APPLYING COGNITIVE RADIO CONCEPTS TO HF COMMUNICATIONS

E. Koski*, W.N. Furman†

*Harris Corporation, U.S.A. ekoski@harris.com
†Harris Corporation, U.S.A. wfurman@harris.com

Keywords: HF, shortwave, cognitive radio, wireless.

Abstract

The concept of cognitive radio, originally proposed in 1998, has since then inspired growing interest and research activity. While the proper definition of the term "cognitive radio" remains debated, the concepts commonly offered as examples of cognitive radio all seem to involve ways in which a radio system can sense relevant features of its environment such as location, spectrum utilization, and spectrum availability, and intelligently adapt its behaviour and resource usage in light of regulatory constraints, equipment state, and other factors, so as to best meet the communication needs of the user. While the Automatic Link Establishment techniques widely used in HF radio systems are frequently offered as an example of an early, limited form of cognitive radio, most of the research attention in this area has been given to communications bands well above the 30 MHz upper limit of HF. In this paper, we first provide a concise overview of the variety of techniques that have been proposed as applications of the cognitive radio concept, and consider the applicability of these techniques to HF communications, in light of the distinctive characteristics of the HF communications medium and its typical uses. We then consider whether there might be distinctive cognitive techniques having promise to improve the effectiveness of HF communications, in spite of their having received little or no attention in other domains, and discuss potential challenges and critical success factors impacting the prospects for successful application of cognitive techniques to HF communications.

1 Introduction

Section 2 of the paper provides an introduction to cognitive radio, discussing its motivation, key concepts, and some emerging cognitive radio systems and research efforts. Section 3 provides a focused discussion of the most visible cognitive radio approach, Dynamic Spectrum Access, and considers its applicability to HF communications. Section 4 steps back to examine the challenges faced in present-day HF systems, seeking opportunities for cognitive radio technology to address these challenges. Section 5 briefly sketches a handful of new HF radio system concepts exploiting cognitive radio concepts to address these challenges, and Section 6 presents conclusions and future work.

2 Cognitive radio introduction

Cognitive radio is a collection of concepts and technologies that have come into being in response to a variety of forces and trends. The telecommunications explosion of the past 20 years has created an ever-expanding assortment of wireless communications applications and products, causing burgeoning demand for communications services and capacity. As the role and impact of wireless communications have become more pervasive, its economic significance has increased accordingly. Emerging applications such as streaming audio and video demand ever-increasing communications bandwidths and stringent quality-of-service guarantees, placing the relatively inelastic supply of radio spectrum under growing pressure. The variety of communications offerings, services, and applications creates an increased cognitive workload for the user, which threatens to limit market expansion unless developers find ways to drive more intelligence into the radio. At the same time, the proliferation of applications and services creates an impetus toward *convergence* – providing a wide variety of services in a single device – lest the user's ability and willingness to carry multiple devices become itself a limiting factor. This in turn creates more stringent requirements on the flexibility, adaptability, and intelligence of the communications device.

The advent of Software Defined Radio has been one response to these forces. By using software to define the capabilities and features of a radio, SDR technology makes it possible for a radio to become a cost-effective, flexible, adaptable, and high-performance platform for a wide variety of communications capabilities and services. By using software to implement and configure radio capabilities, a software defined radio has the potential to become a suitable platform for the kinds of intelligence required to address the challenges described in the preceding paragraph. However, Software Defined Radio does not itself encompass the kinds of radio intelligence required to

- Sense, learn, and adapt to the radio's environment (RF, location, etc.) so as to optimize its use of the radio spectrum resources available to it
- Sense, learn, and adapt to the user's characteristics and requirements so as to optimize the service provided to the user while controlling and reducing the user's cognitive workload.

These are the distinctive objectives of *cognitive radio*.

2.1 Cognitive radio concepts

The goal of cognitive radio is envisioned as the end of a progression through stages in which radio systems become increasingly intelligent and capable [16]. In successive stages, a radio system is:

- Aware. In this stage, radios sense characteristics of their RF, physical, or user environment, consolidate this information, and use it in providing some service to the user. The information may be displayed directly to the user (signal strength, time of day, network loading) or even shared with other radios, but plays no significant role in optimizing the communications performance of the radio system, except through user intervention.
- Adaptive. Adaptive radios use information sensed from their environment to modify aspects of their communications behaviour so as to optimize their communications performance. Examples include changing frequency, bandwidth, modulation scheme, code rate, data rate, or transmit power; a frequency hopping system might change hopset frequencies in order to eliminate blocked channels from the hopset [16]. The key element making these *adaptive* behaviours is that they occur in response to environmental information, rather than being merely scheduled or operator-initiated.
- Cognitive. Cognitive radios add to mere adaptation the elements of a cognitive system, such as having and maintaining a model of the environment that includes state and memory, a capability to learn, and a degree of autonomy in action [16]. Published descriptions of this level of capability are quite aggressive in invoking concepts and criteria from bleeding-edge Artificial Intelligence (AI) research, which might elicit sceptical reactions from radio system engineers needing to develop fit-for-use systems within schedule and budget constraints. Sources such as [1][5][10] provide in-depth descriptions of the cognitive architectures that might be required to achieve the ultimate artificially intelligent radio capability; however, it seems likely that simpler approaches to knowledge representation and machine inference may suffice to realize less ambitious and more domain-restricted forms of intelligent behaviour. One commonly-applied test for *cognitive* systems is their ability to creatively generate novel and unexpected behaviours. It's not clear that such creative behaviour is entirely desirable in radios using a limited, shared public resource; for this reason, most proposed cognitive radio architectures provide for some internal representation of regulatory policy constraints to be applied to radio behaviour [1].

In practice, it can be difficult to define an uncontroversial principled boundary between adaptation and learning. In considering what new concepts might be applicable to HF radio, it's not clear what is to be gained by agonizing over whether a particular concept should be labelled as "cognitive" or "merely adaptive"; this will not be a central concern of this paper.

2.2 Cognitive radio systems and applications

With limited exceptions, cognitive radio technology remains a research area with practical deployment and commercialization still some time away. Isolated capabilities with some claim to be considered 'cognitive' can be found in deployed systems. The Automatic Link Establishment (ALE) capabilities of HF radio systems [9] are occasionally cited as early examples of cognitive radio capabilities [16]. Typically, a radio supporting ALE uses sensing, probing, and monitoring techniques to assess channel utilization (Listen Before Transmit) and channel quality (path loss, noise, interference, Doppler and multipath spread characteristics), scoring channels based on these attributes and using channel scores to select channels for linking. This meets the criteria for an *adaptive* capability as described above; extensions to ALE could arguably cross the boundary into the *cognitive* realm by adding elements such as propagation modelling and prediction within the channel selection process (possibly drawing on location and time awareness), the use of real-time observations to adjust and refine propagation model predictions, or inferring the characteristics of some channels from those of others. Features of widely used cellular and PCS systems such as roaming and power management also fall somewhere along this spectrum.

The greatest commercial impetus toward cognitive radio development has been in the area of Dynamic Spectrum Access (DSA), because of the spectrum contention already occurring and projections that the problem will only worsen, with cellular demand in the GSM and UMTS bands predicted to exceed capacity between 2025 and 2030 [17]. A May 2004 Federal Communications Commission (FCC) Notice of Proposed Rulemaking (NPRM) provides for future unlicensed use of unused spectrum ('white space') in the TV broadcast bands [1][15]. At the same time, an FCC/NTIA 'test bed' program is evaluating concepts for reuse of spectrum presently allocated to public safety communications [11]. Current working drafts of the IEEE 802.11(h,y), 802.16(h), and 802.22 standards are beginning to find room for cognitive capabilities [12]. The time frame for commercial offerings based in these initiatives is not yet definite.

The most visible and fully realized implementation of cognitive radio technologies to date has occurred within the DARPA XG Program, which is focused on Dynamic Spectrum Access as a component of advanced military communications systems. The program seeks to develop, not a single radio system or architecture, but a portfolio of technologies supporting the goal of increasing DoD spectrum access by a factor of 10, while permitting new cognitive radio systems to coexist with legacy systems with no harm to the latter [6]. An XG prototype system underwent a reportedly successful demonstration at Fort A.P. Hill in August 2006, showing the capability of an XG system to form and maintain dynamic connectivity in the presence of operating military and civil legacy radio systems, without harm to the communications of the latter [7].

Clearly, cognitive radio concepts have been most fully elaborated in the area of Dynamic Spectrum Access (DSA); for this reason, the next section of this paper will more closely examine DSA concepts and their potential applicability to HF communications.

3 Dynamic Spectrum Access (DSA)

Dynamic Spectrum Access (DSA) derives its inspiration from the widely reported fact that, while the commonly-used regions of the RF spectrum are completely allocated to existing uses – and frequently to specific users – utilization of these allocated bands is in many cases surprisingly low [8]. The obvious inference to draw from this is that current methods for allocating and using the RF spectrum are needlessly wasteful, and that, by using more intelligent techniques to determine how channels are selected and used, it may be possible to accommodate significantly more users and more traffic within the same bands.

Regulatory practice already has an established distinction between primary and secondary users or "services", defined as follows:

> Stations of a secondary service: are on a non-interference basis to the primary service:
> (a) shall not cause harmful interference to stations of primary services to which frequencies are already assigned or to which frequencies may be assigned at a later date;
> (b) cannot claim protection from harmful interference from stations of a primary service to which frequencies are already assigned or may be assigned at a later date;
> (c) can claim protection, however, from harmful interference from stations of the same or other secondary service(s) to which frequencies may be assigned at a later date. [13]

Traditionally, frequency sharing between primary and secondary users has been assumed to be a manual process in which secondary users monitor frequencies for primary traffic before using them. DSA extends this concept through automation of the processes of channel monitoring, selection, and usage. In a typical DSA system concept, a secondary node monitors a collection of channels or bands for traffic, with the purpose of finding *whitespace* [8] or *spectral holes* [18]: channels or bands in which it is possible for the secondary node to transmit with an acceptably low probability of interfering with primary users' communications.

It can be helpful to view a spectral hole as a multidimensional region bounded in space, time, and frequency. Secondary users avoid interfering with primary users by separating their transmissions from the primary users, in so doing employing some form of *diversity* in a combination of frequency, time, and space. "Diversity" here refers to the separation between the secondary users' transmissions and any primary users' communications with which they could potentially interfere. *Frequency* diversity is self-explanatory (although subject to RF performance considerations such as spectral containment), and is the primary means used for traditional regulatory frequency management. *Time* diversity is a simple matter of not transmitting at times at which other traffic is on the channel, and frequently takes the form of familiar media access techniques such as Carrier Sense Multiple Access (CSMA) or the Listen-Before-Transmit methods used in HF ALE protocols [9]. Media access protocols achieve higher efficiency to the extent that they can assume coordination or cooperation among users of a channel or band, with slotted or *p*-persistent CSMA, TDMA techniques, and trunking techniques requiring successively higher levels of coordination but offering correspondingly higher levels of efficiency as a result. However, a key difference between media access techniques and DSA techniques is that the latter cannot assume any such coordination or cooperation, since the primary users with whom interference must be avoided are typically legacy systems whose technology and behaviour cannot be modified. Time diversity is also crucially dependent on the ability to monitor the channel or band of interest and sense the presence of primary users' traffic; this is made more difficult if secondary nodes lack *a priori* knowledge of the primary users' modulation format or other transmission characteristics.

The additional element of *spatial* diversity is the key to the DSA proponents' hopes of achieving increased communications capacity in a given region of the spectrum. The fundamental assumption is that, by ensuring that a sufficient spatial distance separates any transmitting secondary node from primary nodes, it is possible to limit the secondary nodes' potential interference with primary users to an acceptable level. Tandra et al [18] use the memorable phrase, "… a vase can be filled with rocks and still have plenty of room for sand …", which conveys the fundamental concept very effectively. The distinguishing feature of spatial diversity is that there is no attempt by the secondary node to ensure that a channel is completely unoccupied before using the channel; in fact, so attempting would preclude achieving increased capacity through frequency reuse, which is a conscious goal of this technique. Time diversity by itself uses or adapts media access techniques designed in the first instance for fully connected 'bus' communications media, wherein the medium is in a binary state: occupied or free.

In order to provide additional capacity while limiting interference with the primary network, a secondary network must be engineered so as to realize three key objectives:

1. Avoid interference with primary communications. The precise requirement might be to ensure that the presence of the secondary network does not reduce the signal to interference-plus-noise ratio (SINR) by more than a threshold quantity $\underline{t}$ (in dB).
2. Communicate successfully within the secondary network at no more than the maximum transmit power level permitted by #1.
3. Detect the presence of the primary network with sufficient reliability to meet requirement #1.

Whether and to what extent each of these requirements can be met is determined in a complex way by a variety of system attributes, as follows:

1. Will the secondary transmitter interfere with any primary receiver so as to reduce its effective SINR by more than t dB?
   - Primary transmitter power
   - Primary receiver(s) sensitivity and required SINR
   - Primary receiver(s) noise floor (internal, external)
   - Path loss from primary transmitter to primary receiver(s): PL(PTPR)
   - Secondary transmitter power
   - Path loss from secondary transmitter to primary receiver(s) (accounting for antenna gains): PL(STPR)
2. At the threshold transmit power at which a secondary transmitter reduces the SINR of the worst-case primary receiver by exactly t dB, what secondary communications are possible?
   - Path loss from secondary transmitter to secondary receiver(s): PL(STSR)
   - Secondary receiver(s) sensitivity and required SINR
   - Secondary receiver(s) noise floor (internal, external)
   - Path loss from primary transmitter to secondary receiver(s): PL(PTSR)
3. Can a secondary transmitter detect the primary transmission so as to be able to avoid interfering with it?
   - Path loss from primary transmitter to secondary transmitter: PL(PTST)
   - Secondary transmitter required receive SINR for detection of primary transmissions
   - Secondary transmitter receive noise floor (internal, external)

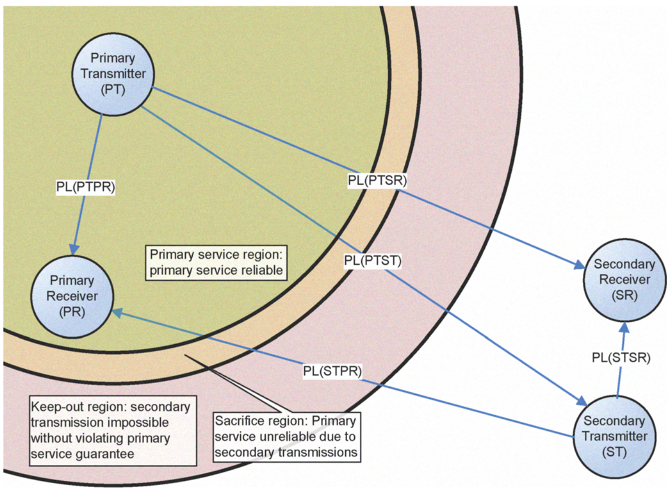

Figure 1. Secondary and primary nodes

Figure 1 represents schematically the situation of a secondary network in the presence of a primary network. The green central region represents the *primary service region*: the region in which primary services are required to be reliable. The yellow region surrounding it represents a *sacrifice region*: the region in which the primary service is rendered unreliable due to the presence of secondary transmitters. The goal of system engineering and management is usually to make this region as small as possible. The outer red region is a *keep-out region*: the region in which secondary transmissions are impossible without violating the requirement of reliable service within the primary service region. In this case, we are assuming that secondary transmitters attempt to detect primary transmissions in order to avoid transmitting within this region. The dimensions of these regions – and hence the extent of the opportunities for useful secondary network communications – are determined by the system attributes listed above.

The most challenging attributes to estimate in any network are likely to be the path loss attributes. In a line-of-sight communications system above 30 MHz, one has a decent chance of estimating the path loss values simply based on the spatial locations of primary and secondary nodes, free space loss equations, and antenna characteristics. Shadowing by land forms, buildings, or even weather can complicate the analysis, so that reliably determining where useful secondary communications can occur is by no means a simple problem [18]. Where it is available, *a priori* knowledge of the locations of primary transmitters (e.g., television broadcast antennas) and receivers can make the analysis much more tractable. No such simplification of the problem is possible if the primary nodes may be mobile.

If the secondary transmitter must rely on its own detection of the primary transmitter's signal to avoid interference, the resulting detection problem is especially challenging. The path loss from primary transmitter to secondary transmitter could be much greater (resulting in a lower signal) than the path loss from secondary transmitter to primary receiver, so that, to avoid interference, the secondary transmitter must be able to detect the primary transmitter's signal at an SINR well below the primary receiver's threshold SINR for successful communications. As a result, signal detection and classification algorithms are a flourishing research area within the field of cognitive radio. Researchers have even suggested that, in many cases, this problem may not be practically solvable just through a secondary transmitter's monitoring of primary transmissions. Instead, researchers propose to solve this problem through cooperative techniques. In one proposal, primary transmitters transmit some sort of pilot signal lending itself to detection. In another, it is proposed that secondary nodes might share channel occupancy information among themselves so as to eliminate the problem of a single secondary transmitter that is in a disadvantaged position to detect primary transmissions. The pilot tone concept is, of course, not applicable when the primary network is composed of 'legacy' nodes whose technology cannot be enhanced with this capability. Sharing of occupancy information adds complexity and overhead, and raises issues concerning the 'aging' and reliability of the shared information.

In assessing the applicability of this sort of DSA concept to HF communications, it is important to consider the role of spatial inferences in analyzing a particular secondary network deployment. A spatial inference plays a crucial role in determining whether a secondary transmitter will interfere excessively with a primary receiver. Path loss is assumed to be at least a fairly predictable monotonic function of path distance, so that if

1. The distance from primary transmitter to primary receiver is less than R_{psr} (the radius of the primary service region), and
2. The distance from primary transmitter to secondary transmitter is greater than R_{kor} (the radius of the keep-out region), then this ensures that
3. PL(PTST) – PL(STPR) $\leq \underline{D}$, the secondary transmitter's detection margin. This in turn ensures that
4. If the secondary transmitter is within the keep-out region, it will reliably detect the primary transmission so as to avoid interfering with it.

Such assumptions are almost never warranted for HF communications. In surface wave communications over any surface other than sea water, different ground characteristics can strongly influence path loss, so that the above inferences would frequently fail when different paths traverse different kinds of ground surfaces [3]. Matters are even far worse for ionospheric communications, in which radio signal coverage areas are frequently not even contiguous, as can be seen in a typical VOAAREA broadcast coverage plot [14]. For these reasons, DSA system concepts of this sort do not appear promising for most HF communications applications.

4 HF challenges and cognitive opportunities

Recognizing how difficult it would be to simply graft the most 'mainstream' cognitive radio concepts, those of Dynamic Spectrum Access, to HF communications prompts us to instead focus on the challenges faced in HF communications as they are practiced today. Designers, managers, and users of HF communications struggle with

- The limited predictability of HF propagation and its variation over time
- The limited bandwidths available for HF communications, imposed by both the traditional 3 kHz allocations designed for narrowband voice use, and the limited extent of the HF band as a whole
- The labor- and knowledge-intensive operating procedures required for successful HF communications
- The limitations of state-of-practice HF protocols and techniques such as ALE: scanning overhead, limited spectrum sensing, etc.
- New communications paradigms such as those of the worldwide internet, and the stringent new performance requirements they place on bearer media such as HF.

At the same time, recent trends in communications technology are giving rise to significant opportunities to address these challenges:

- Software Defined Radio (SDR), which offers a number of specific opportunities for performance optimization and value enhancement of HF communications systems:
  - Wideband sensing and monitoring capabilities made possible by using high-speed A/D converters to sample much or all of the HF spectrum, and using reconfigurable digital filtering rather than fixed analog filters to achieve the radio's required selectivity and blocking tolerance;
  - Wider communications bandwidths and bandwidth adaptation, exploiting the greater flexibility made possible by progressive digitization of IF and RF processing; and
  - Conjoining HF communications capabilities with capabilities in other bands, so that HF becomes but one (very important) capability of a true multiband radio.
- Entrenchment of the concept of a radio as being (among other things) a flexible computing platform makes it natural to envision adding intelligence to radio systems as a way of automating labour-intensive operations, embedding knowledge in the radio, and reducing the user's cognitive workload.
- Increased radio intelligence can further improve system performance by making radio operation more adaptive, and will be necessary to manage the increased operational complexity of radios with multi-*bandwidth* or multi*band* capabilities.

The system concepts briefly described in the next section are just three examples of ways in which techniques drawn from the field of cognitive radio (viewed broadly) can be employed to exploit the opportunities and meet the challenges.

5 Cognitive HF concepts

5.1 Next-generation ALE

HF communications benefit from the well-established use of the standard ALE protocols defined by MIL-STD-188-141B and STANAG 4538. The accumulated years of field experience with these protocols are making it possible to start envisioning the next-generation evolution of ALE. A forthcoming paper by the authors [2] provides an overview of concepts that could be considered, including some from within the cognitive radio domain: TOD-aware frequency selection, frequency pooling concepts (approaching a limited form of DSA), and intelligent power control and power management.

5.2 Ad hoc frequency management

Frequency management is a key challenge to effectively operating and managing HF radio systems. As presently practiced, it requires a multi-tiered process for selection and allocation of frequencies, from national frequency management agencies down to the selection of operating frequencies for an individual net. Because of the complexity of the process, it is often not done well. By bringing more knowledge of propagation and spectrum requirements to the level of the individual radio, it may be possible to make this process much simpler and more reliable.

5.3 Adaptive band selection

Location-awareness is already a well-established feature of HF radio systems, which use GPS-based location information for situational awareness. A multiband radio system combining HF and line-of-sight capabilities could use location information to choose the appropriate band for communications with the radio to be contacted, selecting an LOS band for higher capacity and bandwidth when the other radio is in LOS range, and HF when it is not.

6 Conclusions and future work

In this paper, we have reviewed the background and motivations of cognitive radio, emerging cognitive radio system concepts, and the most visible cognitive radio application, Dynamic Spectrum Access. By examining some of the technical challenges of DSA, we have determined that it appears to be a less promising concept for HF than for line-of-sight wireless media. However, by reconsidering the key challenges faced by present-day HF communications systems, we have been able to identify several areas in which cognitive radio concepts could make valuable contributions to the future evolution of HF radio technology. In future work, we hope to further elaborate and validate the cognitive HF radio concepts sketched in this paper, and to identify and investigate the key technical challenges involved in realizing these system concepts.

Acknowledgements

The authors wish to gratefully acknowledge Roy Breon for his helpful comments on this paper, and the Oxfordshire musicians known as Radiohead for inspiration and ambience.

References

[1] Federal Communications Commission, Notice of Proposed Rule Making FCC 04-113, "Unlicensed Operation in the TV Broadcast Bands", 25 May 2004. http://fjallfoss.fcc.gov/prod/ecfs/retrieve.cgi?native_or_pdf=pdf&id_document=6516214773 (downloaded 8 Feb 2009).

[2] W.N. Furman and E. Koski, "Next Generation ALE Concepts", in *Proceedings of the Eleventh International IET Conference on Ionospheric Radio Systems and Techniques (IRST 2009)*, forthcoming.

[3] J. Goodman, *HF Communications: Science and Technology*, New York, NY: Van Nostrand Reinhold, 1992.

[4] M. Kokar et al, "Roles of Ontologies in Cognitive Radios", in B. Fette (ed.), *Cognitive Radio Technology*, Burlington, MA: Elsevier, Inc., 2006.

[5] V. Kovarik, Jr., "Cognitive Research: Knowledge Representation and Learning", in B. Fette (ed.), *Cognitive Radio Technology*, Burlington, MA: Elsevier, Inc., 2006.

[6] P. Marshall, T. Martin. "XG Communications Program Overview" (presentation slides), 27 Feb 2007. http://www.darpa.mil/STO/Solicitations/WAND/pdf/XG_overview_for_WAND.pdf (downloaded 8 Feb 2009).

[7] M. McHenry, "Adaptive Spectrum Technology: Findings From the DARPA XG Project" (presentation slides), Software Radio Summit, February 20-23, 2007. http://www.sharedspectrum.com/press/pdf/SSC%20McHenry%20Software%20Radio%20Forum_Feb%2016%2007_%20v3.pdf (downloaded 8 Feb 2009).

[8] M. McHenry, "NSF Spectrum Occupancy Measurements Project Summary", Shared Spectrum Company, Aug. 2005. www.sharedspectrum.com/inc/content/measurements/nsf/NSF_Project_Summary.pdf (downloaded 8 Feb 2009).

[9] MIL-STD-188-141B: Interoperability and Performance Standards for Medium and High Frequency Radio Systems.

[10] J. Mitola III, *Cognitive Radio Architecture: The Engineering Foundations of Radio XML.* Hoboken, NJ: John Wiley & Sons, Inc., 2006.

[11] National Telecommunications and Information Administration (NTIA), "Spectrum Sharing Innovation Test-Bed Pilot Program Phase I Test Plan", DRAFT November 2008. http://www.ntia.doc.gov/ntiahome/frnotices/2006/spectrumshare/Draft%20Phase%20I%20Test%20Plan.pdf (downloaded 8 Feb 2009).

[12] J. Neel, "Networking Cognitive Radios" (presentation slides), 8 June 2007. http://www.crtwireless.com/files/CognitiveRadioNetworks.pdf (downloaded 8 Feb 2009).

[13] NTIA MANUAL OF REGULATIONS AND PROCEDURES FOR FEDERAL RADIO FREQUENCY MANAGEMENT January 2008 Edition, May 2008 Revision, Section 4.1.3. http://www.ntia.doc.gov/osmhome/redbook/Cover.pdf (downloaded 8 Feb 2009).

[14] J. Perkiömäki, "VOACAP Quick Guide", 7 January 2009. http://www.voacap.com/index.html.

[15] V. Petty et al, "Feasibility of Dynamic Spectrum Access in Underutilized Television Bands," *DySPAN 2007Proceedings,* Dublin, Ireland: IEEE 2007.

[16] J. Polson, "Cognitive Radio: The Technologies Required", in B. Fette (ed.), *Cognitive Radio Technology*, Burlington, MA: Elsevier, Inc., 2006.

[17] A. Shukla et al, "Cognitive Radio Technology: A Study for Ofcom – Summary Report", Issue 1.1, 12 February 2007. http://www.macltd.com/datafile_downloads/MAC%20Ltd%20-%20Cognitive%20Radio%20-%20Summary.pdf (downloaded 8 Feb 2009).

[18] R. Tandra et al, "What is a spectrum hole and what does it take to recognize one?", forthcoming in Proceedings of the IEEE for a special issue on Cognitive Radio, 2008. http://www.eecs.berkeley.edu/~tandra/pub1.htm (downloaded 8 Feb 2009).

[19] R. Wellington, "Cognitive Policy Engines", in B. Fette (ed.), *Cognitive Radio Technology*, Burlington, MA: Elsevier, Inc., 2006