Cognitive Radio: Ten Years of Experimentation and Development

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ABSTRACT

The year 2009 marked the 10th anniversary of Mitola and Maguire Jr. introducing the concept of cognitive radio. This prompted an outpouring of research work related to CR, including the publication of more than 30 special issue scientific journals and more than 60 dedicated conferences and workshops. Although the theoretical research is blooming, with many interesting results presented, hardware and system development for CR is progressing at a slower pace. We provide synopses of the commonly used platforms and testbeds, examine what has been achieved in the last decade of experimentation and trials relating to CR, and draw several perhaps surprising conclusions. This analysis will enable the research community to focus on the key technologies to enable CR in the future.

INTRODUCTION

Cognitive radio (CR), in its original meaning, is a wireless communication paradigm utilizing all available resources more efficiently with the ability to self-organize, self-plan, and self regulate [1]. In its narrow, however far more popularized definition, CR-based technology aims to combat scarcity in radio spectrum using dynamic spectrum access (DSA) [2]. DSA technologies are based on the principle of opportunistically using available spectrum segments in a somewhat intelligent manner.

Implementation and experimentation work has ramped up in the latter half of the decade. Because of the complexities involved in designing and developing CR systems [3, 4], more emphasis has been placed on the development of hardware platforms for full experimentation and testing of CR features. Since 1999, the first time the term *cognitive radio* was used in a scientific article [1], numerous different platforms and experimental deployments have been presented. These CR testbeds differ significantly in their design and scope. It is now appropriate to ask how mature these platforms are, what has been learned from them, and if any trends from the analysis of functionalities provided by these platforms can be identified. This article answers these questions.

This article has three main sections and contributions. First, we present a primer on the common systems being used for CR research and development. The following section focuses on overviews of the key events in recent years that have helped progress the field of CR and DSA technologies. We then present insights gained from these experiences and look ahead at how the community can grow in the coming years. We conclude in the final section.

CR IMPLEMENTATION: PLATFORMS AND SYSTEMS

We briefly review the most popular existing hardware and software radio systems, dividing these platforms into two headings. First, we deal with reconfigurable software/hardware systems, where the majority of the radio functionality, like modulation/coding/medium access control (MAC) and other layer processing, is performed in software. The burden in terms of processing and functionality on the radio frequency (RF) front-end is intended to be minimal in these cases. Second, we take a look at composite systems comprising a combination of purely software and hardware-based signal processing elements (e.g., field-programmable gate arrays [FPGAs]).

RECONFIGURABLE SOFTWARE/HARDWARE PLATFORMS

We begin by focusing on three research-oriented systems: OSSIE, GNU Radio, and Iris.

OSSIE — The Open Source SCA Implementation::Embedded (OSSIE) project is an open source software package for SDR development [5]. OSSIE was developed at Virginia Tech, and has become a major Linux-based open source SDR software kit, sponsored by the U.S. Nation-

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al Science Foundation (NSF) and the Joint Tactical Radio System (JTRS), among others. OSSIE implements an open source version of the Software Communication Architecture (SCA) development framework supporting SDR development initiated by the U.S. Department of Defense, and it supports multiple hardware platforms. Further information is available at http://ossie.wireless.vt.edu. OSSIE is mostly used at Virginia Tech.

GNU Radio — Arguably, the software defined radio (SDR) system with the most widespread usage is the open source GNU Radio project (http://www.gnuradio.org). It supports hardware-independent signal processing functionalities. Beginning in 2001 as a spin-off of the Massachusetts Institute of Technology's (MIT's) PSpectra code originating from the SpectrumWare project, the GNU Radio software was completely rewritten in 2004. Signal processing blocks are written in C and C++, while the signal flow graphs and visualization tools are mainly constructed using Python. GNU Radio is currently one of the official GNU projects having strong support from the international development community. A wide range of SDR building blocks are available, including ones commonly used to build simple CR-like applications (e.g., energy detection). The GNU Radio project prompted the development of the Universal Software Radio Peripheral (USRP) hardware by Ettus Research LLC, described later.

Iris — Iris is a dynamically reconfigurable software radio framework developed by the University of Dublin, Trinity College. This is a general-purpose processor-based rapid prototyping and deployment system. The basic building block of Iris is a radio component written in C++, which implements one or more stages of a transceiver chain. Extensible Markup Language (XML) is used to specify the signal chain construction and characteristics. These characteristics can be dynamically reconfigured to meet communications criteria. Iris works in conjunction with virtually any RF hardware front-end and on a wide variety of operating systems.

A wide range of components have been designed for Iris that are focused on CR-like systems. Multiple sensing components ranging from simple energy detection to more sophisticated filter bank and feature-based detection components are available. A suite of components for dynamically shaping and sculpting waveforms to make best use of available white space, or components that enable frequency rendezvous between two systems on frequencies that are not known a priori, have also been developed. For development purposes Iris can also interface with Matlab. Iris is predominantly used by the development group at the University of Dublin, Trinity College.

RF Front-Ends — GNU Radio and Iris are designed to carry out the majority of signal processing in software. However, each system requires a minimal hardware RF front-end.

USRP — The most commonly used RF front-end, especially in the research world, is the Universal Software Radio Peripheral (USRP). The USRP is an inexpensive RF front-end and acquisition board with open design and freely available documentation and schematics. The USRP is highly modular; a range of different RF daughterboards for selected frequency ranges may be connected.

Two types of USRP are available. USRP 1.0 contains four high-speed analog-digital converters (ADCs) supporting a maximum of 128 Msamples/s at a resolution of 14 bits with 83 dB spurious-free dynamic range, an Altera Cyclone FPGA for interpolation, decimation, and signal path routing, and USB 2.0 for the connection interface. USRP 2.0 replaces the Altera FPGA with a Xilinx Spartan 3-2000 FPGA, gigabit Ethernet, and an ADC capable of 400 Msamples/s with 16-bit resolution. The reader is directed to http://wwww.ettus.com for further information.

Other RF Front-Ends — A limited number of other RF front-ends are also available for use with these systems. These include the Scaldio flexible transceiver from IMEC, Belgium (http://www2.imec.be/ be en/research/green-radios/cognitive-radio.html), and the Maynooth Adaptable Radio System from the National University of Ireland, Maynooth [6].

COMPOSITE SYSTEMS

The boundary between hardware and software frameworks (or platforms) is not as straightforward as might be assumed. The emphasis in reality is on reconfigurability. A number of composite platforms exist which have both software and hardware components that can be used to facilitate CR systems. Composite systems differ from reconfigurable software/hardware platforms in that composite systems contain all the required components (dedicated hardware and software, documentation, ready-made software packages and modules, etc.) that allow for immediate CR development.

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Iris began life on a general-purpose processor but has also migrated to an FPGA platform. On the FPGA platform, components can be run in software on the PowerPC and/or in hardware on the FPGA logic. The main Iris framework runs on the PowerPC with many of the components mentioned above in the FPGA logic.

BEE — The Berkeley Emulation Engine (BEE) and its successor BEE2 are two hardware platforms developed by the University of California at Berkeley Wireless Research Center. BEE2 consists of five Xilinx Vertex-II Pro VP70 FPGAs in a single compute module with 500 giga-operations/s. These FPGAs can parallelize computationally intensive signal processing algorithms even for multiple radios. In addition to dedicated logic resources, each FPGA embeds a PowerPC 405 core for minimized latency and maximized data throughput between microprocessor and reconfigurable logic. To support protocol development and interfaces between other networked devices, the PowerPC on one of the FPGAs runs a modified version of Linux and a

In addition to the software-centric and composite systems described in this article, it is important to note that several stand-alone components have also been developed. The need for spectrum sensing, an important aspect of CR functionality, has been a driver for this development work.

	USRP2	KUAR	WARP	BEE2
RF bandwidth (MHz)	100	30	40	64
Frequency range (GHz)	DC-5 (non continuous)	5.25–5.85	2.4–2.5 (4.9–5.87)	2.39–2.49
Processing architecture	FPGA	FPGA	FPGA	FPGA
Connectivity	gigabit Ethernet	USB/Ethernet	gigabit Ethernet	Ethernet
No. of antennas	2	2	4	18
ADC performance	400 MS/s, 16 bit	105 MS/s, 14 bit	125 MS/s, 16 bit	64 MS/s, 12 bit
Community support	yes	no (defunct)	yes	no

Table 1. *Summary of popular development solutions for CR, see also [6, Table 2].*

full IP protocol stack. Since FPGAs run at clock rates similar to those of the processor cores, system memory, and communication subsystems, all data transfers within the system have tightly bounded latency and are well suited for real-time applications. In order to interface this real-time processing engine with radios and other high-throughput devices, multigigabit transceivers (MGTs) on each FPGA are used to form 10 Gb/s full-duplex links. Eighteen such interfaces per BEE2 board are available, allowing 18 independent radio connections in an arbitrary network configuration. The BEE2 with network and Simulink capabilities can be used for experimenting with CRs implemented on reconfigurable radio modems and in the presence of legacy users or emulated primary users. Further information is available at http://bee2.eecs.berkeley.edu.

WARP — The Wireless Open-Access Research Platform (WARP) (http://warp.rice.edu) from Rice University, Houston, Texas, is a complete hardware and software SDR design. WARP hardware is very similar in approach to the USRP. A motherboard serves as an acquisition board, while daughterboards serve as data collection boards. As of December 2009, two versions of motherboards were available. The version 2.2 motherboard is connected to a PC via a gigabit Ethernet interface. Motherboard processing is performed by a Xilinx Virtex-II Pro FPGA. Four independent motherboards can be connected at the same time. ADCs operating at 65 Msamples/s with 14-bit resolution are available. Software development for WARP is multilayered. It ranges from low-level very-high-speed integrated circuit hardware description language (VHDL) coding to Matlab modeling. Xilinx Matlab extensions for VHDL are available, and the code for WARP is widely open. As of December 2009, 21 demo implementations of different wireless functionalities using WARP originated from Rice University itself, while 17 are from other institutions around the world.

KUAR — The Kansas University Agile Radio (KUAR) was an experimental hardware platform intended for the 5.25–5.85 GHz unlicensed national information infrastructure (UNII) frequency band with a tunable range of 30 MHz [7]. It featured a Xilinx Virtex II Pro P30 FPGA with embedded PC for signal processing, four independent interfaces between the FPGA and embedded PC, and used an ADC with 105 Msamples/s and 14-bit resolution. The KUAR approach allows split processing between the embedded PC platform and FPGA. KUAR uses modified GNU Radio software to implement its signal processing features.

Other Platforms — Many other custom SDR platforms are available that are unique in both hardware and software design. However, we need to emphasize that these platforms simply provide appropriate hardware and software for the digital processing required, integrated with an RF front-end. Hence, the user of these products does not need to look for a standalone RF front. Some commercial platforms such as the Lyrtech solutions (http://www.lyrtech.com) among others also exist but are not considered in this article. The summary of described components, along with additional parameters, is presented in Table 1.

OTHER SYSTEMS

In addition to the software-centric and composite systems described in this article, it is important to note that several standalone components have also been developed. The need for spectrum sensing, an important aspect of CR functionality, has been a driver for this development work. Examples include Rockwell Collins, IMEC, and sensing devices from the Institute for Infocomm Research (I^{2}R), Singapore, which is addressed later in this article.

Finally, there are some well known DSA-focused SDR platforms that are not used directly in CR experimentation at the moment. The most prominent ones include the Japanese National Institute of Information and Communications Technology SDR Platform [6, Sec. 3.3], FlexRadio and PowerSDR used mainly for amateur radio work (http://www.flex-radio.com), and SoftRock kits (http://www.dspradio.org).

BUILDING CR AND DSA SYSTEMS: EXPERIMENTATION AND TRIALS

Following the brief synopses of the key systems enabling SDR and CR development, we proceed to the second main part of this article. We start with describing the experimental results of multiple platform interactions during recent SDR, CR, and DSA-focused conferences.

OVERVIEW OF IMPORTANT CR EXPERIMENTS

Conference Demonstrations — In the latter part of the last decade, some independent conference venues featured demonstration sessions. The information relating to these events forms our starting point. We focus mostly on the demonstrations presented at IEEE DySPAN and SDR Forum (now Wireless Innovation Forum) conferences, which are the most recognized and largest directly related events in the community.

A demonstration track was first established in the IEEE DySPAN conference series in 2007. Since that year there have been a total of 22 demonstrations. The SDR Forum annual technical symposium, run by the SDR Forum since 1996, organized their first demonstration track in 2007. The demonstrations presented that year comprised only SDR platforms and development kits for engineers. In 2008 real demonstrations were presented. In total, 12 demo platforms were shown, among them three that were related to DSA. During the 2009 SDR Forum conference event, 10 demonstrations were presented, among them three related to DSA systems. Important demos presented outside of these two venues are also included in this survey. The Association for Computing Machinery (ACM) MobiCom '09 included only one CR-like demo from RWTH, Aachen University, Germany. In 2008 ACM MobiCom featured one CR demo from Microsoft Research, China. ACM SIGCOMM '09 included one demonstration from the University of Dublin, Trinity College.

The survey data for this article were collected as follows. From the publicly available data on each demonstration, we have extracted information related to the waveforms used, frequency ranges, form of spectrum sensing, transmit or receive capabilities, control channel usage, type of application used, sponsoring body, and number of developers. We focused only on actual demonstrations, ignoring demos that were either presenting development frameworks only, or based on SDR and reconfigurable platforms that were not related to CR or DSA systems. In total, we have identified 41 relevant demonstrations. For detailed information on each demonstration platform the reader is referred to the respective conference proceedings. The data are as follows:

- IEEE DySPAN '10:
  - –Wright State University, Army Research, United States: "Spectrally Modulated Spectrally Encoded Platform"; sponsored by internal funds
  - –University of Dublin, Trinity College, Ireland, European Union (EU): "OFDM Pulse-Shaping for DSA; Multi-Carrier CDMA for DSA"; both sponsored by Science Foundation Ireland
  - –Institute for Infocomm Research, Singapore: "Communication in TV White Spaces"; sponsored by Singapore Agency for Science, Technology and Research
  - –IMEC, Belgium, EU: "Wideband Spectrum Sensor"; sponsored by internal funds
  - –RWTH, Germany, EU: "Policy Engine for Home Networks"; sponsored by German Research Foundation and EU ARAGORN Project; "OFDM Adaptation Based on Spectrum Sensing"; sponsored by German Research Foundation; "Decomposable MAC Framework"; sponsored by German Research Foundation and EU 2PARMA project
  - –Communications Research Center, Canada: "WiFi Network with Spectrum Sensing"; sponsored by internal funds
  - –University of Notre Dame, United States: "Primary User Traffic Pattern Detection"; sponsored by U.S. National Science Foundation and National Institute of Justice
- SDR Forum '09:
  - –University of Oulu, Finland, EU: "Mobile Ad Hoc Network with Opportunistic CR MAC"; sponsored by internal funds
  - –IMEC, Belgium, EU: "Wideband Spectrum Sensor"; (also IEEE DySPAN '10), sponsored by internal funds
  - –University of Piraeus, Greece, Alcatel-Lucent, Germany, EU: "Dynamic Radio Access Technique Re-Configuration"; sponsored by the EU E^2R Project
- ACM MobiCom '09:
  - –RWTH, Germany, EU: "CR Capacity Estimation"; sponsored by German Research Foundation and EU ARAGORN project
- ACM SIGCOMM '09:
  - –University of Dublin, Trinity College, Ireland, EU: "An FPGA-Based Autonomous Adaptive Radio"; sponsored by Science Foundation Ireland
- SDR Forum '08:
  - –University of Dublin, Trinity College, Ireland, EU: "Cyclostationary Signature Embedding and Detection" (see IEEE DySPAN '07); sponsored by Science Foundation Ireland
  - –Shared Spectrum Company, United States: "XG Radio"; sponsored by DARPA XG Program
  - –Virginia Tech, United States: "Multinode CR Testbed"; sponsorship information unknown
- ACM MobiCom '08:
  - –Microsoft Research, China: "WiFi Network on TV Bands"; sponsored by internal funds
- IEEE DySPAN '08:
  - –TU Delft, University of Twente, Netherlands: "Non-Continuous OFDM with Spectrum Sensing"; sponsored by Dutch AAF Freeband Program
  - –Philips Research, United States: "IEEE 802.11a with Frequency Adaptation"; sponsored by internal funds
  - –Adaptrum, United States: "Wireless Micro-

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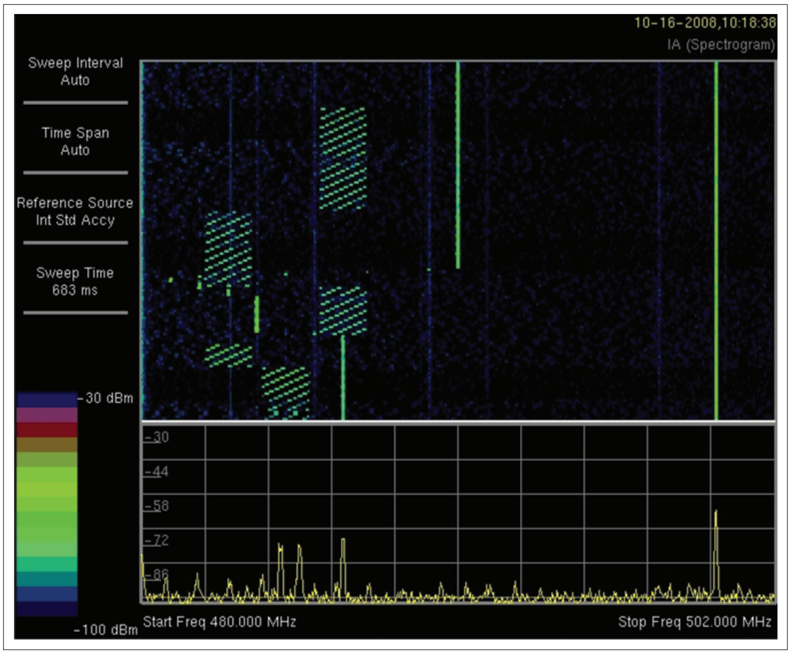

Figure 1. *Measurement results example from IEEE DySPAN '08. In the waterfall plot the narrowband signal is a FM transmission and the broadband signal is an XG radio. The waterfall spans approximately 60 seconds of measurement.*

phone Detection”; sponsored by internal funds

–University of Dublin, Trinity College, Ireland, EU: “Cyclostationary Signature Embedding and Detection” (also SDR Forum ‘08); “Point to Point DSA Link with Spectrum Sensing”; both sponsored by Science Foundation Ireland

–Virginia Tech, United States: “Heterogeneous Cooperative Multinode DSA network”; sponsored by U.S. National Institute of Justice, National Science Foundation, and DARPA

–Institute for Infocomm Research, Singapore: “Transmission over TV White Spaces”; sponsored by the Singapore Agency for Science, Technology and Research

–Motorola, United States: “WiFi-Like Operation in TV Bands”; sponsored by internal funds

–Omesh Networks, United States: “ZigBee-Based Self-Configured Network”; sponsored by internal funds

–Rockwell Collins, United States: “Spectrum Sensor and Signal Classifier”; sponsored by the DARPA XG Program

–Shared Spectrum Company, United States: “XG Radio”; sponsored by the DARPA XG Program

–University of South Florida, United States: “Spectrum Sensing with Feature Detection”; sponsored by internal funds

–University of Utah, United States: “High Resolution Spectrum Sensing”; sponsored by internal funds

- IEEE DySPAN ’07:

–Shared Spectrum Company, United States: “XG Radio”; sponsored by the DARPA XG Program

–Motorola, United States: “WiFi-Like Network in Licensed Bands”; sponsored by internal funds

–Virginia Tech, United States, University of Dublin, Trinity College, Ireland, EU: “Cognitive Engine-Based Radio Reconfiguration”; sponsored by Science Foundation Ireland

–University of Dublin, Trinity College, Ireland, EU: “Cyclostationary Signature Embedding and Detection” (also SDR Forum ’08); sponsored by Science Foundation Ireland

–University of Kansas, United States: “KUAR Presentation”; sponsored by the U.S. National Science Foundation, DARPA, and the Department of the Interior National Business Center

–QinetiQ, United Kingdom: “Spectrum Monitoring Framework”; sponsored by internal funds

–SRI International, United States: “Policy Reasoner Combined with SSC XG Radios”; sponsored by the DARPA XG Program

–University of Dublin, Trinity College, Ireland, EU: “Extensions to XG Policy Language”; sponsored by Science Foundation Ireland

–University of Twente, Netherlands, EU: “Spectrum Monitoring Device”; sponsored by the Dutch Adaptive Ad Hoc Free Band Wireless Communications (AAF) Program

IEEE DySPAN ’07 — During the first ever trial of its kind during IEEE DySPAN ’07, QinetiQ (a U.K. Ministry of Defense contractor) and Shared Spectrum Company carried out a simultaneous transceiver operation test in the UHF band. Data from the evaluation are not publically available as it was considered proprietary information. However, it was found that the Shared Spectrum Company’s detect-and-avoid system could coexist with a very fast hopping single-carrier system in the same frequency band. Further information regarding the demonstrations is available at http://www.ieee-dyspan.org/2007. A wireless trial licence was issued by the Commission for Communications Regulation (Comreg) in Ireland for multiparty trials in this case. Further information is available at http://www.testandtrial.ie.

IEEE DySPAN ’08 — IEEE DySPAN ’08 featured 13 live demonstrations comprising Tx/Rx and Rx-only systems. A special temporary authority license was issued by the FCC for the 482–500 MHz frequency range, allowing multiple companies and academic institutions to occupy and interfere with each other for the duration of the event. The University of Dublin — Trinity College, Shared Spectrum Company (using XG nodes), I^{2}R, University of Utah, Stevens Institute of Technology, OMESH Networks, Virginia Tech, and Motorola demonstrated DSA transceiver systems. Adaptrum, Philips, the University of South Florida, Anritsu, Rockwell Collins, and TU Delft carried out signal detection and analysis work using these transmission sources. This location features several high-power analog TV transmitters in the immediate vicinity. The trials demonstrated that DSA systems and networks could be established and maintained even in close proximity to these high-power TV services and even in Chicago's extremely crowded RF environment. Further information is available at http://www.ieee-dyspan.org/2008.

Figure 1 is an example waterfall plot obtained using an Anritsu MS2721B handheld analyzer inside the conference demo room spanning approximately 1 min. The wideband signal is Shared Spectrum Company's orthogonal frequency-division multiplexing (OFDM) signal from the XG nodes. This was operating on a *do no harm* basis and simply vacated any channel where the received signal level from a non-XG signal exceeded –90 dBm. In one scenario, a narrowband FM signal modulated with a 1 kHz sine wave was swept up and down in the frequency band to serve as a potential interferer to XG. It is clearly seen that the XG signal did move to a vacant channel. This proved that DSA is possible even in the shadow of extremely powerful adjacent channel TV transmissions. However, this also demonstrated the weakness of an energy detection do no harm approach. As an example of a simple denial of service attack demonstration, it was possible to trigger the XG signal to change channels as the detection system was energy-threshold-based. In some cases the XG and narrowband source appear on the same frequency. This is because the transmitted power of the narrowband interferer was reduced, and did not exceed the XG system detection threshold.

IEEE DySPAN '10 — IEEE DySPAN '10 featured 10 demonstrations of DSA systems. While some of the demonstrations possessed the capability to transmit, as was the case with the University of Notre Dame and Communications Research Centre Canada devices, all of them used license-exempt bands only. Two demos, one from RWTH, Aachen University, and one from University of Dublin, Trinity College, demonstrated the capability of non-contiguous OFDM transmission end effective subcarrier suppression techniques, again showing the demonstration using the license-exempt channels only.

Key Commercial Experimentation and Trials — This section presents brief overviews of key commercial trials and experimentation work carried out in recent years that have broken new ground and helped influence the direction of CR and DSA research.

DARPA XG Experimentation — DARPA XG radio was manufactured by Shared Spectrum Company in the early 2000s [8]. It is an implementation of a DSA system using interference detection and avoidance techniques. A policy engine is used for frequency selection and access. The XG radio uses the IEEE 802.16 physical layer, with a 1.75 MHz bandwidth OFDM signal and 20 dBm transmit power. All nodes in the network use a common frequency, despite the availability of more channels at a certain point of time.

One of the most interesting field trial results were presented in [8] by the Defense Advanced Research Projects Agency (DARPA) XG program. The DARPA XG trial was presumably the first private CR system trial ever. On August 15–17, 2006 the U.S. Department of Defense's DARPA demonstrated the capabilities of XG radios to work on a CR-like basis. Tests were performed at different locations in Virginia. Six mobile nodes were involved in the demonstrations, and as the authors claim, a demonstration was successful, proving that the idea of listen before talk communication equipped with policy-based reasoning in radio access is fully realizable. The system demonstrated very short channel abandon times of less than 500 ms (i.e., the time during which the device ceased communication at a certain channel and vacated it) and short reestablishment times (i.e., less than 200 ms) given the lack of pre-assigned frequencies. The reestablishment time is the time taken for the device to select a new channel and resume communications.

The channel abandon goal of 500 ms was mostly met, and problems were mostly due to software and IEEE 802.16 modem glitches. During the experiment U.S. Department of Defense radios were operating in the 225–600 MHz range, and XG radios were selecting unused frequency channels in this range (i.e., one out of six possible), where the number of all possible channels to select was an implementation choice.

Experiences from Spectrum Sensing in the TV Bands — The most prominent hardware trial for spectrum sensing thus far has been the FCC field trial conducted in 2008 by the Office of Engineering and Technology (OET). Five hardware prototypes from Adaptrum, I^{2}R Singapore, Microsoft Corporation, Motorola Inc., and Philips Electronics North America were submitted for examination. The tests covered TV signals and Part 74 wireless microphone signals, in a laboratory controlled environment as well as the actual field. All devices supported sensing of TV signals, while the I^{2}R, Microsoft, and Philips devices also supported wireless microphone sensing.

TV Sensing Laboratory Test: In general, all devices exhibited good sensitivities (better than the –114 dBm threshold established by the FCC [9]) in the laboratory single channel test. The Philips device in particular achieved the best sensitivity in a clean signal environment while the Microsoft device had the best performance in captured signal tests. Most devices were able to maintain good sensitivities when the adjacent channel power was within manageable levels for the devices [10, Table 3-1] for adjacent channel test results. However, the sensitivities were not determined in some cases due to insufficient selectivity, receiver desensitization, or device malfunction. From the measurable detection thresholds, the I^{2}R device threshold was better than –114 dBm for all cases except for one when the $N + 1$ adjacent signal level is at –28 dBm. The Philips device exhibited the best performance at low adjacent signal level of –68 dBm.

In some cases, the XG and narrowband source appear on the same frequency. This is because the transmitted power of the narrowband interferer was reduced, and did not exceed the XG system detection threshold.

We encourage open collaboration between research groups to help progress toward comprehensive demonstrations better linked to real-world scenarios. The IEEE DySPAN demonstrations series provided a glimpse of what value could be generated from these collaborative activities.

Prototype	**ATSC channels**		**NTSC channels**		**Unoccupied**
	Condition I	**Condition II**	**Condition I**	**Condition II**	
Adaptrum	91%	51%	89%	30%	75%
I^{2}R	94%	30%	25%[1]	10%[1]	81%
Motorola (geolocation)	100%	100%	100%	100%	71%
Motorola (sensing)	90%	48%	—	—	64%
Philips	100%	92%	100%	100%	15%

Note: [1] I^{2}R's white space device did not support NTSC but was tested by the FCC for NTSC anyway.

Table 2. *Probabilities of proper channel classification.*

Nevertheless, the future spectrum sensing hardware development should tackle the issues of lack of receiver selectivity and receiver desensitization, especially when the adjacent channels have high powers.

TV Sensing Field Test: Four test conditions (Table 2) were considered by the FCC [10]. Two of these test conditions involved the white space device (WSD) operating within the service contour of a station assigned to the channel. For condition I, the broadcast signal was viewable on a representative consumer TV, and for condition II, the broadcast signal was not viewable on a representative consumer TV. For condition II, we note that there is no mechanism to determine whether a TV signal actually exists in the measurement locations.

All devices, under condition I tests, met the intended probability of detection of over 90 percent for ATSC channels. The geolocation database approach from Motorola was able to identify occupied channels with 100 percent accuracy. For identification of unoccupied channels, the I^{2}R device exhibited the best performance, but not with complete reliability. Ironically, the geolocation-database-based approach did not exhibit the best performance in this aspect, presumably due to incomplete information in the database. This shows that spectrum sensing alone works to some degree, but the performance could be further enhanced especially in the identification of unoccupied channels. Combining a geolocation database with spectrum sensing may be a better option depending on the specific deployment scenario in mind.

Wireless Microphone Test: The field tests for wireless microphone sensing were performed with the I^{2}R and Philips devices at two locations. The Philips device reported all of the channels on which the microphones were designated to transmit as occupied whether the microphone was transmitting or not. The I^{2}R device indicated several channels as available even when the microphones were on. The wireless microphone field tests at first glance did not seem to give convincing results in the capability of the submitted WSDs to detect wireless microphone signals reliably. Nevertheless, the White Space Coalition (WSC) later found out that the wireless microphone operators were improperly transmitting signals on many channels occupied by TV broadcast signals within the protected TV service contours during the field trials [11]. Even so, there is so far no comprehensive trial that proves the acceptable performance of wireless microphone signal detection. As an alternative, the WSC proposed to use beacons for protecting wireless microphone signals.

OBSERVATIONS FROM CR PLATFORMS' INTERACTIONS

We now proceed to the third and final part of this article. We focus on the many interesting conclusions that may be drawn from the observation of the development progress of demonstration platforms for CR-like systems and networks presented earlier. Some of these may seem to be surprising and contradict the common feeling about the way these networks are evolving. We also suggest recommendations to help the community evolve faster and advance the field of research. These are summarized below.

THERE ARE PRACTICALLY NO COMPREHENSIVE CR DEMONSTRATION PLATFORMS

Almost all testbeds presented publicly are more or less focused on DSA functionality. From the surveyed demos, there is not a single one that presents at least a feature of CR that has been proposed in [1], like artificial intelligence (AI) usage in spectrum selection. We presume that the field is not mature enough to provide meaningful demonstrations with AI features. The more exciting AI functionality tends to lend itself better to scenarios involving networks, distributed resources, and higher-plane functionality featuring teamwork and collaboration [12].

We encourage open collaboration between research groups to help progress toward comprehensive demonstrations better linked to real-world scenarios. The IEEE DySPAN demonstrations series provided a glimpse of what value could be generated from these collaborative activities. Further public dissemination of outcomes from these activities in the form of website content and publicly available videos would significantly increase the visibility and impact of this work. This in turn would increase the prospects of collaboration and joint project opportunities with external groups around the world.

OPEN SDR PLATFORMS DOMINATE THE RESEARCH MARKET

As seen in Fig. 2a, the majority of demonstrations use GNU Radio and either the USRP or dedicated RF front-ends. This demonstrates that open source SDR development kits and open hardware platforms are proving to be the most accessible university research platform for DSA-related research. On the other hand, other open source software components supporting development of CR-like systems, such as WARP, Iris, and OSSIE, described earlier, are mostly used by the universities that developed them.

Open sourcing is a valuable means of enticing new users, supporting a wide range of development ecosystems, and increasing the impact of a research platform. Research institutions are encouraged to explore this option. Additional opportunities in the form of bespoke development work, greater employment opportunities for the researchers involved, and the prospects of a development lifetime not restricted by the duration of the project are potential indirect outcomes from this approach.

MANY TESTBEDS ARE NOT DSA IN THE STRICT MEANING OF THE TERM

Surprisingly, the majority of platforms enabling real-world communication and presented in the past couple of years are designed to work in license-exempt bands, where no requirements on primary user protection are present. However, certain issues (e.g., the interference impact of secondary opportunistic usage on primary users, and adjacent channel and dynamic range issues) simply cannot be analyzed properly unless deployed in a frequency band with active real-world incumbents. In addition to these technical constraints, market mechanisms and economic drivers including light licensing and incentive auction schemes cannot be properly trialed in license-exempt bands.

Spectrum regulators can provide wireless test and trial licensing options to help facilitate experiments in non-license-exempt spectrum that more closely meet real-world incumbent scenarios. The Commission for Communications Regulation (Comreg) in Ireland, the Office of Communications (Ofcom) in the United Kingdom, and the FCC (through their special temporary authority license mechanism) are examples of regulators that offer these options. We encourage research groups to avail of these opportunities where possible.

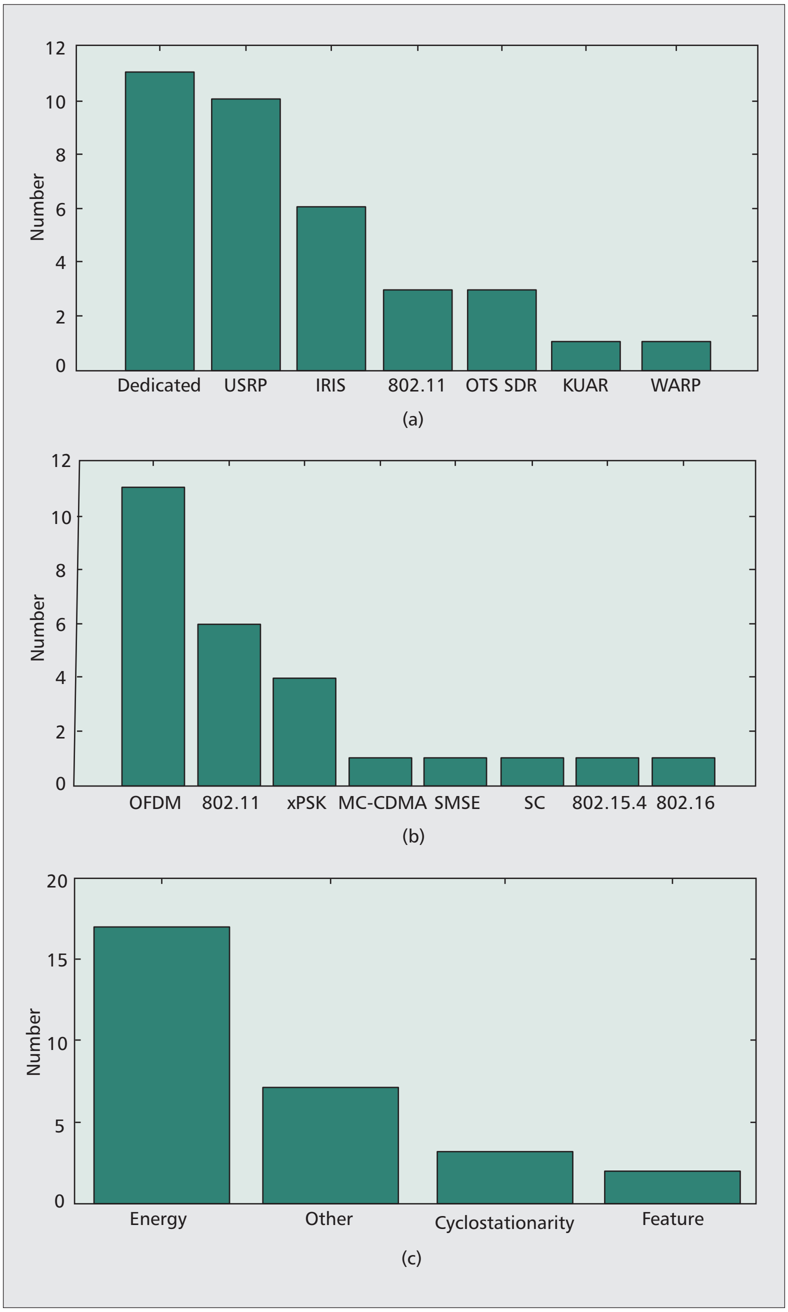

Figure 2. *Current status of CR demonstration platforms presented in this article: a) hardware platforms used; b) waveforms used; c) types of signal detection used (OTS: off the shelf, SC: single carrier, SMSE: spectrally modulated spectrally encoded).*

OFDM IS TYPICALLY THE DESIGN CHOICE FOR WAVEFORMS

Referring to Fig. 2b, the majority of waveforms used have been OFDM-based (including DARPA XG). In addition, some prototypes are based on IEEE 802.11 standards where OFDM is a standard spectrum access scheme. USRP-based testbeds use OFDM to implement noncontiguous forms of this spectrum access scheme, which allows for the dynamic notching and shaping of subcarriers to accommodate detected incumbent frequency user activity. Some other demonstrations not using OFDM are available, like recent University of Dublin, Trinity College demonstrations with multicarrier code-division multiple access (MC-CDMA).

Cost is a major factor in influencing the market adoption of WSD-based technologies. Further real-world trials are required to determine whether sensing and the associated costs can be significantly reduced if geolocation-based approaches can be employed to meet the regulatory guidelines.

Single-carrier (SC) waveform-based research should continue. SC schemes can alleviate the need for highly linear power amplifiers and backoff as is the case for OFDM, thus helping reduce the cost of user terminals. Single-carrier frequency-division multiple access (SC-FDMA) is a variant of OFDM being used for Long Term Evolution (LTE) and LTE-Advanced terminals, the successor to High Speed Download Packet Access (HSPDA). The research community can therefore stand to potentially benefit from extending their existing OFDM-based work to target SC-FDMA, carrier aggregation, and other related LTE-based technologies.

Energy Detection Is the Most Popular Signal Detection Method

Energy detection is used by the majority of the systems addressed in this article to detect the presence of other users in a band of interest. Energy detection offers a greater detection speed and less computational complexity than cyclostationary feature analysis, for example. However, this comes at a cost. Energy detection is not highly regarded for accuracy in low signal-to-noise ratio cases, as noted earlier. Among those demos enabling energy detection only, a few enable cooperation in spectrum sensing. However, it was found during the DySPAN demonstrations that this method is suboptimal and easy to abuse. There are many other interesting and more reliable sensing approaches in existence in the literature, including cyclostationary feature analysis [13, 14] and filter bank techniques [15], which lend themselves to implementation on a variety of the platforms mentioned in this article (Fig. 2c).

Geolocation and Sensing Are Needed for Maximum Reliability but at a Cost

The FCC WSD tests demonstrated that a combination of geolocation and sensing yielded the best results in condition I and II tests. However, the ability to sense signals down to the established thresholds may have implications in terms of significantly higher terminal costs than if a geolocation database approach was used on its own.

Cost is a major factor influencing the market adoption of WSD-based technologies. Further real-world trials are required to determine whether sensing and the associated costs can be significantly reduced if geolocation-based approaches can be employed to meet the regulatory guidelines. The outcomes of this work would also help shape regulatory policy in terms of a stance that balances the need for primary user protection, and helping new markets to emerge and evolve. These factors would in turn help to increase the market adoption prospects of new white space-based technologies.

Lack of Appropriate RF Front Ends

A key bottleneck in CR experimentation has always been (and we believe continues to be) the availability of appropriate frequency-agile RF front-ends that can easily be coupled with the parts of the CR that carry out the digital processing — be they pure software systems like GNU Radio or a mix of hardware and software like the BEE. The USRP has been the most successful product to do just this, especially in terms of accessibility for researchers (Fig. 2a).

We have approached the stage where out-of-the-laboratory tests are now required to significantly progress the field of research. The RF front-end requirements must therefore evolve to support this work. Increased transmit power, frequency range coverage, smaller form factors, increased support for add-on modules, an increased range of interfaces, weatherproof housings, and more adaptable power source facilities are key to facilitating this shift in focus. The research community needs to engage with large equipment vendors to demonstrate ideas and prototype solutions to promote development of new RF front-ends in sufficient quantities to provide for larger-scale research and commercial activities.

Small and Centralized Systems Are the Design Choice for Most of the Platforms

Designers have full control over their platforms with a centralized approach. This avoids the need for a control channel (19 out of 28 surveyed platforms focusing on networking had no control channel enabled); however, it means sacrificing the flexibility of the design. Most demos have two nodes, some have three, and there are a few that might have a few more. Thus, testbeds are small and not of a substantial enough size to really explore or uncover networking issues. There is much less focus on cognitive networks, and when a network focus is present the scenarios typically target single-digit numbers of nodes and centralized scenarios.

The time to increase the scope of the research vision has now arrived. The research community is urged to expand their testbed plans to examine larger-scale and distributed multinode scenarios over wider geographical areas. Collaborative efforts are now beginning to focus on this more, however. Key activities in Europe, for example, include the European Science Foundation's European Cooperation in Science and Technology (COST) IC0902 and COST-IC0905 (COST-TERRA) projects, which focus on applying CR across layers, devices, and networks, and developing a harmonized techno-economic framework for CR and DSA across Europe. Further information on these is available at http://cost-terra.org and http://newyork.ing.uniroma1.it/IC0902.

No Dramatic Increase in the Number of Available CR and Network Prototypes

The number of papers presented including cognitive radio as a keyword increases exponentially every year. However, every year IEEE DySPAN has received a similar number of demonstration submissions. IEEE DySPAN '07, '08, and '10 received 13, 15, and 12 submissions, respectively.

More industry-led research is now required to increase the number of prototype systems from the small set of systems focused on long-term research-only concept ideas.

ONLY ONE THIRD OF THE PRESENTED DEMOS ARE FROM THE UNITED STATES

Although the United States still dominates in research and development of CR-like systems, due to worldwide interest, almost 60 percent of the demos are from Canada, the EU, and Asia.

UNIVERSITIES DOMINATE THE DEMONSTRATION MARKET

As an emerging technology, DSA-based systems are the basis for patent generation and other intellectual property protection endeavors. This is one of the reasons why publicly viewable commercial offerings appear to be slow to emerge. On the other hand, university-created prototypes and research publications concerning these tend to emerge more quickly and involve public dissemination of the work through academic publications to help build the research profile and status of the research group and academic institution.

MORE EMPHASIS IS NEEDED ON REPORTING FAILURES

The development path of an emerging technology includes failures as well as successes. In many cases, the reasons why a particular DSA or CR approach was not successful can be perhaps even more important than the small number of scenarios where the system does live up to its claims. While some technical reports focus on problems associated with DSA-related systems like [10], research publications tend not to focus on this valuable information. By reporting the reasons approaches may not work, the research community can avoid repeating the same mistakes and evolve faster.

EACH DEMONSTRATION WAS DEVELOPED BY A SMALL NUMBER OF PEOPLE

Thanks in part to ready-made SDR systems, available documentation, and, in the case of the USRP, an active community of developers, the number of people involved in demonstrations can be limited. For the case of surveyed demos from the previous section, the average number of developers is approximately three.

ABSENCE OF IEEE 802.22 DEMONSTRATIONS

Interestingly among all presented demonstrations, not a single one implemented the IEEE 802.22 protocol stack. Although some components for IEEE 802.22 have already been developed (e.g., the spectrum sensing module of [16]), none of the universities and companies have focused on these networks. Not only are demos and testbeds for IEEE 802.22 missing; there is also a lack of literature on WRAN networks that directly take into account specifications of the standard to evaluate its performance [3, 4].

> *Interestingly, among all presented demonstrations, not a single one implemented the IEEE 802.22 protocol stack. Although some components for IEEE 802.22 have already been developed (see the spectrum sensing module of [16]), none of the universities and companies have focused on these networks.*

CONCLUSIONS

In this article we have presented a survey of state-of-the-art hardware platforms and testbeds related to CR concepts. We broke this work down into three sections. First, we present a primer on the common systems being used for CR research and development. Synopses of the key events in recent years that have helped progress the field of CR and DSA technologies follow this. Finally, we present insights gained from these experiences in an attempt to help the community grow further and faster in the coming years.

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