A SUMMARY OF COGNITIVE RADIO WORK PERFORMED FOR THE UK REGULATOR OFCOM

Julie Bradford (QinetiQ, Malvern, UK; jbradford@qinetiq.com); Eddie Burbidge (QinetiQ, Malvern, UK; eaburbidge@qinetiq.com); Derek Chandler (Multiple Access Communications Ltd, Southampton, UK; derek.chandler@macltd.com); Mike Kennett (Red-M, Horsham, UK; Mike.Kennett@red-m.com); Paul Levine (University of Surrey, Guildford, UK; p.levine@surrey.ac.uk); Christos Politis, (Ofcom, London, UK; christos.politis@ofcom.org.uk); Anil Shukla (QinetiQ, Malvern, UK; ashukla@qinetiq.com);

ABSTRACT

This paper gives a summary of a year-long study carried out for the UK regulator the Office of Communications (Ofcom) into Cognitive Radio (CR) Technology. This study aimed to answer a number of key questions including:

- What is CR?
- What are the benefits and disadvantages of CR?
- When will CR be deployed?
- How will CR be used?
- How will CR be controlled?
- What are the regulatory issues concerning CR?
- How might CR behave in a changing radio environment?

To answer some of the key regulatory questions the study included the development of a software based CR demonstrator.

1. INTRODUCTION

As the demand for high data rate, wireless services continues to increase so too does the incentive to make better use of available spectrum. Current radio licence assignments in the UK make the RF spectrum appear over used and highly congested. However, measurements of actual spectrum activity show that, depending on location and the time of day, large amounts of spectrum are being wasted under the current "Command and Control" licensing structure [1]. In response to this the UK regulator, Ofcom, has shown a commitment to moving towards more efficient and flexible dynamic spectrum management techniques [2].

In line with this interest Ofcom commissioned a study to gain a better understanding of CR: in particular the technology, knowledge and regulation required to enable CR; the benefits it promises; the problems it may cause and an estimation of when CR will become a reality. This study was undertaken by a consortium comprising of QinetiQ (who led the consortium), Multiple Access Communications Ltd., Red-M, the University of Surrey and the University of Strathclyde. This study was completed in September 2006 and was build on a previous study by the consortium on SDR [3].

2. WHAT IS COGNITIVE RADIO?

The first challenge for the consortium was to define CR and to highlight the aspects of this technology that are of most interest to the regulator.

2.1. Definitions of Cognitive Radio

The following definition of CR was used as a first starting point for this study:

"Cognitive Radio is a wireless system that has an awareness of the environment that it is operating in and can adapt to improve its performance based on this awareness" [3].

It was felt, however, that this was too broad as cognition could be applied to many layers in a system (from physical layer to application layer cf Open System Interconnection (OSI) model). For the purpose of this study this definition was further refined to:

"CR is intelligent signal processing (ISP) at the physical layer of a wireless device".

It was acknowledged that CR may, and, in order to get the best performance, probably should, include ISP at higher layers of the OSI model. This concept of ISP at multiple layers was referred to as a Cognitive Stack or Cognitive Protocol Stack. This separation of Cognitive Radio and Cognitive Stacks focused the study on the area that is of most interest to the regulator; changes in the physical layer and spectrum usage of a radio device.

It was recognized that Cognitive Radio has two essential characteristics; intelligence and flexibility. These are in turn driven by two key technologies; ISP and software defined radio (SDR). As both of these can be split into varying degrees of complexity, we find that Cognitive Radio can also be described in varying dimensions through a matrix with axes of intelligence and flexibility (Figure 1).

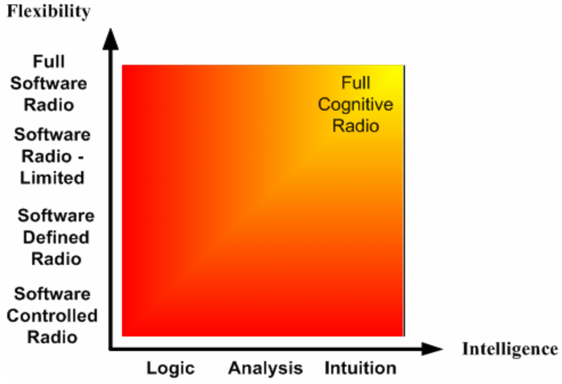

Figure 1 – Cognitive Radio Dimensions

2.2. Benefits of CR

Optimised diversity is the overall benefit of CR. While many of today's radio systems employ fixed diversity schemes such as frequency, time, space, coding, etc., a CR will be able to use these schemes adaptively and intelligently. Furthermore, while a single diversity scheme such as frequency or time appears obvious, additional layers of diversity will arise by combining schemes (for example MIMO combines space and time diversity). These combinations will also be adaptive and intelligent in a CR system. As a result diversity becomes optimised.

For the CR user optimised diversity will translate into an improved Quality of Service (QoS). This is because the CR should adapt to select the most suitable and reliable service for the user's needs at that time. Building on ideas from SDR [3], CR may provide greater availability of service by making use of its flexibility or multiple technologies within one device. In areas of poor or patchy coverage it is likely that the user will experience a graceful degradation of service with CR devices, rather than an abrupt loss of service, because these systems are expected to be intelligent enough to exploit what coverage is available and to optimise the link to make use of it.

A key enabler of capable CR devices is the use of an SDR platform which provides frequency and waveform flexibility as well as the ability to host enabling applications such as spectrum monitoring and the ability to support CR control communications channels. Additional benefits include reduced production costs due to combining waveforms in a single hardware platform and reduced upgrade and maintenance costs via software downloads (possibly over-the-air) rather than through costly hardware changes or terminal replacement As with most emerging technologies, however, these benefits may be offset by initial high costs.

Since improved spectrum efficiency results from optimised diversity, service providers can expect to benefit from CR by being able to accommodate more users and/or provide higher data rates from their current spectrum allocations. Likewise regulators, whose objective it is to ensure efficient use of the electromagnetic spectrum, also stand to benefit from CR. The movement towards flexible CR systems that adapt to a changing environment fits well with the movement from a static "command and control" licensing system to more dynamic market mechanism based licensing structures.

2.3. Challenges of CR

The challenges of CR fall into three main areas:

- Reliable detection of other spectrum users
- Security
- Control techniques and policing

A recognized challenge for CR (as for many other systems) is the hidden node problem. This is where the CR is unable to detect a contemporary radio with whom it shares spectrum. This may be because the "hidden node" is a receiver at the edge of its coverage area. The CR could be outside the coverage area of the transmitter and therefore be unable to detect it, but the CR may still be close enough to the receiving radio to cause interference when it starts to transmit on what appears to be an unoccupied frequency. Nodes can also be hidden due to terrain variations. For example, a CR placed in a hilltop will have a better spectral view than one in a valley. Suggested techniques for overcoming the hidden node problem include improving receiver sensitivities on CR devices, transmitting beacon signals from receivers or making use of a central spectrum database. However, this study did not find evidence of these approaches being tested in practice.

Because CRs are likely to contain an SDR element they will suffer from similar security concerns to that of SDR. If a radio is software-based there is an increased opportunity for hackers to tamper with radios and place viruses on networks to avoid service charges, disable a network or obtain information about other users. The security of SDR devices was investigated in a previous Ofcom study [3]. The overall conclusion from this was that there is not a technological gap between current capabilities and those required for secure SDR implementation. Standardisation is a significant obstacle but much can be learnt from the Internet community in this area.

Watertight techniques for controlling CR systems are difficult to imagine due to the adaptive nature of CR. While CR systems aim to have a minimal effect on the contemporary radio users that they are sharing spectrum with, it is likely that there will be some interference. In order to control this, case studies of sharing schemes will need to be carried out to assess the impact on other spectrum users. This problem expands when CR devices cross international boundaries. The issue of controlling and regulating CR is discussed in more detail in section 5.

3. COGNITIVE RADIO TIMELINE

It can be argued that available technologies, such as Digital Enhanced Cordless Telecommunications (DECT), exhibit CR techniques in that they show a form of awareness and adaptation to their environment [3]. During this study an attempt was made to put these into perspective by mapping them onto the dimensions of the CR matrix discussed earlier. Technology is available today to make devices with cognitive techniques but these largely lie in the bottom left-hand side of the matrix whereas a full cognitive radio would sit at the top right corner, as shown in figure 2. Some predictions for developments in SDR based on improvements in ADC rates [4] were also mapped onto this matrix to show the possible way ahead for CR. When the technology will be available to move to devices making decisions based on intuition rather than logic and analysis is difficult to predict and is likely to be far in the future. However, it is important to note that full CR might not be necessary and that there are significant benefits to be gained from current techniques.

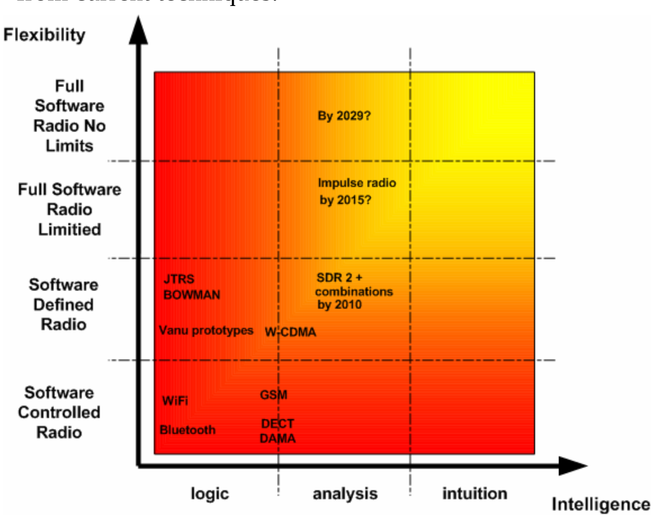

Figure 2 – Timeline for CR developments

4. INDUSTRY VIEWS AND CR APPLICATIONS

4.1. Stakeholder Meeting

This study included a discussion on potential applications for CR. To obtain the views and opinions about CR from the UK communications industry a stakeholder meeting was held in December 2005. More than twenty representatives comprising mobile network operators, wireless terminal manufacturers and regulators attended. The major concerns with CR were the hidden node problem and policing of CR devices. However, if a controlling body such as a frequency band manager were present to give assurances about managing CR devices the attendees could foresee spectrum sharing being possible.

The stakeholder meeting helped the consortium to identify potential applications for CR. These were investigated in more detail after the meeting and the advantages and disadvantages of each are summarised in table 1.

	Advantages	Disadvantages
Mobile multimedia download (e.g. download of music/video files to portable players)	High tolerance of delays	High mobility required – CR must be more sophisticated
	Large volume of CR devices – cost economies	Requires a network of CR base stations providing extensive coverage
Emergency radio system (e.g. video transmission from firemens' helmets)	Low power is required	Poor tolerance of delays
	Very low mobility required	Low volume of CR devices
	No network of CR base stations required	
Broadband wireless networking (e.g. using laptops)	Devices such as laptops tend to be fairly static	Requires a network of CR base stations
	Users might be able to use CR as a backup to WLAN	
	Network use can tolerate delays	
	Large volume of CR devices – cost economies	
	Limited coverage and short range sufficient	
Multimedia wireless networking (e.g. audio/video distribution within homes)	Low power is required	Poor tolerance of delays
	Large volume of CR devices – cost economies	
	Static devices	
	No network of CR base stations required	

Table 1 – Summary of Applications for CR

5. ECONOMIC BENEFITS

The existing allocation of spectrum to cellular services is ≈540MHz. According to the various demand studies including one carried out for this project a spectrum shortage will occur sometime before 2025 [5]. CR could potentially enable the cellular sector to access other bands of spectrum at little cost to legacy users. This will bring about a spectrum efficiency gain in the form of an increase in call-volume capacity, thus relaxing the spectrum constraint. We now address the question: what is the economic benefit from CR? We measure gross welfare gain in terms of consumer surplus, a standard concept in economics. This can be expressed in terms of the proportional capacity increase, k, and the elasticity of demand for cellular services which we have estimated. The net welfare gain takes into account a one-off investment cost, in new handsets, infrastructure etc. In what follows, costs are measured as a proportion of the revenue at the limit of the spectrum capacity.

Suppose that this new investment depreciates completely after T years. Figure 3 plots the investment cost of CR against the minimum proportional increase in call-volume, k, required to break even, for various depreciation lengths. Our estimate of costs is 4.8 per cent of the forecast revenue at the time the spectrum constraint is reached. Given this estimate, from the figure this would require a capacity increase of somewhere between 3 and 4 per cent for a net economic benefit. From studies of efficiency gains from CR this is well below what we anticipate, so our tentative conclusion is that we expect significant net economic gains from CR.

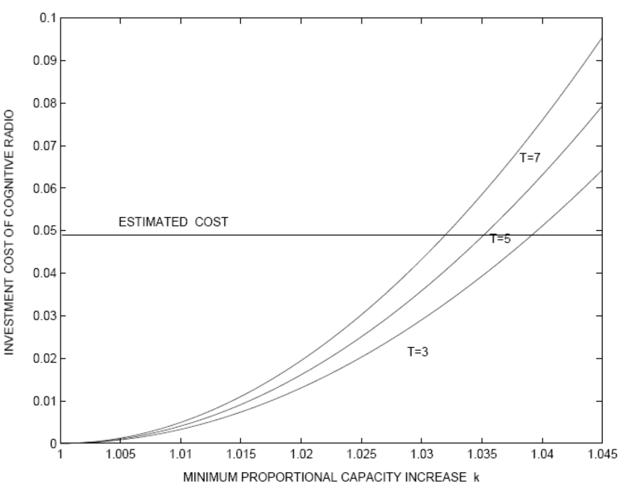

Figure 3 - Minimum Call-Volume Increase, k, required to break even

6. MANAGING COGNITIVE RADIO

6.1. Control Techniques

A short study was carried out into techniques for controlling groups of spectrally aware cognitive radios. The following three key frequency control approaches were examined:

1. using a spectrum database to configure cognitive radios' frequencies;
2. monitoring the frequency environment and updating the spectrum database;
3. sensing the local spectrum environment to create a spectrum register and exploit the spectral gaps.

It was concluded that, in order to combat the hidden node problem and maintain control, some form of spectrum database would be required to inform the cognitive radio system of neighbouring spectrum users. A hybrid system is recommended which involves complementing a spectrum register with local monitoring by the cognitive radio device to ensure that the database is up-to-date. It is envisaged that a control channel would be required to distribute the central database. A key point to note here is that the format of the spectrum database needs to be standardised so that all CR devices can easily interpret the spectrum monitoring information even across international boundaries.

6.2. Regulatory Issues

CR presents a considerable regulatory challenge as it must consider interaction between spectrum allocated to different users. However, the current inefficiency in spectrum usage and increasing demands has ensured that it is a challenge that must be addressed. CR is one technology that will potentially allow a move towards a much more dynamic spectrum market. Ultimately this can make spectrum to be available to those who can best make use of it at any moment (measured in financial or other benefit terms).

Our investigation into regulatory issues for CR was carried out on the assumption that a CR device can be represented by three functional components as shown in figure 4.

The software radio provides the flexibility to the CR. This sets a hardware limit on the frequency range and waveforms that the CR can operate over. The spectrum monitoring block provides the environmental awareness to the CR. The policy box represents the intelligence within the CR and it is here that technology options of the software radio element are combined with the constraints of the current environment and a decision made on how best to configure the CR for the user's current requirements.

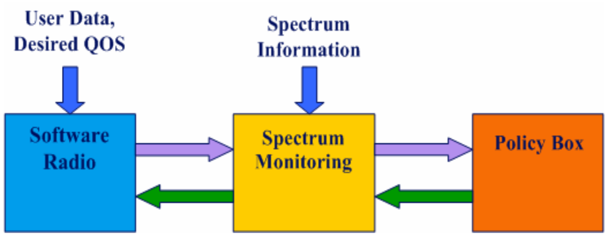

Figure 4 – The key Components of CR

It is anticipated that the focus for the regulator will be on the policy box because this is where the decisions on how to configure the CR are made. This policy box could contain rules and regulations from the regulator that the device must abide by to avoid causing harmful interference to other spectrum users.

As the policy box effectively controls the other two components of the CR, certification should focus on the decisions made in this component. This actually simplifies the certification of the software radio block which traditionally is a challenging area due to its flexibility and multiple configurations. If the software radio is proven to be solely under the control of the policy box then certification of the policy box decisions is key rather than the flexibility of the SDR. As mentioned in section 5.1, the spectrum monitoring block could be greatly enhanced by the provision of a central frequency database. This would ideally be provided by the regulator from a distributed spectrum monitoring network that could also be used to police faulty or illegal radios.

The regulator can significantly assist the development of CR by addressing the following areas.

- Technological advances – Encourage research and development into CR by providing test bands.
- Standardisation – Become actively involved in CR standardisation to ensure harmonisation across international boundaries.
- Large CR spectrum pool – When issuing new licences make efforts to include CR as a secondary user to increase the opportunities available to CR.
- Availability of monitoring data – Making monitoring data readily available will allow the business case for CR to be examined. Availability of monitoring data could also be key in overcoming the hidden node problem.
- Regulatory framework / Policing – Taking a lead on controlling and policing CR devices will provide contemporary legacy users with the assurance they need to be comfortable sharing with CR.

7. DEMONSTRATING COGNTIVE RADIO BEHAVIOUR

7.1. Software-Based CR Demonstrator

A software-based cognitive radio demonstrator that allows single and multiple cognitive radio networks to be deployed alongside existing legacy (or licensed) users was developed (shown in figure 5). The demonstrator not only provides a suitable platform to assess the impact upon legacy users (LU), but also allows the behaviour of a cognitive radio network in a dynamic radio environment to be evaluated.

To ensure realistic results the demonstrator makes use of a synthetic radio environment capable of modelling the RF system parameters (e.g. power, directional antennas, etc.) and the propagation loss that takes account of the attenuation and diffraction across terrain.

This demonstrator provides a powerful tool for examining cognitive radio in different scenarios and also for testing different ideas on how cognitive radio systems should operate and be regulated.

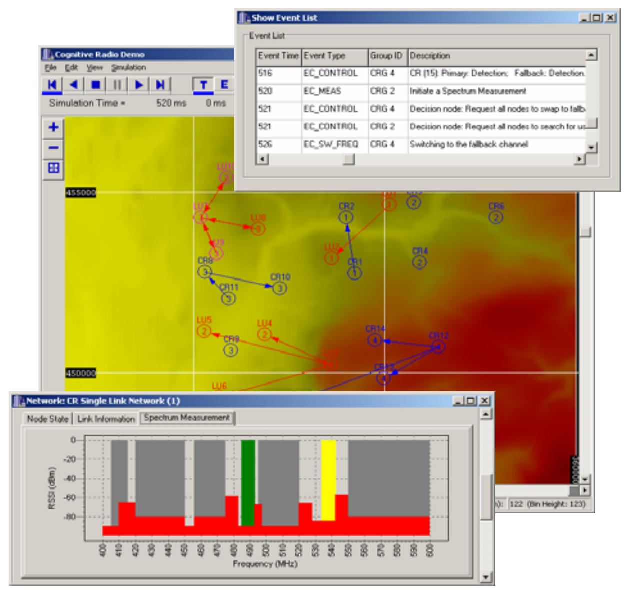

Figure 5 – Software Based CR Demonstrator

7.2. CR Scenarios

During this study the demonstrator was used by the consortium to model the following scenarios:

- CR coexisting with a contemporary private mobile radio (PMR) network
- CR coexisting with multiple PMR networks
- Licence exempt (LE) CR operating within the UHF TV band
- LE CR coexisting with hidden nodes in the UHF TV band

- Multiple CR networks coexisting with each other

During these simulations these observations were noted.

- A CR network can coexist with LUs such as PMR, identifying and using spectrum holes and hopping to a fallback frequency when LUs become active.
- When an LU becomes active on a frequency already being used by a CR, then only a temporary amount of interference is caused to the LU. If the CR is using a bandwidth wider than the LU but has a comparable signal power, then this interference may be low enough for the LU to tolerate.
- Increasing the number of nodes in a CR network does not necessarily solve the hidden node problem. Increasing the sensitivity of at least one CR node was more effective in avoiding hidden nodes. A CR needs to be at least as sensitive as the LU receivers with which it is attempting to share spectrum. In most cases, the CR sensitivity will need to be better than the LU.
- Multiple CR networks attempting to find spectrum holes at the same time are able to sort themselves out and settle on frequencies that do not interfere with each other. Even CRs that behave in a similar, non-random way are able to do this, although it takes them longer than CRs whose decision-making relies more heavily on random elements.

8. SUMMARY

Overall this study has found that cognitive radio is an emerging technology that promises to offer great benefits to all members of the radio community. There are some significant challenges to overcome such as interference avoidance, regulation, security and control.

CR is a natural evolution from SDR (adding intelligence to the SDR terminal) and so SDR maturity is a key enabler. However, it is also key that the correct regulatory environment is in place to encourage CR deployment (i.e. to enable successful business cases for its use to be established) and to facilitate research and development in this area to enable the technology to be matured

9. ACKNOWLEDGEMENTS

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Although this paper does not present any official views of Ofcom, the authors would like to acknowledge their support and advice.

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