Sensing as a service: An exploration into practical implementations of DSA

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Sensing as a Service: An Exploration into Practical Implementations of DSA

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Abstract—**The cognitive radio literature generally assumes that the functions required for non-cooperative secondary DSA are integrated into a single radio system. It need not be so. In this paper, we model cognitive radio functions as a value chain and explore the implications of different forms of organization of this value chain. We initially explore the consequences of separating the sensing function from other cognitive radio functions.**

Index Terms— **Cognitive radio, Economics, Radio spectrum management**

I. Introduction

Cognitive radios (CRs) have emerged as a critical technology for enabling more intensive sharing of unused radio frequency spectrum, or, equivalently, Dynamic Spectrum Access (DSA). In the 12 years since CRs were first proposed [1], working devices have been developed by engineers. To date, most of the focus on implementing CRs has focused on non-cooperative or "opportunistic" secondary sharing models in which the CR is designed as an independent radio system that must share spectrum with a potentially hostile, or at least not explicitly cooperative, primary spectrum user. The CR is presumed to operate in a way that is practically presumed to be invisible to the primary user. The assumed lack of cooperation with the primary user imposes additional technical, operational, and strategic constraints that may add to the complexity and difficulty of evolving commercially successful DSA, CR-enabled radio systems [2]. Relaxing this assumption raises the potential for alternative assignments of CR functionality between the primary and secondary users. In this paper, we explore some of the technical, economic, and regulatory implications of relaxing the presumption of non-cooperation, and consider the benefits of re-organizing the locus of functionality for identifying and managing opportunities for secondary usage. This analysis suggests a richer spectrum of sharing models that may aid in the commercialization of CR and DSA technologies, as discussed in Chapin and Lehr [3].

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The successful commercialization of DSA-based, CR-enabled radio systems will depend on numerous business-related factors, including:

- Availability of low cost, low power user devices (e.g., handsets)
- Sufficient bandwidth available for secondary use on a predictable and cost-effective basis
- Ability to deliver at least "good enough" service quality [4].

The spectrum that is currently targeted for the initial commercialization of such systems for secondary-use, sharing is the TV "white space" spectrum [5].

A. A Critique of Integrated CR systems

Integrated CR systems for non-cooperative secondary sharing are biased toward FDMA/FDD-based sharing because the sensing requirement for TDMA/TDD systems is too short for accurate detection [6]; the same is true of LTE [7]. Thus, these systems may be unable to adequately detect primary users in non-FDMA/FDD systems. Accessing idle spectrum in such systems is likely to require closer coordination between the primary and secondary users.[1]

[1] For example, to access idle spectrum in TDMA systems, the primary and secondary user must be synchronized in time; in CDMA systems, they must be synchronized in time and share the code space.

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B. Cooperative DSA

If DSA systems assume that the primary and secondary users are cooperating, then new sharing opportunities arise. MVNOs already provide an example of cooperative sharing in which the primary and secondary users are closely coupled [8]. More loosely coupled systems have been studied as well (see, for example Tonmukayakul and Weiss [9]).

With cooperative usage models, the primary and secondary users can contract or bargain over the efficient allocation of the burdens of spectrum sharing (i.e., interference and interference-avoidance related costs). For example, if one considers the system as the collection of primary and secondary users, then total system costs might be lower if the sensing function is assigned to the primary user, or alternatively, to a mutually agreed upon third party, rather than imposing the full burden for sensing on the secondary user – as is the case in the current model of non-cooperative TV white space secondary-use sharing.

C. Value Chain of Integrated CR systems

To consider how the functions of an integrated CR might be re-allocated, let us begin by considering the value chain of a DSA system (Figure 1). Value chain analysis has been applied to the wireless industry before (see, for example Maitland et.al [10]), though it has not been applied on a relatively microscopic level such as this. Our value chain is loosely based on the functional architecture of a CR. However, instead of being focused on building a technical architecture, it is oriented toward determining how components add value to the user as communication needs are met.

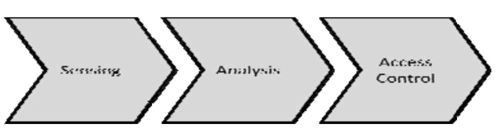

Figure 1 -- CR Value Chain

A user's communication requirement implies capacity and performance requirements. The capacity requirement typically consists of a bit rate or a bandwidth. The specification of the performance requirements varies more with the use of the channel but may include factors such as latency, error rate, signal to interference and noise ratio (SINR), availability, etc. Following Tonmukayakul and Weiss [9], we assume that users may choose one of the following: dedicated licensed channel; unlicensed channel; or, secondary (non-cooperative) use of a dedicated licensed channel. Each of these communications channels has differing performance and cost parameters. A CR adds value to the user if it can meet the communications need with minimal resource consumption.[2]

Opportunistic systems, or those that perform non-cooperative secondary sharing, are typically cognitive radios [11] [12]. To analyze the value chain, let us begin by considering a simple narrowband radio. Such a system would be capable of transmitting in one frequency band with one modulation scheme. Functions that add value to such a simple radio include:

- finding white spaces,
- analyzing the characteristics of these white spaces to match them with the requirement, and
- adjusting the technical transmission parameters so that national regulations (e.g., FCC in the US) are not violated for the band in question.

White space identification (WSI) can rely on acquired environmental information and/or an external database of permissible channels in the region in question. Channel analysis can rely on the information from the detectors or databases and previously obtained information. Parameter adjustment takes advantage of software radio functionality in the radio.

Spectrum sensing is a potentially costly activity. Cognitive radios in their most general form must be able to detect unknown signals at the noise floor of the communications channel. Furthermore, when they are sensing, they are not able to transmit so that sensing reduces their ability to utilize a communications channel. Finally, for a variety of reasons, cognitive radios may need to share this information with other radios. These include the hidden node problem, the need for detection along the entire transmission path, to support the discovery of anomalies, and to support the discovery of other opportunistic secondary users.

These challenges are compounded by the information processing requirements. If the

[2] Resources include monetary and power resources. Since we are considering only opportunistic systems, the price is zero.

transmission is to take place over a geographic region, specific, large-scale infrastructures must be deployed that perform continuous sensing functionalities over that coverage area to avoid interference. This can come in the form of a system of cooperating integrated CRs or through sensor nodes. The amount of information accumulated from these sensor nodes would be significant; even if operators would make the investments required to gather the data, they may well lack the means and the experience to analyze it in real-time and translate the results of such analyses (equally real-time) into control decisions within their networks. The need to aggregate and analyze cross-RAT (within operators) and cross-operator data would further increase this complexity.

II. DIS-INTEGRATION OF WHITE SPACE IDENTIFICATION

In all examples of CRs that we are aware of, the sensing function is incorporated into the individual CR radio. Embedding the cost of WSI in each CR raises the cost of the secondary radio devices and exposes certain security vulnerabilities [2].

An alternative to this approach is to consider a services-based approach to WSI for cognitive radio. While the WSI service may be offered by the primary user (or licensee), it may make sense to have a separate WSI service provider that could provide WSI services across the spectrum bands dedicated to multiple primary users. The WSI provider may play a number of roles. For example, the WSI might simply act as an information provider (returning a catalog of available white spaces to primary and secondary users); or, alternatively, the WSI provider may offer a more complex range of services, including acting as a band manager that negotiates contracts where necessary. A WSI is likely to be able to provide superior detection capabilities to an on-board CR-based system.[3] Enhanced WSI is valuable because it supports higher transmission rates because it is better at avoiding interference with the primary user[4] and is better at detecting channel availability.

To perform this service, let us suppose that the WSI provider constructs a sensor network capable of detecting spectrum holes in space and time, and across multiple frequencies (spanning the dedicated spectrum of several primary users). The WSI may also interact with databases containing spectrum information (such as the one required by the FCC [5]). Since the WSI provider would be aware of the cooperating primary users (voluntary or by regulatory fiat) in the area, it would be able to design antennas and detectors optimized for these users. In contrast, a general purpose CR must have sensing capabilities that span a larger frequency range because they must be able to sense in this as well as other geographic areas where the cooperating primary users may operate on different bands or at different power levels. Because the sensors belong to the same organization (i.e., the WSI provider), the hidden terminal problems are resolved as are the problems with cooperative sensing.[5]

There are likely to be significant scale and scope economies associated with sharing a common WSI infrastructure across all secondary users, rather than requiring each secondary usage radio to implement its own integrated sensing functionality. Since this infrastructure is general purpose, the costs can be distributed over all CRs operating in the geographic area of the WSI provider and may therefore be able to provide higher quality sensing at a lower cost.

In terms of the value Network architecture, the disintegration of sensing functionalities into a discrete role – i.e. a business entity that is not embedded within another one but is self-sufficient in creating and capturing value within the larger context of the business ecosystem – would be a significant step away from the configurations currently under study. As a first example of this, we consider the value network of the systems studied in

[3] We conclude this for economic and technical reasons. Economically, a service provider would have an incentive to out-perform alternatives, such as CR-based sensing systems, and would invest to achieve that. Especially compared with mobile CRs, a sensing network can use better antennas and invest more power in sensing. Sensors can also be placed strategically based on the topography of the region.

[4] This may have monetary consequences as well if penalties are incurred as a result of interfering with the primary user (i.e., license holder).

[5] Cooperative sensing is vulnerable to opportunistic nodes that might deliver false information to improve their throughput. They are also vulnerable to malicious nodes seeking to disrupt communications [21]. A WSI provider solves the cooperation problem through integration [20] and the security problem because sensors can be trusted and their identity verified.

the E^3 project[6], as represented by the Unified Business Model (UBM). Over the life span of three large European Commission funded research projects on Cognitive and Reconfigurable Radio (in the period 2004-2009), the UBM [13] has been a reference metamodel for next generation wireless systems, specifically focusing on the relationships between business roles in Dynamic Spectrum Access ecosystems making use of CR, but also made compatible with more service oriented business scenarios developed within other projects of what was then the Wireless World Initiative [14]. Although concerned with more than just sensing, the projects making use of the UBM do greatly rely on the gathering of contextual information, and significant research effort was spent on Spectrum Sensing Mechanisms as a Cognitive Enabler to be used in conjunction with others, such as a Cognitive Pilot Channel [15].

In terms of business roles, sensing has always been regarded as a functionality integrated into the operator's network, in the device or in both. In the UBM, this was represented by the embedded role of the *Cognitive Network Element Manager* located either in the network (standardized) or in the user device (proprietary) and, besides taking care of cognitive device and network management and reconfiguration process management and respective interactions between the roles involved in certain reconfiguration processes, also responsible for contextual information gathering [14]. It is also because no specific business relationship was envisaged with regard to the exchange of information (such as CR sensing data) between devices and network elements, that a Cognitive Enabler for the exchange of such data (e.g. a Cognitive Control Radio) was not included in the UBM even though it has been studied from a technological point of view in this project.

Another strand of relevant projects are the ones dealing with value network aspects of wireless sensor and actuator networks, i.e. networks deployed with the objective of sensing activity other than spectrum occupancy. One of the main current research projects in the Europe related to this is SENSEI, which began in 2008 and aims to create an architecture that fundamentally addresses the scalability problems for a large number of globally distributed white space devices, taking into account mechanisms and interfaces for accounting, security, privacy and trust [16]. Although the business modeling activities in connection with this project are not finished, the first results do not discuss outsourcing the physical sensing network.

Finally, there is a category of projects dealing specifically with spectrum sensing for aiding Cognitive Radio. Again in the European context, a significant current research effort in this domain is the SENDORA project [17], which aims to develop techniques based on sensor networks for supporting coexistence of licensed and unlicensed wireless users in a same area. Interestingly, the (unfinished) business modeling activities of this project do mention the possibility of disintegrating the sensing activities.[7] However, at least so far this option has not been explored further. Instead, the project has generated some advances in sensor networks for spectrum sensing (see, for example [18]).

A. Simple WSI service

The simplest possible service is that in which a catalog of available white spaces is returned to the CR in response to a query (such as, perhaps, was envisioned by [18]). This could include the available frequency bands and the geographic boundaries where these bands are available. When the primary user requires the spectrum, the WSI service signals all secondary-use CRs that registered with them that the channel is no longer available. In this case, the CR determines, in cooperation with its communications partners, which band(s) to use. Because the CR is unaware of other CRs operating in the region, they must use a MAC protocol to share the spectrum since the WSI service does not provide assistance in mediating channel sharing in this mode.

[6] One of the largest research projects on Cognitive Radio in Europe, under the European Commission's 7th Framework Programme, which concluded in December 2009.

[7] In particular, D1.1 of the project draws up 4 different business scenarios (one actor using CR and WSN to improve running or enhance business, the owner of the radio spectrum sells cognitive spectrum resources to others, a spectrum broker scenario and CR in unlicensed spectrum) and mentions an outsourced WSI as one of three options for all of these scenarios (the other being a broker owned and sensor network self owned).

Such a service imposes a set of technical requirements, notably:

- The existence of a standardized communications channel between the CR(s) and the service provider (e.g., a Cognitive Pilot Chanel (CPC) [15]);
- An ability of the CR(s) to communicate among themselves;
- An ability to detect idle bands even with active secondary users

Detection in the presence of secondary users generally requires a silent period of sufficient duration and sufficient frequency for detection to take place. WSI providers might also engage in out-of-band coordination with primary users as a way to reduce the overhead of spectrum sensing.

In addition, WSI providers should be in a better position to coordinate with primary users since they are persistent in the environment. Repeated successful interactions tend to foster trust. Consequently, WSI providers might be able to coordinate the temporary assignment of non-FDMA/FDD spectrum that might otherwise go unused.

B. *WSI with channel delegation*

This operating mode consists not just of the WSI service but includes channel selection. Thus, the CR request includes the channel requirement (e.g. bandwidth, SINR, duration, geographic coverage) so the service provider returns a recommended channel. The CR must still utilize a MAC protocol for channel sharing.

The technical functionality of the service provider now expands to include spectrum analysis. This involves matching channel characteristics to the requirements of the secondary user and the history of the primary user(s) that have the licenses for that channel.

C. *Secondary sharing band manager*

A further evolution of the service provider would be one who operates as a secondary sharing band manager for spectrum bands where secondary sharing is permitted. Thus, it is not only aware of the primary users but also of all of the secondary users[8]. Such a service would include WSI, channel delegation to secondary users, mediation among secondary users and payment settlement (where necessary). In this case, we may assume that all secondary use is managed and so there is no pure non-cooperative secondary use.

III. Sample Use Cases

Since this approach to DSA enables cheaper radios, we can imagine a few possible use cases that help describe how such an approach to DSA might work.

A. *Ultra-low cost mobile*

In many countries, mobile operators must pay for spectrum use either through *ex ante* auctions or spectrum use fees. This cost will be reflected in the prices of spectrum users. Thus, a carrier that is able to avoid these fees might be able to charge lower prices or reap superior profits. One way such a system could work is as follows:

- The user would first attempt to complete the call on a local WiFi hotspot;
- If the service quality is inadequate, no hotspot is available, or if the hotspot prices are too high, the user would query the WSI service to determine if a suitable band was available;
- If no band was available, the user would “roam” on a licensed spectrum operator’s network and incur the roaming fees.

If the cost of the radios (handsets) are comparable to those of licensed spectrum operators and the WSI service fees are reasonable, then such a service could be economically attractive and offer an entry opportunity that does not exist today. Many handsets today operate on multiple bands and support WiFi; even though this is not the same as a tunable software radio it is suggestive that the first cost condition should be within reach.

Since no WSI service exists today (the concept of using sensing information to steer network and channel selection itself still being a relatively new one), it is difficult to judge whether the service fees would be comparable to what licensed operators must charge their users for spectrum. If a WSI service provider has many clients, then the cost of

[8] We assume that this band manager does not have authority over primary users. Functionality of that kind would be more akin to cooperative primary sharing, which is not the focus of this paper. See Caicedo and Weiss [22] for more on that topic.

the infrastructure is amortized widely across many users so the fees should be quite low. Second, the cost structure of WSI service is similar to telecoms in that a large, geographically specific service is being provided. Also, like telecoms, the incremental cost of this service should be quite small. We should expect prices to reside between incremental cost of service and the imputed license fee. If a competition exists in the WSI market, then this would tend toward the incremental cost side of this range.

B. Public safety

In the US, public safety spectrum consists of many narrowband systems that are captive to particular agencies (i.e., police, fire, emergency medical) [19]. In this scenario, public safety communications would first attempt to use the agency's captive spectrum. If this spectrum is busy or the QoS is unsatisfactory, the user/radio would query the WSI service to determine if a channel with adequate quality existed. Thus, public safety agencies would not have to cede their channels (which has proven to be difficult) but could supplement their channels with unused spectrum. In principle, it would be possible to maintain the existing communications infrastructure and operate the DSA spectrum in parallel on an as-needed basis.

IV. Analysis and Implications

The benefits of outsourcing the sensing function are likely to be greater in the following circumstances:

- When the spectrum environment is dynamic. For example, if a primary users' usage is dynamic over time and space (mobile) and hard to predict; and, when there are likely to be multiple non-cooperating secondary use systems in the same area. The sensing challenge is much more difficult and expensive to implement in terms of increased guard-band behavior which translates into reduced secondary-spectrum availability and higher sensing mechanism costs;
- When the secondary usage CRs confront significant cost, power consumption and/or size constraints; and/or,
- When the CRs may need to operate across multiple dedicated bands in diverse geographic locations.

In the previous section, we have outlined three different approaches to what might be outsourced. Each approach offers a different value proposition to a CR-based communication system, and each has different implications for industry structure and public policy (regulation).

The first approach, which provides a simple sensing-only service, requires that CRs perform spectrum analysis computations as well as any settlements that may be necessary for cooperative secondary sharing (i.e., a temporary spectrum lease from a primary user [9]). Such an approach requires the construction of an infrastructure for the WSI provider. There is no barrier (except market size) to the emergence of multiple providers who might compete on price, geographical coverage, sensing accuracy, spectrum breadth, etc.

The second approach enables the CR to devolve to an agile software radio with MAC, since sensing and spectrum processing functions are provided. MAC functions must still be performed within the radio as multiple secondary radios may be using the same channel. As with the first approach, the emergence of competitive providers is not foreclosed by the technical approach, though market size may limit the number of competitors.

The third approach shifts more functionality to the service provider and allows for even simpler secondary use devices because no MAC is required. In this approach, the service provider acts as a band manager of sorts for the secondary use bands. Because of this role, it is unlikely that multiple band managers would emerge for the same secondary sharing bands. Furthermore, the functions and relationships between the secondary use devices and the service provider would suggest that these may be provided as an integrated system. This could easily become a "walled garden" so that the service provider could monetize the communications service more effectively.

V. Conclusions

CR-based systems are still in their infancy. The technology is still under development and the applications are unclear. As a result, we can expect a variety of industry scenarios as experience is gained with these systems. While the autonomous, opportunistic radio system has been the design goal, there is no reason to believe that this type of system will come to dominate the industry. Various approaches to sharing, which may involve greater degrees of cooperation than is assumed in the pure opportunistic approach are possible and perhaps even more likely in the near term. Similarly, the autonomous radio holds a measure of intellectual appeal, but there is no reason to believe that this might be the only approach to take.

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