About this document

This document constitutes a white paper developed within WG6 of WWRF, concerning Cognitive Radio and Management of Spectrum and Radio Resources in Reconfigurable Networks.

Cognitive Radio and Management of Spectrum and Radio Resources in Reconfigurable Networks

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Abstract:

Wireless communication attracts enormous investments, while at the same time user requirements continuously increase. Moreover, evolution in wireless technologies should keep pace with the aforementioned fields, in order to facilitate the integration of innovative services and applications in everyday communication. Aligned with these thoughts, this white paper constitutes the result of work conducted within the 6th working group of the Wireless World Research Forum with respect to Cognitive Radio and the efficient management of spectrum and radio resources in reconfigurable systems. For this purpose, a technical approach for all anticipated problems related to the management of future systems is initially done, followed in the sequel by an addressing of the impacts of different air interfaces on wireless connectivity. Moreover, the respective regulatory perspectives are also apposed, and promising future research directions are highlighted in the end of this white paper.

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1. INTRODUCTION

The gradual migration of today's wireless communications (2G/2.5G/3G) towards the systems beyond 3G (B3G) reflects the most recent trend in the communications landscape. B3G wireless systems are recognized as such that can achieve high data rate transmissions and provide adequate capacity, cost efficiency and highly sophisticated services, comparable to those offered by wired networks, for a variety of applications, such as interactive multimedia, VoIP, network games or videoconference. As long as the currently known Radio Access Technologies (RATs) are not mature enough to satisfy the aforementioned criteria in a standalone manner [1], the idea of diverse RATs to be optimally combined and coordinated under a global infrastructure called " *B3G wireless access infrastructure*" stands as a basic requirement for the consolidation of B3G systems. Major contributors towards this convergence are the *cooperative networks* concept [2],[3] and the evolution of adaptive (cognitive-reconfigurable) networks [4].

The cooperative networks concept assumes that diverse technologies such as cellular 2/2.5G/3G mobile networks and its evolutions (GSM/GPRS/UMTS/HSDPA), wireless local/metropolitan area networks (WLANs/WMANs), wireless personal area networks, (WPANs) and short range communications, as well as digital video/audio broadcasting (DVB/DAB) can be components of a heterogeneous wireless-access infrastructure and cooperate in an optimal way, in order to provide high speed and reliable connectivity anywhere and anytime [5].The cooperation is materialized through the agreement for exchanging traffic or sharing spectrum among the cooperative NPs and/or the joint configuration of network segments, providing assistance to each other in handling new traffic conditions or service management requests and maximizing the offered QoS levels.

Yet, the realization of the B3G concept based only on network cooperation may not be viable or efficient. First, there can be objections to a business model that requires extensive inter-NP cooperation. Additionally, the cooperative networks concept implies that the whole set of the alternate RATs should be deployed (installed and configured) a priori in both network segments and terminals, which would require constant, potentially risky, investments in software and hardware , whenever new technologies are introduced. Obviously, this can be inefficient, considering that all the technologies are not suitable for all the conditions.

Adaptability (cognition-reconfigurability) is seen as means to overcome the shortcomings identified above. Adaptive networks have the ability to dynamically adapt their behavior (configuration) to the various conditions (e.g., hot-spot situations, traffic demand alterations, etc.) at different time zones and spatial regions, by exploiting deployments with much fewer pre-installed components. This process, in general, imposes (re)configuration actions which may affect all layers of the protocol stack. Such actions indicatively include RAT selection, spectrum allocation, algorithms selection and parameter configuration (at the PHY/MAC layer), TCP adaptation, IP QoS configuration etc (at the Network/Transport layer) or adaptation to appropriate QoS levels (at the Middleware/Application layer). Moreover, framed within the B3G vision is the efficient management of spectrum and radio resources (in general), in order to offer services ubiquitously and in a cost effective manner.

This white paper accordingly focuses on the management of spectrum and radio resources for adaptive networks operating in high-speed, B3G infrastructures. For this purpose, it first presents the functional modules that are necessary for such management actions, while in the sequel, the impact of the air-interfaces on radio resource management is studied. Finally, the regulatory perspectives that keep pace with the necessary convergence actions in telecommunications are apposed. In the end, concluding remarks and orientations try to light the way of future research efforts in this field.

2. TECHNICAL APPROACH

2.1 Radio Resource and Spectrum Management Approaches

There is currently much research and investigation by many industrial organizations and national administrations on the closely related topics of dynamic spectrum management, flexible spectrum management, advanced spectrum management, dynamic spectrum allocation, flexible spectrum use, dynamic channel assignment, and opportunistic spectrum management [1]-[25][54]. Cognitive radio and the closely related technologies of policy-based adaptive radio, software defined radio, software controlled radio, and reconfigurable radio are enabling technologies to implement these new spectrum management and usage paradigms. These concepts are equally applicable to a wide variety of mobile communications systems including public protection and disaster relief (PPDR), military, and commercial wireless networks.

More efficient use of the spectrum is one benefit associated with cognitive radios and the closely related technologies such as policy-based adaptive radio. To be able to achieve this benefit, it is necessary for these advanced radios to be controlled in such a way that underutilized portions of the spectrum can be utilized more efficiently. This has been called opportunistic spectrum management.

For many scenarios, the method of control needed to achieve opportunistic spectrum management through the use of cognitive radio and policy-based adaptive radio is a network issue as well as a radio issue. Network control of these advanced radios includes control of the configuration of the radio and the RF operating parameters. Regulatory policies which govern the allowable behaviour, i.e., RF operating parameters, are part of this network control. The control policies may, for some scenarios also include network operator and user policies.

In general, there are two control models for opportunistic spectrum access or flexible spectrum usage namely the centralized control model and the distributed control model. For each of the control scenarios, spectrum sensing is a critical aspect of the control of cognitive radios and policy-based adaptive radios which employ software defined radio technology.

2.1.1 Centralized

The centralized control model is one in which the management of spectrum opportunities is controlled by a single entity or node which has been referred to as the spectrum broker. The spectrum broker is responsible for deciding which spectrum opportunities can be used and by which radios in the network. A central broker may use sensors from the distributed nodes or may use other means for sensing and spectrum awareness. One application of centralized control is real-time spectrum markets.

2.1.2 Distributed

The second opportunistic spectrum access or flexible spectrum usage control model is the distributed control model. In this model the interaction is “peer-to-peer”. In other words the cognitive radio or policy-based adaptive radio nodes in the network are collectively responsible for identifying and negotiating use of underutilized spectrum. For some scenarios, the distributed control may be between co-operative radio access networks.

2.2 Cognitive Radio

Cognitive radio will lead to a revolution in wireless communication with significant impacts on technology as well as regulation of spectrum usage to overcome existing barriers. Cognitive radio, including SDR as enabling technology, is suggested for the first time in [7]-[9] to realize a flexible and efficient usage of spectrum. Cognitive radio is an enhancement of SR which again emerged from SDR. Thus, cognitive radio is the consequent step from a flexible physical layer to a flexible system as a whole similar to reconfigurable radio.

The term cognitive radio is derived from “cognition”. According to Wikipedia [10][10] cognition is referred to as

- Mental processes of an individual, with particular relation
- Mental states such as beliefs, desires and intentions
- Information processing involving learning and knowledge
- Description of the emergent development of knowledge and concepts within a group

Resulting from this definition, the cognitive radio is a self-aware communication system that efficiently uses spectrum in an intelligent way. It autonomously coordinates the usage of spectrum in identifying unused radio spectrum on the basis of observing spectrum usage. The classification of spectrum as being unused and the way it is used involves regulation, as this spectrum might be originally assigned to a licensed communication system. This secondary usage of spectrum is referred to as vertical spectrum sharing, which is introduced in Section 3.2.2. To enable transparency to the consumer, cognitive radios provide besides cognition in radio resource management also cognition in services and applications. The mental processes of a cognitive radio based on the cognition circle from [8] are depicted Figure 1 Cognition is illustrated at the example of flexible radio spectrum usage and the consideration of user preferences. In observing the environment, the cognitive radio decides about its action. An initial switching on may lead to an immediate action, while usual operation implies a decision making based on learning from observation history and the consideration of the actual state of the environment.

The Federal Communications Commission (FCC) has identified in [11] the following (less revolutionary) features that cognitive radios can incorporate to enable a more efficient and flexible usage of spectrum:

- **Frequency Agility** – The radio is able to change its operating frequency to optimize its use in adapting to the environment.
- **Dynamic Frequency Selection** (DFS) – The radio senses signals from nearby transmitters to choose an optimal operation environment.
- **Adaptive Modulation** – The transmission characteristics and waveforms can be reconfigured to exploit all opportunities for the usage of spectrum
- **Transmit Power Control** (TPC) – The transmission power is adapted to full power limits when necessary on the one hand and to lower levels on the other hand to allow greater sharing of spectrum.
- **Location Awareness** – The radio is able to determine its location and the location of other devices operating in the same spectrum to optimize transmission parameters for increasing spectrum re-use.
- **Negotiated Use** – The cognitive radio may have algorithms enabling the sharing of spectrum in terms of prearranged agreements between a licensee and a third party or on an ad-hoc/real-time basis.

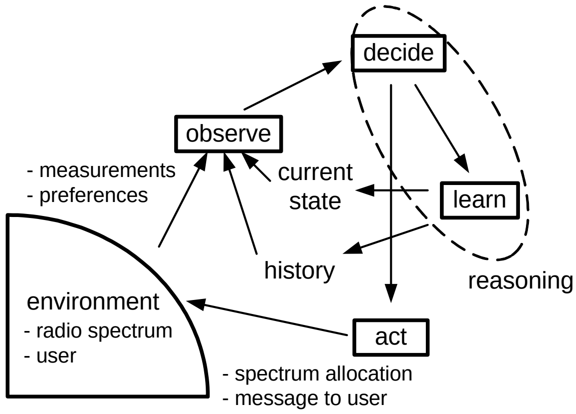

Figure 1: Mental processes of a cognitive radio based on the cognition cycle from [2].

Strictly following this definition modern Wireless Local Area Networks (WLANs) can already be regarded as cognitive radios: IEEE 802.11 devices operate with a listen-before-talk spectrum access, dynamically change the operation frequencies and control their transmission power.

In late research, cognitive radios are also referred to as "spectrum agile radios" [12][13] to indicate an emphasis on dynamic spectrum usage. Mangold et al., [12] focus thereby on IEEE 802.11k for radio resource measurements as an approach to facilitate the development of spectrum agile radios, while Mangold et al. [13] introduce spectrum agile radios as a society of value oriented machines. Basic concepts are taken there from social science to classify the social action of independent decision-makers.

This understanding of cognitive radios is summarized in the following definition of cognitive radio from Haykin [14]:

> *Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming radio frequency stimuli by making corresponding changes in certain operating parameters (e.g., transmit power; carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind: (i.) highly reliable communication whenever and wherever needed and (ii.) efficient utilization of the radio spectrum.*

2.3 Policy Based Adaptive Radio

A major driving requirement for policy-based adaptive radios is the need for opportunistic access to spectrum so that the spectrum is utilized more efficiently. The current method of allotting spectrum provides each new service with its own fixed block of spectrum. Since the amount of useable spectrum is finite, as more services are added, there will come a time at which spectrum is no longer available for allotment. We are nearing such a time, especially due to a recent dramatic increase in spectrum-based services and devices.

However, as noted by the FCC [7][35], there are large portions of allotted spectrum that are unused when considered on a time and geographical basis. There are portions of assigned spectrum that are used only in certain geographical areas and there are some portions of assigned spectrum that are used only for brief periods of time. Studies have shown that even a straightforward reuse of such "wasted" spectrum can provide an order of magnitude improvement in available capacity. Thus the issue is not that spectrum is scarce – the issue is that most current radio systems do not utilize technology to effectively manage access to it in a manner that would satisfy the concerns of current licensed spectrum users. Policy-controlled adaptive radio is one approach for achieving better spectrum utilization, dynamic spectrum management, and flexible spectrum use [8][9].

As noted earlier, software controlled radios may be considered to be a subset of software defined radios as that term has been defined in this document. Policy-based adaptive radio is a software-controlled radio in which the control information includes:

- Policies (regulatory, operational, user)
- Sensor information
- Available RF bands
- Propagation data
- Available protocols
- Performance requirements
- Information about the radio network infrastructure

Policy-based adaptive radio is an approach wherein static allotment of spectrum is complemented by the opportunistic use of unused spectrum on an "instant-by-instant" basis in a manner that limits interference to primary users. This approach is called "opportunistic spectrum access" spectrum management. The basic parts of this approach are to:

- Sense the spectrum in which one wants to transmit.
- Look for spectrum holes in time and frequency.
- Transmit so that you do not interfere with licensees.

The concept of policy-based adaptive radio potentially provides a new regulatory policy framework, particularly for use in unlicensed bands. For licensed bands, it potentially allows licensed holders a method for improved utilization of the spectrum covered by their license. The concept allows for diversity of privacy sources from different regulatory sources. It also allows for policies that change with time and geographical location. The concept will facilitate regulatory traceability provided the computer-coded policies trace to the original regulatory documents.

The key technologies needed for policy-based adaptive radio include:

- Real-time, wideband spectrum monitoring capability achieved at low-power consumption.
- The capability to perform waveform identification and characterization within 10's of milliseconds.
- The capability to synthesize autonomous, dynamic time-frequency-space waveforms.
- The ability to perform network reconfiguration and transformation operations.
- Policy-based meta-language
    - Translates policy rules into radio behavior controls
    - Radio control operating rules are based on policies and situations
    - Decouples the radio technology from the regulatory process

There are a number of research challenges to this adaptive spectrum management including:

- Wideband sensing.
- Opportunity identification.

- Network aspects of spectrum coordination when using adaptive spectrum management.
- Traceability so that sources can be identified in the event that interference does occur.
- Verification and accreditation.

2.4 Functional Architecture for the Management of Spectrum and Radio Resources in Adaptive/Reconfigurable Systems

Adaptive (cognitive/reconfigurable) systems are aware of their environment as well as their own internal structure. The cognitive radio is, for example, aware of the number of multipaths it sees and can adjust the equalization algorithm accordingly. It can even take hints from the information being exchanged by the user to adapt its detecting strategy and power consumption according to the user's behavior.

Such an intelligent radio system has two primary objectives: (1) Highly reliable communication whenever and wherever needed, and (2) efficient utilization of the radio spectrum. The activities in WP5 of E^2R project aim at translating the vision of cognitive radio into reality. This will be done by investigating and introducing concepts in Advanced Spectrum Management (ASM), Advanced Radio Resource Management (ARRM), and Dynamic Network Planning and Management (DNPM). The ASM will optimize the spectrum allocation adaptively. This includes the optimization of guard bands between the Radio Access Technologies (RATs). The ARRM should handle the optimization of traffic through the available RATs. One of the main concerns of ARRM is the vertical handover between RATs. The DNPM algorithms deal with the dynamic radio cell behavior through power allocation and antenna techniques. The ASM, ARRM and DNPM will take the evolution of mobile communication systems one step further towards cognitive radio.

The functionalities of DNPM, ASM and ARRM are closely interlocked and coupled (see Figure 2). Nevertheless the interworking of these three concepts can be considered as three interlocked loops. Each loop reacts based on the output parameters of the adjacent ones. The more inner a loop is located, the faster is their reaction time. Therefore the entities of the middle and inner-loop should be locally decentralized in order to combat delay through the route to a central entity. The function of the outer-loop can be executed in a central entity at a central place, e.g. for GSM in the core network.

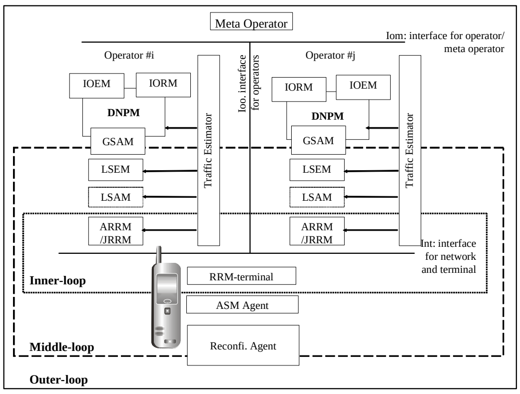

Figure 2: Functional Blocks Overview

Within the outer-loop the network will first be planned and the DNPM will give recommendation to the operator about the needed spectrum in time and space. The operator's entity Inter Operator Economic Manager (IOEM) will decide how to trade spectrum based on the advice of the Inter Operator Resource Management (IORM). The IOEM can offer, demand for spectrum depending on expected traffic. The

DNPM planned the network based on the spectrum trading results and the Global Spectrum Allocation Management (GSAM) computes the best opportunity for spectrum division to the operator's RATs. This happens in long-term based on the reaction of the middle- loop.

DNPM is specified for the O&M system irrespective to its two phases, i.e., the planning phase and the management phase. Referring to the 3GPP documents on telecommunication management network, interfaces for inter-operator and functions for registering, monitoring and controlling the operating frequencies are included in the O&M subsystem. Refereeing to Interface between operators, i.e., the interface supporting inter-PLMN/inter-organization operations, this interface supports the inter-PLMN mobile service provisioning, e.g., for the roaming users, and can be extended as spectrum trading. For high level policy agreement, e.g., access to meta-operator or certain level of service agreement between operators can be transferred through this interface. On the other hand, some fast interactions concerning the spectrum reallocation might directly dedicated in the control plane of the radio subsystem, therefore, in Figure 2, conceptually we allow DNPM partially cover the functions of IORM, IOEM and GSAM.

In the middle-loop a Local Spectrum Economic Manager (LSEM) trades the spectrum of each base station to the users. Based on the trading results the Local Spectrum Allocation Management (LSAM) assigns the RATs operated/used by each spectrum user the gained radio resources as a number of Generic Resource Elementary Credits (GRECs) which are the elementary resource units offered per RAT.

The ARRM reacts fastest and therefore represents the inner-loop. Its task is to trigger and manage the vertical handover and optimize spectrum usage using traffic splitting over different RATs. If a user does not need the whole spectrum gained by negotiation thanks to ARRM, this unused spectrum can be reused for other users. In this case the ARRM triggers the LSAM in the middle-loop to rearrange the spectrum.

3. IMPACT OF AIR INTERFACES

This section presents the main challenges and impact of air interfaces on future wireless systems, with main attention drawn to radio spectrum and the way it should be regulated, so as to cater for the systems' needs.

3.1 Radio Spectrum Regulation

3.1.1 Scope of Radio Spectrum Regulation

Regulation of radio spectrum has its origin in the economic regulation of railroads. Since the beginning of the 19th century, communication services of telephony, radio and television have been regulated according to this model to provide service to the public on a nondiscriminatory basis to fair and reasonable prices and conditions. Regulators approach spectrum regulation in determining how particular bands of spectrum can be used, make rights available to licensees or unlicensed users and define rules constraining the accesses to this spectrum. Ideally, the regulators' decision making targets thereby at the increase of public welfare and it reflects the public interest.

In the context of radio spectrum regulation it has to be distinguished between "trading", as transfer of spectrum usage rights and "liberalization", as weakening of restrictions and limitations associated with spectrum usage rights related to technologies and services.

The regulation of radio spectrum has different characteristics:

- **Licensed spectrum for exclusive** usage enforced and protected through the regulator. Frequency bands sold for being used by UMTS are an example for the exclusive usage rights at licensed spectrum.
- **Licensed spectrum for shared usage** restricted to a specific technology. The frequencies assigned to Digital European Cordless Telecommunications (DECT) and Personal Communications Service (PCS) are an example for this model. The secondary usage of under-utilized licensed spectrum through intelligent radio systems is a different kind of sharing licensed spectrum and will be discussed below.
- **Unlicensed spectrum** that is available to all users operating in conformance to regulated technical etiquettes or standards, like the U-NII bands at 5 GHz.
- **Open spectrum** allows anyone to access any range of spectrum without any permission under consideration of a minimum set of rules from technical standards or etiquettes that are required for sharing spectrum.

The report of the FCC's Spectrum Policy Task Force [15] defines spectrum regulatory mechanisms in a similar way. There, the assignment of spectrum rights is differentiated into an "exclusive use" model, a "command-and-control" model and a "commons" or "open access" model. The "command-and-control" is currently the most often used regulation model and refers to the "licensed spectrum for shared usage" and "unlicensed spectrum".

Radio spectrum regulation has to take influence on the development of access protocols and standards to balance the following goals [16]:

- An adequate QoS should be possible to all radios depending on the supported applications
- No radio should be blocked from spectrum access and transmission for extended durations
- Spectrum management policies and standards should not slow down innovations in the economically significant, but rapidly changing, communication sector
- The limitedly available spectrum should be used efficiently, including special re-use of spectrum and solving the "tragedy of commons" which is described below

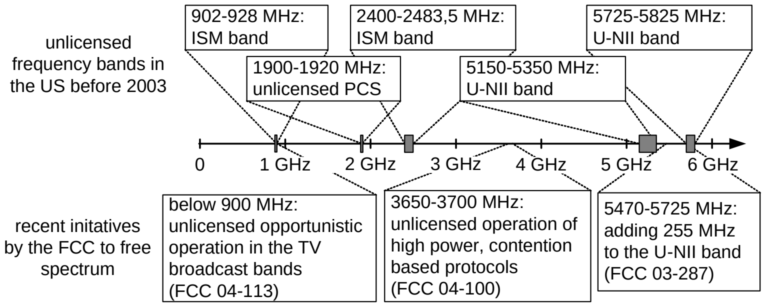

Figure 3: Spectrum for unlicensed operation in the US and recent initiatives of the FCC to free spectrum with a reference on the corresponding document.

- Spectrum can used in a dynamically adaptive way, taking the local communication environment like spectrum usage policies into account
- The costs of devices should be not increased significantly through techniques prescribed by regulation

3.1.2 Licensed Spectrum

Large parts of the radio spectrum are allocated to licensed radio services in a way that is often referred to as "command-and-control". Licensing spectrum covers the exclusive access to spectrum and the spectrum sharing of the licensed spectrum through strictly regulated devices.

In case of exclusive spectrum usage, a license holder pays a fee to have this privilege. Exclusive access rights have the advantage of preventing potential interference which implies dangers to a reliable and thus chargeable communication. In case of spectrum scarcity, licensed spectrum is highly valuable leading to economic profits, as consumers need to pay for using it. Having an immense commercial impact, spectrum licenses can be bounded to requirements which are to be fulfilled like a concrete transmission technology allowed in this spectrum or a certain percentage of population to be reached by the network when purchasing the spectrum for wireless communication. The UMTS auctions in Europe are an example for this.

Today's most often used licensing model is to license spectrum for shared usage restricted to a specific technology. Emission parameters like the transmission power and interference to neighboring frequencies like out of band emissions are restricted. Regulation takes care for protection against interference and for a limited support of coexistence capabilities like Dynamic Channel Selection (DCS) in DECT that are mandatory and part of the standard.

3.1.3 Unlicensed Spectrum

The access to unlicensed spectrum is open but its utilization is strictly regulated. An unlimited number of users are sharing the same unlicensed spectrum. Spectrum usage is allowed to all devices that satisfy certain technical rules or standards in order to mitigate potential interference. Examples for these technical rules are the limitation of transmission power or advanced coexistence capabilities. The usage rights at unlicensed spectrum are flexible and no concrete methods to access spectrum are specified.

Figure 3 illustrates the status of unlicensed spectrum in the US. Besides the Industrial, Scientific and Medical (ISM) bands at 900 MHz and 2.4 GHz, the FCC opened for unlicensed operation in 1990 during PCS rule making 20 MHz at 1.9 GHz for Unlicensed PCS (UPCS). Additionally, FCC reserved in 1997 300 MHz and in 2003 255 MHz at 5 GHz for unlicensed operation. This frequency band at 5 GHz is referred to as Unlicensed National Information Infrastructure (U-NII) band. Contrary to the ISM bands, the usage of the U-NII bands is more restricted: There, limited coexistence capabilities like DFS and TPC, as introduced below, are mandatory [17].

As TV bands in the US are often under-utilized, the FCC proposed in 2004 to allow unlicensed systems the secondary usage of this spectrum [18]. This principle of vertical spectrum sharing is introduced in detail in Section 3.2.2.

In 2004, the FCC also initiated the opening of new spectrum for wireless broadband communication in the 3650-3700 MHz band for fixed and mobile devices transmitting at higher power [19]. It is envisaged, that multiple users share this spectrum through the use of "contention-based" protocols to minimize interference between fixed and mobile operation. These contention-based protocols will help to reduce the possibility of interference from co-frequency operation by managing each station's access to spectrum. The FCC regards this approach as reasonable, cost-effective method for ensuring that multiple users can easily access the spectrum. Besides a few regional constrains, at radar sites and frontiers of the US, fixed stations will be allowed to operate with a peak power limit of 25 Watts per 25 MHz bandwidth, and mobile stations with a peak power limit of 1 Watt per 25 MHz bandwidth. The licensing, service and operation provisions for this spectrum will be placed in Part 90 of the FCC's rules in the "Code of Federal Regulations, Title 47 Telecommunication" in order to reflect the non-exclusive nationwide nature of this spectrum. The status of this frequency band is currently subject to intensive lobbying from different protocol fractions in wireless communication.

3.1.4 Tragedy of Spectrum Regulation

The success of unlicensed spectrum draws to a close, as the severe QoS constrains to spectrum access imposed by the upcoming multimedia applications cannot be fulfilled with today's means for coexistence [20].

In case of short-distance wireless communication, spectrum demand is extremely localized and often sporadic. In such a scenario, the competition for shared spectrum is limited. Therefore, the regulatory instrument of restricting transmission, e.g., limiting the maximum emission power, is successful.

In all other deployment scenarios, as for instance WLANs, unlicensed spectrum usage is a victim of its own success: Too many parties and different technologies are using the same unlicensed spectrum so that it is getting overused and thus less usable for all. In economics the phenomenon is referred to as the "tragedy of commons". Hazlett [21] additionally introduces the "tragedy of the anticommons": Contrary to the over-use of spectrum due to missing regulation of spectrum access, the "tragedy of the anticommons" refers to inefficient spectrum utilization because of too restrictive regulation. The "tragedy of commons" and the associated inefficient over-use of spectrum results to an under-investment into technology and questions thus the "open access" licensing. Therefore, to anticipate the "tragedy of commons", regulators impose restrictions like transmission power. As consequence, many alternative systems are not allowed to operate in such a spectrum which leads again to inefficient under-utilization of spectrum.

3.2 Spectrum Sharing and Flexible Spectrum Access

In this white paper it is differed between primary (incumbent) and secondary users of spectrum, where as secondary users defer to primary users in utilizing spectrum. Regardless of the regulatory model, flexibility and efficiency need to be reflected in spectrum access. Spectrum sharing plays thereby an important role to increase spectrum utilization, especially in the context of open spectrum. Techniques that sense and adjust to the radio environment are essentially required as for instance in unlicensed bands and to enable secondary access to spectrum.

3.2.1 Underlay and Overlay Spectrum Sharing

The open access to most of the radio spectrum, even if the spectrum is licensed for a dedicated technology, is permitted by radio regulation authorities only for radio systems with minimal transmission powers in a so-called underlay sharing approach as illustrated in Figure 4. The underlay sharing realizes a simultaneous uncoordinated usage of spectrum in the time and frequency domain. Thereby techniques to spread the

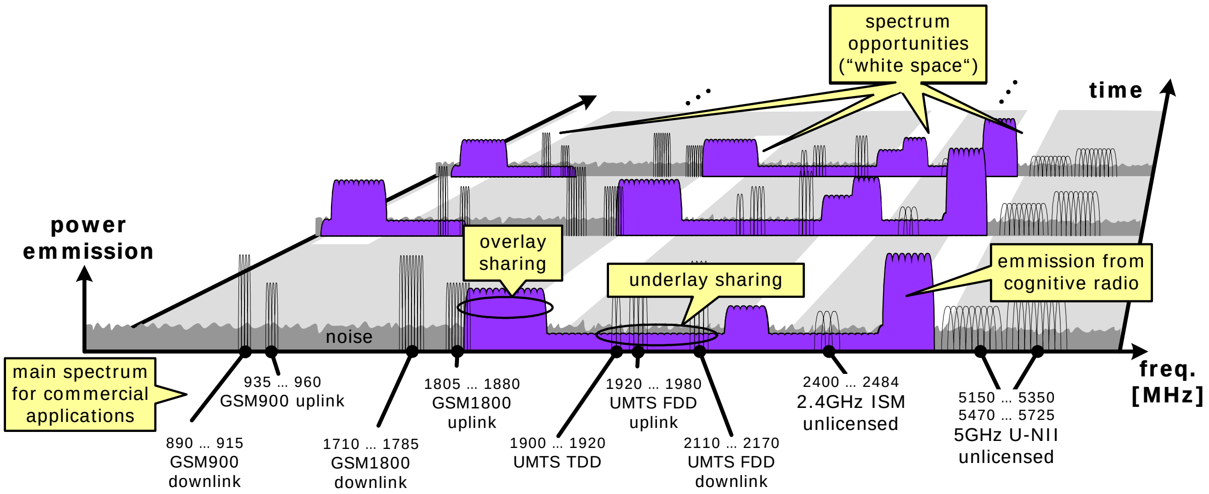

Figure 4: Underlay and overlay spectrum sharing of a frequency agile cognitive radio using spectrum on an opportunistic basis [17].

emitted signal over a large band of spectrum are used so that the undesired signal power seen by the incumbent licensed radio devices is below a designated threshold. Spread spectrum, Multi-Band Orthogonal Frequency Division Multiplex (OFDM) or Ultra-Wide Band (UWB) as introduced below are examples for such techniques. The transmission power is strictly limited in underlay spectrum sharing to reduce the possibility for a potential interference.

The Spectrum Policy Task Group of the FCC suggested in [22] the Interference Temperature Concept for underlay spectrum sharing to allow low power transmissions in licensed (used) bands. The FCC proposes there to allow secondary usage of shared spectrum if the interference caused by a device is below a sufficient threshold. The FCC identifies for this a well defined space between the original noise floor and the licensed signal of the incumbent radios. This space is branded as "new opportunities for spectrum use" [15][22] and it is illustrated in Figure 5. The space refers to the power level of the signals at the receiver in a specific band at a certain geographical location.

Only a small fraction of the radio spectrum is available as open frequency band for unlicensed operation. Nevertheless, these bands have stimulated an immense economic success of wireless technologies like the popular WLAN IEEE 802.11. On the other hand, the actual availability of new spectrum is a seemingly intractable problem. Cognitive radios use flexible spectrum access techniques for identifying under-utilized spectrum and to avoid harmful interference to other radios using the same spectrum. Such an opportunistic spectrum access to under-utilized spectrum, whether or not the frequency is assigned to licensed primary services, is referred as overlay spectrum sharing.

Overlay sharing requires new protocols and algorithms for spectrum sharing. Additionally, spectrum regulation is impacted, especially in case of vertical spectrum sharing as introduced below: The operation of licensed radios systems may not be interfere when identifying spectrum opportunities and during secondary operation in licensed spectrum. DFS is a simple example for how unlicensed spectrum users (IEEE 802.11a) share spectrum with incumbent licensed users (radar stations).

3.2.1.1 Opportunistic Spectrum Usage

Under-utilized spectrum is in the following referred to as spectrum opportunity. The terms "white spectrum" and "spectrum hole" can be used equivalently. To use spectrum opportunities with overlay sharing, cognitive radios adopt their transmission schemes such that they fit into the identified spectrum usage patterns, as illustrated in Figure 4. Thus spectrum opportunities have to be identified in a reliable way. Additionally, their usage requires coordination especially in distributed environments. A spectrum opportunity is defined by location, time, frequency and transmission power. It is a radio resource that is either not used by licensed radio devices, and/or it is used with predictable patterns such that idle intervals

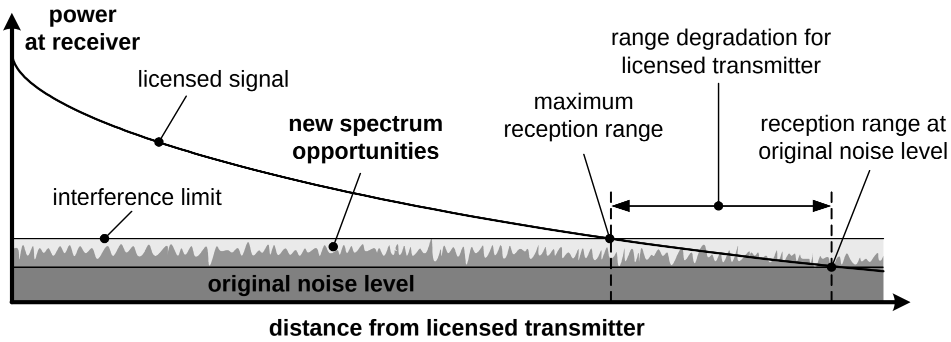

Figure 5: Underlay spectrum sharing corresponding to the Interference Temperature Concept of the FCC [16].

can be detected and reliably predicted. The accurate identification of spectrum opportunities is a challenge, as it depends on the predictability and the dynamic nature of spectrum usage. The frequency and predictability of spectrum usage by primary radio devices is decisive for the success of opportunity identification and the efficiency of its usage by cognitive radios. Therefore, a less frequent and predictable spectrum usage can be regarded as contribution to cooperation as introduced in Section 3.3.

3.2.1.2 IEEE 802.11k

A new type of measurements improving spectrum opportunity identification is developed in the standardization group of IEEE 802.11k [24] which provides means for measurement, reporting, estimation and identification of characteristics of spectrum usage. Spectrum awareness for distributed resource sharing in IEEE 802.11e/k is described in [25] while radio resource measurements for opportunistic spectrum usage on the basis of 802.11k are analyzed in [12]. The improvement of confidence in radio resource measurements as approach to judging reliability in spectrum opportunity identification is discussed in [26].

3.2.2 Vertical and Horizontal Spectrum Sharing

The overlay spectrum sharing with licensed radio systems requires not only fundamental changes in spectrum regulation. Additionally, new algorithms for sharing spectrum are necessary, which reflect the different priorities for spectrum usage of the licensed, i.e., incumbent, and unlicensed radio systems. To reflect this priority, the terms primary and secondary radio systems are often used for the licensed and unlicensed radio systems respectively.

Cognitive Radios will have to share spectrum (i.) either with unlicensed radio systems with limited coexistence capabilities enabling them to operate in spite of some interference from dissimilar radio systems or (ii.) with licensed radio systems designed for exclusively using spectrum. The sharing of licensed spectrum with primary radio systems is referred to as vertical sharing, as indicated in Figure 6, and the sharing between equals as for instance in unlicensed bands is referred to as horizontal sharing. These terms of horizontal and vertical spectrum sharing are first mentioned in [27]. Another example for horizontal spectrum sharing is the usage of the same spectrum by dissimilar cognitive radios that are not designed to communicate with each other directly. These dissimilar cognitive radio systems have the same regulatory status, i.e., similar rights to access the spectrum, comparable to the coexistence of devices operating in unlicensed spectrum. Vertical spectrum sharing promises to have the advantage that neither a lengthy and expensive licensing process nor a re-allocation of spectrum is required.

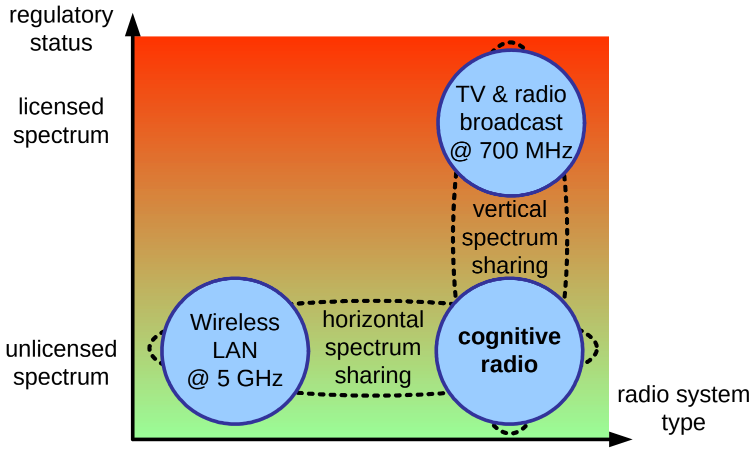

Figure 6: Cognitive radios share spectrum with different radio systems. Depending on regulatory status, vertical or horizontal spectrum sharing is done.

Vertical and horizontal sharing requires the capability to identify spectrum opportunities as introduced above. Cognitive radios are able to operate without harmful interference in sporadically used licensed spectrum requiring no modifications in the primary radio system. Nevertheless, in order to protect their transmissions, licensed radio systems may assist cognitive radios to identify spectrum opportunities in vertical sharing scenarios. This help is referred to as “operator assistance” in the following.

The technology for terrestrial TV broadcasts is currently digitalized. This process will be finalized in the near future (for instance in the US until 2009; in Germany latest by 2010). This digitalization improves the utilization of spectrum, resulting in a reduction of the required spectrum when the number and quality of the TV channels remains unchanged. The usage of the corresponding frequency band is reorganized at the same time in many regulatory domains worldwide. As every broadcast site has to serve a large coverage area, radio transmission is done at high power to guarantee reliable reception throughout the complete coverage area. This implies for many receivers a robustness to interference in case of proximity to the broadcast site, as the signal is received at a higher power than required. Thus reliable operation is possible even if cognitive radios emit some level of interference. Additionally, TV broadcast sites infrequently change their location and the frequencies they are using which simplifies identification of spectrum opportunities.

It is therefore envisioned to allow such unlicensed re-use of the entire TV broadcast band for cognitive radios that scan all TV channels throughout the band and operate only upon identification of spectrum opportunities [18][18]. The working group 802.22 of the IEEE takes up this idea and is working towards the standardization of the unlicensed secondary access to TV bands. The Figure 7 illustrates this scenario: Two adjacent TV broadcasts cites and two independent pairs of communicating cognitive radios are shown. The cognitive radios identify locally under-utilized spectrum, here unused TV channels, as spectrum opportunities. After some knowledge dissemination and negotiation, the pairs of cognitive radios communicate using these opportunities, while frequently scanning the spectrum for signals from primary radio systems.

A licensee may sell temporarily under-utilized spectrum for secondary usage to increase its revenue. Vertical spectrum sharing can be realized in different ways: A beacon signal or busy tone at a foreseen frequency for signalling permission and/or prohibition of secondary operation in licensed spectrum is one approach to vertical spectrum sharing. More complex approaches to vertical sharing are for instance a common control channel [28] or a policy-based secondary usage of spectrum on the basis of spectrum observation [29][30]. The FCC’s proposal [18] identifies three possible techniques how to determine if spectrum is available for secondary usage at a given location:

- A listen-before-talk-based passive sensing to detect the presence of TV signals

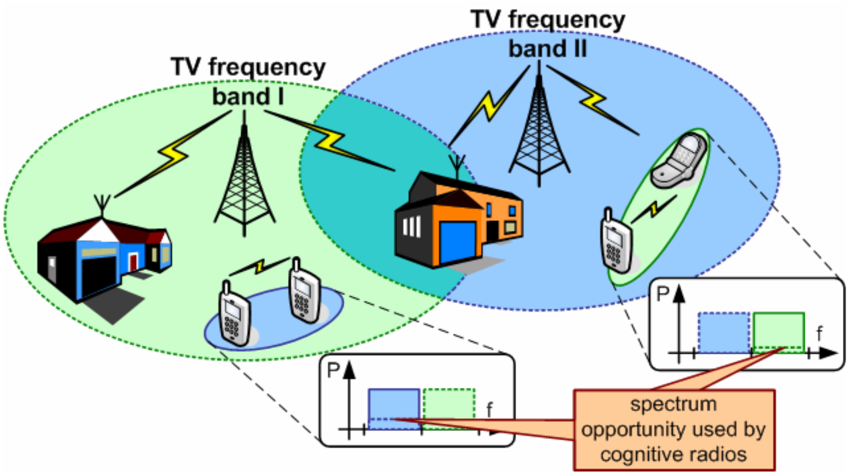

Figure 7: Cognitive radios operating in frequency bands of TV and radio broadcasts. At different locations the cognitive radios identify different frequencies as unused and regard them as spectrum opportunities. This example of vertical spectrum sharing is the basis for IEEE 802.22.

- Introducing a location-based database of used frequencies to check with the help of localization systems whether secondary spectrum usage is allowed
- Using dedicated beacon transmitters that indicate which spectrum is unavailable in a local area

Some concerns against the FCC's proposal are introduced in [31]. Besides others, one concern is that the confusion resulting from the current discussion might discourage the purchase of new digital TVs and might slow down the transition process from analog to digital.

In horizontal sharing, the cognitive radios autonomously identify opportunities and coordinate their usage with other cognitive radios in a distributed way. To avoid chaotic and unpredictable spectrum usage as in today's unlicensed bands, advanced approaches such as "spectrum etiquette" are helpful.

3.3 Coexistence, Coordination and Cooperation

In literature about spectrum sharing, the terms coexistence, coordination and cooperation are often used in different ways. A definition of these terms is given therefore in the following, as these terms are especially important in the context of QoS support.

Means for *coexistence* target at interference avoidance in a distributed communication environment. Consequently, no communication among coexisting devices is required and possible. In case of a less utilized shared spectrum, coexistence capabilities suffice to enable a reliable communication. In the recent years, coexistence has been very successful but is now victim of its own success: Two many often dissimilar radio systems are coexisting in the unlicensed frequency bands like Wi-Fi and Bluetooth. Under such a severe competition for accessing the shared spectrum, no QoS support is possible due to missing coordination. Today's implemented approaches to coexistence have limited interference prevention and their spectrum utilization is very ineffective as coexistence implies only little incentive to conserve spectrum.

Mutual *coordination*, either centralized or decentralized, is required in spectrum sharing to enable the support of QoS. QoS support refers in this context to the exclusive usage of spectrum to a predictable point of time for a certain duration.

Under *cooperation*, altruistic devices delimitate their spectrum usage and carry each others traffic in the hope for benefiting from a potential cooperation when all radios participate. Cooperation comes along with the danger of being exploited by selfish, myopic radios resulting into a disadvantage for the cooperating radios. Cooperation is required in building up one self-configuring network of mutually coordinated radios in a distributed communication environment. The usage of deterministic patterns when allocating spectrum can also be regarded as cooperation. These deterministic patterns help to increase accuracy for other radios for identification of spectrum opportunities and enable a distributed coordination on the basis of observation.

In distributed environments, cooperation can be created and enforce through protocols, either as part of a standard or realized as spectrum sharing etiquette. The enforcement of cooperation is difficult for regulation authorities but may be easier for a license holder.

3.4 Cognitive Pilot Channel (Cognition Enabling Radio Channel) in a Multi RAT Environment

In the context of heterogeneous radio network environment, it is necessary for reconfigurable radio terminals to be able to initiate a new user session, in order to be connected to the most suitable access point of the most appropriate Radio Access Technology (RAT).

In particular after "power on" the mobile does not know which RAT may be the most appropriate or in which frequency bands potential RAT(s) are operating. This last point will be even more critical in the long term when new regulatory approaches to spectrum usage will allow the implementation of Dynamic Spectrum Allocation (DSA) and Flexible Spectrum Management (FSM) (which includes Spectrum Pooling). In this case, the mobile terminal will have to initiate a communication in a spectrum context which is completely unknown due to dynamic reallocation mechanisms. Without any information about the location of RATs within the considered frequency range reachable from the mobile terminal (e.g. 500 MHz ->6 GHz), it is needed to scan the whole frequency range in order to discover the spectrum constellation.

In that context, a Cognitive Pilot Channel (CPC) should provide relevant information (such as frequency bands, available RATs, services, load situation, etc.) to a mobile terminal so as it can initiate a communication session in an optimal way, regarding time, situation and location.

This would allow a number of meaningful advantages from several stakeholder viewpoints:

- It would simplify the selection procedure, avoid a large band scanning,
- The gain for the user would be lower battery consumption,
- It would be an appropriate solution for the implementation of DSA/FSM, hence the advantages for operators and spectrum management regulators, in a dynamically changing radio environment.

The selection procedure using the CPC would consist of the following steps:

- At “switch on”, the mobile listens first to the out band CPC,
- Getting the list of all existing operators and preferred RATs, the mobile selects the most suitable one to camp on.

The information update can be dynamically processed in line with each operator strategy.

3.5 Summary and Conclusion

The different approaches to regulation of spectrum usage which have been introduced in this chapter are summarized in Table 1 and Table 2 in taking the aspect of QoS into account.

In the following Jon M. Peha’s appropriate “Taxonomy for Spectrum Sharing” [32] is refined and extended with the aspect of vertical and horizontal spectrum sharing. His understanding of a cooperative meshed network matches thereby to the cognitive radio network vision as introduced above. The tables differentiate regulation options into primary and secondary spectrum usage. A QoS guarantee always requires some degree of exclusiveness. If a guarantee is not required, primary systems may share spectrum horizontally. Coexistence is less adequate to support QoS while cooperation increases the level of potential QoS. Regulation authorities can delegate the control of spectrum access to one or multiple private entities to enable spectrum trading at secondary markets. A so-called spectrum manager inherits the role of the regulator in this context. Secondary usage might be allowed for underlay or overlay spectrum sharing, provided that secondary radio systems defer from spectrum utilization whenever the license holding primary radios access their spectrum. Secondary radios can try to coexist with primary radios without interfering them in sharing spectrum vertically. Cooperation between secondary and primary radios enables the secondary radios to support QoS with deterministic interruptions. Secondary radio systems are only able to guarantee QoS if the primary radio systems commit themselves not to interfere. This commitment of the licensee introduces trading of spectrum.

In the short term, commercial broadband and cellular networks will require exclusive access to spectrum in order to guarantee QoS to the customers. Restricted secondary spectrum usage and spectrum trading are grades of flexibility to increase the overall efficiency of spectrum utilization. The licensing process itself needs to be accelerated and requires more flexibility to reflect the rapid developments in the market of wireless communication.

In the long term, spectrum used by future wireless broadband systems covering wide areas will most likely be a combination of exclusively accessed spectrum and shared (unlicensed and/or open) spectrum. The exclusively used spectrum enables an issuing of QoS guarantees. The shared spectrum allows an extension of network capacity to provide more services and to increase the number of served customers. Intelligent spectrum sharing algorithms for coordination, as introduced for instance in [29][33][34], improve the efficiency of spectrum usage and extend the radio networks' capabilities to support QoS in using the shared spectrum. The sharing of a common network infrastructure, as for instance introduced in [35], will further facilitate the coordination that is required for QoS support in spectrum sharing.

For indoor, short-range communication at high data-rates, like wireless USB, the advantages of liberalizing spectrum access outweigh its dangers. The cognitive radio approach for flexible spectrum access is ideal for realizing such communication systems: It lies between the two extremes of open and unlicensed spectrum on the one hand, and the "command-and-control" licensing on the other hand. Cognitive radios can be modified to any level of freedom between these two extremes. Due to locally limited operation of

Table 1: Regulation options for primary spectrum usage as refinement of [32].

Regulator controls access	**Licensee controls access**	**Application requirements**
Traditional licensing	Spectrum manager makes guarantees	Guaranteed QoS
Unlicensed band, regulator sets etiquette	Spectrum manager sets etiquette, no QoS guarantee	No QoS support, coexistence, horizontal spectrum sharing
Cognitive radio network, regulator sets protocol	Cognitive radio network, licensee sets protocol	QoS support, cooperation, horizontal spectrum sharing

Table 2: Regulation options for secondary spectrum usage as refinement of [32].

Regulator controls access	**Primary licensee controls access (secondary market)**	**Application requirements**
Not possible	Licensee guarantees QoS	Guaranteed QoS
Unlicensed underlay with opportunistic access	Secondary market with overlay opportunistic access	No QoS support, coexistence, vertical spectrum sharing
Interruptible secondary operation, regulator sets cooperation protocol	Interruptible secondary operation, regulator sets cooperation protocol	Interruptible QoS support, cooperation, vertical spectrum sharing

this application scenario, no tragedy of commons exists and freeing access to spectrum will stimulate innovations and economic success. In distributed environments, policy adaptive cognitive radios provide the necessarily required flexibility and intelligence in spectrum access: Local usage constraints are taken into account while etiquettes enable distributed coordination through cooperation.

The self-organization of cognitive radios will further enhance coverage, capacity, and QoS in wireless communication. Therefore, a flexible regulatory framework is required enabling less-restricted spectrum usage. Operator assistance plays thereby an important role, especially in the field of secondary usage of spectrum and vertical spectrum sharing. Operators can assist in identification of spectrum opportunities and to protect incumbent radio systems. Thus operators might help the cognitive radio network to find an optimal configuration. Cognitive radios will not compete but complement the existing cellular networks operating in licensed frequencies. The development from time-based pricing to service-based revenue models will be further intensified through a further fall in prices for wireless communication.

4. REGULATORY PERSPECTIVES

4.1 Introduction

There are a growing number of regulatory agencies around the world that believe that there is a need for a new approach to spectrum management, spectrum allocation and spectrum utilization [6][35][40][41][42][45][46][47][48][51][53]. The new spectrum paradigm is driven, in part, by the increasingly keen competition for spectrum – a problem common to many parts of the world and to all segments of the communications industry: military, commercial wireless, public safety, etc. This section describes how the advanced radio technologies defined in this White Paper potentially have spectrum management and regulatory implications that may lead to a more effective utilization of spectrum world wide.

4.2 Regulatory Issues to which Advanced Radio Technologies are Applicable

Research and studies conducted under the purview of some administrations have concluded that spectrum management should increasingly depend on the marketplace rather than administrative systems.[1] There are a number of questions associated with the development of a new spectrum management paradigm using SDR and related technologies such as cognitive radio and policy-based adaptive radio. The questions include:

1) To what extent can cognitive radio and policy-based adaptive radio be applied to spectrum management in the unlicensed bands? How much spectrum should be set aside for the unlicensed bands? These are questions that administrations may choose to address.
2) For licensed bands, should national regulators permit cognitive radio access if they wish but not mandate the use of cognitive radio in the band on a secondary use basis? This may be an issue of import to the ITU-R World Radio Conference as well as national regulatory agencies.
3) To what extent can the market be relied upon as a major part of the new spectrum management paradigm?
4) What, if any, broad framework of international rules are needed to promote a new spectrum management paradigm and the use of SDR and related technologies to achieve enhanced efficiency in the use of the spectrum?

The following is a list of some current regulatory issues that are being addressed by various administrations:

- Increasing demands for access to more spectrum
- Requirement for more efficient use of the spectrum
- Spectrum trading
- Dynamic frequency sharing
- Dynamic spectrum management
- Need for a new spectrum management paradigm
- Balance of different types of spectrum management

[1] UK Ofcom, “Radio Spectrum Management Review”; Australian ACA, “Vision 20/20 – Future Scenarios for the Communications Industry – Implications for Regulation; Japan MPHPT, Outline of Report Radio Policy Vision.”

    - "Command and control" – Inflexible frequency assignments
    - "Market mechanisms" – The market manages the spectrum within the constraints of the licenses.
    - "License exempt use" – Nobody controls who uses the spectrum; power constraints or other mechanisms restrict usage to reduce interference.
- Interrelationship of developments in technology, market and regulatory practices.
- Pace of technology development – regulation has to keep up.
- International coordination
- Security (ensure that disruption to communication services can not occur as a result of inadvertent or malicious changes to software in advanced communications devices and systems).
- Interference (ensure that users can use the spectrum assigned to them without disruption).
- Noise temperature
- Certification and conformity issues
- Circulation issues

The advanced radio technologies such as cognitive radio and policy-based adaptive radio are applicable to many of these issues. For the bands designated by administrations for use for unlicensed services, each individual administration is responsible for establishing the rules associated with these bands. Whilst some manufacturers are most interested in the use of SDR because of its potential for decreased costs and quicker time to market, some regulatory agencies have demonstrated interest in SDR, cognitive radio, and policy-based adaptive radio because of the potential for addressing the issues of dynamic spectrum management and dynamic frequency selection to improve the efficiency with which the total spectrum is utilized.

4.3 Requirements

4.3.1 Frequency Band Consideration in the Application of Advanced Radio Technologies

In general, the advanced radio technologies defined herein are applicable to all bands. However, there may be practical limitations such as power, size, weight, and cost and legacy considerations that may restrict the use of these advanced radio technologies. This may be an area of interest for further investigation by various administrations. Some administrations have already started investigating the possibility of increased unlicensed spectrum in which SDR and related technologies could be utilized.

5. CONCLUSIONS

The future of telecommunications is anticipated to be both an evolution of converged mobile communication systems and IP networks; at the same time, cognitive radio capabilities will lead to the ubiquitous availability of a great variety of innovative services, delivered via a multitude of Radio Access Technologies (RATs). To achieve this vision, it is mandatory to identify and embrace the requirements for support of heterogeneity in wireless access technologies; including the requirements and capabilities of different services, mobility patterns, devices, and so forth. The ability of terminals and network segments to seamlessly adapt to changes in the radio environment will be provided through the mechanisms offered by the reconfigurability concept. Moreover, with the use of reconfigurable technologies, a more flexible network architecture can be achieved and programmable network management can be carried out. In the future, network management functions should not only consider the features and capabilities of the actual network elements, but should also include traffic demand, resource and traffic scalability, as well as the cooperation between different networks to efficiently allocate the overall available resources. It is anticipated that, due to the self tuning approach, system performance can be significantly improved. This in turn will help to reduce the deployment and operational cost of networks.

In such context, this white paper tried to present the major reasons and challenges that reconfigurable networks meet it outlined the migration of reconfigurable networks and cognitive radio and set the scene for the basic radio resource management mechanisms needed to embrace their introduction and commercialization. Moreover, since the demand for spectrum gradually increases and will continue to do so in future systems, this paper presented some key-issues with respect to efficiently managing spectrum and brought into view the relevant regulatory perspectives.

In conclusions, future wireless networks with Multi-RAT, multi-frequency, multi-service, multi-function characteristic give NPs the chances for operating the network with high efficiency. Considering the advantages of reconfigurable systems, NPs will be able to plan their network meeting the QoS requirements with reduced Capital of Expenditure (CAPEX). Using the same dimensioning method, at the network management phase, NPs optimize their network resource usage targeting at a maximized QoS level. Moreover, the usage of spectrum will not fluctuate between extreme limts, but be constantly at a rather satisfactory level, giving the opportunity to stakeholders to create, introduce and experience innovative services and applications.

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8. APPENDIX 2: GLOSSARY

Cognitive Radio: A radio or system that senses, and is aware of, its operational environment and employs knowledge representation, automated reasoning and machine learning mechanisms in establishing conducting, or terminating communication or networking functions with other radios. Cognitive radios can be trained to dynamically and autonomously adjust their radio operating parameters accordingly.

Radio control functionality of cognitive radios can be performed through software as in software controlled radios. However, the man-machine interface is replaced in cognitive radios by a set of algorithms that enable the software control to dynamically and autonomously adjust its radio operating parameters (both at the transmitter and at the receiver side).

Frequency Agility: Frequency agility is the ability of a radio to autonomously change its operating frequency to exploit opportunities to use spectrum to optimize use under certain conditions.
Policy: a set of facts and associate rules that specify how a resource (spectrum in the case of this document) may be used.

Policy-Based Adaptive Radio: A radio that is governed by a predetermined sets of rules for behaviour that are independent of the radio implementation regardless of whether the implementation is in hardware or software and both senses and adapts to its environment. The rules define the operating limits of such a radio. The definition and implementation of these rules can be:

- during manufacture or reconfiguration;
- during configuration of a device by the user or service provider;
- during over-the-air provisioning; and/or
- by over-the-air or other real-time control.

A radio is a policy-based adaptive radio if the software control functionality incorporates inputs such as:

- Regulatory policies
- Operational policies
- User policies
- Sensor information
- Available RF bancs
- Propagation data
- Avalable protocols
- Performance requirements
- Information from the radio network infrastructure

Policy Rule: A statement of policy consisting of a set of facts, but not the rules for interpreting. A policy rule has a Selector Description, an Opportunity Description and a Usage Description.

Reconfigurable Radio: A reconfigurable radio is a radio whose hardware functionality can be changed under software control. Reconfiguration control of such radios may involve any element of the radiocommunication network.

Regulatory Policy: A policy that is specified, or likely to be specified by a regulatory authority (such as the FCC or the NTIA in the U.S.A.). Typically, these describe what constitutes valid use of spectrum rather than provide specific instructions to the device on what specific actions to take.
Rule: A statement that describes the logic for interpreting and processing policy. Rules have the form: *condition-implies-action*.

Software Controlled Radio: A software controlled radio is a radio whose radio functionality is controlled by software. Software controlled radios may be considered to be a subset of SDR. A radio can be considered to be a SDR if the radio signal is processed by software; such a radio is not a software controlled radio however, unless this radio signal processing is under software control.

A software controlled radios are a subset of software defined radios, i.e., a radio could be a SDR and not a SCR if the radio incorporates software signal processing of the radio signal but does not incorporate software in the radio control functionality.

Software Defined Radio[2]**:** A radio in which RF operating parameters including but not limited to frequency range, modulation type, or output power can be set or altered by software, and/or the technique by which this is achieved.

> NOTE 1 – Excludes changes to operating parameters which occur during the normal pre-installed and predetermined operation of a radio according to a system specification or standard.
>
> NOTE 2 – SDR is an implementation technique applicable to many radio technologies and standards.
>
> NOTE 3 – Within the mobile service, SDR techniques are applicable to both transmitters and receivers.

Spectrum Overlay: Using adaptive spectrum access techniques to identify underutilized spectrum and to avoid interference conflicts in time, frequency or space with competing spectrum users. Unlicensed spectrum users have used these techniques (e.g., 802.11a Dynamic Frequency Selection) to share spectrum with incumbent licensed users.

Spectrum Underlay: Simultaneous use of spectrum in time and frequency by multiple uncoordinated emitters that takes advantage of modulation techniques such as spread spectrum or ultra-wideband to limit interference between systems. Transmitter power output may be restricted to further limit the possibility of interference. Typically at least one of the emitters is a spread spectrum signal with a large amount of processing gain to insure that the undesired signal power seen by an incumbent licensed user is below a designated threshold.

System Policy: A policy representing dynamic, location specific, or capability based guidance, intended to constrain and influence XG radio behaviors, decisions, and actions. The system policy is likely specified by a system administrator and typically specifies inputs beyond those available in regulatory policy. It can provide specific strategies or instructions to the radio.

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[2] ITU- R Draft New Report, ITU-R M.[IMT.SDR] Report on Software Defined Radio