System Design for Cognitive Radio Communications

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***Abstract*— The rising number and capacity requirements of radio systems bring about an increasing demand for frequency spectrum. Cognitive radio offers a tempting solution to this problem by proposing opportunistic usage of frequency bands that are not occupied by their licensed users. Since it is a rather new concept, there is no consensus on the practical implementation of cognitive radio communications. In this paper, a comprehensive system design for cognitive radio is presented. The details of spectrum sensing and dynamic spectrum shaping, which constitute the basics of opportunistic spectrum usage, are given. It is proposed to transmit the spectrum sensing related information via on-off keying (OOK) modulated ultrawideband (UWB). The limits on the range of one-to-one cognitive communications are discussed. A processing gain based approach that leads to an increased range for cognitive networks is proposed. Different signaling options for the real data communications are given, and among these options an impulse radio that employs raised cosine filters is investigated in detail.**

I. INTRODUCTION

Modern wireless systems aim at offering a wide variety of high data rate applications to numerous users at the same time. In order to realize this objective, they have to overcome the practical constraints imposed by the resources they need such as power and spectrum, which are limited in nature. Since the number of wireless systems is increasing very rapidly, the scarcity of these resources, especially of the frequency spectrum, becomes a more vital problem day by day.

Cognitive radio [1] is a concept that targets at a future solution for the spectrum scarcity problem by proposing an opportunistic spectrum usage [2] approach, in which frequency bands that are not being used by their licensed users are utilized by cognitive radios. Since cognitive radios do not need to have a license and since they do not affect the operation of licensed systems, this approach leads to a highly economic and efficient usage of the frequency spectrum.

The primary properties of cognitive radio are its sensing, awareness, adaptation, and learning capabilities, as well as its memory. In this paper, we are going to especially focus on sensing and adaptation aspects. A cognitive radio system might be able to sense numerous factors such as the spectrum, RF environment, the available nodes in its network, and available power. The adaptation capability, on the other hand, includes adapting the system, transmission, and reception parameters without any need to user intervention.

Cognitive radio systems continuously scan the spectrum and detect the holes in the spectrum, which are the frequency bands owned by a licensed user, but are not being used at a particular time and at a specific location [3], [4]. They exploit the spectrum holes making use of their ability to adapt their parameters to changing conditions rapidly. Every time when the spectrum is sensed and the spectrum holes are detected, they shape their transmitted pulse in such a way that the spectrum occupied by the pulse fits into the spectrum holes. In cognitive radio communications, one of the major issues is how to share the spectrum sensing information with other cognitive users. In the literature, it is considered to have an allocated control channel to transmit this information [5]. In some 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 [6], [7].

The contribution of this paper is threefold. First, it is proposed that the cognitive users share the spectrum sensing information via underlay ultrawideband (UWB) simultaneously with the real data communication. Second, for the transmission of real data, various options are discussed and the implementation of an impulse radio that employs pulses shaped by raised cosine filters is investigated. Third, the range of one-to-one duplex cognitive communications is determined, and a method that is based on providing the UWB signals with processing gain is proposed to increase the range of cognitive networks.

The paper is organized as follows. In Section II, the practical implementation of opportunistic spectrum usage is explained. Dynamic pulse shaping is investigated in Section III. Details of communications between transceivers in a cognitive network are provided in Section IV, and numerical results are given in Section V. Section VI addresses the conclusions and possible future research topics.

II. OPPORTUNISTIC SPECTRUM USAGE

A. Spectrum Sensing

The first requirement for opportunistic utilization of owned bands is to periodically scan the spectrum and to detect the spectra that are temporarily not being used, which can be called *white bands*. A commonly used name for this operation is *spectrum sensing*.

An important concern about spectrum sensing is about how to set the boundaries of the spectrum targeted by cognitive radio. Considering the extreme abundance of frequency spectra that may contain white bands, it is obvious that even in the case of cognitive radio communications, which is conceptualized to remove the borders around open spectrum access, the targeted spectrum should be limited. Among the numerous reasons, the primary ones are that this way

- It can be possible to sample the received signal (after the down-conversion) at or above the Nyquist rate even with the current technology, which enables digital processing of the signal.
- The computational burden associated with spectrum sensing can be restricted to a reasonable level, leading to limited hardware complexity.
- The analog front-end required for a very wide spectrum scan (including a wideband antenna, wideband amplifiers and mixers), which have a rather high cost, can be avoided.
- It can be prevented that a single type of cognitive radio occupies the majority of the bands that are open to opportunistic usage.

The spectrum allocation for different types of cognitive radios (like mobile phones, WLAN modems, and palm devices) can be done by regulatory agencies such as the FCC depending on the intended range and the throughput requirement of the specific application. From this point of view, high data rate cognitive radios aiming at wide range applications such as TV broadcast systems should be assigned wider target spectra at lower frequency bands, whereas relatively low rate, short range communication devices like cordless phones may be allocated narrower bands at higher frequencies.

B. Spectrum Shaping

The second requirement for opportunistic spectrum usage is to dynamically adapt the transmission parameters to comply with the changing spectral conditions. A cognitive radio can accomplish this by modifying the shape of its transmitted pulse in such a way that the spectrum of the pulse fills the detected white bands as efficiently as possible. The details regarding pulse shaping for opportunistic spectrum usage are provided in Section III.

C. Cooperation of Transmitter and Receiver

In the cognitive communications we propose, it is assumed that both the transmitter and the receiver have transmission and reception capabilities. In order to match the results of the spectrum sensing operation done by both parties, each of them will transmit the information regarding the white spaces they have detected. We propose that the transmission of spectrum sensing results is done via low power UWB signaling that complies with the FCC regulations. Since this transmission will be accomplished in an underlay manner, it can be done simultaneously with the real data communication without affecting each other.

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. 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 [8].

Once both parties of communication receive the spectrum sensing information obtained by the other party, they logically 'AND' the white spaces each of them has detected separately. The reason behind this operation is that frequency bands can be considered available for opportunistic usage only if both parties classify them as white space. Depending on the knowledge about the common white spaces, each party designs a new pulse shape. Since the new pulses designed by both parties will be the same, this method has the very advantageous feature that it enables highly efficient matched filtering during the real data traffic. To be more clear, what the receiving party uses as the template to match the received pulse will be (almost) the same as the transmitted pulse by the other party, leading to a high correlation between them, and hence, to a successful matched filtering.

D. Steps of Practical Implementation

Steps of practical implementation of opportunistic spectrum usage can be summarized as follows.

- Capturing any signal in the target spectrum (e.g. 2.1-2.3 GHz) by using an appropriate antenna and analog band pass filter,
- Analyzing the spectral content of the received signal either by analog means:
  - Sweeping the target spectrum via a mixer and passing the down-converted signal through an IF filter with a narrow pass-band (to obtain an acceptable frequency resolution),
  - Determining the existence of signals inside the target spectrum by using an energy detector that consists of a square law device, an integrator, and a comparator,
  - Labeling the binary output of the energy detector as *occupied* or *white space* (see Fig. 1-e),
- or by digital means:
  - Down-converting the signal to an IF frequency,
  - Sampling the signal at a rate above the Nyquist rate and digitizing it (applying analog-to-digital conversion),
  - Computing the power spectral density either by taking the Fast Fourier Transform (FFT) and squaring, or by applying more advanced power estimation methods such as Welch's method or Thomson's multitaper method,
  - Comparing the obtained power spectral density with a pre-determined power threshold. This way, determining the occupied spectra and the white spaces,
- Comparing the bandwidths of the white spaces with a pre-determined minimum bandwidth in order to find out if they are wide enough to be utilized,
- Transmitting the information regarding the usable white spaces to the other party via UWB signaling,
- Receiving the white space data from the other party,
- Finding the common white spaces,
- Designing a pulse shape that utilizes as much usable white space as possible,
- Initiating the cognitive communication and repeating the entire sensing process at a regular period.

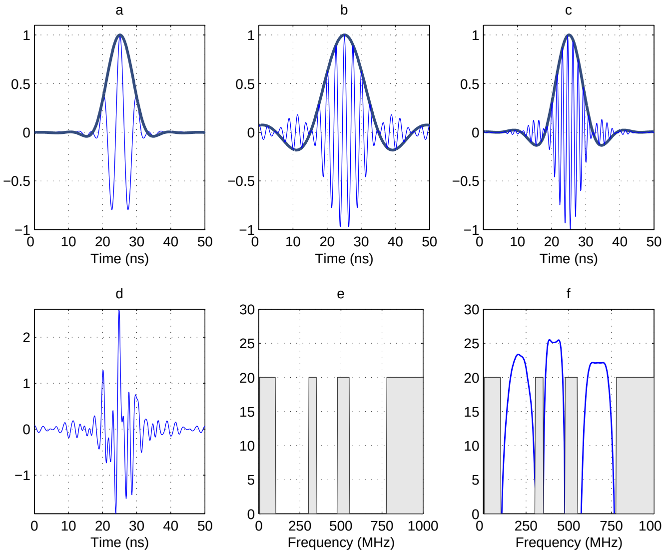

Fig. 1. a-,b-,c- Separate pulses obtained via raised cosine filtering that fit into different white spaces. d- Sum of separate pulses. e- Binary classification of frequency bands as 'occupied' or 'white band'. f- Spectrum of the designed pulse filling the white spaces.

III. SPECTRUM SHAPING BY ADAPTIVE PULSE DESIGN

The objective of cognitive radio is to design a pulse shape whose frequency spectrum will occupy as much white space as possible. Different methods to implement pulse shaping for cognitive radio are given in [9]-[14].

A primary option for filling the white spaces is to employ Orthogonal Frequency Division Multiplexing (OFDM). OFDM provides the cognitive radio with a high spectral flexibility with its ability to simply turn on and off different sub-carriers according to changing spectral conditions. OFDM based implementation of spectrum shaping can be found in [9], [10].

Another spectrum shaping approach is based on the usage of Prolate Spheroidal Wavelet Functions (PSWF). These functions have a pulse width and bandwidth that can be controlled simultaneously, and they are able to be shifted to anywhere in the spectrum without a need for up- and down-conversion. Spectrum shaping methods employing the PSWF based approach are provided in [11], [12], and [14].

The method we focus on for shaping the spectrum of the transmitted pulse is based on the usage of raised cosine (or root raised cosine) filters. In this method, first, the information regarding the usable white spaces is utilized to determine the center frequencies f_{c_i} and bandwidth B_i of each white band U_i for $i = 1, 2, ..., N$, where N is the total number of white bands. In the next step, making use of its awareness property, the cognitive radio selects the raised cosine filters $r_i(t)$ that are the most suitable for each U_i. Filling a higher percentage of a white space requires a higher roll-off filter, which corresponds to a longer symbol in time leading to inter-symbol interference (ISI) or a lower throughput. Hence, the cognitive radio determines the filter to be used according to the amount of available bandwidth and the data rate required. The selected filters are multiplied with digitally generated cosine signals yielding

$$\phi_i(t) = cos(2\pi f_{c_i} t) \cdot r_i(t) \ . \qquad (1)$$

$\phi_i(t)$ can be exemplified as in Fig. 1-a, -b, and -c, which are generated using $r_i(t)$ with roll-off coefficients 0.9, 0.3 and 0.5, respectively. Each of these pulses is filling one of the white spaces in Fig. 1-e. The final pulse shape (demonstrated in Fig. 1-d) is obtained by taking the sum of all these separate pulses

$$p(t) = \sum_{i=1}^{N} \phi_i(t) \ , \qquad (2)$$

and it fills the white spaces as shown in Fig. 1-f.

IV. RANGE OF COGNITIVE COMMUNICATIONS AND COGNITIVE NETWORKS

In cognitive radio communications, in order to make sure that the intended frequency spectrum is not in use, both parties of communication have to scan the spectrum and inform each other about the spectral conditions. We contemplate that there should not be a gap between the sensing ranges of them. 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. Therefore, the receiving sensitivity of both parties has an integral role in determining the range of communication. We assume a rather high sensitivity around $-120dBm$ to $-130dBm$ and 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)

$$P_{rx} = \frac{P_{tx} \, \lambda^2}{(4\pi)^2 \, d^2} \ , \qquad (3)$$

where λ is the wavelength, and d is the distance. With these assumptions, it is seen that the scope of cognitive radio is limited to $50m$ to $150m$, which is comparable to the range of WLANs. If the targeted range of communications is wider than this level, or if the cognitive devices are experiencing shadowing and are hardly able to detect the existence of licensed users, a network of collaborating cognitive nodes may be an effective solution.

In our study, the focus is on a cognitive network (see Fig. 2) whose nodes communicate with each other using UWB to exchange spectrum information. The fact that UWB signaling is proposed may seem to be contradicting with the aim of increasing the range of cognitive radio because of the limited range of UWB. However, looking at the bit error rate (BER) expression for OOK modulated UWB signals

$$Q(\sqrt{\frac{N_s A E_p}{2N_0}}) \ , \qquad (4)$$

where N_s is the number of pulses per symbol, A is the pulse amplitude, E_p is the received pulse energy, and the additive white Gaussian noise (AWGN) has a double sided spectrum of $\frac{N_0}{2}$, it is seen that increasing N_s, which can be accomplished by repeated transmission of data, results in lower

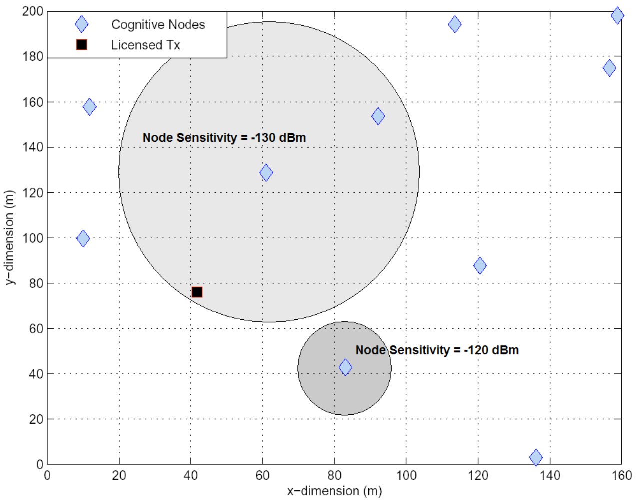

Fig. 2. Network of Cognitive Transceivers (Sensitivity ranges are not drawn to scale).

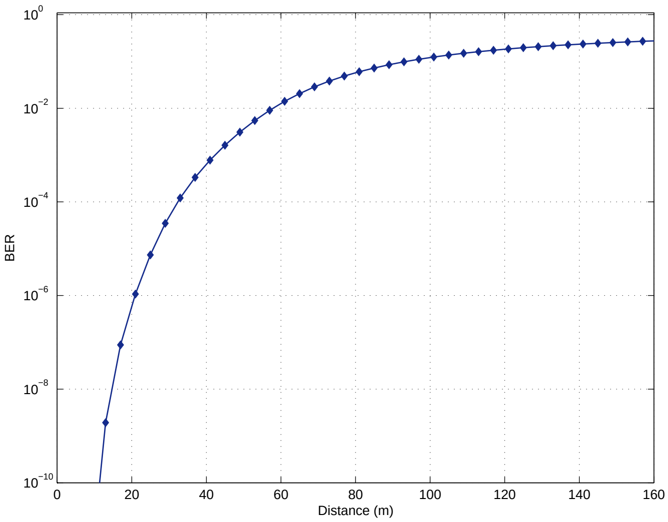

Fig. 3. BER vs. distance between the nodes for UWB signaling.

BER. This fact leads to a very advantageous feature of UWB called *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 such information, processes it, and transfers it to other cognitive users.

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 the common white spaces. This way, the range of cognitive communications can be extended to the coverage area of a medium-sized network.

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 white bands become less and less, and after some point their amount becomes insufficient to ensure the minimum quality of service (QoS). For the details of how the common white bands are going to be shared by the cognitive nodes in the network, the reader can be referred to [15] and [16].

V. NUMERICAL RESULTS

Computer analysis and simulations are performed regarding the practical implementation of cognitive radio communications. These are related to the transmission of spectrum sensing results via UWB, the range of cognitive communications, and the capability of a cognitive network to detect a licensed system. In the simulations regarding the UWB signaling, the channel model $CM3$ in [17], which corresponds to an office environment with line-of-sight (LOS), is utilized. All parameters used in these simulations are listed in Table I.

We performed a theoretical analysis investigating the performance of OOK modulated UWB data transmission depending on the distance between a cognitive transmitter-receiver pair. According to [17] the path loss assumed can be shown as

$$L(d) = L_0 + 10n\, log_{10}(\frac{d}{d_0}), \tag{5}$$

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

$$N = -174 + 10\, log_{10}(R_b)\ , \tag{6}$$

where R_b is the throughput. In Fig. 3, the effect of distance on the probability of error is demonstrated. The results show that the BERs obtained for up to $40m$ are still acceptable. For further distances, however, some processing gain is definitely needed. The processing gain is obtained by repeated transmission of the same information. We did a simulation that investigates the number of repetitions required in order not to exceed the BER obtained at $40m$, which corresponds

TABLE I

LIST OF SIMULATION PARAMETERS

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 NF	17 dB
Implementation Loss	3 dB
Throughput (R_b)	20 Mbps
Integration Interval	30 ns

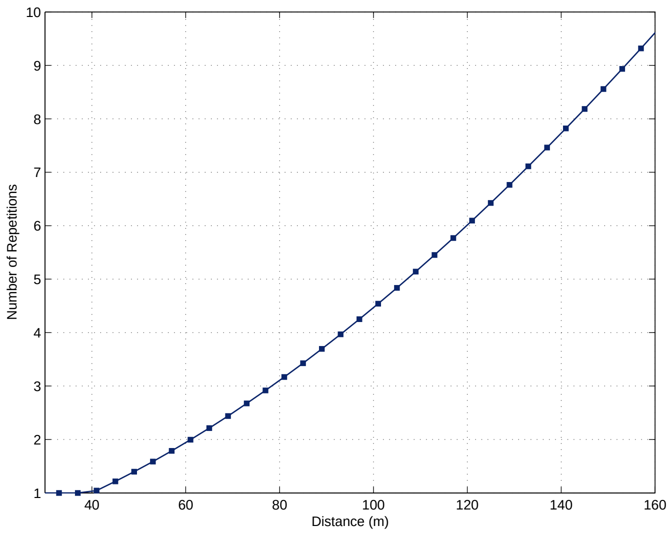

Fig. 4. Repetition rate required for reliable UWB signaling vs. distance.

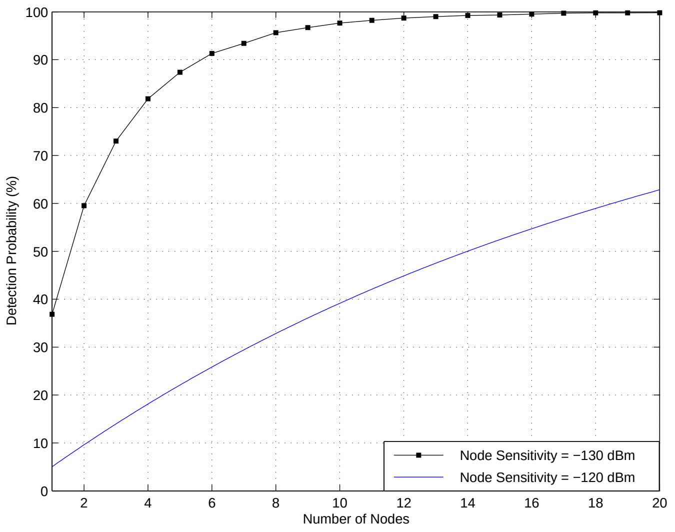

Fig. 5. Probability of the licensed transmitter being detected by the cognitive network.

to $10^{-3.2}$. The number of repetitions needed vs. the distance is shown in Fig. 4.

A 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. Fig. 2 demonstrates a network composed of cognitive radio devices. The nodes in the network are randomly distributed in a $200m$x$200m$ area inside a building. It is assumed that there is a licensed transmitter, which is a $GSM900$ cell phone transmitting at $-60dBm$, 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. 5.

VI. CONCLUSIONS AND FUTURE RESEARCH

In this paper, a complete system design for practical cognitive radio implementation is presented. The details of spectrum sensing and pulse shaping are discussed. The transmission of spectrum sensing information via UWB is proposed. The range of one-to-one cognitive communications is investigated, and a method for extending the range of cognitive networks is addressed.

Cognitive radio is a widely open extensive research area. Possible future research topics include determining the most suitable target spectra for different types of cognitive radios, investigating the complexity and reliability of different spectrum sensing techniques, and determining the optimum size for cognitive networks.

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