Impact of Cognitive Radio on Future Management of Spectrum
(Invited Paper)

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Abstract—Cognitive radio is a breakthrough technology which is expected to have a profound impact on the way radio spectrum will be accessed, managed and shared in the future. In this paper I examine some of the implications of cognitive radio for future management of spectrum. Both a near-term view involving the opportunistic spectrum access model and a longer-term view involving a self-regulating dynamic spectrum access model within a society of cognitive radios are discussed.

I. INTRODUCTION

Spectrum availability in current wireless communication systems is decided by regulatory and licensing bodies. The mainstream spectrum management approach, adopted around the world, is based on a static spectrum allocation model known as Command & Control. In this model the available radio spectrum is divided into fixed and non-overlapping blocks, separated by so-called guard bands, assigned to different services and wireless technologies. These blocks are then licensed for exclusive use to carriers, radio and TV broadcasters, specialised mobile radio operators, the military and public safety applications. Equivalent Isotropically Radiated Power (EIRP) and out-of-band emission (i.e interference to neighbouring frequencies) within each band are rigidly defined in the licences’ terms. Regulation takes care of protection against interference and provides a limited support for coexistence capabilities.

Static spectrum assignment combined with the phenomenal growth in demand for spectrum are the reasons behind the commonly shared feeling of spectrum scarcity. Cognitive radio (CR) [1], [2], [3] is currently considered as one of the most promising solutions to the aforementioned scarcity problem by enabling a highly dynamic, device-centric spectrum access in future wireless communication systems. A CR can adapt the operation parameters of its radio (frequency band, modulation, coding etc) and its transmission or reception parameters on the fly based on cognitive interaction with the wireless environment in which it operates.

Advances brought about by cognitive radio technology and software-defined radio (SDR) not only hold great promise for a much more efficient dynamic access to spectrum, they are also driving and enabling radically new models of spectrum management. In the US FCC (Federal Communications Commission) proposed to allow opportunistic access to TV bands by cognitive radios already in 2004 [5]. Prototype cognitive radios operating in this mode have been put forward by Philips, Microsoft [8] and Motorola. Furthermore, the emerging 802.22 standard for cognitive radio access to TV bands [9], [10] is at its final stage of development. Adopting a more cautious approach, the UK regulator, Ofcom (Office of Communications), initially refrained from allowing license-exempt operations of cognitive radio [6]. However, in what is potentially a radical shift in policy, in its recently released Digital Dividend Review Statement [7] Ofcom is proposing to “allow licence exempt use of interleaved spectrum for cognitive devices” [7]. Furthermore Ofcom has “decided not to set aside any of the digital dividend exclusively for licence-exempt use”, arguing that “the opportunity cost of setting aside spectrum just for licence-exempt use would be high, and the additional benefits would be limited given the prospects of cognitive access to interleaved spectrum” [7].

With both the US and the UK adapting the opportunistic spectrum access (OSA) model we can expect that, if successful, this new paradigm will become mainstream in the toolbox of spectrum regulators worldwide. However, future implications of cognitive radio may go well beyond the adaptation of the OSA model. In the long run the advanced capabilities of cognitive radios may allow the Command & Control spectrum management model to be entirely replaced by a radically new dynamic spectrum access model within a society of cognitive devices. In this model cognitive and highly reconfigurable wireless devices self-regulate their access and sharing of spectrum on behalf of the users, based on a minimum set of imposed policies and through a continuous process of communications, negotiation, trading and cooperation.

The aim of this paper is to examine in some detail such future modes of spectrum management which are both driven and enabled by the emergence of cognitive radio and technolo-
gies such as software-defined radio [3] and spectrum pooling [20].

The rest of this paper is organised as follows. Since the concept of cognitive radio means different things to different people, we provide in section II a definition of CR which will be used through the rest of the paper. Section III describes and critically explores opportunistic access with cognitive radios, with particular emphasis given to cognitive operation in UHF/VHF TV bands. In section IV we examine the paradigm of dynamic spectrum access with cognitive radio, and put forward the notion of a self-Regulatory access model, which shows interesting analogies with the way pedestrian traffic is self-regulated in our societies. We conclude this paper in Section V with conclusions.

II. DEFINING COGNITIVE RADIO

The term cognitive radio (CR) was first introduced by Mitola [1] as “the point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communication to: (a) detect user communications needs as a function of user context and (b) to provide radio resources and wireless services most appropriate to those needs”. Recently the term cognitive radio has been used in a narrower sense for radio systems that have adaptive spectrum awareness. The FCC, for example, defines it in the following way [5] (a similar definition is also used by Ofcom):

“A Cognitive Radio (CR) is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. The majority of cognitive radios will probably be SDR (Software Defined Radio) but neither having software nor being field programmable are requirements of a cognitive radio.”

From the above it can be seen that there is no unique definition for cognitive radio and depending on the focus (e.g. users requirements versus system requirements) and applications different definitions can be put forward. The two main characteristics that come forward in most definitions, however, are reconfigurability and intelligent adaptive behaviour.

In the rest of this paper we shall adopt the following definition:

A cognitive radio is an autonomous radio that can intelligently adapt its operational characteristics (frequency, waveform, modulation, power, antenna) on the fly, in response to changes to its electromagnetic environment while complying with spectrum policies, with the aim of optimally meeting user’s requirements for wireless access.

In the above by intelligent adaptive behaviour we mean the ability to adapt without being a priori programmed to do this, i.e. via some form of learning. For example, a handset that learns a radio frequency map in its surrounding could create a location-indexed RSSI vector (Latitude, Longitude, Time, RF, RSSI) and uses a machine-learning algorithm based on which it switches its frequency band or base station as the user moves [2]. Furthermore, the term ‘radio’ is taken to mean any system that communicates with other systems via a modulated signal within the radio frequency spectrum.

From the above definition it follows that cognitive radio functionality requires the following capabilities:

- **Flexibility and agility**: the ability to change the wave-form and other radio operational parameters on the fly. This is to a limited extent possible with the current multi-frequency multi-access radios. However, full flexibility become possible when cognitive radios are built on top a software-defined radio. An SDR is a radio in which the properties of carrier frequency, signal bandwidth, modulation and network access are defined by software. In addition to SDR, another important requirement to achieve flexibility, which is often overlooked, is reconfigurable and/or wideband antenna technologies to support wide-band spectrum agility.

- **Sensing**: the ability to observe and measure the state of the environment, including spectral occupancy. Sensing is necessary if the device is to change its operation based on its current knowledge of Radio Frequency (RF) environment.

- **Learning and adaptability**: the ability to analyse sensory input, recognise patterns and modify internal operational behaviour based on the resultant analysis of the new situation, not only based on pre-coded algorithms and heuristics but also as a result of a learning mechanism. The IEEE 802.11 MAC layer allows a device to adapt its transmission activity to channel availability that it senses. However, this is achieved using a pre-defined listen-before-talk and exponential backoff algorithm, and so an 802.11 device is not cognitive.

In addition to the above core abilities the operation of a cognitive radio often requires location awareness in order to be able to respond to spatially variant regulatory policies or spatially variant spectrum availabilities.

III. OPPORTUNISTIC SPECTRUM ACCESS WITH COGNITIVE RADIO

Cognitive radio technology is being intensively researched as a key enabler for the opportunistic spectrum access model [13], [12]. In this operational mode a cognitive radio acts as a spectrum scavenger. It continuously performs spectrum sensing over a range of frequency bands, dynamically identifies unused licensed spectrum (the so-called White Spaces), and then operates in this spectrum at times and/or locations when/where it is not used by incumbent radio systems. In this mode a cognitive radio may coexist with the primary users either on a not-to-interfere basis or on an easement basis, which allows secondary transmissions as long as they are below some acceptable interference threshold. We note that opportunistic spectrum access can take place both on a temporal and a spatial basis. In temporal opportunistic access a
cognitive radio monitors the activity of the licensee in a given location and uses the licensed frequency at times that it is idle. An example of this is the operation of cognitive radio in the UMTS bands [14]. In spatial opportunistic access low-power cognitive devices identify geographical regions where certain licensed bands are unused and access these bands without causing harmful interference to the operation of the incumbent in nearby regions. The operation of cognitive radios in TV bands, for example, is primarily based on spatial opportunistic access to these bands, and will be discussed further in the following sections.

A. Cognitive access to TV bands

Broadcast television services operate in licensed channels in the VHF and UHF portions of the radio spectrum. The regulatory rules in most countries prohibit the use of unlicensed devices in TV bands, with the exception of remote control, medical telemetry devices and cordless microphones. In the US and the UK regulators are currently in the process of requiring TV stations to convert from analogue to digital transmission. This Digital Switchover is expected to be completed in the US in 2009 and in the UK in 2012. A similar switchover process is also underway or being planned in the rest of the EU and many other countries around the world.

After Digital Switchover a portion of TV analogue channels become entirely vacant due to the higher spectrum efficiency of digital TV (DTV). These cleared channels will then be reallocated by regulators to other services, for example through auctions. In addition, after the DTV transition there will be typically a number of TV channels in a given geographic area that are not being used by DTV stations, because such stations would not be able to operate without causing interference to co-channel or adjacent channel stations. These requirements are based on the assumption that stations operate at maximum power. However, a transmitter operating on a vacant TV channel at a much lower power level would not need a great separation from co-channel and adjacent channel TV stations to avoid causing interference. Low power unlicensed devices can operate on vacant channels in locations that could not be used by TV stations due to interference concerns [18]. These vacant TV channels are known as TV White Spaces, or interleaved spectrum in the parlance of the UK regulator.

Fig. 1 shows, as an example, the chart of the UK’s analogue TV frequency bands and how these will be divided after digital switchover into cleared and interleaved spectrum [7].

The FCC adopted a Notice for Rulemaking (NRM) in 2004 proposing to allow unlicensed radio transmitters to operate in the broadcast TV spectrum at locations where that spectrum is not being used [5]. The proposed new rules would, in principle allow the operation of both fixed and portable broadband devices on a non-interference basis. Very recently, a similar statement proposing to allow unlicensed operation of cognitive radio devices in interleaved spectrum was released by Ofcom as part of its Digital Dividend Review (DDR) [7].

Oppportunistic operation of cognitive radios in TV bands, however, is conditioned on the ability of these devices to avoid harmful interference to licensed users of these bands, which in addition to DTV include also wireless microphones [18]. FCC discusses three methods for ensuring that unlicensed TV band devices do not cause harmful interference to incumbent: control signals, position determination, and cognitive radio. In the following we shall briefly discuss these methods.

With the control signal method, unlicensed devices only transmit if they receive a control signal (beacon) identifying vacant channels within their service areas. The signal can be received from a TV station, FM broadcast station, or TV band fixed unlicensed transmitter. Without reception of this control signal, no transmissions are permitted. In the position determination method, an unlicensed device incorporates a GPS receiver to determine its location and access a database to determine the TV channels that are vacant at that location. There are at least two issues associated with this method [18]: 1) the accuracy and completeness of the database and 2) the ability of unlicensed device to determine its location. Finally, in the cognitive radio method, unlicensed devices autonomously detect the presence of TV signals and only used the channels that are not used by TV broadcaster.

B. How much spectrum are we talking about?

The fundamental reason why TV spectrum has attracted much interest is an exceptionally attractive combination of bandwidth and coverage. Signals in TV bands, travel much further than both the WiFi and 3G signals and penetrate buildings more readily. This in turn means that these bands can be used for a very wide range of potential new services, including last mile wireless broadband in urban environments, broadband wireless access in rural areas [9], [10], new types of mobile broadband and wireless networks for digital homes.

On the other hand, the available spectrum for cognitive access varies from location to location and depends strongly on the population density. In rural areas, where the population density is low, there is also low concentration of TV transmitters, and a large number of TV channels could be vacant. On the other hand, in urban areas the density of TV transmitters could be very high, and therefore the number of unused TV channels (White Spaces) at a given location could be very limited. In order to to assess the importance of cognitive access to TV...
bands it is therefore important to have realistic estimates of the amount of spectrum (spectrum opportunity) that is associated with this mode of access.

Spatial variations in TV White Spaces can be assessed from a TV transmission database, which specifies the location of transmitters, the frequencies they use at a given location, and the typical coverage area of the transmitter. Fig. 2 shows schematically a typical setup for the operation of a cognitive radio base station which operates in a given location in TV White Spaces which are available at that location. The CR transmission should not cause harmful interference to TV receivers both within the coverage area of nearby transmitters, and at the edge of this area. To achieve this the CR device can transmit on the TV bands used by these transmitters only if its position is a minimum “keep-out” distance away from the edge of their coverage area [10].

In a simplified picture, based on the pathloss model [21], the keep-out distance can be obtained as follows. Denote with $R_{tv}$ the maximum coverage radius of the TV station, and with $P_{cr}$ and $P_{tv}$ the transmit power of the TV transmitter and the CR transmitter, respectively. Then, in order to avoid interference with TV receivers that are at the edge of the coverage area, we must have:

$$\frac{P_{tv}}{P_{cr}} \leq \frac{P_{cr}}{R_{tv}^\alpha} \geq \beta_{th},$$ (1)

where $\beta_{th}$ is the sensitivity threshold of a TV receiver, and $\alpha$ is the pathloss exponent. This yields:

$$R_{cr} \geq \left(\frac{\beta_{th} P_{cr}}{P_{tv}}\right)^{1/\alpha} R_{tv}. \quad (2)$$

Consequently, a CR device at location $r$ can use the frequencies associated with a TV station located at $R_j$ only if

$$|r - R_j| \geq \left[1 + \left(\frac{\beta_{th} P_{cr}}{P_{tv}}\right)^{1/\alpha}\right] R_{tv}. \quad (3)$$

Repeating the above procedure for every TV transmitter, one can obtain the total number of TV transmitters in a given region whose associated frequencies can be used by a CR operating with a specified transmit power $P_{cr}$ at location $r$, from which the total number of TV bands available for opportunistic access can be obtained from information of TV transmitters’ frequency allocation plans.

Using a similar approach, but taking into account the actual service contours of TV transmitters, Brown and Sicker [22] have made estimates of the spectrum available to CR devices at a number of locations in the US, as a function of the transmit power (or equivalently transmission range) of a cognitive radio. Using New York City, as an example of a highly populated urban area and Buffalo, as an example of a rural area, they show that the availability of spectrum for cognitive access greatly depends on location and transmission range. In the case of Buffalo, about 50 TV channels (300 MHz) would be available for a CR transmitting to distance of up to 10 km. On the other hand, in New York, the maximum number of available channels is only 4 (24 MHz) and drops sharply beyond a 10 km transmission range.

We are currently investigating spatial variations in the TV White Spaces (interleaved spectrum) which will become available in the UK. A preliminary study by Ofcom, however, indicates that “at any one location, around 100 MHz on average is not being used by DTT (Digital Terrestrial Television) and could, in principle be used by licence-exempt devices” [7]. Comparing this amount of spectrum with, e.g., the total UK 3G spectrum (~ 75 MHz) it can be seen that the potential spectrum opportunity available for cognitive access is significant. Effective utilisation of this opportunity for commercial applications, however, requires further research in the development of new algorithms for incumbent detection, as well as new approaches for effective pooling of discontinuous TV channels [25].

IV. NEXT GENERATION DYNAMIC SPECTRUM ACCESS WITH COGNITIVE RADIO

As spectrum liberalisation [23], trading [24] and a technology-based approach to interference management becomes increasingly mainstream, the radio technologies that allow the paradigm of Dynamic Spectrum Access (DSA) will enable more dynamic and efficient management of the spectrum resources [16]. The IEEE P1900 working group defines DSA in the following way [26]

“Technique by which a radio (system) dynamically adapts to select operating spectrum to use available (in local time-frequency space) spectrum holes with limited spectrum use rights.”

The concept of DSA is not new. Indeed, BT’s Fusion phone and the Unique phone from Orange are two examples of

1. We note that usually one requires that channels adjacent to an occupied TV channel should also be avoided by CR devices in order to eliminate adjacent channel interference effects [19].
consumer products which dynamically select spectrum based on the operating environment. Both products employ a technology known as Unlicensed Mobile Access (UMA) and are strictly limited to a choice between either WiFi/Bluetooth or GSM/3G bands. Although this choice happens on a dynamic basis, the spectrum landscape itself remains static. Dynamic spectrum access techniques need not be limited to simple choices between alternative bands.

The introduction of spectrum liberalisation and trading [24], [17], combined with increased ability of devices to change their radio operations on the fly, may lead to far more adventurous forms of DSA [27], [16]. Devices will be able to dynamically vary their operating spectrum over a wide range of frequency bands, allowing them to access these bands on a just-in-time basis and according to their market price. This may happen either upon instruction from a base station which dynamically negotiate and acquire spectrum on behalf of user devices, or autonomously by devices themselves [12]. Some, less congested, bands may be available at a significantly lower cost (or even free) than the more popular bands and devices would be able to utilise these, ensuring that users remains connected at a price that supports their utility.

When combined with higher levels of built-in cognitive intelligence, advanced pooling techniques and reconfigurable antenna technologies the concept of DSA can be taken still further. The entire available spectrum may be divided into a very large number of equally-sized elementary subchannels (ESC). Depending on their requirements devices may pool together and utilise a number of (not necessarily contiguous) ESCs, and then vacate some or all of these when they are not longer required or when other more suitable ones become available. The static and highly fragmented spectrum landscape of today will be replaced with a highly dynamic quasi-continuum landscape, in which each device navigates its own way using its cognitive and adaptive capabilities, in order to optimally meet user’s requirement for wireless access.

To illustrate the above concept, we can draw an analogy with vehicular and pedestrian traffic. The recently emerging DSA systems can be compared to how vehicular traffic on a multi-lane highway operates. Here vehicles are free to choose which lane they occupy and can change lane, but are restricted in their manouvers to switching between a number of marked lanes. In contrast, future DSA systems are more akin to the pedestrian motion in a busy pedestrianised street. Here there are no well defined lanes and only a minimum set of rules are imposed externally. Each pedestrian autonomously navigate and manoeuvre his/her own way in the crowd, using a cognitive cycle which involves choosing a position and direction of motion that best satisfies his/her own personal goals and dynamically adjusting his/her movements and pace based on his/her perception/prediction of the movement of other pedestrians and the restrictions imposed by the environment.

V. CONCLUSIONS

In this paper we examined how the emergence of cognitive radio may impact the way spectrum will be managed and regulated in both the near (next 5 years) and more distant (next 10 – 20 years) future. We showed that the emerging paradigm of opportunistic spectrum access by cognitive radios is already making an important impact on the way the highly valuable spectrum in the VHF/UHF TV bands will be accessed, managed and shared in the US and the UK. If successful, this new mode of access may be adopted by other regulators around the world. It may also be extended to other portions of the licensed spectrum, such as the 3G and the newly released WiMAX bands. opportunistic access to such bands, however, may need to be supported by new mechanisms such as real-time trading and spectrum leasing which create economic incentive for the incumbents to allow secondary utilisation of their spectrum when it is idle. We saw that Opportunistic access by cognitive radios is also threatening the current licenced-exempt model where non-cognitive device operate in free-for-all bands which are set aside for their operations.

In the long run, with rapid advancement of device reconfigurability and cognitive capabilities, we may see the spectrum management model based on rigidly defined frequency bands disappear altogether. Instead, the spectrum will be managed as a continuum-type resource whose access and sharing is largely self-regulated by a society of cognitive devices which are engaged, on behalf of their users, in a continuous process of communications, negotiations, trading and cooperation.

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