Evolution of Spectrum-Agile Cognitive Radios: First Wireless Internet Standard and Beyond

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ABSTRACT

Spectrum agile radios, also known as cognitive radios, have received much attention from researchers recently. Although the promise of cognitive radios in terms of increased access to spectrum was widely recognized very early, specific applications that utilize cognitive radio techniques have only recently began to develop.

In this paper we briefly describe the first wireless Internet standard that is based on Cognitive Radio techniques, namely IEEE 802.22, and discuss its performance with respect to one aspect of cognitive radios, namely operation over multiple frequency channels.

Furthermore, we discuss the evolution of cognitive radios beyond IEEE 802.22 by identifying some of the key factors that affect it, which in turn guide our research in cognitive radio PHY and MAC design.

Categories and Subject Descriptors

C.2.5 [Network Architecture and Design]: Wireless Communication.

General Terms

Algorithms, Performance, Design, and Standardization.

Keywords

Spectrum agile radios, cognitive radios, dynamic spectrum access, multi-channel access.

1. INTRODUCTION

Over the last decade or so the wireless community has developed and introduced a large number of applications. The phenomenal

success of wireless networking applications based on WiFi and bluetooth is being followed by UltraWideBand (UWB) and WiMax. This explosion in wireless applications will continue, with the newest application being Cognitive Radio (CR) based Wireless Regional Area Networks (WRANs).

These new applications require additional spectrum. While there is growing evidence that the existing unlicensed spectrum (for example, in 2.4 GHz band) is crowded, other frequency bands such as the television band are already allocated, however, unused [1].

As a result, the FCC is proposing a tiered access rights model [2] for dynamic access to spectrum. Such dynamic spectrum access (DSA) will result in increased utilization of the spectrum and quicker launch of new applications. The tiered access rights model allows preemptive access to the spectrum (for exclusive use) for users of higher access rights, whereas users with lower access rights use the spectrum opportunistically, in the absence of users of higher access rights. With this approach, the usage of the spectrum can be tailored to the needs in a given location at a given time, while ensuring the coexistence between various systems sharing the same frequency bands.

Cognitive radios are aware of the electromagnetic spectrum environment around them and make adjustments to their transmission characteristics accordingly, in a manner consistent with the tiered access rights model. Specifically, we define cognitive radios as having the following capabilities:

(a) Dynamic Spectrum Access (DSA): CRs must quickly and robustly detect the presence of incumbent users, who have preemptive rights to access the spectrum, to avoid causing interference to these users,

(b) Dynamic Spectrum Sharing (DSS): CRs must be aware of other cognitive radio networks of likely similar access rights and coexist with these networks, and,

(c) Dynamic Spectrum Multi-channel operation (DSM): CRs must be spectrum-agile and provide seamless operation over multiple channels, potentially simultaneously.

The first cognitive radio based wireless internet standard is IEEE 802.22, which incorporates all the three capabilities of a cognitive radio discussed above, namely DSA, DSS and DSM, and is designed to operate in the TV bands. Beyond this first application, several factors determine the evolution of future CRs. These

factors include evolution of spectrum regulation permitting spectrum access, state-of-the-art in device and circuit technologies for wideband operation, state-of-the-art in designing flexible wireless devices, and finally, pull from application scenarios. From an industrial research perspective, these factors guide the choice of research topics in physical (PHY) and medium access control (MAC) layers.

In this paper, we (a) briefly present the first wireless Internet standard that is based on CRs, namely, IEEE 802.22, and discuss its DSM related features and their performance within this standard, and (b) discuss the impact of each of the aforementioned factors on the evolution of future CR based applications.

For DSA and DSS related features of IEEE 802.22 please see [3].

2. FIRST COGNITIVE RADIO BASED WIRELESS INTERNET STANDARD: IEEE 802.22

2.1 Introduction

The technical and operational requirements of WRAN networks based on 802.22 are described in detail in [4]. Here we summarize (a) the requirements for incumbent detection response times, service capacity and coverage range, and (b) key challenges in designing a cognitive radio based WRAN system in order to meet all the specified requirements.

The WRAN system must detect the presence of the DTV, analog TV and wireless microphone services at low SNR levels of –116 dBm (within 6MHz), –94 dBm (within 6 MHz) and –107 dBm (within 200 KHz), respectively. In addition, its response times, in terms of vacating a channel when an incumbent appears on that channel, are defined by Dynamic Frequency Selection (DFS) timing parameters [5] [6]. The most critical parameters, namely, channel detection and move times are of the order of 2 seconds.

The service coverage of a WRAN system is nominally 30 km, however, if regulation permits higher transmit power limits, its range must cover up to 100 km. In addition, the WRAN system is expected to provide a capacity of 18 Mbps per TV channel and offer a service comparable to Cable/DSL. This translates to a peak data rate of 1.5 Mbps downstream and 384 Kbps upstream per user.

Cognitive radios enable DSA based on tiered access rights; however, require the refinement of the traditional architecture for communication systems. The key challenges in designing the

WRAN system include:

• DSA: accommodation of tiered access rights and time-changing nature of incumbents with preemptive access rights;

• DSM: achieving capacity and long range (nominally 30 km, however, up to 100 km) operation;

• DSM: the need to increase spectrum utilization versus the complexity of wideband operation, namely, operation in multiple frequencies and in non-contiguous bands;

• DSS: the need for self-coexistence in a TDMA system since the intended bands are to be operated in an unlicensed mode, and a new WRAN service can start in an uncoordinated fashion;

• DSA and DSS: the need for coordination of quiet periods among these otherwise uncoordinated networks;

• DSA and DSS: management of channel measurements, namely, which channel to measure, what measurement reports to communicate, which measurements to aggregate;

• DSA: notification of the presence of incumbents, and recovery from sudden lost connection due to incumbents.

In this paper we focus on DSM aspects of 802.22, please see [3] for DSA and DSS aspects.

2.2 Channel Bonding and Aggregation

CRs must be spectrum-agile and provide seamless operation over multiple channels, potentially simultaneously. Two DSM or dynamic multiple channel access mechanisms are supported in the draft 802.22 standard, namely, channel bonding and channel aggregation. The dynamic channel bonding approach shown in Figure 1 (and discussed below) enables adjacent (contiguous) vacant television channels to be bonded together and utilized for data communication. Such bonding is needed to meet the channel capacity and range requirements for WRAN as discussed above. In addition, the base station can also perform channel aggregation by operating over multiple non-contiguous channels, invoking multiple PHY/MACs stacks, as shown in Figure 2.

A new superframe structure is defined to support channel bonding and other features (support for other features is discussed elsewhere [3]). This superframe structure consists of a preamble and a Superframe Control Header (SCH), which are repeated in all the bonded channels, as shown in Figure 1. When a yet unassociated Consumer Premises Equipment (CPE) wants to join the network, it must first know if channel bonding is in use. If the CPE operates on any one of the bonded channels and receives the
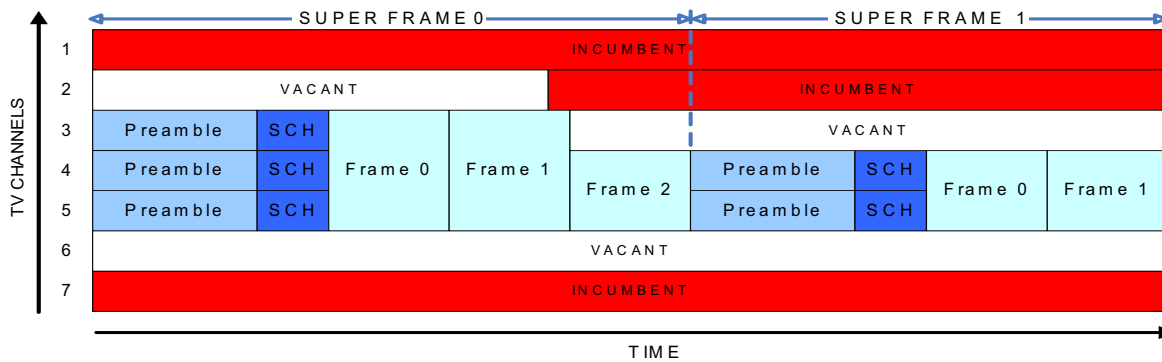

Figure 1: This figure shows the superframe structure in 802.22 that supports, among features, dynamic channel bonding.

SCH, it can determine if bonding is used. This superframe structure allows dynamic channel bonding[1], in other words, channels can be bonded and un-bonded from one superframe to the next, depending upon the absence or presence of incumbents.

The operation of dynamic channel bonding is illustrated in Figure 1. Initially, channels 1 and 7 are occupied by incumbents. The WRAN operates on channels 3, 4 and 5, leaving adjacent channels 2 and 6 vacant as required. The superframe preamble and SCH are repeated on all the bonded channels, as explained above. During frame 1 of superframe 0, another incumbent starts to operate in channel 2. The WRAN detects this incumbent and vacates channel 3 from frame 2 onwards. Superframe 1 then consists of bonded channels 4 and 5.

2.3 Key Benefits of Bonding

Key benefits of channel bonding are:

(a) capacity increases linearly with bandwidth but only logarithmically with signal power or SNR,

(b) better multi-path diversity, since small bandwidth signals can have deep fade or flat fade, whereas, wider-bandwidth signal provides more frequency/multipath diversity, and,

(c) better interference mitigation, since wider-band reduces the impact of narrow-band interference.

In addition, an architecture allowing channel bonding and channel aggregation, while increasing spectrum utilization on a need basis, keeps costs low since the client stations (i.e., CPEs) operate only in contiguous bands and do not require high performance and high cost radio frequency front-ends.

2.4 Performance Evaluation

In this section, we present performance evaluation of channel bonding, including channel capacity (see Figure 3 and Figure 4) and range (Table 1).
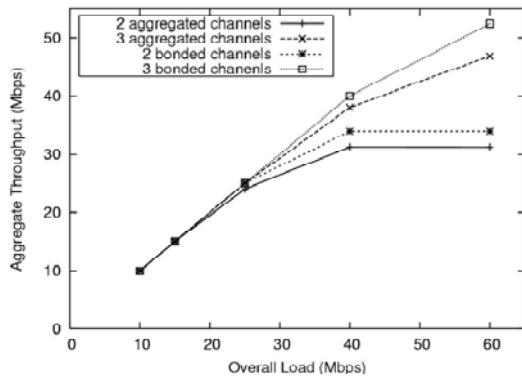

Figure 2: Throughput for bonding and aggregation.

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[1] Note that this is the first standard that allows dynamic channel bonding. IEEE 802.11n does permit bonding, however, since these networks operate in ISM bands where no incumbents are present, channel bonding is static.
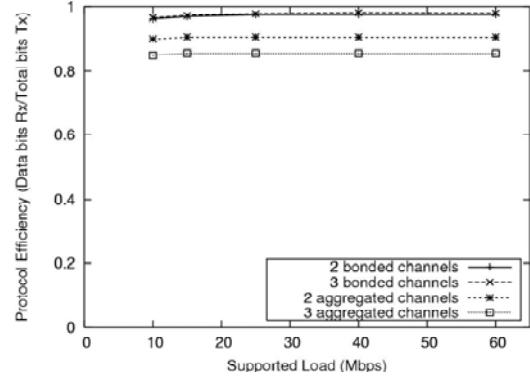

Figure 3: Protocol efficiency.

We also present network joining times (see Figure 4) which are slightly increased due to channel bonding, however, are shown to be within reasonable limits.
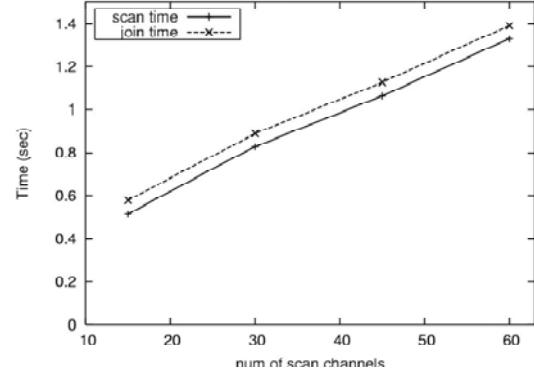

Figure 4: Network joining times.

modulation	QPSK	64-QAM	16-QAM
coding rate	1/2	2/3	1/2
Throughput/channel	**5**	**19**	**29**
center frequency	0.7	0.7	0.7
bandwidth	**6**	**6**	**18**
Distance	**30000**	**6000**	**30000**
Tx power	4	4	12
Tx averg power	36.0	36.0	40.8
TX antenna gain	0.0	0.0	0.0
Rx power			
free space path loss	119	105	119
Rx antenna gain	12	12	12
cable and other losses	3	3	3
Total received avrg power	-74	-60	-69
Receiver noise figure	4	4	4
Noise power	-106	-106	-101
Interference allowance	3	3	3
Received SNR	25	39	25
Required SNR	4	20	10
Implementation/OFDM loss	6.0	6.0	6.0
Link Margin	15.4	13.3	9.4

Table 1: Line-of-sight link budget calculation, showing a range of 30 km.

3. EVOLUTION OF COGNITIVE RADIOS BEYOND 802.22

Several programs sponsored by the National Science Foundation (NSF) and Defense Advanced Research Projects Agency (DARPA) are active in the area of cognitive radios. The NSF ProWin, the DARPA XG and the DARPA WANN all are related one way or the other to cognitive radios. Common to these government programs is a vision for the development of cognitive radio platform[2]. These CRs operate over a very wide range of frequencies, for instance, up to 6 GHz.

In the commercial world, however, for a number of reasons this vision will take longer to materialize. Several factors determine the evolution of future CRs, beyond the IEEE 802.22 based wireless internet application discussed in Section II. Rather, we envision that cognitive radios will evolve in a step-by-step fashion. Firstly, we expect spectrum regulation to progressively allocate more bands for unlicensed use. Furthermore, regulations permitting, CRs will likely evolve in steps with respect to (a) spectrum foot print, namely, initially narrow band cognitive radio systems will be developed and deployed, and later wide band systems, (b) flexibility, namely, first generation fixed protocol systems will be followed by field upgradeable etiquettes. This step-by-step approach is depicted in Figure 6 (x-axis for spectrum footprint, and y-axis for flexibility), and discussed in the following. In addition from an application point of view, we believe that fixed cognitive radios will be developed first and will be followed by portable and mobile (e.g. cellular) ones.

3.1 Impact of Spectrum Regulation

Currently the FCC is considering opening up the television bands for unlicensed operations in the US, as discussed in its Notice of Proposed Rule Making (NPRM) [8]. Briefly, this FCC NPRM envisions two types of applications in the television bands: fixed/access and personal/portable. Devices belonging to the fixed/access type are intended for rural broadband access applications, and are permitted higher transmit power, up to 36 dBm. Whereas, personal/portable type devices are allowed up to 20 dBm.

Beyond the television bands, we anticipate a step-by-step approach to permitting more unlicensed use of the spectrum.

3.2 Impact of Wideband Physical Layer Technologies

In addition to regulations, a number of technical challenges (and opportunities) remain in realizing the wideband vision. These challenges include the development of cost-effective devices and circuits that operate over a wide band of frequencies. There are two aspects of wideband operation (a) wideband tunability and (b) wideband communications. It is interesting to note that a number of promising options for the former challenge (i.e., wideband tunability) are becoming available, for example, based on Radio-Frequency Micro-Electro-Mechanical Systems (RF-MEMS). However, wideband communication requires components such as Analog to Digital Conversion (ADCs) whose bandwidth and

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dynamic range requirements pose significant challenges in terms of both cost and power consumption. See [10].

The implication of this assessment from the point of view of PHY and MAC layer design is that although wideband communication provides better quality-of-service (especially lower delay) [11] developing solutions for wideband tunable (over several GHz), yet not-so-wideband communication (tens of MHz), provides a major impact. Such system architecture puts greater emphasis on the MAC and higher layers for better coordination between devices within a network in order to achieve higher throughputs, as discussed in [11]. Hence, the DSM aspects of cognitive radio, such as multi-interface radios and multi-channel MACs, become more relevant.
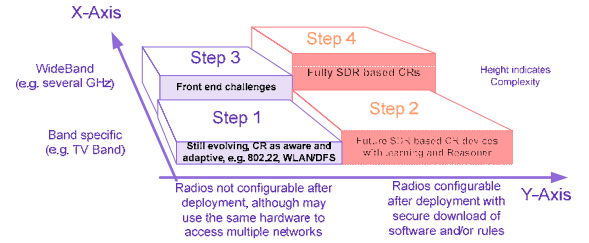
Figure 5. Evolution of CRs. All radios in this figure are cognitive and perform DSA, DSS and DSM functions. Note that step 3 may happen earlier than step 2.

3.3 Impact of Flexibility, Reconfigurability

The other axis of evolution of CRs is flexibility. Flexibility is needed to meet different requirements in commercial and military wireless networks. In commercial wireless networks, which typically tend to be infrastructure oriented, flexibility to adapt a radio system's transmission characteristics (spectrum usage) based on external factors is key. In military networks which tend to be infrastructure-less, however, flexibility in the implementation of CRs is used to provide robust end-to-end services in an ad-hoc network. Originally, a popular vision for CRs was that they are an extension of software defined radios (SDR). In fact, the terms SDR and CR were coined by Joseph Mitola [7] with such a vision in mind. SDRs clearly provide flexibility to CRs, however if they is not carefully designed can result in significant cost/complexity penalties. In the following we discuss the unique advantages of SDR-based CRs, and the challenges associated with it.

In current commercial wireless networks (operating both in licensed and unlicensed bands), devices are increasingly built using programmable platforms, see for example EVP [9]. Programmable platforms provide a number of benefits, including flexibility of design during manufacturing and upgradeability after deployment. In addition, they result in smaller form factor, since these modes are implemented in software, and hence lower cost.

Which functionality of spectrum-agile radios is upgradeable after deployment depends upon the design and architecture of such programmable platforms — for example, hardware-software partitioning. Key metrics to consider in architecting programmable platforms are cost, power and size to meet given application performance requirements such as throughput, delay, range and robustness. For example, a low-throughput application can be enabled by a complete SDR solution in some frequency

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[2] It may be pointed out that the DARPA XG is focused on developing policy-based radios, which are related to CR, rather than a radio platform.

bands, while high-throughput applications (several Mbits/s to Gbit/s radios) need more hardware components to meet commercial requirements.

Some of unique advantages of a full SDR based CR stem from reconfigurability after deployment which can be used to (a) build one product and deploy worldwide accommodating various regulatory requirements, and (b) accommodate evolving protocols and etiquettes. The DARPA XG program is developing a programmable language (based on DAML) to configure radios on the fly for the former application, that is, to accommodate various regulatory domains worldwide. They define a policy engine or kernel within the XG radio that can be certified, and that operates upon policy rules that may be authored by various regulatory authorities. Cognitive algorithms, based on policy reasoner, may be needed to deconflict contradictory policies. On the other hand, the use of a policy language to accommodate evolving protocols and algorithm based on learning remains a distant goal.

In summary, SDR-based CRs provide some unique advantages from the point of view of the need for flexibility and programmability after manufacturing, smaller form factor, faster time-to-market, etc. However, as application becomes more and more broadband, more and more PHY components become hardware oriented and are implemented as fixed functions. Therefore, cleverly architected and designed flexible multi-modal systems may have the greatest impact. Evolution of programmable wireless networks in the sense of using a language such as DAML to program field deployed wireless devices with new protocols remains a distant goal.

4. CONCLUSIONS
The promise of spectrum agile cognitive radios in terms of increased spectrum access has been widely recognized. Specific applications that utilize cognitive radio techniques are just beginning to emerge. In this paper we present IEEE 802.22, which is based on cognitive radio techniques, is used for wireless Internet applications. Specifically, we present DSM aspects of 802.22, and analyze its performance. We also identify and discuss some of the key factors that drive the success of cognitive radio beyond IEEE 802.22.

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