

Net!Works European Technology Platform

Expert Working Group on

Spectrum Crunch

White Paper

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List of Acronyms

A/D	Analogue to Digital
CAPEX	Capital Expenditures
CoMP	Coordinated Multi-Point
CR	Cognitive Radio
CRN	Cognitive Radio Networks
D/A	Digital to Analogue
DSA	Dynamic Spectrum Access
DSL	Digital Subscriber Line
E2E	End to End
FDN	Fibre Distribution Network
GPS	Global Positioning System
HCI	Human Computer Interfaces
HSPA	High Speed Packed Access
IMT	International Mobile Telecommunications
ITU-R	International Telecommunications Union – Radiocommunications Sector
LEDs	Light Emitting Diode
LTE	Long Term Evolution
MAC	Media Access Control
MIMO	Multiple Input Multiple Output
NUM	Network Utility Maximization
OAM	Operation, Administration and Maintenance
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operational Expenditures
OSI	Open Systems Interconnection
OSS	Operations and Support Systems
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio Access Technology
SDR	Software Defined Radio
SH	Spectrum Hole
SON	Self Organising/Optimizing Network
TV	TeleVision
UHF	Ultra High Frequencies
UMTS	Universal Mobile Telecommunication System
WDM	Wavelength Division Multiple Access
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WRC	World Radio Conference
WS	White Space

Table of Contents

Executive Summary.....	5
1 Rationale.....	6
2 Research priorities.....	7
2.1 New Wireless Network Topologies	7
2.2 New Air Interface Technologies	8
2.3 Self Organized Networking and Cognitive Radios.....	10
3 Technology Road Map.....	14
4 Summary and Conclusions.....	15
5 Recommendations.....	17

Executive Summary

This White Paper presents the implications from the expected traffic increase (thousand fold over this decade and still growing into the next), which would quickly saturate today's networks. While a steady increase of the spectrum allocated for mobile communication is foreseen, unfortunately, it will most likely fall short of the expected traffic increase leading to a "spectrum crunch" that needs to be tackled by using spectrum ever more efficiently. Additionally technologies are needed in support of deployment of a much higher number of base stations in a cost efficient way. These technologies will help utilize presently unused and new frequency bands in order to overcome problems of wireless backhaul whilst minimising the effect of patchy/fragmented spectrum allocations. 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.

The main aim of this White Paper is to present technologies with the prospect to enable future networks to serve the growing demands of their users, providing also insights on the directions the research should have, in order to mature these technologies to a level that allows them to be picked up for system design and standardization.

1 Rationale

Globally, the demand for broadband wireless communications is drastically increasing every year. A major factor contributing to this development is the ever-increasing number of users subscribing to broadband internet services using their mobile devices. This is accelerated by the trend towards flat-rate subscriptions. Moreover, new devices, such as smart-phones and tablets with powerful multimedia capabilities, are entering the market and are creating new demands on broadband wireless access. Finally, new data services and applications are emerging which are key success factors for the mobile broadband experience. All these factors together result in an exponential increase in mobile data traffic in the wireless access system. This trend is expected to continue to a similar extent over the next decade.

Recent studies and extrapolations from past developments predict a total traffic increase by a factor of 500 to 1000 within the next decade. These figures assume approximately a 10 times increase in broadband mobile subscribers and 50–100 times higher traffic per user. Besides the overall traffic, the achievable throughput per user has to be increased significantly. A rough estimation predicts a minimum 10 times increase in average, as well as in peak, data rate. Moreover, essential design criteria, which have to be fulfilled more efficiently than in today's systems, are fairness between users over the whole coverage area, latency to reduce response time, and better support for a multitude of Quality of Service (QoS) requirements originating from different services.

An emerging factor in the overall design of next generation systems is the energy efficiency of the network components and its deployment. The environmental impact by reducing the CO₂ emissions is essential for the ecosystem. Moreover, increased energy efficiency of the network reduces operational expenses, which is reflected in the cost per bit. This measure is important given the expected traffic and throughput growth until 2020.

It is essential that broadband wireless access systems in 2020 can meet these requirements. Achieving this will have strong impact on the economy in the broadband wireless sector, from the device and component manufacturers up to the network and service providers. Today's wireless systems are far from fulfilling these requirements and strong efforts in research and development are necessary in this coming decade. Consolidated efforts are necessary from all players in academia and industry to develop innovative technologies and deployment scenarios which can guarantee to meet the demands on broadband wireless in 2020.

To have a globally-harmonized approach for specifying and developing broadband wireless networks, the ITU-R has established a successful framework by setting minimum requirements for next generation systems. This global effort started with the definition of IMT-2000 systems for 3G standardization. Recently, 4G systems have been specified which have to fulfil the IMT-Advanced requirements. The ITU-R is expected to analyze the demands and requirements for the next generation of broadband wireless systems to guide and harmonize the future developments towards 5G.

There are expectations from the network operators that new spectrum for mobile services will be allocated at the World Radio Conference (WRC) in 2015. However, it can already be forecast today that, it will not be sufficient to support the predicted traffic demands for 2020 by some distance. Thus, technologies with increased spectral efficiency, as well as new heterogeneous network deployments with distributed cooperation of devices, have to be developed. It is not unconceivable to see yet another new air interface, if significant gains can be obtained by introducing a new access scheme.

2 Research priorities

2.1 New Wireless Network Topologies

On a network topology level, the main tools to cope with the spectrum crunch are denser and denser node deployments and enhanced coordination. However these require advancements in several other areas to make this feasible both technologically and economically:

Multilayer Multi Radio Access Technology Networks

Future networks will need to be deployed much more densely than today's networks and, due to both economic constraints and the availability of sites, will need to become significantly more heterogeneous and use multi radio access technology (RAT). They will become more heterogeneous in terms of: transmit power, antenna configuration (number, height and pattern of antennas), supported frequency bands, transmission bandwidths, 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 (e.g., fibre, leased lines with technically- or commercially-limited bandwidth, DSL-like lines, microwave links, or in-band relaying). Diverse radio access technologies will need to be integrated, such as: LTE, including LTE-Advanced; UMTS, including HSPA; Wi-Fi; future radio-access technologies; or any combination thereof. Last, but not least, the overall allocated spectrum will be more fragmented and may be shared according to new licensing modes.

Procedures, such as radio resource management and optimizations thereof, will, therefore, need to be revisited in the light of these trends and new technologies will need to be flexible to support all cases without generating excessive overhead. Smart self-configurability and autonomous self-adaptation are key features to adapt to a variety of design criteria. In this way, the user experience, including availability of required data-rates, latencies and other QoS parameters, should be provided in a consistent and secure way, whilst simultaneously meeting deployment criteria like energy and cost efficiency.

Energy Efficiency

Both the heterogeneous network topology and network management need to be fundamentally rethought and redesigned for better energy efficiency, dimensioning virtually all quantitative parameters, such as the ratio between large and small cells, the form factors, and the number of hops to a node with wire-line backhaul, in a harmonized and holistic way and not individually. The backhaul organization deserves particular attention, especially for cloud computing/processing approaches. Moreover, besides solutions that are theoretically ideal, research should also take into account practical constraints including desires to reduce electromagnetic radiation in general.

Switching nodes on and off, depending on the actual traffic has been the most obvious technique to do, but some critical points need to be addressed in the future. For one, keeping nodes alert while they are asleep (standby) still requires a non-negligible amount of energy. In this context, an entirely passive technology would be desirable that does not require any energy at all while being idle. This would require a technology leap, as opposed to further fine-tuning of existing technologies. A complementary aspect is to switch on nodes before they are actually needed, introducing a proactive element in the management. This in turn requires some statistical insight in the network and user behaviour.

Cooperation of Wireless Network Nodes

The conventional cellular structure will be complemented by novel network topologies in the IMT-Advanced compliant networks. Possible extensions include self-organising mesh-type networks with direct user-to-user communication and different levels of cooperation or coordination between end-user devices and/or network nodes. The most promising, albeit the most challenging, approach for providing the much-needed capacity and coverage increase, particularly for cell-edge users, is coordinated between transmissions, which facilitates multi-user pre-coding techniques across distributed antenna elements or other network nodes in effectively utilising the interference. This can be used to improve the utilization of the physical resources

(space, time, frequency, phase) by exploiting the available spatial degrees of freedom in a multi-user multiple input multiple output (MIMO) channel (e.g., collaborative scheduling in combination with 3D-beamforming). However, these technologies have not yet reached a high-enough level of maturity; thus, further research efforts have to be spent.

Radio Access Resource Sharing

The densification of the wireless network i.e. reduced inter-site (antenna cluster) distances will boost capacity and reduce total radiated power and thus energy consumption. Exploitation of cloud technologies, equipment/resource sharing and virtualisation are key enabling technologies to achieve this cost-efficiently and increase areas and degrees of coordination, a necessary prerequisite for higher traffic at lower cost. These technologies are, however, still in their infancy, needing many breakthroughs and refinements to reach a stable status for deployment including synchronization requirements of low-cost base stations and architectures supporting also loose synchronization e.g. interference alignment techniques.

Broadband Radio over Fibre

This is a further virtualization step, where even the D/A and A/D converters are centralized and analogue signals are forwarded as optical carriers (optionally with wavelength division multiple access (WDMA)) via a Fibre Distribution Network (FDN) to/from the antenna heads, which only contain analogue electrical/optical converters and amplifiers. Key challenges for this approach include minimising the energy consumption, maintaining or improving link linearity and reducing signal conversion times. This requires substituting, as much as possible, electronic processing with the corresponding optical processing. Such high-speed, photonic-driven (and integrated) signal processing systems may support high bandwidth at high carrier frequencies from a much larger number of antennas than with conventional network nodes. They still require research regarding algorithms addressing user mobility, traffic routing and delivering, energy consumption, congestion, and capacity optimization, to cope with the considerably higher attenuations at higher bands.

New Radio Access Architectures

Current cellular systems are designed with extensive in-band signalling, putting a limit on achievable spectral efficiency. This problem is exacerbated with trends towards smaller and smaller cell topologies for example resulting in excessive mobility related signalling. To achieve, simultaneously both spectral and energy efficiencies, it is high time to move away from traditional cellular architecture and investigate into new and alternative architectures where signalling messages and user data can be supported and optimised for capacity and energy efficiencies irrespective of cell size. This calls for a physical separation between control and data planes. For both on-line spectral and energy efficiencies optimisation in network operation such new architectures must take into account users' and cells' active and idle states and manage network resources intelligently and dynamically whilst maintaining the overall system stability. Physical separation between control and data planes brings about new research challenges, notably synchronisation between such planes.

2.2 New Air Interface Technologies

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, spectral and energy efficiency, robustness, 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 (for example, in link geometry distribution) 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.

Basic Transmission Technologies

Orthogonal Frequency Division Multiplexing (OFDM) is the transmission technology used in the most recently developed wireless technologies, such as LTE/LTE-Advanced and WiMAX. Being a kind of *multi-carrier* transmission scheme, OFDM provides a low-complexity means to handle, and even take advantage of, radio-channel frequency-selectivity, due to the small sub-carrier spacing and the possibility for scheduling in the frequency domain. At the same time, OFDM spectral efficiency, flexibility, and robustness are a compromise

with the need for a cyclic prefix and the required guard bands. 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 thus 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.

Advanced Multi Antenna Transmission/Reception

The use of multiple antennas at the transmission and/or receiver side is an important way of greatly enhancing the efficiency and robustness of the air interface. Although multi-antenna transmission/reception is today 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, both on link and system level. This includes more robust multi-antenna transmission (e.g., in terms of limited channel knowledge), as well as extending the capabilities of the multi-antenna transmission schemes 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. In theory, this would provide a path towards enormous enhancements in terms of system efficiency. However, the introduction of such massive antenna configurations for wireless communication requires extensive work, both in terms of the antenna technology itself and in terms of transmission and reception algorithms needed to efficiently utilize the antenna system.

Advanced Interference Handling

The link performance in mobile broadband systems is today often limited by interference from other nodes of the system. Relatively primitive means to suppress such interference at the receiver side have already been introduced in state-of-the-art wireless-communication systems. However, the ever-increasing ability for computationally-intensive signal processing, even in hand-held terminals, opens up new opportunities for more advanced methods in interference suppression/elimination or even utilisation. Research is needed to realize such schemes, both on their basic principles and on their integration into wireless networks. A very specific type of interference impacting the receiver of a radio unit is its own transmit signal. In all systems of today (apart from simple repeaters), such interference is handled by separation of transmission and reception either in frequency (frequency division duplex) or in time (time division duplex). If the interference of the transmitted signal could be suppressed by other means, such as advanced receiver processing and specific antenna configurations, this could, at least in theory, *double the capacity*. Means to achieve this have been demonstrated in academia and the scheme becomes of particular interest in small cells scenarios, when transmit and receive signal level difference is smaller than in other settings (e.g., macro-cellular). However, significant work is still needed to make such schemes practically useful. In particular, extending the bandwidth and dynamic range of such systems are a priority. The implications of such schemes extend beyond the physical layer and could potentially transform, even revolutionise, higher layers of the network and allow previously intractable problems to be solved.

Disruptive Transmit and Receive Architectures

Concerning hardware, the major challenge will be the size of the components. For reasons of cost and practicality, network nodes will be significantly smaller in size in the future. To date, this goal is pursued by improving existing technologies, but at some point in time, the limits will be reached and a technology leap will be necessary here as well. Outsourcing tedious computations 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 energy-saving potential. 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 in mind; some call for highest energy efficiency; for others, the emphasis would be on robustness and security. This variety in requirements and roles necessitates major improvements in designs in terms of flexibility, both for the network and the architectural design of the nodes.

Visible Light Communications

In the last decade visible light communications 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 Light Emitting Diodes (LEDs). White LEDs are expected to replace the conventional lighting sources, particularly as efficiency of these devices is continuously improving. One can expect that solid-state illumination will replace other sources in the near future. Whilst LEDs are good source of illumination, they

can be modulated with high-speed data, resulting in visible light optical links. There is more than 300 THz of bandwidth readily available in such optical channels. Moreover, optical transceivers are typically simple, inexpensive and low power. For indoor scenarios (e.g. home, office, etc.), optical downlinks are possible where information is confined within the room. Furthermore, as no radio waves are used, no interference to other equipment is created. This is of great advantage in sensitive environments such as hospitals, airplane cabins, and others. There are, however, several challenges that need to be tackled before visible light communications is widely adopted. They include developing techniques that will help to mitigate problems caused by ambient light and shadowing. Visible light communications does not compete with radio communications, but complements it. Extremely simple transceivers easily support several tens of Mbps, and more advanced systems have been demonstrated to operate at data rates well above 1 Gbps.

Energy efficiency

Air-interface and associated technologies are key to energy efficiency, if designed with that in mind. Promising approaches include the employment of multiple antennas that go beyond the existing MIMO schemes in current technologies. Moreover, an inconvenient property of today's technologies is that they require a large overhead for channel estimation and mobility support, which consume a significant part of the system power in low-load situations. Hence, completely new transmission paradigms must be envisaged in design of new air interface and in enhancement of existing ones.

User Context

Modern smartphones may allow predicting user behaviour including user location and data transfers using their sensors such as: GPS, gyroscope or accelerometer combined with calendar information and past activities. This allows for several possibilities for radio resource management optimisation such as:

- Send or receive emails with large attachments, send or download large files not necessarily immediately but at the ideal time / position for the wireless network (requiring less spectrum and energy), still in time to satisfy user expectations and possibly even before the user request.
- Providing users advice when / where to get optimum service (e.g. closer to the base station).
- Signalling can be optimized based on the user context.

Important research questions to facilitate this approach include:

1. Algorithms to determine and predict user context/activity
2. Evaluating the potential of this approach, regarding both more efficient spectrum and energy utilization.
3. Defining a generic framework to be introduced in future systems/standards for enabling this approach

This technology can be combined with various other approaches of system optimization for future wireless systems by advancing not abstract low level performance figures but focusing on end-to-end context specific user requirements and directing scarce resources (spectrum, energy, ...) as well as optimizing the network on all levels towards where most value is created for the users in their respective contexts.

2.3 Self Organized Networking and Cognitive Radios

Future wireless networks will face diverse challenges, amongst which are efficiencies in cost and resources including the growing but still scarce spectrum resource. All aspects of mobile networking still can and, more importantly, have to be improved to meet future requirements. Capacity and coverage have been continuously enhanced for many years, but never match completely the increasing demands. An always important topic is resource efficiency, both in terms of installed/active equipment and in terms of shared resources to harvest on statistical multiplexing. Moreover, in the time of climate change and operational cost, energy efficiency has become more and more important.

To continue the process of improvement and innovation with respect to these wireless networking characteristics, many key enabling technologies are available, but there are still many issues unsolved and require in-depth investigation in a holistic manner before they can be deployed. The following sections will go into more details with respect to these.

Inter Layer Network Optimization

Undoubtedly, future wireless communication networks must provide a large range of services, including voice, data and streamed multimedia, at reasonable cost and QoS, comparable to competing wire-line

technology. This increased demand may lead to a need for employing new network topologies, such as multi-hop wireless networks, mobile ad-hoc networks and deeper integration of wire-line and wireless networks.

A fundamental problem in designing such complex systems is the derivation of a network control mechanism, comprising flow control, routing, scheduling and physical resources management that can provide QoS guarantees and ensure the network stability under a large set of service demands. Traditionally, these control decisions are optimized independently at different network layers. Every layer controls a subset of the decision variables and observes a subset of parameters and variables from other layers. Thus, each layer in the protocol stack hides the complexity of the layers below and provides a set of services to the layer above. While the general principle of layering is widely recognized as one of the key reasons for the enormous success of wire-line data networks, there is now a worldwide recognition that it is no longer efficient, especially in the case of wireless networks. Globally-efficient designs of wireless networks cannot be achieved without crossing the boundaries of the standard Open Systems Interconnection (OSI) layers.

Radio Access Network Operation

The tendency in radio network management is to allow system optimisation at local level as much as possible: the systems are getting more and more decentralized. The long-lasting dilemma has thus been on finding a right balance between centralise control vs. self-organised networking (SON). As small cells will have a more important role in the future and optical fibre backhaul is becoming more feasible to deploy, the system architectures based on local centralised clusters of small cells become of interest for global optimisation of the cluster operation(e.g., following the NUM framework). An alternative approach is to allow full flexibility at each small cell, leading to true SON behaviour.

Energy Efficiency

In an intelligent future wireless network, the connections for delivering services should also be designed from an energy efficiency perspective. This means that the service plane should be intelligent enough to use the least amount of radio resources and energy as possible and utilise the maximum allowed latency as much as possible. Hence, instead of offering a more or less uniform bit pipe with varying delivery capabilities, the services could be delivered intelligently to also take advantage of the operation environment (e.g., existence of alternative access networks, including infrastructure-based or infrastructure-less, availability of bandwidth, radio propagation environment, predicted user mobility pattern, etc.) and to scale the quality according to available delivery capabilities (e.g., scalable video encoding). This is important from both energy efficiency and quality of experience (QoE) points of view. Furthermore, availability of ample spectrum allows transmitting data with lower spectral but higher energy efficiency e.g. by using lower modulation schemes and less complex receiver algorithms, enabling globally optimal tradeoffs.

Cognitive Radio Networks

Wireless networks in the legacy and the Future Internet context will have to satisfy an increasing volume of applications (e.g., various new concepts like smart infrastructures, various information flows like video and data apart from voice, various end-points, namely, machines and smartphones, etc.) and an increasing volume of associated demand and traffic. Moreover, as there is fierce and intense competition in telecommunications, there is pressing need for cost efficiency in the satisfaction of the application/demand/traffic requirements. Cost-efficiency requires savings in various cost components, e.g., the capital expenditures (CAPEX), the operational expenditures (OPEX), etc. Cognitive radio networks have the potential to become a main contributor in this direction. This derives from their self-management/awareness/organization capabilities, as well as from the knowledge they can obtain through inherent machine learning functionality. In the light of the aspects above, cognitive radio networks can efficiently complement/extend and add sophistication to a wireless communication ecosystem.

A cognitive radio network is based on opportunities regarding the links (i.e., Radio Access Technologies, spectrum, transmission power, etc.), as well as the nodes (i.e., devices, terminals, relays, access points serving cells of various sizes, etc.) that can be used for its formation. They can be created, in a particular location and time period, for the efficient application provision and the resolution of capacity and coverage problems, either in the wireless access or in the backhaul. Efficiency will stem from the higher resource utilization that can be achieved (opportunity exploitation), the lower energy consumption of the infrastructure, the handling of situations through adaptations and without needing to resort to worst-case oriented planning,

the capability for automated and knowledge-based handling of situations. All these have the potentials to lead to decreases in the CAPEX and the OPEX, as well as to fast and reliable management.

Advanced intelligence should be developed for realizing cognitive radio networks. The intelligence of a cognitive radio network requires research work for yielding capabilities for the perception and reasoning regarding the context of operation, decision-making regarding its creation/maintenance/release, as well as learning regarding the contexts encountered, the decisions taken to handle them, and the alternate ways they could be handled. The context of operation refers to the traffic requirements, radio environment conditions, mobility levels, the status and capabilities of devices and potential links.

The research on cognitive radio networks will necessitate the precision and evaluation of scenarios and requirements regarding their role in extending wireless access infrastructures. Next in the agenda can be the development/refinements of functional and system architectures, also taking into account the integration with the overall wireless world. In order to complement the architecture work, there needs to be elaboration and ultimately specification of control channels for the cooperation of the cognitive management components. Efficient, stable and scalable algorithmic solutions are needed. Special emphasis needs to be placed on validation, especially, by means of experiments, trials and pilots. Concrete links with standardization and regulation should be evolved and exploited for producing the framework that can lead to exploitation.

Spectrum Packing

Most prominent component of future mobile traffic increase is expected to be due to video-type services. It makes sense to enhance the existing broadcasting functionality in mobile networks so that the dense infrastructure of cellular networks can be even better exploited for offering spectrally efficient mass multimedia delivery, thereby also offloading the mobile broadband (unicast) access.

Furthermore, for broadcasting, the introduction of state of the art digital broadcasting technologies like DVB-T and DVB-T2 enables more dense frequency reuse, thereby leaving less white space between service areas of a TV channel. With the appropriate dense transmitter network and technology, using e.g. cellular broadcasting solutions, nation-wide Single-Frequency-Networks (SFN) are possible for nation-wide broadcast content. This enables significantly increased "packing" of TV spectrum. This opportunity has been exploited to only a small extent at the ITU Regional Radio Conference Geneva06 broadcasting frequency re-planning activity. Studies have shown that secondary use of TV white spaces is possible, however, of limited value for macro cellular networks. The prime focus should therefore be on reducing the white space wherever possible by packing broadcasting channels more densely, so that larger amounts of contiguous spectrum can be re-farmed and thereby be reused without the burden implied by white space operation.

However, many research challenges remain to be addressed mainly towards making mobile broadcasting more efficient in terms of spectral and energy efficiencies by utilising and optimising as much as possible the advanced techniques developed in mobile broadband cellular systems such as MIMO techniques for diversity and beamforming thereby reducing the current gaps between mobile broadcasting and mobile broadband. Research also should be focused on provision of technologies for multicasting at cell-level and multi-cell levels and for energy efficiency develop targeted broadcasting technologies as opposed to current "everytime and everywhere" broadcasting.

Spectrum Sharing

Research on spectrum has focused or even hyped on the secondary use of the UHF band and TV white spaces using mainly geo-location database techniques as the most basic way of spectrum sharing. The scope should be extended to opportunistic way of spectrum sharing to any commercially viable segments of the whole frequency spectrum, under the vision that any portion of spectrum that is not being used at a certain time and location can be used, regardless of the specific frequency range, bandwidth, and contiguity of available frequencies. This vision would significantly drive a breakthrough in the envisaged new paradigms of spectrum usage. The International Telecommunications Union – Radiocommunications Sector (ITU-R), estimated that the overall spectrum demand for mobile radio in 2020 will be 1280–1720MHz. Sharing of the radio spectrum is the most developed and well-known solution for current under-utilised spectrum bands and future "Spectrum Crunch" problem. This mechanism should encompass different techniques (at both device and network side) in terms of administrative, technical and policy-based, to improve spectrum utilisation in licensed and license-exempt bands. Dynamic Spectrum Access (DSA) is the key functionality of the cognitive

radio technology that enables cognitive devices to observe radio frequency bands and adapt their transceiver parameters based on its internal and external knowledge to explore and exploit interim spectrum holes opportunistically. Eventually cognitive radio may pave the way to effectively reaching a less fragmented spectrum allocation by making larger chunks of spectrum available for communication, if not permanently then at least temporarily on a secondary basis but still simplifying creation of devices.

Self-organizing Systems for Extreme Automation

The management of the mobile network infrastructure plays an important role in achieving the requirements in terms of constant performance optimisation, fast failure recovery, and fast adaptations to changes in network loads, architecture, infrastructure and technology. The increasing network heterogeneity (multiple RATs and multiple layers running in parallel, fully or partially uncontrolled deployment patterns) and dynamicity lead to increasing complexity and efforts of the Operation, Administration and Maintenance of mobile networks. Self-organising Networks (SON) are the first step towards the automation of (mobile) networks Operation, Administration and Maintenance (OAM) tasks, introducing closed control loop functions dedicated to self-configuration, self-optimisation, and self-healing. First generation SON functions need to be individually configured and supervised by a human operator. This manual configuration and tuning is getting less and less practical due to the increasing complexity of the SON system, since multiple SON functions being operated in parallel may have interdependencies and lead to network performance degradations due to inconsistent or conflicting configuration.

Extremely automated systems have to follow high-level operator goals regarding network performance and reliability. These systems have to autonomously ensure and control a conflict-free and coordinated operation of multiple SON-functions, providing automated control not only at (low-level) SON-function level, but also at the high-level network management, network planning and Operations and Support Systems (OSS) level.

CR Networks (CRN) describe a radio network which employs a cognitive process (i.e., involving thinking, reasoning, remembering) and learning capabilities in order to achieve end-to-end goals. This applies to both, the horizontal network view (i.e., including all the protocol stack of wireless networks, both radio access and backhaul / transport) as well as the vertical management view (i.e., abstracting network elements and their configuration towards a holistic high-level view). Control loops need to work not only for single independent functions, but need to be extended for the complete environment to be managed, which may involve several layers of control loops. The control loop diagnosis and decision making processes need to be adapted automatically by learning, e.g., based on the results of previous actions, in order to improve their effectiveness and efficiency, leading to a cognitive processes driven and controlled through high-level operator goals.

Advanced Human Computer Interfaces (HCI) are required to define and acquire the high-level business and technology driven operator goals, end-user requirements, and network capabilities. The cognitive management of the underlying infrastructure uses the knowledge-based inference and diagnosis of the current network state together with occurring performance issues and failures as basis for an autonomous creation and enactment of an optimised network plan and configuration which reflects the operator's high-level end-to-end goals. Methodologies need to be researched for the acquisition, analysis and improvement of knowledge representing semantics of operational goals and strategies, network properties, and historic and current network status enabling an automated reasoning for the alignment of different CRN functionality at runtime.

3 Technology Road Map

	In 5 Years	In 10 Years	In 15 Years
Network	<ul style="list-style-type: none"> - small cells - Cloud RAN - local intra-site coordinated multipoint (CoMP) - inter-site cooperation - coverage relays - fast inter-RAT load balancing 	<ul style="list-style-type: none"> - smaller cells - baseband cloud - inter-site CoMP - interlayer coordination - capacity relays - mobile and multi-hop relays - network-controlled device-to-device - inter system load balancing 	<ul style="list-style-type: none"> - 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
Radio	<ul style="list-style-type: none"> - <i>data rate</i>: several tens of Mbps up to 100 Mbps, - <i>bandwidth</i>: up to 40 MHz - <i>antennas</i>: roughly 10 layers spatial multiplexing - <i>first features of user context</i> 	<ul style="list-style-type: none"> - <i>data rate</i>: several 100 Mbps up to 1 Gbps - <i>bandwidth</i>: at least 100 MHz - <i>antennas</i>: tens of cooperative antenna elements - <i>user context aided radio resource management</i> 	<ul style="list-style-type: none"> - <i>data rate</i>: multi-Gbps - <i>bandwidth</i>: GHz range - <i>antennas</i>: hundreds of cooperative antenna elements
Energy	<ul style="list-style-type: none"> - network architectures are adapted to energy efficiency needs - intelligent switching on/off of resources using current technologies is optimized 	<ul style="list-style-type: none"> - novel transmission schemes and novel form factors for equipment are employed 	<ul style="list-style-type: none"> - technology leaps provide further enhancements
Cognitive Radio	<ul style="list-style-type: none"> - opportunistic spectrum access in femto cells 	<ul style="list-style-type: none"> - spectrum usage data bases - cognitive engines for access networks - self reconfigurable multi standard chips in MIMO systems 	<ul style="list-style-type: none"> - secondary spectrum use supported by sensing - licensed user behaviour prediction in multimedia stochastic networks

Spectrum	<ul style="list-style-type: none"> - opening TV white space with advance cooperative cognitive protocols - geo-location cooperating 	<ul style="list-style-type: none"> - licenses shared by co-operating operators - multi antenna signal processing - dynamic spectrum access location based - any free portion of spectrum usable - advanced spectrum handoff and spectrum mobility mechanisms regarding inherent QoS. 	<ul style="list-style-type: none"> - dynamic spectrum access - dynamic spectrum management (sensing, sharing, trading) among operators - cooperative spectrum hole prediction mechanisms in multi standard stochastic systems. - visible light communication
SON	<ul style="list-style-type: none"> - SON for LTE-A, SON for multi-layer and multi-RAT, SON Coordination (light) 	<ul style="list-style-type: none"> - SON for heterogeneous networks, E2E SON including radio, core, backhaul, transport - Fully coordinated SON at Network level (operator domain) - Cognitive learning mechanisms for SON improvement - High-level operator goal driven network management using multiple-layer control loops 	<ul style="list-style-type: none"> - Cognitive Radio Networks with cognitive learning and reasoning capabilities - Automated improvement of management mechanisms - Fully high-level operator goal driven E2E network management including all network domains

4 Summary and Conclusions

Radio access techniques need significant development to meet the predicted capacity requirements for the future. There is no single obvious solution but the solution shall be a combination of several alternatives and will depend on the time and place. There are several promising approaches to take in networking, radio access and modem implementation, which are briefly summarized in the following.

Key Drivers

- 500-1000 times capacity increase requirements
- Shortage of spectrum
- Energy efficiency requirements
- Wide-scale utilisation of small cells
- Availability of super-broadband optical fibre
- Flexible spectrum use

Potential Technical Approaches

- Heterogeneous networking solutions
- Large MIMO constructions
- More efficient duplexing and modulation techniques
- Co-operative networking technologies

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- All-photonic RF
- Mobile cloud processing techniques
- Inter-layer network optimization
- Clustered small cells
- New Radio Access Architectures leading to physical separation between control and data planes
- Spectrum packing of broadcasting services in mobile cellular systems
- Software defined radio (SDR)
- Visible light communication
- Utilize user context and prediction for radio optimization

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) Significant improvements of the wireless network have to be explored by strengthening the research efforts towards innovative cooperation and coordination schemes for network nodes in a flexible heterogeneous network deployment.
- R2) In order to meet the high requirements on 5G systems, research on new radio technologies (access, multiple antenna schemes, interference handling, etc.) must have high priority.
- R3) Research into new radio access architectures-Logical and physical separation between control and data planes for achieving both spectrum and energy efficiencies
- R4) Full integration between mobile broadcasting and mobile broadband communications
- R5) There is a strong need for collaboration between wireless experts and optics experts towards new network technologies with very high performance at reasonable costs.
- R6) 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.
- R7) Cognitive capabilities have to be incorporated in the network design on all layers supporting a flexible network adaptation at low operational costs, towards providing exactly the performance required for the determined user context.