative transmission.

Benefits from diversity in time, physical space and frequency should be increasingly sought in combination, whereas current techniques typically only see use of only two of these dimensions.

3.2.3.3 Disruptive Transmit and Receive Architectures

The future of mobile communications will include a vast variety of communication nodes with various sets of requirements and roles. Some have to be designed with primarily the Quality of Experience (QoE) in mind, some call for the highest energy efficiency, while for others the emphasis will be on robustness and security. This variety in requirements and roles needs major improvements in designs in terms of flexibility, concerning both the network and the architectural design of the nodes. Outsourcing computation intensive tasks to the network cloud is already a new and promising paradigm, but power amplifiers and other components will also have to be revisited with respect to the energy-saving potential.

3.2.3.4 Visible Light Communications

The visible light is part of the EM spectrum that has unregulated optical bandwidth between 400THz (780nm) and 800THz (375nm). This part of spectrum is beneficial as it is licence free and has no known health concerns. As visible light has no interference with RF, it allows simultaneous exploitation of both spectrum bands for 5G small cell networks. To support the capacity, efficiency and security proposed in 5G, it is beneficial to have such optimum usage of the EM spectrum.

In the last decade visible light communications (VLC) has been a subject of increasing interest and development due to scarcity of radio spectrum. Such interest can be traced back to the relatively recent development of white LEDs (Light Emitting Diodes) and by the fact that there is more than 300 THz of bandwidth readily available in such optical channels. There are, however, several challenges that need to be tackled before VLC is widely adopted. They include developing techniques that will help to mitigate problems caused by ambient light and shadowing, and evaluating capacity for VLC. It is indeed essential to show that full-fledged optical wireless networks can be developed by using existing lighting infrastructures. This includes multi-user access techniques and interference coordination.

VLC is relevant not only because is expected to impact both low data rate applications, e.g., positioning or asset tracking, and high data rate applications, e.g. video transfer, but also by the possibility to combine communication and energy harvesting. Light communications can also be applied to constellations of small satellites (e.g., Cube Sats) both from earth to space as well as inter satellite for providing global coverage.

3.2.3.5 Energy Efficiency

Energy efficiency of mobile networks has for long not been a dedicated research or design topic, yet efficiency has continuously improved. This has been driven by hardware gains due to Moore's Law and better utilisation of high SNR channels (modulation close to Shannon's limit). Further, smartphones and data flat-rates have driven the utilisation of services, so that systems are more and more operating in a heavily loaded mode than in a coverage limited deployment with high energy consumption for little traffic. These effects promise a 1000x improvement of energy efficiency within the next 5 years. However, both of these drivers for energy efficiency are more or less exhausted. The expected further growth of data subscriptions, data rates and data volumes threatens to drive up energy consumption, deployment cost and operation cost of mobile networks. A new 5G system concept needs to drastically reduce the energy consumption per Mbit. All aspects of a mobile communication system need to be studied and improved for higher energy efficiency: hardware efficiency (especially in new bands in the 30-90GHz range), reduction (coordinated transmission, beamforming and massive MIMO), new radio waveforms with less control overhead, deployments with shorter transmission ranges (ultra-small cells, D2D), faster transition from idle to connected mode (connection-less transmission, control overlay separate from data services, dynamic network management (load adaptive and context aware activation of additional resources), task offloading, and service provisioning (content caching, multicasting, opportunistic transmission).

3.2.3.6 Machine type Communications

Massive Machine-to-Machine (M2M) communication is expected to be one of the major drivers for new radio access technologies in 5G, fostered by a ubiquitous and transparent coverage for the massive deployment of sensors, actuators, RFtags, smart metering, and other Machine-Type Devices (MTDs). Forecasts indicate that in 2020 cellular networks will likely serve a factor 10 to 100 more MTDs than personal mobile phones with the number of MTDs connected to single base stations in the range from 10.000 to 100.000. While current cellular standards were conceived for relatively few devices with high data rates, a single MTD often only generates small amounts of user data, shows very diverse channel access or traffic patterns (triggered, periodically, sporadic or random), needs to be low-cost and very energy efficient to operate for long-lifetimes. As a consequence, new radio access technologies are required that are capable to support signalling and access structures of massive Machine-Type Communication (MTC), e.g., novel physical layer and medium access layer technologies. As an example, technologies with less PHY and MAC signalling overhead need to be designed for handling the low data rate, sporadic MTC access achieving a balanced payload to overhead ratio. Significant improvements in energy efficiency against performance are also needed. Future MTC will benefit from energy scavenging and emerging paradigms for passive or extremely low power system operation (e.g., based on wake-up radios, passive backscattering technologies). One of the major challenge in designing novel MTC technologies is the huge variety of requirements in M2M communication ranging from very resource efficient highly reliable, low latency cases to latency and error robust long-term data acquisition applications. Recent approaches exploiting statistical MTC signal structures such as sparse multi-user detection facilitating a joint data detection and signal acquisition or exploiting correlation properties of sensor signals minimizing the access attempts have shown to be promising for the application in 5G cellular networks. Furthermore, recent work in random access design has shown promising new schemes that enable very high efficiency random access even for massive number of MTDs. The communication paradigm in M2M systems spans from traditional unicast/multicast/broadcast primitives to data centric/anycasting/geocasting. System level optimization is needed to scale up to dense, city scale systems. The fact many applications require information that can be provided (according to anycasting, geocasting, or data centric networking paradigms) but any among a group of MTDs creates significant opportunities for system level optimizations. Such optimizations can exploit knowledge on the channel, energy availability, and MTC resources to provide the information required by the applications by solving the trade-offs between maximum energy, throughput and latency performance.

Since machine type, human-to human and human-to-machine generated traffic have different characteristics, future 5G networks have to deal with such new traffic patterns. 3GPP has a task group working on specifying the services and features of MTC for network improvements. The MTC services proposed by 3GPP can help address some concerns as QoS, still in early stage of development on this type of communications, helping in optimizing the coexistence of different use cases on the same network (different QoS for different MTDs, as traffic requirements and patterns differ widely according to the use case in MTC).

Below is a table that shows the identified service types in MTC:

MTC Feature	Feature description
Low mobility	Rarely moving or only moving within a certain area
Time controlled	MTC data delivery only during predefined time intervals
Time tolerant	Data transfer can be delayed
Packet Switched (PS) only	MTC device supports only PS services
Small data transmissions	Only small amounts of data are exchanged
Mobile originated	Only MTC devices utilizing only mobile originated communications
MTC monitoring	Monitoring events related to particular MTC Devices

Priority alarm	Priority alarm generation upon the occurrence of a particular event
Secure connection	Secure connection between MTC devices and MTC servers required
Location specific trigger	Triggers MTC devices in a particular area
Network provided destination for uplink data	Uplink data to be delivered to a network provided destination IP address
Infrequent transmission	Long period between two data transmissions
Group based MTC features	Functions for associating a MTC device to multiple MTC groups

Table 1: MTC features in 3GPP

Traffic flow types for testing QoS parameters on next generation model networks can be found on the ITU-T recommendation Q.3925, where the characteristics of the traffic flow on ubiquitous sensor networks section is of interest when modelling MTCs.

3.2.3.7 Terrestrial Broadband-Broadcast Convergence

Today, mobile radio and terrestrial broadcasting are completely separated realms. Mobile radio networks are of the LTLP (Low Tower Low Power) type whereas High Tower High Power (HTHP), due to economic reasons, is characteristic of broadcasting. LTE, the most advanced mobile radio technique, includes a specification of a broadcast mode, but the use of it is still at a very early stage. DVB-T2, its counterpart on the broadcast side, is only applicable for the purposes of broadcasting. On the other hand, the use of broadcast and broadband are coming closer and closer to each other. Internet connectivity is becoming common for TV sets. Each smartphone and tablet computer is a possible TV and radio set. At the same time, an approximation of technologies is taking place as well. LTE and DVB-T2 are both OFDM-based at a comparable level. Consequently, it is an obvious option to merge mobile radio and broadcasting systems in the future. The next stage of development of mobile radio techniques (“5G”) could have an inherent hybrid character, suitable for mobile radio and broadcast services of all kinds equally. Consequently, it should support the combined and flexible use of HTHP and LTLP networks in broadcast layers. The key requirements for 5G technologies concerning the integration of broadcast capacities still need to be clarified.

3.2.4 Spectrum

Spectrum remains the critical resource for all radio communications, which the mobile sector have increasing managed to secure to successfully roll out services to citizens across Europe. However as technology improves in terms of spectrum efficiency and bit rate our precious spectrum allocations remain segmented in islands. This presents problems in mobile terminal design, as space limits the number of antennas, especially as the frequency getting lower. LTE advanced have introduced a technique to join the islands, carrier aggregation, but phones can only implement a limited number of individual bands, and an even smaller number of band combinations. This is creating a fundamental limit on the maximum bit rate and trunking efficiency that can be achieved in real devices with physical size limitations. This has to be overcome if 5G systems are to meet their goals.

There is underutilized spectrum in the millimetre-wave frequency bands above 30GHz, which is a potentially viable solution for achieving tens to hundreds of times more capacity compared to current 4G cellular networks. Historically, mmWave bands were ruled out for cellular usage mainly due to concerns regarding short-range and non-line-of-sight coverage issues. Recent results from channel measurement campaigns and the development of advanced algorithms and a prototype, clearly demonstrate that the mmWave band may indeed be a worthy candidate for next generation (5G) cellular systems[7].

[7] See Rangan, S.; Rappaport, T.S.; Erkip, E., "Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges," Proceedings of the IEEE , vol.102, no.3, pp.366,385, March 2014

3.2.4.1 Sharing – different schemes, business models

Spectrum sharing between different technologies has long been seen as one way to increase the maximum contiguous chunks of spectrum available for mobile services. Bands such as the original GSM 900 and 1800 MHz have now been opened up to the latest LTE technologies. However, there are fundamental limits that have led 3GPP to only allowing 10 MHz allocations in the 900 MHz band (LTE band 8), and 20 MHz at 1800 MHz (LTE band 3) with reduced receiver sensitivity. Hence, as operators work together with spectrum, site, and radio sharing, the impact on the maximum bit rate and spectrum efficiency is limited.

Beyond these aspects, one has to look into the sharing of spectrum between different services (e.g., broadcast and Internet) and service providers due to the underutilised spectrum in many bands, because the entities or systems to which spectrum is allocated do not use it continuously, from the perspectives of space and/or time and/or even frequency. The development of techniques to efficiently use these spectrum slices could improve their use, and minimise the problems of lack of spectrum for the increased number of services and usage that are fitting into today's bands for mobile and wireless communications.

Research should be focused in providing a way in which all communication services can opportunistically use any portion of non-used available spectrum. This opportunistic use will lead to maximum efficiency of spectrum use and will also pave the way for a dramatic reduction of economic waste regarding the provision of future increased spectrum resource demand communication services.

For allowing a realistic implementation of a European-wide Dynamic Spectrum Access framework and scenario, there is the need of establishing a related economic and market model which supports it. The establishment on the principle of a secondary market approach is one of the most promising business approaches. Such model would exploit the already proved efficiency creation that financial secondary markets foundations provide, which have already been extended to other assets. In the scope of spectrum sharing between spectrum owners, this approach would introduce the figure of "spectrum brokers" as neutral harmonizers of prices and facilitator of economical interchanges between spectrum owners. This would be a breakthrough in spectrum allocation policies, fostering economic efficiency and the implementation of an automatic and real-time spectrum allocation scenario.

3.2.4.2 New allocations below 6GHz

WRC-15 aims at concluding the years of negotiations over the digital dividend. CEPT[8] has been mandated by the European Commission to develop a preferred technical (including channeling) arrangement and identify common and minimal (least restrictive) technical conditions for wireless broadband use in the 694 -790 MHz frequency band for the provision of electronic communications services. ECC PT1 is developing the response to this EC mandate, supported by CPG PTD on that issue, this will almost certainly limit the available bandwidth of a single LTE channel to 10 MHz.

Early preparations for WRC-18 have not seen any move to bring the 40 separate LTE global frequency bands together. Migration of existing services is seen as a fundamental roadblock that could take decades to resolve. Thus, it appears that no new allocations below 6GHz for terrestrial 5G services are possible, although refarming opportunities should be studied to support the booming needs of 5G users.

3.2.4.3 mmWave bands

Due to the combined problem of the increased shortage of new exclusive spectrum for mobile broadband systems below 6 GHz and of the fragmentation into small islands, higher frequency bands have been gaining increasing interests. mmWave spectrum can enable large bandwidth frequency resources.

[8] For more information about CEPT, see http://www.cept.org/cept/about-cept

Bands for mmWave are typically defined as being in the frequency range of 30-300 GHz. For the field of 5G research the target is a range between 20 to 90 GHz, and the research in this field should look to EMF aspects, link budgets, propagation issues, and channel model description. Later stages of 5G research may look to a wider range of potential spectrum. Both fixed and satellite links currently use mmWaves and a key research issue is how mobile can share these bands equitably.

Figure 4 shows the atmospheric impact on the chosen band. Different application and deployment scenarios may call for use of different band selections. For 5G, the mmWave band use will not be an independent radio system, instead it will be a component part of the 5G air interface design, and integrated with as a mobile broadband system, together with the legacy generations.

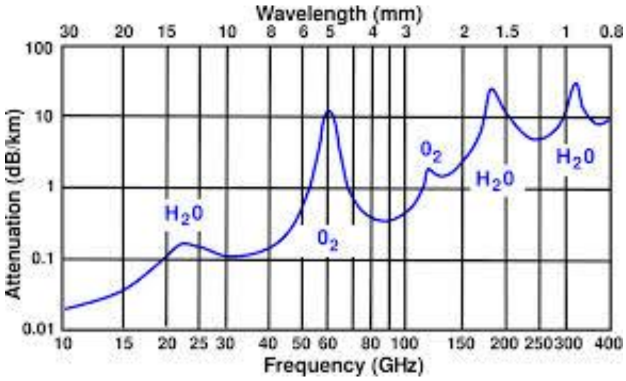

Figure 4: Atmospheric attenuation under different frequency bands, not including rain or clouds

mmWave will be used for user access, backhaul and fronthaul applications, meshed relay implementations, potentially sharing the same radio resources. In contrast to current mmWave research, 5G will look to a wider range of applicable spectrum. In order to increase the distance over which a mobile terminal will be able to communicate with a base station, novel design concepts are being considered for the 5G harmonized air interface, not re-using IEEE and 3GPP concepts with their known shortcomings. Close integration with the mobile broadband concept will allow new ways of load balancing, system operation and procedures.

3.2.4.4 Spectrum and Satellite

The 5G air interface has the challenge of incorporating a range of different traffic types from the high rate video down to the low rate IoT applications and serving applications with a range of latency requirements. We see that the integration and interoperability of satellite and cellular 5G is essential to extract the combined benefits of both sectors. In this respect, we need to adopt as far as possible a common AI. The drivers in the **satellite channel** are however different compared to those in the cellular—multipath is not so important but the channel is non-linear and suffers from more latency inhibiting adaptation—depending on the satellite orbit. There is much to gained from an integrated terminal which uses as much commonality as possible with terrestrial via ideas of implementing software MAC for example. This needs to be coupled to the energy reduction that can be achieved in the terminal design. Receivers for bursty communications are an area of research that will benefit the role of satellites in IoT. Multicarrier schemes such as filter bank systems with appropriate modulations that offer optimal spectral efficiency and frequency granularity are being investigated in terrestrial wireless but also have commonality in satellite systems. As already mentioned, increasing the spectrum available to both satellite and terrestrial systems via cognitive techniques represents an opportunity.

3.2.5 5G Channel Model

With the novel system design of 5G networks the knowledge of the propagation and channel conditions in a radio link needs to improved, during communication, so that the system can take advantage of this, hence, increasing performance in coverage, interference, data rate, capacity, delay, dependability, and set-up, among many other metrics. Furthermore, many aspects still need a better understanding, like depolarisation and influence of vegetation and new materials. Antennas are part of the radio cannel, and their increasing active role in the communication link implies that new approaches are taken not only on antenna design (considering both the electrical specifications and the increasing mechanical constraints) but also on their performance characterisation in random operating conditions.

Therefore, the existence of accurate propagation and channel models for both mobile and satellite are a key component in the quest for 5G, supported by theoretical development, simulation approaches, and measurements. Concerning the last ones, given the human and financial effort required to perform them, a coordinated perspective is strongly desirable.

Given the rationale above, quite a number of research priorities can be established, addressing the many dimensions at stake, and crossing them (actually, the simultaneous consideration of multiple of theses dimensions is quite a challenge per se) . Further research and development is required in the following areas of propagation and radio channels models:

- very high speed scenarios, associated to transportation (e.g., trains) and to environment variation (e.g., vehicle to infrastructure);
- a more accurate characterisation for "new" deployment scenarios (several body postures, interior of transportation means, all possible location of devices, consideration of the huge range of applications, including body-centric, crowded environments, transportation, and machine-to-machine, among many others);
- multiband and wideband signals, and carrier frequencies above UHF, namely millimetre waves, and not neglecting Tera-Hertz; accounting for the impact of small scale fading in channel estimation problems;
- very short range communications, accounting for the influence of the surrounding environment;
- statistical characterisation of complex environments, addressing space, time, space-time and frequency correlation, obstacles and vegetation, polarisation;
- characterisation of antenna performance, namely a statistical approach for radiation patterns and beamforming, and in near-field conditions;
- Integration of systems to provide improved coverage and user QoE, e.g., via satellite and cellular integration;
- An explicit (striving to be implicit) consideration for security and resilience, considering all aspects of availability, confidentiality and integrity.

Furthermore, other axes should be considered, complementary to the previous ones:

- more efficient tools and algorithms (e.g., on ray-tracing), namely for full three dimensional characterisation of environments, but dealing with the complexity-accuracy trade-off;
- propagation and channel measurement techniques, enabling to obtain time and spatial characteristics in a more efficient way, taking both deterministic and statistical approaches;
- enablers of accurate position estimation, security, maximum capacity and massive MIMO, energy efficiency, and other applications of these models for "high layers".

3.2.6 Highly Flexible Communication Systems

5G networks will consist of heterogeneous networks interoperating in a clever way offering seamless networking to the user. This will require from all linked network devices the flexibility to switch to the best operating mode available to offer the best experience to the user or the requested service. Configurability of the mobile SoC, the underlying hardware and software will be key to support the necessary flexibility in space and time. Higher integration of various functionality in the mobile SoC based on 'More than Moore' technology evolutions and novel signal processing and circuit architectures based on 'More Moore' scaling evolution will be essential to build fully integrated flexible network devices.

3.2.7 Energy Efficient Devices and Networks

Higher performance, higher flexibility should not come at a cost of increased energy consumption. A large variety of devices ranging from sensor-like devices over high-capability personal devices will exist in the network. Energy efficiency is mandatory for all these devices. Semiconductor technology scaling will help this evolution, but possibly not as strong as it has been over the last decade. Smarter design and implementation to cope with lower power consumption will be a big challenge. Rethinking the fixed network infrastructure will be equally important to improve the energy efficiency of the network itself.

3.2.8 Implementation Challenges

Semiconductor technology scaling has driven mobile communication systems for the last ten years. And technology scaling, although it might look different in the future, will remain the main engine pushing the evolution of the mobile networks in the 5G era. Technology scaling will enable integration of previously unseen complexity levels, processing of high data speeds and miniaturization of future network devices with more functionality and high energy efficiency. It will allow future network devices to cope, in a flexible way, with a heterogeneous network environment offering optimized services anyplace, anytime.

Implementation and integration based on advances in semiconductor (and nano-) technology will remain an essential ingredient for economic and industrial players to take up a leading role in the market space. Intensive R&D has improved mobile communication systems significantly in the last 20 years in many ways:

- **Higher compute speeds and integration** of digital functions support the increased data speeds and far more complex signal processing algorithms.
- **Improved semiconductor devices** allow more performing analogue circuits capable of wider frequency bands, higher sensitivity and better resistivity to unwanted effects as interference, blockers, …
- **Reduced power consumption** of the systems on chip (SoC) enable real mobile devices with acceptable power autonomy.
- **Higher integration** of analogue and digital functions give way to miniaturized the communication devices based on SoC with strong reduction of external components.

5G networks will build on the continued (r)evolution of mobile SoCs. The 5G mantra of a 1000 times rate increase will result in much faster data processing needs. Going from 100Mbps to 100Gbps networks will have an impact on all functionality of the mobile SoC: it will require higher signal processing speeds for digital logic and higher signal bandwidths in the analogue transceivers. Further semiconductor technology scaling combined with clever design techniques will increase the signal frequencies and data speeds of the integrated circuits.

Moreover complex signal processing algorithms will be inevitable to support the future 5G networks and the increased performance in terms of data capacity and link quality. Current trends show the exploration of many variations of MIMO technology as the basis of future networks and increased capacity: massive MIMO, SDM, beam-forming, … These trends prove that efficient implementation of complex algorithms at high speed will be essential in signal processing for 5G communication systems, both on the device and the infrastructure side. This will pose many challenges on the implementation of the future mobile SoC.

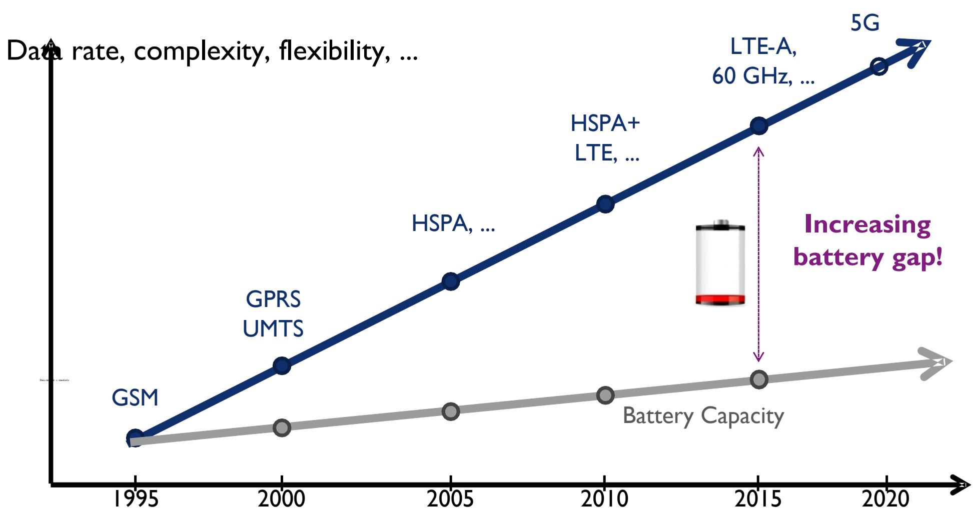

Figure 5: Increased mobile SoC performance challenges energy efficiency and implementation complexity

3.3 Virtualization

Telecom infrastructures have been traditionally based on a complex set of interconnected proprietary hardware appliances running different types of distributed protocols. These protocols usually require specialized vendor-specific configuration tools. More often than not, the deployment of a new service required yet another hardware box to be installed and configured. Besides, all these specialized hardware suffer from short lifecycles compared to the fast innovation pace and unexpected customers' demands. This heavily increases the capital expenditures (CAPEX). Moreover, the operation of the network has also been traditionally very complex, as it involves the configuration of heterogeneous hardware, with different APIs and tools, often requiring human intervention, and thus increasing the operational expenditures (OPEX).

Networks are evolving towards becoming a very dynamic and flexible environment consisting of virtual resources that can be instantiated and released on demand to timely meet customers' demands or to optimize operator's internal processes. These virtual functions are interconnected by virtual links that are also set-up dynamically to best serve multiple network services. The existing Network Function Virtualization (NFV) initiative and Software Defined Networking (SDN) tools and concepts represent today a first step in this direction. However, future 5G networks will be much more complex, and will have to cope with much more exigent demands, in terms of data traffic semantics, the granularity of the deployed functions, resulting system, connectivity requirements, service heterogeneity, system dynamics, QoS and network capillarity. An efficient control and management of such networks becomes crucial to overcome this increasing complexity, where dynamic and automated functions will play a key role.

In order to tackle these serious issues, operators started to make use of network and service virtualization techniques. Applied to networking, virtualization enables, for example, co-locating multiple instances of network functions and services on "general purpose" hardware, which is shared among users. This first step in the direction of a tighter integration of the networking and IT worlds already brings significant savings in terms of CAPEX and OPEX, as well as other advantages, such as reduced time-to-market to deploy new services, reduced conformity and integration testing, better flexibility to scale and evolve existing services, and lower risk barriers to perform service innovation. Virtualization in networking also enables the creation of virtual networks, i.e., of network views independent of the actual hardware and its topology. Both other topologies and other protocol stacks can be created. And we can even go beyond the current slicing of networking technologies (e.g., VLANs) and also fuse network links, nodes and whole segments to single entities, therefore reducing management efforts.

Moreover, virtualization enables the emergence of new business models, allowing the provisioning of tailored network services for specific tenants and application purposes. Virtualisation brings the opportunity to deploy almost independent virtual infrastructures for each tenant, configured. Through this, network services are efficiently offered to a specific set of communication devices, enabling an easy uniform administration of a domain e.g. an enterprise or an M2M specific domain. Through this means, the virtualization enables the separation of concerns between different specialized communication systems, thus enabling their easy control, adaptation and administration.

However, sharing common physical infrastructures creates security concerns that have to be addressed to ensure isolation among virtual resources and services.

In the following, we discuss the relevant research priorities in the virtualization area that are likely to address these challenges.

3.3.1 Efficient RAN Sharing for Multi-Tenancy

Future 5G networks will be denser to achieve the capacity increase provided by the deployment of smaller cells. In this scenario, reducing the overall costs is of paramount importance. One way of doing that is by enabling an efficient sharing of the network infrastructure. Existing sharing mechanisms are limited and not sufficiently transparent to the network tenants. RAN virtualization techniques are ultimately to provide logical isolated pieces (slices) of the access infrastructure to individual tenants, so they can operate them as if each virtual slice were a single real physical infrastructure. A well-coordinated sharing of the access infrastructure yields a higher throughput per area, but lots of research work is still needed to achieve that.

Cloud-based RAN centralization techniques help reducing the costs associated with highly dense networks by offloading the intensive processing to a cloud. These clouds will support different deployment architectures, from small and localized clouds in the street cabinet or even on current large-scale antenna poles to data-centres. The advantage of these solutions is that software can be upgraded and scaled on the fly. In addition, the centralized architecture is ideally suited for joint scheduling of radio resources, handling inter-cell interference and implementation of advanced architectural concepts such as carrier aggregation. However, the high capacity and strict requirements on delay and jitter pose a serious challenge to the design of an efficient fronthaul in the centralized architecture. This challenge becomes even more important with the virtualization added on top of the centralized architecture.

Secondly, the sharing of the access infrastructure is not limited to the radio access interface and should be extended to include the backhaul network. Again, mechanisms to properly share the backhaul and offer a virtual RAN+backhaul network are still at very early stages.

Another important aspect to be considered when creating virtual networks on top of an access network composed of heterogeneous radios and very densely deployed small cells is energy efficiency. By doing a proper monitoring and orchestration of the physical resources, base stations can be selectively turned off and on, as required to cope with the different demands. An operator managing the physical infrastructure can dynamically update the configuration of the different virtual networks, to better meet the service level agreements (SLAs) of the different tenants.

The basic concept of cloud-RAN is to separate the digital baseband processing units (BBUs) of conventional cell sites, and move the BBUs to the "cloud" (BBU pool or BBU hostelling) for centralized signal processing and management. Hence, multiple questions must be answered in order to deal with these new concepts, for example, for the different scenarios of the C-RAN architectures, what is the optimum position of the base band pool and where can be placed? Is it near the central office, or close to cell sites? What is the optimum hybrid wireless –optical fibre can be deployed to minimize the latency and increase the bandwidth?

As a conclusion, with RAN virtualization it becomes possible to have new operational models based on sharing of RAN resources. This approach will reduce CAPEX and OPEX costs while improving the overall RAN utilization.

3.3.2 Co-existence with Existing Network Deployments

A seamless integration of existing networks with future virtual ones is a critical system design aspect that needs to be carefully tackled. Multiple vendor, technology and administrative domain feed to the problem of integration and a future proof solution is required. Network operators cannot update all their deployments towards a fully virtualized environment, but they will start by doing some green field networks that will co-exist with legacy systems. This requires standardized interfaces and the definition of proper hooks to link the virtual network entities with the real ones. In order to be able to function gracefully, the virtualized environment has to be integrated with the physical environment such as Remote Radio Heads, Internet points of presence, interconnection between different tenant domains or integration with transport nodes. It is outmost important that the end-to-end communication characteristics are supported in an integrated manner over all these domains.

Virtualisation is also a key enabler for the efficient deployment of network entities on top of different tenant infrastructures, types such as the satellite, fixed and mobile terrestrial systems via a unified and virtualised management infrastructure for both systems.

In this context, it is especially important to consider co-existence aspects with 3GPP network architectures, allowing parts of a mobile operator's deployment to be partially or fully virtualized while keeping other parts of existing deployments.

3.3.3 Software Defined Networks and Virtualisation in the Satellite domain

There will be a paradigm shift in network design to allow networks to react to the demands of the users wherever they are—'demand attentive networks'. This will be brought about by virtualisation in the network and software that allows the dynamic reconfiguration of the network to give users the perception of infinite capacity for their application. The extension of current trends in virtualisation and "softwarisation" - especially in the domains of SDN and NFV- to satellite infrastructures is indeed a very attractive perspective for the satcom community. By exploiting SDN/NFV enablers, satellite equipment vendors developing specialised networking equipment for specific use (onboard or ground), have the potential to "open" their platforms by making them programmable and reconfigurable. As for satellite network operators, the virtualisation paradigm is expected to be a very attractive revenue source, offering them the ability to monetize their infrastructure by offering new services and by charging customers according to the actual usage of in-network resources. The application of NFV and "Cloud RAN" aspects to satcom paves the way towards the full virtualisation of satellite head-ends, gateways/hubs and even satellite terminals, thus entirely transforming the satellite infrastructure, enabling novel services and optimising resource usage. In this context, several enhancements/adaptations of current SDN/NFV technologies (e.g. extensions of the Openflow protocol) are envisaged, in order to be fully applicable to the satcom domain and exploit satellite-specific capabilities.

Virtualisation is considered as the key enabler for the efficient integration of the satellite and terrestrial network domains. Via the unified management of the virtualised satellite and terrestrial infrastructures, fully integrated end-to-end network “slices” can be provided, integrating heterogeneous segments in a seamless and federated way. This will enable ‘opportunistic integration’ of the satellite and terrestrial resources and thus improve interoperability.

3.3.4 “On the fly” Virtualization and Adaptability

In order to quickly and flexibly adapt to all the different requirements and constraints imposed by the heterogeneous services that future 5G networks are expected to serve, network virtualization techniques need to be much more agile than current technologies, in setting up new virtual network entities with programmable data forwarding path whilst keeping an optimal energy consumption balance. This feature is especially required in order to obtain a fast-adaptable robust network addressing features such as load balancing, high availability and redundancy as expected from a carrier-grade operator system. From the booting time required to have a new network entity up and running, to temporal addition/removal of networks, to the time needed to move a virtual entity from one physical location to another one, all these procedures need to be intensively researched and optimized. Alternatively, other abstractions than using Virtual Machines should be considered. There are, for instance, several promising paths within IT security and server/host virtualization communities that allow extremely rapid creation of isolated execution containers without the overhead of booting a new system.

At the same time, for a full-fledged network virtualization, server and host virtualization are insufficient alone. To achieve independent, isolated virtual topology creation and ubiquitous virtual attachment, both link/path and node aggregation and splitting techniques will require both new protocols and processing rules in the routers and other network devices.

3.3.5 APIs and SLAs to External Actors

Network virtualisation enables creation and co-existence of multiple networks over the same physical infrastructure each serving different demands and/or services. In such scenario, it is important to enable external actors, such as service and application providers, to use appropriate configuration interfaces. As the complexity of each virtual environment is foreseen to be equivalent to a physical deployment with a high level of scalability, it is foreseen that a simplified governance API will be provided, for each tenant in which full control is provided however lacking the automatic adaptation features. For example, a content distributor may wish to configure a virtual network in a way that its video delivery service is assured to meet the customer SLA. This is one of the key technical enablers towards the emergence of new business models in the ICT sector in the coming years.

3.3.6 Terminal Virtualization

Network virtualization must not be limited to the infrastructure providing connectivity, but should extend to the end-user device. A customer might be subscribed to multiple services and access networks simultaneously enabled by virtualization techniques at the mobile terminal.

It would be useful to provide different isolated services using the same terminal. For example, a user might get access to enterprise services via one virtualized end-user terminal, while accessing personal multimedia content using a different virtualized device, optimized to receive that kind of content. This trend is already discernable at the horizon with the current trends for BYOD and the resulting problems in the enterprises and the recent introduction of isolation functions in the modern terminals.

3.3.7 Performance and QoS

The virtualization (possibly iterated) of a network and ICT infrastructure can bring several challenges in terms of the level of QoS that can be guaranteed in and by the virtualized resources at each level. The performance behaviours (in terms of, e.g., bandwidth, delay, jitter) of virtualized network resources (e.g. nodes, links) can be severely disrupted if proper QoS isolation techniques are not applied when implementing virtualization. This applies to both past/present data plane virtualization techniques (e.g. NFV), and future ones. Also, the challenge is made more complex by the nature (e.g. deterministic vs statistical multiplexing) and heterogeneity (virtual networks made of homogeneous vs heterogeneous technologies and resources) of the physical data plane to be virtualized.

3.3.8 Cost and Performance Analysis

It is important to study the impact of virtualizing the network functions on the key metrics cost and performance. This will in turn be the key input to the strategic question of which elements to virtualize in the network and how. To this end sub-variables such as elasticity, link utilization, portability and *processing overhead* need to be identified and evaluated, which will influence the cost and performance. For example, it needs to be investigated as to how will the virtualisation of a network function and the use of a hypervisor impact the *processing speed* compared to a physical network function. The key metrics should be evaluated depending on the actual use cases that are studied.

4 Roadmap

Highlighted in yellow are all topics which are not clear enough (not precise enough, not defined), in blue are all topics which are possibly redundant, in purple are all topics which are inconsistent in the timeline.

	Technology	T<=2015	2015<T<2020	T>2020
5G requirements	**Cellular Broadband**	• 5G Technical and spectrum requirements • 4G evolution	• Standardisation • Radio interface • Radio access and converged core architectures and technologies • SDN/NFV Technologies • D2D • Field trials and testing	• Deployment • New releases
	Narrowband terrestrial network (e.g. for M2M & IoT)	• Mix of different proprietary & standard technologies such as 2G, 3G	• Standardised radio interface • Migration to 4G • Field trials and testing	• Integration of M2M and Cellular systems
	Satellite	• Mix of different proprietary and standard satellite technologies: FSS[9]/BSS[10] (IP based), MSS[11] (2G and 3G) • Hybrid broadcast/ broadband (FSS/BSS) • Backhaul SDN/NFV integration • 5G intelligent routing	• 4G service delivery via FSS/BSS/MSS • ETSI/DVB/5GPPP standards • Early lab demo's	• 5G service delivery via FSS/BSS/MSS • Integration of MSS satellite in the M2M/IoT sensor network for global coverage
Wireless Subsystem	**Novel RAN Architectures**		• Ultra small cells • Immersed radio (massive multi antenna) • Radio virtualization • Complete inter layer/system CoMP • All photonic RF "leaky RF fiber" • Cooperative relays • Load balancing with multitude of systems incl. full device-to-device • Efficient heterogeneous backhaul/fronthaul	• Extensive use of Cloud RAN • Ultra high capacity backhaul/fronthaul • Seamless support for device centric architectures • Native support for D2D • Local data caching • Convergence with satellite Radio Access Networks
	Radio & Air Interface	• Multi carrier on satellite • Latency/synch • Cellular/satellite integration	• Evolution of existing standards • Incorporate satellite air interface into 5G standard. • Satellite lab demo's • Wireless multiple access • Advanced modulation and coding • Radio resource allocation • 3D Massive MIMO beamforming • Interference mitigation • Visible light communications	• Demo over satellite • Disruptive new radio • New waveforms and coding schemes • Extensive use of advanced multi-antenna transceivers techniques • Native support for different cooperative multi-antenna transceiver schemes • Support for realtime broadcast and multi-cast services, e.g. UHD/3D TV/HBBTV and

[9] FSS = Fixed Satellite Service
[10] BSS = Broadcast Satellite service
[11] MSS = Mobile Satellite Service

			• More accurate channel and propagation models	broadcast-broadband convergence • Availability of high resolution 3D geographic information for propagation modelling
Wireless Subsystem	**Satellites**	• Orbit studies • Frequency bands • MBAntennas • Interference/RA	• Specify 5G sat architecture • ESA ITT's for key elements • In Orbit tests	• Satellite launch and early tests • Operational with IoT
	Ground segment & terminals	• Feeder diversity • GBBF/OBBF • Integrated terminal • Energy minimisation • Hand overs	• Demo integrated networking • Terminal prototypes • IoT terminals	• Demo's on integrated sat/terr network
	Energy		• Dynamic systems (sleep modes, context awareness) • Backscatter VLC communication. • Small cells and D2D • Indoor deployments and beyond-HetNet • Energy-harvesting aware M2M communication • Resource and spectrum sharing between operators	• Wake up radio equipped M2M systems • High data rate passive short-range (femtocell size) M2M communications • New Transceiver designs (GaN, Class S, adaptive) • Energy efficient medium access and mobility (Separate control connectivity, Dual connectivity, Cell-less systems, connection-less systems)
	Spectrum	• Satellite co-existence mechanisms • Evaluate gains in spectrum use in satellite • Ka/Q/V/E bands	• New spectrum above 6 GHz • "Critical bandwidth" wideband fading limitations • Licenses shared by co-operating operators • Dynamic spectrum access location based • Advanced spectrum handoff and spectrum mobility mechanisms regarding inherent QoS. • Satellite demo's in lab • Satellite spectrum included in standards • Regulatory acceptance of satellite integration	• Industry and regulatory body consensus on leveraging mmW spectrum for new broadband mobile radio systems • Avoidance of bandwidth overspreading by means of seamless routing • Utilization of large continuous chunks of spectrum under 90 GHz, e.g. 20-50 GHz • Dynamic spectrum management and sharing (sensing, sharing, trading) among operators • New spectrum above 90 GHz • Franchised data bases operation and trials in satellite • Visible light communication
Network virtualisation & software networks	**NFV – Network Function Virtualisation**	• Serving Gateway • Packet Data Network Gateway • CloudEPC • Mobility Management • Pre-defined function migration	• Billing as a Service • Terminal virtualization • Radio and capillary network functions virtualised • On demand function migration	• Virtual firewalls • Automated function migration
	SDN – Software Defined Networking	• Centralized Network service orchestration	• Automated Flow Management • Automated Life Cycle Management • Distributed Network service orchestration	• Policy driven self-organization and management • Automated placement of virtual firewalls • Automated management and monitoring functions (performance/reliability/SLA management/ security)
	NaaS – Network as a	• VPN over virtualized networks	• APIs for Management and Data Planes	• Freely definable private or open networks

	Service PaaS / IaaS		• Automated network analytics	
	Hypervisor	• Optimised for OS or specific hardware platform	• Bare metal hypervisor with increased hardware support	• Dedicated designed hypervisor hardware
	Security Trust	• Centralised trust anchor	• Distributed trust	• Fully Dynamic Trust
	Core	• Some network functions provided in virtualized environments (NFV) • Initial deployment of SDN-based transport networks • Isolation of traffic based on VLAN-like tagging • Monitoring of overall status • One core fits all approach	• Definition of all-virtual core networks (e.g., vEPC) • Enablement of automatic and dynamic connection of new RAN & Core elements to the operator network • Smart monitoring and trend analysis based on Data Analytics • Definition of new function specific customized core functions	• On-demand function specific and context-aware core deployment using shared transport network
	Access	• Basic RAN sharing based on eNodeB location sharing among operators • Static configuration of RAN splitting among operators • Decommission of points of attachment based on static rules	• Generic virtualization of heterogeneous RAN elements • SDN at the Wireless Interface • SDN-based control and configuration • Interfaces for dynamic creation and decommission of virtual points of attachment	• On-demand Heterogeneous generalized RAN sharing • On-demand deployment of customized RAN elements
	Multi-tenancy and Orchestration	• Static agreements between operators based on SLAs	• Definition of APIs for coordination of different virtualized operator's cores over shared RAN and transport infrastructure • Unification of network management control operating over shared infrastructure	• On the fly sharing of network infrastructure through dynamic orchestration of network functions and elements belonging to different operators
Converged connectivity	**Network heterogeneity**	• Independent networks, integrated at the level of interface selection in the terminal • No switch across administrative domains	• Solutions for integrated mobility management of multiple technologies at network level • Prototypes on Coordinated multi-owner networks	• Deployment of integrated multi-technology networks
	Identification & Location	• Content identification and location are tightly coupled (e.g., HTTP information requests) • Initial implementation of information-centric networks	• Information forwarding decoupled from specific storage placing (a-la CDN)	• Information uniformly retrieved by name • APIs providing information naming for content reachability
	Multimedia Mobility & Management	• Multimedia service disruption minimized by buffering, caching and app-layer control	• Multimedia sessions redirected to network points of attachments nearer to the content (e.g., CDNs)	• Supporting mobility for high-quality media at any speed on a worldwide scale
	Intelligent Handovers	• ABC made feasible by offloading and IP mobility management, by multiple standards • Complementary access	• Flow mobility mechanisms operating over interfaces (hardware abstraction layers) • Fully supported multihoming	• Policy-based, QoE-aware, ABC with seamless offloading • Cloudifcation of network functions will integrate flow

		networks increasingly require less direct user intervention		mobility mechanisms into software configurable networking aspects
	Localisation	• Simulation sat+cellular	• Lab demos' with services • Included in standards	• 5G demo's in sat+terr domain • Services operational
	Agile Management	• Proprietary solutions per operator and services provider	• Standardised interfaces • Prototype Integration with sensing, service and reconfigurable networking infrastructures	• Integrated network, service and management frameworks commercially deployed
	Resilience	• Architectures study • Security evaluation • Hand over evaluation	• Demo's in lab • Included in standards • Equipment prototypes	• 5G Demo operation in sat/terr hybrid network
	Satellite	• Applications of integrated satellite and terrestrial systems for remote locations	• Satellite and Terrestrial Integration at network and service levels	• Satellite a component for content dissemination and ubiquitous connectivity
	IoT	• 6LoWPAN commonly deployed • First country-wide IoT/M2M networks, supporting mobility	• Massive m2M deployment • First trials in opportunistic routing for D2D in M2M	• IPv6 stacks for IoT & M2M deployed (Mobile IP) • QoE for mobile IoT

5 Recommendations

R1) Investigate and define disruptive network architectures harnessing all available network technologies and services to address the 5G challenges.

   a. Reorient traditional efforts to target significantly more complex, diverse, and unstable scenarios
   b. Launch efforts for increased network heterogeneity, looking for (meta-) architectures that can be evolvable, while retaining optimal advantages of existing solutions under control of different operators
   c. Design mechanisms to ensure co-existence of virtual networks with existing infrastructure, security and efficient management of virtualized networks and services
   d. Investigate synergies between SON and Software Defined Networking (SDN) architectures and protocols

R2) Investigate, develop and deploy the necessary access, networking (core & transmission) and virtualization technologies that will drive the advances of 5G system components and meet the KPIs outlined in Section 2.

   a. Develop scenarios where the control and management planes are increasingly complex and aware of user and network context, including tailored network behaviour per user and device.
   b. Initiate activity on advanced network and service virtualization to enable efficient RAN & backhaul sharing as well as efficient integration of satellite and terrestrial domains
   c. Develop technologies that, based on specific services/users/networks contexts, allow dynamic and flexible creation and operational control of both of virtual networks and the underlying infrastructure resource container
   d. Allocate/assign new spectrum beyond 6 GHz for meeting the requirements in 5G systems
   e. Develop new radio technologies (scale of channel modelling to small and complex scenarios, access, multiple antenna schemes, interference handling, etc.), including visible light communication for both terrestrial and satellite communications

R3) Investigate, formulate and incorporate the driving system-level principles, such as flexibility and programmability, that will allow for implementing the 5G vision across the developed technologies

   a. Investigate current and future network deployments that allow for network/infrastructure/resource sharing at all levels

R4) Investigate, formulate, and foster the right business models for 5G systems that allow for a virtuous cycle of investment across the entire existing value chain as well as possible new ones

   a. Investigate the impact of virtualizing the network functions on cost and performance

R5) Engage with the wider stakeholder community through efforts like roadshows, common test beds, joint (co-)developments and early deployment efforts, and others.

R6) Investigate the right policy and standardization framework for managing networked assets, spectrum as well as computing resources to foster the truly cross-value-chain collaboration in 5G.

6 Open Issues

The following list of issues (among others) has been created for a wider discussion within the community:

1. Do you see missing connectivity research priorities in the 2015-2020 timeframe?

2. In your opinion, how should the domain of 'wireless', 'cellular' and 'satellite' be presented in the context of 5G ? What level of integration should we have between these worlds (e.g., service level, air interface level…)? Are there any specific research priorities that should be kept separate between satellite and cellular?

3. Currently the impact of 5G research and innovation projects on future standards is envisioned mainly for wireless systems. Do you foresee big impacts on standards in other domains? If yes, please precise, which domains and why.

4. What are your views on the timelines of the following topics: Device to Device, Internet of Things, convergence between satellite and cellular networks, Visible Light Communication, cloudEPC, integrated multi-technology networks? More precisely, when do you foresee standardization efforts, demos from industrial players and trials with end users? Do not hesitate to decompose the topics in smaller items to be more precise in your views.

5. Among the topics which are in the roadmap, which ones should lead to Research & Innovation projects in 2016-2017 in your opinion? Please precise the maturity you foresee in 2016-2017 for each topic (technologies development, system definition, pre standardisation, industrial demo, field trial…).

6. Do you feel that important milestones should be defined that complement the roadmap in Section 4? If so, what are the particular targets for these milestones, e.g., the demonstration of innovative networking features at the 2018 Winter Olympics in Korea and 2020 Summer Olympics in Japan or the fulfilment of important KPIs by parts of the overall 5G system?