The Roles of Ultra Wideband in Cognitive Networks

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***Abstract*—Cognitive radio is a recent concept that is expected to lead wireless communications to a new era. A proper candidate for the physical layer implementation of cognitive radio networks is ultra wideband (UWB), because UWB is highly competent in satisfying many basic requirements of cognitive radio. Beside this, UWB can also provide various kinds of supportive uses to cognitive radio systems that are realized by means of other wireless technologies. In this paper, a number of possible roles that UWB can take in cognitive networks are discussed in detail.**

***Index Terms*— Cognitive radio, cognitive node, impulse radio, spectrum sensing, UWB-OFDM.**

I. Introduction

Cognitive radio is a novel concept for future wireless communications, and it has been gaining significant interest among the academia, industry, and regulatory bodies [1]. Cognitive radio provides a tempting solution to increasing spectral crowding by introducing the opportunistic usage of frequency bands that are not heavily occupied by their licensed users. It proposes to furnish radio systems with awareness, sensing, adaptation and learning about hardware capabilities, power, available spectrum, networks, nodes, infrastructures, radio channel, interference, and noise temperature, as well as local policies. The primary advantage targeted with these features is to enable the cognitive systems to utilize the available resources such as hardware, power, spectrum, and network, in the most efficient way, and to provide an optimum communication quality.

An interconnected set of cognitive radio devices that share information is defined as a pure cognitive network [2]. Cognitive networks aim at performing cognitive operations such as sensing, accessing, and managing of the spectrum, managing other available resources, and making user-independent and intelligent decisions based on cooperation of multiple cognitive nodes. The primary cognitive radio communication requirements include,

- ability to sense and measure critical parameters related to hardware, power, spectrum, environment, channel, and network ,
- ability to exploit variety of spectral opportunities,
- ability to offer flexible pulse shape and bandwidth according to available hardware, spectrum, and network resources,
- adjustable data rate, adaptive transmit power, information security, and limited cost,
- negligible interference to licensed systems, and
- capability to adapt itself to changing link qualities.

When the wireless systems that are potential candidates for cognitive radio are considered, ultra wideband (UWB) seems to be one of the tempting choices because it has an inherent potential to fulfill some of the key cognitive radio requirements. On top of this, especially impulse radio (IR) based 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 these distinctive properties, UWB is considered as one of the enabling technologies for cognitive radio networks in this paper.

The organization of the paper is as follows. In Section II, the primary UWB features are addressed from the point of satisfying the cognitive radio requirements. Section III discusses implementation of cognitive radio via UWB. In Section IV, the supportive roles that UWB may have in a cognitive network are investigated. Section V concludes the paper.

II. Suitability of Ultra Wideband for Cognitive Radio

Considering the main features of ultra wideband, it is seen that there is a strong match between what the cognitive radio requires and what UWB offers. In the following, the UWB features will be investigated from the point of satisfying the requirements of cognitive radio.

A. Limited Interference to Licensed Systems

Cognitive radios aim at an opportunistic usage of licensed frequency bands under the condition 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. 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 FCC regulations in the USA. When a UWB system is operating in the underlay mode, it is almost impossible that any co-existing licensed system is affected by it. On top of this, underlay UWB can employ various narrowband interference avoidance methods [3]. 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. Shaping the spectrum in such a way is possible with a single simultaneous transmission. 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.

B. Dynamic Spectrum

At different operating dimensions such as at different times and locations, the available bands for cognitive communications can vary, therefore, 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.

C. Adjustable Data Rate and Quality-of-Service

In cognitive communications, any increase in the utilization of the bands by the licensed systems can force the cognitive radio to decrease its data rate and Quality-of-Service (QoS), or even to terminate its communication. Therefore, cognitive radio systems are expected to be able to adjust their throughput 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. This adjustment is much simpler in UWB-OFDM. 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.

D. Adaptable Transmit Power

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) 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.

E. Adaptive Multiple Access

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 adjusting 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.

F. Information Security

The primary objectives targeted with cognitive radio include preserving the privacy of information. In an ideal scenario, cognitive radio will provide communication over any network and over any spectrum. Therefore, the traditional security that is applicable to communication over dedicated network and spectrum may not provide adequate information security over heterogeneous network and spectrum components. UWB is one of the systems that inherently provides information security. 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, by direct sequencing, or a combination of both. 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.

G. Limited Cost and Complexity

Being a future wireless concept and to realize a wide deployment, 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 circuitry. The RF front-end required to send and capture UWB signals are also quite simple 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.

Low complexity hardware is preferable in cognitive radio to facilitate its wide implementation and ease of maintenance. The UWB is a prime candidate to fulfill this need. UWB inherently operates in the baseband, which eliminates the need for mixer and other hardware components required to upconvert a baseband signal to a higher frequency. This, in turn, reduces the hardware complexity compared to other technologies and presents UWB as a desirable candidate for cognitive radio.

III. Implementing Cognitive Radio via Impulse Radio

Owing to its very tempting adaptive features addressed in Section II, impulse radio UWB can be considered as a suitable candidate to realize cognitive radio. Since the pulses transmitted by IR-UWB directly determine the spectrum occupied, a careful selection of the set of pulses to be utilized is essential for an opportunistic spectrum usage via UWB.

The IR-UWB implementation method proposed in [4] can be considered as an example for UWB based cognitive radio implementation. This method employs pulses shaped by raised cosine (or root raised cosine) windows, and it assumes that detailed information about the spectrum opportunities is available through the spectrum sensing performed beforehand. Cognitive radio selects the raised cosine windows that are most suitable for each of the spectrum opportunities according to the amount of available bandwidth and the data rate needed. Each of the selected pulses is mixed with a locally generated cosine signal at the center frequency of the targeted spectrum opportunity, so that it is upconverted to the corresponding frequency band. The final pulse shape is obtained by taking the sum of all these separate pulses, and hence, this combined pulse fills all the spectrum opportunities considered.

As in the case of the raised cosine windowing based implementation method mentioned, impulse radio based UWB technologies can be a convenient way of realizing cognitive radio. However, it has to be kept in mind that under the current FCC regulations, the overlay mode of UWB is not permitted, and it is reasonable to consider that similar spectral limitations will be mandated upon UWB systems in other regions of the world, as well. Under these conditions, it should be stated that IR-UWB can be *the technology* for cognitive radio only when the regulatory agencies are convinced that IR-UWB devices are equipped with advanced sensing and spectrum shaping capabilities that leave zero possibility to interfering with licensed users.

IV. Secondary Uses of UWB in Cognitive Networks

Due to current spectrum regulations that restrict UWB systems in the overlay mode, a complete UWB based implementation of cognitive radio might not become a reality in the near future. However, apart from 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.

UWB can be assigned to various supportive roles in cognitive radio networks. These include sensing the spectrum with a UWB-OFDM receiver, sharing the spectrum sensing information and other various data via UWB, locating the nodes in a cognitive network by means of IR-UWB, identifying the nodes via UWB, and sensing the physical environment/channel with IR-Radar. In the following, these supplementary roles of UWB will be discussed.

A. UWB-OFDM Receiver as a Spectrum Sensor

Spectrum sensing is one of the most integral parts of cognitive radio concept. There are numerous approaches considered for spectrum sensing, and UWB is an inexpensive option among them. In [5], it is demonstrated that an OFDM based UWB receiver can be utilized as a spectrum sensor under certain conditions.

In the OFDM based implementation of UWB, 128 subcarriers that are separated by $4.125 MHz$ are used. Therefore,

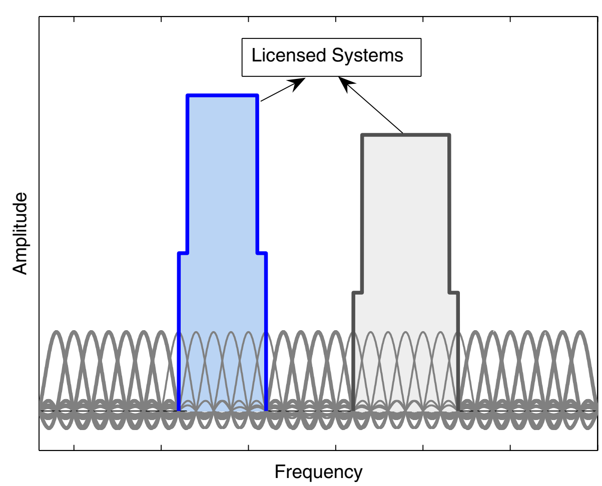

Fig. 1. Detection of licensed systems in a cognitive network via UWB-OFDM.

the receiver of this UWB system can be considered as a spectrum measurement device with $4.125MHz$ resolution, which gives a rather rough information about the occupancy of the spectrum. The way how the licensed user signals look inside the scanned UWB spectrum is illustrated in Fig. 1.

There are some modifications that need to be done on the UWB receiver in order to use it as a spectrum sensor. The first one is about the automatic gain control (AGC). Since, compared to licensed systems, the power level of UWB is close to the noise floor, the AGC that is set for measuring UWB signals can not be used for detecting licensed signals because the power range of these signals can be very wide. Hence, taking into account the limited number of bits available in the analog-to-digital converter (ADC) of the receiver, the AGC should be adjusted so that the receiver can detect a wide variety of power levels. The second modification is related to the low noise amplifier (LNA) that is used to strengthen the received signal. Since the power of licensed signals are out of the linear operation range of the LNA, it is not possible to detect the licensed systems. Therefore, it is necessary to exchange the LNA with a regular amplifier that can handle the wide power range of licensed signals.

B. Spectrum Sensing Information Exchange in Cognitive Networks

In cognitive networks, it is mandatory that all participating nodes agree on the spectral opportunities to be utilized. Therefore, spectrum sensing information exchange is a major issue in cognitive networks. In some works in the literature, it is considered to have an allocated control channel to transmit this information [6], [7]. In some other works, it is proposed to have a centralized controller that gathers this information, decides spectrum availability, and allocates distinct bands to different cognitive users [8]. An alternative to these methods is to transmit spectrum sensing results via low power UWB signaling [4]. Since this transmission will be accomplished in an underlay manner, it can be done simultaneously with the real data communication without affecting the real data regardless of the wireless technology employed. 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 a simple non-coherent receiver such as an energy detector, and to employ on-off keying (OOK) modulation. By using a proper mapping scheme (from sensing results to binary codewords), coding, and OOK modulation, spectrum information can be conveniently shared among the nodes.

One of the aims of cognitive radio is to increase the range of communication as much as possible. At the first glance, UWB signaling may not seem to be very appropriate for this purpose because of the limited range of underlay UWB. In [4], it is shown that by applying the necessary amount of processing gain, which corresponds to a repeated transmission of the same data, the farthest nodes in a cognitive network can be enabled to contact each other. Although this results in a lowered throughput, it is acceptable because of the low data rate required to transmit the spectrum sensing information.

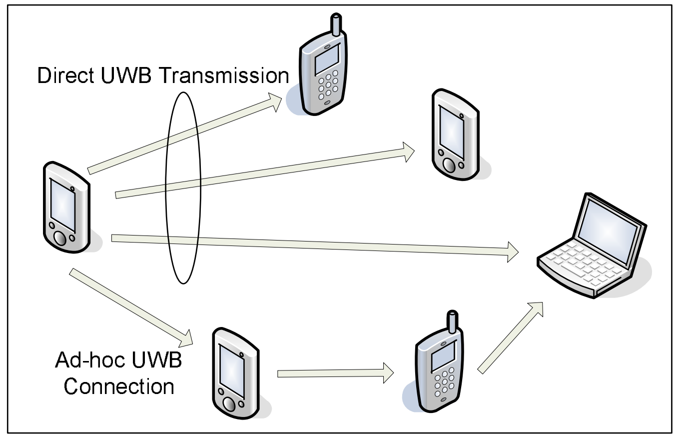

Fig. 2. Sharing the spectrum sensing information via IR-UWB signaling in a cognitive network.

Spectrum information can also be shared in an ad-hoc multi-hopping scheme instead of a long range transmission (see Fig. 2). In this method, multiple nodes collaboratively share the information and route this information to other nodes using low power, low cost UWB technology. This way, in essence, a UWB based sensor network is formed.

C. Sharing Various Kinds of Supportive Data via UWB

Cognitive communications do not necessarily have to be based on indoor networks that are mostly made up of personal mobile devices. Cognitive networks can be established to enable military communications or communications at extreme outdoor conditions such as natural disaster situations.

In outdoors, the factors affecting the cognitive communications will be quite different than in indoor scenarios. The weather and temperature conditions are some of the most important ones among these factors. The range of a wireless device used outdoors can considerably decrease when there is a thick fog in the air, for example. Therefore a moisture level sensor may be very instrumental. To determine rain and snow, a high resolution camera combined with a digital signal processor (DSP) that can recognize the type of precipitation, can be utilized. A temperature sensor embedded in the device can help to adjust the temperature dependent hardware parameters and to verify that the weather condition is detected correctly.

It is known that wireless systems operating at lower frequencies have better penetration capabilities. If a cognitive network has information about the weather conditions, it can adjust its communication frequency accordingly. In a foggy environment, for example, the spectral opportunities at lower frequencies can be preferred, or the transmission power can be increased to maintain the communication range targeted under normal conditions.

It is apparent that it would not be feasible to embed the numerous sensors or a digital camera and DSP to each outdoor

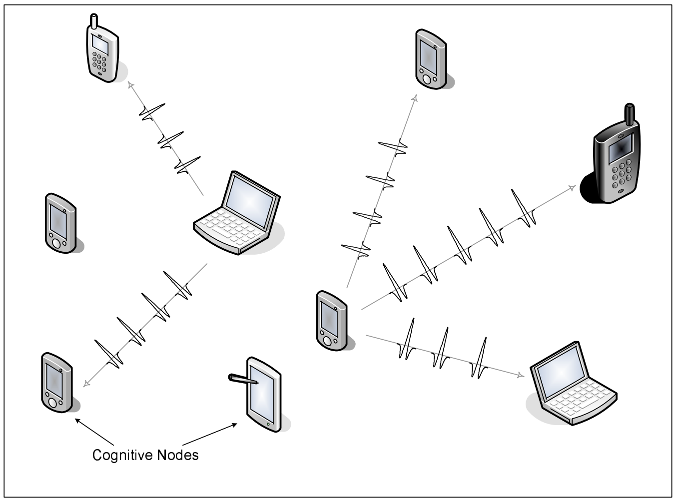

Fig. 3. Nodes in a cognitive network can determine the positions of other nodes via IR-UWB.

communication device. However, it would be enough that each of these sensing capabilities exists in only one of the nodes in a cognitive network, if these nodes were able to communicate the corresponding data to the other nodes. Ultra wideband can fulfill a vital role for this purpose. As in the case of spectrum sensing information exchange, any type of channel related additional data required for outdoor communications can be shared simultaneously with the real data between the cognitive nodes via ultra wideband.

D. 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 system in addition to being communication systems [9]. 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 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 adjusted. 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 multiplied. 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.

E. Cognitive Node Identification via UWB

In cognitive communications, every cognitive device might be given a serial number during manufacturing. Since this number is unique to each cognitive device, it would uniquely identify each cognitive device.

Cognitive devices can transmit their serial numbers steadily via ultra wideband. This way cognitive devices can recognize each other, and secure cognitive communications can be established between targeted cognitive nodes. This mutual authentication of cognitive radio devices is necessary for secure communication over heterogeneous network and spectrum. Other useful data can accompany this serial number. These include

1) a beacon that indicates if the device is currently communicating or it is in the stand-by mode. This information can be extremely useful because it would allow spectrum allocations to be done accordingly. If a cognitive node can inform the other nodes about its existence even if it is not in the active mode, some bandwidth can be assigned to this sleeping node. This way, the highest possible number of nodes in a cognitive network can utilize a given band at the same time.
2) some short data that identify the device by providing information about the type of modulation and coding it uses, its bandwidth, and its carrier frequency. This kind of data can enable different types of cognitive radios recognize each other very easily. Currently, a significant concern about the cognitive radio communications is how to supply the advanced cognitive devices with spectral sensing capabilities that would allow these devices not just to detect the existence of other systems, but also to determine the type of modulation and coding they are using. Since this technology requires rather complex algorithms and very costly hardware, the feasibility of such advanced cognitive devices becomes questionable. However, if the cognitive devices provide information

about their transmitted signal properties via UWB, there may be no need for advanced sensing algorithms, and this would be a big step toward the realization of the cognitive radio concept.

F. 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 [10], [11]. Practical implementations of impulse radar have been addressed in [12]-[16]. 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 [17].

V. Conclusion

In this paper, the attractiveness of UWB for cognitive radio networks is addressed from two main points. First, UWB is considered as a direct means of practical cognitive radio realization. In this approach, the UWB features such as negligible interference, dynamically adjustable bandwidth and data rate, and adaptive transmit power and multiple access are discussed. The second approach considers UWB as a source of supplementary uses for cognitive radio networks. Numerous uses are addressed in the paper include sensing the spectrum with UWB-OFDM receiver, exchanging various supportive information via UWB, locating the nodes in a cognitive network by means of IR-UWB, and sensing the physical environment or the channel with IR-radar.

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

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