Cognitive Communications

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INTRODUCTION

The demand for wireless broadband applications is continuously increasing. Two key technologies of this (r)evolution are Software Defined Radio (SDR) and Cognitive Radio (CR): they are expected to provide more efficient management of radio resources and to improve re-usability of equipment. Radio spectrum is an important and natural resource shared by various types of wireless services. It can be repeatedly re-used, if certain technical conditions are met. In particular, radio spectrum can simultaneously accommodate a limited number of users. Currently, spectrum regulatory framework is based on static spectrum allocation and assignment policy (ITU, 2008).

Nevertheless, related radio spectrum observation surveys have proved that most of the allocated spectrum is not fully used (FCC, 2002; FCC, 2003, SSC, 2005). The measurements of the Federal Communications Commission (FCC) in several cities (e.g. Atlanta, New Orleans, and San Diego) in 2002 revealed that there are large variations in the intensity of spectrum use below 1 GHz. Similar spectrum measurements conducted in Europe (i.e. Germany, Spain, Netherlands, Ireland, France, Czech Republic) show higher spectrum occupancy if compared to USA, but still rather low, e.g. 32% for the band 20-3000 MHz in Aachen area, Germany. (Steadman et al., 2007; Wellens & Mähönen, 2009; Lopez-Benitez & Casadevall, Valenta et al., 2010). The solution to this inefficacy spectrum usage can be represented by the CR technology, as depicted in details in the following sections.

The remainder of this article is organized as follows. First, the background section reviews the story and the state-of-art of the CR technology. Then, dynamic spectrum access methodologies are discussed in details, and the cognitive cycle is introduced along with the benefits achievable with CR networks. Finally, the business case criteria are highlighted, while future directions and conclusions summarize the key topics of this article.

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BACKGROUND

CR is the technology allowing radio equipment to obtain knowledge of its radio environment and to dynamically adjust its operational parameters in order to improve its performance (Mitola & Maguire, 1999; Drozd et al., Mitola, 2000). SDR technologies are a natural platform on which to build in new cognitive features: SDR functionality is seen as the foundation for development of CR functionality. In particular, SDR is a radio communication system where components that in the past have been typically implemented in hardware (e.g. mixers, filters, modulators/demodulators, detectors, etc.) are instead implemented by means of software.

Cognitive radio as a new concept was firstly introduced by Joseph Mitola and Gerald Maguire in (Mitola & Maguire, 1999) where CR is presented as an extension of SDR enhancing flexibility of personal wireless services. Cognitive radio architecture as an integrated agent for SDR in the intersection of personal wireless technology and computational intelligence is further developed in Mitola's Doctoral Dissertation (Mitola, 2000). A CR is assumed to be a fully re-configurable radio device that can cognitively adapt itself (Haykin, 2005):

1. To the communications requirements of its user,
2. To the radio frequency environment in which it is operating,
3. To the various network and regulatory policies.

CR is an intelligent wireless communication system that is aware of its surrounding environment 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 in real time, with two primary objectives: highly reliable communications whenever and wherever needed and efficient utilization of radio spectrum (Matinmikko et al., 2008). Fully capable CR is unlikely to be achieved in the next years, but certain CR features will be gradually implemented in radio equipment in the next future.

Cognitive radio using opportunistic spectrum access has the possibility to improve spectrum utilization efficiency and in perspective to allow next generation mobile networks access radio spectrum bands (Berlemann et al., Haykin, 2005; Akyildiz et al., 2006). Although cognitive radio is an interesting and disruptive concept promising significant improvements in radio spectrum usage efficiency, it still faces a lot of research challenges in its way from concept to practical implementation in everyday use, as shown in the following.

DYNAMIC SPECTRUM ACCESS

Active coexistence of primary licensed and secondary users in space, time and frequency domain impose unique challenge to the spectrum management in cognitive radio systems. Basic spectrum management functions are spectrum decision, spectrum sharing and spectrum mobility (Akyildiz et al., 2009). Spectrum access models can be categorized as exclusive use and shared use models. Characteristic of dynamic exclusive model is that radio spectrum is used exclusively by one system in a determined spectrum hole. In order to improve spectrum efficiency some level of flexibility is introduced. At different points in time, the cognitive users can access the radio spectrum under defined rules. Flexibility helps licensees to put spectrum to its most valuable use with the most effective technology, without waiting for a regulator's permission. Two approaches have been proposed under this model: spectrum property rights and exclusive dynamic spectrum allocation (Berlemann et al., 2005). Primary users having spectrum property rights can have various levels of flexibility. They can use assigned radio spectrum however they wish, or they could be restricted to specific radio service or technology. Licence is assigned for temporary basis with long duration or for permanent usage. Using spectrum property right licensee of spectrum can trade, lease or borrow parts of spectrum on secondary spectrum markets to cognitive radio user. Economy and market forces will therefore play an important role in driving toward the most profitable and efficient use of this limited resource (Benedetto & Tedeschi, 2013).

The second approach, exclusive dynamic spectrum allocation aims to improve spectrum efficiency exploiting the spatial and temporal traffic statistics of different services. Based on observed traffic statistics, spectrum is shared between different services. In a given region and at the given time, spectrum is assigned to services on exclusive use, but this allocation varies at a much faster scale than the static policy. Dynamic spectrum allocation can take advantage of daily user's migration from residential to business areas, or day and night variations of usage statistics. Furthermore, governmental and emergency applications have exclusive access to large portions of radio spectrum which are rarely used. This radio spectrum can be also used for some commercial application under dynamic spectrum allocation model.

In shared use spectrum access model, the radio spectrum can be simultaneously used by a primary user and a secondary user, if satisfying interference constraint. In this model, unlicensed users can opportunistically access the radio spectrum if it is not occupied or fully used by primary users. Licensed spectrum is consequently opened to secondary users, while limiting the interference observed by primary users. Interference constraints for secondary users have to be defined carefully in order to allow primary users to operate without noticeable reduction of service quality. Underlay or interference avoidance model allows concurrent transmission of primary and secondary users in ultra wideband fashion. The transmit power of the secondary user is limited so that the generated interference is below the noise floor for the primary user. Due to power constraints systems using underlay model can be used only for short-range communication. By spreading transmitted power over ultra-wide frequency band (UWB), secondary users can achieve high data rates on short distances. In the spectrum overlay model, a primary user receives an exclusive right to spectrum access.

However, if the spectrum is not utilized at a particular time or frequency, it can be opportunistically accessed by secondary user. Cognitive radio opportunistically communicates in a non-intrusive manner over the spectrum holes. In particular, Figure 1 reports an illustration of the meaning of spectrum hole in space, while Figure 2 relates to the spectrum holes in frequency and/or time domains.