Cognitive Radio

> *A cognitive radio is an adaptive, multi-dimensionally aware, autonomous radio system that learns from its experiences to reason, plan, and decide future actions to meet user needs.*

Standards groups and regulatory bodies around the world are increasingly seeking new ways of using, allowing access to, or allocating spectrum. This was made clear during the SDR Forum's Global Regulatory Summit on SDR and Cognitive Radio Technologies (June 2005), when standards, regulatory, and other key stakeholder representatives from around the world discussed their spectrum management challenges and goals, and the role of new technologies.

This interest in developing new spectrum utilization technologies—combined with both the introduction of SDR and the realization that machine learning can be applied to radios—is creating intriguing possibilities for new and promising technologies such as cognitive radio.

1 Definition

Although the term cognitive radio—coined by Joe Mitola III in 1999—has evolved over time and now has several specific meanings in a variety of contexts, it is most commonly perceived as "the next step up" for software defined radios emerging today. Within the wireless industry, consensus is growing that many of the key attributes of cognitive radio—its promise to deliver a radio that is aware of its radio frequency (RF) environment, can adapt to this environment, and consequently can adjust its operating parameters—are best (if not only) enabled through SDR technology.

The SDR Forum, which has several initiatives under way to support the continued development of cognitive radio, is in the process of drafting a definition that summarizes a cognitive radio as shown in the inset above.

Other perspectives within the industry describe a cognitive radio as a device that can:

- autonomously exploit locally unused spectrum to provide new paths to spectrum access;
- roam across borders and self-adjust to stay in compliance with local regulations;
- negotiate with several service providers to connect a user at the lowest cost;
- adapt themselves and their emissions without user intervention; and/or
- understand and follow the actions and choices taken by their users and over time learn to become more responsive and to anticipate the users' needs.

2 Areas of General Operation

The three basic areas of radio operation where cognitive radio can make an immediate impact are human-machine interface (HMI), radio-centric operations, and network-centric operations.

1. In the area of *HMI*, cognitive radio technology can provide a level of automation that can simplify the user interface to a complex device.
2. For *radio-centric operations*, the adaptive RF signal-in-space formation and adaptive modulation provide adaptation capabilities under cognitive control that could improve system performance based on observed conditions.
3. More *network-centric applications* of cognitive radio could include the autonomous selection of network membership (e.g., 3G/Wi-Fi hotspot/WiMax) or cognitive/predictive handoff where the cognitive device anticipates the need to hand off based on prior experience rather than simply by following predefined algorithms based solely on signal level. That is, the device *recognizes* that it regularly traverses the same path (i.e., daily commute) and over time, *learns* when it is going to enter a "bad spot" and *reasons* to hand off to a different system before the outage occurs.

3 Spectrum Utilization Efficiency

To be sure, spectrum utilization efficiency is not the only benefit of cognitive radio technology; however, it is one of the more high-profile possibilities, in part due to the economics of being able to sublease spectrum as needed. The supply of available radio frequency spectrum is often described as being in a state of shortage. Whereas demand for spectrum in the most useful frequencies exceeds supply, some statically allocated spectrum bands experience low utilization. A

cognitive radio that is capable of exploiting unused or lightly used spectrum will have great value in improving efficiency of spectrum utilization.

Based on the technology advancements of SDR, a cognitive radio could:

- easily operate on multiple frequencies with a variety of power levels and modulation bandwidths;
- incorporate sophisticated control algorithms to prevent or reduce interference so more spectrum can be exploited;
- provide the capacity to move the regulators from a band-by-band set of rules to more mega-policies, enabling both new technologies and new entrants; and
- assist the regulator to serve the public interest by providing spectrum when and where it is needed by using technology to satisfy the ever-increasing spectrum demand and streamline the licensing process.

4 Current Regulatory Landscape

Most of the current spectrum assignment rules in place around the world challenge the dynamic spectrum access aspect of cognitive radio due to the rigid table of allocations derived from historical allocation and assignment methods. Attitudes have begun to change, and there is growing interest by regulators to study the possibilities of allowing dynamic spectrum access.

A snapshot of the current regulatory and licensing landscape for cognitive radio is as follows:

- From an international perspective, pre-regulatory activity has begun in all three ITU areas (Americas, Europe/Africa, and Asia), most notably in Australia, Korea, Sweden, the United Kingdom, and the United States.
- The U.S. Federal Communications Commission (FCC) has been one of the more proactive regulator bodies in its support of cognitive radio via its spectrum policy task force and cognitive radio Notice of Proposed Rulemaking (NPRM). Rulemaking for the 3650-3700 MHz refers to contention-based operation that can be interpreted as benefiting from cognitive technologies.
- The partitioning and disaggregation clauses in recent commercial spectrum license rulemaking proceedings also indicate the FCC's desire for more flexible spectrum access, and the SDR/CR rules apply to device certification. Many of the bands have secondary use regulations that could be exploited by cognitive radio solutions with little to no additional rulemaking.

Going forward, regulations that could speed cognitive radio development and deployment include dynamic spectrum access and interference metrics, and authorization for experimental licenses to prove-out the technology before adopting new rules.

5 Market Drivers

In addition to the regulator community's interest in cognitive radio, the commercial, civil, and defense sectors also have specific interests in this type of highly functioning radio.

- Commercial market drivers include spectrum access for increased capacity and new wireless internet services as well as international harmonization. Work under NSF (DIMSUM) is addressing spectrum brokering between basestations and providers.

  In addition, cognitive radio can increase carriers' revenues by facilitating new spectrum-based and location-based services. This is achieved by improving system performance, reducing frequency planning complexity, facilitating secondary market agreements (i.e., spectrum brokering), and increasing capacity through access to more spectrum. For a new carrier, this is critical because it provides initial market entry. Equipment manufacturers will also benefit due to the increased demand for wireless devices.
- Civil market drivers include public safety and domestic security requirements for multi-network interoperability and spectrum-on-demand for emergencies.
- Defense industry drivers include rapid set-up time through reduced planning requirements and simplifying human-machine interface for user-friendly use of complex devices, international spectrum access, and multi-networking.

Initial applications for cognitive radio could include dynamic spectrum access such as Dynamic Frequency Selection (DFS) in the Unlicensed National Information Infrastructure (U-NII) bands, DARPA's Next Generation Radio (XG) and connectionless in defense applications, machine-learning for improved wireless performance, and autonomous network association/membership. In the future, cognitive radio could be used to develop the broadband mobile wireless Internet infrastructure to support all wired Internet user applications (e.g., music and video downloads, e-mail connectivity, and mobile TV) over the wireless Internet with its inherent benefit of mobility.

6 Technical Drivers

A variety of technical advances have been made in both the "cognitive" and "radio" sides of cognitive radio. On the radio side, the continued development of software defined radios that exploit the processing flexibility of DSPs running on programmable chip technologies is creating new opportunities for high-performance, extremely flexible radios. On the cognitive side, cognitive processing and computing opportunities are being developed by a wide range of commercial, defense, and research organizations, such as the DARPA Information Processing Technology Office (IPTO).

Many of the capabilities of a cognitive radio are achievable with today's technology. In fact, numerous organizations around the world are currently developing what can best be described as rudimentary cognitive radios. Technical challenges still need to be addressed, however, for the development of an ideal cognitive radio. These challenges include the need to develop:

- efficient, agile, RF front ends and verification, validation, and authentication (VV&A) of operational characteristics;
- wideband linear, adaptive filtering and amplification; and
- advanced cognitive processing for applied learning, reasoning, and knowledge representation algorithms for specific wireless domain solutions.

7 SDR Forum Activity

Cognitive radio represents a logical extension for the SDR Forum. By its very definition, software defined radio is the ability to reconfigure a radio's operating parameters—and that is exactly why it is so attractive for cognitive radio technology. In this effort, the SDR Forum has the appropriate resources, talent pool, and commitment in place to provide tightly focused technical analysis and broad cross-disciplinary research on this issue.

The SDR Forum has several cognitive radio initiatives under way. Most recently, the Forum has created a Cognitive Applications Special Interest Group and a Cognitive Radio Working Group to leverage the role of SDR in the continued development of cognitive radio technology.

The Cognitive Applications Special Interest Group is studying the business case, market drivers, regulatory, and other cross-disciplinary implications of SDR within a Cognitive Radio framework, and the Cognitive Radio Working Group is working to produce technical guidance and standardization to design, develop, and

implement cognitive concepts and features based on SDR technology and architecture.

In addition, the Forum's Regulatory Committee has taken an active role in cognitive radio-related regulatory proceedings around the world and has endorsed cognitive radio in its response to the FCC's "Notice of Proposed Rule Making" on this issue.

Through these and other initiatives, the SDR Forum will continue to work to provide a broad view of the business, regulatory, and technical implications of cognitive radio by providing key leadership to insure factual representation of the state of the art in technology and applications, and by providing overall technical leadership within the industry.