James Neel
james.neel@crtwireless.com
Cognitive Radio Technologies, LLC
Dec. 12, 2007

How do cognitive radio systems promote the efficient use of the radio spectrum?

Cognitive radio systems promote the efficient use of radio spectrum by:

- Exploiting highly localized information in auto-designing systems
- Hastening the evolution of more spectrally efficient radio technologies
- Enabling new applications

Exploiting highly localized information in auto-designing systems

The small-scale fading characteristics of a channel can vary by 30-40 dB over distances of a few wavelengths. Occupied spectrum and its susceptibility to interference varies greatly from band to band, moment to moment, and place to place. The demands placed on a waveform vary from application to application. The expectations of an application vary from user to user. Because of the wide range of circumstances, it is well known that any system optimization is highly dependent on how well the design assumptions match the operating conditions.

Because a traditional (non-cognitive) system lacks post-deployment awareness of its operating condition, traditional radio systems must be designed prior to deployment for a worst-case scenario which may never happen or for a one-size fits-all solution to a representative subset of possible scenarios. In either case the deployed system will generally be suboptimal as conditions change. Through its mechanisms to gain information about its operating environment, its own capabilities, and the needs of the user, a cognitive radio has the information necessary to auto-design the optimal solution to meet the demands and constraints of its current, and highly localized, scenario.

To give a feel for the spectral efficiency gains which would be possible by a cognitive radio aware of its operating conditions, consider the impact of the following techniques available to cognitive radio: dynamic spectrum access, multi-user diversity, intelligent link coding, and micro-policy.

Dynamic Spectrum Access

As shown in numerous studies, somewhere between 5% and 25% of allocated spectrum is unused depending on the time, location, and band. When fallow spectrum is made productive, spectral efficiency can be improved by a factor of 4x-25x (assuming minimal impact on existing systems). Larger gains from dynamic spectrum access will be realized from cognitive radios with the ability to make finer resolution measurements and allocations and to accurately predict spectral availability.

Multi-user Diversity

Because geographically dispersed users experience independent time-varying channels, schedulers that preferentially communicate with only those users not experiencing fades at that instant can easily improve average link margins by 20-30 dB (theoretically gaining between 6 to 10 bps/Hz/m^2). With more localized information available and a greater number of adaptable parameters, additional gains are possible. For instance, OFDM systems which permit scheduling in both time and frequency further reduce the probability of a link operating in a fade thereby allowing communications to occur in optimal settings rather than worst-case or even average conditions. In theory, multi-user diversity can be applied to any signal space dimension to allow communications optimized on a user-by-user basis. Signal space dimensions which have been proposed for multi-user diversity include frequency, time, space (beam patterns or MIMO algorithms), and spreading codes. Beyond these physical layer parameters, communications could be optimized on a per-user basis by adapting MAC algorithms, routing algorithms, network topology, source coding, and application parameters.

In general, the greater the number of signal space dimensions available for adaptation and the better the quality of information available, the greater the gain from multi-user diversity techniques. Because cognitive radio provides a natural platform for gathering and processing the requisite information and for controlling the necessary adaptations, cognitive radio should be viewed as promoting the adoption of multi-user diversity techniques and thus promoting the more efficient use of radio spectrum.

Intelligent Link Coding

Even when a cognitive radio is concerned with only a single link/user, cognitive radio holds the possibility of significantly improving spectral efficiency. First, any of the adaptations discussed for multi-user diversity can be applied to improve the efficiency of a single link, e.g., scheduling transmissions bursts or adapting carrier frequencies around fades, adapting antenna array algorithms or modifying spreading codes to reshape the transmitted signal around fades or interfering signals. In general, the better a cognitive radio can understand its operating conditions, the needs of the user/application, its own capabilities, and the more adaptations the cognitive radio can control the greater the spectral efficiency gain which is possible.

Second, when armed with information about an interfering signal and its environment, a cognitive radio could employ dirty-paper-coding to null the interferer and greatly improve capacity. More generally, cognitive radios operating with less-than-perfect information can apply joint-source-channel-coding techniques whereby knowledge of channel conditions and knowledge of which aspects of the application are most critical to the user’s perception of service can be used to intelligently apply source and channel coding and to adapt the transmitted waveform in a manner such that the transmission maximizes the user’s perceived quality of service. For instance, allocating the least significant bits to the subcarriers with the worst SINR and the most significant bits to the subcarriers with the best SINR.

Because cognitive radio provides a natural platform for gathering and processing the requisite information and controlling the necessary applications, cognitive radio should be viewed as promoting the adoption of intelligent link coding techniques and thus promoting the efficient use of radio spectrum.

Micro-policy

Thanks to the efforts made to develop software defined policy languages, such as the one developed by the xG program, spectrum policy can be more finely crafted and adapted more rapidly. A software defined policy could be used to support spectrum policies which vary with time, space, frequency, user, application or any other conceivable dimension. This means rather than operating under one-size-fits-all policy solutions of traditional systems, spectrum policy for cognitive radios can be fine-tuned to reflect varying localized conditions. While we know of no study which characterizes the gains possible from applying micro-policies, we believe the gain could be quite significant. To operate in a micro-policy regime it will be important that cognitive radios be capable of reasoning about policy as they shift from one micro-policy regime to another. Also in practice, it may also be necessary to turn micro-policy generation over to a cognitive radio with meta-policies defined for the policy generating cognitive radio.

Hastening the evolution of more spectrally efficient radio technologies

Traditionally, when a new radio technology was developed, it would be deployed in new devices operating in a new band while legacy devices and technologies continued to operate in older bands. Because of this approach, the spectral efficiencies of previously allocated bands and of transmissions of older devices would never improve until they were replaced and the band reallocated – a slow and rarely used process.

With the advent of software radio – the platform on which the SDR Forum believes cognitive radio will be implemented – it is no longer necessary to deploy new devices to deploy new radio technologies. Instead, a software update, perhaps over-the-air or via a certified agent, can add new radio technologies to an existing device. Due to regulatory concerns, this does not necessarily mean that the device can freely transmit the new radio technology over existing bands, but spectral regulations are being reconsidered that enable such operation. For instance, it is conceivable that with the recent ITU approval, devices originally intended to transmit W-CDMA or cdma2000 signals could shortly be transmitting WiMAX if the proper certifications are made.

Cognitive radio goes much further than software radio in promoting the evolution of more spectrally efficient technologies.

First, the ability to perform dynamic spectrum access means that higher efficiency waveforms can operate alongside legacy waveforms in legacy band allocations. Thus spectral efficiency gains from new technologies need not be constrained to newly allocated bands.

Second, if proper knowledge representation and information exchange languages are developed, new more efficient waveforms and techniques could be autonomously distributed throughout the world as one cognitive radio “teaches” another, significantly accelerating radio evolution.

Third, the ability to operate with software and post-deployment defined policies will lead to more rapid evolution of spectrum policy. Like the ability to download new software, the ability to download new policy will greatly shorten the time required to move from policy formulation to policy implementation. In theory, the reduced time from formulation to implementation should have the effect of lowering the cost to institute policy changes which in turn should promote a greater willingness to experiment with policy (and thus hasten its evolution).

Fourth, cognitive radio effectively adds a new computerized army of waveform inventors as radios learn new waveforms and parameter combinations by trial and error and by reasoning. Techniques for automating waveform invention on cognitive radios are currently being developed using techniques from nonlinear programming (e.g., genetic algorithms or simulated annealing), decision theory, mechanism design, and knowledge-based reasoning. While the creative power of a single cognitive radio will surely lag that of a human, the collective creativity of billions of cognitive radios will significantly augment human inventiveness and may even outstrip the creative capacity of mankind.

Enabling new applications

Additionally, cognitive radio provides the possibility of new applications which will dramatically improve spectral efficiency. While these applications are too numerous to exhaustively list, consider the potential impact of cooperative communications, spectral economics, and automated radio resource management.

Cooperative communications

Beyond merely taking into account the existence of other radios in its environment and working around them, a cognitive radio can work with other radios to improve spectral efficiency. For example in the proposed 802.16h amendment, transmission times are coordinated to reduce collisions thereby reducing retransmissions. Radios can work together to effect a single more efficient transceiver as proposed in collaborative MIMO. More intense processing or information databases can be distributed across idle radios which could allow lower complexity radios to leverage higher complexity and more spectrally efficient waveforms.

Spectral economics

In addition to measuring spectral efficiency in terms of bps/Hz/m^2, spectral efficiency could also be measured in terms of the economic value/Hz/m^2. An example of how cognitive radio can add to economic spectral efficiency can be seen by considering dynamic spectrum markets wherein spectrum is bought and sold and resold and subdivided in real-time or near real-time. In general, such a system will tend towards spectrum being allocated towards the most economically profitable activities thereby raising total economic spectral efficiency. A similar gain is seen in the proposed US nationwide dual-use communications network which supports commercial and public safety traffic. By supporting the dynamic dual-use of spectrum, significant economic value is added to spectrum which would otherwise mostly lie idle. Note that by decreasing the amount spectral idle time, dual-use commercial/public-safety networks also significantly increase traditional spectral efficiency metrics.

Automated Radio Resource Management

Beyond the techniques described for multi-user diversity and intelligent link coding, cognitive radios could also effectively manage radio resources in ways which have impact far beyond their immediate purview. For instance, how channels are allocated across a network can have a significant impact on aggregate system performance and aggregate system spectral efficiency. Cognitive radios which automate radio resource management, whether via centralized, distributed but cooperative, or distributed and noncooperative techniques, can bring the benefits of radio resource management to networks that lack a clear means for performing radio resource management (e.g., consumer WiFi deployments). Similarly, automating radio resource management means that network optimization need not be discarded when conditions change due to updated policy definitions or a changing operating environment.