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Cognitive Radio – Trends and Research Challenges

STEFAN MANGOLD, ANDREAS JAROSCH AND CLAUDE MONNEY **Cognitive radio is a revolutionary technology that aims for remarkable improvements in efficiency of spectrum usage. It will change the way the radio spectrum is regulated, but also requires new enabling techniques such as improved spectrum sensing and dynamic spectrum assignment.**

These techniques, together with the software definition for reconfigurable radios, will enable an early and successful roll-out of cognitive radio, which can affect many traditional businesses. In this article, we discuss the enabling techniques, summarise trends in research, regulation and standardisation, and identify open research problems.

It is exciting to experience the emergence of the information society in our daily life. Access to the Internet has become an everyday custom, and the successful roll-out of wireless communication networks is opening up previously unknown advancements in education, healthcare, public safety, and many other aspects. With such a growth in demand for communication services, it is no surprise that the "digital divide" between people remains a significant challenge. There is a vast gap in opportunities between individuals who routinely use the Internet and wireless communication services, and those who do not. This is referred to as digital divide, a problem that public and private institutions are approaching together in various ways. For example, Swisscom promotes initiatives such as "Help Point" for educating citizens and "School Net" to support broadband access to the Internet for every school. With these initiatives, people of every age are learning more about established and future communication services, and are encouraged to use them to their benefit. With such initiatives being evidently successful, the information society will continue to emerge, and demand for wireless communication services will grow. Therefore, future generation wireless networks are considered necessary for the support of emerging services with their increasing requirements. Significant amounts of radio spectrum will be needed at dynamically changing times and locations.

Spectrum Scarcity

This need for radio spectrum is a problem. The electromagnetic radio spectrum is a precious natural resource. Despite the recent advancements in communication technology such as Multiple Input Multiple Output (MIMO) antennas, third generation cellular networks and their integration with wireless Local Area Network (LAN) IEEE 802.11™, it is difficult to foresee how a truly connected information society can be established, given today's regulation of radio spectrum. With the existing regulatory framework, access to radio spectrum is frustratingly difficult. Large parts of the spectrum are allocated to licensed radio services in a way that is often referred to as command-and-control. Open access to most of the radio spectrum is only permitted for radio systems with minimal transmission powers in a so-called underlay sharing approach. Ultra wideband is an example of underlay sharing. The overlay sharing approach, i.e. the free access to open spectrum, is generally not permitted. Only some fractions of the radio spectrum, the unlicensed bands, are openly available. Unlicensed bands cover a very small fraction of the entire radio spectrum. However, throughout the last decade, these bands enabled a variety of enormously successful wireless technologies and services, among others the popular wireless LAN IEEE 802.11™. On the other hand, the actual availability of spectrum for new services is a seemingly intractable problem. The complicated and time-consuming radio regulation process remains an overarching reality, and hence hinders innovation and the establishment of new technologies. As a result, large parts of the radio spectrum are not efficiently used. Measurements show that less than 20% of the licensed radio spectrum is in use at any location and at any given time. The existing radio regulatory regime is too complex to handle the increasingly dynamic nature of emerging services.

Cognitive Radio as a Solution

The cognitive radio approach promotes a technology as well as changes in radio regulation to overcome the existing barrier. Cognitive radios improve the efficiency of spectrum utilisation. They typically operate at frequencies that were originally licensed to other (incumbent, primary) radio services, and in addition at available frequencies in unlicensed bands. A cognitive radio, however, is not necessarily restricted to the existing licensing for primary radio systems, and operates at any unused frequency, whether or not the frequency is assigned to licensed, primary services. This is referred to as overlay sharing, which obviously requires new protocols and algorithms for spectrum sharing. It also involves important regulatory aspects: Cognitive radios must not interfere with the operation of licensed radio systems when identifying spectrum opportunities and during operation in licensed spectrum. This is explained in more detail in the following paragraphs, where we discuss enabling technologies and trends, and required changes in spectrum regulation. As a first step, the recently started activities on unlicensed re-use of TV broadcast channels are discussed. Further, we provide a characterisation of what cognition means in our context.

Enabling Techniques and Trends in Regulation

Motivated by recent achievements in the area of software defined radio, in 2003 the US regulator Federal Communications Commission (FCC) issued a public notice, indicating support for cognitive radio. This attracted industry together with the research community to further discuss how to ease current regulatory constraints. As with the Internet Protocol (IP), with Mobile Ad Hoc Networks (MANET), ultra wideband, and other innovations for wireless communication, it is however again the defence community that is the driving force for the realisation of cognitive radio. Their natural focus is the military domain, but it is an often stated objective that innovative concepts will find their way into the commercial sector. The Defence Advanced Research Projects Agency (DARPA) in the US established the NeXt Generation Communications (XG) program, which aims at developing a de-facto standard for cognitive radio, and dynamic spectrum regulation. One of the DARPA XG objectives is to consider off-the-shelf products and existing standards, in order to keep development costs reasonably low, and to involve the commercial industry sector from the beginning. This is also indicated by the publicly issued request-for-comments, where DARPA XG is seeking feedback from interested industry.

The FCC defines cognitive radios as radio systems that continuously perform spectrum sensing, dynamically identify unused ("white") spectrum, and then operate in this spectrum at times when it is not used by incumbent radio systems. Strictly following FCC's definition, modern wireless LANs could already be referred to as cognitive radios: Modern wireless LAN IEEE 802.11™ devices operate with a listen-before-talk spectrum access and with dynamically changing frequencies and transmission power. However, such existing standards provide only a subset of the required techniques for cognitive radio, and do not cover the full range of objectives for efficiently re-using the licensed spectrum. DARPA XG therefore goes beyond the FCC approach, and develops a framework for machine-understandable policies that would enable cognitive radio devices to make intelligent decisions. More details about this highly innovative approach are discussed later in this article. It should be noted that there are projects in the European "6th Framework Programme for Information Society" that aim at developing concepts similar to XG.

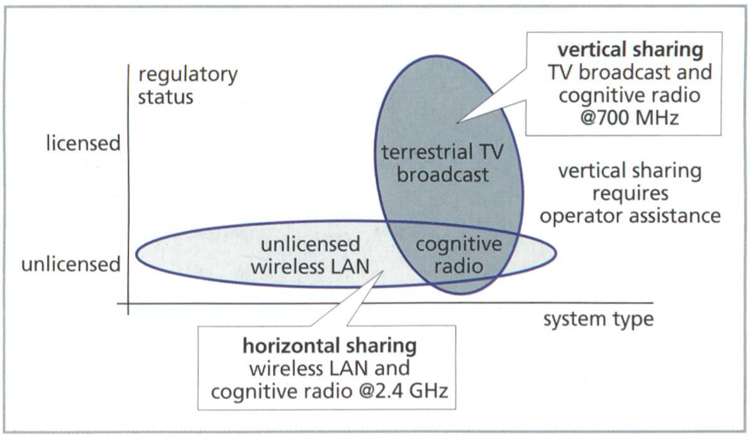
With the cognitive radio approach, technologies are improved for spectrum scanning and for most reliably identifying and representing spectrum opportunities. Feature detectors that identify characteristics of the radio signals emitted by incumbent systems will help to detect spectrum usage. Protocols are developed for disseminating knowledge about spectrum usage, and algorithms are developed for using spectrum in a shared environment, either in horizontal or vertical sharing, which is explained in the next section.

Spectrum Regulation Changes

Cognitive radio means not only improving technology, it also requires fundamental changes in the way radio spectrum is regulated. Figure 1 illustrates the relation of horizontal and vertical sharing, which are the main levels of spectrum sharing we are focusing on. Depending on the regulatory status of the radio systems that operate in the same spectrum, cognitive radios share spectrum with radio systems that are designed to access spectrum with different priorities. To reflect this priority, licensed and unlicensed radio systems are sometimes referred to respectively as primary and secondary radio systems. Either licensed radio systems designed to operate in exclusively assigned bands, or unlicensed radio systems designed to live with some interference from dissimilar radio systems may share spectrum with cognitive radios. Figure 1 indicates that sharing with primary radio systems is referred to as vertical sharing, and sharing with secondary radio systems is referred to as horizontal sharing. Apparently, dissimilar cognitive radios that are not designed to communicate with each other may also share the same spectrum. This is another common example of horizontal sharing, because the dissimilar cognitive radio systems have the same regulatory status, i.e. similar rights to access the spectrum.

For vertical and horizontal sharing, a cognitive radio must be capable of detecting under-utilised spectrum, i.e. spectrum opportunities, also referred to as "white space" spectrum. Typically, spectrum opportunities change over time and vary depending on the location of the cognitive radio. To protect the licensed radio systems and their services in vertical sharing scenarios, other radio systems such as operated by Swisscom may assist cognitive radios in identifying spectrum opportunities. Hence, regulation would be changed towards dynamic spectrum assignment. Even more flexibility and a higher level of freedom could be envisioned for horizontal sharing, eventually with less predictable outcome. Here, the cognitive radios would identify opportunities autonomously. To avoid chaotic and unpredictable spectrum usage as in today's unlicensed bands, advanced approaches such as "spectrum etiquette" and "value-orientation" are helpful. Spectrum etiquette is today already discussed for existing unlicensed bands in various regulatory bodies and standardisation groups.

Fig. 1. Horizontal sharing and vertical sharing. Depending on the regulatory status of the incumbent radio systems, cognitive radios share spectrum with different types of systems.



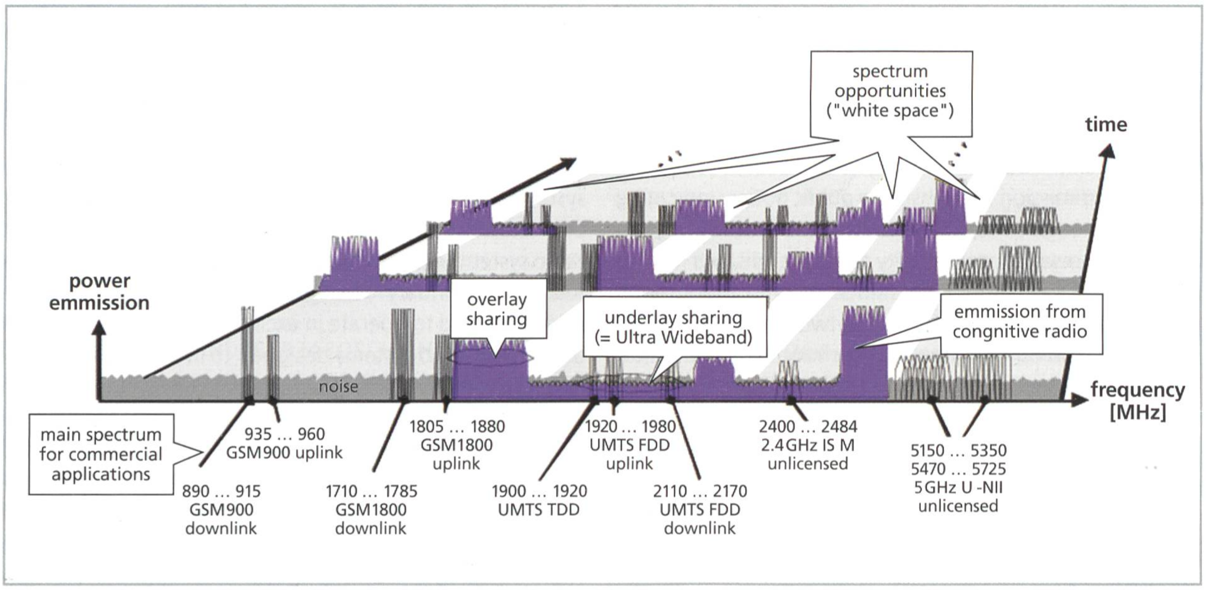
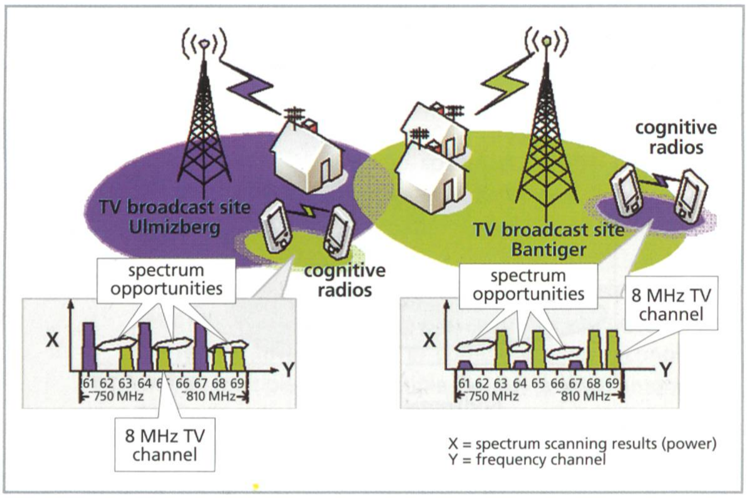


Fig. 2. Opportunistic spectrum usage by cognitive radios in a wide range of frequencies.

To guarantee fairness and efficiency, the way a cognitive radio makes decisions must be traceable for regulators. In traditional radio systems, algorithms for spectrum management, such as power control and channel selection, are implemented in many radio devices, but are vendor-specific and not visible to the outside world, for example regulators. As a result, today's standards and regulation have to drastically constrain parameters like power levels and frequency ranges for operation, to achieve a minimum level of interoperability, spectrum efficiency, and fairness in spectrum access. The unique characteristic of cognitive radios on the other hand is that their radio resource management algorithms are weakly constrained by standards or regulation. This implies that the entire algorithms for decision-making in spectrum management have to be visible to the outside world, and control mechanisms for regulators have to be developed. For this purpose, DARPA XG proposes to realise such a control mechanism with a machine-understandable policy language. We discuss more details on this unique approach below.

Figure 2 illustrates the full vision of overlay sharing and open spectrum. Unlike underlay sharing of radio systems like ultra wideband, cognitive radios are permitted to share spectrum in an overlay approach: Transmission powers of cognitive radios exceed ultra wideband limits and may be even similar to the powers of incumbent radio systems. This clearly requires intelligent decision-making and/or operator assistance for protecting licensed services, and mitigating interference.

Fig. 3. Cognitive radio in the TV band: At different locations, the cognitive radio devices detect different frequency channels as free and interpret them as opportunities for their own communication. This example for vertical spectrum sharing is discussed at IEEE 802.22™ standardisation.



Unlicensed Re-Use of TV Broadcast Channels

The terrestrial TV broadcast band is currently in the process of being reorganised for the roll-out of digital video broadcast. This change is pursued in parallel in many regulatory domains worldwide. However, even with digital broadcast, high transmission powers for large coverage areas per broadcast site are used to guarantee reliable reception throughout the coverage area. This implies that many TV receivers for example close to the broadcast sites will be served with unnecessarily high power, and can therefore reliably operate even if some level of interference is emitted by cognitive radios at close proximity. It is therefore envisioned to allow such 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. This is proposed for IEEE 802.22™, an emerging radio standard for access networks, designed to operate in the TV broadcast channels. Figure 3 illustrates this scenario: Shown are two adjacent TV broadcast sites and two independent pairs of cognitive radio devices that re-use parts of the spectrum for their own communication. Locally unused TV channels are identified as spectrum opportunities, and after some knowledge dissemination and negotiation, the pairs of cognitive radio devices communicate by using these opportunities. During their active communication, cognitive radios continue to scan the spectrum from time to time for signals from primary radio systems, i.e. the TV broadcast signals, in case the scenario should change.

What makes a Radio "Cognitive"?

Ever since Joseph Mitola established the phrase "cognitive radio" in his thesis, many definitions of what a true cognitive radio may look like have been discussed in literature. This variety of diverse understandings often leads to confusion, and the many promises moreover lead to high expectations about what is achievable with the cognitive radio approach. Our vision of cognitive radio builds on the DARPA XG vision. As discussed before, a cognitive radio is typically built on a software-defined radio, and can be defined as a wireless communication system that is aware of its environment. According to Webster's dictionary, cognition refers to an act or process of knowing, including awareness, recognising, judgment, and reasoning. Such actions can be realised at various levels of detail. Recent developments in the area of machine-learning, semantic web, and machine-understandable knowledge representation allow the efficient implementation of a cognitive radio in the form of a so-called reasoner. The reasoner makes the actual decisions on how to share spectrum. A reasoner is a software process that uses a logical system to infer formal conclusions from logical assertions. It is able to formally prove or falsify a hypothesis, and is capable of inferring additional knowledge. The so-called first order predicate logic is the simplest form of a logical system considered to be useful for such a reasoner. As a simple example, a reasoner may be fed with the knowledge ("all cognitive radio devices are capable of operating at frequencies below 3.5 GHz"). A statement ("white space at 2.0 GHz") would enable this reasoner to infer ("spectrum usage permitted at 2.0 GHz"). This example can easily be extended to a more complicated scenario where knowledge about the history of spectrum usage at this particular frequency, or about licensed radio systems expected to operate there, would be included.

However, inferring statements from other statements, as illustrated in the example, requires a structured and machine-understandable knowledge base for representing knowledge about radio communication. Such a knowledge base has to be constructed by human domain experts, before the machines will be able to interpret, consume, reuse, and eventually extend the knowledge. For this, semantics are needed to define truth and valuations – so-called radio semantics. To construct radio semantics is one of the key research problems to be solved.

Knowledge must be represented in a machine-understandable way, using languages such as the Web Ontology Language, abbreviated as "OWL". OWL is a rich language based on the Extendable Markup Language (XML), that allows not only first-order logics, but also higher-order, class-based reasoning. With this approach, the decision-making, i.e. the algorithms will become traceable, which is important for the application of cognitive radio: Only radio systems whose behaviour is traceable for example during certification, should be granted the freedom to use the licensed spectrum openly, in overlay sharing.

Conclusion

Extending the availability of today's radio spectrum is a natural interest of nationwide operators. With a more flexible regulatory framework, cognitive radios will improve coverage, capacity, and quality of service of future radio networks. Operator-assisted cognitive radios can radically enhance the efficiency of spectrum usage. The novel cognitive radio approach 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 radio can be modified to any level of freedom between these two extremes. The chosen level depends on the constraints that regulators want to keep in order to coordinate the spectrum. With cognitive radio, spectrum assignment and licensing will become more dynamic. Greater flexibility in responding to emerging demands of the information society, as well as to market demands, will be the result. Whereas initial work on cognitive radio was focusing on defence scenarios, European and US regulators and standardisation groups are now putting emphasis on cognitive radio for the commercial sector. This will have an effect on the way spectrum is coordinated, and how it will be assigned to wireless communication services in the future.

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