COGNITIVE TECHNIQUES FOR ULTRAWIDEBAND COMMUNICATIONS

Wasim Q. Malik and David J. Edwards

Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, United Kingdom
Email: {wasim.malik, david.edwards}@eng.ox.ac.uk

Invited Paper

Keywords: Cognitive radio, software defined radio, ultrawideband.

Abstract

Cognitive radio is an emerging wireless technology that allows dynamic system reconfiguration, promising dramatic improvements in spectrum utilisation. Unlicensed spectrum sharing is the theme that binds cognitive radio and ultrawideband technologies. This paper presents an assessment of cognitive techniques for ultrawideband systems, highlighting the characteristics of this highly flexible, spectrum efficient regime. The performance improvements expected from cognitive ultrawideband systems are evaluated and the research challenges posed are discussed.

1 Introduction

Cognitive radio (CR) refers to the regime where the end-to-end communications system is aware of its propagation environment and adapts to it [1]. Several advantages can be gained from a CR system, such as more efficient spectrum utilisation, increased interference avoidance, improved multiuser capability, and higher overall system performance. The defining attribute of CR is its operational flexibility based on spectrum sensing. Although CR is still in the conceptual stages at this time, this emerging wireless technology offers exceptional promise for the future.

Spectrum usage awareness has different – albeit related – contexts for narrowband and wideband communications. In carrier-based narrowband systems, it implies that the CR scan the available spectrum range and selects the optimal operating frequency, at which the baseband signal is then modulated. Spectral scanning is performed in wideband CR systems also, but the outcome determines the spectral region that the wideband signal will occupy. Typical wideband signals, such as those obtained with direct-sequence or swept-frequency modulation, occupy a contiguous band of frequencies. It follows that for CR to be beneficial, the frequency range it can scan must be wider than the spread signal bandwidth.

Ultrawideband (UWB) signals have fractional bandwidths of over 20% or absolute bandwidths of over 500 MHz, radically altering the characteristics of the propagation channel [2]. The Impulse Radio (IR) scheme by Win and Scholtz pioneered the application of UWB technology to wireless communications [3]. From the perspective of system design, a variety of options become available for CR operation over a large bandwidth. IR can utilise optimal signal waveforms adapted to the channel conditions. Multiband UWB systems, such as MB-OFDM [4], can also benefit from the selection of the optimal subcarriers and subbands. Several of these adaptability options and the tradeoffs involved will be discussed in this paper.

Traditionally, CR refers to spectrum sensing followed by adaptation. However, a more generalised description can be obtained by including the overall propagation environment in CR modelling and design. We take the latter approach in this paper, and consider several important factors, such as noise and multipath, in addition to interference. We then present some UWB system design strategies and analyse the achievable performance improvement due to channel cognition.

2 The Cognitive Radio Architecture

The concept of CR, as well as the nomenclature, is attributed to Mitola [1], who proposed it as a conceptual extension of software defined radio (SDR). The term SDR was incidentally also coined by him to identify the switch from hardware-dominated, fixed and “dumb” wireless terminals to software-oriented, adaptable and smart communications devices. This initial work sparked an interest in a class of novel radio network architectures with extensive runtime flexibility and adaptability. Such cognitive techniques, inspired from artificial intelligence and agent-based processing, promise a large performance improvement in future wireless communications, primarily by more intelligent utilisation of the available resources.

CR signifies a class of reconfigurable communications devices that can sense external stimuli and adapt dynamically. A CR device can detect other users in the environment and alter its frequency, power, modulation, coding, and other transmission parameters in real-time. This flexibility results in the ability to coexist and avoid interference, as well as to populate the spectrum densely. The real-time detection of spectrum occupancy can be based on passive sensing, geolocation with spectrum usage databases, or dedicated beacon transmitters to indicate spectrum unavailability.

In addition to the traditional sense of spectrum agility for interference minimisation, the CR adaptation can be based on several other physical propagation aspects of the radio environment. The wireless channel is best modelled using a multidimensional formalism, incorporating the time, frequency, polarisation, space, angle, and other possible signal dimensions. We therefore contend that environmental cognition over all available degrees of freedom is the way forward for CR theory and practice. A large vacuum exists, however, in the available research results on CR at this time, but the mounting interest in this emerging technology is expected to fill this gap soon.

The greatest motivation for CR comes from the fact that the radio spectrum is very expensive and scarce yet severely under-utilised with large time-frequency-space white-spaces or holes [5]. A recent study by the US Federal Communications Commission (FCC) revealed that the radio spectrum utilisation in the band below 3 GHz varies vastly, ranging from 15% to 85% [6], and even lower above 3 GHz. The FCC also acknowledged the potential of opportunistic spectrum utilisation with CR to ameliorate this loss [7]. This development, however, raised concerns in several quarters and has since been the subject of debate [8]. In the UK, the Ofcom is also currently studying the feasibility of CR and the policy changes it would involve.

Several known tools have been used for the analysis and modelling of CR systems. Mitola's original work borrowed heavily from the concepts of machine learning and artificial intelligence. He thus proposed that CR networks would be self-organising, behaving like an ant colony [9]. Genetic algorithms have been used to describe the evolutionary nature of adaptive CR platforms [10]. Game theoretic analysis has also been prominent, where the CR problem is formulated in terms of a number of autonomous entities competing for spectrum [5]. Information theoretic formalism has also been used recently to demonstrate that two independent, cooperating CR channels can use dirty paper coding to overcome mutual interference and approach the information theoretic MIMO channel capacity [11].

3 Cognitive Ultrawideband Systems

This section addresses some of the key areas where the exploitation of CR techniques can make significant improvements to UWB communications technology.

3.1 Interference Mitigation and Coexistence

UWB emissions can possibly interfere with a range of other communications and electronics devices operating in the vicinity if not carefully controlled. Especially vulnerable to interference are the services that share the spectrum with UWB, such as IEEE 802.11a wireless local area networks (WLAN). This has been a serious concern and has led to prolonged debates between UWB's opponents and proponents. CR presents a candidate mechanism for avoiding interference and is therefore an elegant solution to interoperability and coexistence issues. When one or more narrowband services are operating in a given space, a UWB link can use cognition to minimise the interference to those services. Depending on the specific application, the spectrum occupation rule can consist of assigning priority to the more mission-critical service. This can be achieved by the cognitive filtering of the UWB signal spectrum to remove the frequencies where interference may occur. The signal occupying the rest of the band can then be transmitted without the requirement of any further sophisticated signal processing for interference rejection at the receiver.

Spectrum shaping in this manner can be applied to both single-band and multiband UWB signals. Impulse Radio UWB uses Gaussian-like pulses with very wide bandwidths for baseband UWB signalling. A cognitive implementation of IR can mitigate narrowband interference using simple adaptive notch filtering at the desired frequency. A more sophisticated alternative is the soft spectrum adaptation (SSA) scheme which is based on carefully designed waveforms [12]. Pulsed multiband schemes can be restricted to the desired subbands using UWB waveforms with sharp subband occupancy, avoiding the spectral regions where other services may be present [13]. In multiband OFDM (MB-OFDM) systems, the data bits are modulated over a number of subcarriers occupying a band of approximately 500 MHz [4]. MB-OFDM allows interference mitigation through the suppression of the corresponding subcarriers. Waveform sculpting by the introduction of subcarrier notches along with active interference cancellation has been shown to achieve 70 dB suppression at the desired frequencies [14].

3.2 Frontend Distortion Compensation

Due to the large bandwidths involved, various RF components used in real UWB implementations may depict nonideal and nonuniform behaviour. These can include the antennas, amplifiers, filters, modulators, and other components. We showed in [15] that real UWB antennas suffer from large nonuniformities in the radiation pattern due to the phase centre translation with frequency, resulting in directionally- and spectrally-varying signal dispersion. A CR system can be used to partially overcome this antenna distortion using a closed-loop approach. After sensing the composite spectral conditions including the antenna effects, it can modify the signal waveform applied to the antenna with the help of an appropriate pre-distortion filter.

The nonlinear response of various RF components in the transmit and receive chains can also distort the signal. In practice, this nonlinear behaviour is dominated by the power amplifiers. Thus a transmit frontend amplifier can distort the signal fed to the antenna, producing intermodulation products and harmonics. While undesired for any CR network with spectrum sharing due to electromagnetic compliance concerns, the effect is even more catastrophic for UWB signals as the extraneous signal components could fall in-band and the desired signal could then be unremovable with simple methods. The problem is further compounded in active antenna array systems, where the combined effect of the extraneous frequency components and the angular-spectral antenna response can degrade the signal quality considerably. Under such circumstances, an end-to-end cognitive linearisation scheme is the most effective strategy. This can be achieved with a cognitive estimation of the overall signal distortion, followed by transmit pre-distortion filtering. The adaptive pre-distortion can be realised conveniently with a digital implementation.

3.3 Power Conservation

Mobile communications devices and sensors generally derive their power from batteries. A key design consideration in such systems is to reduce the requirement for recharging or replacement of the batteries by reducing the power consumption. This is especially true for sensors deployed in locations where access is not easy, such as in battlefields or on tall buildings. CR-based optimal power transmission can reduce the total transmitted power level without significant performance degradation. Thus in a flexible spectral shaping CR system, a given frequency subband that experiences signal loss due to fading or interference can be switched off, so that no power is injected and wasted in that unfriendly region of the spectrum. The overall effect would be an increase the power efficiency of the system.

3.4 Fading Mitigation

UWB systems offer excellent fade resistance due to the frequency diversity from spreading the signal over a large band. With appropriate transmission and reception schemes, the fading range of typical indoor UWB systems is as low as 5 dB [16]. The pathloss, however, varies significantly over the frequency band [17]. The required bit-energy-to-noise ratio for acceptable error performance can vary by up to 10 dB between the MB-OFDM subbands [17]. The fading performance can therefore be further improved with the knowledge of this pattern along with adaptive power allocation. By operating in subbands with lower fading, a CR transmitter can enhance transmission efficiency. This concept is similar to adaptive subcarrier loading in conventional OFDM systems, in which the signal power is distributed among the OFDM subcarriers with lowest fading. The consequent increase in the received signal-to-noise ratio (SNR) can improve the better bit-error rate (BER) performance, and a higher order modulation can be employed to increase the information rate. In addition, the coverage range can be extended, partially overcoming a major performance hurdle for UWB devices.

3.5 Multiple-Antenna System Performance

Spatial sensing and filtering can complement frequency filtering and reduce the hardware requirements associated with the latter. Spatial processing can be achieved with multiple-antenna arrays. An array-based system can also be used for angular processing. It can determine the direction of the intended receiver and the unintended listeners, followed by beamforming towards the receiver avoiding interference. This is especially under line-of-sight propagation, which is a common scenario for short-range indoor wireless communications applications. Transmit beamforming can, however, be impractical in UWB systems, as it may result in a violation of the spectral mask in a given direction without sophisticated spatial power control.

Multiple-input multiple-output (MIMO) techniques, which also use antenna arrays, are deployed in applications where it is desired to increase the data-rate and system reliability. With spatial multiplexing, a MIMO array can scale up the spectral efficiency linearly with the array size. UWB systems with MIMO arrays can support data-rates sufficient for high-definition multimedia wireless transmission [18]. Feedback MIMO systems can exploit the channel state information for optimal power allocation at the transmitter in the spatial dimension, i.e., among the antennas. As a result, the system capacity is increased further than that with equal power allocation used when the transmitter does not know the channel. At low SNR per signal dimension (space, frequency, polarisation, etc.), optimal power allocation can improve the capacity by several orders of magnitude. As the SNR per dimension in UWB systems is typically very low, UWB MIMO communications with channel cognition at both ends of the link can achieve extremely large improvements in the information rate.

4 Engineering Considerations

CR technology has not yet been incorporated into the industrial standardisation or commercial design process. With UWB's own standardisation and product development process still under progress, it may be several years before cognitive UWB devices become a reality. But given the large performance gains that intelligent processing can provide, cognitive UWB technology promises to pervade the wireless multimedia communications industry in the future. This section highlights some of the major tradeoffs involved in the implementation of CR UWB systems.

4.1 Implementation Complexity

The implementation complexity of CR UWB is a major hurdle, as it cannot be handled sufficiently well with the current device technology. Intelligent runtime processing and adaptation requires a large amount of digital signal processing (DSP) power. The complexity associated with UWB, arising from its high frequency and large bandwidth characteristics, complicates the design of CR under this regime even further. Current UWB implementations generally include extensive analogue electronics, which fails to offer the same flexibility and adaptability as soft implementations using DSPs. Digital technology, however, continues to evolve at a rapid pace, and can be expected to achieve the processing power required for all-digital implementation of cognitive UWB in the future. Furthermore, with rapid progress in ultrafast and nano-electronics, terahertz switching speeds may become commercially feasible in the future. Superconductor-aided rapid single-flux quantum (RSFQ) logic will facilitate the implementation of circuits considered prohibitively complex under the current semiconductor technology.

4.2 Resource Overhead

Adaptive algorithms provide improved performance but generate a certain overhead, which may manifest itself in terms of wasted resources or extra runtime processing. Thus, once CR UWB system implementation becomes realistic, issues related to the resource overhead will also need to be addressed. The methodology for approaching this problem lies in the application-specific analysis of the tradeoffs between the performance gain and overhead cost.

4.3 Propagation Effects

A narrowband outdoor mobile channel suffers from fast fading, causing it to vary rapidly and complicating the task of channel estimation and tracking. In feedback systems, delayed channel feedback can introduce encoding errors. In contrast, the slow-fading nature of UWB propagation channels makes adaptation and feedback more feasible. This also allows the periodicity of environmental sensing to be reduced and a low-capacity feedback link to be employed. In addition to greater data transmission efficiency due to lower control signalling overhead, CR UWB will enjoy greater reliability as a result of accurate channel state information.

4.4 Regulatory Issues

At present, the regulatory issues involved in both UWB and CR are being considered by the radio communications authorities in several countries. These are related to spectrum allocation, pricing, electromagnetic coexistence, and polite protocol development. In particular, spectrum pricing and revenue strategies under these regimes are attracting great attention. The challenge arises from the fact that UWB emissions are undetectable by an unintended eavesdropper, and are therefore hard to police or tax. Furthermore, for a CR UWB system, as the instantaneous signal bandwidth will not be constant, the spectrum usage may more appropriately be determined in terms of the bandwidth-duration product than the bandwidth alone. A preliminary protocol framework for spectrum pooling and renting in this manner was outlined by Mitola [9], but it needs refinement and extension to the UWB regime. Such complications necessitate a renewed radio legislation effort considering the fundamentally unique characteristics of this new signalling paradigm. Once these issues are resolved, however, cognitive UWB will provide a large amount of radio spectrum for wireless communications, increasing the spectral efficiency manifold. Considering that the mobile operators recently bought 3G spectrum licenses for up to £6 billion in the UK, the availability of several gigahertz of additional spectrum for shared use could potentially generate immense revenue for regulators and governments.

5 Conclusion

This paper has addressed some of the emerging trends in radio communications, noting that ultrawideband and cognitive radio technologies hold the key to the future of wireless systems. Underlining their natural relationship and emphasising the potential benefits of their joint exploitation, it has highlighted the performance boost that environmental cognition can provide to both single-band and multiband UWB implementations. Several open issues have been pointed out for further research, and a future vision has been provided. Given that UWB and CR share desirable many characteristics – most prominent among them the concept of opportunistic and collaborative spectrum usage – it appears likely that the synergetic combination of these two emerging technologies will be at the forefront of a wireless future.

Acknowledgement

This work was supported by the Engineering and Physical Sciences Research Council, UK, via Grant GR/T21769/01.

References

[1] J. Mitola and G. Q. Maguire, "Cognitive radio: making software radios more personal," *IEEE Pers. Commun.*, vol. 6, Aug. 1999.

[2] B. Allen, M. Dohler, E. E. Okon, W. Q. Malik, A. K. Brown, and D. J. Edwards (eds.), *Ultra-Wideband Antennas and Propagation for Communications, Radar and Imaging*. London, UK: Wiley, 2006.

[3] M. Z. Win and R. A. Scholtz, "Ultrawide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications," *IEEE Trans. Commun.*, vol. 48, Apr. 2000.

[4] A. Batra*, et al.*, "Multiband OFDM physical layer proposal for IEEE 802.15 Task Group 3a," IEEE P802.15-03/268r0-TG3a, July 2003.

[5] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE J. Select. Areas Commun.*, vol. 23, Feb. 2005.

[6] "Spectrum Policy Task Force Report," Federal Communications Commission, Washington, DC, USA FCC 02-155, 2 Nov. 2002.

[7] "Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies," Federal Communications Commission, Washington, DC, USA FCC 03-332, 17 Dec. 2003.

[8] M. J. Marcus, "Unlicenced cognitive sharing of the TV spectrum: the controversy at the Federal Communications Commission," *IEEE Commun. Mag.*, vol. 51, May 2005.

[9] J. Mitola, "Cognitive radio for flexible mobile multimedia communications," *Mobile Networks and Applications*, vol. 6, Sept. 2001.

[10] T. W. Rondeau, B. Le, C. J. Rieser, and C. W. Bostian, "Cognitive radios with genetic algorithms: intelligent control of software defined radios," in *Proc. Software Defined Radio Forum*. Phoenix, AZ, USA, Nov. 2004.

[11] N. Devroye, P. Mitran, and V. Tarokh, "Achievable rates in cognitive radio channels," *IEEE Trans. Inform. Theory*, vol. 52, May 2006.

[12] H. Zhang and R. Kohno, "Soft-spectrum adaptation in UWB impulse radio," in *Proc. IEEE Int. Symp. Personal Indoor Mobile Radio Commun.* Beijing, China, Sept. 2003.

[13] X. Wu, Z. Tian, T. N. Davidson, and G. B. Giannakis, "Optimal waveform design for UWB radios," *IEEE Trans. Sig. Proc.*, vol. 54, May 2006.

[14] H. Yamaguchi, "Active interference cancellation technique for MB-OFDM cognitive radio," in *Proc. Eur. Microwave Conf.* Amsterdam, The Netherlands, Oct. 2004.

[15] W. Q. Malik, D. J. Edwards, and C. J. Stevens, "Angular-spectral antenna effects in ultra-wideband communications links," *IEE Proc.-Commun.*, vol. 153, Feb. 2006.

[16] M. Z. Win and R. A. Scholtz, "Charaterization of ultra-wideband wireless indoor channels: a communication-theoretic view," *IEEE J. Select. Areas Commun.*, vol. 20, Dec. 2002.

[17] W. Q. Malik, D. J. Edwards, and C. J. Stevens, "Frequency dependence of fading statistics for ultrawideband systems," *IEEE Trans. Wireless Commun.*, (in press).

[18] W. Q. Malik, D. J. Edwards, and C. J. Stevens, "Measured MIMO capacity and diversity gain with spatial and polar arrays in ultrawideband channels," *IEEE Trans. Commun.*, (in press).