Cognitive Radio Experimentation World

Project Deliverable D2.1
Definition of Internal Usage Scenarios

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Abstract: This document presents five internal usage scenarios that focus on different areas of cognitive radio and cognitive networking research. In each of those a general wireless setup is identified. Aspects of scientific and practical relevance are studied in individual use cases.

The first usage scenario holds research objectives and experiments related to context awareness and sensing of a wireless environment. The second scenario is focused on robustness and quality of service in cognitive radio applications. The third, fourth and fifth usage scenarios deal with the question of how to make use of context information to enhance communication in different applications and frequency ranges.

This document is to serve as a guideline for the definition of external usage scenarios in later stages of the project and will play a central role in the Definition of the Federation Functionality.

Keywords: Cognitive Radio, Cognitive Networking, Dynamic Spectrum Access, Usage Scenario, Use Case, Licensed, Unlicensed, General Requirements

Revision History

Nicola Michailow TUD	Incorporated internal reviewers' comments	26 Jan 2011
Nicola Michailow TUD	Added Executive Summary, final formatting	30 Jan 2011

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Executive Summary

This document presents the definition of internal usage scenarios. A usage scenario is a general wireless setup build from an existing base of cognitive components and testbeds. In each usage scenario, a number of wireless experiments are defined as use cases. They aim to explore particular points of scientific or practical interest. Relevant frequencies for these experiments are the ISM band, the TV bands as well as the LTE bands. In this document, five internal usage scenarios that make use of federated testbeds and components are described. The corresponding use cases are of exemplary nature and do not aim to cover all possible combinations of cognitive radio applications and frequency bands.

The first usage scenario is dedicated to advanced sensing techniques, as knowing the wireless environment is a common foundation for all cognitive radio and networking related applications. Therefore the respective use cases deal with context awareness in ISM, TV and LTE bands. In the second usage scenario, it is investigated how robustness and Quality of Service can be enhanced by cognitive radio algorithms and hardware. The third usage scenario deals with the coexistence of wireless systems in terms of horizontal resource sharing. For this purpose, the cooperation of cognitive systems and cognitive devices is studied in an environment where frequency resources are shared among a number of wireless communication systems, as it is the case in the 2.4 GHz ISM band. The fourth and the fifth usage scenario research coexistence in terms of vertical spectrum sharing. In that case, cognitive radio systems are set to operate in frequencies where other systems have prioritized access rights to the wireless resources, as in the TV and LTE bands.

The usage scenarios and use cases are characterized by “goals”, “approach” and “key features”. They will serve as a guideline for the task of deriving the requirements for the federation of cognitive components and testbeds.

List of Acronyms and Abbreviations

AP	Access Point
BAN	Body Area Network
CBAN	Cognitive Body Area Network
CN	Cognitive Networking
CR	Cognitive Radio
DSA	Dynamic Spectrum Access
DTT	Digital Terrestrial Television
DVB-H	Digital Video Broadcasting - Handheld
ECC	Electronic Communications Committee
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HVAC	Heating, Ventilation and Air Conditioning
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific and Medical
LTE	Long Term Evolution
M2M	Machine to Machine
MAC	Medium Access Control
OSA	Opportunistic Spectrum Access
PAX	Passenger or seat onboard an aircraft (used in the travel industry)
PHY	PHYsical layer
PMSE	Programme Making and Special Events (denotes a set of wireless devices, such as microphones, cameras…)
QoS	Quality of Service
RF	Radio Frequency
SDR	Software-Defined Radio
SIR	Signal to Interference Ratio
SNR	Signal to Noise Ratio
UC	Use Case
UHF	Ultra High Frequency (300…3000 MHz)
US	Usage Scenario
VHF	Very High Frequency (30…300 MHz)
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WS	White Space
WSD	White Space Devices
WSN	Wireless Sensor Network

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Terminology

With the goal to create a common understanding of the terminology that is used in this document, a definition of various expressions will be given in this section.

Cognitive radio (CR) refers to a communications system or a device that has the means to monitor its wireless environment and is capable of adjusting its transmission parameters (1). It acts based on the observations while following a certain policy to share limited wireless resources with other privileged, concurring or coexisting participants.

With **cognitive networking (CN)**, the cognitive features of a communications system are extended from a single device to a general, cross-layer concept for the entire network. While CR typically addresses PHY and MAC aspects, CN includes all layers of a communication system.

A **usage scenario (US)** is a wireless arrangement that is motivated by general research objectives. Based on a high-level description of the setup, wherein CR devices (or components of CR devices, or testbeds) interact with their wireless environment, various *use cases* are derived to study more concrete aspects of scientific or practical relevance.

An **internal usage scenario** is developed by the initial partners in the set-up phase of the project.

An **external usage scenario** is developed during one of the open call stages of the project.

A **use case (UC)** is determined to address a particular aspect of the corresponding usage scenario. Within an individual use case, a limited subset of problems and approaches to their experimental research are provided.

A use case that has been selected for implementation will be referred to as a **showcase** in the later stages of the project.

The terms **licensed spectrum** and **licensed band(s)** will be used to address radio frequencies that are subject to regulatory constraints and thus require a license to be used. **Licensed access** will refer to a user who transmits in those frequencies and owns a license for its exclusive operation. **Unlicensed spectrum** and **unlicensed access** will accordingly mean the opposite.

Following from this, **horizontal resource sharing** can be distinguished as a policy for dynamic spectrum access in unlicensed bands, where all participants have the same priority (from regulators point of view) and compete for the same wireless resources. Hence, **cooperation in unlicensed bands** involves techniques to improve throughput and spectral efficiency not from an individual participant's point of view but for the entire medium.

In analogy, **vertical resource sharing** denotes communication with a clear hierarchy in the priorities to access a wireless resource. In that case, **cooperation in licensed bands** again aims to improve throughput and spectral efficiency for the medium, but additionally adds the condition that a communication device may not infringe the hierarchy by posing interference to systems with higher priorities.

1 Introduction

Even though radio spectrum is considered a scarce resource, studies have shown that large portions of the licensed spectrum are under-utilized, when time and geographical location are taken into account (2). In this context, dynamic spectrum access is considered by the scientific community as one of the key solutions towards more efficient utilization of this limited physical resource. In the scientific community, several models for spectrum access with varying degrees of freedom are studied (3).

Among those, cognitive radio and cognitive networking are one promising approach that involves several aspects exceeding the scope of traditional wireless communications systems. Novel features from the technical side include software-defined radio (SDR) capability, frequency agility and spectrum sensing functionality while components for observing the wireless environment, adapting to given conditions and learning from past decisions are brought along by the cognitive aspect.

Typical cognitive radio scenarios involve wireless communications systems that operate in the Industrial, Scientific and Medical (ISM) band because of its internationally accepted open sharing model as well as in the frequencies that are being freed up in the switchover from analogue to digital TV broadcast, also known as the digital dividend. In cognitive radio, challenges arise from the large diversity of existing wireless standards that operate in these frequencies and the unpredictable behavior in terms of channel access and traffic load when different wireless systems coexist. Further, a question of interest to mobile operators is whether and how cognitive radio can be brought to coexistence with established cellular networks of 2G, 3G and 4G. Therefore, other cognitive radio scenarios are also addressing cooperative and collaborative dynamic spectrum access in licensed bands.

The cognitive radio paradigm was proposed more than a decade ago (1). However, the technology is yet in an early stage of development. Hence, research in the cognitive radio and cognitive networking domains appears as a necessity. As introduced above, the complexity of this endeavor is huge and thus it calls for advanced methodologies.

To approach these challenges, this document specifies five internal usage scenarios for experimental-driven research that utilize the CREW infrastructure of federated testbeds. For each usage scenario, a number of use cases are identified in order to address particular aspects of relevance in detail. Figure 1 gives an overview of all usage scenarios and groups them with the corresponding frequency bands.

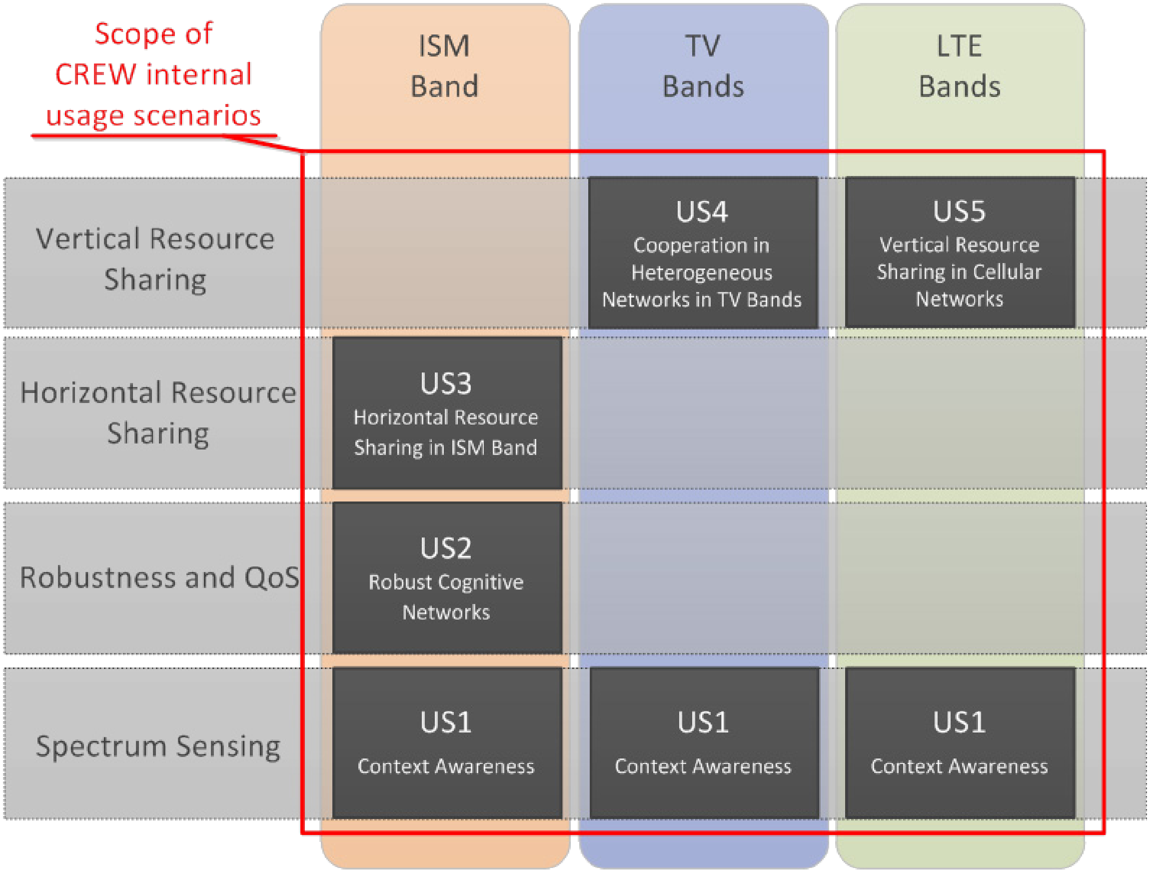

Figure 1: The Internal Usage Scenarios presented in this document are of exemplary nature and cover only a subset of many possible combinations of CR applications and frequency bands.

2 Definition of Usage Scenarios

2.1 Usage Scenario 1: Context Awareness for Cognitive Networking

The Cognitive Radio was first described by Mitola in (1) as a decision making layer in which *"wireless personal digital assistants and the related networks were sufficiently computationally intelligent about radio resources, and related computer-to-computer communications, to detect user needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs"*. This means a CR should be context-aware to allow for this rich adaptation.

Six years after Mitola's first CR article, Simon Haykin recapitulated the CR idea as an enabler of brain-empowered communication (4). He identified six key parts of CR: awareness, intelligence, learning, adaptivity, reliability and efficiency. Thus, his definition broadly complies with Mitola's viewpoint. In his seminal paper, Haykin instantiated CR for Opportunistic Spectrum Access (OSA). In this simplified cognition cycle only 2 key elements of his CR are instantiated: environment awareness (radio-scene analysis and channel estimation) and adaptivity (transmit power control and dynamic spectrum management). Most of the research on cognitive radio context awareness has hence followed this OSA definition, and following this a lot of research has focused on the design of spectrum sensing techniques.

Since this spectrum sensing as a first step towards context awareness is so important in the CR, a specific usage scenario is dedicated to it. To facilitate this, the CREW testbed will be equipped with a range of spectrum sensing solutions.

Context awareness use cases further focus on the ISM or unlicensed bands, on cellular or licensed bands, or on sensing for the TV White Spaces which are the OSA bands.

Title	Context Awareness for Cognitive Networking
ID	US1
Goals	Collect information for cognitive network(s) so that it is possible to adapt to the environment dynamics.
Key Features	Controllable and repeatable context for cognitive networks (for instance the interference environment) and controllable and repeatable ways to obtain this information at run-time by the cognitive network (for instance by spectrum sensing).

Table 1: Internal Usage Scenario 1

2.1.1 Use Case 1.1: Context Awareness in the ISM Bands

Context awareness in the ISM bands can be relevant in many use cases. For instance, all use cases of Usage scenario 2 might require information about spectrum use or possible interference in the 2.4 or 5 GHz ISM band. Focus of this use case 1.1 will be on sensing of and between two specific technologies used in the ISM band: IEEE 802.15.4 and IEEE 802.11. In a first approach (approach 1), it will be studied how the IEEE 802.15.4 network can sense the presence of the IEEE 802.11 networks, using off-the-shelf IEEE 802.15.4 hardware and possibly also dedicated sensing solutions. For that, it will be required to compare the performance of different sensing solutions for the specific case of sensing the IEEE 802.15.4 technology. Conversely, in a next approach (approach 2), it will be studied how the IEEE 802.11 network can sense the IEEE 802.15.4 devices using off-the-shelf IEEE 802.11 hardware or using dedicated sensing solutions. For approach 1 and 2, it will be important to know how to characterize the performance of different sensing solutions in sensing a specific wireless technology. Finally, sensing solutions will be compared in sensing both IEEE 802.15.4 and IEEE 802.11, and differentiating between them. This is approach 3 in which differentiation between technologies becomes important.

Title	Context Awareness in the ISM Bands
ID	UC11
Goals	Low-cost low power sensing for improved coexistence between heterogeneous technologies.
Approach	*1) Comparing solutions for sensing of 802.15.4 only* *2) Comparing solutions for sensing of 802.11 only* *3) Comparing solutions for sensing of both technologies from 1) and 2)*
Key Features	Sensing Hardware: ISM bands Sensing functionality: detect between heterogeneous technologies Sensing constraints: low cost and low power

Table 2: Internal Use Case 1.1

2.1.2 Use Case 1.2: Context Awareness in the TV White Spaces Licensed Bands

Sensing for the TV White Spaces (TVWS) is one of the most researched approaches for context awareness for cognitive radios. The debate about TVWS has been centered around the technical rules that should be set to allow reuse of the spectrum while ensuring sufficient guarantees towards the licensed users. One of the very first initiatives, the IEEE 802.22 standard, focused the effort on a sensitivity threshold that should be met (5). For instance, the 802.22 working group specifications require detectors to have a sensitivity of -116 dBm, which corresponds to a SNR=-20dB for those channels(6). This corresponds to a design-time worst case safety margin of roughly 20 dB (7). The fundamental sensing problem is that the channel sensed by a secondary transmitter does not provide all necessary information to that secondary transmitter. This problem is illustrated in Figure 1. The Secondary Transmitter can only sense the channel between the Primary Transmitter and itself. The relevant information is however in the channels towards the receiver, which should be able to receive the Primary Transmission with sufficient signal quality. To account for this uncertainty, large sensing margins are typically assumed. As a result, the sensing problem is very tough and fundamentally, there seems to be little solutions to this problem when relying on local sensing only. The realization of this had led to the research of alternative techniques, such as distributed sensing (8) and the database approach(4).

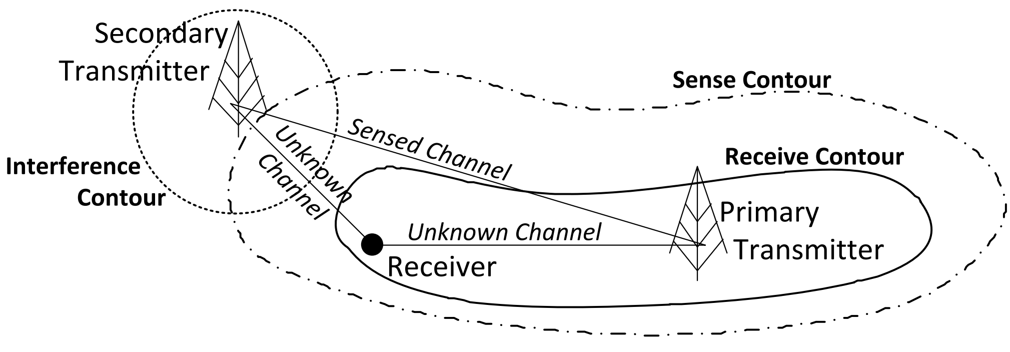

Figure 2: Spatial reuse of the TV White Spaces requires large safety margins to ensure that the receive contour of the primary transmitter is protected.

A recent study published by the ECC (4) confirms these results. For the protection of the DTT service they claim a sensitivity requirement as low as -165 dBm. For the protection of the PMSE, they claim that "*In some cases, this may lead to very low detection threshold, far below the WSD receiver noise floor, which would make this technical quite impractical*". As a result, for those services, the use of a geolocation database is believed to be the most effective. However, they also admit that to date it is not clear what information should be put in those databases.

The use of a geolocation database allows to determine offline all relevant information about both unknown channels from any location to any receiver, solving the problem illustrated in Figure 1. The idea (4) would be to generate a database that includes for each location a list of allowed frequencies and power levels. This information can indeed be determined from off-line models or even field measurements. Although to date it is not yet determined how the database would be computed are determined, it is already known that also the database involves some challenges for the secondary transmitter since it would have to determine its location as accurately as possible. Ofcom takes into account the possibility of poor geolocation capabilities, giving errors up to 100m [7]. While this seems very inaccurate compared to the performance of GPS devices, it is realistic since GPS has a very poor performance indoor. Also, it cannot be assumed that every device would be equipped with an expensive GPS receiver.

In the use case for context awareness in the TV White Spaces, the approach is to compare different solutions for context awareness: local sensing, distributed sensing and database approaches. This is in line with the current debate in the TV White Spaces context.

Title	Context Awareness in the TV White Spaces Licensed Bands
ID	UC12
Goals	Achieve a reliable sensing to avoid interference to licensed users. Focus on sensing the licensed technology.
Approach	*1) Comparison of different sensing solutions for local sensing* *2) Distributed versus local sensing (for reliability improvements)* *3) Sensing versus Database*
Key Features	Sensing hardware: TV White Spaces Sensing functionality: detect licensed technology Sensing constraints: reliability

Table 3: Internal Use Case 1.2

2.1.3 Use Case 1.3: Reliable Sensing of Cellular Systems

When cognitive radio is used, the primary network quality of service must not be degraded by the eventual presence of a secondary user. That is why reliable sensing methods have to be considered and for this purpose TV bands approaches from UC12 (local, distributed, database sensing) should also be researched for cellular frequencies.

An additional extension of this use case, however, is to sense with an antenna array and to perform detection, identification and physical characteristics estimation (level, Signal to Interference Ratio (SIR)) of base stations sharing the same frequency channel based on space-time processing algorithms. When the antenna array receives several sources from different emitters, the multichannel processing consists in recombining the signals received by the different antennas in order to detect and demodulate each received source – the other received sources are considered as interference that the processing allows to reject. Signal separation can be performed thanks to spatial characteristics of the received signals which can be detected even with very low SIR. Moreover the use of an antenna array can significantly increase the sensing sensitivity by adding spatial diversity to the system.

Downlink interference analysis of LTE will be performed knowing the characteristics of the standard and using a 4-antenna array.

Title	Reliable Sensing of Cellular Systems
ID	UC13
Goals	Achieve a reliable sensing to avoid interference to licensed users. Improve the sensitivity of classical mono-antenna sensing methods especially in presence of several sources.
Approach	*Space-time processing algorithms to spatially separate sources and have detection capability at highly negative SIR* *Robustness to fast fading thanks to spatial diversity*

Table 4: Internal Use Case 2.3

2.2 Usage Scenario 2: Robust Cognitive Networks

This scenario focuses on applications that require robust communication, which is important in several domains, for example, in the health monitoring sector, in wireless control and automation or emergency services. Cognitive networks are an ideal candidate for providing robust communication: being aware of the surrounding radio environment, cognitive networks can avoid harmful interference and use frequency agility to improve communication quality.

Instead of a taking a cooperative approach that attempts to share radio resources among different systems/networks (c.f. for example Usage Scenario 3), in this scenario the focus is on applications that require to achieve a certain QoS (Quality of Service) in a potentially uncooperative RF environment. Reliable communication may, however, be required only sporadically by the application, for example a human health monitoring system that suddenly detects a potentially critical state or a temperature monitoring application that is also capable of fire detection.

While cooperation between different systems / networks will not be considered, cooperation within the cognitive network will be investigated. For example, cooperative spectrum sensing may be used to increase probability of detecting an interferer or malicious jammer. The scenario will allow to investigate the related tradeoffs (e.g. detection probability vs. energy consumption). Mobility will be a common feature in this scenario: we consider both, mobility of the interfering networks, as well as mobility of the cognitive network (under our control), for example Use Case UC21 will investigate how a mobile body area network can be extended by cognitive capabilities.

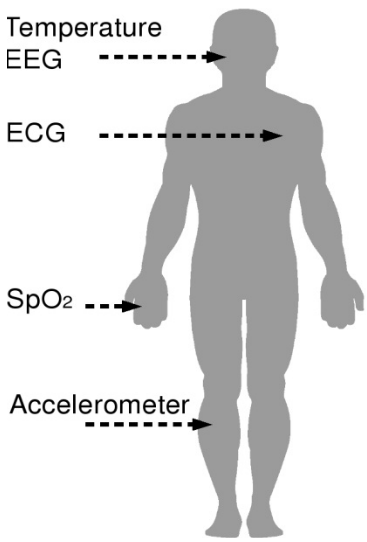

Figure 3: Monitoring physiological parameters with a BAN.

One of the key enablers of this scenario is the ability to create controllable and repeatable interference environments in which the developed concepts can be evaluated and compared. We provide both, interference scenarios with other networks (e.g. 802.11, Bluetooth, 802.15.4) as well as scenarios with intentional harmful interferers (e.g. malicious jamming of a certain spectrum band). In addition to creating / reproducing real radio interference, we also investigate the possibility to emulate interference. This is achieved by externally controlling the sensing process of the CR nodes used in the experiments e.g., based on real interference patterns previously recorded.

Title	Robust Cognitive Networks
ID	US2
Goals	Achieve reliable communication that is robust to RF interference from other (mobile) wireless networks or malicious jammers by means of *frequency agility* without cooperating with these interferers.
Key Features	Controllable and repeatable interference environments as well as the option to emulate interference which allow to evaluate and compare results; mobility of interferers and system under test will be taken into consideration.

Table 5: Internal Usage Scenario 2

2.2.1 Use Case 2.1: Cognitive Body Area Networks

Body Area Networks (BANs) allow monitoring of the human body with a detail and pervasiveness that is opening new application opportunities in domains ranging from personalized health-care and assisted living to sport and fitness monitoring. BANs typically realize a star topology with a limited number of nodes (e.g. 10) attached to various part of the body (Figure 3) where they monitor physiological parameters.

Previous studies have shown that RF interference can cause significant performance degradation in a BAN, e.g. when the BAN moves through realistic urban environments. Since BANs are mobile, during their network lifetime they may be exposed to much more dynamic RF interference environments than stationary networks -- traditional frequency diversity schemes, developed for stationary networks, might thus not be appropriate or have at least to be revisited/adapted. We use the term Cognitive Body Area Networks (CBAN) to describe mobile BANs that are able to estimate and adapt to such dynamic interference situation.

The goal of this use case is to investigate different CR techniques that allow maintaining QoS in the CBAN despite RF interference from external, mostly stationary wireless technologies (such as WLAN APs). We will define a reference BAN configuration and derive traffic patterns common in BANs. In a series of experiments we will then evaluate interference detection/mitigation techniques under various controlled, reproducible interference setups. For these experiments RF interference patterns will be collected in various realistic urban environments and then reproduced (in a lab) or emulated.

Title	Cognitive Body Area Networks (CBAN)
ID	UC21
Goals	Investigation of CR techniques that allow to maintain QoS in the mobile CBAN despite RF interference from external, mostly stationary wireless technologies. Intra-BAN cooperation (cooperative spectrum sensing within the BAN) may be utilized, but cooperation with interfering networks will not be considered. Special attention is paid to mobility.
Approach	*Experimental evaluation of the developed concepts*
Key Features	Monitored Quantity: QoS in the CBAN (packet delivery rate, latency, energy consumption) Network topology of the CBAN: star topology. Node density: 5-10 nodes attached to a human body; mobility (human walking); RF interference traces collected in different realistic urban environments

Table 6: Internal Use Case 2.1

2.2.2 Use Case 2.2: Cognitive Building Automation

Wireless sensor networks have the potential to enable energy-efficient building operation, yet it is still unclear whether they can meet the reliability constraints imposed by some applications, e.g. burglar alarm applications or applications involving actuation. As the number of wireless devices increases, RF interference in commercial and home buildings is becoming omnipresent and interference is nowadays typically regarded as one major cause for network unreliability. Frequency agility is a remedy to avoid, or at least mitigate the effects of RF interference, and lately there have been several proposals that have integrated frequency agility mechanism in wireless communication protocols to increase network reliability. They typically utilize frequency hopping mechanisms, i.e. changing the transmission frequency in a well-defined manner during network operation. Current proposals range from employing a network-wide, static (pseudo-random) channel hopping pattern(4), over more dynamic blacklisting approaches (5) to proposals that argue that distributed, local decisions are required, because RF interference may be distributed very unevenly over the typical office/home building (certain parts of the spectrum will be available only in some geographic locations of the deployment). Ultimately, this is related to the geographic dimensions (note that, because building automation systems usually cover a larger geographic area, they will typically involve a mesh topology and thus require multihop communication) and to the specific RF interference environment; however, so far an investigation of the following trade-offs in several realistic environments is still missing:

(a) Local vs. Network-wide Frequency Agility

When should local (distributed/per-link) channel diversity mechanism be favored over network-wide schemes (where all nodes change the channel in unison)? Especially if the distribution of RF interference has high variance over space and frequency, local/per-link decisions are likely to achieve better accuracy/performance. However, local decisions will be costly in terms of energy consumption, because the channel (RF environment) will be monitored in parallel on multiple nodes, per individual link. On the other hand, if network-wide hopping is employed then the monitoring/channel-sensing task might be shared among different nodes (e.g. in a round-robin fashion), possibly resulting in reduced energy-consumption and increased network lifetime, but likely at the cost of less accurate predictions.

(b) Adaptive vs. Static Frequency Agility Mechanisms

Is it sufficient to employ a static (pseudo-random) hopping pattern which is used by all nodes, or should the system sense and adapt the channel selection dynamically? There is a corresponding trade-off between energy spent for sensing and the performance of the channel selection.

The CREW federation will provide an ideal test ground for investigating these trade-offs in different interference environments, because it will enable realistic and reproducible interference scenarios.

Title	Cognitive Building Automation
ID	UC22
Goals	Investigation of trade-offs for network reliability in realistic environments with a high density of wireless devices.
Approach	*Trade-off 1: Local vs. network-wide schemes for frequency agility* *Trade-off 2: Adaptive vs. static frequency agility mechanisms*
Key Features	Monitored Quantity: Network reliability Network topology: Mesh Node density: Variable number of nodes covering a large geographical area

Table 7: Internal Use Case 2.2

2.2.3 Use Case 2.3: Cognitive Wireless Cabin Management System in Air Planes

In future aircraft, an increased number of wireless systems will be installed to satisfy requirements regarding flexibility, weight reduction and reduction of installation effort. Since a great number of aeronautic systems are safety critical or at least safety relevant, availability, reliability and quality of service (QoS) are crucial performance indicators of novel system implementations.

A good example for such a wireless aircraft system is the cabin management system. It incorporates functions for audio announcements from the flight attendants that have to be delivered with low latency and jitter to the passengers, as well as control functions for reading lights, flight attendant calls (PAX calls) and the control of signs (fasten seatbelt, no smoking). Whereas this system nowadays is based on wired data buses, future system implementations shall be based on wireless communication to increase the system flexibility and to reduce the time it takes to reconfigure the cabin. The latter is an important step to reduce turnaround times in cases where the seat configuration has to be adapted to the passenger volumes and demands (business/economy seating).

Figure 4: Cabin management system demonstrator.

Spectrum in general is a scarce resource. Particularly the low market volume of aeronautic applications makes it economically almost impossible to get assigned a dedicated frequency band that is worldwide available for such an application. The usage of an ISM frequency band (e.g. 2.4 GHz) would be an alternative, but interference with access networks installed at airports, as well as such originating from wireless applications brought into cabin by passengers (e.g. Bluetooth headsets, laptops with activated Wi-Fi adaptors) has to be expected. Since the audio function of the cabin management system is safety relevant (audio announcements are required for evacuation purposes), the presence of such spectral interferers must not render the system in-operational.

With the usage of cognitive radio, the system performance in terms of availability and reliability could significantly be enhanced, by introducing a suitable protocol to change the system frequency when an interferer has been detected.

This use case has different goals. First of all, different spectrum sensing hardware and algorithms should be assessed and compared, to identify the best candidate technology for such a system environment. The implementation and recording of dedicated interference scenarios enables further system evaluations based on defined and repeatable test conditions. In a second step, the federated testbed should be used to implement a protocol to enable the dynamic spectrum usage of the use case system. Based on the output of a spectrum sensing entity, a software defined radio platform shall be dynamically reconfigured to avoid disturbance by the interferer. Finally, the test bench shall be used to evaluate the performance of the developed algorithms regarding quality of service.

Title	Cognitive Wireless Cabin Management System
ID	UC23
Goals	Investigation of the suitability of cognitive radio to increase system reliability in the presence of interferers.
Approach	*1) Evaluation of spectrum sensing techniques* *2) Dynamic spectrum usage protocol implementation* *3) Performance evaluation*
Key Features	Monitored Quantity: Network reliability Network topology: Infrastructure Node density: One wireless node per seat group (2 to 4 seats), resulting in 40 to 200 nodes per aircraft. Assuming 10 to 30 interferers.

Table 8: Internal Use Case 2.3

2.3 Usage Scenario 3: Horizontal Resource Sharing in ISM bands

In our everyday professional and private lives, an increasing number of devices are used that rely on wireless networking connections. Wireless Wi-Fi based LAN networks are omnipresent and provide laptops, tablets and smartphones with internet connectivity, Bluetooth is used to control gaming consoles or to make hands free telephone calls, audio and video is streamed wirelessly in and around our homes and offices when watching television, listening to the radio, or using a baby monitor. Burglar alarms use wireless signals to detect human presence. In home, office and public buildings, wireless domotics may be installed that monitor and control HVAC installations, control the window screens or adjust the lighting levels.

The devices in the above examples share the fact that they most often operate in the unlicensed ISM frequency bands, originally reserved for Industrial, Scientific and Medical purposes, occupying the frequency spectrum around 2.450GHz and 5.800 GHz. As the number of wireless devices used in home, office and public buildings is increasing, more and more devices have to compete for the same limited amount of spectrum, which leads to increasing coexistence problems in the ISM bands.

The focus of this scenario is on creating algorithms, protocols and networking architectures allowing different wireless networks and wireless devices to cooperate in such way that the use of the limited spectrum resources is optimized. In such optimized, *cognitive networking* environments, individual nodes or networks do not operate in a selfish way, but cooperate to achieve more efficient use of the spectrum and enhance the wireless network experience for the user. Both cooperation between heterogeneous networks technologies (e.g. Bluetooth and Wi-Fi) as well as cooperation between different homogeneous technologies (e.g. two independent sensor networks) are considered.

Key features allowing exploration of the cognitive networking paradigm are the availability of a large number of nodes supporting heterogeneous networking technologies, the possibility to compare cognitive networking solutions based on cheap sensing (e.g. integrated in sensor nodes) versus cognitive networking protocols using the sensing data from more expensive sensing solutions, and a controlled wireless experimentation environment allowing repeatable experiments. To assist researchers during the development and with the performance analysis of their solutions, wireless benchmarking techniques may be employed. These techniques allow analyzing the *solutions* under test, as well as the *wireless environment* of the devices under test, thus simplifying comparison between subsequent developments and assuring the trustworthiness of the experiments.

Title	Horizontal Resource Sharing in ISM Bands
ID	US3
Goals	Enhance the quality of the wireless networking experience through optimization of the ISM spectrum use. The optimization is achieved by letting different homogeneous and/or heterogeneous networks cooperate more efficiently through the provisioning of cognitive networking.
Key Features	Controllable and repeatable realistic interference environments. Comparability of wireless solutions in different realistic reference scenarios, allowing a correct analysis of multiple candidate solutions or subsequent developments. Stable and monitored wireless test environment, ensuring relevance of the performed experiments. User-friendly tools supporting the experimenter in running experiments, and subsequently collecting and processing results.

Table 9: Internal Usage Scenario 3

2.3.1 Use Case 3.1: Horizontal Resource Sharing in Home Environments

Inside a home environment, several wireless devices and control systems might be operating within a relatively small area. Consider a home where three Wi-Fi access points are used, to which multiple laptops are connected. Bluetooth is used to control a gaming console, and a Zigbee based sensor network is used to monitor temperatures and control the heating and ventilation; for this purpose, one sensor node is mounted in each room. Inside the home, a microwave oven and baby monitor is regularly used. A wired network connection is available in selected rooms in the house.

Within the home environment, the number of devices is relatively constant, the devices are known, and are all under the control of the home owner.

The goal of this use case is to develop and analyze cognitive networking solutions that will help the different wireless nodes and systems to better coexist. These cognitive networking solutions include methods to collectively decide on configuration parameters (at radio, MAC, and network level), and cooperative networking mechanisms, based on distributed sensing of the environment through spectrum monitoring, as well as packet monitoring at the network level.

To this end, a reference configuration of a house is reenacted in the testing environment. Traffic patterns common to a home environment are determined and are replayed in the testing environment. Other nodes, different from the actual testing nodes representing the devices in the house, are used to collect data at the network level (packet sniffing) and spectral traces (through sensing devices). Based on this data and data collected by the nodes under test, different solutions may be analyzed and fairly compared in terms of spectral efficiency, network throughput or network delay.

During the development of the cognitive networking solutions, an evolution of the sensing components that are available to the experimenter is expected;

At first, expensive sensing components are only used by the testbed to provide spectral monitoring during the experiments. The information on which the cognitive nodes base their decisions will only be collected through data collection (packets, noise levels, …) by the nodes taking part in the experiment (having only basic sensing functionality, offered by off- the-shelf radios).

In a next step, the question may be asked to what extent the information of more advanced sensing solutions (e.g. fast and accurate spectrograms or feature detection) located in the home environment may be used as a way to optimize the cognitive networking solutions.

At some point in the future, "expensive" sensing solutions may become available in each end-user node. The question may then be asked how this impacts the performance of the ISM cognitive networking protocols.

This evolution adds an additional dimension to the cognitive networking problem, as it allows different versions of the cognitive networking protocols to be explored and compared.

Title	Horizontal Resource Sharing in Home Environments
ID	UC31
Goals	Development of cognitive networking protocols to enhance coexistence of ISM devices in a home environment.
Approach	*1) Cognitive networking protocols, using limited functionality of the nodes (e.g. noise scan, packet loss monitoring)* *2) Cognitive networking protocols, using one or more advanced sensing components located in the wireless environment* *3) Cognitive networking protocols for nodes with advanced sensing support*
Key Features	Wireless technologies under test: heterogeneous ISM Wireless environment: - limited, fixed number of devices - limited dynamism - nodes owned by single user

Table 10: Internal Use Case 3.1

2.3.2 Use Case 3.2: Horizontal Resource Sharing in an Office Environment

The second use case is an evolution of the first use case, which adds complexity to the home environment case in two ways:

The scale of the network is larger: the Wi-Fi network now consists of a larger number of access points, and many more associated clients. Furthermore, there are a large number of sensor nodes installed, supporting building automation. Bluetooth is used to synchronize mobile devices, support wireless keyboards and wireless mice.

A relatively large number of visitors enter the office environment. During meetings, they might access the internet simultaneously, considerably occupying the local 2.4 GHz ISM spectrum. Moreover, devices of visitors cannot necessarily be controlled, making the network optimizations more challenging.

In this use case, it can be studied how the scale of the network and the different characteristics of the end-users impact cognitive radio solutions. As in use case 2.1, these experiments are supported by a stable and controllable testbed infrastructure, which is behaving as an office environment. Once again, using the information available from the three different types of sensing components will impact the performance, possibilities, and financial cost of the developed solutions.

Title	Horizontal Resource Sharing in an Office Environment
ID	UC32
Goals	Development of cognitive networking protocols to enhance coexistence of ISM devices in an office environment.
Approach	*1) Cognitive networking protocols, using limited functionality of the nodes (e.g. noise scan, packet loss monitoring)* *2) Cognitive networking protocols, supported by one or more advanced sensing components located in the wireless environment* *3) Cognitive networking protocols for nodes with advanced sensing support*
Technical Parameters	Wireless technologies under test: heterogeneous ISM (mainly 2.4 GHz) Wireless environment: - large number of nodes, large node density - increased network dynamics and a changing number of users - most nodes under single administrative domain, but also visiting nodes

Table 11: Internal Use Case 3.2

2.3.3 Use Case 3.3: Horizontal Resource Sharing During an Exhibition

This third use case represents an evolution of the second use case, which adds complexity to the office environment case:

- The network scale is larger: there are more access points, and more clients. Many sensor nodes are used for building automation.
- There are large numbers of external and mobile users, whose devices cannot fully be controlled.
- Several networks are co-located, which are owned by different organizations (visitors, exhibitors, local organization…). As such, interactions are more challenging and cognitive strategies may need to be rethought.

Furthermore, in this case, it is relevant to study how a network can be set up quickly on site, as the place where the exhibition is held may not be equipped with a suitable network infrastructure. Therefore, fast network deployment strategies are to be considered that are able to process spectral and network information quickly to determine the most fitting parameters for initial network configuration.

As in the previous two use cases, the testbed infrastructure is used to recreate the network environment under evaluation as well as to support experiment execution and analysis, and the evolution of the sensing components adds an additional dimension to the cognitive networking approaches.

Title	Horizontal Resource Sharing During an Exhibition
ID	UC33
Goals	Development of cognitive networking protocols to enhance coexistence of ISM devices during an exhibition. Development of fast network deployment mechanisms.
Approach	*1) Cognitive networking protocols, using limited functionality of the nodes (e.g. noise scan, packet loss monitoring)* *2) Cognitive networking protocols, supported by one or more advanced sensing components located in the wireless environment* *3) Cognitive networking protocols for nodes with advanced sensing support*
Technical Parameters	Wireless technologies under test: heterogeneous ISM Wireless environment: - very large node density - high network dynamics, a changing number of users - high number of co-located networks operated by different administrative domains

Table 12: Internal Use Case 3.3

2.4 Usage Scenario 4: Cooperation in Heterogeneous Networks in Licensed Bands

Nowadays unlicensed spectrum is becoming overcrowded due to excessive use. This results in higher numbers of frame collisions, competition between different devices and ultimately decreased throughput in these bands. For this reason, certain underutilized licensed bands are being looked into as an opportunity to alleviate these strains on wireless networks TV bands are of particular interest due to the switch from analog to digital broadcasting, and the resulting digital dividend, and to the possibility of making opportunistic use of interleaved spectrum...

Unfortunately, switching a technology from one frequency to another is not as simple as changing the carrier frequency at which it operates. Other factors such as path loss, multipath effects, the ability to pass through walls and the permissible amount out of band emissions are all likely to change if the operating frequency changes. These must all be taken into account to ensure smooth integration of new technologies into different frequency environments.

Many studies across Europe and the United States have shown that vast amounts of the licensed spectrum are under-utilized. In Ireland, the Communications Regulator (ComReg) has introduced a licensing programme which allows manufacturers and researchers to make use of this unused spectrum, on a temporary lease, provided that it is used for tests or trial of new and innovative technologies. This licensing programme is called Test and Trial <www.testandtrial.ie>. It has been used in the past in the testing and trial of WiMAX, reconfigurable software-based radio, on-board Aircraft GSM services, digital terrestrial television (DTT), Mobile TV (DVB-H) and many other wireless technologies.

Transmission in the TV bands by an unlicensed user is for the most part not allowed. This makes experimentation in these frequencies more difficult as we rarely have the opportunity to test new ideas or approaches that involve transmission in those bands.

Title	Cooperation in heterogeneous networks in TV bands
ID	US4
Goals	To explore the utilization of TV “white spaces” and investigate feasibility of secondary user implementation in the TV bands.
Key Features	Software defined radio – Iris TV band Test and Trial license

Table 13: Internal Usage Scenario 4

2.4.1 Use Case 4.1: Geographical White Space Sensing

Before we consider any experiment that involves transmission in licensed bands, it seems prudent to explore some sensing experimentation that does not require any permission or licensing. First of all, various pieces of sensing equipment could be used to map the frequencies of the TV bands at different geographical locations and therefore identify which parts of the spectrum are idle at different locations and perhaps construct a mapping of geographic location of a section of a major city detailing the levels of utilization of interleaved spectrum in the TV bands.

Title	Geographical white space sensing
ID	UC41
Goals	To create a mapping of a specific geographical area, showing the frequency band availability at key points on the map. Opportunistic use by secondary users can then rely on a geolocation database containing such information.
Approach	*1) Set sensing equipment up at strategic points of a selected geographical area.* *2) Sense the area for a certain frequency for a predetermined period of time.* *3) Repeat for all frequencies of interest.*
Key Features	Multiple sensing platforms Suitable geographical area

Table 14: Internal Use Case 4.1

2.4.2 Use Case 4.2: Detection of Wireless Microphones

Another serious consideration to be made when conducting any sensing experiments in the TV bands is the process of detecting wireless microphones (mics). A wireless mic is a microphone that is connected to its respective amplifier or recorder by wireless transmission. These mics are known to transmit in various different frequency bands including TV bands. They operate as an underlay network in the VHF and UHF bands and since they are considered licensed incumbant users of TV spectrum (and sometimes referred to as licensed secondary users), anyone who wishes to transmit on these frequencies without causing interference to the licensed users must be able to detect and avoid these wireless mics. With this in mind, we propose a series of experiments that attempt to detect these transmissions

Title	Detection of wireless microphones
ID	UC42
Goals	To detect the presence of wireless mics in TV bands.
Approach	*1) Transmit a sample wireless mic signal.* *2) Use a feature detection algorithm to detect the presence of a wireless mic signal.*
Key Features	Signal generator with wireless mic signal. Feature detection for wireless mics.

Table 15: Internal Use Case 4.2

2.4.3 Use Case 4.3: Transmission and Detection in TV Bands

Moving on from sensing experiments, there are also several experiments involving transmission that can help validate techniques for interference avoidance and interference tolerance between primary and secondary users in the TV bands. These experiments can be conducted using DVB-T signals can also be carried out in the TV bands, taking advantage of "test and trail" license programme One that may prove interesting would be to emulate a TV transmission over a relatively large distance (say campus wide) and then, at the same time, have a link between two radios using the real-time reconfigurability of Iris software-defined radio to shape the signal and avoid interfering with the emulated TV signal. Ideally we would like to see the Iris link operating in the same band as the primary transmission when out of its geographical range and then enter then cell radius of the TV transmission and dynamically avoid it by means of adaptive dynamic spectrum access (DSA) techniques. This would be a unique opportunity of the testbed federation as experiments such as this performed in the past would only have been able to focus on the sensing part of the process and would not have been able to demonstrate its DSA capabilities.

Title	Transmission and detection in TV bands
ID	UC43
Goals	To opportunistically detect and avoid a primary user without causing unacceptable interference.
Approach	*1) Transmit a sample DVB-T signal.* *2) Detect the DVB-T transmission.* *3) Reconfigure the centre frequency of the secondary user link, and/or perform spectrum sculpting to coexist with the primary signal without causing unacceptable interference.*
Key Features	Signal generator with TV signal generator (DVB-T) Sensing platform Iris - Software defined radio.

Table 16: Internal Use Case 4.3

2.5 Usage Scenario 5: Cognitive Systems and Cellular Networks

In cognitive radio system, vertical spectrum sharing is a policy for dynamic spectrum access. For a given set of frequency bands, it involves a clear separation between primary and secondary systems. Typically, the primary users are considered to be operating under a license received from regulatory bodies, while the secondary users communicate on a non-interfering basis and are subject to strict constraints regarding interference.

In the course of the development of next generation cellular networks, one particular, novel kind of service that is being considered is machine-to-machine (M2M) communication. Providing an infrastructure for M2M-devices is seen to have the potential of creating revenues from new areas of business that cannot be foreseen yet. M2M communication is closely linked to research in the area of wireless sensor networks (WSN). WSN put different requirements to the network operator than conventional cellular communication does. This includes the capability to handle potentially large number of devices with different levels of mobility and high as well as low traffic loads. Further, power consumption and complexity are of foremost significance. The variety of possible applications calls for a higher flexibility in many aspects, compared to what is provided by currently established standards.

Cognitive radio solutions are a prominent approach to address above issue. For mobile network operators, one particularly relevant question in this context is, whether and how cognitive radio can be brought to coexistence with established cellular networks of 2G, 3G and 4G. Therefore this cognitive radio scenario addresses coexisting multi-carrier systems in licensed bands.

Title	Dynamic Spectrum Access in Cellular Networks
ID	US5
Goals	Sensing of a cellular primary system and monitoring the impact of a secondary system within its bandwidth.
Key Features	Primary system acts as a passive infrastructure. Performance parameters of the primary cellular system can be monitored.

Table 17: Internal Usage Scenario 5

2.5.1 Use Case 5.1: Impact of Cognitive Networking on a Cellular Primary System

To pave the way for further research on CR applications in cellular bands and partly motivated by the aforementioned possible application in M2M communications, this use case targets spectrum overlay techniques in the LTE frequencies. For the envisioned setup, an LTE transmission link serves as a licensed primary system with high priority, while an independent secondary overlay system of lower priority looks for opportunities to communicate in unused frequencies. Primary and secondary systems are considered separate entities that do not exchange information (e.g. about their scheduling).

The goal is to use knowledge about available resources that is obtained through advanced spectrum sensing techniques and apply it in a frequency agile transmission scheme of the secondary system in such way, that interference to the primary system is kept minimal. The impact of the secondary system is evaluated by measuring the performance parameters of the primary system e.g. SINR, packet error rate and throughput.

This setup allows from the primary system's point of view to compare policies for channel selection and techniques for interference avoidance, as well as to evaluate the reliability of different spectrum sensing methods.

Title	Impact of Cognitive Networking on a Cellular Primary Systems
ID	UC51
Goals	Investigate the impact of a cognitive secondary system on a primary cellular system.
Approach	*1) Set up primary system and make resources available for secondary use.* *2) Set up secondary transmission to coexist with the primary system.* *3) Monitor impact on primary system.*
Key Features	Monitored quantity: Packet Error Rate, SINR of primary cellular system Network topology: Primary and secondary system are independent and do not exchange information mutually.

Table 18: Internal Use Case 5.1

3 Conclusions

This document has presented a number of usage scenarios with focus on different areas of cognitive radio and cognitive networking. In each scenario, a general arrangement of CR components and their interaction with the wireless environment is found. Various aspects of scientific and practical relevance are studied in use cases. A total of five usage scenarios are distinguished.

A prerequisite for cognitive radio enhanced communication is context awareness. The first usage scenario is focused on advanced spectrum sensing techniques, which aim to provide information about the wireless environment at given location and time. The associated use cases target the acquisition of context awareness in the ISM bands, in TV bands and in the LTE bands. Key aspects include low cost, low power solutions as well as accuracy and reliability of the gathered information.

The frequency agility of cognitive radio solutions makes them capable to avoid harmful interference once it is detected and thus enhance robustness of the communication. When radio resources are subject to an open sharing model as in the ISM bands, this is especially relevant and therefore subject of the second usage scenario. The related use cases research robustness in a CBAN which faces a highly dynamic interference environment, in building automation where interference conditions are likely to change across the network as well as in a cabin management system in an aircraft which is a safety critical application.

In home, office and public environments, the number of wireless devices occupying the unlicensed 2.4 GHz and 5 GHz ISM band is steadily increasing and their coexistence is bound to become problematic at a certain point. This motivates to dedicate a use case to the research of algorithms, protocols and networking architectures for cognitive networking solutions that can enhance the wireless network experience for the users.Heterogeneous and homogeneous systems exhibiting characteristic features of a home, an office and a public environment are studied in use cases, where number and control power over the devices varies. An analysis of cost vs. performance gain is also of interest.

Studies in the past have shown how large parts of the licensed spectrum are under-utilized. In order to achieve more efficient use of frequency resources and as an alternative to crowded unlicensed bands, cooperation of heterogeneous networks in licensed bands is focused on in the fourth use case. Particular points of interest are geographical white spaces sensing to obtain a map of frequencies for given locations, the detection of wireless microphones that are considered licensed underlay secondary systems as well as dynamic spectrum access in TV bands.

Further, cognitive radio and networking solutions in cellular networks are taken into consideration, in order to be prepared for the requirements of future wireless applications. For this purpose it is important to show that cognitive devices can coexist with already deployed infrastructure.

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