Cognitive Radio: The New Frontier for Antenna Design?

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We have all probably heard the complaints that the radio spectrum is too crowded to introduce any new wireless services, and that the limiting factor behind development of faster wireless networks is the lack of available wireless bandwidth. Although it is true that a majority of the useful radio spectrum is already allocated to different wireless services, the FCC found in 2002 that monitoring of the wireless spectrum for a period of time does not reveal restrictive signal congestion [1]. The reality is that those who have licenses to various portions of the spectrum do not always use their allocation, at least not in all of the places all of the time. In fact, the spectrum can be idle up to 90% of the time!

Today, research in cognitive radio is aimed at developing efficient wireless communication strategies to make use of this unused spectrum. The idea is to make smart wireless devices that can observe their RF environment and detect unused frequency bands in real time. That way, we can operate more of wireless devices in the same frequency bands that are already in use. It is desirable to develop devices that can learn from their observations and make their own decisions about when and how to transmit without disrupting any existing wireless connections.

The question for us, as antenna engineers, is what role can antennas play in all of this?

Obviously, there is a need for antennas that can make a cognitive radio (CR) system work with other devices across multi-bands, multi-standards or multi-channels. Since these new devices must both learn *and* adapt to their RF environment for the purpose of establishing seamless communication with other RF devices, can antennas also be designed to learn and adapt or reconfigure themselves? At the physical layer, the defining characteristics of the envisioned system include a) *cognition:* the ability of spectrum sensing across multi-bands, multi-standards and multi-channels to detect and classify RF activities of interest, and the ability to decide in which band and under what standard the radio needs to establish communication with a chosen RF device via learning and reasoning, and b) *reconfigurability*: the ability to adapt RF communications parameters such as standard, carrier frequency, power transmission, modulation format, coding scheme and data rate entirely in software, without having to change hardware.

To be able to autonomously detect and establish communication with another RF device in its range, the RF device should be able to monitor and sense its RF environment to detect RF activity, classify a detected RF activity as one of several possibilities, and establish communications in appropriate modes. Due to impairments inherent in the wireless channel as well as ambient noise, it is possible that a cognitive radio device can either mistakenly detect or miss an RF device in its range as well as misclassify a detected device.

Dynamic spectrum sharing (DSS) is arguably the concept that has drawn the most attention from the research community in cognitive radio today. Some of the spectrum sharing proposals can be identified as being hierarchical-access methods, in that there is usually a primary system that owns the spectrum rights and a secondary system that wants to access this spectrum whenever possible, as shown in Figure 1.

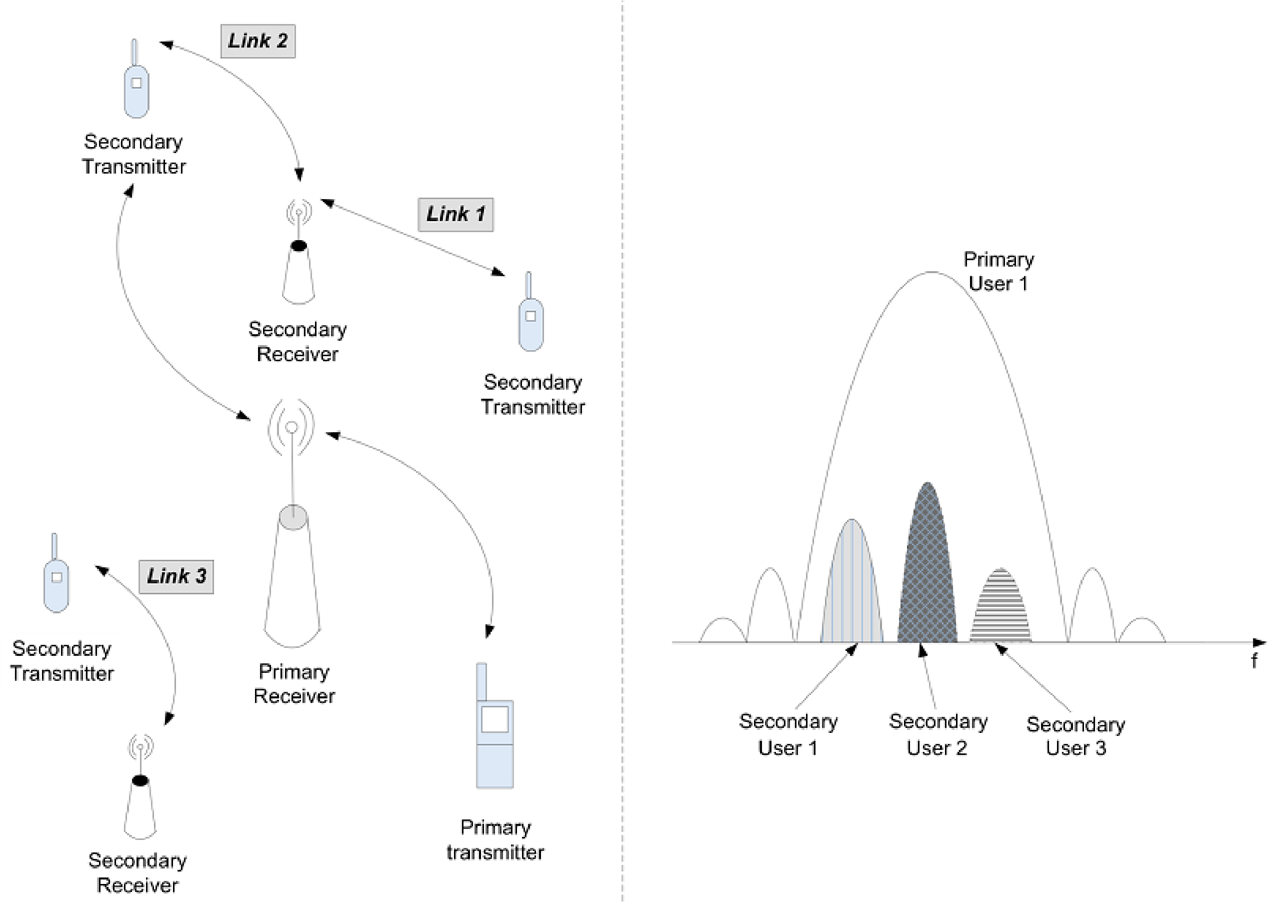

Figure 1. Primary users (owners of the spectrum) and secondary users that want to access the same spectrum when not utilized

From Figure 1, using the concept of Dynamic Spectrum Access (DSA) [2], the secondary users are only expected to access the spectrum either when primary users do not use their spectrum (overlay) or when the secondary users are within a specific interference margin (underlay). This has led to cognitive radios as an enabling platform in realizing such dynamic spectrum sharing due to built-in cognition that can be used to observe, learn from and adjust to the RF interference [3-4].

In [5], Jayaweera and Li also proposed the new concept of dynamic spectrum leasing (DSL) as a new paradigm for DSS in cognitive radio networks. As opposed to passive spectrum sharing by the primary users as in DSA proposals, leasing provides the primary users with an explicit incentive to allow secondary users to access their licensed spectrum. Unlike in the DSA systems considered in existing literature, the primary users in a DSL network can actively manage the interference they see from the secondary transmissions by adapting their interference cap according to the observed RF environment and required Quality-of-Service (QoS).

It is obvious that for a successful implementation, it is critical that a cognitive radio device has built-in intelligence and cognition to effectively learn from its observations and past actions, and to correct its behavior as necessary in real-time. Hence, the proposed cognitive radio devices are to be designed based on the following four-step cognition cycle (ODAL loop), shown in Figure 2.

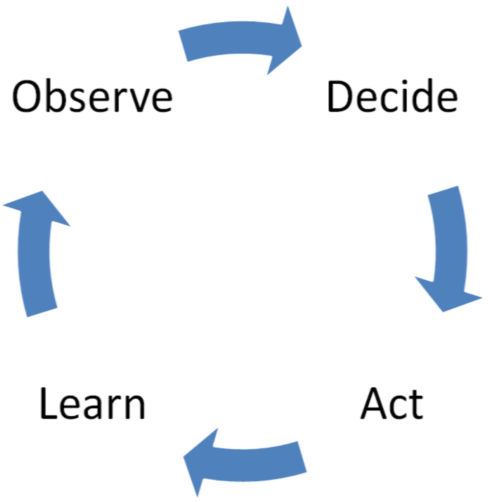

Figure 2. The ODAL cognition cycle of future smart cognitive radio devices.

- **Observe (Self-awareness)**: Scan and sense the RF environment for detection of RF activity across multiple bands, standards and channels, followed by classification of detected signals. This requires developing efficient techniques for spectrum sensing, detection and classification, as well as solutions to hidden-terminal problems. Antenna research into this area has only just begun. A simple energy detector here is not enough: we need to be able to detect both direction and the availability of frequency bands. How do we scan the environment? One may have to use a smart antenna array, a wideband antenna or a reconfigurable antenna. An antenna for MIMO applications may also be required as part of the final product. How can we use a MIMO as the frequency changes? Can we device a reconfigurable MIMO antenna that can operate at frequencies of 700 MHz (TV band) to 10 GHz for example?

- **Decide (Intelligence):** Based on observations and past experience the RF cognitive device must determine which possible actions from its current state is optimal and decides on its course of action. This entails developing a cognitive engine that has reasoning, planning and decision-making capabilities. This is one of the main aspects separating Software Defined radio (SDR) from Cognitive radio (CR). Cognitive radio has this cognition and intelligence built in to learn from previous experience. Algorithms such as neural networks, support vector machines and any other machine learning algorithms can play a big role. Perhaps algorithms based on particle swarm optimization, genetic algorithms etc., can also play a role here as well.

- **Act (Reconfigurability):** Adapt and respond to the observed RF environment. This is a ***critical requirement*** to make the RF Cognitive radio resilient to any EM interference. This entails developing a unifying parameterized representation for multi-standard, multi-channel and multi-band signals, Software Defined Radio implementations of parameter-controlled communications and reconfigurable microprocessor (FPGA) solutions. In my opinion, this is where antenna engineers can really make an impact. How can we design truly reconfigurable antennas that can sense the entire spectrum of interest and minimize interference and multipath problems within several frequency bands? Do we design a wideband antenna, or use a number of antennas that can be used to sense, receive and transmit?

- **Learn (Cognition):** Learn the RF environment, from past observations and decisions, to be able to anticipate, predict and correct communication standard, mode of operation, and RF parameters. Machine learning techniques such as neural networks and support vector machines can be used to train these devices to not only learn how to adapt, but also how to predict changes in the RF environment. This is an area that is usually left to communication engineering researchers. However, I believe RF engineers, especially those who are working in the field of radio wave propagation, can have a serious impact in coming up with data and scenarios to help train a certain cognitive device for different communication channels and RF environments [6-7].

Antenna Design

So, the main question is what is the best approach in designing antennas for cognitive radio? Although there has been some work at both the antenna level [8] and RF circuits [9], and some initial suggestions [10-11] on how to tackle the RF sensing of the environment and the communication aspect, all designs are preliminary in nature and still untested. As of yet, there are no guidelines on how to design the best reconfigurable antenna for cognitive radio.

Antennas need to be able to change the direction of the main lobe on a real time basis and at different frequencies. Consider the spectrum occupied in the 2.4 GHz ISM Band by a single WiFi transmitter (22 MHz bandwidth) and a Bluetooth Piconet (8 – 1 MHz wide transmitters) as shown in Figure 3 [6]. Each of the Bluetooth transmitters can appear anywhere in space (as depicted by the varying amplitudes) and anywhere in the 79 MHz wide ISM band.

Let us assume that we are among the transmitters, i.e. arrayed in some random pattern about our location, that occupy the spectrum as shown in Figure 3. Let us further assume that we have to maximize the gain in the direction of the Bluetooth transmitters while directing a null towards the WiFi signal to prevent saturation of our input amplifier chains. To further complicate the problem, this adjustment must be done on the order of no more than several microseconds (the Bluetooth transmitters hop once every 625 microseconds), quickly enough to allow the cognitive radio time to determine available bandwidth for transmission and then actually transmit.

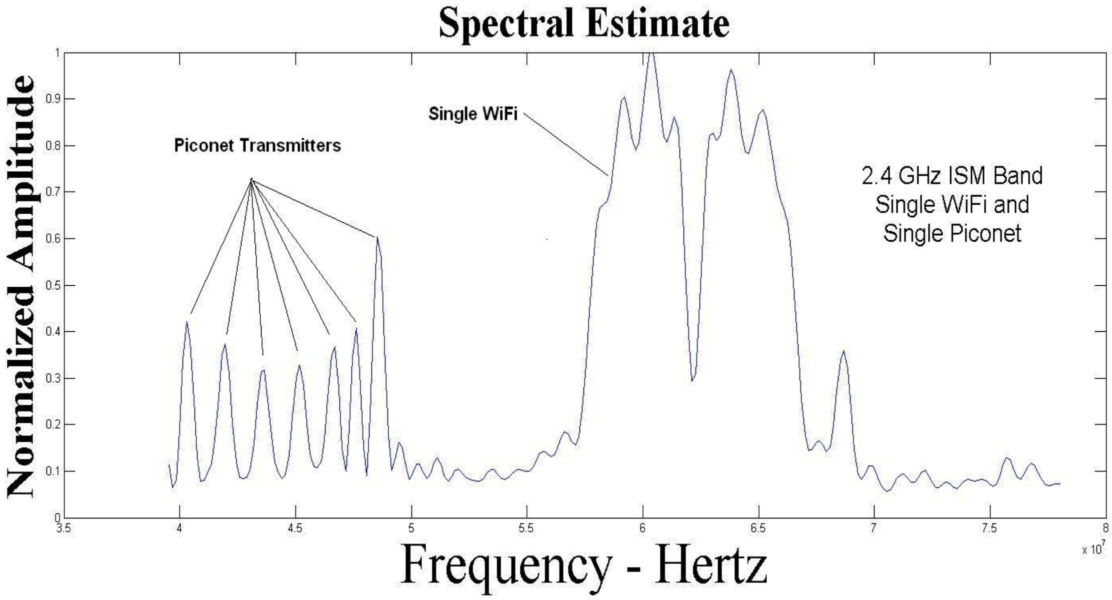

Fig. 3. A sample of spectral detection where several Piconet transmitters and WiFis operate.

We can see that a fixed-delay antenna array will not be able to change the beam pattern on a real time basis, hence the need for a reconfigurable antenna that allows us to change the beam pattern on a regular and rapid basis, and at different frequencies over the frequency band of interest. For MIMO applications, this becomes a very serious challenge since we will need either multi-frequency reconfigurable array antennas or UWB array antennas capable of performing these MIMO applications, let us say from 700 MHZ to 10GHz. The fact is that for whatever antennas we place on the device, we need the capability to sense the spectrum, to communicate, and to subsequently re-sense the spectrum. Although the ability to do this with only one antenna would be great, we will most likely need at least two sets of antennas, one to sense the spectrum and one to communicate as shown in Figure 4. Peter Hall et al. [10-11] have suggested a couple of possible architectures that can be employed.

In the first architecture, the “sensing” wideband antenna and omni-directional can be used to search for free frequency bands, whereas the second antenna, which is both frequency-reconfigurable and more directional, can be used to tune to the band chosen for communication.

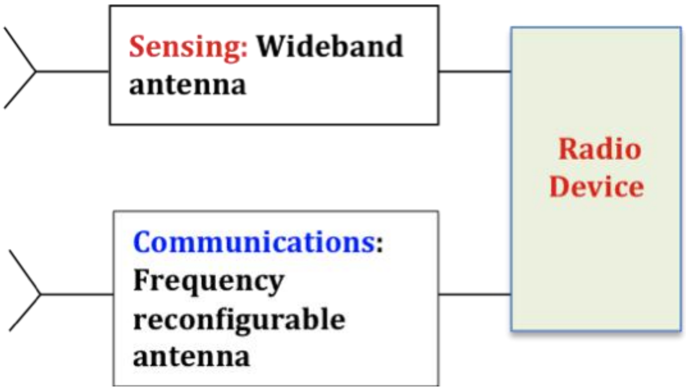

Fig. 4. A “sensing” wideband antenna and multifrequency communication antenna architecture

In the second architecture, a single antenna is envisioned where the wideband and frequency reconfigurable antenna are integrated into one unit to do both the sensing and the communication part. This certainly a can yield more compact antenna versions than the two separate case, but it is also a more challenging design in terms of minimizing the coupling and interference between the two antennas.

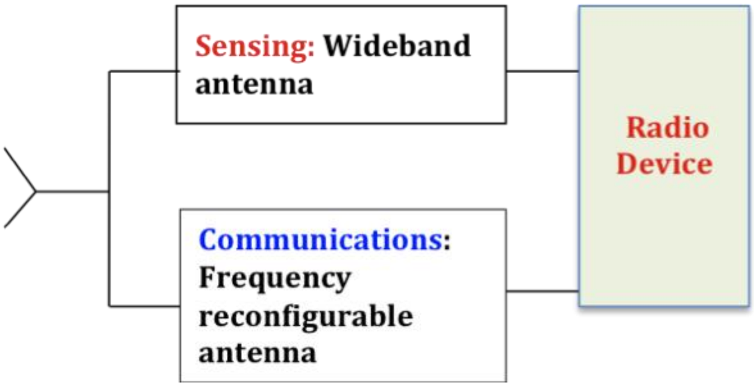

Fig. 5. A combined "sensing" wideband antenna and multifrequency communication antenna architecture

If more channel capacity and assess improvement is desired, then one will need to use a MIMO design in place of the reconfigurable frequency antenna [12-14]. This is a design that will definitely present many challenges in terms of also making the MIMO array antenna reconfigurable within a wide frequency range (or a wideband MIMO design) while at the same time diminishing interference and coupling from the wideband sensing antenna.

Antenna Intelligence

Although there is no such thing as an "intelligent" or "smart" antenna, the cognition and learning part of cognitive radio is currently being tackled by communication and computer scientists [15]. Their emphasis, however, is in the area of detecting and characterizing the communication channels properties, such as frequencies, transmission rate, modulation etc. There is another level of learning and cognition for which I believe antenna and RF engineers are better suited. A certain level of "intelligence" can be built into the radio device using several algorithms (such as neural networks, particle swarm optimization, support vector machines, and genetic algorithms, to name a few) in order to develop the next generation of responsive circuits and cognitive radio required to develop a real-time reconfigurable radio device. The aim is to have a device with "intelligent" antennas that can recognize their environment, collaborate between themselves during sensing and communication, reconfigure their radiation, polarization, or frequency and even self-tune themselves based on changes in their environment or operational mission. In other words, we want to design some truly "smart" reconfigurable antennas.

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Bio and Photo

Christos G. Christodoulou received his Ph.D. degree in Electrical Engineering from North Carolina State University in 1985. He served as a faculty member in the University of Central Florida, Orlando, from 1985 to 1998. In 1999, he joined the faculty of the Electrical and Computer Engineering Department of the University of New Mexico, where he served as the Chair of the Department from 1999 to 2005. He is a Fellow member of IEEE and a member of Commission B of USNC/URSI, Eta Kappa Nu and the Electromagnetics Academy. He served as the general Chair of the IEEE Antennas and Propagation Society/URSI 1999 Symposium in Orlando, Florida, as the co-chair of the IEEE 2000 Symposium on Antennas and Propagation for wireless communications, in Waltham, MA, and the co-technical chair for the IEEE Antennas and Propagation Society/URSI 2006 Symposium in Albuquerque.

Currently, he is an associate editor for the AWPL, the International Journal of RF and Microwave Computer-aided Engineering, and the IEEE Antennas and Propagation Magazine. He was appointed as an IEEE AP-S Distinguished Lecturer (2007-2009) and elected as the President for the Albuquerque IEEE Section in 2008. He served as a associate editor for the IEEE Transaction on Antennas and Propagation for six years, as a guest editor for a special issue on "Applications of Neural Networks in Electromagnetics" in the Applied Computational Electromagnetics Society (ACES) journal, and as the co-editor of a the IEEE Antennas and Propagation Special issue on "Synthesis and Optimization Techniques in Electromagnetics and Antenna System Design" (March 2007). He has published over 300 papers in journals and conferences, has 12 book chapters and has co-authored 4 books.

His research interests are in the areas of modeling of electromagnetic systems, reconfigurable systems, machine learning applications in electromagnetics, and smart RF/photonic antennas.