COST IC1004 White Paper on
SCIENTIFIC CHALLENGES TOWARDS 5G
MOBILE COMMUNICATIONS

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Executive summary

This White paper states the view of the researchers of the European COST Action IC1004 on the future of Mobile Communications technology beyond 4G.

The growth rate of wireless data traffic will be huge in the coming years, mainly because a second revolution is expected at the terminal side, by which mobile data communications will include any device, not only those carried by humans. In the near future, machines, sensors, vehicles, smart cities and health devices will be wirelessly connected, and will load the networks with different data traffic patterns, setting new specific requirements. The new scenarios to be incorporated through this massive number of devices into Mobile Communications Networks may be regarded as a new generation of wireless networking entities, grouped in local or wide areas, in which coordination and communication elements are necessary, as well as new group mobility functions.

In the medium term vehicles will become integrated parts of the radio access network, not just terminal nodes, and will benefit the networks through their capability to relay communications links to other vehicles or to passengers. In beyond 4G technologies, vehicles are expected to enhance four main applications of radio communications: infotainment to passengers, vehicular cloud services, traffic safety, and traffic efficiency.

In beyond 4G technologies the role of wearable and implanted devices in people lives will be to revolutionize health monitoring, wellness and assisted living. The Wireless Body Environment is intended to give humans in the near future an enhanced and intuitive interaction with surrounding technologies. This interaction is to be boosted by a network of body implanted or wearable devices, operating in the short-range, around and inside the human body, and able to exchange health and other data in real-time.

Urban environments are expected to take advantage of the wireless technologies in several key applications, which are already the bases of the current Smart City deployment: optimise the transportation into cities, offer personalised services to citizens, and give the Community improved management and social services.

In further developments of machine to machine and other types of sensors connectivity, the mobile communications in the coming years is expected to lead to a scenario in which every electronic device is wirelessly connected. These future scenarios in radio communications give rise to situations where a huge number of devices are located in physical proximity, generating large amounts of independent traffic with different requirements, and at the same time are to share the same pool of radio resources. The number of contenders for the radio resources in such situations can potentially be much higher than those manageable by traditional wireless architectures, protocols and procedures, so Radio Access Networks have to evolve to new paradigms.

The Cloud Radio Access Network concept is already being developed as a potential evolution of the Mobile network architecture, and in the future it can be expanded to include not only Radio Access but also Core functionalities, in what is referred to in this paper as Network Virtualisation. This concept refers to the capability of pooling underlying physical resources or logical elements in a network, and it takes advantage of current technologies of Software-Defined Networking and Cloud Services.
In addition to the Radio Network technology evolution, Spectrum is the key for the future of Wireless Communications. Radio Access systems, services and applications need to be more efficient in terms of energy and spectrum usage reducing the signalling load, the latency, enriching user experience, and maximising the spectrum efficiency. Some approaches are already considered for future networks, such as opportunistic access, cognitive radio, and co-primary usage in shared bands, among others, but an intensive review of which bands, where and how the Spectrum is used or shared is required for a successful deployment of beyond 4G technologies.

COST IC1004 researchers’ view of the future of Radio Access Networks is analysed in this paper, under the assumption of three facts: wireless terminals will evolve to get any device connected, access networks are to change their architectural basis in the coming years, and spectrum usage strategies should be revisited to ensure the efficient connectivity of the coming massive wireless traffic scenarios.

As a result of such analysis, the paper identifies a list of relevant scientific challenges for the coming years:

- The architecture of radio access networking has to complete its evolution from the current distributed antenna systems and radio resources sharing to the Cloud RAN and Virtual Access Network models.
- There are many challenging requirements for future wearable and implanted devices to enable Wireless Body Environment communications, and to offer the users an extended set of applications to health, connectivity and assisted living.
- The implementation of massive MIMO in radio access will improve the cost/performance ratio in mobile networks, but requires a review of some current technologies to make the concept feasible to its full extent.
- In vehicular communications there is a trend to convert cars into moving relays, in addition to other traffic applications, but some challenges in connectivity, propagation modelling and antenna systems remain open.
- Efficient, universal and resilient wireless access for future networks requires new approaches to Spectrum management, initially based on the fusion of sharing, opportunistic access, cognitive radio and location aware concepts.
- A paradigm shift is required to create a network-aware physical layer to provide much more efficient networks, in which an important component will be physical layer network coding.
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List of Acronyms:

BAN: Body Area Network
BS: Base Station
CAPEX: Capital Expenditure
CoMP: Coordinated Multi-Point
C-RAN: Cloud-RAN
CSI: Channel Status Indicator
DAS: Distributed Antenna System
DC: Data Centre
DU: Digital Unit
eNB: Evolved Node B
EPC: Evolved Packet Core
IoT: Internet of Things
ITU: International Telecommunications Union
M2M: Machine to Machine
MIMO: Multiple-Input Multiple-Output
MME: Mobility Management Entity
OECD: Organisation for Economic Co-operation and Development
OPEX: Operational Expenditure
OTA: Over-The-Air
QoS: Quality of Service
RAN: Radio Access Network
RANaaS: RAN as a Service
RAT: Radio Access Technology
RRM: Radio Resource Management
RU: Radio Unit
SDN: Software-Defined Networking
SGW: Serving Gateway
SLA: Service Level Agreement
SMS: Short Message Service
TDD: Time Division Duplex
VM: Virtual Machine
VNO: Virtual Network Operator
WBE: Wireless Body Environment
WBEN: Wireless Body Environment Network
WLAN: Wireless Local Area Network
WMAN: Wireless
WPAN: Wireless Personal Area Network
WSN: Wireless Sensors Network
INTRODUCTION:

Mobile Communications are exponentially evolving to allow any electronic device wirelessly to connect to the Internet. As smartphones have become a revolution in the wireless user’s experience, a second revolution at the terminal side is expected, and the future traffic growth rate will be huge, due to the extension of the mobile data communications to machines, vehicles, sensors, and smart objects.

Wireless Body Environment Networks (WBENs) are expected to provide new functionalities and applications in people’s every-day life such as sport, leisure, gaming and social networks. Cars will become moving nodes, relaying connectivity to their passengers to provide infotainment and enhanced services, as well as connecting to the car sensors and to the road infrastructure to improve the traffic safety and efficiency. Cities will reach the paradigm to become Smart, providing optimised services for transportation, and personal, community and logistics management. This will necessarily mean locating a huge number of devices, which generate independent traffic with different patterns.

All these heterogeneous wireless devices must be connected to each other in a massive moving data scenario that can be called the Wireless Internet of Things.

The concepts under which the current Radio Access Networks (RANs) and Terminals have been deployed are based on the evolution of the Cellular Networks concept, and are quickly approaching their scalability limits. RANs currently make sub-optimal use of the spectrum and energy (bits/joule), because they are based on fixed spectrum allocation and hierarchical network infrastructure. In the coming years, new terminals, devices, applications and services will surge onto the market, forcing the RANs to offer extreme levels of throughput, capacity, coverage and ubiquity. This raises many scientific challenges, including a fundamental review of the basis of the current RAN, leading to an Ultra-flexible architecture, extremely efficient Radio Access Technologies and new approaches for a smarter Spectrum Management strategy.

The scope of the paper is to analyse the potential scenarios for mobile wireless services in and after 2020, and to identify the technological challenges which are best suited to the research skills and interests of COST IC1004 members. The paper is organised in two sections: Section A describes the view of COST IC1004 on the future scenarios for Wireless Communications systems. Section B summarises the scientific and technology challenges arisen from such scenarios, to be tackled in the coming years.
A. Future new scenarios for wireless communications

A.1. The second terminal revolution: beyond human interfaces

A.1.1. Overview

It is already widely discussed that any electronic device is suitable to be wirelessly connected to others or to infrastructure, so the future universe of moving and static wireless links can be as large as the one for microcontrollers, and the number of IP mobile connected devices to be expected by 2020 may easily exceed 10 billion [GSMA2013]. Looking back 10 years, there was not a single touch-screen portable tablet on the market, no cloud data storage, etc. The key driver of the mobile networks boost has not been the radio technology itself, but the new user devices and their associated software services.

In the coming years, a second revolution at the terminal side is expected, and the future traffic growth rate will be huge, due to the extension of the mobile data communications to include any device, not only those carried by humans. This is mainly, though not only, about machines, vehicles, smart cities and health sensors.

![Figure 1. Future scenarios of wireless communications, every device to be connected.](image)

Every such scenario has different rewards from the economic and the societal perspectives, and opens new challenges for the future RAN technology. From the technical viewpoint, any of those four new scenarios in Mobile Communications can be seen as the raising of a new generation of Wireless Sensors Networks (WSNs), either local or wide area, with coordination and communication entities and group mobility. In the case of automobiles and Body Area Networks (BANs), a coordinated group of sensors is intending to communicate with an infrastructure network or to other mobile devices. In the scenarios of smart city and connected home, a moving terminal is intending to get information from neighbouring wireless devices and sensors. It will be then necessary to find a way to efficiently merge those types of WSNs with future Mobile RANs.
A.1.2. Manage a future car, drive a mobile base station

The automotive industry is increasingly adapting wireless sensors and communications systems to improve the connectivity of their vehicles. Four main aspects will benefit from radio communications: infotainment services to passengers, vehicular cloud services, traffic safety, and traffic efficiency.

According to [METIS D1.1] a mobile communication system beyond 4G should support 1000 times higher mobile data volume per area, 10 times to 100 times more connected devices, 10 times to 100 times higher typical user data rate, 10 times longer battery life for low power devices and 5 times smaller end-to-end latency; where the numbers are relative to today’s 4G systems. Some of these challenges can be addressed with a denser base station deployment; however this is not feasible from a cost or an energy perspective. Utilising vehicles (cars, buses, trucks, trains, etc.) in a smarter way is therefore of great importance.

In beyond 4G wireless communications, the vehicles will be integrated parts of the system, not just end-nodes. In essence, vehicles can act as mobile base stations, which will be beneficial when meeting future challenges, especially with respect to filling coverage holes, supporting local capacity needs that appear unpredictably in time and space, and providing good quality of experience for the passengers.

In addition to serving as a mobile base station, a vehicle can sense its environment to support a multitude of applications. For instance, real-time traffic and environmental monitoring is truly enabled, which in turn enables real-time traffic management to increase the efficiency of the transport system and reduce its environmental impact.

Connecting vehicles to the cloud with a stable, high-rate, low-latency wireless link will bring many benefits. Heavy calculations and storage can be off-loaded to the cloud, vehicle maintenance will be facilitated, and novel services can be delivered to vehicle customers with a very short time-to-market.

An emerging area of great significance for the safety and comfort of people as well as for the environment is cooperative traffic safety and traffic efficiency applications. Such applications require vehicles and road infrastructure (road signs, traffic lights, toll booths, etc.) to exchange information to make the transport safer (fewer accidents, injuries, and fatalities) and more efficient (fewer traffic jams, fuel consumption, and emissions). Hence, wireless communications is a crucial enabling technology for these applications.

A.1.3. Cities to have senses, and become smart

The Smart Cities concept has been developed during recent years mainly, but not only, on the basis of urban sensor networks, which provide information either to a centralised management system or to the moving devices around them.

This concept is an evolution of the intelligent room and intelligent building ideas, and is addressed to both people living and working in the city and people organising and administering the urban infrastructure. The following key ongoing applications provide the bases of the Smart City deployment:
- optimised transportation: providing real time traffic information, different means of transportation and their combination, dynamically adapting street signalling to reduce congestion and pollution,
- personalised services: for shopping, administration, planning of new business, cultural, leisure, security and health,
- community services: social activities, matching people with common interests,
- management services: light, temperature and pollution control, flow of traffic, gas, water and electricity, monitoring streets, pipes and bridges, emergency responses, public transportation monitoring, plan new public transport,

From the network deployment perspective, a huge set of advanced technologies is required for a full implementation of Smart Cities, and substantial effort to integrate them will be essential. The same happens with manufacturers, operators, service providers and city administrators, since close collaboration is envisaged among them. All the existing wireless networks (cellular 2G/3G/4G and beyond, point to point, WLAN, WPAN, WMAN, mesh networks), and also the user terminals, mostly smartphones, which are today's main moving transceivers, will play an important role to facilitate Smart City deployment. Their role as personal standalone network access devices will change in future networks, when the handheld will be active as a cooperative networking node, and then be able to measure environmental parameters through its own sensors, as well as to geo-reference them, thus contributing to Smart City monitoring procedures. An approach to this concept is found in some recent cases where, to reduce the number of nodes, sensors have been installed on public transportation vehicles like buses or taxis, having the advantages of being mobile sensors, especially for easier maintenance and update.

Machine to Machine (M2M) and Internet of Things (IoT) communications have been fundamental for definition of the Smart City concept, combining wired and wireless networks to transmit sensor data in an efficient way. There are research challenges in finding solutions when an extremely dense population of wireless communication devices are closely located and generate independent traffic with different patterns, posing the need to share the same pool of radio resources while avoiding network failure and maintaining a high spectrum and energy efficiency. This becomes especially critical when fast moving and fast on-off devices are considered. Although all layers of the stack can suffer from these problems, attention should be focused on solutions at the PHY, MAC and LLC layers of the wireless systems, defining new techniques and also reusing existing techniques designed for other purposes. The Smart Grid concept will be fully implemented in the form of distributed networks, not only collecting and reporting data, but also making intelligent decisions, particularly those addressing energy saving.

One long-standing and still largely unsolved issue is the inherent limitation of radio propagation in the Smart City context. First of all, the large variety of scenarios makes it difficult to design the system based on a “one-size-fits-all” radio channel model. Then, the current spectrum crowding and the large spread of penetration loss values actually challenges the idea that low RF frequencies should be preferred (e.g. 400 MHz) thanks to their easier penetration. In addition, Smart City and IoT devices need to be low cost, which adds important constraints, requiring small size, simplicity, low transmitted power and low energy consumption. Therefore, this still calls for improved radio channel models, able to express the large variability of propagation attenuation at the frequencies of interest, taking into account the relevant use cases.
It is expected that the definition of next generation inter-operable protocol stacks and open standards for M2M/IoT will move from well-known wireless protocols such as ZigBee, RFID, Bluetooth or proprietary protocols, to the current 802.15.4e, 6LoWPAN, RPL, etc., and then to yet-to-be-defined protocols intended to unify and improve wireless sensor networks.

Finally, a relevant challenge in Smart Cities is how to manage the Big Data supplied by the City, to select which services are to be open or kept as private data, to assure the protection level required by different types of data and to assign the proper manager of such big data sets. Here, the concept of City Labs will take on extremely high importance in the next few years. In the City Labs concept, the network and the data will be open to research and to scientists to analyse and test proposals intended to improve the different networks and protocols, as well as to implement predictive tools and to develop new applications for extracting information from the data, among other possibilities.

A.1.4. The body becomes wirelessly connected for Health and Wellness

Body communications will enable a new generation of services and applications that give the user an enhanced and intuitive interaction with surrounding technologies. This interaction is boosted by a network of body implanted or wearable devices, operating in the short-range (the immediate environment around and inside the human body), that can exchange important data (e.g., health parameters) in real-time. Further research will enable the design of body communication systems that can be integrated into smart suits or uniforms, as well as accessories (e.g., glasses lenses, watches, jewellery). Health systems will also benefit from the integration of wireless on-body and in-body sensors, with applications to healthcare, remote monitoring, wellness and assisted surgery, among others. To mention one relevant statistic, it is expected that in 2017 Mobile Healthcare can help to cut costs by around 400 billion dollars in OECD countries [GSMA2013].

The wireless body environment (WBE) is intended to revolutionize health monitoring, with its huge number of possible applications in the home and hospital, for elderly care and emergency cases. The basic concept of WBE is to transfer the vital signs of a patient, sportsman, fireman, and so on to the respective unit for further action. Moreover Wireless Body Environment Networks (WBENs) are expected to provide new functionalities for applications in people’s every-day lives such as sport, leisure, gaming and social networks. As this service permits remote monitoring of several patients simultaneously, it could also potentially decrease health care costs.

The WBE should contribute extensively to improvements in quality, access and efficacy of health care, providing health professionals with access to timely, relevant information at the point of need. The medical motivation is to increase survival rates and improve health outcomes through easy and fast diagnosis and treatment. The goal for homecare services is to improve quality of life and independence for patients by supporting care at home.

WBE radio is developing as a more advanced and separate addition to wireless communication in general. While its basic operating characteristics are the same as all radio systems, there are many features and specific problems that justify dealing with it separately from other forms of wireless communication, such as battery life, low power, low cost, small size, body postures, and in-body propagation. Body environment applications
are designed for short-range applications with relatively low power and are regulated by the telecommunication authorities. Also, the devices are operated in or close to a human body, which affects the communication performance. Therefore, it is currently difficult to predict a reliable operating range for these systems, due to lack of knowledge of propagation characteristics, human posture, and movements.

![Fig. 2. Possible communication links for wireless body environment networks.](image)

The designers of such systems face a number of challenging tasks, especially since the human body is partially conductive and consists of materials of different dielectric constants, thickness and characteristic impedance.

Fortunately, there exist several mitigation approaches which can increase link reliability, based e.g. on multi-device operation and associated data/signal processing techniques. For instance, in the highly constrained situation of a person lying in a bed, the signal propagation from a device hidden by the body must find its way to the surrounding information system, a problem which will require addressing from a multi-level perspective (device placement on the body, propagation in difficult conditions, diversity techniques and signal aggregation...).

### A.1.5. From extremely dense traffic scenarios to moving networks

On the basis mentioned above that every electronic device is to be wirelessly connected, future scenarios in radio communications will give rise to situations where a huge number of devices are located in physical proximity (in the space domain, relative to radio coverage ranges), while generating independent traffic with different patterns and needing to share the same pool of radio resources to create some type of network topology.

These situations come from static and low mobility devices, as in machine-to-machine and machine-to-infrastructure communications, which are to improve industrial automation; or the connected home multimedia systems and sensors, where revenues are expected because of the increase of wireless data traffic while improving the user experience within the concept of connected living. Also high dense traffic occurs in high mobility scenarios, such as public events (either planned or unexpected), and in many others, such the smart cities mentioned above, as well as offices, smart grids and smart metering. In any of these
situations, the number of contenders for the radio resources can potentially be much higher than those manageable by traditional wireless architectures, protocols and procedures.

Such extreme situations do not occur often, but may happen, and in some cases may occur in regular operation, for example in stadiums, in clothing stores (where thousands of RFID tags may exist), or in a huge depot of some company. In all cases, the possibility of maintaining highly efficient connectivity using wireless communications can provide significant added value as it may solve many problems.

When the possibility of high mobility is considered, and devices which appear and disappear from the network very quickly, in a mixture of frequency bands, radio technologies and configurations, the engineering challenges can be remarkable. Indeed, when hundreds or thousands of devices share the same radio resources, the current systems simply do not work.

In fact the huge number of moving connected devices in certain areas, either accessing centralised services or getting information from sensors in their surroundings, increases the interest in developing selfish ad-hoc dynamic network configuration strategies. The popular term to describe these situations is “moving networks”, where many new concepts in network coding, relaying, self-organisation, or opportunistic caching, among others, are to be developed.
A.2. **New paradigms for Network Architecture: ultra-flexible RAN**

It is obvious that the concepts for developing future Networks and Terminals are already evolving. Networks architectures are becoming to ever more flexible, developing towards the Cloud RAN concept, based on technologies such as distributed antenna systems, and evolving beyond it towards what can be called “ultra-flexible RANs”. Will this not also mean that the Operator’s role will also evolve? In fact, the operation of a Mobile Network, which traditionally was based on a single owner of the Core and Radio Access infrastructures, who is at the same time the service provider for its customers, tends to become diffused in the virtual operation of shared RAN facilities, opening the door for Virtual Operators as service providers, Radio Resource Providers who own the spectrum and manage its access, RAN providers owning the infrastructure, etc. This scenario for Infrastructure Networks is in principle the basis of the future ultra-flexible RAN, in both technology and operation.

The explosive increase of capacity demand from mobile communication users has resulted in more dense deployments involving a growing number of Base Stations (BSs). These have high power consumption, and capital and operational expenditure (CAPEX and OPEX), associated with site rental, air-conditioning expenses, etc. BSs have been dimensioned for peak traffic loads, which increases 100 times every 10 years, while in practice the offered traffic varies drastically both geographically and temporally. In fact, measurements report that 50% of the sites generate 10% of the revenue, while 20% of the BSs carry 50% of the traffic. On top of this, the average revenue per user is decreasing. On the other hand, fibre availability is already a requirement for many operators, in urban areas, where 90% of the sites in dense areas have a fibre link available, of which 96% are within a distance shorter than 10 km to central office, which today aggregates tens of sites [PIZ2012].

In RAN deployment, it is by now obvious that installing smaller cells in areas where infrastructure can provide the required backhaul connectivity, is the current natural evolution of the radio access network infrastructure. The cost of its deployment vs. the amount of data they can handle is beginning to be competitive compared to other solutions. But these small cells will also require new techniques for configuration, management and optimisation. Self-configuration of such elements of the access networks is expected, as well as coordinated behaviour among groups of small cells together with the neighbouring network sites. Small cells change the classical concept of the cellular network, from the traditional geometric approaches for coverage and service area analysis, and change also resource management concepts such as “neighbour” to “partner” cell.

Going one step further in the evolution of network infrastructure, the use of Distributed Antenna Systems (DAS) for mobile access in small areas, mainly - but not only - indoors, will largely eliminate the concept of “cell”. This will occur at least in the sense that cells will not be the stable projection of the service area created by some radiating elements from a single site, but a dynamic set of positions to which a service connection is provided by a combination of signals generated in a cooperative manner from several distributed antennas.

A novel approach that makes Radio Access Networks (RANs) even more efficient is referred to as Cloud-RAN (C-RAN), a centralised processing, collaborative radio, real-time cloud computing and clean RAN systems [NGMN2013]. In C-RAN, a BS is split into a low-
cost remote Radio Unit (RU) and a software-based Digital Unit (DU), instantiated on a Virtual Machine (VM). RUs and DUs are linked by a low-latency and high-bandwidth optical fronthaul network. Each central office, constituted by a Data-Centre (DC), aggregates multiple DUs’ VMs into a so-called DU-pool, which may be of different Radio Access Technologies (RATs), as shown in Figure 3.

C-RAN brings to RANs the advantages of the cloud: resource-sharing, elasticity, on-demand and pay-as-you-go. Based on real-time virtualisation technology, C-RAN minimises CAPEX and OPEX costs, by aggregating multiple DUs’ per central office. It enables the fast, flexible and optimised deployment and upgrade of RANs, supporting pay-per-use models. It also eases the flexible and on-demand adaptation of resources to non-uniform traffic. Besides this, the centralised processing of a large cluster of RUs also enables the efficient operation of inter-cell interference reduction and Coordinated Multi-Point (CoMP) transmission and reception mechanisms, and eases mobility between RUs.

To make the future Mobile Networks sustainable from an economic viewpoint, it should provide more and cost less, both metrics being equally important. Flexible architecture concepts like Cloud RAN address these challenges, although in many cases the research effort highlights the performance enhancement aspect only. However, beyond 4G mobile wireless service provision in a 2020 time horizon will also require cost-effective technologies for the provision of ubiquitous coverage, and the flexible management of centralised resources.

With this dual performance–cost goal in mind, the Cloud RAN concept should be expanded in order to include not only the RAN but also EPC (Evolved Packet Core) functionalities, in what could be called Network Virtualisation.

Network Virtualisation refers to the capability of partitioning and/or pooling underlying physical resources (e.g., sites, racks, base band cards) or logical elements (e.g., RAN and EPC nodes) in a network, and it is usually associated with the concepts of software-defined networking (SDN) and cloud services. Some operators consider Network Virtualisation as a fundamental tool for making the network manageable, and a lever for modifying (opening) the mobile network infrastructure ecosystem, without precluding the incorporation of performance-enhancement technologies like CoMP or interference management, which is not necessarily a primary goal.
Currently, the first step in the network virtualisation journey involves only the BS. Pooling many BSs’ baseband processing capabilities allows the support of advanced features that require tight synchronisation between sites and the exchange of large quantities of information. The most common approach is to reuse the functional division adopted for the implementation of an open interface between the baseband processing unit and radio processing unit within a base station, as it is proposed by the Open Base Station Architecture Initiative [OBSAI] or at the Common Public Radio Interface specification [CPRI].

However, this approach leverages on the availability of a low cost and high speed transport infrastructure to link the baseband unit and the remote radio one. CPRI data rates, well above 1 Gbps, unfortunately make this assumption unrealistic in the medium term, even considering data compression techniques that are expect to produce data rate reductions of the order of 3:1 or 2:1. CPRI, designed for short intra-site links and based on simple baseband IQ signal sampling, is definitely not adequate for base station virtualisation in realistic deployment scenarios. Therefore, an open research field is to devise “fronthaul throughput optimised” base station partitioning, which could be performed at the PHY layer, but before the IQ signal generation, or splitting the protocol layers and assigning them to different sites. Physical layer network coding (PLNC) is a strong candidate for this approach.

Future steps in the network virtualisation process could be based on two main requirements:

- Supporting mobility of network functions between different locations in order to adapt to different deployment options.
- Supporting different sets of functionalities by means of software over the same generic hardware.

The role of Operators is also expected to evolve, from the current RAN sharing approaches to a full virtual operation concept. In fact, the operation of mobile networks, which traditionally was based on a single owner of the Core and Radio Access infrastructures, who is at the same time the service provider for its customers, tends to become diffused in virtual operation of shared RAN facilities, opening the door for a combined architecture with Virtual Network Operators as service providers, Radio Resource Providers who own the spectrum and manage its access, RAN providers owning the infrastructure, etc. This will have a large impact on the development of novel integrated and flexible services based on RANaaS (RAN as a Service). The scenario of Infrastructure Networks is in principle the basis for a future ultra-flexible RAN, in both technology and operation.
Among the supporting knowledge required to develop these networks, is that of the radio channel. The requirement for robust and resilient wireless access requires that the characteristics of the propagation channel are addressed in a more complete manner than before, when link outage could be accepted by the user to some extent. Site specific network planning will tend to be used much more than at present, in order to provide adequate access in cases that would previously be treated as poorly-performing outliers, not specifically addressed. Thanks to the widespread availability of computing power, physical propagation tools which make use of digital terrain and building maps will be used within operational networks in order to better optimise the allocation of resources and ensure correct access in the worst cases and in quasi real time. Obviously, further progress in the validity and accuracy of such tools will be required and will drive research in this area so as to find a suitable trade-off between precision and computation time. In addition, the possibly distributed character of the nodes challenges the traditional cellular model, with concepts such as stationarity and shadowing becoming less well defined than before. This calls for radio channel modelling research to move away from base-station centric approaches and take into account a whole new range of concepts.

A.3. Simplify to improve: Green, Efficient and Ubiquitous Broadband

From the Mobile Communications perspective, and looking also to other related disciplines, the user interface revolution is crucial for the required evolution of terminals and networks. A factor which has changed dramatically with the launch of touch-screen terminals is the “user latency”. If the “time-to-type” a command in a mobile keyboard in previous years is compared to the “time-to-touch” in today’s tablets, a factor of 10 is easy to reach. Hence the time between uplink packet transmissions from these new generation terminals has greatly decreased, and previous traffic models for uplink load have become obsolete. The activity of the user when accessing wireless services might give rise to a new revolution in the coming decade, since other interfaces are under development, such as gestural (in glasses or lenses), muscular (using on-skin sensors), or even brain activity sensors in the long term. Any such human interfaces will boost a new era of applications and services and, of course, give rise to new requirements for wireless connectivity and mobile networking. The only way to make the coming services and applications efficient at the RAN side is to reduce the signalling load, to reduce latency, to enrich user experience, and to maximise spectrum efficiency.

To date, the improvement of the user’s experience has been achieved by widening the network, the inclusion of new infrastructures, new frequency bands, and additional transmission systems. Three generations of Radio Access already coexist in Mobile Networks, and little effort has been expended to improve the overall energy and spectrum efficiency. Thus the metric of Joules per Bit per user is so far useless in RAN deployment. Moreover, even with the deployment of 4G technology, RANs continue to offer broadband access to a limited percentage of locations. This is true even in densely populated areas, where broadband radio access is available, but where interference limits capacity to well below its theoretical maximum. This means that overall the deployed RAN is still making sub-optimal use of the spectrum and energy (bits/joule).

One recently proposed approach to increasing the radio link efficiency, in terms both of spectrum and energy, is Massive MIMO. Massive MIMO involves base stations that are
equipped with a large number of antennas, say a few hundred. Very large antenna arrays have already been shown to have interesting theoretical properties [MAR2010] [RUS2013], and the expected impact of Massive MIMO in future radio networks is major since it is a leap forward that will provide the means to enable ubiquitous broadband access, thanks to its properties of efficient spectrum usage, higher capacity and very low energy consumption.

Massive MIMO antennas with an order of magnitude (or greater) more elements than in systems deployed today, i.e. a number of elements $(M)$ in the hundreds, is a very new and hot area currently under research. The basic method exploits a large number of antenna elements, and hence, available degrees of freedom, and offers a number of benefits such as increased antenna gain $(10 \log_{10} M$ for a linear array), reduced TX power (by a factor $M$), reduced required power per antenna element by a factor $M^2$ [MAR2010], ability to eliminate bulky coax cables and hence reduce power loss (increased power efficiency), ability to use more efficient power amplifiers and as a result reduce cooling demands (increased power and energy efficiency), increased radiation pattern resolution hence reduced interference (massive capacity).

But the favourable theoretical properties of massive MIMO are still to be proved in practice, and to be designed according to the future scenarios where mobile communications are to be deployed [PAY2012] [GAO2012]. Future radio access links using massive MIMO will benefit from its particular properties such as the fact that high-dimensional channel matrices approach the asymptote of random matrix theory, so radio channel characteristics that were random before now start to appear deterministic. Another benefit will be the unprecedented thermal noise averaging to the point where the performance-limiting factor of a massive MIMO system is interference from other transmitters. Finally, the increased aperture of very large antenna arrays allows for unparalleled resolution capabilities.

A.4. Wider and broader links but, where and how in the Spectrum?

Assuming that the amount of data traffic is to grow by two orders of magnitude in the coming decade, no matter what will be the type of traffic and the “killer” applications or services in these future networks, what is evident is the need for more resources to deal with more than 10 times more mobile data traffic in 5 years from now, and potentially even 100 times in 2020. These “resources” could of course come from additional spectrum, although this is scarce below 3GHz and less feasible after the second digital dividend, but obviously still available in higher frequency bands for short range broadband connections.

Spectrum is as always the keyword for the future of Radio Communications. Which bands should be considered for the coming scenarios? There is no doubt that for Mobile operation in open areas the UHF band is the best possible allocation, but these bands are becoming overloaded under the current access technologies, RAN infrastructures and services provision schemes. If UHF has to remain the main allocation for such systems, with many thousands of moving terminals per square kilometre, new concepts for efficient spectrum usage will have to appear.

Among other approaches, opportunistic access to certain frequency bands, cognitive radio, co-primary usage in shared bands, and massive and distributed MIMO are already under deployment. At the other end, systems at 60GHz and above, even up to 400GHz, are
currently under consideration as the natural way of providing wireless Gigabit links, but this is limited to short range radio access to infrastructure, focussing the wireless “networking” problem on managing the location of terminals and the distribution of services though access points over wired infrastructure.

Some spectrum bands were already identified by the International Telecommunications Union (ITU) during the World Radiocommunication Conference of 2012 in Geneva [ITU2012] as potential allocations for spectrum sharing technologies. Sharing spectrum bands requires consideration not only of technologies but also of regulatory policies, and new applications and services for the end users derived from such approaches.

On the wireless terminal side, the complexity has increased with the inclusion of several new bands in simultaneous operation for the same network access. The heterogeneity of the RAN spectrum and access modes has been enforced by the rapid increase in demand for mobile data, but has become a drawback for the design of radio terminals, and its energy efficiency. If the future of mobile communications evolves through the inclusion of new spectrum bands on current cellular infrastructures, terminals will soon reach their limit of reliability. An open question is whether the best focus for coming generations of mobile terminals and networks should be to drive it to a single access technology operating in multiple bands, jumping to the best frequencies to adapt to different range, environment, throughput and power requirements for the potential huge range of services to be connected; or whether alternatively to improve the baseband procedures in the terminal so as to accept different radio access operation modes in the same frequency band.
B. Research Challenges

**Challenge 1. Paving the way to the new RAN architecture paradigm: From Cloud to Virtualisation**

The extension of Virtualisation into RANs, addressing the virtualisation of radio resources by an additional layer in the network architecture, enables much more efficient management of RAN capacity. In addition, developing the procedures for moving functionalities between different locations in the RAN, would give networks the flexibility to adopt the best architecture configuration and resource allocation options in every deployment scenario. Finally, a paradigm enabled by C-RAN is the capability to offer a cloud-based, multi-tenant and heterogeneous RAN as a Service, i.e., to simultaneously offer to multiple tenants – Virtual Network Operators (VNOs) – resources according to specific Service Level Agreements (SLAs)

This challenge requires the development of new concepts in RAN technology, among others:

- Design of the **network architecture** that enables an efficient implementation of Virtual RANs, taking into account the harmonisation with LTE architecture, overcoming the limitations and constrains of RAN sharing.
- Identification of functionalities to be **centralised** and those to be **distributed**. Some eNB functionalities should be better centralised (e.g., L2 procedures, scheduling), although some EPC functionalities could be distributed (e.g., colocation of some MME/SGW functionalities with the eNB upper layers). Identification of where these functionalities could be located, including their dynamic allocation, under a concept that could be called functional mobility.
- Implement mechanisms for supporting this **functional mobility**, including alternatives like SDN/OpenFlow.
- Develop **Radio Resource Management** algorithms for the efficient use of this novel architecture, so that full capacity can be used in the most efficient way, considering not only services’ specific aspects but also users’ profiles.
- Develop efficient **balancing of resources** between Data Centres to flexibly and efficiently satisfy agreed SLAs. In this sense, it is of utmost importance how DUs are virtualised in a single or multiple Virtual Machines, decomposing specific functions in an efficient and scalable way, and how Software-based DUs are aggregated on a single or multiple DCs.
- Find the best dedicated mechanisms for the **integrated management of virtual radio resources in RANaaS** operation. This is supported by an elastic on-demand allocation of resources, enabled by detection and prediction mechanisms for resource usage, to optimise the offered services. Virtualisation capabilities for software-based DUs, enable them to be split into multiple instances per tenant (VNO), as well as the isolated management of the associated resources. This solution would provide a flexible way of instantiating, scaling and releasing RAN resources wherever and whenever needed.
Challenge 2. Enabling Technologies for Wireless Body Environment Networks

The number of connected devices which will be on the human body surface and in-body for monitoring will make the body environment a local wireless network, either connected to the infrastructure or isolated, probably controlled by a mobile terminal located in a pocket, glasses or watch. This local network has to use low power transmission, and be at the same time as efficient and adaptive as possible in terms of throughput, robustness, latency and reliability. To make such Wireless Body Environment Networks a reality, some technical challenges are identified:

- Deep knowledge of around-the-body and in-body propagation channels. To ensure the efficient performance of body environment wireless communication the electromagnetic wave propagation must be characterised and modelled with respect to environment, antenna, body postures, and body movements. Given the number of possible node positions this results into a multitude of different channels, which need to be completely modelled. In particular time-varying radio channel models are essential for the evaluation of communications link performance over the various frequencies of interest. Moreover a huge step-forward in antenna-propagation joint modelling is needed, since the radio channel in WBE is strictly dependent on the radiating element.

- Understand the behaviour of human body tissues at different frequencies, to efficiently design antennas, especially for an implant case, and to foster the flourishing of new applications which can operate with minimal power, which is one of most important requirements for wireless body environment network applications.

- Adopt new criteria for antenna design to adapt them to the specific WBE scenarios. Antennas for WBE must be small, often a fraction of a wavelength for most use cases, and have to be designed with respect to their emplacement in or on the body. For instance, on-body communications should be low-profile and favour the propagation of surface waves to enhance budget links. Investigation of in-body antenna efficiency enhancement should be carried out to extend implant communication range. Moreover in order to increase user comfort, new biocompatible materials should be investigated to realize flexible and stretchable antennas.

- In WBEs each application has specific requirements in terms data rate, latency, maximum error rate, security and privacy. Optimising WBE radio networks will mean dealing with the optimal location of sensors on the body, coordination with several types of devices as well as modelling the body dynamics, covering complex and realistic scenarios.

- Specific investigation should be carried out into PHY-MAC cooperative and flexible protocols to handle the different requirements. Eventually virtual MIMO approaches should be used to enhance diversity against the effects of human movement.

- Interference between BANs and already existing wireless systems, but also between different BANs should be investigated.
Challenge 3. Optimal Deployment of Massive MIMO Networks

The Massive MIMO concept is by now fully defined, but many aspects concerning the deployment of such technology in current RANs are still to be addressed. The modelling, planning, tuning and optimisation of these new RAN elements should at least be focused on solving the following challenges:

- **Massive MIMO propagation channel modelling** based on channel sounding experiments to verify theoretical characterisation. The correlation properties of the channel are of major importance, even more so than for conventional MIMO because of the possibility to achieve very large spatial diversity gains with massive MIMO. Massive MIMO channels differ from conventional MIMO channels in that they experience large-scale fading over the antenna array and in that their drastically increased spatial resolution may challenge the now still widely accepted notion of multipath clusters. Both effects are expected to help reduce the correlation between spatial sub-channels, but extensive channel sounding campaigns are needed to confirm this.

- **Hardware options:** low cost hardware for hundreds or even thousands of transceiver chains along with the inevitable impairments and accompanying calibration requirements, as well as parallel baseband signal processing, broadband or multi-band antenna elements, array configurations and compacting techniques (e.g. dual polarization) taking into account mutual coupling, mounting problems and aesthetics.

- **Fast signal processing:** low complexity, probably linear, optimum algorithms for real time processing of huge amounts of data.

- **System issues:** channel reciprocity and TDD for different operational scenarios, the CSI quality and effect on performance for different antenna deployments; RRM algorithms operating in the time, frequency and space domains (including sub-array options); spectrum sharing; frequency band, air interface, and cell layer selection strategies; initial user acquisition, using for example blanket coverage or space-time block coding.

- **Network planning issues:** low emission requirements for Green networks and network planning for coverage; very high capacity and QoS versus SONs and SON policies; the option of a different ‘signalling network’ with low density wide area coverage base stations; techno-economic analysis for the different network deployment options (e.g. heterogeneous networks with hierarchical cell structures and support from relays) as well as combination with high speed optical network infrastructure and best deployment strategies.

- **Field trials:** Although the potential of massive MIMO has been demonstrated in some theoretical research papers, there is a clear need for extensive field trials to prove the capabilities of the technology and also to highlight problems that cannot be predicted from theory, and hence will point to new directions and solutions.
Challenge 4. Unveiling and exploiting the vehicular radio environment

Although much is known about traditional cellular wireless channels, this is not the case for vehicle-to-vehicle or vehicle-to-roadside channels due to low antenna heights, high mobility, complex propagation environments, and particular constraints on antenna systems installed in vehicles. This is especially true for higher frequencies such as are used for IEEE 802.11p, which is solely designed for vehicle-to-vehicle communication.

- To design an efficient wireless communication system requires detailed channel knowledge, which currently is lacking. This deficiency needs to be addressed by channel measurement campaigns and channel modelling work.
- Channel measurements campaigns are also important to create simulation environments which are close to reality. Such environments can minimise the time for testing automotive connectivity systems.
- Antenna systems for vehicles are an important area that must be further developed. A major challenge is how to provide a stable, high data rate, and efficient backhaul link between the vehicle and the fixed network (e.g., a macro base station), while at the same time providing good coverage around and inside the vehicle for the access links (i.e., the last hop to the end device). Moreover there is still a lack in system level assessment of vehicular antennas, in order to rate different antenna systems against one another. Cost and aesthetic design are further requirements, which make the antenna system design task quite challenging.
- Quite closely connected to the antenna systems is the development of channel coding, modulation, and medium access control for highly mobile vehicular networks.

Challenge 5. Maximise Spectrum Efficiency, ensure Wireless Access universality and resilience

The generalised use of wireless access in nearly every aspect of private and professional lives, gives rise to severe challenges for these technologies, in particular to ensure the availability of spectral resources to meet the demand, and the capability of the systems to ensure reliability in the access at any place and any time, at a sufficient quality of service. In particular, Spectrum Sharing with other systems must be better guaranteed, by analysing the potential to share spectrum with non-cellular systems, e.g., fixed radio links, radars, and broadcast systems, among others.

- Study of radio aspects for the sharing of spectrum between cellular systems and other systems, e.g., taking advantage of rotating radars, narrow beam antennas in fixed radio links, and time-slotted transmissions in broadcast, to enable the transmission of information in mobile and wireless systems.
- Taking advantage of specific services and applications (e.g., Machine-to-Machine, SMS, or Cloud based applications) to establish efficient transmission algorithms for user information, as well as for networks’ signalling and control.
- Regaining the spatial domain, in conjunction with the frequency domain, to establish algorithms that make an efficient use of the both, by splitting transmission into several frequency bands, according to spatial location.
Challenge 6. A Network-Aware Physical Layer for Multihop Networks

The above analysis has shown that networks of the future will involve many nodes cooperating to provide services to terminals and route data through what will become a multihop wireless network. This applies both to the Radio Access Network, where Cloud RAN, CoMP and distributed antenna systems all involve many entities forwarding data to one another, and to newer applications such as to the Wireless Body and Vehicular environments, Smart Cities, etc., which often involve many small devices. However, conventional physical layer technologies still treat individual point-to-point links separately, with signals from other nodes treated as interference. A paradigm shift is required to create a network-aware physical layer, which exploits these signals to provide much more efficient networks. An important component of this will be physical layer network coding (PLNC), but until now this has been exploited only in small-scale networks such as two-user, two-way relays, and has not achieved practical application.

- PLNC will need to be applied in more complex networks, involving multiple relays, sources and destinations, and more than two hops.
- PLNC schemes are required which incorporate error control coding, and which are robust to fading states of the channel.
- Practical issues related to the network-aware physical layer must be addressed, including synchronisation, frequency-selective channels, and channel estimation.
- The paradigm will also require a transformation of RRM and other higher layer functions, as many such functions (including routing and multiple access) can now be performed at the physical layer, while other new functions, such as adapting the network coding, must be implemented in a distributed manner, based on self-organisation.
- Channel models have until recently treated individual links separately, and have not addressed the correlation of channels across a network. Models which account for correlation at larger scales will be required properly to evaluate this concept.

Challenge 7. Modelling, Testing, Standardizing the future Wireless scenarios

Tackling the above research challenges is particularly important because it will allow us to provide scientifically sound input to standardization activities and thereby ensure the success of beyond 4G systems. Furthermore, achieving resilience will require a much more realistic and accurate representation of the radio propagation channel than currently exists, in order to cover more use cases, especially given the complexity of network architectures, which now include macro-, micro- and small cells, down to pico/femto cells in a continuous "seamless" access system.

- Models and tools will be needed which are able to combine the characteristics of these various propagation environments and realistically describe transitions from one to another in a holistic representation, including time variant and mobile users. The challenge will be to achieve suitable representations in the many scenarios of interest at a reasonable research effort, based on past experience and well-chosen new study cases.
- A related challenge is to achieve a much improved accuracy/reliability in deterministic (site specific) propagation simulation tools, which will help reach the goal while limiting the amount of experimental work (very much like what is done in e.g. aeronautics, where simulators are heavily used in the plane design phase). In particular, a better and more cost effective description of diffuse scattering will be required, as well as the hybridisation of fully deterministic and stochastic models, able to account for details of the environment which cannot be described explicitly.

- **Man-made** inter- and intra-system interference models, which are closely related to Cognitive Radio topics like spectrum sensing but also determine the environment in which the predicted systems have to operate and hence in which they should be tested.

- **Subjective** Over-the-air (OTA) testing metrics, i.e. based on user perception because a mix of services is likely to determine the mix of radio system technologies employed to render these services.

- A paradigm shift from testing a single device in isolation over a single communication link towards the testing of communication performance in live networks over multiple, distributed links, not necessarily in the same frequency bands.
CONCLUSIONS

By 2020, Wireless Communications Networks will serve not only very dense populations of mobile phones and nomadic computers, but also other devices and sensors located in machines, vehicles, health systems and city infrastructure. The spectrum and energy efficiency of current approaches are not sufficient to cope with the expected huge demand for wireless data density.

The *Wireless Internet of Things* in 2020 will require revolutionary approaches in Radio Access Technologies, Networks and Systems to overcome the limits of the current hierarchical cellular deployments, the layered networking protocols and the centralised management of spectrum, radio resources, services and contents.

A set of scientific challenges for the coming years have been identified in this paper according to the IC1004 view of the future Mobile Communications scenarios. These challenges are focused on four main new paradigms in Future Wireless Networks: Virtualisation of Radio Access Networks, generalised Massive MIMO deployment, the terminals becoming Moving Relays to many new types of wireless devices, including cars, body sensors and machines, and the search for new strategies for smart Spectrum Management and Radio Resource sharing.
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[OBSAI] Open Base Station Architecture Initiative, 2002; www.obsai.com


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