Cognitive Radio Techniques for Wide Area Networks

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ABSTRACT
The cellular wireless market has begun the transition to data centric services including high speed internet access, video, high quality audio, and gaming. Communications technology can meet the need for very high data link speeds, and can also improve network throughput, but dramatically more spectrum will be needed to provide ubiquitous wireless data service. Cognitive radio is a new technology that allows spectrum to be dynamically shared between users. It offers the potential to dramatically change the way spectrum is used in systems and to substantially increase the amount of spectrum available for wireless communications. This paper introduces cognitive radio and explains the promise, possible operating modes, and benefits it may offer.

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General Terms
Design.

Keywords
Cognitive radios, unlicensed spectrum, unlicensed wide area network.

1. INTRODUCTION
Recent advances have enabled wireless handsets with data download capability of 1-10Mbps. In the next few years, this will be extended to roughly 100Mbps and then on to over 1Gbps in the next decade. This ability to handle data at very high speed will enable consumers to easily handle high quality audio, video, and high resolution images. However, it is often overlooked that as high performance wireless data services are widely deployed, lack of additional spectrum will become a serious limitation.

Advanced CDMA air interface technologies, such as HSDPA, offer spectral efficiencies on the order of 1 bit/second/Hz. With OFDM technology and MIMO techniques, it is anticipated that the spectral efficiency will increase to 3-4 bits/second/Hz. Today's mainly voice services typically demand ~10kbps, so it is easy to see that typical data users might well demand 100X-1000X the data throughput of voice users. If air interfaces can be made 4X more efficient than today's systems, this still drives a raw demand of 25X-250X the available spectrum. While reasonable arguments can be made that future systems will be viable with less spectrum that this aggressive prediction, it is clear that very large amounts of additional spectrum will be needed in any case.

Of course, opening such a dramatic amount of spectrum is a very significant challenge. In most developed countries, the bulk of the available spectrum is already assigned. In addition, antenna size limitations and electromagnetic wave propagation characteristics limit useful spectrum for cellular handsets to the range of a few hundred megahertz to roughly 3 GHz. However, the FCC's Spectrum Policy Task Force Report [1] identified that most spectrum goes unused the majority of the time. Consequently, spectrum scarcity is driven mainly by archaic systems for spectrum allocation and not by a fundamental lack of spectrum. How to open additional spectrum, whether it should be licensed or unlicensed, and the economic implications of these decisions, has been a topic of considerable debate [2]. Cognitive radio, the topic of this paper, offers a possible solution based on a more sophisticated system for allocating spectrum that can dramatically increase the amount of spectrum available to network operators and individual users.

The fundamental concepts of cognitive radio are covered in section II. These techniques include methods for monitoring spectrum use with highly sensitive receivers, assessing interference temperature limits of primary users, and optimizing network utilization by adapting radio parameters. In section III, an alternative technique based on an intelligent network is explained. Section IV provides a brief introduction to the practical and regulatory aspects of cognitive radio deployment.

2. FUNDAMENTAL CONCEPTS
In 2004, the FCC issued a notice of proposed rule making (NPRM) that raised the possibility of permitting unlicensed users to temporarily "borrow" spectrum from licensed holders as long as no undue interference is seen by the primary user [3]. Devices that borrow spectrum on a temporary basis without generating harmful interference are commonly referred to as "cognitive radios" [4]. Basic cognitive radio techniques, such as dynamic frequency selection (DFS) and transmit power control (TPC), already exist in many unlicensed devices. However, to reach the full promise of cognitive radios, many significant design challenges lie ahead.

Before beginning operations, cognitive radios must obtain an estimate of the power spectral density (PSD) of the radio spectrum to determine which frequencies are used and which frequencies are unused. In order to accurately measure the spectrum, a highly sensitive radio will be required to measure signals at their cell edge. Consider the example of digital TV which lies at the cell

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edges; the received signal will be just barely above the sensitivity of the receiver. For a cognitive radio to be able to detect this signal, it needs to have a radio that is considerably more sensitive. If the cognitive radio is not capable of detecting the digital TV signal, then it will incorrectly determine that the spectrum is unused; thereby leading to potential interference if this radio spectrum is used, i.e., the signal transmitted by the cognitive radio will interfere with the signal the digital TV is trying to decode. This situation is often referred to as the "hidden node problem". Another example of a hidden node is shown in Figure 1. In this example, transmissions between UE1 and UE2 cannot be detected by UE3 or UE4, even though UE3 and UE4 are within signaling distance of UE1 and UE2. Therefore, UE3 and UE4 may determine that the spectrum is unused and decide to transmit a signal and potentially interfere with the ability of UE1 and UE2 to correctly receive signals. These examples show the necessity for highly sensitive radios for cognitive devices.

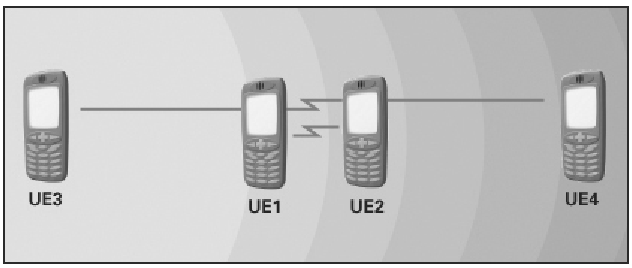

Figure 1. Hidden Node Problem

Further, when the spectrum is occupied, the cognitive radio must also be able to estimate the "interference temperature" that the primary user can tolerate, i.e. the transmit power level that a cognitive device can utilize without raising the noise floor of the primary user's device beyond a specified amount. In many cases, this specified amount is on the order of 0.5 dB to 1.0 dB, but will depend heavily on the link margin available at the primary user's receiver. The interference temperature can be determined with at least two pieces of information: an estimate of the signal bandwidth used by the primary user, and the distance between the cognitive radio and the victim device. The signal bandwidth can be used to determine the noise floor for the victim device, while the distance can be used to determine the received signal strength seen by the victim device as a function of transmit power used at the cognitive radio. Assuming that the noise floor at the victim receiver is allowed to rise by a pre-specified amount, it is easy to calculate the maximum allowed transmit power for the cognitive radio. Of course, this analysis is very simplistic and can be refined even further if the cognitive radio can blindly classify the type of signal and corresponding data rates used by the primary user. This extra knowledge would determine the exact sensitivity requirements for the victim device.

Clearly, the previous discussion depends on an accurate estimate of the radio spectrum conditions. Since the spectrum use is constantly changing, the estimate will need to be continuously updated in order to ensure that the primary users are always being protected from interference. Additionally, a simplistic view of the radio transmission path is assumed. In a real-world case, the propagation path from the cognitive radio transmitter to the primary user's receiver might be quite complicated. For example, obstacles between the two could substantially attenuate the signal, meaning that the cognitive radio could transmit at a much higher power level than would normally be assumed. However, the alternate possibility, that reflections of the transmitted signal could enhance interference at the primary receiver, is also possible. Consequently, lack of information regarding the transmission paths between the various transmitters and receivers in a cognitive radio network would create a very serious design challenge.

Until now, this discussion has focused primarily on protecting the primary users from harmful interference. However, a significant challenge also lies in the design of the receiver of the cognitive radio. Emissions from primary users will also result in interference for the cognitive radio. Since emissions from primary users are uncontrollable, the cognitive radios must use advanced radio designs, such as a multi-user detector, to deal with the interference and ensure that the desired signals can be reliably decoded.

Finally, to be able to take advantage of the ever changing spectrum conditions, the cognitive radios need to be adaptable in the spectrum, power levels, modulation schemes, and protocols that they use. This is especially challenging for mobile radio environments in which channel conditions can change rapidly when vehicular speeds are involved. Considerable research still needs to be performed in these areas in order to reach the full promise for cognitive radio.

3. UNLICENSED WANS

An alternative approach to cognitive radio is illustrated in figure 2 [5,6]. The left side of the figure shows radio communication links both between UEs and BTSs and the right side illustrates the backhaul network. The concept of an RCC (RF Control Channel) is used to coordinate the spectrum access of all the UEs in the system. The RCC ensures that all radio traffic avoids interference and explicitly solves the hidden node problem. Before any radio communication takes place, each UE and BTS announces its intentions over the RCC. All UEs and BTSs in active communication monitor the RCC to ensure that all intended new communication links will not interfere with them. In the case that a new session will create harmful interference, objections are raised over the RCC to signal that the new session may not use the resources it intended to.

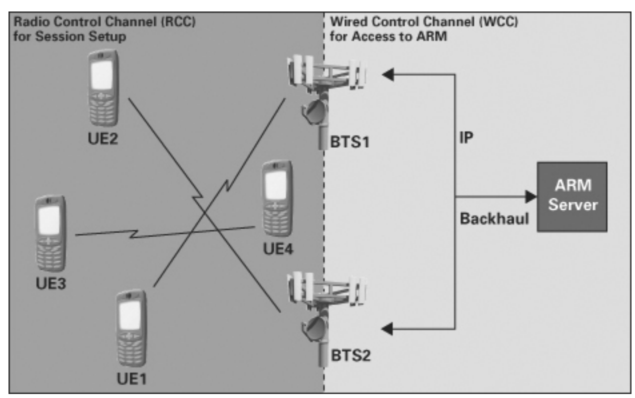

Figure 2. UWAN System

On the infrastructure side of figure 2, a wired control channel (WCC) is implemented to allow the BTSs to communicate with each other and to access the ARM (Available Resource Map) database. The ARM is a real time map of all radio activity in the network. Each transmitter is required to have GPS or other positioning technology so that it can report its precise location, power level, transmission band, modulation format, and SNR conditions. With access to the ARM, each BTS can control the UEs it is servicing and control its spectrum use to avoid interference and to allow powerful and efficient modulations and coding to be employed.

Since each BTS in the network has access to the real time ARM database, UEs that are serviced by a BTS operate much as today's UEs. They request service from the BTS over the RCC and operate under the direct control of the BTS. Link control information such as the UE's position, power level, and channel quality metrics are communicated to the BTS not over the RCC, but rather, are multiplexed with payload data in the communications channel in use. In this way, traffic on the RCC is minimized. For UE to UE communication, the individual UEs have no access to the ARM, so they must search for available resources by analyzing the band and announcing their communication plans over the RCC. Nearby BTSs, if there are any, will become aware of the UE to UE communication link by monitoring the RCC. To avoid excessive traffic on the ARM, UE to UE communication links are normally limited to pedestrian speeds. Since the range of handheld UEs is limited to a few kilometers anyway, this is not viewed to be a serious limitation.

The UWAN system allocates spectrum fundamentally on a "first come – first served" basis. However, it is easy to see that some level of system etiquette can substantially improve system performance. This is illustrated in figure 3 where the three short channel links can consume the entire system capacity if each chooses to access a different channel. However, since the links are short, they can easily reuse the same channel, allowing capacity for the long link shown. While figure 3 is very simple, it is easy to see that the situation in a real network is decidedly more complex. Multiple users accessing multiple BTSs, users sharing channels (OFDMA for example), and mobile users must be accounted for. Additionally, UE to UE links that must operate without benefit of the ARM have to be considered.

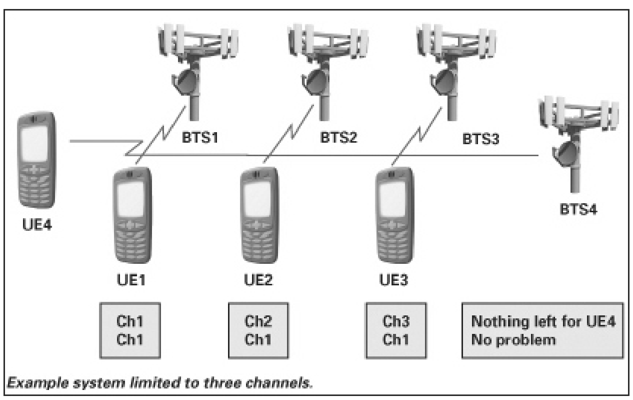

Figure 3. UWAN Etiquette

User priority is another aspect of spectrum sharing systems that must be considered. A system is needed to ensure that heavy users don't simply consume all system capacity (the tragedy of the commons). Simple schemes are possible that reward users for making efficient use of spectrum and ensure fair access. One possible solution is to keep a priority number in each UE. The priority number would only be used to determine which user would be allowed to access the system first if total system resources were limited. User priority might be established by linking the priority number to the total energy radiated by a UE in a past time period (perhaps over the last several hours). Such a system would offer highest priority to the "good user" who least consumed system resources (i.e. minimized his or her total radiated energy) in the immediate prior period. Of course, emergency personnel, police, and other high priority users could be consistently assigned top priority in the system.

The performance optimization of a cognitive radio system must consider multiple perspectives. On the one hand, a system based on autonomous radios might consider that each UE optimize the benefit it provides to its individual user. Modulation formats, coding and the like could be optimized to maximize throughput from an individual perspective. As noted above, however, such a system leads to wasteful use of overall system resources and would allow one user to benefit at the expense of others. The introduction of control channels and the ARM in a UWAN allows the overall system to share enough information with the individual UEs to allow overall system performance optimization. However, even in a UWAN, the UEs still have cognitive capability and still affect decisions about how to utilize spectrum.

The importance of optimizing system level performance drives the use of optimization schemes in cognitive networks (whether or not a UWAN system is used). Research in this area is still in an early phase. Game theory has been proposed as a possible useful technique [7]. Game theory allows a set of rules for decision making, including both hard requirements and etiquettes, to be imposed on the UEs and other decision making entities in a network. Channel conditions, available spectrum, interference levels, alternative modulations, coding, and the like can be simulated and the overall network throughput and service to the individual UEs can be assessed. It is also possible to allow the network to adapt to current conditions and adjust the decision making process to optimize current performance. The use of genetic algorithms has been proposed for this purpose [8].

Of course, many aspects of the UWAN need additional research. The protocol for the RCC network synchronization, the organization and access of the ARM, development of effective system etiquettes, priority schemes, optimal air interfaces, security [9], and even regulatory aspects are only a few of the areas needing additional attention. However, analysis of the UWAN system indicates that these problems can be overcome with available technology, providing hope that a practical UWAN could be deployed in the near future.

4. DEPLOYMENT OF COGNITIVE RADIO

Regulatory and public policy aspects cannot be overlooked when contemplating the deployment of any radio system. Cognitive radio offers special challenges in this regard since various cognitive radio technologies might react differently in different real world scenarios. Depending on the specific algorithms employed, it is possible to imagine situations in which certain radios might transmit while others would determine that the potential for harmful interference is too great. Of course, incumbent spectrum license holders fear that harmful interference could impact the performance of their systems.

However, cognitive radio technology can also simplify regulatory policy. Since users can share spectrum, the demand for special use licenses should be reduced. As blocks of spectrum become available, a policy of converting them to shared-access bands would avoid the need for auctions and stimulate development. Much as automobiles are subject to pollution and safety requirements, cognitive radio technologies could be required to meet ever increasing requirements for spectral efficiency, effective etiquette, and resistance to interference.

It is noteworthy that the UWAN concept has the potential to explicitly protect the spectrum rights of incumbent license holders. License holders can be guaranteed immediate and top priority access to their spectrum and all spectrum made available for UWAN use on a temporary basis could be rapidly recovered by the primary license holder if needed. A good example of this is the potential for shared use of spectrum reserved today for military use. In most parts of the country, this spectrum goes unused most of the time, making it ideal for shared use spectrum. However, in the event of an emergency, a network based system such as the UWAN could easily evacuate the full band on a nationwide level for immediate and exclusive military use. This ability is also critical to cellular operators, where the large additional spectrum pool, dramatically reduced costs, and ability to guarantee service through use of incumbent licensed spectrum makes the UWAN very attractive.

With increased focus over the past few years on system security and survivability, it is also important to note that distributed intelligent systems, such as cognitive radio, offer benefit in the event of attacks or natural disasters. While a conventional cellular system depends heavily on centralized control, a cognitive system is capable of establishing communications even if some network elements are out of order. Since spectrum is shared, spectrum can continue to be used even if one entity's (or network operator's) system has failed. And, with UE to UE direct link ability, some level of communication can be maintained even if backhaul networks and base stations are no longer in service.

5. CONCLUSIONS

Cognitive radio introduces a new level of sophistication to wireless communications technology. Basic cognitive radios operate autonomously and depend on highly sensitive receivers and device learning to know when and how spectrum can be accessed. An alternative approach, the UWAN, employs an intelligent network to distribute more information to the cognitive devices so that better decisions can be made. In both cases, some research challenges remain to be overcome before a truly practical system might be deployed. In spite of the technical challenge, it is clear that existing approaches to spectrum management, which date to the very early days of radio technology, will soon be insufficient to meet the demands of modern wireless communications. Cognitive radio offers hope to meet this demand with a system that is compatible with existing deployed wireless systems, stimulates new innovation, reduces regulatory burden, encourages market competition, preserves the rights of incumbent spectrum license holders, and benefits the populace overall.

6. ACKNOWLEDGEMENTS

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