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Cognitive Radio and Management of Spectrum in a Multi Radio Access Technology Environment

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Abstract- 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, heterogeneity in wireless access technologies; including the requirements and capabilities of different services, mobility patterns, devices, and so forth. Since the demand for spectrum gradually increases and will continue to do so in future systems, this paper present some key-issues with respect to efficiently managing spectrum and brought into view the relevant regulatory perspectives. Moreover, the usage of spectrum will not fluctuate between extreme limits, but be constantly at a rather satisfactory level, giving the opportunity to stakeholders to create, introduce and experience innovative services and applications.

Keywords: Cognitive radio, Radio Access Technologies (RATs), Cognitive Pilot Channel (CPC), Dynamic Spectrum Allocation (DSA).

I. 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* concepts [2], 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.

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 [3].

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 airinterfaces 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.

II. TECHNICAL APPROACH

2.1 Radio Resource and Spectrum Management Approaches

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.

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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 [1].

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 policybased 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 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
o Mental processes of an individual, with particular relation
o Mental states such as beliefs, desires and intentions
o Information processing involving learning and knowledge
o 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. To enable transparency to the consumer, cognitive radios provide besides cognition in radio resource management also cognition in services and applications [7].

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:

o **Frequency Agility** – The radio is able to change its operating frequency to optimize its use in adapting to the environment.

o **Dynamic Frequency Selection** (DFS) – The radio senses signals from nearby transmitters to choose an optimal operation environment.

o **Adaptive Modulation** – The transmission characteristics and waveforms can be reconfigured to exploit all opportunities for the usage of spectrum.

o **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.

o **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.

o **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.

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. Cognitive radios are also referred to as “spectrum agile radios” to indicate an emphasis on dynamic spectrum usage. 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; carrierfrequency, 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 [8].

2.3 Policy Based Adaptive Radio

As noted by the FCC, 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[8].

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 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.

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 [9].

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

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 E2R 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 Figure 1. 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[10].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 1, conceptually we allow DNPM partially cover the functions of IORM, IOEM and GSAM.

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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 [11].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.

1. *Radio Spectrum Regulation*

3.1.1 Scope of Radio Spectrum Regulation

The regulation of radio spectrum has different characteristics:

o **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.

o **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 underutilized licensed spectrum through intelligent radio systems is a different kind of sharing licensed spectrum and will be discussed below.

o **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.

o **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 "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:

o An adequate QoS should be possible to all radios depending on the supported applications

o No radio should be blocked from spectrum access and transmission for extended durations

o Spectrum management policies and standards should not slow down innovations in the economically significant, but rapidly changing, communication sector

o The limitedly available spectrum should be used efficiently, including special re-use of spectrum
and solving the "tragedy of commons"

o Spectrum can used in a dynamically adaptive way, taking the local communication environment
like spectrum usage policies into account

o The costs of devices should be not increased significantly through techniques prescribed by regulation

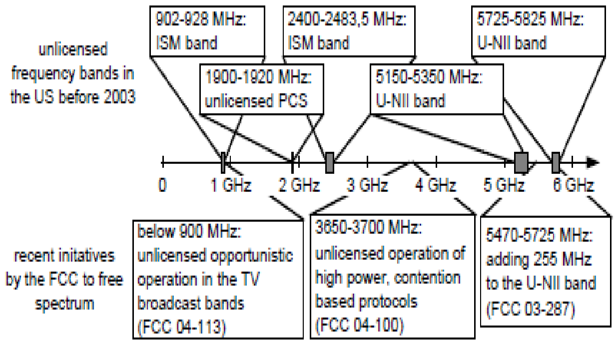

Figure 3: Spectrum for unlicensed operation in the US and recent initiatives of the FCC to free spectrum with a reference on the corresponding document.

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.

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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 TV bands in the US are often under-utilized, the FCC proposed in 2004 to allow unlicensed systems the secondary usage of this spectrum.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 [12].

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.

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 [13].

3.2 Spectrum Sharing and Flexible Spectrum Access

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 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 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” and it is illustrated in Figure 4 . 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.

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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).

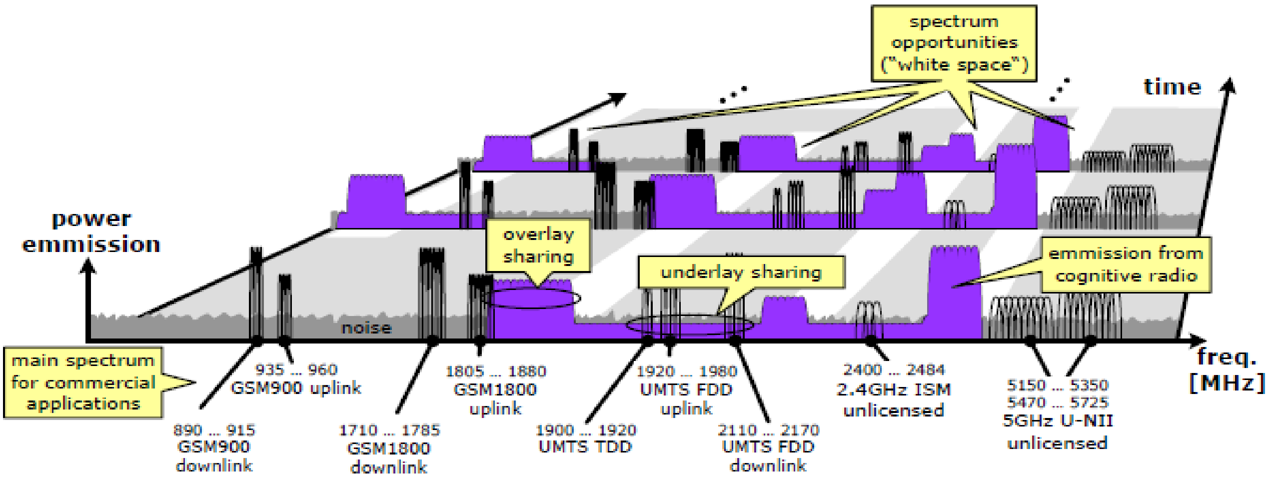

Figure 4: Underlay and overlay spectrum sharing of a frequency agile cognitive radio using spectrum on an opportunistic basis [17].

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 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.

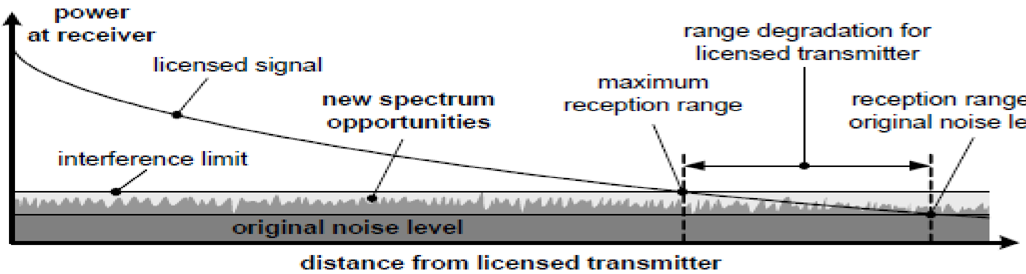

Figure 5: Underlay spectrum sharing corresponding to the Interference Temperature Concept of the FCC [16].

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 while radio resource measurements for opportunistic spectrum usage on the basis of 802.11k are analyzed in. The improvement of confidence in radio resource measurements as approach to judging reliability in spectrum opportunity identification is discussed in [13].

3.2.2 Vertical and Horizontal Spectrum Sharing

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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. 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.

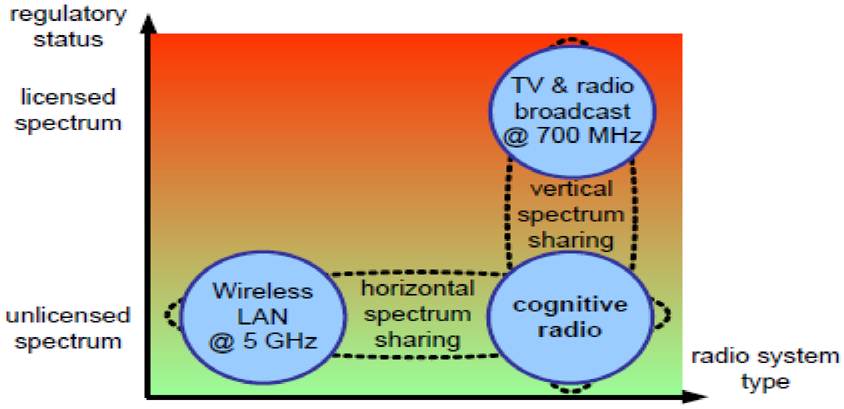

Figure 6: Cognitive radios share spectrum with different radio systems. Depending on regulatory status, vertical or horizontal spectrum sharing is done.

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. 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 signaling 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 [14] or a policy-based secondary usage of spectrum on the basis of spectrum observation. The FCC's proposal identifies three possible techniques how to determine if spectrum is available for secondary usage at a given location:

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

o Introducing a location-based database of used frequencies to check with the help of localization systems whether secondary spectrum usage is allowed

o Using dedicated beacon transmitters that indicate which spectrum is unavailable in a local area

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 [15].

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.

3.5 Summary

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" 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, 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, will further facilitate the coordination that is required for QoS support in spectrum sharing.

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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

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 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.

III. 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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