Chapter 15

COOPERATIVE TECHNIQUES IN THE IEEE 802 WIRELESS STANDARDS: OPPORTUNITIES AND CHALLENGES

Explicit Macro Cooperation in Practice

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Abstract: Recently, cooperative techniques have drawn much attention in industry and academia for throughput enhancement, coverage extension and spectral efficiency improvement. They have long been used to improve the reliability and scalability of mesh communication networks. The IEEE 802 standards are concerned with the personal area network, the local area network, and the regional area network, among others. Each network has its limitation to deliver the required throughput and quality-of-service to the end users. Recently, there have been several attempts to adopt cooperative techniques into IEEE 802 standards to overcome those limitations. In the sequel, we address the opportunities and impending challenges in adopting emerging cooperative techniques in IEEE 802 standards.

Keywords: cognitive radio, cooperative techniques, mesh network, multihop techniques, relay.

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1. Introduction

IEEE wireless standards are addressed by the IEEE 802 LAN/MAN Standards Committee. Wireless Local Area Networks (WLAN), Wireless Personal Area Networks (WPAN) and Wireless Metropolitan Area Networks (WMAN) have been gaining much attention as they can offer easily deployable networks with high throughputs that fit the needs of bandwidth-demanding applications. These applications, such as multimedia, real-time video, VoIP (voice-over-IP), are foreseen to be driving the commercial embrace of next generation wireless networks. The LAN/PAN/MAN will be an integral part of the global network that will support ubiquitous wireless access. It is not surprising that the most advanced communication techniques have found their ways into the IEEE standards. In particular cooperative techniques are now being seriously considered in many Working Groups of the IEEE 802 standards committee.

Cooperative techniques have only recently received considerable attention. Theoretic as well as practical approaches have been taken. Theoretic problems, such as the capacity of networks using cooperative techniques, remain largely

Table 15.1. The IEEE 802 standardization activities that address cooperative techniques across the different Working Groups.

IEEE group	Scope	Operation scenario	Type of cooperation
802.15 TG 3, 4, 5	High rate wireless personal area network (WPAN)	Mesh networking	Cooperative retransmission
802.11s WG	Local Area Network (LAN) MAC enhancement for reliable and easily scalable network	Mesh Networking	Peer-to-peer cooperation
802.16-2004	Metropolitan Area Network (MAN) MAC enhancement for reliable and easily scalable network	Mesh Networking	Peer-to-peer cooperation
802.16 MMR-SG	Coverage extension, Throughput enhancement, Spectral efficiency improvement in MAN	Relay	Multihop relay, cooperative transmission
802.22	Wireless Regional Area Network (WRAN)	Fixed centralized point-to-multipoint for unlicensed operation in TV bands	Cognitive radios

unsolved. Yet, IEEE 802 standards have already started working on incorporating cooperative techniques into current standards development. Although it is clearly recognized that cooperative techniques offer great opportunities, this early adoption also poses a lot of challenges.

Cooperative techniques appear at several levels of the network:

- Cooperative transmission among mobile stations (in centralized or non-centralized networks)
- Cooperation among networks (*e.g.* for traffic load balancing, handover, spectrum sharing)
- Cooperation among mobiles and networks in unlicensed operation
- Cooperation between licensed and unlicensed spectrum users.

An interesting outcome of this challenge is where theory meets practice. Although a lot of fundamental theoretical results are not available (*e.g.* for mesh networks or cognitive radio networks even with simple channel models) practical approaches provide solutions for real-life systems. It is likely that theoreticians will also benefit from this approach.

Cooperation among networks that utilize different radio access technologies embodies one of the fundamental characteristics of foreseen 4G networks. In that sense, IEEE standards present a lot of opportunities to approach the necessary cooperative techniques that will need to be implemented in the more complex 4G networks.

In this chapter, we briefly summarize the main IEEE standard activities addressing cooperative techniques, namely mesh networks, cooperative or multihop relay, and spectrum sharing or cognitive radio techniques. Our main goal is to identify the opportunities and challenges in incorporating the cooperative techniques into the standards. The rest of the chapter is organized as follows: The mesh mode MAC layer enhancement for IEEE 802.11 is considered in section 2; The mesh techniques for 802.15 PAN networks are addressed in Section 3; The mesh operation and cooperative or multihop relay techniques for 802.16-2004 and 802.16e standards are considered in Section 4 and Section 5, respectively; Finally, spectrum sharing or cognitive radio techniques are addressed in Section 6 for the 802.22 standard.

2. Mesh MAC Enhancement in IEEE 802.11s

The IEEE 802.11 standard is concerned with wireless local area networks in unlicensed (ISM) bands in indoor environments such as office, home, etc. It evolved through 802.11a, 802.11b and 802.11g with maximum throughputs up to 54 Mbps. As laying wires in homes, offices and public areas is cumbersome and expensive, WLAN have become very popular recently. They also have the flexibility of allowing the terminals to move within the coverage area. The demand for higher throughput increases with the variety of services such as video, gaming, etc. The WLAN 802.11 standard has also evolved to deliver higher throughput to the terminals. The 802.11 WLANs can be deployed in either infrastructure mode or ad-hoc mode. In infrastructure mode, terminals are connected to an access point wirelessly and the access point is connected to either the wired or wireless backhaul network such as DSL, cable, IEEE 802.16, etc. The access point functions are similar to those of a base station in a cellular network. In the ad-hoc or mesh mode, the terminals communicate wirelessly with each other in the coverage range in a peer-to-peer fashion. There is no access point present in this type of network. As the mesh network is easily scalable and has the ability to reconfigure and self-heal around a blocked path, this architecture is reliable and preferred over the infrastructure network.

The new evolution of 802.11 standards, named 802.11n, has been discussed in the Task group (TG) 'n' to deliver about 10-fold higher throughputs than the current 54 Mbps [IEEE11web, 2006]. Recently, another evolution of 802.11 using mesh networking, named 802.11s, has been discussed in TGs. This Task Group is concerned with upgrading the 802.11 MAC layer operation to self-configuring and multihop topologies. It may support broadcast, multicast and unicast traffic in the network. There are a few network element functionalities defined in the TGs such as mesh point, mesh access point, and mesh portal. The mesh point is the basic element. It collects information about the neighboring mesh points, communicating with them and forwarding the traffic. The mesh access point is a mesh point that has the capability to function as the 802.11 access point. The mesh portal is a mesh point, which connects the mesh network and a non-802.11 network. Figure 15.1 depicts the network element functionalities.

The TGs received around 15 proposals for the initial call for proposals in June 2005. As of November 2005 only two main proposals remain on the table. They are the SEE mesh and the Wi-Mesh Alliance proposals. The SEE mesh proposal was put together by a consortium of major companies, included which Intel, Nokia, Motorola, NTT DoCoMo, Texas Instruments and Samsung. It introduced the concept of mesh portal for interoperability in mesh networks and to accommodate other 802.11 WLAN (old or new) services in the network. The Wi-Mesh alliance companies include Nortel Networks, Thomson, InterDigital Communications, NextHop Technologies, and Philips, among others. Their proposal was claimed to be equipment vendor independent and operable in indoor and outdoor situations. The usage models for 802.11s are categorized into four main items depending on the deployment, propagation characteristics and required service. The basic residential model contains a small number of nodes and its main characteristic is to provide a low-cost,

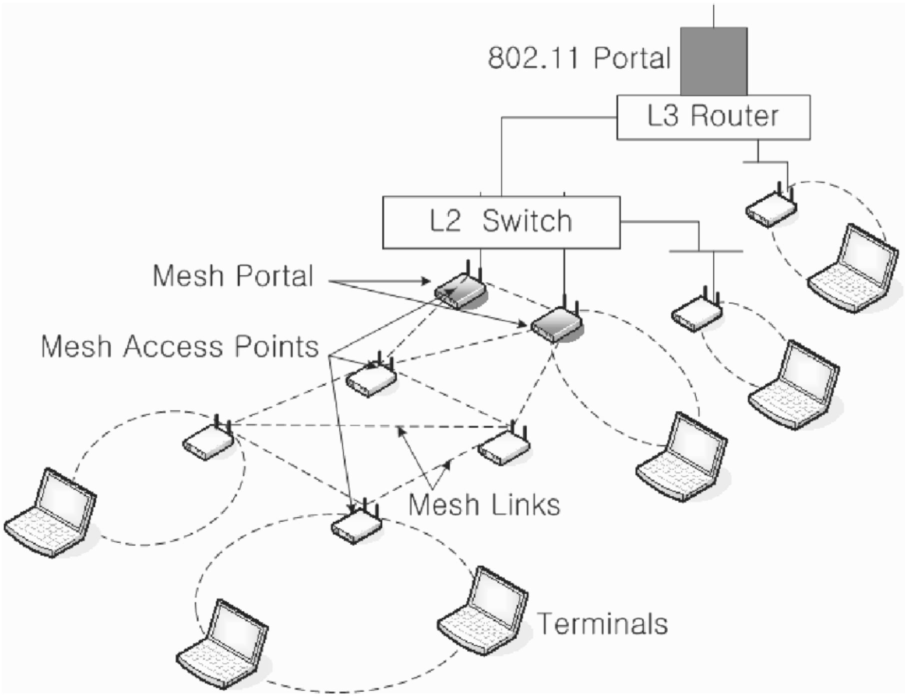

Figure 15.1. The IEEE 802.11s mesh operation from IEEE P802.11-04/0730d3 [802wireless-world, 2006].

high performance and easily deployable mesh network to remove the radio frequency dead-spots. Other usage models include the office, campus/public access network and public safety networks. The office and campus/public access models contain a relatively large number of nodes and a wider coverage area. The public safety model is to form a relatively smaller easily deployable network during emergency situations.

In summary, mesh networking is a suitable solution for LANs to provide easily scalable, reliable, flexible and cost effective networks.

3. Mesh Mode Operation in IEEE 802.15

The IEEE 802.15 Standards defines the physical and medium access control layers for short-range communications Wireless Personal Area Networks using the ultrawideband (UWB) technology. Data rates from 250 kbps (802.15.4) to 55 Mpbs (802.15.3), with communication distances from 1 to 75 meters, are expected. The IEEE 802.15.5 standard is the mesh extension to 802.15 [IEEE15web, 2006].

In comparison with the mesh operation in 802.11 networks described in the previous section, the 802.15 differs in the way terminals act as nodes in the mesh network. In 802.11, which is an infrastructure mesh, only Access Points are nodes of the mesh network, whereas in 802.15, which is a client mesh, user terminals are the nodes of the mesh network. As a result, the mesh control layer must now also address network performance and control, in addition to coverage and range extension. This feature requires collective behaviors to be implemented. Thus cooperation is required at the network level. In particular in large mesh networks, local routing decisions result in sub-optimal global routing, leading to unacceptable QoS performance. In order to guarantee QoS to critical applications, local network information must be shared globally. The challenges of propagating network information to every node lie in the overhead required for transmitting that information, and the delay between the time the information is sent by a node and received by all other nodes, which could render the information obsolete due to the time-varying nature of the Mesh WPAN. Nodes in the mesh network should therefore cooperate to propagate control and data streams of other nodes, hopefully resulting in a benefit for every single node in the network. Moreover, cooperative re-transmission mechanisms using nodes as relays, built on ARQ protocols and cooperative coding, also offer further enhancement to the physical and medium access control layers.

An important characteristic of WPAN is the low transmission powers due to energy-limited battery-operated devices. Another distinguishing feature of WPAN networks is proactive power management. It is well known that relaying, multihop and cooperative transmission techniques can help save energy. MAC protocols can also be designed to allow nodes to participate in cooperative routing for power savings, and to go into energy-saving modes as often as possible.

Cooperation is also often required for the coexistence or sharing of resources by collocated networks. In addition to contention-based access to the channel for delay-insensitive applications (with a carrier sense multiple access (CSMA) approach for collision avoidance), delay sensitive applications rely on beacons to ensure isochronous transmissions in IEEE 802.15.3. In the scenario of simultaneous operating mobile piconets, collisions of such beacons would prevent the successful transmission of delay-sensitive data. Cooperation between the piconets is thus necessary to avoid this undesirable situation. The beason mode of operation specifies a superframe structure with a subframe for the transmission of beacons, and a PAN coordinator to address coexistence. However, the beacon mode of operation is currently not allowed in the mesh mode.

To conclude on PAN, due to the short communication ranges, a mesh architecture is natural, but it requires advanced cooperative techniques in order to be scalable and reliable. The power-limited nature of the devices is also addressed by cooperative transmission and routing techniques.

4. Mesh Mode Operation in IEEE 802.16

The IEEE 802.16-2004 is an OFDM, OFDMA and single carrier based fixed wireless LAN/MAN standard in licensed bands of 10-66 GHz approved in June 2004. It improved and consolidated the previous standards such as 802.16-2001, 802.16a-2003, and 802.16c-2002. The MAC layer supports the point-to-multipoint and optional mesh network topology [IEEE, 2004]. The optional mesh mode operation was initially defined in the the 802.16a-2003 standard with basic signaling, message formats, etc. Subsequently, the mesh mode specifications were integrated and improved in the IEEE 802.16-2004 revised standard. Unlike the point-to-multipoint mode, there are no clearly separate downlink and uplink subframes in the Mesh mode. Each terminal communicates with a number of neighboring stations instead of communicating with a base station. There are a few terminals, which function as gateway to the backhaul network and provide some of the base station functions.

In the IEEE 802.16-2004 standard, centralized scheduling, distributed scheduling, and a combination of both scheduling schemes are used. If centralized scheduling is employed, the mesh base station nodes functions are similar to the base station in the point-to-multipoint mode. The mesh base station provides the control and scheduling decisions. When distributed scheduling is employed, all terminals, including the mesh base station, transmit their data after coordinating with the two-hop neighborhood and broadcast their scheduling information, such as available resources, requests and grants [IEEE, 2004]. It is assumed that no interference occurs between nodes that are two hops away. Thus, the mesh with two-hop neighborhood suffers from the hidden terminal problem [I.F. Akyildiz, 2005]. The inter node interference is one of the major factors affecting the network capacity and the scalability in mesh networks. If the inter node interference is taken into account in the radio resource allocation, better spectral efficiency may be obtained. In centralized scheduling, resources are allocated in a more centralized manner. The mesh base station gathers requests for resources in uplink and downlink from the terminals within a range of a few hops. It makes the decision and transmits the scheduling message which is not the actual schedule to the terminals. The terminals use a predetermined method to calculate the actual scheduling information depending on the system parameters [IEEE, 2004]. The mesh network with centralized scheduling has limited scalability. It can only support around 100 subscribers due to the structure of centralized scheduling messages.

5. Mobile Multihop Relay PHY/MAC Enhancement for IEEE 802.16e

The modification to PHY and MAC layers in the 802.16-2004 standard was considered in the IEEE 802.16e task group to include mobile and nomadic applications [IEEE16e, 2006]. The task group was approved in December 2002. It incorporated advanced techniques such as MIMO, LDPC codes, scalable OFDMA, adaptive modulation and coding (AMC), into the IEEE 802.16e to deliver broadband access to mobile and nomadic subscribers. This task group completed its activities and submitted the draft standard for approval by the IEEE standards committee in September 2005.

The demand for higher data rate keeps on increasing with new wireless services. Adaptive modulation and coding may cause non-uniform coverage of the IEEE 802.16e systems at the boundary of the cells. To overcome these impediments, modifications to the PHY and MAC of IEEE 802.16e was proposed and a study group was formed in July 2005 to develop methods for using multihop relay and cooperative techniques.

The study group was named the mobile multihop relay study group and defined its goals as coverage extension and throughput enhancement. These goals will be achieved through the modification of the frame structure and the addition of new protocols for relay operation, while keeping the backward compatibility for the point-to-multipoint mode in IEEE 802.16e. As the mesh type of operation is already incorporated in the IEEE 802.16-2004, it will not be considered in this study group. The other major requirements are that one end of the relayed path should be the a base station or a mobile station, and to efficiently provide a multihop or relay path to a mobile station or to a base station with a small number of hops. The operating scenarios under consideration in the mobile multihop relay study group are summarized in Table 15.2 [IEEE16, 2006].

Table 15.2. Table The topology and operating scenarios considered in IEEE 802.16 MMR-SG.

Topology	Scenario	
	Infrastructure	Client
Mesh operation	No	No
Fixed	Yes	Yes
Nomadic	Yes	Yes
Mobile	Yes	No

As described in the table the mobile client relay will not be considered by this Study Group due the complexity, battery life of the client relay, and security.

In recent years there has been a lot of interest in the industry and academia in multihop relays and cooperative diversity systems. At this point we need to make the distinction between relays and repeaters. The repeaters are the networks elements which receive, amplify and transmit without any baseband processing [of Visions 2003 (WWRF), 2006]. They are basically bidirectional amplifiers. They are normally used to extend the coverage in shadowed areas within a cell or extend the cell coverage. The use of repeaters is already addressed in the 3GPP cellular standard [3GPP, 2006a], [3GPP, 2006b].

Since the relay stations are not connected to the network backhaul, they are low cost and low power elements. The relays can be placed in such a way to reduce the propagation losses between the relay and the mobile users in order to improve the coverage and throughput. The relaying operation can be carried out in either the time or the frequency domain. With time domain relaying, the same frequency is used by the base station and the relay station, and they share the channel temporally. Different frequencies are used by the base station and the relay station with frequency domain relaying, and they transmit during the same time slot. The relays can employ forwarding schemes such as

- Amplify and forward
- Decode and forward
- Estimate and forward
- Store and forward

The detailed description of these schemes is out of the scope of this chapter, however we briefly discuss the impending challenges in adopting them. In the amplify and forward scheme, the received signal is just amplified by a fixed gain. It is essentially similar to an analog repeater and simpler to implement. However, interference enhancement may occur and instability may result in the system. In the decode and forward scheme the received signal is fully decoded and reencoded, and then transmitted by the relay station. It poses the danger of error propagation and higher latency. In the estimate and forward scheme, the data is estimated and transmitted by the relay station. It is similar to the decode and forward scheme but relatively simpler at the expense of the performance. It also has the drawback of error propagation and higher latency. In the store and forward scheme, the relay node in the relay chain receives the data, stores it and transmits it as required by the particular protocol. This scheme also has the drawback of higher latency and requires large buffer sizes. The relay or cooperative techniques can also be used in conjunction with advanced techniques such as MIMO, space time coding, adaptive modulation and coding, and advanced channel coding. We briefly summarize the candidate techniques proposed in the literature and their inherent challenges in their adoption for a standard.

1 Virtual Antenna array

A source multicasts the desired data to number of relays, which in turn retransmit the processed data to the destination. The destination may intelligently combine and process the received data to obtain higher throughput and spatial diversity [Dohler, 2003]. The challenges for this scheme are to obtain the channel state information at the relays, synchronization, cluster information for relays, etc.

2 Distributed MIMO and space time coding

A source transmits the desired data to a number of closely spaced relays. They fully decode the data and then using space-time coding or spatial multiplexing or any other advanced MIMO technique in distributed manner, they transmit the data to the destination [Laneman and Wornell, 2003]. As in virtual antenna arrays the channel state information may be needed at the relays and the relays may need to exchange their channel state information and other control information among them.

3 Coded cooperation

The channel coding and cooperative relaying are integrated in coded cooperation [Hunter and Nosratinia, 2005], [A. Nosratinia and Hedayat, 2004]. Different error correction schemes are used in the direct and the relayed paths depending on the channel conditions. In general, various channel coding methods can be used in this framework such as block codes including LDPC codes, convolutional codes, Turbo codes. The major impediments of this scheme are the decoding complexity and the large overhead in transmission.

In conclusion, there are many cooperative or multihop relay techniques proposed in the literature for coverage extension and throughput enhancement. However, the 802.16 mobile multihop relay study group is the first attempt to induct them into a standard. It is early to say whether cooperative techniques or other already known mature techniques serve the purpose effectively.

6. Cognitive Radio/Spectrum Sharing Techniques in IEEE 802.22

The Working Group 802.22 on Wireless Regional Area Networks (WRAN) was created in November 2004 to address the use of cognitive radios in unlicensed spectrum operation in TV bands [WG, 2006]. This approach was prompted by a Notice of Proposed Rule Making from the FCC, which was released in December 2003 [Commission, 2004]. This Notice of Proposed Rule Making proposes to open the licensed TV band in the United States to unlicensed operation by spectrum-agile devices, provided they do not interfere with incumbent license users. This is a new approach to spectrum management, prompted by the observation that licensed spectrum is mostly unused in certain locations and at certain times. Thus the current approach of allocating the spectrum has been recognized to be inefficient in the light of the shortage of spectrum unanimously observed.

The scope of cognitive radios capabilities in IEEE 802.22 is more limited than the original definition of Mitola [Mitola, 2000], for which a comprehensive review is available in [Haykin, 2005]. However, even in its limited approach to the problem, the FCC opened the door to many challenges in the definition of a standard adopting these principles. The IEEE 802.22 WRAN Working Group aims for a fixed wireless broadband access in regional areas where TV bands will be largely unoccupied most of the time. The scope of receivers with cognitive capabilities is thus limited to switching spectrum bands and controlling their emitted power to avoid creating interference to nearby TV receivers. TV receivers located inside the noise-protected contour of a TV station are entitled to protection. The noise-protected contour is defined by the quality of TV reception in terms of the value of the Desired-to-Undesired ratio at the TV receiver. For NTSC TV, it is referred to as the Grade B contour [O'Connor and A., 1968]. However even such a limited approach in a very particular scenario poses the challenges of cooperative sensing, cooperative decision-making, cooperative power control, coexistence among such unlicensed networks operating in the same band, and coexistence with other types of unlicensed devices, and the design of efficient physical and medium access control layers to support these requirements.

In October 2005, the Working Group has approved the functional requirements upon which proposals have been submitted in November 2005. The main lines of the functional requirements [IEEE802.22, 2006] in term of interference management can be summarized as follows. The WRAN is a large area network operating in rural or sub-urban areas, where a base station will cover a cell of radius from 33 km up to 100 km where propagation conditions permit. Broadband Internet services will be delivered to the Consumer Premise Equipment (CPE), which is fixed and possibly professionally installed at the user's home or office.

The CPEs and the WRAN base stations have an obligation to protect all TV receivers in the TV bands within the noise-protected contour of a licensed TV operation. Apart from TV stations, other incumbent users include Part 74 devices in the United States (wireless microphones), Public Land Mobile Radio System (PLMRS) services, and emergency services, which must also be protected whenever they appear within the interference range of the WRAN. While TV stations mostly change on a monthly, or possibly on a daily basis if they are turned off during the night, the behavior of wireless microphone users are more unpredictable in space and time. Sensing periods and durations, as well as the range of frequencies sensed by one CPE, will determine how well an incumbent service can be protected. Cooperative sensing should be performed from all sensing measurements in order to provide an accurate and updated state of the radio scene, which can be used to control transmission parameters of the CPEs to meet the interference requirements.

The operation of the WRAN is point-to-multipoint, with the base station controlling the CPEs in a Master/Slave relationship. The restrictions on CPEs capabilities can be listed as follows:

- CPEs can only transmit when being told by the base station.
- CPEs can only sense as told by the base station.
- CPEs can only change their parameters (transmit power, modulation, error control code, antenna beam) when ordered by the base station.

However, even though the base station controls the CPEs, cooperation is required in the way that sensing measurements are collectively used at the base station to achieve a better detection and a better radio resource utilization, and cooperative power control is required to meet the interference requirements at the boundaries of the noise-protected contours.

The fewer degrees of freedom of the CPEs, compared to the more general cognitive radios of Mitola, are meant to provide more assurance that incumbent license users will be protected. For example, an ad-hoc network is not allowed to be formed by co-located CPEs, even locally. This requirement avoids bursts of signaling for network set-up, and collisions that necessarily occur in CSMA/CA types of systems. In fact, even very short bursts, on the order of a few milliseconds, can dramatically disrupt the operation of a wireless microphone that is transmitting live action from a sports game. However, the centralized operation also has the advantage to allow for advanced cooperative sensing techniques, and to simplify coexistence between overlapping WRAN cells operated by the same or different operators. When all information is collected and analyzed by the base station, the centralized decision can make better use of radio resources. Given that TV stations are also fixed in space and change rarely with time, the radio resource allocation can be optimized given that the base station benefits from a sufficient amount of time to perform the radio-scene analysis and the optimization. The trade-off will be an increase in signaling for reporting all sensing information, and increased computational requirements at the base station, whereas some coexistence problems could have been be solved locally by the CPEs if they were allowed to.

The usual problems encountered in detecting the presence of licensed users and adapting one's transmitter functions to limit the amount of interference to the licensed users have been addressed in the academic literature, but many problems remain unsolved. In particular we can list the following issues that are directly related to the IEEE 802.22 standard:

- Hidden node problem: a CPE estimates its distance to the noise-protected contour of a TV station by measuring the TV signal it receives. If the CPE is in a region affected by shadow fading, it might determine that there is no TV signal or make a wrong estimate of its distance to the nearest TV receiver, resulting in its decision to transmit with a larger power than would be allowed to meet the interference requirements.

- Even though it has been proven that licensed users can still operate in the presence of licensed spectrum users, it is still not clear whether a cognitive radio network can achieve any useful throughput [Hoven and Sahai, 2005]. In this sense, the IEEE 802.22 WRAN standard should provide such a proof.

- Cooperative sensing is needed to improve the detection threshold of incumbent signals. However the probability of false alarm must be tightly controlled and efficient algorithms for decision fusion and data fusion are needed for that purpose. A related problem arises from the lack of accurate models of high order statistics for shadow fading, which are required to determine the probabilities of detection and false alarms accurately.

- Cooperative power control must be provided by the base station in order to ensure the interference levels created by simultaneously transmitting CPEs do not exceed the incumbents' thresholds. It is known that a sea of unlicensed users acts as an equivalent single unlicensed user experiencing a path loss exponent decreased by two [Tandra and Sahai, 2005] in the propagation channel between its transmitter and a nearby TV receiver.

- Sensing range vs. interference range for heterogeneous devices: coexistence with incumbent users that transmit at low power is a problem, given that the interference range of the CPE can be larger than the detection range of the incumbent user (*e.g.* a wireless microphone).

- Coexistence between unlicensed spectrum users: game theoretic approaches will most likely provide the required solution. However without centralized control they might result in trial and errors or transient states leading to contentions that create unwanted interference to incumbent users. Even though contention-based principles could be used to access control channels it is not clear whether these solutions could be used to access traffic channels. Game theoretic approaches have been considered in the literature for spectrum sharing of a few devices, or between at most two networks. Yet it has been recognized that they could sometimes lead to solutions that are far from optimal even in these simple cases. For instance, a Nash equilibrium could result in a very inefficient use of the spectrum with a very low throughput compared to easily found heuristic solutions [Clemens and Rose, 2005]. Game theory could provide sets of rules to use in deterministic algorithms. Yet it must be demonstrated that these rules are scalable to large networks.

- Coexistence between wide-area incumbent and license-exempt networks. The coverage area of the WRAN is of the same order as the coverage area of a TV station. In general, the cognitive networks that have been considered in the literature have a much smaller coverage than the incumbent service, which allows the unlicensed user to use low powers and still achieve acceptable throughput. However in the case of the WRAN, large powers will need to be radiated by the WRAN base station and CPEs, resulting in more stringent spatial constraints for operation.

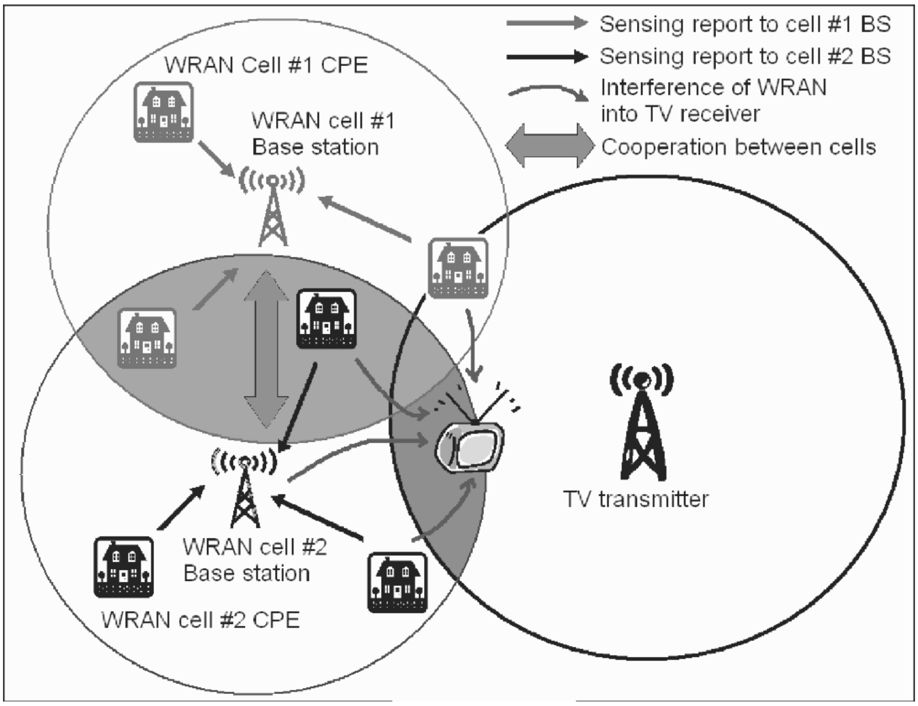

Figure 15.2. Operating scenario for two overlapping WRAN cells coexisting with a television broadcasting station.

Figure 15.2 illustrates some of the above mentioned issues. In this figure, two partially overlapping WRAN cells operate near an operating TV station. Both WRAN cells could belong to the same operator, or to different operators. In both cases, cooperation is required between the two cells to ensure that:

- The interference created by all CPEs into nearby TV receivers within the noise protected contour of the TV operation does not exceed the interference threshold.
- The CPEs in the overlapping (blue) area can coexist and achieve useful data rates.

Cooperation is also seen as the collection of sensing reports from all CPEs belonging to the same cell. The base station of that cell collects this information, and performs cooperative sensing. Sensing reports are coordinated among CPEs by the base station, which controls the frequency bands sensed by each CPE, the sensing integration time, the sensing period, and the type of interference being targeted by specific sensing techniques, like a simple energy detector or a cyclostationary feature detector. Using database location information, the base station can make sure that sensing is performed accurately while providing small sensing periods to guarantee useful operation of the WRAN for high data rate and delay-sensitive applications. Cooperation between base stations operated by the same or different operators could consist of several options. It is unlikely that different providers would share location information of their own CPEs to protect their market interests. However, wide-area sensing measurements results and the density of CPEs could be shared for the coexistence (blue) and interference into incumbent (green) regions. Negotiations need to take place between the base stations to dedicate operating and backup channels to each cell in the overlapping regions, while leaving as many degrees of freedom as possible in other areas to get the maximum benefit of opportunistic spectrum access.

Another issue that has not been broadly addressed is the amount of control information needed to operate a cognitive radio network. The 802.22 approach is that of a point-to-multipoint network with centralized decision-making to decide whether cognitive radio devices are allowed to operate in a certain frequency band with a maximum allowable transmit power. This approach, even though it should provide more stability and security for the incumbent license users, puts a burden on control channels, which need to convey a large amount of information between the users' terminals and the base station.

Another important issue is the protection of devices licensed under Part 74 of the FCC. These devices, such as wireless microphones, do not occupy spectrum for a long time, but are very sensitive to interference. They also operate on a short-range, much shorter than the range of the WRAN. Therefore, WRAN devices would have difficulty detecting the presence of Part 74 devices, but they would create unacceptable levels of interference to the Part 74 devices. In that context, cooperative sensing is absolutely necessary, and appropriate and novel protocols for spectrum occupancy must be designed. A Study Group within the 802.22 has been created in September 2005 to enhance the detection and protection or Part 74 devices. One of the principles that this Study Group will look at is the possibility of requiring the use of a beacon by Part 74 devices, such that the beacon's detection range will match the interference range of CPEs into Part 74 devices. The necessity of pilots has been recognized in the academic world [Tandra and Sahai, 2005], also because the detection threshold of incumbent users signals must be much lower than the decoding threshold of these signals in order for cognitive radios to offer the appropriate protection.

Finally, with respect to the emerging technologies related to cognitive radios that are expected to find their way into IEEE standards, an effort is ongoing for defining these technologies more accurately than is actually available. The IEEE P1900 Standard Series on Next Generation Radio and Spectrum Management sponsored by the IEEE Electromagnetic Compatibility Society and the IEEE Communications Society, have been approved early 2005. The IEEE P1900.1 Working Group will develop standard terms, definitions and concepts for spectrum management, policy defined radio, adaptive radio and software defined radio. The IEEE P1900.2 Working Group will develop a recommended practice for interference and coexistence analysis, while the IEEE P1900.3 Working Group will develop a recommended practice for conformance evaluation of software defined radio (SDR) software modules. A brief introduction to this new standard can be found in [Siller and Boutaba, 2005].

To conclude on the IEEE 802.22 Working Group activities, even a limited-scope cognitive radio network poses tremendous challenges, for which no definite solution exits neither in the academic nor in the industry world. This standard provides a unique opportunity for industries and universities to create a cognitive radio network with solid foundations, and to address some of the most fundamental problems of cognitive radios.

7. Conclusions

The IEEE standards provides a forum where industry and academia can jointly promote advanced technologies into emerging standards. These standards address communication networks ranging from Personal Area Network to Regional Area Networks. Each standard presents its own challenges, and many of the proposed solutions rely on cooperative techniques. Cooperation appears at the terminal level, at the network level, and between networks. The main applications of cooperative techniques have emerged from the introduction of mesh networks (11, 15 and 16) with the use of relays and cooperative transmission, as well as to address the coexistence between 802 standard networks themselves and with licensed spectrum users. It is expected that as these networks grow, and as their numbers grow, cooperative behaviors will be the key to scalability and reliability of these networks. Cooperative techniques have just found their way into the IEEE 802 standards, and still a lot remains to be accomplished to ensure the goals will be reached successfully.

References

3GPP (2006a). 3GPP 25.106, UTRA repeater radio transmission and reception.

3GPP (2006b). 3GPP 25.956, UTRA repeater planning guidelines and system analysis.

802wirelessworld (2006). 11-04-0730-03-000s-draft-core-terms-and-definitions-802-11s.doc. http://www.802wirelessworld.com.

Nosratinia, A. Hunter T. E. and Hedayat, A. (2004). Cooperative communication in wireless networks. *IEEE Communications Magazine*.

Clemens, N. and Rose, C. (2005). Intelligent power allocation strategies in an unlicensed spectrum. In *Proceedings of the IEEE Dynamic Spectrum Access Networks Conference (DySPAN 2005)*, Baltimore, MD.

Commission, Federal Communications (2004). Notice of Proposed Rule Making. ET Docket no. 04-113.

Dohler, M. (2003). *Virtual Antenna Arrays*. PhD thesis, King's College London, University of London, Strand, London.

Haykin, S. (2005). Cognitive Radio: Brain-Empowered Wireless Communications. *IEEE Journal on Selected Areas in Communications*.

Hoven, N. and Sahai, A. (2005). Power Scaling for Cognitive Radio. In *Proceedings of IEEE WirelessCom 05 Symposium on Emerging Networks, Technologies and Standards*, Hawaii, USA.

Hunter, T. E. and Nosratinia, A. (2005). Diversity through coded cooperation. *IEEE Transactions on Wireless Communications*.

IEEE (2004). IEEE Std 802.16-2004. IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems.

IEEE11web (2006). IEEE 802.11 Standard Web Site. http://grouper.ieee.org/groups/802/11/.

IEEE15web (2006). IEEE 802.15 Standard Web Site. http://www.ieee802.org/15/.

IEEE16 (2006). C80216mmr-05/d040. http://www.ieee802.org/16.

IEEE16e (2006). IEEE P802.16e/D12. IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed and mobile Broadband Wireless Access Systems, Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands.

IEEE802.22 (2006). Functional Requirements for the 802.22 WRAN Standard. doc.: IEEE 802.22-05/0007r46, http://www.ieee802.org/22/.

Akyildiz, I. F. Wang, X. and Wang, W. (2005). Wireless mesh networks: a survey. *to be published in Elsevier, Computer Networks*.

Laneman, J. N. and Wornell, G. W. (2003). Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks. *IEEE Transactions on Information Theory*, pages 2415–2425.

Mitola, J. (2000). *Cognitive radio: An integrated agent architecture for software defined radio*. PhD thesis, Royal Inst. Technology (KTH), Stockholm, Sweden.

O'Connor, See and A., Robert (1968). Understanding Television's Grade A and Grade B Service Contours. *IEEE Transactions on Broadcasting*.

of Visions 2003 (WWRF), Book (2006). Relay-based deployment concepts for wireless and mobile broadband cellular radio. http://www.wireless-world-research.org/.

Siller, C. and Boutaba, R. (2005). The President's Page, Standards - A New Challenge for COMSOC. *IEEE Communications Magazine*.

Tandra, R. and Sahai, A. (2005). Fundamental limits on detection in low SNR under noise uncertainty. In *Proceedings of IEEE WirelessCom 05 Symposium on Emerging Networks, Technologies and Standards*, Hawaii, USA.

WG, IEEE 802.22 (2006). Ieee 802.22 working group on wireless regional area networks. http://www.ieee802.org/22/.