# Cognitive UWB-OFDM: Combining Ultrawideband with Opportunistic Spectrum Usage

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*Abstract*— **In a continuously expanding wireless world, the number of radio systems increases every day, and efficient spectrum usage becomes a more significant requirement. Ultrawideband (UWB) and cognitive radio are two recent and exciting technologies that offer a new approach to the spectrum usage. The main objective of this paper is to combine these two technologies. The strength of orthogonal frequency division multiplexing (OFDM) based UWB in co-existing with licensed systems is investigated. The *opportunity* concept is defined, and the requirements of the opportunistic spectrum usage are explained. It is proposed to take the UWB-OFDM from the current underlay implementation, and evolve it to a combined underlay and opportunistic spectrum usage technology, leading to cognitive UWB-OFDM. This way, we aim at making UWB more competitive in the wireless market with extended range, higher capacity, better performance, and a wide variety of applications.**

## I. INTRODUCTION

Wireless communication systems have been evolving substantially over the last two decades. The explosive growth of wireless technologies is expected to continue in the future, leading to a spectrum shortage. In order not to limit the economic and technological improvement of the wireless world, it is necessary to find immediate solutions regarding the spectrum usage. Two exciting cutting-edge solutions for this problem are ultrawideband (UWB) and cognitive radio [1].

UWB is a promising technology for future short-range, high-data rate wireless communication networks. It has many tempting features such as low power consumption, significantly low complexity transceivers, and immunity to multipath effects. Cognitive radio, on the other hand, aims at a very efficient spectrum utilization employing *smart* wireless devices with awareness, sensing, learning, and adaptation capabilities [2]. As a solution for the spectrum scarcity problem, cognitive radio proposes an opportunistic spectrum usage approach [3], in which frequency bands that are not being used by their primary (licensed) users are utilized by cognitive radios. Both UWB and cognitive radio do not require a license and they do not affect the operation of primary systems. Therefore, they lead to a highly economic and efficient usage of the frequency spectrum.

Impulse radio and orthogonal frequency division multiplexing (OFDM) are the two options for implementing UWB. In this paper, we are going to focus on OFDM based UWB. OFDM has become a very popular technology due to its special features such as robustness against multipath interference, ability to allow frequency diversity with the use of efficient forward error correction (FEC) coding, capability of capturing the multipath energy, and ability to provide high bandwidth efficiency. OFDM can overcome many problems that arise with high bit rate communications, the most significant of which is the time dispersion. It offers a number of possibilities in terms of adapting the transmission parameters such as the transmit power, cyclic prefix size, modulation and coding, and the number of sub-carriers. In OFDM systems, adaptation can be done over each packet (as in the case of single carrier systems), as well as each carrier or a small group of carriers. In other words, it can be accomplished independently over narrower bands rather than the entire transmission band.

Systems with a spectral allocation similar to UWB are often referred as *underlay* systems. The severe power limitations on underlay systems restrict their usage to only very short range applications. The main contribution of this paper is that we propose a cognitive UWB-OFDM approach that supplements the underlay UWB with an overlay opportunistic spectrum usage approach, and aims at increasing the range, data rate, and quality of unlicensed communications. We investigate the potential behavior of cognitive UWB-OFDM under many different scenarios, in which either UWB-OFDM or opportunistic spectrum usage may be more preferable.

The organization of the paper is as follows. In Section II, the coexistence of UWB-OFDM and narrowband systems is discussed, and a new temperature sensing algorithm is mentioned. In Section III, opportunity is defined, and the opportunistic spectrum usage concept is presented. In Section IV, cognitive UWB-OFDM is introduced. In Section V conclusions and possible future research topics are given.

## II. COEXISTENCE OF UWB-OFDM AND NARROWBAND SYSTEMS

UWB systems occupy a very wide spectrum that overlaps with the spectra of numerous narrowband systems without requiring a license. This fact causes serious concerns on the side of the narrowband system operators. Therefore, significant amount of research has been carried out lately to quantify the effect of UWB signals on narrowband systems [4]. The transmitted power of UWB devices is controlled by the regulatory agencies (such as the FCC in the United States), so that narrowband systems are affected from UWB signals only at a negligible level. This fact puts significant limitation on the variety of applications, maximum data rate, and transceiver design options [5]-[9].

Since the allowed UWB transmit power level is very limited, for being able to co-exist with licensed systems, resistance to

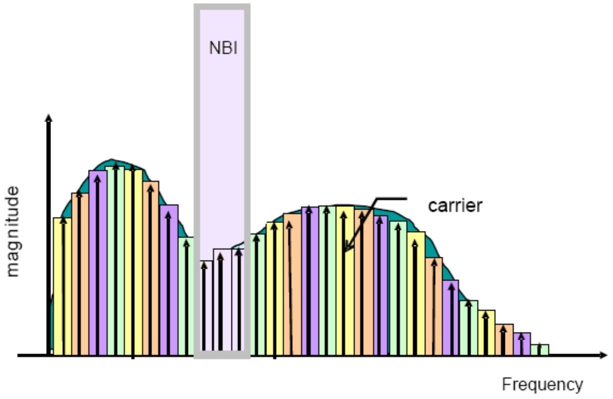

Fig. 1. A simple NBI scenario for UWB-OFDM systems.

narrowband interference (NBI) becomes highly significant for the implementation of UWB. This fact is a strong motivation behind employing OFDM in UWB applications. OFDM's resistance against NBI depends on its ability to turn the transmission on and off on separate carriers depending on the level of interference temperature. A common NBI model considered for OFDM is a zero-mean Gaussian random process that occupies certain carriers along with the white noise as

$$S_n(k) = \begin{cases} \frac{N_i+N_w}{2}, & \text{if } k_1 < k < k_2 \\ \frac{N_w}{2}, & \text{otherwise} \end{cases} , \tag{1}$$

where $k$ is the carrier index, and $\frac{N_i}{2}$ and $\frac{N_w}{2}$ are the power spectral densities of the narrowband interferer and the white noise, respectively.

In UWB-OFDM, NBI can be avoided easily by an adaptive OFDM system design. As the simple interference scenario illustrated in Fig. 1 shows, NBI corrupts only some carriers in the UWB spectrum. Therefore, only the information that is transmitted over these frequencies will be affected from the interference. If the interfered carriers can be identified, transmission over these carriers can be avoided. In addition, by sufficient FEC and frequency interleaving, jamming resistance against NBI can be obtained easily. Avoiding or adapting the transmission over the strongly interfered carriers can provide more spectrum and power efficiency, as they increase the immunity against NBI, and hence relax the FEC coding power requirement.

### *A Noise Temperature Estimation Technique*

In [10], a noise temperature estimation technique for UWB-OFDM systems is developed, where the noise and interference are not interpreted as a single white noise term (which is the way they have been interpreted in the literature so far), instead, the color and other statistics of the interference have been taken into account for improved interference temperature estimation. Conventional algorithms assume that the noise statistics remain constant over the OFDM frequency band, and thereby average the instantaneous noise samples to get a single estimate. In reality, noise is often made up of white Gaussian noise along with correlated colored noise that affects the OFDM spectrum unevenly. In [10], an adaptive windowing technique is employed to estimate the noise power that takes into account the variation of the noise statistics across the OFDM sub-carrier index as well as across OFDM symbols.

## III. OPPORTUNISTIC SPECTRUM USAGE

One of the fundamental ideas put forward with the cognitive radio concept is that licensed bands can be utilized by secondary users at times when they are not being used by their owners. In this opportunistic way of spectrum usage, it has to be guaranteed by the unlicensed systems that their operation does not affect the primary users. Although this approach is similar to the UWB from the point that both are unlicensed, there are two main differences between the opportunistic usage and UWB. First, UWB systems are forced to occupy a band of at least 500MHz width, which is not the case for the opportunistic usage; and second, for UWB communications there is a strict transmit power limitation, whereas in opportunistic usage the transmitted power can be comparable to licensed systems' power.

### *A. Sensing the Spectrum Opportunities*

A solid understanding of the opportunistic spectrum usage concept requires that *opportunity* is defined clearly. Cognitive radios periodically scan the spectrum and detect the spectra that are temporarily not being used by their licensed users, which can be called *white bands*. In many works, white bands are directly taken as the spectrum opportunities. However, there are spectral, temporal and spatial requirements that a white band has to satisfy in order to be useful and to be considered an opportunity [11], [12]. These requirements can be listed as follows.

1) Opportunity is not an instantaneous white space in spectrum. It is necessary to monitor a white space continuously over a time frame (in the order of seconds) and ensure that it does not display an erratic behavior, i.e. for a reasonably long time the noise temperature in that band resides below a certain threshold, and the band remains as a white space.
2) It may not be reliable to consider a white band an opportunity if it is detected by only one single cognitive radio device. The reasons include that the device has a limited sensing range, as well as that it may be experiencing shadowing. Optimally, the spectrum has to be sensed by numerous cognitive nodes over a region that goes well beyond the range of a single cognitive device. A band can be considered a candidate for being a spectrum opportunity only if it is detected as white by many cognitive nodes at different locations that exchange the spectrum sensing information with each other.
3) If a frequency band to be utilized is too narrow, it may be hard for the cognitive radio to generate a temporally limited pulse shape that fits into that band. Therefore, a white band has to be wider than a certain bandwidth for being targeted for opportunistic spectrum usage.

Apparently, the main reason behind these requirements is to minimize the risk of causing interference to licensed systems.

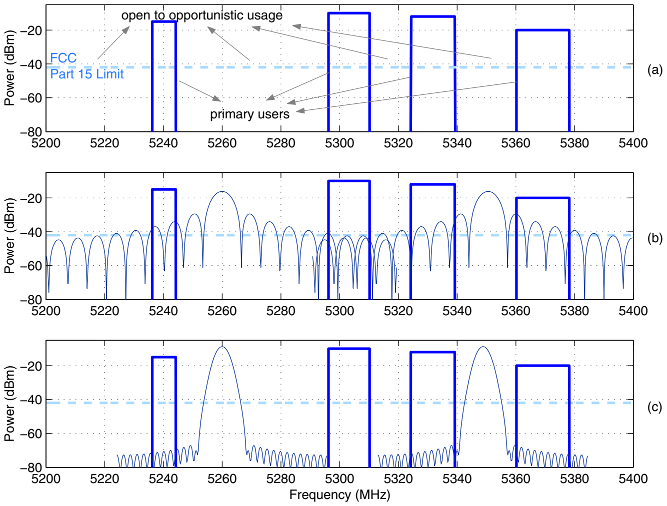

Fig. 2. a. A snap-shot of the spectrum in time. b. Opportunistic spectrum utilization employing time limited sinusoids. c. Opportunistic spectrum usage employing special pulses.

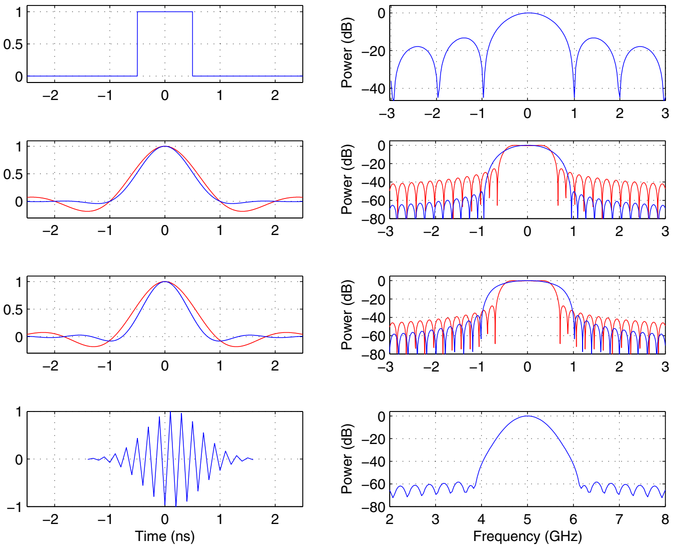

Fig. 3. Different pulse shapes and their spectra a. Rectangular window. b. Raised cosine windows with roll-off factors $\alpha = 0.3$ and $\alpha = 0.9$. c. Root raised cosine windows with roll-off factors $\alpha = 0.3$ and $\alpha = 0.9$. d. A high order prolate spheroidal wavelet function.

Beside this, such an opportunity definition is optimum from the point of minimizing the computational burden, as well, because it saves a cognitive radio from doing computations and changing its parameters without ensuring the dependability of a white band.

### *B. Adapting the Transmission Parameters*

The second part of opportunistic spectrum usage is the adaptation phase. A cognitive radio has to dynamically adapt its transmission parameters to comply with varying spectrum opportunities. Adaptation is done by modifying the transmitted power level and the pulse shape in such a way that the spectrum of the pulse fills the detected spectrum opportunities as efficiently as possible. While doing this, it has to be strictly ensured that the leakage from the opportunistic bands to the licensed systems in the adjacent bands remains at a negligible level (illustrated in Fig. 2). Therefore, it is very important to employ special pulses that

- have sharp fall-offs and suppressed side lobes in the frequency domain
- are limited both in time and bandwidth,
- have a pulse width and bandwidth that can be controlled simultaneously,
- and are able to be shifted to anywhere in the spectrum.

If the transmitted pulses are time limited sinusoids (as in the case of OFDM) and no windowing is used, the resulting side lobes may be unacceptably high (see Fig. 3-a). A possible solution is using the prolate spheroidal wavelet functions (PSWF), which satisfy the above requirements to a large extent (shown in Fig. 3-d). Spectrum shaping methods employing the PSWF are provided in [13] and [14].

Another method for shaping the spectrum of the transmitted pulse is based on the usage of raised cosine (or root raised cosine) filters, which can be exemplified as in Fig. 3-b (and c). In this method, depending on the information about the center frequencies $f_{c_i}$ and bandwidths $B_i$ of different spectrum opportunities, the cognitive radio selects the raised cosine filters $r_i(t)$ that are most suitable for each opportunity. 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 desired data rate. The selected filters are up-converted to $f_{c_i}$, and then, the final pulse shape is obtained by taking the sum of these up-converted filters

$$p(t) = \sum_{i=1}^{N} cos(2\pi f_{c_i} t) \cdot r_i(t) \ . \tag{2}$$

## IV. COGNITIVE UWB-OFDM

Under the current FCC regulation, UWB systems are allowed to have a very limited transmit power. Hence, all current UWB efforts both from industry and academy are in the direction of making UWB systems work in an underlay scenario, and aim at wireless personal are networks (WPAN), only. In this paper, we propose to take the UWB-OFDM from its current form, and furnish it with opportunistic spectrum usage capabilities, leading to cognitive UWB-OFDM. We consider cognitive UWB radios to be capable of switching between UWB and opportunistic spectrum usage, whichever is more advantageous.

In the UWB-OFDM communications that we contemplate, for UWB devices without cognitive capabilities, the power limitations specified with the published spectral masks will remain as they are. For the cognitive UWB radios, however, we expect the regulatory agencies to provide additional freedom for the transmitted power. A motivating example is the fact that the Spectrum Policy Task Force (SPTF) of the FCC has already been considering alternative ways of allocating the spectrum

[15]. By raising the power level, it is aimed to free the UWB devices from being restricted to short range applications.

Being able to implement both, cognitive UWB-OFDM systems decide between UWB-OFDM and opportunistic usage according to the conditions. One of the main decision criteria is that UWB-OFDM can make instant changes in the spectrum it occupies by turning on and off some carriers depending on the spectrum usage of licensed systems. Opportunistic usage, on the other hand, requires that a band is scanned by a number of cognitive radios, remains available for a certain time, and satisfies some spectral quality conditions; and, hence, is not suitable for speedy changes.

Opportunistic usage may be especially attractive for applications that require a high quality-of-service (QoS) because of its high transmit power and wide band usage (relative to narrowband systems). Also, if the available bands, which may be targeted for either UWB-OFDM or opportunistic usage, are at high frequencies, the latter can be a better option because of the higher energy absorbtion of the channel at those frequencies.

Although, in general, opportunistic usage seems to be more advantageous and desirable than UWB-OFDM, in certain scenarios, such as the ones listed below, cognitive UWB radios may have to select UWB-OFDM.

- If some primary users have a frequency hopping signal and, hence, the spectral conditions are changing very fast, the cognitive radio may not able to keep track of the spectrum opportunities and it can switch to UWB-OFDM.
- If the primary user is time hopping, cognitive radio might need to monitor the spectrum for an extra long time frame and may still not determine the timing sequence, or may be unable to adapt itself to continuously changing spectrum.
- If the primary user is mobile (or steadily moving in a certain area), it may be risky to use the spectrum opportunistically because the communication of the primary system can be easily disturbed. Hence, UWB-OFDM can be employed.
- The bands open to opportunistic usage may be too much divided by narrowband systems (into a number of separated narrow bands), leading to extra long pulses in time. Again, in this case UWB-OFDM can be preferable.
- If numerous licensed users join and leave the spectrum in a frequent manner (like in a GSM band), opportunistic usage may not be feasible.
- Opportunistic usage requires setting a threshold in order to determine whether a certain band is occupied. If the noise floor in a band is changing continuously, it may not be possible to determine a reliable threshold, and UWB-OFDM may be preferred.
- Gray bands (the bands in which the noise temperature is not as low as in the white bands) can be a potential target for UWB-OFDM.
- If the spectrum sensing results from different nodes in a cognitive network do not match to a large extent, this may indicate that either some of the nodes are being shadowed (and can not detect primary users) or the spectrum sensing information of some nodes can not be transmitted (or detected) correctly. In both cases, as a precaution, switching to UWB-OFDM can be reasonable.
- Even if there is an adequate amount of spectrum open to opportunistic usage, the number of cognitive users that target at this spectrum might be too high, forcing some of these users to switch to UWB-OFDM.

## V. CONCLUSIONS AND FUTURE RESEARCH

In this paper, the a cognitive UWB-OFDM approach that makes use of both OFDM based UWB and opportunistic usage is proposed. The resistance of UWB-OFDM against interference caused by licensed systems is investigated. The opportunity concept is defined in detail. Different spectrum shaping methods are discussed. Related future research topics include determining the performance of cognitive UWB-OFDM systems under different spectral conditions, and the implementation of spectrum sensing information exchange between cognitive nodes in a cognitive network.

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