Report on the

FP 7 Consultation Meeting

Future Mobile and Wireless Radio Systems: Challenges in European Research

on February 6, 2008 in Brussels

Organised by the European Commission
DG INFSO Unit D1 "Future Networks"

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Preface

In Framework Programme 6 (FP6), research in the area of mobile and wireless systems has been funded by the EU with approximately 263 million euros for 52 FP6 projects. Driven by this programme, European industry has federated in the Wireless World Initiative (WWI) toward a common technological, industrial, regulatory, and service approach to systems beyond 3rd generation (B3G). As a result, activities in the mobile communications field have made significant progress toward advanced communication technologies, systems, and services, enabling seamless mobile and wireless access solutions across a range of heterogeneous network infrastructures.

While first Framework Programme 7 (FP 7) projects have started in 2008, the European Commission is in the process of defining the next Work Programme 2009-2010. In a business environment based on technology standards that are typically associated with very high intellectual property value, the associated goal of FP7 is to maintain a strong European leadership on mobile radio technologies.

Building on the success of mobile telephony and text messaging as a mass market, third-generation mobile broadband services are now becoming increasingly available, with UMTS/HSPA terminals hitting the market and UMTS/LTE prototypes being demonstrated. In addition, IEEE 802 fixed wireless technologies, such as WIFI and WIMAX, have become popular in recent years, especially for laptop users in "hot spots".

Beyond that, envisioned advanced mobile communication systems are expected to offer broadband mobile applications with access to high-quality multimedia content and offer communication with and among objects, machines, and devices. These systems are aimed to be operated in both available and future candidate frequency bands. During the World Radiocommunications Conference 2007, in total "only" 392 MHz additional radio spectrum for mobile communications in Region 1 in relatively small fragmented bands has been agreed on with some remaining uncertainty concerning the availability of these bands.

The fragmentation and shortage of available radio frequency bands and the multiplicity of standards for wide area, local area, and short range communication have raised the demand for better spectrum efficiency, new system topologies, interworking, and multi-mode systems that might be realized with flexible radio technology.

Micro- and nano-electronics have made significant progress towards nano-scale devices and will enable radio transmission techniques that seemed unrealistic a few years ago.

What are the ways forward for European research on advanced radio transmission paradigms that go beyond the systems currently proposed for the evolution of mobile and wireless systems? With the purpose of incorporating the views of key experts in the field of radio systems, the European Commission services responsible for the area have organized this consultation workshop. The focus has been set on spectrum-efficient and flexible radio systems, i.e., visionary concepts for radio techniques that go beyond the systems currently proposed in standardization of mobile and wireless systems.

The discussion was structured around the following questions:

1) What are the changing requirements for future radio transmission techniques, e.g., new frequency bands, flexible spectrum usage?

2) What research has to be done to significantly increase spectrum efficiency?

3) What are the long-term opportunities for future radio transmission offered by micro- and nano-electronics, what are long-term limits?

4) How can long-term scientific considerations fit into existing standardization and regulation roadmaps?

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Executive Summary: Research Priorities for Future Mobile and Wireless Radio Systems

The anticipated exponential growth of the data rates in mobile and wireless radio systems follows the one experienced in fixed (wireline) systems. New charging and business models such as wireless flat rates will be a key driver for this growth and create traffic demands according to those that the users will be familiar with from their experiences in fixed network environments. Such high data rate applications include the next generation (3D) Internet with 3D graphics and animations.

Due to the recent decisions of the World Radiocommunications Conference 2007 (WRC-07) on the identification of new spectrum for International Mobile Telecommunications (IMT) that includes third generation (3G) and future (e.g., fourth generation) wireless communication systems, it will be very difficult to obtain dedicated IMT-Advanced spectrum for several operators in a given area based on the identified bands, since the anticipated high data rates of IMT-Advanced require a large bandwidth per operator. Therefore, new adaptive spectrum sharing models have to be designed and the spectral efficiency of future wireless radio systems has to be increased. Moreover, the energy consumption of future wireless radio systems should be reduced, which creates inter-disciplinary research challenges including semiconductor technology, hardware, networks, services, and radio transmission.

To be able to design and evaluate such energy efficient, adaptive wireless system concepts that are more sensitive to the environment und use sophisticated scheduling schemes, advanced models are required to model the channel dynamics realistically in time, frequency, and space. Also channel models for new types of networks, such as wireless sensor networks, body area networks, and car-to-car communications, have to be developed.

Advanced multiple antenna techniques such as multi-user Multiple-Input-Multiple-Output (MIMO) systems are a key component to increase the spectral efficiency of wireless communication systems, to provide an efficient coverage of high data rates (also to users on the cell edge) along with an efficient support of extremely high data rates, and to enhance the interference management.

Moreover, cooperation between base stations (multi-cell approaches) and cooperation between mobile terminals can enhance the spectral efficiency significantly. The latter includes relaying between inner-cell and outer-cell users. It allows to overcome the attenuation and even to perform distributed beamforming. If multiple layers of the Open Systems Interconnection (OSI) model are treated jointly (cross-layer designs), significant gains can be achieved by integrating, for example, the physical layer and the network layer.

Future wireless networks can be enhanced dramatically by taking serious advantage of the heterogeneous network environment, by applying spectrally more efficient transmission schemes, and by deploying novel network topologies. These include ad hoc networking, mesh networks, peer-to-peer communications, relaying, classical cellular networks, distributed antennas, and vehicular networks. A key question is how different types of networks could be managed jointly. Interworking between these networks is essential.

Cognitive radios (in a wider sense) are environment aware, self reasoning, and learning capable radios that can change any of their parameters or protocols based on interaction with the environment in which they operate. It is expected that these systems autonomously exploit locally unused spectrum to provide new paths to spectrum access. From the user point of view, the cognitivity is the enabler for seamless services in heterogeneous network environment with a single terminal. Interoperability of networks is the key technology enabler. Thereby, cognitive radios create a disruption in the way we handle and operate connectivity. The biggest changes include a flexible spectrum usage, an increased awareness in network nodes, and more autonomous decisions by communication devices. This will have a clear impact on standardization and regulation roadmaps. Regulatory constraints on apparently “unused” spectrum bands need to be investigated to assess the potential for cognitivity. To this end, terminal positioning techniques have to be improved, especially in multi-path and non-line-of-sight environments or when satellite-based techniques do not work. Moreover, real-time high-resolution spectrum analysis techniques have to be developed.

Information and communication theory can help in identifying complex, interdisciplinary fundamental research problems in the field of wireless communication networks by formulating the right questions about performance and by finding the right tools to answer those questions. This would permit to characterize the information and communication theoretical limits of wireless communication networks and to find algorithmic solutions to approach those limits. Key questions for research include how to deal with interference, how to optimally use relays, and how to use multiple antennas.

To satisfy the quality of service requirements of the users and to minimize the transmit power, a large frequency span should be used by introducing scaleable air interfaces that are adaptive with respect to the transmission bandwidth and the carrier frequency. Such a reconfigurable network requires heterogeneous access management, resource management, and signaling procedures. Note that such a flexibility does not necessarily require different standards.

Furthermore, frequency and standards agile base stations have to use multi-standard baseband processing which could be realized by a multiprocessor array network on chip to provide a simultaneous operation of multiple air interfaces. Transceiver architectures for large signal bandwidths are needed, including power amplifier linearization schemes and digital correction mechanisms for radio frequency (RF) imperfections. Moreover, efficient RF and microwave hardware implementations are necessary including advanced RF and microwave technologies like digital power amplifiers, RF- Microelectromechanical systems (MEMS), Gallium Nitride (GaN) technology, tunable filters, and RF reconfiguration.

1. Introduction

This report summarizes the results of a consultation meeting about "Future Mobile and Wireless Radio Systems" that was organized by the European Commission on February 6, 2008 in Brussels.

In Section 2, we summarize the requirements and the challenges for future radio transmission techniques and deal with their data rate requirements (Section 2.1), spectrum requirements and their associated challenges (Section 2.2), energy efficiency (Section 2.3) as well as advanced channel models (Section 2.4). An overview of the research that is required to significantly increase the spectrum efficiency is given in Section 3. In particular, we cover multiple antenna systems (Section 3.1), relaying and base station cooperation (Section 3.2), heterogeneous network environments (Section 3.3), cognitive radios (Section 3.4) as well as important topics in information and communication theory (Section 3.5). Finally, long-term opportunities for future radio transmission offered by micro- and nano-electronics are described in Section 4, before the agenda of the FP 7 consultation meeting on "Future Mobile and Wireless Radio Systems" is presented in the appendix.

2. Requirements and Challenges for Future Radio Transmission Techniques

2.1 Data Rate Requirements

Figure 1 depicts the expected data rates in fixed and wireless communication systems. The exponential growth of the data rates in wireless systems has followed the one experienced in fixed (wireline) systems with a time offset of less than 5 years. New charging and business models such as wireless flat rates will be a key driver for this growth and create traffic demands according to those that the users will be familiar with from their experiences in fixed network environments. Such high data rate applications include the next generation (3D) Internet with 3D graphics and animations.

This is in line with the vision of the Wireless World Research Forum (http://www.wireless-world-research.org) that expects that up to 7 trillion wireless devices will serve up to 7 billion people by the year 2017. Thereby, people will always be connected to the Internet.

As a consequence, we will run out of usable spectrum, and an increased spectral efficiency as well as more intelligent ways of accessing and allocating the spectrum are required.

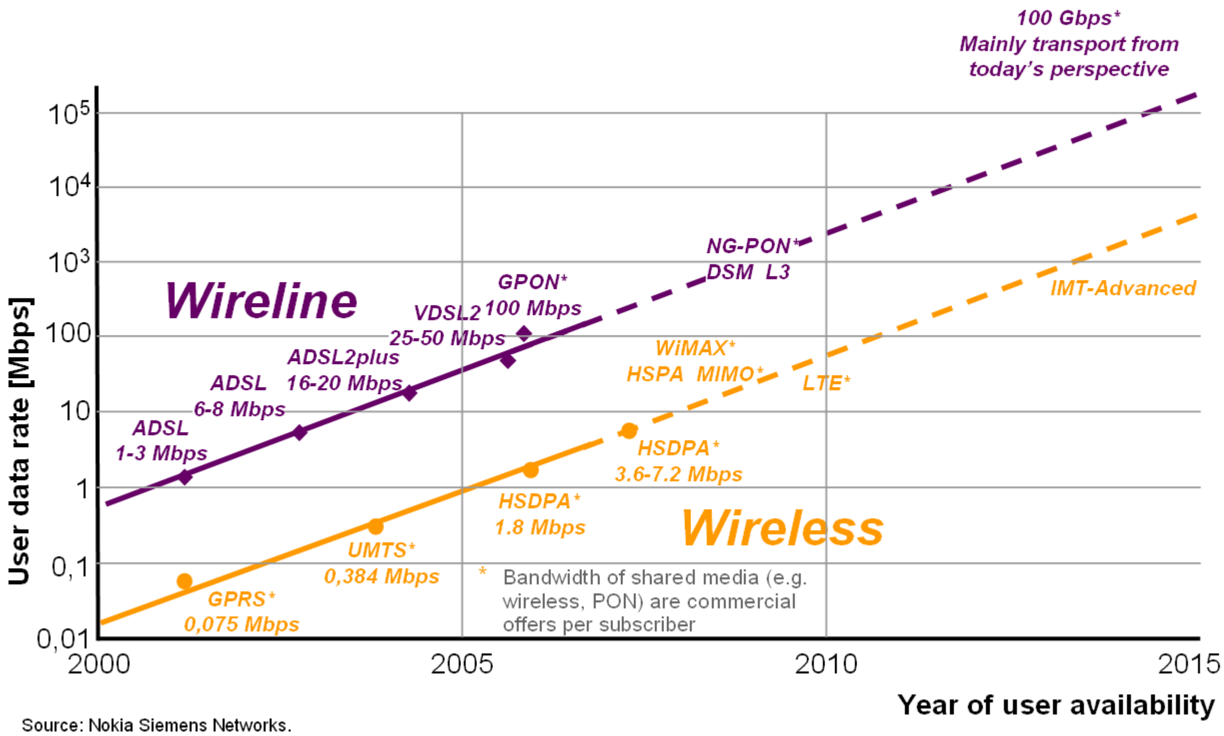

Figure 1: Expected data rates in fixed and wireless communication systems

2.2 Spectrum Requirements and Challenges

Due to the recent decisions of the World Radiocommunications Conference 2007 (WRC-07) on the identification of new spectrum for IMT that includes third generation (3G) and future (e.g., fourth generation) wireless communication systems, it will be very difficult obtain dedicated IMT-Advanced spectrum for several operators in a given area based on the identified bands, since the anticipated high data rates of IMT-Advanced require a large bandwidth per operator. In Region 1 (Europe including all of Russia, the Middle East, and Africa), a total of "only" 392 MHz of additional radio spectrum has been assigned for mobile communications in relatively small fragmented bands with some remaining uncertainty concerning the availability of these bands. Therefore, new adaptive spectrum sharing models have to be designed and the spectral efficiency of future wireless radio systems has to be increased.

The identified consecutive bands divided by the necessary carrier bandwidth per operator may not result in a sufficient number of operators to support competition. Therefore, infrastructure sharing may be required to support a quality of service with sufficiently wide carrier bandwidths and competition between different operators.

The natural resources frequency spectrum and energy are limited. The higher the carrier frequency becomes, the more difficult are the propagation conditions. Doubling, for example, the carrier frequency in an environment that has a path loss exponent of 3, results in a 9 dB higher propagation loss (1/8 of the power), the cell radius shrinks to 50 %, the cell area shrinks by 25 %, and 300 % more base stations are required to cover a given area, which results in a three times higher investment for operators as well as more energy consumption. Therefore, spectrum in the low frequency range would be beneficial for cellular communications. Due to higher frequencies more efficient topologies and much more efficient transmission techniques are needed.

Spectrum in the ***lower frequency range***, e.g., at 450 MHz, is associated with lower propagation loss and, therefore, a better coverage. Typically, there are smaller spectrum slices, thus the capacity is smaller. Lower Doppler frequencies provide support for a higher mobility, e.g., fast trains. Moreover, the lower transmit power leads to lower emissions and lower power consumption. Thus, the spectrum in the lower frequency range is most valuable from a coverage point of view.

Spectrum in the ***higher frequency range***, e.g., at 3.5 GHz, associated with higher propagation losses. Therefore, the coverage is worse. Typically there are larger spectrum slices. Therefore, the available capacity is larger. To provide coverage, a higher transmit power or smaller cells are required, which leads to larger emissions and a higher power consumption. Thus, the spectrum in the higher frequency range is most valuable from capacity point of view (since a larger part of the spectrum is available in this range).

In ***coverage limited scenarios***, i.e., either in an indoor environment or with big reuse clusters much larger than 1 (with a high spectrum demand to be in the noise-limited case), providers can cut the cost and increase the service data rates by dynamic spectrum management to enable multiple operators (e.g., with different profiles like business and leisure) in the scarce frequency bands at low carrier frequencies. This enables high peak user data rates and a competition among service providers also at low carrier frequencies. New business models have to be developed (with supporting infrastructure) were the unused spectrum can be *traded*. Moreover, this new business model has to give incentives to be spectrally efficient also at low loads for a particular operator.

In ***capacity limited scenarios***, i.e., the interference-limited case, operators might use higher carrier frequencies in the multi-GHz range, e.g., at 20 – 30 GHz. Here, potentially a wider spectrum is available. In this case, however, only a small range can be covered, where un-obstructed line-of-sight might be required. Also in this scenario, dynamic spectrum management leads to new business models and the supporting infrastructure for spectrum trading has to be provided. A large bandwidth per operator enables a high spectrum efficiency due to multi-user scheduling, link adaptation, and adaptive antenna gains. Reliable services can be realized due to fast retransmission schemes. Moreover, the unused spectrum can generate revenues from spectrum trading. Future local area operators might include traditional telecommunications operators, local operators (e.g., shopping malls, office buildings), and micro operators.

Challenges to be overcome at ***multi-GHz carrier frequencies*** include the radio frequency (RF) front-end (co-design the physical layer design with the RF hardware to mitigate impairments). In short range scenarios, the high carrier frequencies enable a dense spatial frequency reuse with many nodes (higher capacity per area). If multiple hops are used, only a few base station sites are required. In this case, quality of service (QoS) requirements on short delays can still be met with a wide system bandwidth. This, however, requires a fast digital hardware, where parallel physical layer algorithms are implemented. Furthermore, the corresponding channel models at high frequencies with a rich spatial information have to be developed.

Challenges and opportunities with ***multiple hops at high carrier frequencies*** include new cellular structures with cooperation to realize macro-diversity gains. In this scenario, the capacity will be more smooth as a function of the cell radius and movable to where users are instantaneously (moving cell structures and networks). Moreover, the system should be able to coordinate and collaborate over multiple ’cells’ to achieve macro-diversity gains. It should also adapt in three dimensions in dense metropolitan areas using advanced channel knowledge and integrate peer-to-peer cooperation.

The multiple nodes should be realized via very cheap hardware. There will be hybrid networks, where the core infrastructure (that guarantees a minimum quality of service) is owned by the operator, but with user incentives and network support for user added nodes. Resource management schemes should be developed to control the quality of service along with supporting business models. Reliable and efficient handover schemes can be realized by predicting the user mobility. Moreover, there are opportunities for moving networks with group handover as well as multicast support.

2.3 Energy Efficiency

The transmitted data volume increases approximately by a factor of 10 every 5 years, which corresponds to an increase of the associated energy consumption by approximately 16 – 20 % per year. Currently, 3 % of the world-wide energy is consumed by the ICT infrastructure which causes about 2 % of the world-wide CO_2 emissions (which is comparable to the world-wide CO_2 emissions by airplanes or one quarter of the world-wide CO_2 emissions by cars). If this energy consumption is doubled every 5 years, serious problems will arise. Therefore, the energy consumption of future wireless radio systems should be reduced, which creates inter-disciplinary research challenges including semiconductor technology, hardware, networks, services, and radio transmission, where schemes have to be designed that operate with a reduced transmit power.

Energy efficient mobile computing requires an energy efficiency in the user terminals for mobile computing at high carrier frequencies to save battery life time. Short hops are important for low peak power requirement. Nevertheless, antenna array and macro-diversity gains can be realized. A co-design of the hardware and the physical layer is required to mitigate hardware impairments. *Advanced schedulers and measurement schemes* should predict the channels, based on rich channel model information, to transmit with high instantaneous data rates and mainly on good resources. Moreover, the buffer levels should also be predicted. Thereby, the terminals can sleep as much as possible to save energy.

Long-term scheduling schemes are important to decide when to transmit and when to receive. For non-real-time services, service latency is the most important parameter for the user experience. As memory is constantly becoming more cost efficient (with a smaller footprint), the user terminal should act as a cache for pre-fetched data based on predicted user service consumption patterns. Terminals can receive pre-fetch data during off-peak hours and instantly download increments only. This enables a time-aligned transmission of popular services to multiple users on the downlink using multicast and might be facilitated by peer-to-peer transmission of cached data.

2.4 Advanced Channel Models

To be able to design and evaluate such energy efficient, adaptive wireless system concepts that are more sensitive to the environment and use sophisticated scheduling schemes, advanced models are required to model the channel behavior realistically in time, frequency, and space.

Therefore, the dynamics of the channel have to be investigated and modeled. Depending on the environment and the carrier frequency, stationarity regions have to be found in space and time. Also channel models for new types of networks, such as wireless sensor networks, body area networks, and car-to-car communications, have to be developed.

Moreover, adequate models for the prevailing channel state information and multi-user interference in multiple antenna systems are needed, e.g., MIMO systems that interfere with one another. Here, also the role of diffuse multi-path has to be investigated. The evaluation of cognitive radio systems also requires channel models of the same environment on different carrier frequencies at the same time and at the same location.

3. Research to Significantly Increase the Spectrum Efficiency

As compared to current wireless radio systems, the spectral efficiency of future systems has to be improved significantly to reduce the cost of these wireless radio systems. This can be achieved via advanced signal processing algorithms (interference cancellation, efficient signal processing for multiple antenna systems, etc.). It took 20 years of engineering research (1987 – 2007) to improve the spectral efficiency of GSM (0.1 bits/s/Hz/sector) by a factor of approximately ten to get LTE with a spectral efficiency of about 1.2 bits/s/Hz/sector. Therefore, more research is required to get further improvements that might be achieved in the areas of multiple antenna systems, relaying and base station cooperation, heterogeneous network environments as well as cognitive radios. Note that cognitive radios as such do not improve the spectral efficiency. Such systems may use additional frequency bands, which would otherwise not be used. (In fact, more spectrum than the originally identified bands would be used.) A key concept would be to mitigate the impact of intra- and inter-cell interference, because in the noise-limited case modulation and coding schemes are already rather close at the Shannon bound.

3.1 Multiple Antenna Systems

The adoption of multiple antenna techniques in future wireless systems is expected to have a significant impact on the efficient use of the spectrum, the minimization of the cost of establishing new wireless networks, on the optimization of the service quality provided by wireless networks, and the realization of transparent operation across multi-technology wireless networks. Nevertheless, the design of future generation smart antenna systems involves a number of challenges, such as re-configurability to varying scenarios in terms of propagation conditions, traffic models, mobility, transceiver architectures, mobile terminal resources, i.e., battery life time, quality of service requirements for different services, and interference conditions. The design of robust solutions matched to the reliability of the available channel information is required in order to account for the impact of channel estimation errors and feedback quantization and delay. Moreover, the system architecture as well as implementation and complexity limitations need to be taken into account in the design of multiple antenna techniques.

Advanced multiple antenna schemes are a key component to increase the spectral efficiency of wireless communication systems, to provide an efficient coverage of high data rates (also to users on the cell edge) along with an efficient support of extremely high data rates, and to enhance the interference management. Using multiple antennas at the transmitter, we can transmit multiple data streams to individual users (spatial multiplexing) as well as multiple users at the same time, which is referred to as a multi-user MIMO system.

Nevertheless, SDMA (Space Division Multiple Access) concepts did not take off, when they were introduced for the first time. This is due to the fact that proper scheduling concepts through cross-layer designs had not been available at that time. Moreover, the only available feedback was for power control and did not take into account that channel state information is required at the transmitter (CSI-T).

- In FDD systems with a dedicated feedback channel, the CSI-T quality depends on the feedback rate.
- In FDD system without feedback, a partial CSI-T knowledge may be obtained by estimating reciprocal channel components (angles, delays). Nevertheless, the robustness of such schemes has to be investigated.
- In TDD systems, the beamformer may use uplink channel impulse response estimates (since the average channel behavior is reciprocal), where the quality depends on the ”ping-pong time”, i.e., the time interval between the channel estimation and the downlink transmission (frame structure), and the channel coherence time.

Open problems in this area include:

- Multi-user MIMO communications in frequency selective channels and in the interference channel
- Optimum design of *reduced feedback* schemes for multi-user MIMO systems
- Low complexity downlink transmission strategies
- The impact of multiple access (scheduling) protocols on the design of multi-user MIMO algorithms as proper scheduling allows for simplified transmitters and simplified MIMO/multi-user detectors that are able to save battery life time.

3.2 Relaying and Base Station Cooperation

Moreover,

- cooperation between base stations (multi-cell approaches) and
- cooperation between mobile terminals

can enhance the spectral efficiency significantly. The latter includes relaying between inner-cell and outer-cell users. It allows to overcome the attenuation and even to perform distributed beamforming. If multiple layers of the OSI model are treated jointly (cross-layer designs), significant gains can be achieved by integrating, for example, the physical layer and the network layer. First research results already exist for the two-way relay channel. In this case, joint network and channel coding (JNCC) that combines distributed channel coding and network coding (in conjunction with turbo decoding and hybrid ARQ) can increase the throughput by more than 150 % relative to point-to-point transmission using the same energy and bandwidth. The currently emerging field of network coding being still in a theoretical stage should be carefully monitored for its potential to generate applications in cellular mobile systems in order to allow further capacity enhancements.

The currently emerging field of network coding, which is still in a theoretical stage, should be monitored carefully for its potential to generate applications in cellular mobile systems in order to allow further capacity enhancements.

The coverage and capacity on the uplink are limited by thermal noise at the base station and intra-cell interference from active users in the same cell and on the same frequency. Moreover, taking into account frequency reuse, the (unpredictable) inter-cell interference from active users in neighboring cells becomes a problem. This can be overcome via base station cooperation with (turbo) interference cancellation using a joint decentralized detector. Simplified schemes have to be designed as a full joint detector would be too complex and the backhaul load on the optical terrestrial link should be limited.

3.3 Heterogeneous Network Environments

Future wireless networks can be enhanced dramatically by taking serious advantage of the heterogeneous network environment, by applying spectrally more efficient transmission schemes, and by deploying novel network topologies. These include ad hoc networking, mesh networks, peer-to-peer communications, relaying, classical cellular networks, and distributed antennas. A key question is how different types of networks could be managed jointly. The major issues related to different opportunities to increase the intelligence include

- opportunistic spectrum use and spectrum sharing,
- spatial domain utilization to improve the capacity,
- user location information and location awareness,
- user co-operation,
- existence of multiple radio access technologies,
- exploitation and acquisition of channel state information and channel statistical behavior information,
- traffic pattern knowledge including long-term monitoring and prediction as well as
- network topology awareness in a mobile device.

Vehicular networking could be thought as one of the first application areas for the new wireless networking concepts to boost also the development of other wireless applications and related technologies. The automation and amount of electronics of cars will continue to increase, and a car is a natural intelligent environment waiting for the full deployment of wireless technologies.

In this case, broadband access is provided almost everywhere (“always connected”) and accurate position information is available. Context sensitive services will emerge for drivers and passengers on the road to enrich their experience and to improve safety. Moreover, these context sensitive services will also support other parties like car manufacturers. Therefore, driving will become an interactive session with the surrounding real and an available virtual environment.

Challenges include the multi-radio access (always-best connectivity), the mobility and the radio channel dynamics, the fast changing sensory information within a vehicle and to the vehicle as well as the data and information exchange and dissemination within a car, between cars, and to the car.

3.4 Cognitive Radios

Cognitive radio in the general sense (which is not only spectrum-sensitive, but also environment-sensitive) refers to either a network or a wireless node that changes its transmission or reception parameters to communicate efficiently by avoiding interference with licensed or unlicensed users. This change of parameters is based on the active monitoring of several factors in the external and internal radio environment, such as radio frequency spectrum, location information, user behavior, and network state. Thus, we have an environment aware, self reasoning, and learning capable radio that can change any of its parameters or protocols based on interaction with the environment in which it operates.

It is expected that these systems autonomously exploit locally unused spectrum to provide new paths to spectrum access (which has impacts on spectrum agility and regulation). One could negotiate with several service providers to connect a user at the lowest cost or maximum data rate provider (which has impacts on protocol and business models). Thereby, the operational behavior and the emissions are autonomously adapted (which has impacts on the requirements for reconfigurability and multi-standard as well as multi-mode transceivers). Systems have to learn to become more responsive and to anticipate (and even direct) user requirements (smart behavior).

From the user point of view, the cognitivity is the enabler for seamless services in heterogeneous network environment with a single terminal. The multi-modality and enormous complexity of the network is completely hidden from the user. Cognitivity for the manufacturers means more generic and flexible terminal and network element structures. From the access operator point of view, the network control is automated. Interoperability of networks is the key technology enabler. Due to spectrum agility, interoperability, and flexibility, some sort of deregulation can be foreseen from the regulator’s point of view.

Thereby, cognitive radios create a disruption in the way we handle and operate connectivity. The biggest changes include a flexible spectrum usage, an increased awareness in network nodes, and more autonomous decisions by communication devices. Note that cognitive radios (in a wider sense by taking into account context awareness and location) can create new services and applications that take advantage of the increased awareness of the devices (e.g., the location information), combined with the more flexible spectrum use. Coexistence of different systems, which may share the same or adjacent bands, needs to be ensured.

Impact on Standardization and Regulation Roadmaps

Cognitive radio will not be a single radio technology, but an umbrella of several radio technologies. Therefore, there is a need for standardization to ensure their interoperability and coexistence. This regulation should be technology independent. It should be investigated, which bands might be accessible for cognitive approaches. A move towards cooperative spectrum sharing between different systems might ease the spectrum scarceness. This could be facilitated via the introduction of a cognitive pilot channel. A clear definition of “harmful interference” (related to quality of service and availability requirements) for the different systems would simplify the work towards frequency sharing regulations and standards.

Localization of Terminals

Traditional terminal positioning techniques are based on satellite or time of arrival estimates using multiple base stations. This becomes more complicated in case of multi-path and fails in non-line-of-sight (NLOS) environments. To improve satellite systems in NLOS situations and enable terminal positioning when satellite systems doe not work (indoor, urban canyon,…), power delay profile fingerprinting might be used in the future, as the power delay profile provides position specific characteristics. This technology requires a detailed data base about the multi-path propagation environment as a function of the terminal location. Such a data base might also include information about the dominant directions of arrival (spatial signature) and the MIMO channel rank and thereby reduce the feedback requirements, once the position of the terminal has been estimated. Moreover, some sort of averaging is required as the power delay profile is an instantaneous function, which might not be stable over time. Moving trees, bushes, cars and people change the propagation conditions significantly as a function of time

Spectrum Analysis

Real-time spectrum analysis is not only required for spectral sensing in future cognitive radio systems, i.e., to estimate the noise floor and to identify as well as to characterize the spectrum holes. It is also beneficial for channel estimation (equalization), channel matrix identification (in MIMO systems), multi-carrier communications (real-time analysis and synthesis), beamforming (spatial domain), and radio scene analysis. Currently, the employed spectrum analysis techniques are still in its “FFT stage”, but their “high-resolution” counterparts have to be developed. An open issue is the identification of unknown spread spectrum signals, which are hidden in noise as in military applications.

The requirements for future agile systems include a high-resolution in the frequency domain, a large dynamic range, accurate and reliable noise floor estimation, a fast acquisition, a combination of several functions like simultaneous spectrum sensing and multi-carrier reception, broadband capability, a scalability of the parameters, and a high signal identification capability to identify primary/secondary users in cognitive radio systems as well as jammers (interference).

Thus, a sophisticated spectrum analyzer (and spectrum synthesizer) has to be developed for future terminals that has a high performance, a great flexibility and adaptivity as well as a capability of multiple functions. Of course, its complexity will be a critical issue.

3.5 Information and Communication Theory

Information theory has had a large impact on the design of wireless communication networks in terms of a theoretical formulation of fundamental limits and by being a diver of new, more effective designs (like CDMA, OFDM water-filling, power control strategies, multi-user detection, Turbo and LDPC codes, MIMO and space-time codes, trellis-coded modulation, fountain codes, network coding).

A wireless communication network as a whole is a very complex system due to

- the time-varying environment (multipath fading channel),
- the multiplicity of users,
- the different quality of service (QoS) needs,
- the conflicting optimization criteria and constraints (sum-capacity, fairness to individual users, ...), and
- the various sources of interference and disturbances (additive, multiplicative, random, identifiable disturbances,...).

Thus, there is a huge difference with respect to the simple point-to-point additive white Gaussian noise (AWGN) channel, for which many information theoretic results have been obtained in the past. Obtaining performance limits as simple and compact as for the point-to-point AWGN channel (Shannon theory) seem unrealistic. Information and communication theory can help in identifying complex, interdisciplinary fundamental research problems in the field of wireless communication networks by formulating the right questions about performance and by finding the right tools to answer those questions. This would permit to (at least partially) characterize the information and communication theoretical limits of wireless communication networks and to find algorithmic solutions to approach those limits.

Key questions for research include

- How to deal with interference?
- How to optimally use relays?
- How to use multiple antennas?

Therefore, the following research topics can be identified:

- **Fundamental limits in wireless communication networks**
    - Scaling laws for energy-limited large networks
    - Full theoretical understanding of diversity
    - Separation theorems in source, channel, and network coding
    - Capacity of multiple relay wireless communication networks
    - Partial channel state information and feedback
    - Mismatched co-decoding
- **Diversity techniques and signal processing**
    - The use of diversity/relaying/cooperation among spatially distributed nodes
    - Coding and signal processing techniques for MIMO channels
    - Algorithms to acquire channel state information in diversity techniques
    - Fast adaptive coding and modulation schemes
- **Cross-layer design of wireless communication networks**
    - Coding and signal processing techniques that incorporate higher layer protocol information
    - MAC (multiple access channel) and routing protocols that take advantage of physical layer capabilities such as space-time coding, interference cancellation, and spatial diversity techniques
    - Coding and network protocols for delay sensitive applications
    - Distributed source, channel, and network coding
    - Codes operating at a rate exceeding capacity (if you exploit relaying)
    - Network coding for wireless multi-hop networks

In particular, the following asymptotic regimes can be investigated:

- very quiet scenario (high SNR, fading and interference limited, appropriate for studying multiple antenna systems)
- very noisy scenario (low SNR, energy-limited and energy-aware communications: spread over as many degrees of freedom as possible, ultra-wideband systems)
- very large scenario (many nodes, look at large networks and ask how the capacity scales with the number of nodes)

Theoretical tools to solve these challenges include random matrix theory, estimation theory, optimization theory, and control theory.

4. Long-term Opportunities Offered by Micro- and Nano-Electronics

Due to the fact that the wireless traffic is massively growing, but the available spectrum is limited, dynamic spectrum usage is required (software defined radio, cognitive radio). To satisfy the quality of service requirements of the users and to minimize the transmit power, a large frequency span should be used by introducing scaleable air interfaces that are adaptive with respect to the transmission bandwidth and the carrier frequency. Such a reconfigurable network requires heterogeneous access management, resource management, and signaling procedures. Note that this does not necessarily require different standards.

Furthermore, frequency and standards agile base stations have to use multi-standard baseband processing which could be realized by a multiprocessor array network on chip to provide a simultaneous operation of multiple air interfaces. Transceiver architectures for large signal bandwidths are needed, including power amplifier linearization schemes and digital correction mechanisms for radio frequency (RF) imperfections.

Moreover, efficient RF and microwave hardware implementations are required including advanced RF and microwave technologies like digital power amplifiers, RF-MEMS, Gallium Nitride (GaN) technology, tunable filters, and RF reconfiguration. The tuning elements could be switches or varactor variometers that can be operated at high power (due to the required higher order modulation schemes) to realize software defined duplexers. Linearity requirements are, of course, an issue. Digital power amplifier architectures promise large gains in efficiency. Due to over-clocking, high speed switching power transistors are needed. In the future, nano switch arrays for fast power switching might be able to solve this problem by replacing the transistors.

RF-MEMS might be used for the reconfiguration of the frequency range, as compact and tunable planar duplex and bandpass filters are necessary. Currently, RF reconfiguration at high powers for frequency agility with filters is still an open problem. RF impairments provide a challenge for future wireless radio systems. These include “dirty RF” like non-linearity effects (in power amplifiers or low noise amplifiers), aperture jitter, I/Q imbalance, phase noise, flicker noise, and digital noise. Moreover, vector processors and hardware accelerators should enable an extremely low power, high-speed, real-time scheduling of the tasks on future multi-processor system-on chip designs. Moreover, battery technologies must to be able to cope with the increased power needs of new VLSI systems

Appendix: Agenda of the FP 7 Consultation Meeting on "Future Mobile and Wireless Radio Systems"

Organiser and contact person: Peter Stuckmann (peter.stuckmann@ec.europa.eu)
Rapporteur: Prof. Martin Haardt, Ilmenau University of Technology

09:45: General Introduction, Rainer Zimmermann, EC, Head of Unit "Future Networks"

10 – 11 h: What are the changing requirements for future radio transmission techniques, e.g., new frequency bands, flexible spectrum usage?

Prof. Jens Zander, KTH Stockholm: "Cooperative & Competitive Wireless Access – Implications, Results, and Research Challenges"

Werner Mohr, Nokia Siemens Networks, München, "Impact of spectrum identification for mobile and wireless communication on future radio system research"

Prof. Ernst Bonek, TU Wien, "Back to the roots - Characterization of the wireless channel for new applications"

Prof. Matti Latva-aho, University of Oulu, "Vehicular networking – opportunities and challenges"

11 – 12 h: What research has to be done to significantly increase spectrum efficiency?

Prof. Sergio Benedetto, Politecnico di Torino, NEWCOM++, "Information and communication theory for mobile networks"

Prof. Joachim Hagenauer, TU München, "Gains with Relays and Base Station Cooperation in Cellular Systems"

Prof. Dirk Slock, EURECOM, Sofia-Antipolis, "Some 4G+ Wireless Communication Challenges"

Prof. Tommy Svensson, Chalmers: "Opportunities in Future Wireless Networks"

13 – 14 h: What are the long-term opportunities for future radio transmission offered by micro- and nano-electronics, what are long-term limits?

Prof. Gerhard Fettweis, TU Dresden: "Capacity Enablers and Challenges for Achieving the 3D Mobile Internet"

Prof. Maurice Bellanger, CNAM Paris: "Real time spectrum analysis in future agile radio systems"

Dominique Noguet / Laurent Herault, CEA LETI Grenoble: "Spectrum-efficient, cognitive and opportunistic radio systems" (not presented due to sickness)

Georg Fischer, Alcatel-Lucent, Nürnberg, "Necessary components and subsystems for efficient frequency and standards-agile cognitive radio systems"

14 – 15 h: How can long-term scientific considerations fit into existing standardization and regulation roadmaps?

Raphael Visoz, Orange Labs, Paris, "Promising Paradigms for Mobile Wireless Systems"

Kari Kalliojärvi, Nokia Research Center, Helsinki, "Impacts of Paradigm Changes to Mobile Ecosystem"

Friedbert Berens, STM, Geneva, "Spectrum Sharing System Regulation and Standardization in Europe - Lessons Learned"

15 – 17 h: Discussion and conclusion: What are the most promising paradigms and research priorities (common and divergent views)?