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Expert Working Group on

Next Generation of Wireless Networks

White Paper

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List of Acronyms

QoE	Quality of Experience
FBMC	Filter Bank Multi Carrier
MTC	Machine Type Communications
CR	Cognitive Radio
SDN	Software Defined Networking
OAM	Operation, Administration and Maintenance
SON	Self-organising Networks

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Executive Summary

Currently, research has being carried out to design technology portfolios that will make 5G a reality. Yet, there is no consensus on the technology itself. Industrial and academic focus as rather fallen on the challenges and new usages that need to be addressed in the future generation of 5G wireless networks. Among these, capacity increase and higher rates (Gbit/s wireless throughput), the extraordinary explosion of traffic volume including both mobile wireless high data rate and Machine Type Communications (MTC), the massive growth of connected devices and the large diversity of uses cases and related requirements will require additional technologies to support such revolutionary evolution of wireless networks.

This White Paper provides insights on the directions the research should have, for system design and standardization, in order to meet the technical challenges of future 5G wireless networks and indeed contribute to increase capacity, scalability, latency and energy consumption of current systems and decreasing electromagnetic pollution and carbon footprint. Section 2 defines the research priorities with respect to defining the research and technology challenges that have the potential to lead to innovation and economic impacts, while Section 3 presents the technology roadmap setting as horizon the next decade and intermediate milestones every five years. Finally, the summary and conclusions are presented in section 4 and in section 5 the recommendations for further researching are given.

1 Rationale

The ubiqitous network availability with growing density and complexity of network devices threatens to increase the power consumption and carbon footprint of mobile networks. The fast growing traffic volume and new usage patterns (e.g. high quality video on mobile devices and devices always-connected to social networks and services) rises the system utilisation and thus further increases the power consumption of the networks. This growth in energy consumption not only impacts the global climate, but also puts severe burden on the business case of the network operators. Technical solutions for future 5G systems will only be succesful if they combine higher performance and better services with lower energy consumption. All aspects of the 5G system need to be considered, i.e. hardware efficiency, new radio waveforms, shorter transmission ranges, faster transition from idle to connected, energy efficient device operation and offloading of energy consuming operations, dynamic network management (load adaptive and context aware) and service provisioning (content caching, multicasting).

2 Research priorities

2.1 New Spectrum

2.1.1 Spectrum as Critical Resource for 5G

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 millimeter-wave frequency bands, 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 published 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 [RRE14].

2.1.2 Sharing – different schemes, business models

Spectrum sharing 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 lead 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 also into the sharing of spectrum with other services (E.g. broadcast) and systems, since there is underutilised spectrum in quite many bands, just because the entities or systems to which spectrum is allocated do not use it in a continuous way, from the perspectives of space and/or time and/or even frequency. The development of techniques to efficiently use these slices of spectrum could definitely 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, 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 sharing policies, fostering economic efficiency and the implementation of an automatic and real-time spectrum sharing scenario.

2.1.3 New Spectrum Allocations below 6GHz

WRC-15 will hopefully conclude the years of negotiations over the digital dividend. CEPT[1] 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.

2.1.4 mmW 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.

mmWave bands 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[2], and the research in this field should look to EMF aspects, link budgets, propagation issues, and channel model description. Some interesting additional bands under investigation are in the range of 200-300 GHz. 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.

[1] For more information about CEPT, see http://www.cept.org/cept/about-cept
[2] satellite services already deployed in some frequency bands such as 17.3GHz to 21.2GHz, 27.5GHz to 31 GHz and 37,5-42;5 GHz / 44.5 – 51.4 GHz

Figure 1

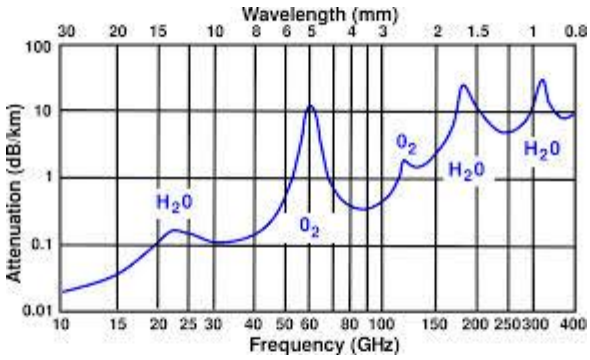

Figure 1: Atmospheric attenuation under different frequency bands

Figure 1 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. 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 any IEEE and 3GPP concepts with their known short comings. Close integration with the mobile broadband concept will allow new ways of load balancing, system operation and procedures.

2.2 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:

2.2.1 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 band-widths, directional blindness [MSM], multi-hop architecture [GRE14], 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 [DMCSD-1] 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.

2.2.2 *Efficient Wireless Backhauling*

Due to novel network architectural components and explosion of such network nodes, single and multi-hop [GRE14] 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, millimeter 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 fiber 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 [MP2013].

2.2.3 *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.

2.2.4 *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.

2.2.5 *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 [PSP12].]. QoE in a 5G network should be definitely improved by exploiting experimental measurements collected by the mobile devices. This would enable a sampling of the key network and QoE parameters in space and time with a very high granularity, thus improving the optimization capabilities with respect to current drive tests. Lab and field tests conducted both at radio, user and service level, i.e., End-2-End (E2E), could be even substituted or simplified by the adoption of proper APIs integrated in all elements (from nodes to terminals), in order to enable the assessment and optimization of the network based on actual QoE performances.

2.2.6 Bringing computational resources closer to the end user

Enabling heterogeneous mobile devices with advanced computational capabilities, within controllable latency constraints dictated by the Quality of Experience and minimum energy consumption, requires bringing radio and computational resources closer to the end user. Current mobile cloud computing addresses this issue, but latency control over wide area network is often difficult to implement. A possible way to overcome this bottleneck is to endow base stations with additional cloud functionalities and federate them through a hierarchical system so that the network edge device may decide whether to run its application locally, if possible and convenient, or in a nearby cloud-enhanced small cell base stations (or federation of them) or in the distant cloud, depending on which choice ensures minimum energy consumption and the respect of latency constraints. In this way, radio and computational resources are allocated and balanced optimally, depending on both radio channel status and computational load. The dense deployment of base stations may be a key enabler of this strategy, paving the way to a really pervasive computing system, scalable on demand.

The resulting Distributed cloud computing for Radio Access Network optimization (D-RAN) envisaged above is not to be seen in contrast with current Centralized-RAN (C-RAN) approach, but rather as a complement to C-RAN, depending on traffic needs (e.g. especially latency requirements). The right concatenation of C-RAN and D-RAN strategies could give rise to a truly scalable system, able to meet the strict latency requirements of 5G networks and avoid potential bottlenecks of a purely centralized approach.

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.

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. 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.

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.

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.

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.

VLC can also be applied to constellations of small satellites (Cube Sats) for providing global coverage.

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 flatrates 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 subscribtions, 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 10-60GHz 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 seperate 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).

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 [ZZS+13].

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 vs. 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 [BSD13] 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 [SP13, ZZ12]. 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 a table 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.

2.3.7 Broadband-Broadcast Convergence

Today, mobile radio and 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.

2.4 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.

2.4.1 Research priorities

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 [LP12];
- 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”.

2.5 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).

2.6 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. Following challenges should be tackled to enable the next generation networks.

2.6.1 Higher signal processing speeds with increased complexity

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 a lot of challenges on the implementation of the future mobile SoC.

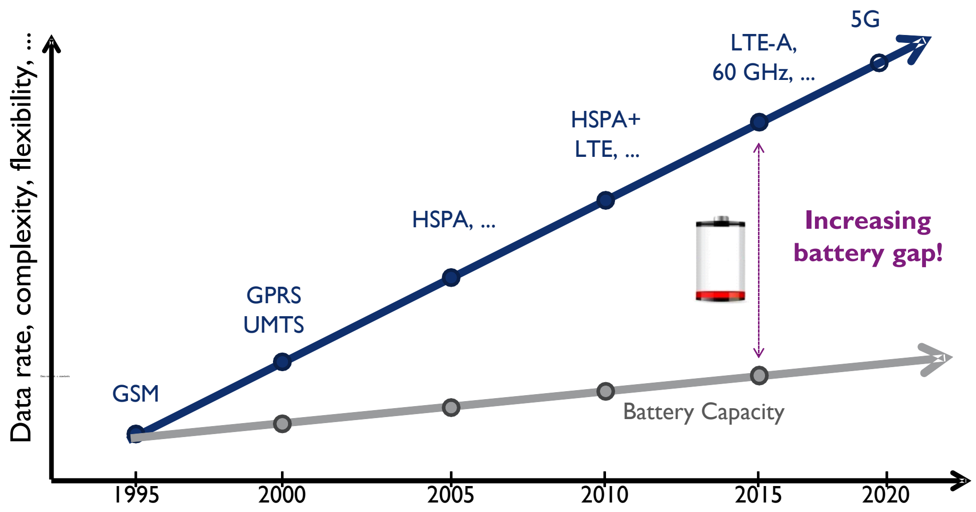

Figure 1 Increased mobile SoC performance challenges energy efficiency and implementation complexity

2.6.2 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.

2.6.3 *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.

2.7 Impact on Future Standards

5G 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 were 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. The a.m. channel models and spectrum demand analysis can be a very valuable input for 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 Technology RoadMap

	<2020	<2020+
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	- Evolution of existing standards - Wireless multiple access - Advanced modulation and coding - Radio resource allocation - 3D Massive MIMO beamforming - Interference mitigation - Visible light communications - More accurate channel and propagation models	- 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 broadcast-broadband convergence - Availability of high resolution three-dimensional geographic information for propagation modelling
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	- 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.	- Industry and regulatory body consensus on leveraging of mm-wave spectrum for new broadband mobile radio systems - Avoidance of bandwidth overspreading by means of seamless routing [GRE14] - 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 - visible light communication

4 Summary

Today there is not a consensus on the technology itself, or even if there will be single or multiple approaches, that will make 5G a reality. This White Paper provides insights on the research and innovation directions addressing the fundamental challenges and the technological roadmap for the wireless system design and standardization of future 5G mobile broadband wireless networks.

5 Recommendations

With the drastic traffic increase predicted for 2020 and beyond, strong research efforts on innovative evolutionary and revolutionary radio access network solutions are indispensable. These efforts need consolidated activities between industry and academia on a global scale. The following recommendations for successfully setting up joint research initiatives have been identified:

R1) New spectrum beyond 6 GhZ is needed for meeting the high requirements on 5G systems

R2) New radio technologies (scale of channel modeling to small and complex scenarios, access, multiple antenna schemes, interference handling, etc.)

R3) Visible Light Communications need to be investigated for both terrestrial and satellite communications in order to show that full-fledged optical wireless networks can be developed by using existing lighting infrastructures.

R4) Future network deployments have to allow for network/infrastructure/resource sharing on all levels in order to meet the fast changing demands on network resources and operation.

R5) Future hardware has to support the **increased data speeds** and far more complex signal processing algorithms while enabling real mobile devices with acceptable **power autonomy** be **more flexible** and reconfigurable.

R6) Synergies between SON and Software Defined Networking (SDN) architectures and protocols should be investigated.

R7) Adopt realtime measurements and proper APIs (radio and context/user related) made available in network elements in operation (including terminals), in order to enable the assessment and optimization of the network based on actual QoE performances.

R8) Endow base stations (and terminals) with additional cloud functionalities enabling distributed cloud computing for radio access network optimization.

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