Chapter 18
The Symbiosis of Cognitive Radio and Wireless Mesh Networks

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Abstract Although wireless mesh networks (WMNs) have quickly been successfully deployed, the dual usage of wireless communication makes them very resource dependent. Proposed cognitive radio (CR) concepts appear to be a good solution to provide WMNs with additional bandwidth and improved efficiency. In addition, we believe that applying CR to WMN can be very beneficial to CR, speeding the development and acceptance of the technology.

18.1 Introduction

Wireless mesh networks (WMNs) would, of course, benefit from additional wireless bandwidth. In fact, a WMN's dual use of wireless communication for both user access and data transit places additional strain on a already scarce resource, compared to other wireless networks (such as WLANs). To date, most mesh systems have been designed to use unlicensed spectrum, particularly the 2.4 GHz band used by IEEE 802.11 b/g. As this spectrum is unlicensed, it is also heavily used – not only by other 802.11 devices, but also by a wide range of other devices, including cordless phones, remote controls, and even microwave ovens.

However, obtaining additional spectrum is very difficult. Under the current system of spectrum allocation, spectrum is strictly allocated, with only a few small pockets that are unlicensed. This leaves two options: either use (along with a large number of technologies and users) the unlicensed spectrum, or obtain (at great expense) spectrum to dedicate specifically to a WMN. For a technology such as mesh, both options are potentially very limiting to the applications where it can be deployed.

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There are however indications that the system is changing. Many of the players responsible for spectrum allocation have acknowledged the need for a more advanced, more dynamic system – a system that makes better, more efficient use of available bandwidth. A concept has emerged of a radio system the gathers all available information about its environment, then uses this information to determine the most effective way – when, where, and how – to communicate. This concept is cognitive radio (CR).

Cognitive radio is currently only a concept, an eventual goal for intelligent wireless communication. However, as a general concept, it incorporates many ideas, from many existing research fields. In fact, one of the driving forces behind the rise of the CR concept has been the increased resource demand of new types of wireless networks, including mobile ad hoc networks, and wireless meshes.

However, not only will the development of CR technology benefit WMNs, but WMNs can potentially contribute greatly to both the development and implementation of cognitive radio. Although CR is envisioned as universal wireless technology, not one bound to any particular network structure, specific characteristics of WMNs suggest that WMNs could be a great facilitator of the technology.

As a result, the paths of WMNs and cognitive radio appear to be closely intertwined. In this chapter, we will present an overview of CR work, focusing on how it relates to WMNs.

18.2 Background

18.2.1 Radio Communication

In this chapter, although other types of wireless communication exist (microwave, visible light, acoustics, etc.), our discussion will be confined to radio communication. Radio communication uses a transmitter to encode information and generate radio waves. These electromagnetic waves occurring at low frequencies, in the range of 3 Hz to 30 GHz, propagate through the air. A receiver is used to detect and decode the signal.

The characteristics of radio waves are very important in the wireless world. The transmitter creates a wave with a certain power. However, as the wave travels, it attenuates, reflects, and refracts. The characteristics of transmission are dependent on the frequency used. Although lower frequencies (below $\sim$10 GHz) will pass through some obstacles, higher frequencies require a clear line of sight. All of this complexity makes modeling the wireless environment extremely difficult.

At the receiver, the signal quality must be great enough to allow the signal to be decoded. To properly receive the transmission, a sufficient signal-to-noise ratio (SNR), or signal-to-interference-plus-noise (SINR) must be achieved. Unfortunately, there is a great deal of radiation within the radio spectrum, both naturally occurring and generated by transmissions. The required SNR is dependent on the characteristics of the antenna, receiver, and the encoding scheme used.

In today's world, many radio devices are often operating in close proximity to one another. This makes interference between devices extremely troublesome, as two transmissions may mutually interfere with each other, preventing one or both from being properly received. The devices may be using the same network or technology, or could have entirely different purposes. A system for controlling who uses spectrum – where, when, and how – is required to ensure communication can occur effectively.

Fortunately, the radio spectrum can be shared along three dimensions – frequency, time, and space. The total spectrum space is large relative to the needs (and power capabilities) of individual devices/communications. Therefore, communications only use a small band (frequency range). Different bands can be used simultaneously. Wireless resources are also completely renewable, so individual transmissions can be made one after another. Finally, because of the attenuation properties of signal propagation, spectrum can be reused geographically, if the distance between devices is great enough that signal interference is low enough relative to signal strength (that is, the required SINR is maintained.

18.2.2 Spectrum Allocation

To ensure that wireless spectrum is used and shared effectively, the resource is tightly regulated. Regulatory bodies set out rules on what, where, and how spectrum can be used, and who can use it. The system that has been developed relies principally on frequency-division. Spectrum is sub-divided into frequency bands, and allocated to particular uses or users. Geographical divisions also occur, because of both political borders and regional requirements.

In the USA, the Federal Communications Commission (FCC) [2] is a government agency responsible for regulating wireless spectrum. The canadian radio-television telecommunications commission (CRTC) [3] has similar responsibilities in Canada, and similar agencies exist in other countries. In addition, the international telecommunications union (ITU) [4] and its Radiocommunication subcommittee (ITU-R) is a UN agency responsible for coordinating spectrum allocation worldwide. The ITU-R works to coordinate spectrum allocation internationally, to allow certain technologies to use the same spectral bands throughout most of the world, as well as to avoid major interference problems across international borders.

The current allocation of frequency bands has been arrived at as a result of a number of different methods for allocating spectrum. Many frequencies have been allocated to, or reserved for public service uses (e.g., governmental, military, or emergency services). Some frequencies are allocated because of their historical placement – as technologies are developed, they use a particular frequency. As the technology is adopted, it becomes increasingly difficult to change the allocation, even if technology advances no longer require that band to be used. Certain frequencies have been allocated for open use – these unlicensed bands (such as the 2.4 GHz band used by 802.11 b/g) can be used by any user or technology, as long as certain power rules are met. The Canadian spectrum map can be found in [67].

Most regulatory bodies now favor the spectrum auction as the method of choice for allocating new frequency bands [5]. The FCC has conducted spectrum auctions since 1994, with spectrum licenses granted to the highest bidder. The auction system replaced the previous "best public use" method, where applicants were required to demonstrate that their proposal would deliver the most benefit for the public. After obtaining a spectrum license, the licensee is given exclusive use of that spectrum, subject to the conditions of the license (e.g., location, power constraints).

18.2.3 Spectrum Usage

Although the current system of fixed spectrum allocation and spectrum auctions is straightforward, it suffers from a few problems. Most notably, with the ever-increasing numbers and types of wireless devices, new spectrum is becoming increasingly scarce. Bandwidth is becoming increasingly expensive, and difficult to obtain. However, studies of existing spectrum usage have yielded an interesting result.

Spectrum is vastly under-used. Although certain frequencies, in certain locations, are heavily congested, studies have shown that the overall spectrum is remarkably quiet [6]. For example, measurements were taken at six locations. Overall spectrum usage was only 5.2% (averaged over the six locations), and although certain bands were heavily used in some areas, even the location with the highest occupancy had a total use of only 13.1%. This means that, despite the incredible value of wireless resources, they are to a large extent wasted. This is to be expected to some extent – usage is dependent on need. However, in some cases, overall spectrum use was quite low, despite the fact that certain bands were very heavily used. In these cases, wireless demand was clearly present, confined to a small band while other spectrum is idle.

Because of the historical nature of the allocation system – the long life of spectrum licenses, the current allocation may not be ideal. Many older technologies make inefficient use of their resources. However, there is a large investment in existing technologies, making replacement undesirable.

18.2.4 Change

In 2003, the FCC charged a task force with looking at the way spectrum allocation is performed. The Spectrum Policy Task Force (SPTF) investigated ways to evolve the "command and control" approach to spectrum regulation [7]. In their report, the task force acknowledged the inefficiencies of the current license system. They found that current spectrum policy could not keep up with technology, and identified the need for a new system that allow better use of the existing spectrum resources. In particular, they identified the need for the new system to be more dynamic, responding better to changes in usage and to new technologies.

18.3 Cognitive Radio

As the regulatory agencies were acknowledging the need for a more dynamic system or resource allocation, a concept had emerged within academic literature. This concept incorporated many different ideas from several research fields. Although unrealizable in the short term, it caught on as a unifying vision of how a future radio device might behave. This concept is cognitive radio.

18.3.1 What is Cognitive Radio?

The term "cognitive radio" is generally credited to J. Mitola. It first appeared in 1999, in an article coauthored by G.Q. Maguire [8]. This was followed by Mitola's PhD dissertation in 2000 [9]. The dissertation described a language for describing and communicating the characteristics of a device's radio interface. In the work, he used the term "cognitive radio" to describe a device that used its awareness of its environment to intelligently choose the best parameters to use for its own communications.

The concept of applying intelligence to communication is not a new one. Patterning wireless on the characteristics of human conversation has long been a topic of research. However, the identification of the CR concept is indicative that the underlying technology has reached a point where such a system is becoming realistic. Several key factors point in this direction.

First, there has been an incredible boom in wireless networks and devices. With the near ubiquity of WLAN access, it is easy to forget that the IEEE 802.11 standard is only about a decade old [10]. Even the popularity of cellular phones is relatively recent, even though the first commercial networks were deployed almost thirty years ago (1979). However, today, many locations are serviced by variety of different wireless technologies and service providers.

Second, this boom has increased interest in wireless research. New types of wireless networks, particularly multihop networks such as mobile ad hoc networks (MANETs) and sensor networks have made the scarcity of wireless resources abundantly clear. A huge number of new protocols were proposed to improve the efficiency of communications, especially routing [11] and MAC protocols [12]. In addition, this work revealed a need to consider cross-layer information in protocol design.

Third, technological advances have made software-defined radio (SDR) possible and increasingly capable [13]. SDR allows the behavior of the radio to be controlled by software, rather than in fixed hardware. This goes beyond basic parameter configuration, to allow control over all aspects of the radio interface, including frequency, modulation, power, and medium access control. SDR allows a device to switch between different network technologies, using a single physical radio. SDR focuses on specifying architectures and the wireless interface, an important component for building CR devices [14].

With these factors coming together, it was becoming possible to realistically envision the cognitive radio concept. CR is a future technology, a target towards which research will progress. However, before this goal can be achieved, a large number of issues must be addressed. Many of these issues have been studied in the context of various types of networks, including WMNs, however, all of this work must be brought together within the CR view. Bringing CR to fruition will require developmental work in engineering, architectural design, protocol development, network management, and applications, not to mention overcoming regulatory obstacles.

18.3.2 Key Characteristics of a Cognitive Radio

The development of cognitive radio will need to take advantage of many different technologies to succeed. By its nature, CR must allow new technologies to coexist with current devices. However, as a long-term goal, many of these new technologies are still in their infancy; others may not even have been conceived yet. With this in mind, this section attempts to give a picture of CR as it is currently envisioned.

18.3.2.1 Advanced Interoperability

The CR will take advantage of advanced technologies to have significantly greater capabilities than current radio interfaces. Current work on antenna technologies: antenna arrays, MIMO, and adaptive beam-forming give some idea of what might be expected, with advances in digital signal processing allowing radio devices to gather as much information as possible [15–17]. Ultrawideband radio (UWB) is also a possibility for using the medium without adding significantly to overall interference levels [18]. However, as technologies progress, different devices will have different capabilities, and one of the goals for cognitive radio is a system for all of these devices to operate effectively within the environment. As previously mentioned, at least the first generation of CR devices will have to coexist with existing noncognitive wireless technologies.

18.3.2.2 Frequency Agility

CR devices are envisioned to be highly flexible in the way that they send and receive. In addition to MIMO (Multiple in, multiple out capabilities), they will be frequency agile, being able to dynamically adjust the frequencies and bandwidth of their transmissions. This functionality is envisioned to go well beyond the basic capabilities of SDR however, with the adaptive ability to fill fragmented spectrum holes as required by the current radio environment. In addition, a CR will require a much better ability to detect different types of transmissions, including those spread over a range of frequencies [19].

18.3.2.3 Awareness

This ability to detect transmissions will give the CR a greatly improved ability to gather information about its radio environment. The ability to sense and measure channel conditions, throughout the spectrum, is only the beginning. The CR will rely not only on current information, but will also retain a memory of its environment [20]. It will therefore also need improved systems for maintaining this information.

Not only more aware of its surrounding, a CR will also have an increased level of selfawareness. This includes awareness of its hardware, applications, user characteristics, and particularly its goals. For example, knowledge of the application may provide traffic characteristics and requirements [21].

18.3.2.4 Cognition

The CR uses its awareness of the environment to make decisions on how to best meet its operational goals. The gathered information is analyzed to determine the optimal set of parameters for each communication. The CR must decide what transmission must occur – to whom, on what network – and when and how the transmission will occur. Because of the very large number of variables, both in terms of awareness and decisions, the CR decision-making process will have to be fairly advanced, with the ability to adapt and learn [20].

The collected awareness will be stored to maintain a memory, and modeled to predict future conditions. Prediction may take the form of sophisticated pattern recognition of cycles or trends, or the simple recognition of poor conditions, with the expectation that future conditions will improve. A CR that senses, stores, and uses its awareness effectively should have an advantage over less capable devices. It will develop a better strategy to be used in competition with other nodes [22].

18.3.2.5 Collaboration

By its nature, radio communication is dependent on collaboration. At the minimum, sender and receiver must collaborate, however in reality the open nature of the wireless medium demands that far more nodes must be involved. The CR must consider the interactions between not only different nodes in its network, but in all networks – in fact, the CR's abilities allow it to choose to interact with different networks.

18.3.3 How Cognitive Radio Changes Spectrum Management

The CR's envisioned capabilities differ considerably from any previous radio interface. Its awareness and cognitive abilities allow it to be very flexible and dynamic. Although it would be possible for a CR to operate within the current spectrum rules (i.e., fixed band allocations), the true benefits may come from the combination of CR development and changes to spectrum management.

Open Spectrum is one of the first major works considered to address the cognitive radio concept [23]. An Open Spectrum Policy (OSP) has been proposed so that available spectrum can be more fully used. Recognizing the need for incumbent technologies to continue to function correctly, researchers have proposed different methods for CR devices to use the same licensed frequencies – while still avoiding interference with existing devices either spatially or temporally.

The IEEE 802.22 Working Group is addressing this approach, looking at ways to share the frequencies occupied by broadcast television [24]. Several approaches have been proposed for re-using this spectrum. First, over-the-air TV bands currently have guard bands between the reserved channels. These guard band frequencies are not used – they are designed so that adjacent TV channels do not interfere with each other. As a result, a CR could use these gaps, as long as it could control its signal so that it does not cause any problems for TV receivers. A second option relies on technological improvements giving CRs far greater sensitivity and signal processing ability than existing devices. Cognitive radios can then communicate at transmission powers and ranges that are low enough to avoid interfering with TVs. Third, if a CR can determine when and where there are no users of the primary (incumbent) technology, it may be able to make full use of the spectrum [25]. IEEE has also established a Standards Coordinating Committee on Dynamic Spectrum Access Networks. SCC41, continues the work of the P1900.X standards development committee [26], and is currently developing guidelines for the use of dynamic access throughout the radio spectrum.

Open spectrum illustrates the important ability of cognitive radio to share spectrum with existing technologies. In allowing a CR to use licensed spectrum, it capitalizes on previously wasted bandwidth. The CR must always ensure that it does not interfere with spectrum usage by the primary user. However, even this contravenes current spectrum allocation rules and licenses.

Therefore, changes to spectrum management are required to make cognitive radio a reality [27]. At the minimum, certain spectrum licenses must be made available for spectrum sharing according to known methods, as in the example of 802.22. However, with regulatory agencies considering major changes to spectrum allocation, a dynamic system could better match the flexibility of CR.

Different proposals exist as to what form a more dynamic spectrum allocation system might take. These include shorter-term licenses (and more frequent auctions), licenses allowing for secondary cognitive use while maintaining primary user rights and priority, and a fully dynamic spectrum market. The latter option presents the most flexibility, with the ability to buy, sell, trade, or lease spectrum rights. For example, if a spectrum licensee decides that it will not fully use its bandwidth, it may arrange with another party to temporarily lease the extra resources.

18.4 Applying Cognitive Radio to a WMN

The nature of WMNs makes them prime candidates for applying cognitive radio. In this section, the characteristics of WMNs will be discussed, and the potential benefits of CR considered.

18.4.1 WMN Characteristics

WMNs are designed to provide wireless network access to user devices. However, rather than requiring a wired connection to each access point, mesh access points (MAPs) are interconnected wirelessly. This greatly reduces the cost of deploying the network, and allows additional flexibility in the placement of nodes. User devices communicate with a MAP via an access link. The traffic is then forwarded through the mesh, from MAP to MAP, via transit links. This multihop forwarding delivers traffic to a gateway, nodes within the mesh that possess an additional interface to the Internet. This network structure is depicted in Fig. 18.1. Some traffic may also flow between two WMN users – this peer-to-peer traffic does not need to pass through the gateway, staying within the mesh. However, most traffic is likely to occur between a WMN user and a second endpoint elsewhere on the Internet [28].

Both the access link and the transit links operate via wireless communication. Although the gateway link could also be wireless, most works to date have assumed

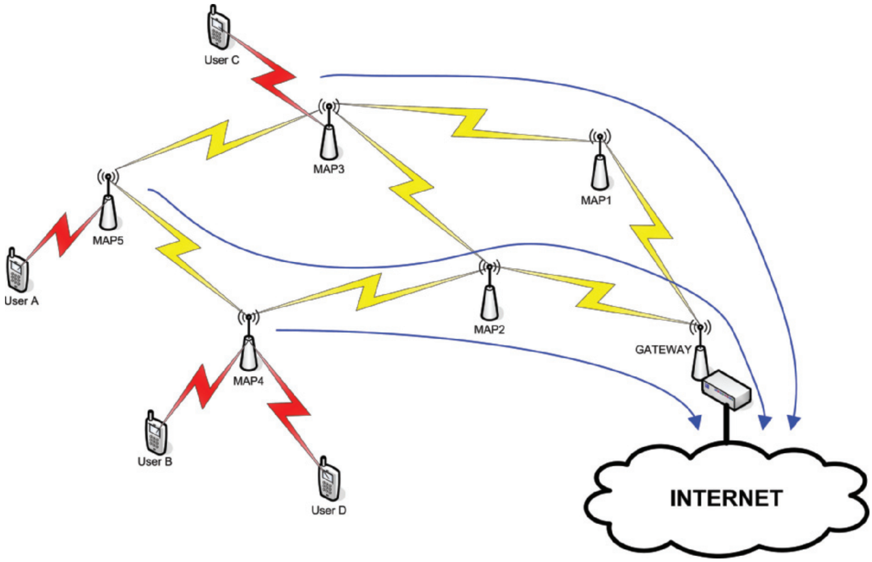

Fig. 18.1 A wireless mesh network

it to be wired. Many works have also considered the access and transit links to operate over separate wireless interfaces and on different channels. Typically, the transit network is the limiting factor in a WMN. Several things contribute to this: first, the wireless medium is openly shared, requiring traffic from multiple links to share the same bandwidth; second, multihop forwarding requires a single traffic packet to be transmitted multiple times to reach its destination; third, the presence of the gateway tends to accumulate traffic in its region, as most traffic flows either to or from the gateway. Therefore, the nodes and links surrounding the gateway not only carry the most traffic, but also interfere with each other so that this large volume of traffic must share the available bandwidth [29].

Added to this is the fact that existing MAC protocols do not make efficient use of the wireless channel. The IEEE 802.11 DCF is most frequently used in WMN works. However, the CSMA mechanism of DCF is designed primarily for use in WLANs. In multihop wireless networks, the floor acquisition model of the RTS-CTS mechanism results in each link requiring a large number of neighboring links to remain silent. This limits the network's ability to re-use the medium and have transmissions occur simultaneously [30].

Some existing WMN products use directional antennas within the transit network to alleviate some of the interference and medium re-use issues. For example [31], uses directional antennas to communicate between MAPs. This, combined with the use of multiple channels, allows multiple links to operate simultaneously. However, even in this case, the throughput capacity of the network is limited by the ability of the gateway to send and receive through its transit interface.

18.4.2 Benefits of CR to WMNs

18.4.2.1 Providing Additional Bandwidth

The ability to use any spectrum that is not being used could greatly improve WMN performance. A WMN could cover a large geographical area, however unlike a cellular network, the area is covered in relatively small pieces. The far smaller coverage areas and close proximity of adjacent MAPs mean that transmissions can occur with much lower transmission power. As a result signals are much more localized.

Areas where frequencies are not being used could exploit these channels, providing the WMN with valuable additional bandwidth. If the WMN is intelligently deployed, especially by placing gateways and their resulting congestion in areas where the most spectrum is usually available, then the network capacity could be significantly improved. However, determining such a deployment could be complicated, as frequency use could be transient. Transient frequency holes that could be used by the WMN would result in a highly variable network capacity, making QoS delivery challenging.

18.4.2.2 Rebalancing the Access and Transit Network Bandwidth

Without requiring full CR capabilities, a WMN could use CR techniques to make better use of the wireless channels available to it. Using a technology such as 802.11, several equal-sized channels can be used (three non-overlapping channels in 802.11b/g). However, if both the access and transit links use the same technology, the transit network has far lower throughput capacity than an individual access link. The access channel is under-used, as the transit network is incapable of handling the total traffic if every MAP fully uses its access link.

Numerous works have considered the use of multiple channels and/or multiple interfaces within a multihop wireless network to increase the network throughput capacity. Multichannel MACs must co-ordinate which nodes should use which channels, and when. One option is to use a fixed control channel [32]. Nodes request resources on the control channel, then switch to an alternate channel for the transmission of data. Other approaches assign home channels to nodes [33]. To contact a particular node, a sender must switch to that node's channel.

Nodes with multiple interfaces can use different channels simultaneously. In [34], each MAP has two transit interfaces. One is used for the uplink (towards the gateway), while the other handles the downlink (away from the gateway). Other schemes may have additional network interfaces (k-NICs) to use additional channels. However, as shown in [35], adding interfaces selectively within the network can yield similar improvements by alleviating the bottleneck.

A similar result can be gained using CR. The ability to dynamically allocate and use frequencies allows for more bandwidth to be allocated in the bottleneck regions. Even without additional bandwidth, a redivisioning of the channels assigned to access and transit would result in an increased capacity, as well as a more complete use of all channels (Fig. 18.2).

18.4.2.3 Changing the Nature of Gateways

If every MAP is a CR node, they already have the capability to use the equivalent of an additional interface. With wireless technologies such as IEEE 802.16 (WiMAX) emerging [36], it could be possible to also use wireless for the gateway link as shown in Fig. 18.3. All WMN nodes would then only require a power connection. It would also allow a much larger number of gateways to be placed within the network,

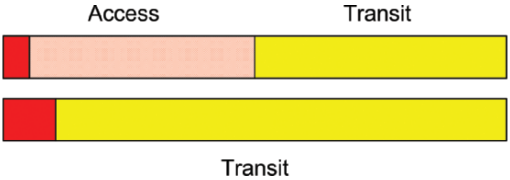

Fig. 18.2 Balancing the access (*dark*) and transit (*light*) networks – wasted access bandwidth is shaded

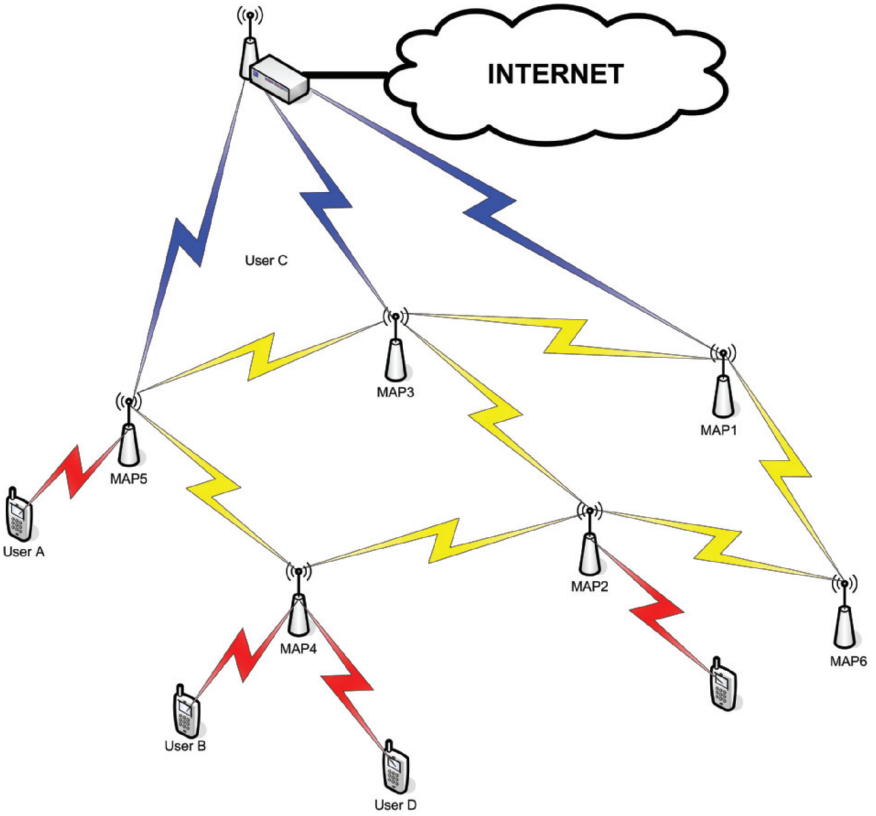

Fig. 18.3 Wireless gateway links feeding mesh gateways

which would reduce both the distance traffic would need to flow, and the number of nodes served by each gateway. This architecture would also allow for greater path redundancy and possibly the opportunity for a node to exploit multiple gateways simultaneously to maximize throughput.

18.4.2.4 Multiple User Technologies

With a CR interface, MAPs could possibly support user devices utilizing a variety of different wireless technologies. For example, although user devices may eventually have a full CR interface, a large number of legacy devices already exist. The CR could allow these devices to continue to be used to connect through the WMN, by offering that technology among its modes of access. This does create some complications however, as it will require an understanding of how different technologies work together and interfere with each other [37].

18.5 CR Research

Clearly there is a lot of work to be done to take cognitive radio from its current vision to a usable technology. As a long-term goal and a combination of a number of components, one of the keys will be to find ways to allow intermediate technological advances to enter mainstream use before the completion of a fully capable cognitive radio. This is particularly true for CR, because of the nature of current spectrum regulations. In this section, we address some of the key research areas for CR, considering the existing work and what advances must be made in order for CR to be realized.

18.5.1 Transmission

Perhaps one of the most difficult areas to predict in terms of future progress are the characteristics of physical antennas and transceivers. It is therefore a major challenge to create a technology such as CR that must adapt and incorporate these technologies into the system. Although current research and developments give an indication of some of the capabilities of the next generation of PHYs, the CR architecture will have to be extremely flexible.

However, researchers are beginning to explore the limits of the capabilities for radio techniques. Works on information theory are starting to develop a picture of how much usable information can be encoded on a channel using different techniques. For example, ultrawideband communication (UWB) spreads a communication over a very wide frequency band [38]. To avoid interfering with other nodes operating with those frequencies, it uses a very low transmission power. Therefore, a UWB receiver can detect the short-range transmissions, while it contributes very little to the overall noise floor experienced by other nodes. Information theory works are finding the capacity regions for these works – the theoretically achievable rates for multiple transmissions within the same frequencies [39, 40].

UWB, directional antennas, multiple-in multiple-out (MIMO), and frequency agility are all examples of current research areas that are likely to become (and in some cases already are) part of next-generation wireless communication systems. As digital signal processing techniques (and processing speed) continue to improve, these technologies will mature. However, at this point it seems likely that different devices will continue to have different capabilities, depending on hardware factors such as processors, memory storage, physical size, and power supply.

18.5.2 Awareness

Building awareness is a key function to cognitive radio. However, there is a huge volume of environmental data that can be collected, and not only must it be collected, it must also be shared with others as appropriate.

In current wireless technologies, data collection is typically very simplistic. Consider two common systems. In a cellular system, medium access control is typically centrally controlled. It is aware only of its own clients, and only requires knowledge of the frequencies it controls. An 802.11-based WLAN is slightly more complicated, with the clients required to sense the medium under the carrier-sense multiple access (CSMA) scheme. Only a limited memory is maintained, as captured by the backoff scheme.

Previous works have shown that extending this awareness even a little can be quite difficult. Even spectrum sensing is much more difficult, when wide spectrum is considered. The dynamic nature of the wireless medium also causes problems. For example, several works on MANETs and WMNs have attempted to evaluate the quality of links between nodes [40, 41]. Small changes in position, the physical environment, or environmental noise, can often cause major changes in the achievable link quality. Therefore, knowledge must exist, not only about the received signal, but also about the source, so that further results can be extrapolated.

Mitola's original work on CR addressed this point. The radio knowledge representation language (RKRL) was designed to allow devices to represent information about their radio characteristics [9]. Sharing this knowledge allows other radios to adapt their own communications, whether to communicate with the device, or to avoid interfering with it. Another concept, Interference Temperature, was proposed as a metric for estimating the cumulative interference energy at a receiver [42]. However, the concept behind this work was determined to be "not a workable concept" and investigation by the FCC was terminated in May 2007. An alternative approach appears in [43], where the spectrum resource is divided into virtual cubes, with the dimensions of the cubes representing time, frequency, and power.

For CR, one special type of awareness involves knowledge about primary spectrum users. The location and activity of these users is important, as CRs must avoid interfering with them. Primary users can be either active (transmitters or transceivers) or passive (receiver only). CR devices can detect active primary users by sensing the medium, although an idle user could be missed. However, passive users are problematic. As receivers (e.g., a television), passive users do not transmit any signal. Therefore, a CR must rely on other information to reveal the presence of a passive user.

This is an excellent example of how a CR must combine information from a variety of sources to understand its complete radio environment. Different approaches could be used for identifying a passive primary user. One option is to maintain a database of user locations and characteristics that CRs must check before using certain frequencies [44]. Frequencies that may have passive users (or even idle active users) would be considered required knowledge for all CR devices. Another option would be to protect a passive user with a simple CR device, responsible for notifying other CR nodes of the user's presence [45].

A CR should be aware of network load and application conditions. This knowledge may be required for several networks – both networks the node is involved in, as well as others that affect the radio environment. Gathering this information could be expensive. Active techniques such as probing may yield better information, however passive techniques have less impact on the network. For a CR, its sensing capabilities should allow it to rely heavily on passive sensing – gathering information by overhearing it.

18.5.3 Sharing Information

Nodes can also gather information by sharing with other cognitive radios. Because of differences in location, configuration, and history, different nodes will have a different set of collected knowledge. Communication between CR devices can extend the knowledge a node has about its environment beyond what it can obtain on its own. Certain information (such as location) may only be attainable based on collaborative sensing, where several nodes share and combine their information.

If we consider location determination, one approach is to incorporate a GPS receiver into each device. However, this has limitations in terms of cost, complexity, size, and usability. Although GPS functionality may eventually be included within the capabilities of a CR – a GPS receiver must have far higher sensitivity than current radios – alternative solutions are being investigated. A number of variants of the problem exist, from locating mobiles in a conventional WLAN [46], to establishing a complete map of positions in an ad hoc network. The amount of information used varies, from received signal strength [47] to simple connectivity [48].

If all nodes can determine signal strength, why would they choose to use only connectivity data? This illustrates one of the problems faced in sharing spectrum data between nodes. Two receivers, depending on their own characteristics, can obtain very different measurements. Therefore, although an individual node may have more detailed information, to combine it, the information must be reduced to a form that is mutually compatible.

In addition, systems must be able to control or limit the information that is exchanged, or else the communication process could overwhelm resources. There is a huge volume of data that could be collected. In fact, even relatively simple exchanges can overwhelm a dynamic network, as has been seen in the propagation of routing information in MANETs [11].

The field of sensor networks has yielded considerable work that is closely related to this problem. Sensor networks are designed to gather information, but inherently filter it as it is communicated to the necessary location within the network [49]. Sensor network protocols are also designed to be lightweight, minimizing the resources required for them to operate. However, many sensor network protocols focus on relaying information to a sink node, whereas communication within a CR-based network could have to be more distributed, depending on the network topology.

18.5.4 Decision Making

The cognitive radio communication process is very different from a conventional wireless interface. The conventional process is very linear, modeled on a protocol stack. For example, consider a basic WLAN device. An application generates packets. Routing determines the destination for the packets, and sends them to the appropriate interface. The network interface uses the medium according to a predetermined MAC protocol (e.g., the 802.11 DCF), then transmits the packet according to the interface's specifications and configuration. By comparison, the CR interface is decidedly nonlinear.

In the CR, all parts of the communication must be decided. This includes what to send, as well as where, when, and how to send it. All aspects of the communication are part of the decision, and are governed by the user preferences and goals – including whether or not to communicate at all. All of these decisions are closely interrelated, and cannot be made independently of one another.

The CR decision-making process can be viewed as the ultimate destination for work on cross-layer protocols. Cross-layer protocols have been popular in recent years for MANETs, where it was realized that considering network conditions such as routing and congestion in medium access decisions can yield improved performance [50, 51]. CR takes this to the extreme, utilizing all available information in all communication-related decisions.

18.5.4.1 What to Send

The decision of what to send is typically beyond the scope of the wireless interface. Data is simply passed to the interface with the expectation that it will be transmitted according to the communication protocol. A CR can decide to communicate now or wait until later, or adjust the traffic according to the characteristics of the network and the wireless resources.

Adaptive applications are an example of network conditions impacting on what to send [52]. A QoS-sensitive voice application might adjust its sound quality (e.g., sampling rate, stereo/mono) to match the available resources of the network. An adaptive web client might reduce image resolutions (or not load images) if it is using a low bandwidth connection.

18.5.4.2 Where to Send it

The flexibility of a CR allows it to connect to different networks. This ability is similar to some existing devices that have multiple interface cards, although the CR will have the ability to connect to any available network. This may be used to allow vertical handoff [53], depending on network coverage, or simply to choose the preferred network. This may be dependent on cost, availability, congestion, or QoS [54]. The CR could even make use of different networks for different traffic types.

In addition to network choice, the CR must also consider the routing of traffic. For single hop wireless networks, this is reasonably simple, although the CR should be able to make full use of mobility management techniques as it moves between access points, to ensure optimal handoffs [55]. For multihop networks, the routing process may be far more complicated. The CR may even consider whether or not a route is established in determining whether or not a particular network should be used.

18.5.4.3 How to Send

The question of how to send depends heavily on the decision of where to send. Depending on the network chosen, many or all of the communication parameters will be predetermined by the technology being used. However, in other cases – for example in a MANET made up of CR nodes, or even just an ad hoc connection between two devices – the communicating nodes have to choose the appropriate parameters based on the current environment.

This is where the full flexibility of cognitive radio appears. The cognitive radio can choose each parameter for the communication to best fit the environment it is in.

18.5.4.4 When to Send

There are two aspects to the question of when to send. There is the question of medium access control. The MAC determines when (combined with how) to access the medium for each communication. We will cover this in more detail in the spectrum management section. On a larger time scale, having knowledge of past conditions and a model of future conditions may create a scenario where best effort traffic is not necessarily sent immediately, as quickly as possible. A CR may predict that conditions will improve, because of more available resources, a lower price, a particular network, etc. In this case, it may choose to delay the communication, waiting for the preferred conditions.

18.6 Thoughts for Practitioners

With the current spectrum allocation system, the medium access method is dependent on the technology deployed in each particular band. Even technologies operating in unlicensed spectrum use specific channels, and then use a MAC protocol to negotiate traffic within that channel. With the importance of the MAC protocol, a large quantity of wireless research has been devoted to improving the MAC protocols, especially the 802.11 DCF. Numerous works have addressed adding priority mechanisms, handling multiple channels, using directional antennas, utilizing cross-layer information, and much more.

However, as the move towards cognitive radio allows, and likely requires, the reconsideration of the allocation system, we now consider the types of system that could emerge, and some of the key issues that must be dealt with.

The simplest approach would likely be to continue with the current system with only minor changes to allow additional dynamic access within spectrum holes. Under the condition that primary systems must be fully protected, cognitive radio usage would be strictly limited to scenarios such as 802.22's use of the TV broadcast bands. Each proposed system could be thoroughly tested within each band under consideration.

However, it appears that regulatory agencies are prepared to implement greater changes than this [56]. Therefore, more dynamic systems are being created. The proposals vary in three major ways. First, on what time-scale should spectrum be allocated? Second, should a centralized or a distributed approach be used? Third, should access be scheduled or contention-based?

For the first question, long allocation periods are good for licensees, particularly if they need to deploy infrastructure. Long periods allow them to invest in their network, with the security that they will have the resource for a certain length of time. However, this creates a system that is less dynamic, and less responsive to change, resulting in inefficiencies. Shorter periods are more flexible and responsive, at the expense of stability.

There are several possible solutions to this question. One option to address this instability would be to use short licenses while giving a priority to renewing an existing license. This would allow an operator to obtain a license and deploy infrastructure, with a reasonable expectation that they can maintain the license as long as the spectrum is adequately used. Another approach would be to have a system of variable-length licenses, with extended licenses being granted as required. In the extreme, with fully cognitive nodes, even a system with fully open spectrum could be envisioned.

The question of centralized versus distributed is dependent on the length of licenses. For very short leases, the fully centralized approach of a single regulatory body would be overwhelmed. Similarly, a highly distributed system would be unnecessary for very long leases. In reality, some type of hybrid or hierarchical system is likely. Consider the spectrum server solution presented in [57]. In this system, clients request resources from a centralized server, which allocates spectrum. Similarly [58], presents a framework for real-time spectrum auctions. To scale, these systems would likely require many servers, with extensive coordination, however they can be effective at avoiding conflicts in spectrum allocations.

The fully distributed case is in fact the question typically considered in medium access control, where individual nodes or links must obtain a spectrum opportunity to communicate. At this scale, spectrum allocation can be very fine, with resources allocated for single flows or even single packets. With allocation handled at this level of precision, no additional MAC protocol would be needed. In [59], a distributed allocation scheme is presented where groups of nodes bargain with each other for spectrum access. With the geographical limitations of wireless communication, distributed decisions become quite natural. However, the difficulty lies in knowing how the decision affects more distant nodes.

Scheduled or contention-based? This is an interesting question for dynamic spectrum. Although the opportunistic nature of contention seems to lend itself naturally to the task, the inefficiency of contention-based approaches seems contrary to cognitive radios goals. However, this inefficiency arises predominantly from the expense of the contention process relative to the length of the communication. Although WLANs typically contend for a single packet transmission opportunity, a more flexible spectrum license could be more feasible.

Scheduled spectrum allocation could be very efficient, with very little spectrum wasted. The challenge lies in creating this schedule, whether centrally, or in a distributed manner [60]. In part, the cost of scheduling resources is dependent on the dynamics of the nodes. As seen in MANETs, high mobility, or highly variable traffic requirements require frequent changes to the schedule, increasing the cost of computation and communication.

One proposal for spectrum management has been to facilitate the concept of a secondary spectrum market [61]. The concept allows the current allocation system and spectrum rights to be maintained, while making better use of wireless resources. Many current licensees object to dynamic spectrum access and the Open Spectrum concept, as it infringes on their spectrum, a resource that they may have acquired at considerable expense. A secondary market would maintain the rights of the primary spectrum license, and in fact allow the licensee to make additional profit from their residual resources [62].

A secondary market involves the primary licensee re-leasing any residual bandwidth that they cannot use. Consider a cellular provider with a set of frequency channels. The provider must have sufficient resources to avoid blocking incoming calls and to keep call dropping due to handoff to a minimum, even during busy periods. During low periods, there is a large amount of residual capacity that goes unused. A secondary market allows the provider to lease this residual capacity to another provider, if required. This can ability can be used to effectively pool resources, leading to a dramatically improved level of QoS [63].

One further area of spectrum management requires consideration. Enforcing spectrum rights is already difficult under the current system, and dynamic spectrum usage further complicates it. Currently, spectrum is protected primarily through regulation and control over radio emitters. In the US, the FCC approves radio-emitting devices only after extensive compliance testing, to ensure they operate as required, without generating harmful interference. Detecting transmissions from unauthorized users is important, as they may impact on QoS and, in the case of intrusions, may present a security risk [64].

Dynamic spectrum necessitates an integrated enforcement solution. Mechanisms for secure devices have been proposed, so that devices were ensured to observe proper channel etiquette to transmit [65]. It has also been suggested that this etiquette could be captured within a channel license, which could be limited in duration to ensure their eventual expiration [66]. In addition, the sensing capabilities of a CR suggest that a distributed approach to detect rogue transmissions could be created [67].

18.7 Directions for Future Research

The development of CR could be a long process, however WMNs present several characteristics that could assist in bringing CR technology, or at least some parts of it, to use much sooner.

18.7.1 Static Core Topology

The relatively static nature of the WMN could greatly simplify CR systems. This effect has already been seen in the development of WMNs from MANETs – by removing the mobility, routing overhead is reduced and the technology becomes feasible. For CR, the fixed network changes the problem of collecting awareness of the network's surroundings. The WMN nodes provide a static frame of reference against which environmental data can be collected. Although mobile users and external interference sources may change throughout the life of the network, the WMN can establish normal values and possibly even identify periodic or predictable behavior.

18.7.2 Spectrum Information Collection

The WMN also presents a distributed infrastructure to collect spectrum data at a large number of locations. Interference levels are most important at the destination rather than the source, so to ensure harmful interference is not created, a CR system will need to be able to check levels at several sites. The presence of many user devices may also assist in the process, as CR-capable devices may assist in this detection process – in essence operating as sensor nodes (Fig. 18.4). It will be important to develop systems for collecting this data and maintaining it in a relevant form.

18.7.3 Traffic Awareness

As the primary traffic pattern in a WMN is focused to and from the gateway, knowledge about network traffic is fairly easy to obtain. The gateway is in a position to learn about traffic either by observation or reservation. Collecting information about other MAP-to-MAP flows in the network will require additional communication if this information is needed for network-wide resource management decisions.

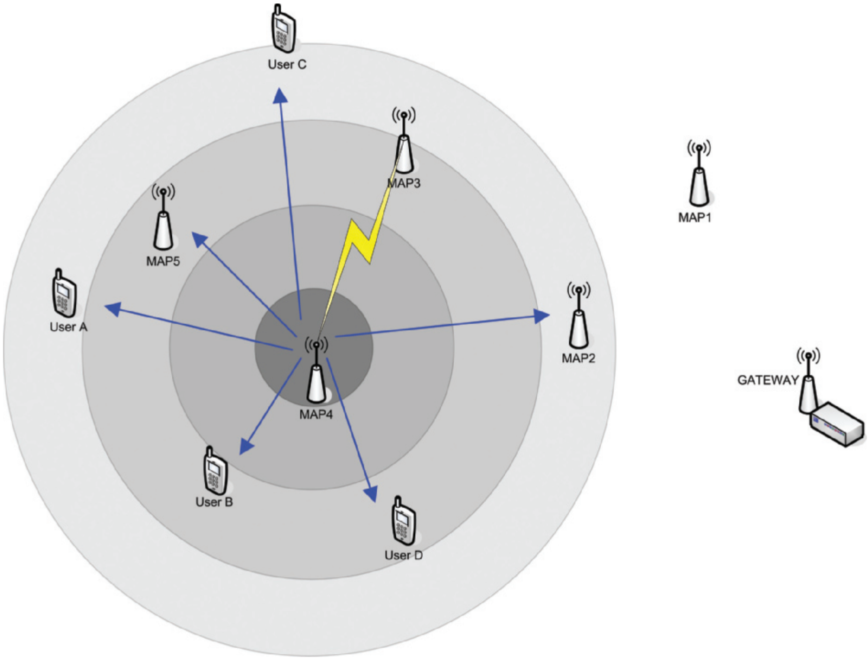

Fig. 18.4 CR devices act as sensors to gauge interference levels

18.7.4 Data Distribution and Decision Making

After the data is collected, it must be shared to ensure that the appropriate nodes have access to it. The structure of the WMN suggests that these decisions can be initially limited to within the mesh infrastructure. Although the WMN may receive sensing data or send control instructions to mobile devices, the processing and decision-making could occur solely within the mesh itself. This could greatly reduce the scope of data distribution.

18.7.5 Spectrum Monitoring and Policing

In order for cognitive radio to be initially accepted by policy-makers, it is extremely important that primary spectrum rights be protected. Using the sensing capabilities of the WMN, the WMN may be able to collaborate to detect users and determine the location of illegal transmissions. For users that violate spectrum policy, the WMN could also play a role in actively policing the action by denying or reducing that user's future service, through fines or pricing premiums, or by reporting the violation to the authorities.

18.8 Conclusions

Changes are coming to wireless communication and spectrum management. The explosive increase in wireless use has made them necessary. Fortunately, wireless technology has also matured sufficiently to the point where such changes are possible. The concept of cognitive radio can now serve as an ultimate goal to guide future research.

The implementation of cognitive radio will play an important role in the continued development and deployment of WMNs. Although WMNs have enjoyed remarkable success, they are, by their nature, very demanding of wireless resources. CR brings to WMNs the potential to exploit a large quantity of unused bandwidth, and the flexibility to improve the efficiency of communication.

In this chapter, we have provided a high-level view of what a cognitive radio is, and how it will operate. However, CR represents a major change in thinking, and will require the development of a large number of different technologies to achieve its goals. Although many of these technologies are under exploration in various fields, their combination into one CR system will be a tremendous task.

It is our view that although WMNs will benefit from CR, cognitive radio technology may benefit as much or more by being used for WMNs. WMNs have certain characteristics that constrain some of the problems that must be faced by CRs. In particular, the fixed infrastructure could provide a framework for gathering and maintaining information about its environment. The WMN structure fits naturally with both centralized and distributed approaches, which can be used in creating and enforcing spectrum allocation policies.

Despite the promise of cognitive radio, it faces many obstacles to obtaining authorization from regulatory bodies. However, we believe that by developing CR in conjunction with WMNs, a deployment, at least within a limited spectrum region, could be achieved much more readily. With both technologies benefiting from this relationship, a successful demonstration could suppress concerns about a new spectrum paradigm, and pave the road for the full realization of cognitive radio.

18.9 Terminologies

1. *Cognition*. The functions and processes of intelligence. These include learning, inference, decision-making, and planning. The development of knowledge.
2. *Cognitive radio*. The accumulation and use of knowledge about all aspects of the wireless environment for the purpose of intelligently deciding how to most effectively exploit wireless resources.
3. *Software defined radio*. A radio that is implemented in software rather than hardware, allowing for a far greater degree of control and re-configurability.
4. *Frequency agility*. The ability of a radio device to use a variety of different radio frequencies.

5. *Unlicensed spectrum*. Radio spectrum frequencies that are allocated for open use. These frequencies can be used by any device as long as they follow certain power and interference constraints.
6. *Open spectrum policy*. Policy advocating an increase in the openness of spectrum allocation. This includes not only the increase of available unlicensed spectrum, but also the opening up of existing licensed spectrum, possibly through cognitive radio techniques.
7. *Regulators*. Decision-making bodies responsible for the management of spectrum resources, e.g., the FCC in the USA or the CRTC in Canada.
8. *Spectrum auction*. One of the common methods for allocation of spectrum resources. A spectrum auction involves the release of a block of frequencies by the regulator. Parties submit bids to obtain a license for those frequencies.
9. *Spectrum license*. The right to dictate the usage of a particular set of frequencies. The license is granted to the licensee by the regulator.
10. *Fixed spectrum allocation*. The current system of spectrum allocation whereby each frequency channel is assigned to a particular purpose. Any changes occur via the regulatory process, usually over very long periods of time.

18.10 Questions

1. Explain how wireless resources can be both scarce and under-used.
2. Wireless spectrum has become a very valuable resource. Compare spectrum to two other natural resources in terms of renewal, scarcity, usage, overuse, etc.
3. List and describe three pros and three cons for an existing spectrum owner to open their resources to CR.
4. Compare current wireless communications to human speech. How are they similar? How are they different?
5. How does cognitive radio change the comparison in Q4?
6. How would using a wireless technology such as WiMax benefit a WMN?
7. Use a simple example to show why a WMN with equal channels dedicated to the access and transit links cannot fully use its available bandwidth.
8. Can one node detect a spectrum violation under the current system?
9. Can one node detect a spectrum violation in a CR system?
10. What systems do you think are necessary for implementing a secondary spectrum market?

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