Multicarrier Communication and Cognitive Radio

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ABSTRACT
In this article, we review different multicarrier communication methods for cognitive radio (CR) systems. Cognitive radio is an exciting and promising effort for solving the spectrum crowding problem. There, the secondary users (SUs) need to dynamically and reliably determine spectral holes and transmit data in these resources without interfering with other parts of the frequency band. To determine free spectral portion, each SU has to be equipped with a spectrum analyzer (spectrum sensing). To ovoid from interfering with other band, it is widely accepted that a multicarrier modulation technique should be adopted (spectrum shaping). Multicarrier modulation, in particular Orthogonal Frequency Division Multiplexing (OFDM), has been successfully applied to a wide variety of digital communications applications over the past several years. In the following, we present some of the requirements for cognitive radios and explain how OFDM can fulfill these requirements (further, spectrum sensing and shaping).

1 INTRODUCTION

With emerging technologies and with the ever increasing number of wireless devices, the radio spectrum is becoming scarcer every day. On the other hand, measurements show that wide ranges of the spectrum are rarely used most of the time while other bands are heavily used. However, those unused portions of the spectrum are licensed and thus cannot be utilized by users other than the license owners. Hence, there is a need for a novel technology that can benefit from these opportunities. Cognitive radio arises to be a tempting solution to spectral crowding problem by introducing the opportunistic usage of frequency bands that are not heavily occupied by licensed users. It can be defined as an intelligent wireless system that is aware of its surrounding environment through sensing and measurements; a system that uses its gained experience to plan future actions and adapt to improve the overall communication quality and meet user needs. One main aspect of cognitive radio is its ability to exploit unused spectrum to provide new ways of communication. Hence, cognitive radio should have the ability to sense and be aware of its operational environment, and dynamically adjust its radio operating parameters accordingly. For cognitive radio to achieve this objective, the Physical Layer (PHY) needs to be highly flexible and adaptable. A special case of multicarrier transmission known as OFDM is one of the most widely used technologies in current wireless communications systems and it has the potential of fulfilling the aforementioned requirements of cognitive radios inherently or with minor changes. By dividing the spectrum into sub-bands that are modulated with orthogonal subcarriers, OFDM removes the need for equalizers and thus reduces the complexity of the receiver. Because of its attractive features, OFDM has been successfully used in numerous wireless technologies including Wireless Local Area Network (WLAN), Wireless Metropolitan Area Network (WMAN), and the European Digital Video Broadcasting (DVB). It is believed that OFDM will also play an important role in realizing cognitive radio concept by providing a proven, scalable, and adaptive technology for air interface. In this chapter, the application of OFDM to cognitive radio is discussed. We identify the advantages of OFDM over other technologies and provide challenges associated with its application to cognitive radio.

2 Basic OFDM System Model [1]

A simplified block diagram of a basic OFDM system is given in Figure 1. Ina multipath fading channel, due to the frequency selectivity, each subcarrier can have different attenuation. The power on some subcarriers may be significantly less than the average power because of deep fades. As a result, the overall BER may be dominated by a few subcarriers with low power levels. To reduce the degradation of system performance due to this problem, channel coding can be used prior to the modulation of bits. Channel coding can reduce the BER significantly depending on the code rate, decoder complexity, and SNR level among other factors. Interleaving is also applied to randomize the occurrence of bit errors and introduce system immunity to burst errors. Coded and interleaved data is then mapped to the constellation points to obtain data symbols. This step is represented by the modulation block of Figure 1. The serial data symbols are then converted to parallel data symbols which are fed to the Inverse Discrete Fourier Transform (IDFT) block to obtain the time domain OFDM symbols. Time domain samples can be written as:

$$x(n) = IDFT\{X(k)\} = \sum_{k=0}^{N-1} X(k)e^{j2\pi nk/N} \quad 0 \le n \le N \quad (1)$$

where $X(k)$ is the transmitted symbol on the kth subcarrier and N is the number of subcarriers. Time domain signal is cyclically extended to avoid residual Inter-Symbol Interference (ISI) from the previous OFDM symbols. Baseband digital signal is converted analog signal through the Digital-to- Analog Converter (DAC) block.

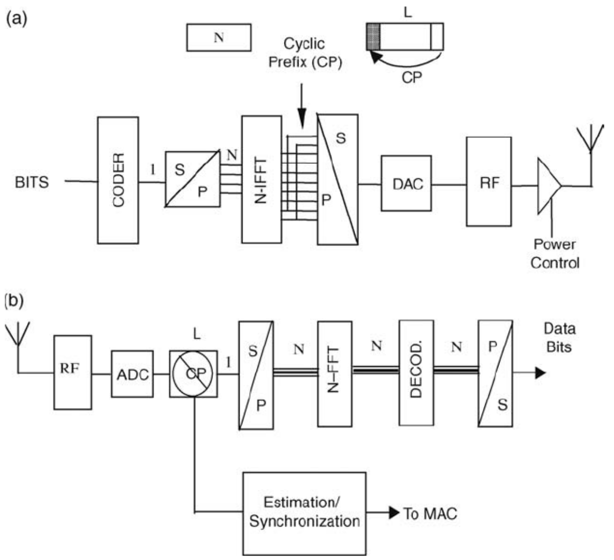

Fig. 1. (a) Transmitter block diagram and (b) receiver block diagram

Then, the signal is fed to the Radio Frequency (RF) frontend. The RF frontend up-converts the signal to the RF frequencies using mixers, amplifies it using Power Amplifiers (PAs), and transmits the signal through antennas. In the receiver side, the received signal is passed through a band-pass noise rejection filter and down-converted to baseband by the RF frontend. The Analog-to-Digital Converter (ADC) digitizes the analog signal and re-samples it. After frequency and time synchronization (which are not shown in the figure for simplicity), Cyclic Prefix (CP) is removed and the signal is transformed to frequency domain using the Discrete Fourier Transform (DFT) block. A simplified baseband model of the received symbols in frequency domain can be written as:

$$Y(k) = H(k)X(k) + W(k) \tag{2}$$

where $Y(k)$ is the received symbol on the kth subcarrier, $H(k)$ is the frequency response of the channel on the same subcarrier, and $W(k)$ is the additive noise plus interference sample which is usually assumed to be a Gaussian random variable with zero mean and variance of σ^2_w. Note that OFDM converts the convolution in time domain into multiplication in frequency domain, and hence simple one-tap frequency domain equalizers can be used to recover the transmitted symbols. After DFT, symbols are demodulated, deinterleaved, and decoded to obtain the transmitted information bits. Figure 2 shows a typical OFDM waveform in frequency domain. The figure shows the orthogonal subcarriers that modulates the transmitted data. For a given bandwidth, the communication channel affects some of the design parameters of the OFDM system. The main parameters of an OFDM system are the symbol time, subcarrier spacing (or consequently the number of subcarriers), and CP length. The transmitted signal usually arrives at the intended receiver either directly (what is

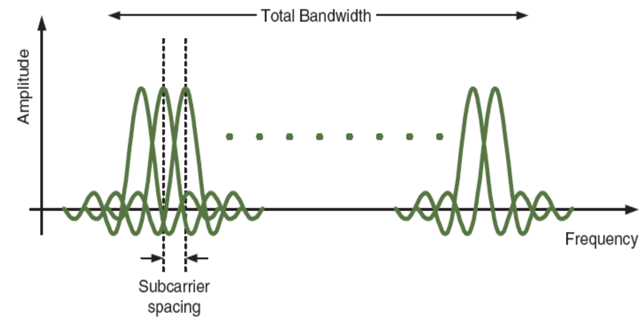

Fig. 2. OFDM waveform.

called Line-of-Sight (LOS) communication) or after being reflected on surfaces of buildings, cars, and other surroundings in the environment (also called as None-Line-of-Sight (NLOS)). As a result of the signal being reflected on multiple surfaces, the received signal becomes a sum of the transmitted signal with different delays and gains corresponding to the multiple paths the signal travels through. Such a channel is usually referred to as multipath channel (see Figure 3).

of the signal equally which results in distortion of the received signal. On the other hand, ISI is the interference between consequent OFDM symbols. Due to receiving multiple copies of the signal with different delays, a symbol can leak part of its energy into the following symbol. If not dealt with, both frequency selective fading and ISI can result in a significant degradation of system performance.

Channel equalizers are usually used to compensate multipath effects. Equalizers can considerably increase the system complexity as their complexity increases depending on the number of channel paths. In OFDM system, however, the need for equalizers can be avoided by careful system design. To avoid ISI, symbols duration are extended by adding a guard band to the beginning of each symbol in what is known as CP. If we define the delay spread (or multipath spread) of the channel as the delay between the first and last received paths over the channel, the CP should be longer than that delay. On the other hand, frequency selective fading is avoided by decreasing the subcarrier spacing or consequently increasing the number of subcarriers. We define the channel coherence bandwidth as the bandwidth over which the channel could be considered flat. Since ODFM signal can be considered as group of narrow band signals, by increasing the number of subcarriers, the bandwidth of each subcarrier (subcarrier spacing) becomes narrower. By choosing the subcarrier spacing to be less than the coherence bandwidth of the channel, each subcarrier is going to be affected by a flat channel and thus no channel equalization is needed. Another channel effect that should be considered in OFDM system design is mobility. For fixed communication systems, the channel can be considered constant over time.

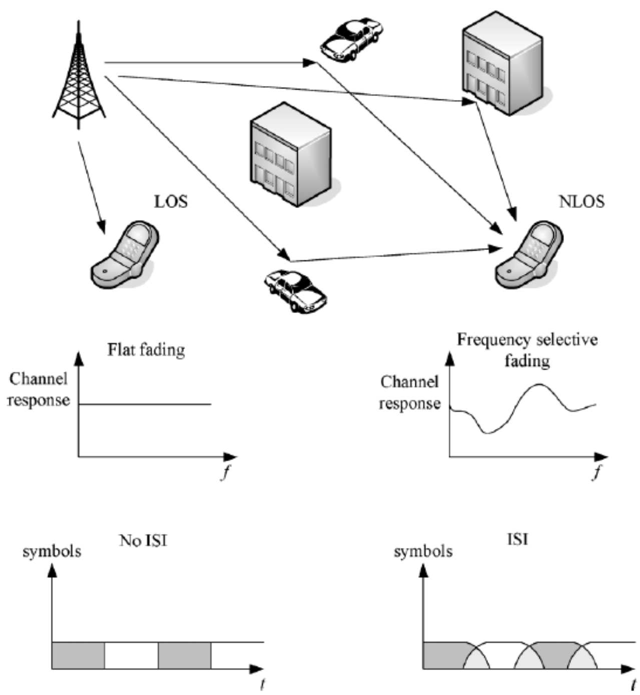

Fig. 3. Illustration of multipath fading.

However, if either transmitter or receiver is mobile, the channel is going to vary over time resulting in fast fading of the received signal. Coherence time of the channel is defined as the time over which the channel is considered constant. To avoid fast fading effect, OFDM symbol time is chosen to be shorter than the coherence time of the channel. In the frequency domain, mobility results in a frequency spread of the signal which dependents on the operating frequency and the relative speed between the transmitter and receiver, also know as Doppler spread [2]. Doppler spread of OFDM signals results in Inter-Carrier Interference (ICI) which can be reduced by increasing the subcarrier spacing. In conclusion, while increasing the symbol time reduces ISI effect, shorter symbol time is desirable to avoid fast fading of the signal. And while decreasing subcarrier spacing reduces ICI, narrower subcarrier spacing helps avoiding frequency selectivity. As a matter of fact, there exists an optimum value of these parameters that should be used to improve the system performance [3].

3 OFDM-BASED COGNITIVE RADIO

Application of OFDM to cognitive radio brings about new aspects and challenges to system design. The cognitive OFDM conceptual model considered in this chapter is shown in Figure 4. The cognitive engine is responsible for making the intelligent decisions and configuring the radio and PHY parameters. The spectral opportunities are identified by the decision unit based on the information from policy engine as well as local and network spectrum sensing data.

The policy engine provides information to the cognitive engine concerning the current policies to be considered depending on the system location. This will ensure that the cognitive radio will not use illegal waveforms or breach any policies. On the other hand, the local spectrum sensing unit process the spectrum information and identify licensed users accessing the spectrum, their signal specifications such as the their bandwidth and power level, and detect spectrum opportunities that can be exploited by cognitive radio.

Once the required information is available, the decision unit can make a conclusion on the best course of action for the system. The decision includes choosing the appropriate channel coding, modulation, operation frequencies, and bandwidth. At this stage, OFDM technology gets the upper hand over other similar transmission technologies with its adaptive features and great flexibility. By only changing the configuration parameters of OFDM (see Table 1 for some example parameters) and radio, the cognitive system can communicate with various radio access technologies in the environment, or it can optimize the transmission depending on the environmental characteristics.

The radio circuit is divided into a digital part (digital IF, ADC, and DAC) and an analog part (software tunable analog radio). Both parts are reconfigurable by the cognitive engine to increase the flexibility of the system. This includes controlling the operating frequency, bandwidth, filters, and mixers. Even antenna parameters (e.g. number of antennas, beam forming) can be configured to improve the system performance.

4 Why OFDM is a Good Fit for Cognitive Radio

The underlying sensing and spectrum shaping capabilities together with flexibility and adaptiveness make OFDM probably the best candidate for cognitive radio systems. In the following, we present some of the requirements for cognitive radios and explain how OFDM can fulfill these requirements.

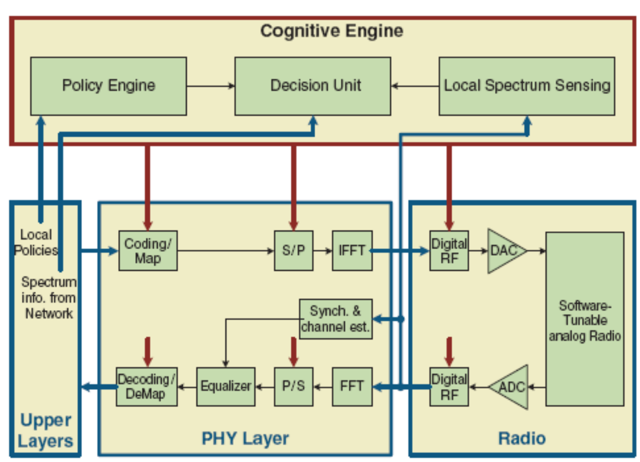

Fig 4. OFDM-based Cognitive radio system block diagram.

Standard	IEEE 802.11(a/g)	IEEE 802.16(d/e)	IEEE 802.22	DVB-T
FFT size	64	128, 256, 512, 1024, 2048	1024, 2048, 4096	2048, 8192
CP size	1/4	1/4, 1/8, 1/16, 1/32	Variable	1/4, 1/8, 1/16, 1/32
Bit per symbol	1, 2, 4, 6	1, 2, 4, 6	2, 4,	2, 4, 6
Pilots	4	Variable	696, 192, 384	62, 245
Bandwidth (MHz)	20	1.75 to 20	6, 7, 8	8
Multiple accessing	CSMA	OFDMA /TDMA	OFDMA /TDMA	N/A

Table 1. OFDM-based wireless standards.

4.1 Spectrum Sensing and Awareness

Cognitive radio should be able to scan the spectrum and measure different channel characteristics such as power availability, interference, and noise temperature [4]. In addition, the system should be able to identify different users' signals in the spectrum and also identify if they are either licensed or rental users. These abilities allow cognitive radio system to identify unused parts of the spectrum and spectral opportunities. However, since for a rental system it is important not to interfere with other licensed systems using the spectrum, other measures should be taken to guarantee an interference-free communication between rental users. One approach is to share the spectrum sensing information between multiple cognitive radio devices to decrease or even eliminate the probability of interference with licensed users. On the other hand, more sophisticated algorithms can be used for sensing the spectrum.

While the efficiency of the spectrum sensing and analyzing process is important for a successful implementation of cognitive radio, the processing time can be even more important. The periodicity of spectrum sensing should be short enough to allow for detection of new spectrum opportunities and, at the same time, to detect licensed users accessing the previously-identified-as unused parts of the spectrum. On the other hand, if spectrum sensing is done so frequently, the overhead of sharing such information will increase reducing the spectrum efficiency of the whole system not to mention the increase in system complexity. In OFDM systems, conversion from time domain to frequency domain is achieved inherently by using DFT. Hence, all the points in the time–frequency grid can be scanned without any extra hardware and computation because of the hardware reuse of Fast Fourier Transform (FFT) cores. Using the time–frequency grid, the selection of bins that are available for exploitation (spectrum holes) can be carried out using simple hypothesis testing. The DFT outputs can be filtered across time and frequency dimensions to reduce the uncertainty in detection as well. Note that the resolution of the frequency grid is dependent on subcarrier spacing.

4.2 Spectrum Shaping

After a cognitive radio system scans the spectrum and identifies active licensed users and available opportunities, comes the next step: spectrum shaping. Theoretically, it is desired to allow the cognitive users to freely use available unused portions of the spectrum. Cognitive users should be able to flexibly shape the transmitted signal spectrum. It is desired to have control over waveform parameters such as the signal bandwidth, power level, center frequency, and most of all a flexible spectrum mask. OFDM systems can provide such flexibility due to the unique nature of OFDM signaling. By disabling a set of subcarriers, the spectrum of OFDM signals can be adaptively shaped to fit into the required spectrum mask. Assuming the spectrum mask is already known to the cognitive radio system, choosing the disabled subcarriers is a relatively simple process [5].

The main parameters of an OFDM system that can be used to shape the signal spectrum are number of subcarriers, subcarrier's power, and pulse shaping filters. Increasing the number of subcarriers for a fixed bandwidth allows the OFDM system to have a higher resolution in the frequency domain. However, this results in increasing the complexity of the FFT operations and thus increasing the overall system complexity. Subcarrier power can be used to shape the signal into the desired mask. One reason to assign subcarriers different powers is to better fit into the channel response. For example, subcarriers with higher SNR values can be assigned lower power than those with lower SNR to improve the overall system BER. Another reason is to reduce the adjacent channel interference from an OFDM system by reducing the power assigned to edge subcarriers. An example of spectrum sensing and shaping procedures in OFDM-based cognitive radio systems is illustrated in Figure 5. Two licensed users are detected using the output of FFT block, and subcarriers that can cause interference to

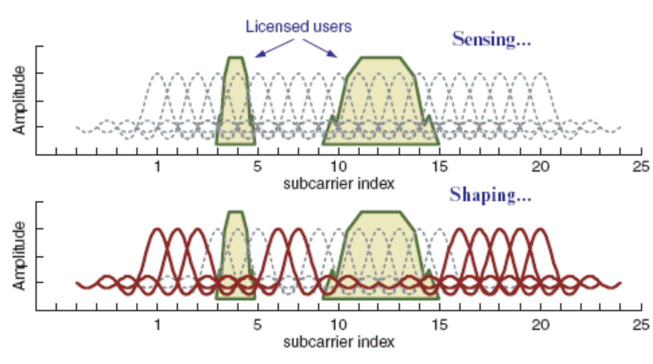

Fig. 5. Spectrum sensing and shaping using OFDM.

licensed user are turned off. The transmitter then uses the free parts of the spectrum for signal transmission. In addition, pulse-shaping filters can also be used to reduce the interference to adjacent bands. More discussions on reducing interference is introduced in Section 5.

4.3 Advanced Antenna Techniques

Advanced antenna techniques are not necessarily required for cognitive radios. However, they are desirable as they will provide better spectral efficiency which is the primary motivation for cognitive radio. Smart antennas and MIMO systems can be used to exploit the spatial dimension of spectrum space (e.g. through beam forming) to improve the efficiency. In essence multi-antenna systems can help to find spectral opportunities in the spatial domain and can help to exploit these opportunities in full. The use of MIMO techniques offers several important advantages including spatial degree of freedom, increased spectral efficiency and diversity [6]. These advantages can be used to increase the spectrum utilization of the overall system. Furthermore, beamforming, diversity combining, and space-time equalization can also be applied to cognitive OFDM systems. Another application of adaptive antenna techniques is the reduction of the interference in OFDM systems [7].

MIMO systems commonly employ OFDM as their transmission technique because of the simple diversity combination and equalization, particularly at high data rates. In MIMO–OFDM, the channel response becomes a matrix. Since each tone can be equalized independently, the complexity of space–time equalizers is avoided and signals can be processed using relatively straightforward matrix algebra. Moreover, the advantages of OFDM in multipath are preserved in MIMO–OFDM system as frequency selectivity caused by multipath increases the capacity.

4.5 Multiple Accessing and Spectral Allocation

The resources available to a cognitive system often have to be shared among users. Several techniques can be used to achieve such tasks. OFDM supports the well-known multiple accessing techniques such as TDMA, FDMA, and CSMA. Moreover, CDMA can also be used together with OFDM for multiplexing different users, in which case the transmission is known as Multicarrier Code Division Multiple Access (MC–CDMA) or Multicarrier Direct Spread Code Division Multiple Access (DS–CDMA) [5]. OFDMA, a special case of FDMA, has gained tremendous attention recently with its usage in fixed and mobile Worldwide Interoperability for Microwave Access (WiMAX). In OFDMA, subcarriers are grouped into sets each of which is assigned to a different user. Interleaved, randomized, or very flexible multiple accessing and spectral allocation capability for cognitive radios without any extra complexity or hardware. The allocation of subcarriers can be tailored according to the spectrum availability. The flexibility and support of OFDM systems for various multiple accessing enables the interoperability and increases the adoption of cognitive radio as well.

4.6 Interoperability

Another desirable feature of cognitive radio is interoperability. Interoperability can be defined as *the ability of two or more systems or components to exchange information and to use the information that has been exchanged* [8].

Since cognitive radio systems have to deal with licensed users as well as other cognitive users, the ability to detect and encode existing users' signals can expedite the adoption and improve the performance of cognitive radio systems. Furthermore, some recent unfortunate events manifested the importance of interoperability in terms of wireless communications for the first responders. For interoperability problems, cognitive radio can improve the disaster relief operations by developing the coordination between first responders. For such tasks, OFDM is one of the best candidates as OFDM signaling has been successfully used in various technologies. Systems based on OFDM include 802.11a and 802.11g Wireless LAN standards, Digital Audio Broadcasting (DAB), DVB, and WiMAX. Only the knowledge of the signal parameters used by the desired users will be needed (see Table 1). However, for such task to be successful, the cognitive radio system should be built around a software defined radio architecture. In addition, the cognitive radio system should have all the standard-related information required to decode other signals, such as the data and pilot mapping to the frequency subcarriers, frame structure and the coding type and rate.

5 Challenges to Cognitive OFDM Systems

As an intelligent system with features such as awareness, adaptability and learning, cognitive radio represents the future of wireless systems with the promise of offering solutions to various communication problems as outlined in the previous section. However, with this new technology, new challenges appear, raising interesting research topics. In the considered OFDM-based cognitive radio systems, the challenges can be grouped into three categories as illustrated in Figure 6.

The first category includes the challenges that are unique to classical OFDM systems including Peak-to-Average Power

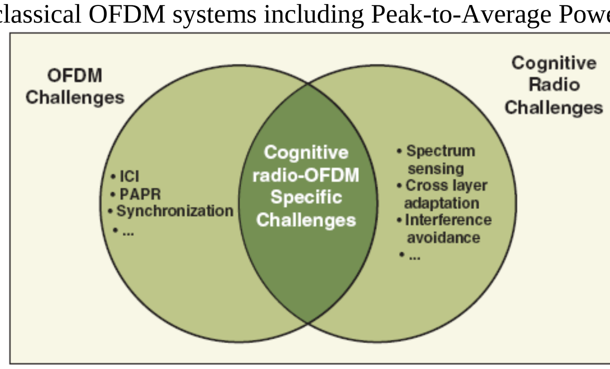

Fig. 6. Research challenges in cognitive radio and OFDM

Ratio (PAPR), sensitivity to frequency offset and phase noise, synchronization, etc. The second category includes problems faced by all cognitive radios such as spectrum sensing, cross layer adaptation, and interference avoidance. Our main focus in this chapter is on the third category: challenges that arise when OFDM technique is employed by cognitive radio systems. In the following, some challenges and approaches for solving them are given.

5.1 Spectrum Shaping

One of the main challenges in OFDM cognitive radio systems is spectrum shaping. In OFDM-based systems, spectrum shaping means determining the subcarriers to be used by the OFDM system while keeping the interference to and from primary users at a negligible level. Once spectrum sensing information is acquired, this knowledge should be utilized to select the subcarriers to be used by the secondary/cognitive users. This problem is addressed in by using energy detectors over each subcarrier. Moreover, a detection criterion is used to determine used subcarriers. Spectrum sensing is directly related to the sensing problem for spectrum hole identification. However, cognitive radio might prefer to skip some opportunities depending on the power and network traffic requirements.

5.2 Effective Pruning Algorithm Design

Once the subcarriers to be used are determined, there might be many subcarriers that are deactivated. In such a case, the efficiency of FFT algorithms can be increased and/or execution time can be decreased by removing operations on input values which are zero, a process known as pruning. Designing effective pruning algorithms is important for cognitive OFDM systems for achieving higher performance. Specific implementation of pruning technique for CR-OFDM systems is discussed in [9].

5.3 Signaling the Transmission Parameters

OFDM system can adjust its waveform by turning off some subcarriers in order to exploit the available spectrum holes (see Figure 11.5). The receiver, however, should be informed about subcarriers that are deactivated and that are to be used. Signaling of this information should be performed carefully in order to prevent interference to primary users while keeping the bandwidth loss at minimum. Detection of those unused subcarriers can also be performed blindly. However, to the best knowledge of the authors, no work in this area has been done yet. One method to reduce the overhead due to signaling is proposed in. The activation/deactivation of subcarriers is performed over a block of subcarriers instead of each individual subcarrier. Hence, the signaling overhead can be reduced by a factor of each block's size. Moreover, depending on the channel quality and available resources, parameters like FFT size, CP size, etc. can be changed and this information should also be conveyed to the receiver.

5.4 Synchronization

Synchronization is another important issue that needs to be addressed in OFDM system design. With the introduction of cognitive radio, new aspects are introduced to the problem. The NBI, which can interfere with the preamble, is one of the problems. Furthermore, the incomplete subcarrier set might be an issue for preambles, and pilots might fall into unused subcarriers if used. Moreover, if multiple user accessing is employed, the subcarriers can be assigned to different users. To keep the orthogonality between subcarriers and avoid interference, all users should be synchronized to the receiver. In [10], it is shown that longer preambles are needed in CR-OFDM systems as compared to conventional systems. Moreover, new preamble structures are introduced and their performance for time and frequency synchronization is investigated.

5.5 Mutual Interference

Mutual interference should be carefully considered when designing cognitive radio systems. The side lobes of modulated OFDM subcarriers are known to be large as shown in Figure 7. As a result, there will be power leakage from used subcarriers to nulled subcarriers which causes interference to the licensed users. Various methods are proposed in the literature to reduce this leakage and to enable co-existence of cognitive-OFDM systems with primary license owner systems. One method is to make the *sinc* function (see Figure 8) decay faster by windowing the time domain OFDM samples [4,11].

Similar techniques have already been investigated to reduce ICI and out-ofband radiation in OFDM systems [30, 31]. In, a raised-cosine window is applied. By changing the roll-off factor of the raised-cosine window, interference reduction of upto 6 dB has been achieved. Figures 8 and 9 show way the interference can be greatly reduced as most of the interference comes from the neighboring subcarriers.

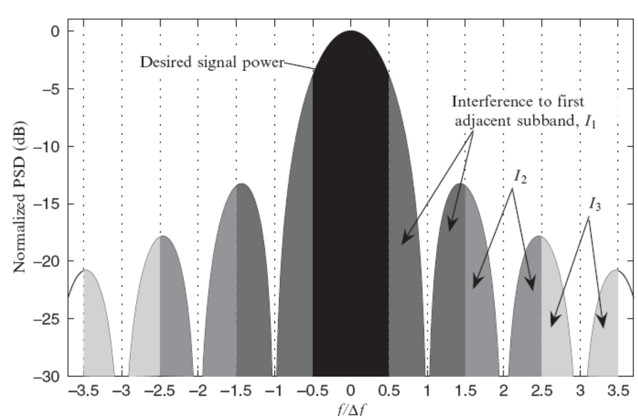

Fig. 7. Power spectrum density of a single OFDM subcarrier.

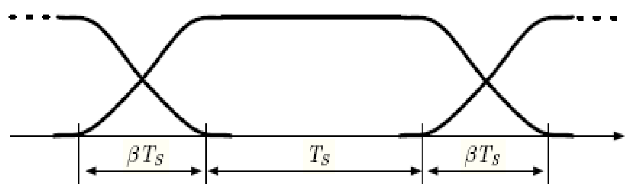

Fig. 8. Raised cosine windowing with different roll-off (β) values.

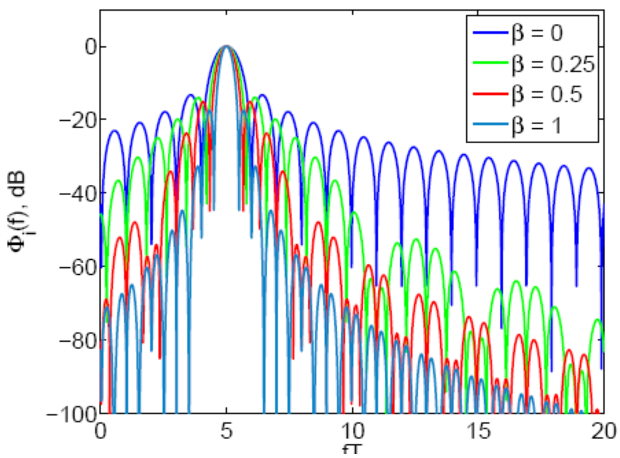

Fig. 11.10. Roll-off effect on the PSD of a single OFDM subcarrier.

However, the obvious disadvantage of this method is the reduction of spectral efficiency. Instead of deactivating the neighboring subcarriers, their values can be determined actively in order to cancel the interference in the deactivated bands. This technique is proposed in and referred to as active interference cancellation and cancellation carriers, respectively. It is shown that the performance can be improved, however, determination of the values for cancellation subcarriers is complex as it requires optimization. One last method for reducing the interference to and from the narrowband primary users is subcarrier weighting. In this method, the subcarrier weights are determined in such a way that the sidelobes of the transmission signal are minimized according to an optimization algorithm which allows several constraints. This way, more than 10 dB reduction in the sidelobes of OFDM signal can be achieved. Note that subcarrier weighting requires constant envelope modulation such as BPSK or QPSK. Moreover, the receiver does not need to know the weighting sequence as the phase information is not changed. In addition to the aforementioned challenges, there are other issues for practical implementation of OFDM cognitive radio systems. While cognitive radio is such a promising technology, more research is needed to build a practical system with affordable complexity.

6 Multi-band OFDM

In previous sections, only Single-Band OFDM (SB OFDM) systems were considered. In this section, using OFDM signaling over multiple bands is discussed along with the advantages and motivations of using Multi-band OFDM (MBOFDM). The proposition of MB-OFDM for UWB is addressed. However, the discussion of MB-OFDM is not limited to one application but rather it is presented from a broader point of view.

For systems utilizing wide bands of the spectrum, multi-band signaling approach –where the total bandwidth is divided into smaller bands– can prove to be more advantageous over using single band signaling. While using a single band simplifies the system design, processing a wide band signal requires building highly complex RF circuitry for signal transmission/reception. In addition, high speed ADCs are required to sample and digitize the signal.

Moreover, higher complexity channel equalizers are also needed to capture sufficient multipath signal energy for further processing. On the other hand, multi-band signaling relaxes the requirements on system hardware as smaller portions of the spectrum are processed at a time. Furthermore, dividing the spectrum into smaller bands allows for better spectrum allocation. The system can drop some of the available bands to achieve other goals (e.g. avoid interference, save power, allow for multiuser accessing). For OFDM-based cognitive radio, the question becomes when to use multiband and when to use single band. Given a certain scanned spectrum shape, choosing the number of bands depends on various parameters. Required throughput, hardware limitations, computational complexity, number of spectrum holes and their bandwidths, and interference level are examples of what could affect cognitive system's choice. We further illustrate the importance of multi-band signaling with the next example.

Consider the scenario, where a cognitive radio senses the spectrum and finds the results shown in Figure 10. Two spectrum holes are detected with 10 and 15 MHz bandwidth. One of the spectrum holes contains narrow band interference. The detected vacancies in the spectrum are 1 GHz apart. In such scenario, if the system chooses to use SB-OFDM, then the bandwidth of the OFDM signal is going to be 1.025 GHz. A signal with such bandwidth requires ADCs with very high sampling rate capability. In addition, a large number of subcarriers is required to guarantee that subcarriers can better fit into the spectrum holes as well as to keep the subcarrier's channel relatively flat. Unfortunately, large number of subcarriers results in a more complex FFT operation. Moreover, in order to avoid the narrow band interference in the 15 MHz band, the system drops two out of three subcarriers that are used to fill the spectrum hole, resulting in a low spectrum efficiency. By using MBOFDM, the spectrum holes can be filled with two OFDM signals with 15 and 10 MHz bandwidths. Hence, ADCs with practical sampling rates can now be used. A large number of subcarriers is not necessary for either OFDM signals in that case. In addition, the system has more control over the signal spectrum in each band due to the small subcarrier spacing. Hence, avoiding narrow band interference is done with lower spectrum loss. However, the system is now processing two OFDM signals.

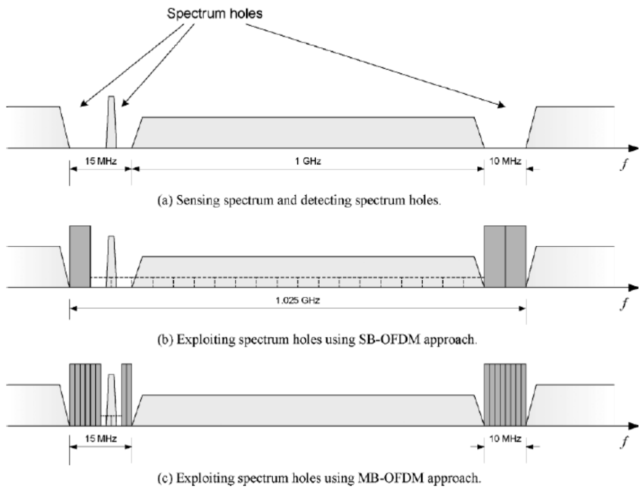

Fig. 11.11. Filling spectrum holes using SB-OFDM or MB-OFDM signals.

While sampling frequency is reduced in MB-OFDM case, the system is performing receiver algorithms (e.g. synchronization, channel estimation, and equalization) separately for each band.

7 Conclusion

Cognitive radio is an exciting and promising effort for solving the spectrum crowding problem. On the other hand, OFDM technique is used in many wireless systems and proven as a reliable and effective transmission method.

OFDM can be used for realizing cognitive radio concept because of its inherent capabilities that are discussed in detail in this chapter. By employing OFDM transmission in cognitive radio systems; adaptive, aware and flexible systems that can interoperate with current technologies can be realized. However, the identified challenges need to be studied further in order to find solid solutions.

The adoption of OFDM in cognitive radios may happen in two ways: current wireless technologies might evolve to have more and more cognitive features or new systems might be developed that has full cognitive features. In either case, we foresee that OFDM will be the dominant PHY technology for cognitive radio.

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