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UWB-Based Cognitive Radio Networks

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8.1 Introduction

As wireless communication systems are making the transition from wireless telephony to interactive internet data and multi-media type of applications, the desire for higher data rate transmission is increasing tremendously. As more and more devices go wireless, it is not hard to imagine that future technologies will face spectral crowding, and coexistence of wireless devices will be a major issue. Considering the limited bandwidth availability, accommodating the demand for higher capacity and data rates is a challenging task, requiring innovative technologies that can offer new ways of exploiting the available radio spectrum. Ultra-wideband (UWB) and cognitive radio are two exciting technologies that offer new approaches to the spectrum usage.

Ignited by the earlier work of Mitola [1], cognitive radio is a novel concept for future wireless communications, and it has been gaining significant interest among the academia, industry, and regulatory bodies [2]. Cognitive radio provides a tempting solution to spectral crowding problem by introducing the opportunistic usage of frequency bands that are not heavily occupied by their licensed users. Cognitive radio concept proposes to furnish the radio systems with the abilities to measure and be aware of parameters related to the radio channel characteristics, availability of spectrum and power, interference and noise temperature, available networks, nodes, and infrastructures, as well as local policies and other operating restrictions. The primary advantage targeted with these features is to enable the cognitive systems to utilize the available spectrum in the most efficient way. An interconnected set of cognitive radio devices that share information is defined as a cognitive network. Cognitive networks aim at performing the cognitive operations such as sensing the spectrum, managing available resources, and making user-independent, intelligent decisions based on cooperation of multiple cognitive nodes. In order to be able to achieve the goals of the cognitive radio concept, cognitive networks need a suitable wireless technology that will facilitate collaboration of the nodes.

Ultra-wideband is defined as any wireless technology that has a bandwidth greater than 500 MHz or a fractional bandwidth[1] greater than 0.2. Ultra-wideband systems have been attracting an intense attention from both the industry and academic world since 2002, when the US Federal Communications Commission (FCC) released a spectral mask officially allowing the unlicensed usage of UWB. There are two commonly proposed means of implementing UWB. These two technologies are the Orthogonal Frequency Division Multiplexing based UWB (UWB-OFDM) and the impulse radio based UWB (IR-UWB).

Under the current FCC regulation, UWB is a promising technology for future short- and medium-range wireless communication networks with a variety of throughput options including very high data rates. UWB's most significant property is that it can coexist in the same temporal, spatial, and spectral domains with other licensed/unlicensed radios because it is an underlay system. Other tempting features of UWB include that it has a multi-dimensional flexibility involving adaptable pulse shape, bandwidth, data rate, and transmit power. On top of these, UWB has a low power consumption, and it allows significantly low complexity transceivers leading to a limited system cost. Another very important feature of UWB is providing secure communications. It is very hard to detect UWB transmission as the power spectrum is embedded into the noise floor. This feature introduces very secure transmission in addition to other higher layer encryption techniques.

When the wireless systems that are potential candidates for cognitive radio are considered, UWB seems to be one of the tempting choices because it has an inherent potential to fulfill some of the key cognitive radio requirements. Along with the inherent UWB attributes mentioned, especially IR-UWB offers some extraordinary uses that can add a number of extra intellective features to cognitive systems. These special uses are brought by the high multipath resolution property, which enables UWB to act as an accurate radar, ranging, and positioning system. Examples of specific UWB features include sensing the physical environment to enable situation awareness, and providing geographical location information.

Owing to all its distinctive properties mentioned, in this chapter, UWB is considered as one of the enabling technologies of cognitive radio networks. The flow of this chapter is as follows. Cognitive radio and cognitive networks are described in Sect. 8.2. The basics of UWB and its suitability for cognitive networks are addressed in Sect. 8.3. Finally, in Sect. 8.4, various UWB cognitive networks related issues are discussed in detail.

8.2 Cognitive Networks and Cognitive Radio

When we look at the evolution of wireless standards and technologies, it can be seen that the adaptive features and intelligent network capabilities are gradually adapted as the hardware and software technologies improve. Especially, with the recent trend

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[1] Fractional bandwidth = $2 \cdot \frac{F_\mathrm{H}-F_\mathrm{L}}{F_\mathrm{H}+F_\mathrm{L}}$, where F_H and F_L are the upper and lower edge frequencies, respectively.

and interest in software defined radio based architectures, cognitive radio and cognitive networks attracted more interest. In addition to these, the increasing demand for wireless access along with the scarcity of the wireless resources (specifically the spectrum) bring about the desire for new approaches in wireless communications. Therefore, even though cognitive networks and cognitive radio terms have recently become popular, it is actually a natural evolution of the wireless technologies. With the emergence of cognitive radio and cognitive network concepts, this evolution process has been more formalized and structured. Also, with these new concepts the perception of adaptation and optimization of wireless communication systems gained new dimensions and perspectives. Especially, the emergence of cognitive networks (with cooperative functions and cognitive engine concepts) is a promising solution for the barrier that arises from the flaws of the conventional layered design architecture.

The term "cognitive radio" defines the wireless systems that can sense, be aware of, learn, and adapt to the surrounding environment according to inner and outer stimuli. Overall cognition cycle can be seen as an instance of artificial intelligence, since it encompasses observing, learning, reasoning, and adaptation. Adaptation itself in the cognition cycle is a complex problem, because cognitive radio needs to take into account several inputs at the same time including its own past observations as a result of learning property. Although the adaptation of wireless networks is not a new concept, the previous standards and technologies strive to obtain an adaptive wireless communication network from a narrower perspective (commonly focused on a single-layer adaptation with a single objective function) as compared to that of cognitive radio, which considers a global adaptation that includes multiple layers and goal functions.

For many researchers and engineers, the cognitive radio concept is not limited to a single intelligent radio, but it also includes the networking functionalities. However, within this chapter, we will use the term of cognitive networks to define the networking functionalities of the cognition cycle. Hence, cognitive networks can be defined as intelligent networks that can automatically sense the environment (individually and collaboratively) and current network conditions, and adapt the communication parameters accordingly. Comparing the cognitive radio and cognitive networks definition, it can be seen that the definitions are similar, except cognitive networks have more broader perspective that also include all the network elements.

Cognitive networks are expected to shape the future wireless networks with important applications in dynamic spectrum access, and co-existence and interoperability of different wireless networks. Among the special features of cognitive networks, the leading ones are advanced interference management strategies, efficient use of wireless resources, safe and secure wireless access methodologies, and excellent Quality of Service (QoS). In spite of all these great features and possibilities, being a new concept, the cognitive radio network poses many new technical challenges. As it will be described in the subsequent sections, such networks have requirements in dynamic spectrum management, power and hardware efficiency, complexity and size, spectrum sensing and interference identification, environment awareness, user awareness, location awareness, new distributed algorithm design, distributed spectrum measurements, QoS guarantees, and security. Addressing these requirements is very critical for the success of these networks in wireless communication market, and the authors of this chapter believe that ultra-wideband technology and networking has the capability to accommodate some of these key requirements as it will be discussed throughout this chapter.

8.3 UWB Basics and UWB's Suitability for Cognitive Networks

The two main techniques considered for UWB physical layer are the impulse radio and OFDM. In this section, first, the fundamentals of both of these technologies will be given to provide a technical background. Then, by providing a one-by-one matching between various cognitive radio needs and UWB properties it will be explained how suitable UWB is for cognitive networks.

8.3.1 Background on UWB

According to the current FCC regulations in the USA, UWB systems are allowed to operate in the 3.1–10.6 GHz band without a license requirement. However, the transmit power of these systems is strictly limited. Both in indoors and outdoors, UWB systems are not permitted to transmit more than −42 dBm/MHz in the specified band. This limitation ensures that the UWB systems do not affect the licensed operators that use various frequency bands in the UWB band. However, it should also be kept in mind that it is not unlikely that revisions can be made in the UWB-related FCC regulations, especially regarding the transmit power limits. In the near future, if the UWB radios are provided with cognitive properties that allow them to sense the spectrum to determine the occupancy of their target bands and to ensure the absence of licensed users, it is possible that regulatory agencies may consider to offer more freedom to UWB.

Impulse radio based implementation of UWB is carried out by transmitting extremely short low-power pulses that are on the order of nanoseconds [3,4] as illustrated in Fig. 8.1. Impulse radio UWB is advantageous in that it enables to employ

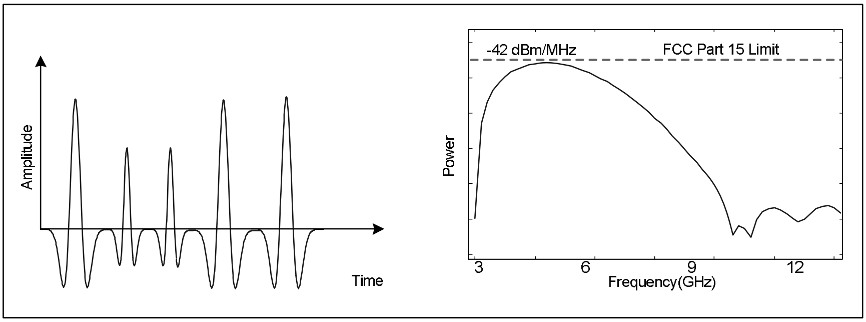

Fig. 8.1. Impulse radio based UWB pulses and the spectrum of a single pulse.

various types of modulations, including on-off keying (OOK), pulse amplitude modulation (PAM), pulse shape modulation (PSM), pulse interval modulation (PIM), pulse position modulation (PPM), and phase shift keying (PSK) [5].

For multi-user access, IR-UWB systems employ time hopping (TH) codes that are specific to each user [6]. These specific pseudo-random noise (PN) codes enable the UWB system to provide access to multiple users conveniently. The multi-user parameters can be adaptively modified according to the change in number of users. To enable more users to communicate, for example, the UWB system can increase the number of chips in each frame at the expense of decreasing each user's data rate.

Different types of receivers can be utilized for IR-UWB communications which include coherent receivers (such as Rake and correlator receivers) as well as non-coherent ones such as energy detector and transmitted reference receivers. Along with the flexibility in modulation methods and receiver types, IR-UWB also offers a variety of options regarding the shapes of the transmitted pulses. Various analog and digital methods to implement pulse shaping for impulse radio can be found among others in [1,3–39].

Besides being a communication system, IR-UWB is a precise radar technology as well as a highly accurate ranging and positioning system. These extra features are owed to the fact that IR-UWB systems have an excellent multipath resolving capability because of the extremely wide frequency band that they occupy.

In OFDM-based UWB, orthogonal subcarriers are employed to modulate the transmitted data. Figure 8.2 shows a typical OFDM waveform in frequency domain. As long as the total occupied bandwidth is not less than 500 MHz, the number of subcarriers and the subcarrier spacing may be assigned various values according to the needs. In the current multi-band OFDM planning, which divides the entire UWB band into 14 subbands, each subband is considered to be 528 MHz and contain 128 subcarriers. The subcarrier spacing is usually chosen to be less than the channel coherence bandwidth. This enables that each subcarrier goes through a flat fading channel. Hence, the UWB-OFDM receiver needs a simple equalizer implementation to recover the originally transmitted signal. One of the most tempting properties of

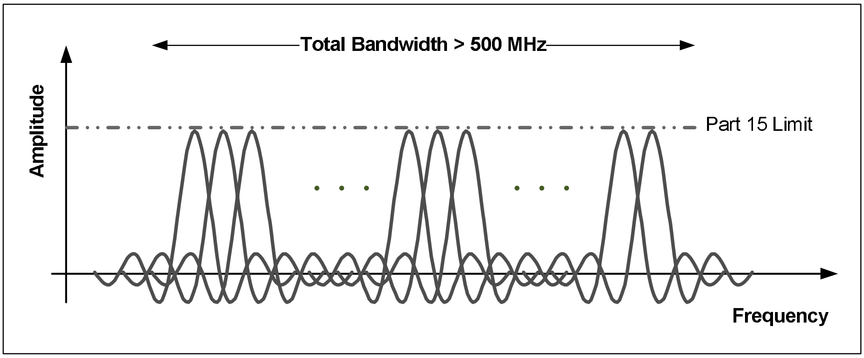

Fig. 8.2. OFDM based UWB waveform.

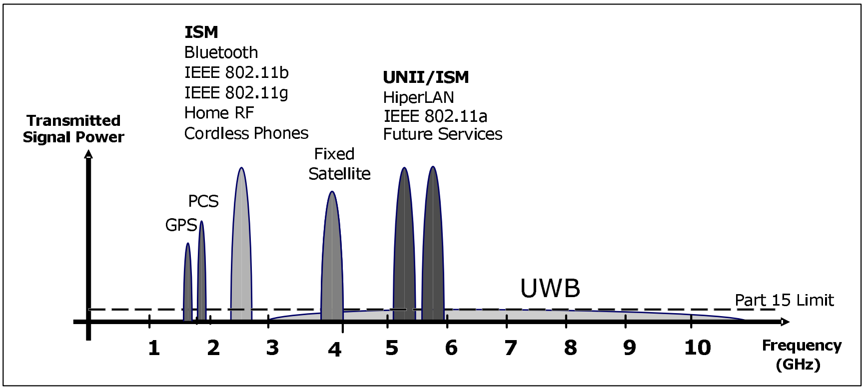

Fig. 8.3. Narrowband systems and UWB spectrum.

UWB-OFDM is the easiness of avoiding interference to licensed systems. A UWB-OFDM transmitter can avoid jamming a licensed signal by simply turning off the subcarriers that overlap with the spectra of the licensed system.

The final significant feature of UWB is its interference immunity. UWB has a considerable resistance against the multi-user access interference (MAI), which is investigated in detail in [4, 35–38]. UWB systems are immune to not only MAI, but also against narrowband interference (NBI), which is caused by the licensed and unlicensed systems that exist in the frequency band occupied by the UWB system [5, 17–37], which are illustrated in Fig. 8.3.

8.3.2 Cognitive Radio Requirements vs. UWB Features

One of the main goals targeted with cognitive radio is to utilize the existing radio resources in the most efficient way. To ensure the optimum utilization, cognitive radio requires a number of conditions to be satisfied. A wireless system that is a potential candidate for cognitive radio applications is expected to fulfill some of these conditions.

The primary cognitive radio requirements include

- negligible interference to licensed systems,
- capability to adapt itself to various link qualities,
- ability to sense and measure critical parameters about the environment, channel, etc.
- ability to exploit variety of spectral opportunity,
- flexible pulse shape and bandwidth,
- adjustable data rate, adaptive transmit power, information security, and limited cost.

At this point, if the main properties of UWB are considered, it is seen that there is a strong match between what the cognitive radio requires and what UWB offers.

In the following, the primary features of UWB will be investigated from the point of satisfying the requirements of cognitive radio.

Cognitive radios aim at an opportunistic usage of frequency bands that are owned by their licensed users. Therefore, one of the most significant requirements of cognitive radio is that the interference caused by cognitive devices to licensed users remains at a negligible level.

UWB offers the possibility of being implemented both in *underlay* and *overlay* modes. The difference between the two modes is the amount of transmitted power. In the underlay mode, UWB has a considerably restricted power, which is spread over a wide frequency band. In this mode, it complies with the corresponding regulations of the FCC in the USA. When a UWB system is operating in the underlay mode, it is quite unlikely that any coexisting licensed system is affected from it. On top of this, underlay UWB can employ various narrowband interference avoidance methods.[2] In the overlay mode the transmitted power can be much higher. However, this mode is only applicable if the UWB transmitter ensures that the targeted spectrum is completely free of signals of other systems, and, of course, if the regulations allow this mode of operation. If these conditions are met, the transmitted UWB power can be increased to a certain level that is comparable to the power of licensed systems. UWB can also operate in both underlay and overlay modes simultaneously. Depending on the spectrum opportunities, the signaling and the spectrum of the transmitted signal can be shaped in such a way that part of the spectrum is occupied in an underlay mode and some other parts are occupied in an overlay mode.

Apparently, in any mode of operation, UWB causes negligible interference to other communication systems, if it does at all. This special feature of UWB makes it very tempting for the realization of cognitive radio.

One of the main features of the cognitive radio concept is that the targeted frequency spectrum is scanned periodically in order to check its availability for opportunistic usage. According to the results of this spectrum scan, the bands that will be utilized for cognitive communication are determined. Since at different times and locations the available bands can vary, cognitive radio is expected to have a high flexibility in determining the spectrum it occupies.

Flexible spectrum shaping is a part of UWB's nature. In IR-UWB, since the communication is basically realized via the transmission of short pulses, varying the duration or the form of the pulses directly alters the occupied spectrum. In UWB-OFDM, on the other hand, spectrum shaping can be conveniently accomplished by turning some subcarriers on or off according to the spectral conditions.

The availability of unused bands is of vital importance for the continuity of communications in cognitive radio. Any increase in the utilization of the bands by the licensed systems directly results in narrowed freedom for the cognitive radio, which can force it to decrease its data rate and QoS, or even to terminate its communication. Therefore, cognitive radio systems are expected to be able to adjust their throughput

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[2] For a detailed discussion of narrowband interference avoidance and cancelation methods in UWB systems, the readers are referred to [37].

according to the available bandwidth. They should also provide a solution for the cases when the available bandwidth is so limited that the communication cannot be continued.

UWB systems are able to make abrupt changes in their data rates. An IR-UWB system responds to a decrease in available bandwidth by switching to a different pulse shape that is wider in shape. If there is more band to use, it can respond by doing the opposite. The adjustment of the occupied bandwidth in UWB-OFDM is much simpler. The subcarriers that overlap with the occupied bands are turned off, and this way, the data rate is decreased.

On top of its flexible data rate property, UWB provides an exceptional solution regarding the dropped calls. As mentioned earlier, UWB can be performed both in underlay and overlay modes. Assuming that the normal operation mode is overlay, in cases when it becomes impossible to perpetuate the communication, UWB can switch to the underlay mode. Since the licensed systems are not affected by UWB when it is in the underlay mode, this gives the UWB the opportunity to maintain the communication link even though it is at a low quality.

The existence of licensed systems and other unlicensed users is not the only limitation regarding the secondary usage of the spectrum. The spectral masks that are imposed by the regulatory agencies (such as the FCC in the USA) are also determinative in spectrum usage in that they set a limit to the transmit power of wireless systems. UWB offers a satisfactory solution to the adaptable transmit power requirement of cognitive radio. Both UWB-OFDM and IR-UWB systems can comply with any set of spectral rules mandated upon the cognitive radio system by adapting their transmit power.

Since the cognitive radio concept includes free utilization of unused frequency bands, there will be a number of users willing to make use of the same spectrum opportunities at the same time. Therefore, cognitive radio networks should be able to provide access to multiple users simultaneously. During the operation of a cognitive radio, changes may occur in the overall spectrum occupancy, or the signal quality observed by each user can fluctuate because of various factors. These changes may require the cognitive radio to modify its multiple access parameters accordingly.

UWB is very flexible in terms of multiple access. In IR-UWB, by modifying the number of chips in a frame, the number of users can be determined. In UWB-OFDM, on the other hand, the subcarriers assigned to each user can be decreased in order to allow more users to communicate. Therefore, also from the point of adaptive multiple access, UWB proves to be a proper candidate for cognitive radio applications.

The primary objectives targeted with cognitive radio include preserving the privacy of information. UWB is one of the systems that have information security in their nature. If a UWB system is working in the underlay mode, because of the very low power level, it is impossible for unwanted users to detect even the existence of the UWB signals. Therefore, underlay UWB is a highly secure means of exchanging information. Overlay mode UWB, on the other hand, can also be considered a safe communication method. In overlay IR-UWB, multiple accessing is enabled either by time hopping or by direct sequencing. Therefore, receiving a user's information is only possible if the user's time hopping or spreading code is known. UWB-OFDM also provides security by assigning different subcarriers to different users. The level of security can be increased by periodically changing these subcarrier assignments. Apparently, UWB is a secure way of communicating in both its underlay and overlay modes. Hence, UWB can be considered a strong candidate for cognitive radio applications in terms of information security.

Being a future wireless concept, cognitive radio targets at a low cost for each of its components. This is necessary for the system to be able to reflect the profit earned by using the spectrum in an opportunistic way (rather than purchasing a license) to its subscribers. UWB signals can be generated and processed by inexpensive transceiver circuitries. The RF front-end required to send and capture UWB signals are also quite uncomplicated and inexpensive. Therefore, UWB communication can be accomplished by employing very low cost transmitter and receivers. This property of UWB makes it very attractive for cognitive radio, which aims at limited infrastructure and transceiver costs.

8.4 Cognitive UWB Network Related Issues

As it is pointed out throughout the previous section, UWB is highly competent in satisfying many basic requirements of cognitive radio. Therefore, employing UWB in cognitive radio networks could be very instrumental for the successful penetration of cognitive radio into the wireless world. Nevertheless, since today's spectrum regulations prohibit employing UWB systems in the overlay mode, UWB based implementation of cognitive radio might not become a reality in the near future. However, besides being a strong candidate for practical cognitive radio implementation, UWB can be considered as a supplement to cognitive radio systems that are realized by means of other wireless technologies. Therefore, it can be concluded that this way or the other, UWB will be an inseparable part of cognitive radio applications.

UWB can offer various kinds of support to cognitive radio network. These include sharing the spectrum sensing information via UWB, locating the cognitive nodes in a cognitive network by means of IR-UWB, and sensing the physical environment/channel with IR-Radar. In the following, various cognitive UWB networks related issues including these supplementary uses of UWB will be discussed.

8.4.1 Spectrum Sensing Information Exchange in Cognitive Networks

In order to be able to opportunistically utilize the available licensed frequency bands, cognitive radio systems periodically scan their target spectrum and detect the spectrum opportunities. In cognitive networks, it is mandatory that all nodes agree on the spectral opportunities to be utilized. Therefore, it is a major issue for a cognitive node to share the spectrum sensing information with the other nodes. In some works in the literature, it is considered to have an allocated control channel to transmit this information [33]. In some other works, it is proposed to have a centralized controller that gathers this information, decides for spectrum availability, and allocates distinct bands to different cognitive users [8, 10]. An alternative to these methods is to transmit spectrum sensing results via low power UWB signaling that complies with the FCC regulations [34]. Since this transmission will be accomplished in an underlay manner, it can be done simultaneously with the real data communication without affecting it regardless of the wireless technology employed to realize the cognitive radio itself. Considering the relatively low throughput needed to transmit the sensing information as well as the low cost transceiver requirement, it turns out to be a proper option to use an uncomplicated non-coherent receiver such as an energy detector, and to employ on-off keying (OOK) modulation.[3] By using a proper mapping scheme (from sensing information to binary codewords), coding, and OOK modulation, spectrum information can be conveniently shared between the nodes.

A cognitive network (see Fig. 8.4) can be realized by allowing its nodes to communicate with each other using UWB to exchange spectrum information. One of the aims of cognitive radio is to increase the range of communication as much as possible, and at the first glance, UWB signaling may not seem to be very appropriate for this purpose because of the limited range of underlay UWB. The answer to this question can be obtained by looking at the bit error rate (BER) expression for OOK modulated UWB signals. This BER expression can be stated as

$$\mathrm{BER} = Q\Big(\sqrt{\frac{N_\mathrm{s} A E_\mathrm{p}}{2N_0}}\Big) \tag{8.1}$$

where N_s is the number of pulses per symbol, A is the pulse amplitude, E_p is the normalized pulse energy, and the additive white Gaussian noise (AWGN) has a double sided spectrum of $\frac{N_0}{2}$. In this expression, it is seen that increasing the number of

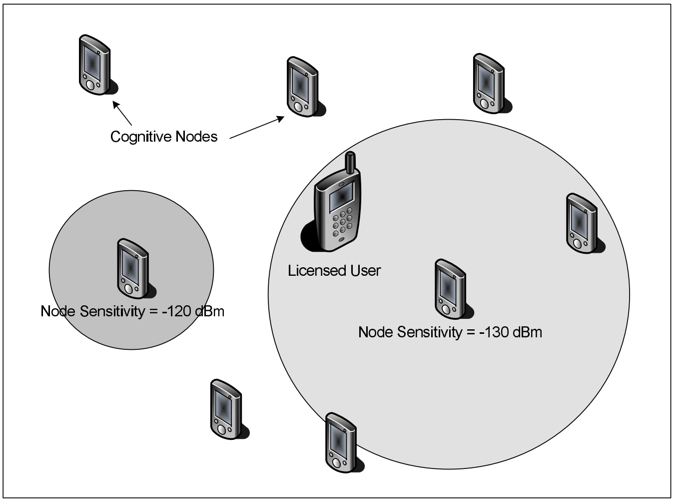

Fig. 8.4. Network of cognitive transceivers.

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[3] The implementation issues regarding the OOK based energy detector receivers such as estimating the optimal threshold and determining the optimum integration interval can be found in [24].

pulses per symbol results in lower BER. Increasing N_s requires a repeated transmission of data, i.e. processing gain. By applying the necessary amount of processing gain, it can be made possible that the farthest nodes in a cognitive network can share the spectrum sensing information. Although this comes at the expense of lowered throughput, it is not a limiting factor in this case because a quite low data rate is enough to transmit the spectrum sensing information. By enabling all the nodes in a cognitive network to talk to each other via UWB, there is no need

- either to allocate a separate channel for sharing the sensing information,
- or to employ a centralized controller that collects this information, processes it, and sends it to the cognitive users in the network.

Spectrum information can also be shared in an ad-hoc multi-hopping scheme that uses UWB. This way, long range transmission is not needed. Multiple nodes collaboratively share the information and route this information to other nodes using low power, low cost UWB technology. In essence, a UWB based sensor network with the collaboration of multiple radios is formed.

8.4.2 Receiving Sensitivity of Cognitive Nodes and Size of Cognitive Networks

In cognitive radio networks, in order to make sure that the intended frequency spectrum is being used by its licensed user, all nodes involved in communication have to scan the spectrum and inform each other about the spectral conditions. It is not hard to imagine that there should not be a physical gap between the sensing ranges of the nodes. If the sensing ranges are not at least partially overlapping, there is always a risk that a licensed user located inside the gap between the sensing ranges is not detected, which would cause the cognitive nodes to jam the licensed user's signal. Therefore, the receiving sensitivity of the nodes in the network has an integral role in determining the range of communication. As an example, assume a rather high sensitivity around -120 dBm to -130 dBm and consider free space propagation, in which the transmitted power (P_{tx}) and received power (P_{rx}) are related to each other by the Friis equation (ignoring the system loss and antenna gains)

$$P_{rx} = \frac{P_{tx}\,\lambda^2}{(4\pi)^2\,d^2} \tag{8.2}$$

where λ is the wavelength and d is the distance. With these assumptions, it is seen that the distance between two cognitive nodes can go up to 50–150 m, getting the cognitive network classified as a medium-sized network according to its coverage area.

The sensing information received from all the other nodes in the network can be combined in each node, and pulse design can be done according to the common white (unused) spaces. Increasing the network size results in an increased probability of overlapping with licensed systems. This fact sets a practical limit to the size of the cognitive network, because continuing to enlarge the network, the common available spectra become less and less, and after some point their amount becomes insufficient to ensure the minimum QoS. For the details of how the common white bands are going to be shared by the cognitive nodes in the network, the readers are referred to [9, 11] and [22].

8.4.3 Locating the Cognitive Nodes via IR-UWB

Owing to the extremely wide band they occupy, IR-UWB systems have an advanced multipath resolving capability. This desirable feature enables these systems to be considered as a means of highly accurate (centimeter range) positioning besides being communication systems [16]. Because of this reason, IR-UWB is the primary candidate for the IEEE 802.11.4a standardization group, which aims at determining a new physical layer for very low power, low data rate communications with a special emphasis on accurate location finding.

The positioning capability can make IR-UWB systems an excellent supplement for small sized cognitive networks. Since such networks aim at not interfering with other radios in their physical environment, it can be very beneficial for them to be able to determine the locations of the nodes in the network closely. Having information about the precise locations of the nodes in a cognitive network, accurate and high efficiency beamforming [20] can be achieved towards the direction of the target nodes. Also, spatial nulls can be generated towards undesired receivers/signal sources to avoid interference. Beamforming can be accomplished by planar antenna arrays, which can be put onto very small areas for high-frequency systems (such as 60 GHz radios), and these arrays can be employed even by wireless nodes that are smaller than a hand palm in size.

The accurate positioning capability of IR-UWB can also be utilized to determine the transmit power adaptively. Using the positioning data, the distance between the transmitting and receiving nodes can be found, and based on the distance information the radiated power can be set. Such an implementation would not only optimize the power consumption but also help to ensure the link quality between the distant nodes.

Another nice utilization of the positioning capability can be tracking cognitive nodes or devices that are mobile. Updating the corresponding positioning information in a frequent manner, a cognitive node can be tracked in space. This way, any communication link directed to it would not be lost although its location is changing continuously.

Examples of using the positioning feature to augment the cognitive communication quality can be increased. All these examples lead to the idea that IR-UWB can leverage cognitive radio networks by providing a very strong support through its accurate positioning capability.

8.4.4 Sensing the Physical Environment of Cognitive Radio Network with Impulse Radar

Among the various impulse radio UWB applications, impulse radar is one of the oldest, and it has been used especially for military purposes [29, 40]. Practical implementations of impulse radar have been addressed in [4, 31–41]. As in the case of the other IR-UWB applications mentioned so far, impulse radar can improve cognitive communications from a number of aspects when combined with cognitive radio systems.

One of the potential uses of impulse radar can be to determine objects and walls in the indoor environments. Determining the objects can yield a rough estimation of the directions of multipath components, which can improve the channel estimation. Determining the walls, on the other hand, yields information about the physical borders of an indoor network, which may be very useful when establishing a cognitive network.

In mobile applications, impulse radar can allow to estimate the speed of the mobile users, it can enable a cognitive mobile device to measure its own speed. Such a capability would result in being able to estimate the Doppler spread and the channel coherence time, which are important parameters to know in mobile communications.

Impulse radar can also be used to detect the movement of human beings in the wireless channel, which can be very effective on the link quality between cognitive nodes especially for extremely high-frequency systems such as the 60 GHz radios [15].

8.4.5 A Cognitive Network Case Study

In order to provide a case study, computer analysis and simulations are performed regarding the practical implementation of a cognitive radio network. These simulations are related to the transmission of spectrum sensing results via UWB, the range of a cognitive network, and the capability of a cognitive network to detect a licensed system. In the simulations regarding the UWB signaling, the channel model $CM3$ in [13], which corresponds to an office environment with line-of-sight (LOS), is utilized. All parameters used in these simulations are listed in Table 8.1.

Table 8.1. List of simulation parameters for UWB signaling.

Parameter	**Value**
-10 dB Bandwidth	500 MHz
Freq. range	3.1–3.6 GHz
Geometric center freq.	3.34 GHz
Channel model	Office LOS (CM3)
Reference path loss	35.4 dB
Path loss exponent (n)	1.63
Rx antenna noise fig.	17 dB
Implementation loss	3 dB
Throughput (R_b)	20 Mbps
Integration interval	30 ns

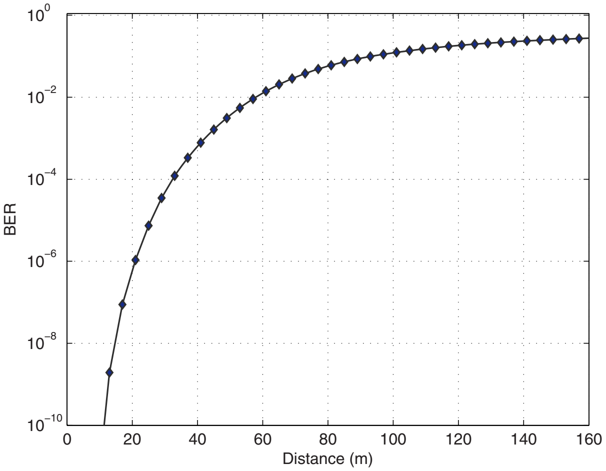

Fig. 8.5. BER vs. distance between the nodes for UWB signaling.

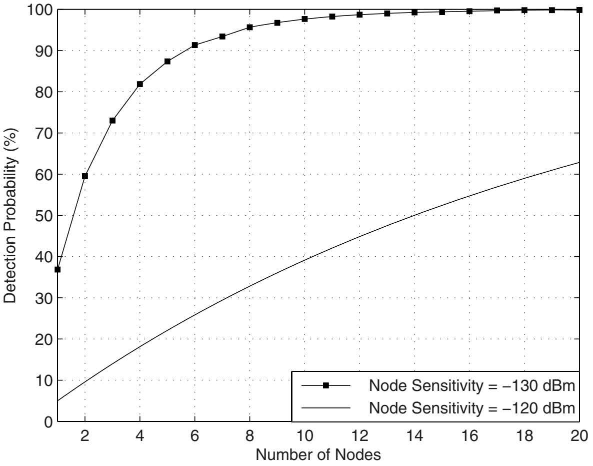

Fig. 8.6. Probability of the licensed transmitter being detected by the cognitive network.

A theoretical analysis is performed to investigate the performance of OOK modulated UWB data transmission, which is used to share the spectrum sensing results in a cognitive network, depending on the distance between a cognitive transmitter–receiver pair. According to [13] the path loss assumed can be shown as

$$L(d) = L_0 + 10n \log_{10}\left(\frac{d}{d_0}\right) \tag{8.3}$$

where the reference distance (d_0) is set as 1 m, L_0 is the path loss at d_0, and n is the path loss exponent. The average noise power per bit is

$$N = -174 + 10 \log_{10}(R_{\mathrm{b}}) \tag{8.4}$$

where R_b is the throughput. In Fig. 8.5, the effect of distance on the probability of error is demonstrated. The results show that the BERs obtained for up to 40 m are still acceptable. For further distances, however, some processing gain is definitely needed.

Another simulation is done to investigate the effect of the number of nodes on the probability of a licensed system being detected by the cognitive network. Figure 8.4 demonstrates a network composed of cognitive radio devices. The nodes in the network are randomly distributed in a 200 m × 200 m area inside a building. It is assumed that there is a licensed transmitter, which is a $GSM900$ cell phone transmitting at -60 dBm, whose location is random, as well. Depending on the level of the node sensitivity, the number of nodes required to make a reliable detection might vary. The results of this simulation are demonstrated in Fig. 8.6. It is seen that an increase in the number of nodes certainly increases the detection probability. However, a low node sensitivity may lead to a considerably high number of nodes to be employed.

Conclusion

In this chapter, the attractiveness of the UWB technology for purposes of implementing cognitive radio networks is investigated from two main approaches. The first one considers UWB as a direct means of practical cognitive radio realization. Under this approach, the UWB features such as negligible interference to licensed systems, dynamically adjustable bandwidth and data rate, and adaptive transmit power and multiple access are discussed emphasizing their closeness to the cognitive radio requirements. UWB is shown to be a proper candidate for implementing the cognitive radio networks. The concern regarding UWB's being the technology of cognitive radio is that the overlay mode operation of UWB is currently not allowed by regulatory agencies. Therefore, this option may have to be deferred until it is proven that licensed systems can co-exist with specifically designed overlay UWB systems that have advanced sensing and spectrum shaping capabilities.

The second approach considers UWB as a source of supplementary uses for cognitive radio networks. Among the numerous uses that will enhance cognitive communications, some significant ones such as sharing the spectrum sensing information via UWB, locating the cognitive nodes using UWB, and providing awareness via impulse radar are addressed in this chapter.

It should be emphasized that even in the case that the impulse radio UWB is not accepted as the means of implementing the cognitive radio networks, its supplementary uses are so beneficial that UWB cannot be separated from cognitive radio systems of future.

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