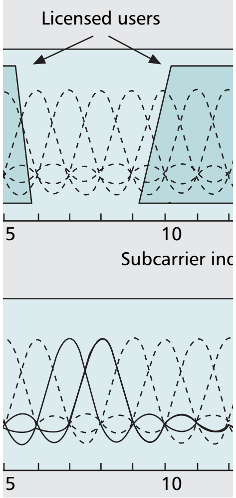
ACCEPTED FROM OPEN CALL

OFDM FOR COGNITIVE RADIO: MERITS AND CHALLENGES

HISHAM A. MAHMOUD, TEVFIK YÜCEK, AND HÜSEYIN ARSLAN, UNIVERSITY OF SOUTH FLORIDA



The authors discuss CR systems and their requirement of a physical layer, and they investigate the orthogonal frequency division multiplexing technique as a candidate transmission technology for CR.

ABSTRACT

Cognitive radio is a novel concept that enables wireless systems to sense the environment, adapt, and learn from previous experience to improve the quality of the communication. However, CR requires a flexible and adaptive physical layer in order to perform the required tasks efficiently. In this article, CR systems and their requirement of a physical layer are discussed, and the orthogonal frequency division multiplexing technique is investigated as a candidate transmission technology for CR. The challenges that arise from employing OFDM in CR systems are identified. The cognitive properties of some OFDM-based wireless standards also are discussed to indicate the trend toward a more cognitive radio.

INTRODUCTION

With emerging technologies and with the increasing number of wireless devices, the radio spectrum is becoming increasingly congested. On the other hand, measurements show that wide ranges of the spectrum are rarely used most of the time, whereas other bands are used heavily. Depending on the location, time of the day, and frequency bands, the spectrum actually is underutilized. However, those unused portions of the spectrum are licensed and thus cannot be used by systems other than the license owners. Hence, there is a need for a novel technology that can benefit from these opportunities. Cognitive radio (CR) is a tempting solution to the spectral crowding problem through the introduction of the opportunistic usage of frequency bands that are not heavily occupied by licensed users (LUs) [1]. CR can be defined as an intelligent wireless system that is aware of its surrounding environment through sensing and measurements and that uses its gained experience to plan future actions and adapt to improve the overall quality of communication and meet the requirements of users.

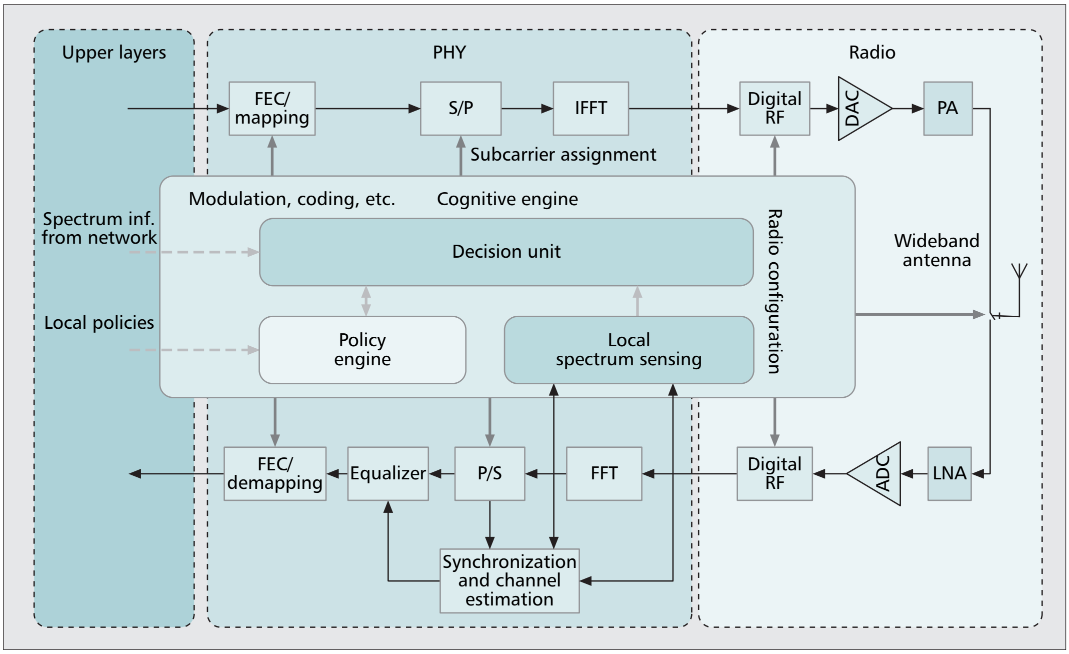
A main feature of CR is the autonomous exploitation of locally unused spectrum to improve spectrum utilization. Other features include interoperability across several networks, devices, and protocols; the capability of roaming across borders while remaining in compliance with local regulations; and the capability of adapting the system, transmission, and reception parameters without user intervention; as well as the ability to understand and follow actions taken and choices made by users in order to learn and become more responsive over time. The focus of this article is the ability of CR to sense and be aware of its operational environment and dynamically adjust its radio operating parameters accordingly. For CR to achieve this objective, the physical layer (PHY) must be highly flexible and adaptable. A special case of multi-carrier transmission known as orthogonal frequency division multiplexing (OFDM) is one of the most widely used technologies in current wireless communications systems. OFDM has the potential of fulfilling the aforementioned requirements of CR inherently or with minor modifications. Because of its attractive features, OFDM has been successfully used in numerous wireless standards and technologies. We believe that OFDM also will play an important role in realizing the concept of CR by providing a proven, scalable, and adaptive technology for air interface.

In this article, the OFDM technique is investigated as a candidate for CR systems. CR features and requirements are discussed in detail, and the ability of OFDM to satisfy these requirements is explained. In addition, we discuss the challenges that arise from employing OFDM technology in CR.

The article is organized as follows. In the next section, OFDM technology is introduced, and a basic system model for OFDM-based CR is presented. We then discuss the merits of OFDM technology and its advantages when employed by CR systems. Challenges to a practical OFDM-based CR system and possible solutions are addressed in the following section. We then look into present and future technologies that use OFDM with cognitive features. The final section concludes the article.

OFDM-BASED CR

OFDM is a multi-carrier modulation technique that can overcome many problems that arise with high bit-rate communications, the most serious of which is time dispersion. The data-bearing symbol stream is split into several lower-rate streams, and these streams are transmitted on different carriers. Because this splitting increases the symbol duration by the number of orthogo-



■ **Figure 1.** *OFDM-based CR system block diagram. All of the layers can interact with the cognitive engine. OFDM parameters and the radio are configured by the cognitive engine.*

The underlying sensing and spectrum shaping capabilities of OFDM, together with its flexibility and adaptivity, probably make it the best transmission technology for CR systems.

nally overlapping carriers (subcarriers), multipath echoes affect only a small portion of the neighboring symbols. The remaining inter-symbol interference (ISI) is removed by extending the OFDM symbol with a cyclic prefix (CP). Using this method, OFDM reduces the dispersion effect of multipath channels encountered with high data rates and reduces the requirement for complex equalizers. Other advantages of OFDM include high spectral efficiency, robustness against narrowband interference (NBI), scalability, and easy implementation using fast Fourier transform (FFT).

In this article, we assume a CR system operating as a secondary user in a licensed band. The CR system identifies available or unused parts of the spectrum and exploits them. The goal is to achieve maximum throughput while keeping interference to a minimum for primary/licensed users. An example of such a CR system could be the IEEE 802.22 standard-based system where the spectrum allocated for TV channels is reused. In this case, the TV channels are the primary users, and the standard-based systems are the secondary users (more details follow in later sections). A block diagram of the CR-OFDM system considered in this article is shown in Fig. 1.[1] The cognitive engine is responsible for making intelligent decisions and configuring the radio and PHY parameters. The transmission opportunities are identified by the decision unit based on the information from the policy engine, as well as local and network spectrum sensing data. As far as the PHY layer is concerned, CR can communicate with various radio-access technologies in the environment, or it can improve the quality of communication depending on the environmental characteristics, by simply changing the configuration parameters of the OFDM system (see Table 1 for example parameters) and the radio frequency (RF) interface. Note that coding type, coding rate, interleaver pattern, and other medium access control (MAC) and higher layer functionalities, and so on, should also be changed accordingly.

Why OFDM is a Good Fit for CR

The underlying sensing and spectrum shaping capabilities of OFDM, together with its flexibility and adaptivity, probably make it the best transmission technology for CR systems. In the following, we present some of the requirements for CR and explain how OFDM can fulfill these requirements. A summary and the strength of OFDM in meeting these requirements are presented in Table 2.

Spectrum Sensing and Awareness

One of the most important elements of the CR concept is the ability to measure, sense, learn, and be aware of important operating conditions. This includes parameters related to the radio channel characteristics, availability of spectrum, interference temperature, and the radio operational environments. In addition, the system should be aware of user requirements and applications, available network infrastructures and nodes, and local policies and other operating restrictions. CR must identify and exploit the unused parts of the spectrum in a fast and efficient way. In OFDM systems, conversion from time domain to frequency domain is achieved by using FFT. Hence, all the points in the time-frequency grid of the operating band of the of the OFDM system can be scanned without any extra hardware or computation due to the reuse of the hardware of the FFT cores. Using the time-frequency grid, a the selection of bins that are available for exploitation (spectrum holes) can be carried out using simple hypothesis testing. In [2, 3], FFT is applied to the received signal. By using the output of FFT, the receiver tries to detect the

---

[1] *Some OFDM functions are ignored or simplified in order to simplify the figure.*

[2] *For more details and for more advanced algorithms, see the next section (Adapting to the Environment).*

	Parameters					
Standard	**FFT size**	**CP Size**	**Bit per symbol**	**Pilots**	**Bandwidth**	**Multiple access**
IEEE 802.11 (a/g)	64	1/4 of FFT size	1, 2, 4, 6	4	20 MHz	CSMA[a]
IEEE 802.16 (d/e)	128, 256, 512, 1024, 2048	1/4, 1/8, 1/16, 1/32 of FFT size	1, 2, 4, 6	Variable	1.75 to 20 MHz	OFDMA[a]/TDMA[a]
IEEE 802.22	1024, 2048, 4096	variable	2, 4, 6	96, 192, 384	6, 7, and 8 MHz	OFDMA/TDMA
DVB-T	2048, 8192	1/4, 1/8, 1/16, 1/32 of FFT size	1, 2, 4, 6	62, 245	8 MHz	NA

[a] Carrier sense multiple accessing (CSMA), orthogonal frequency-division multiple access (OFDMA), time-division multiple access (TDMA)

Table 1. *OFDM-based wireless standards.*

existence of a primary user in the band. In [3], more than one FFT output (averaging in time) is used. However, averaging in time increases the delay or temporal overhead. In [4], the averaging size (number of FFTs) is adapted to increase the efficiency in a cooperative sensing environment. A primary user's signal usually is spread over a group of FFT output samples because the bandwidth of a primary user is expected to be larger than the considered bandwidth divided by the FFT size. Using this fact, the FFT output is filtered for noise averaging to obtain better performance [5]. In these sensing algorithms, the availability of FFT circuitry in OFDM systems eases the requirements on the hardware. Moreover, the computational requirements of the spectrum-sensing algorithm is reduced because the receiver already applies FFT to the received signal to transform the received signal into the frequency domain for data detection.

SPECTRUM SHAPING

After a CR system scans the spectrum and identifies active LUs, other rental users, and available opportunities, the next step is spectrum shaping. Ideally, it is desirable for cognitive users to use available bands in the spectrum freely. It is desirable to have a flexible spectrum mask and control over waveform parameters such as signal bandwidth, power level, and center frequency. 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 shaped adaptively to fit into the required spectrum mask.[2] Assuming the spectrum mask is already known to the CR system, choosing the disabled subcarriers is a relatively simple process.

An example of spectrum-sensing and shaping procedures in OFDM-based CR systems is illustrated in Fig. 2. The two LUs are detected using the output of the FFT block, and subcarriers that could cause interference with these LUs are turned off. The transmitter then uses the unoccupied part of the spectrum for signal transmission.

ADAPTING TO THE ENVIRONMENT

Adaptivity is one of the key requirements of CR. By combining gathered information (awareness) with knowledge of the current system capabilities and limitations, CR can perform various tasks. CR can adapt its waveform to interoperate with other friendly communication devices, choose the most appropriate communication channel or network for transmission, and allocate the best frequency to transmit in a free band of the spectrum. The system waveform also can be adapted to compensate for channel fading and null any interfering signal. OFDM offers a great deal of flexibility in this regard as the number of parameters for adaptation is quite large [6].

An OFDM-based system can adaptively change the modulation order, coding, and transmit power of each individual subcarrier based on user requirements or the channel quality [7]. This adaptive allocation can be optimized to achieve various goals such as increasing the system throughput, reducing bit-error rate (BER), limiting interference to LUs, increasing coverage, or prolonging unit battery life. In multiuser OFDM systems, the subcarrier allocation to users can be done adaptively, as well, to achieve the same goals [8].

One of the attractive features of OFDM for broadband communications is its ability to operate using simple one-tap equalizers in the frequency domain. To maintain this feature, the subcarrier spacing in set to be less than the channel coherence bandwidth. In addition, to avoid ISI, the system appends a CP to each symbol with a duration longer than the maximum channel-delay spread. Based on estimated channel parameters, an OFDM-based CR system can adaptively change the length of the CP to maintain an ISI-free signal while maximizing the system throughput [9].

Similarly, an OFDM system can adaptively change the subcarrier spacing to reduce intercarrier interference (ICI) or the peak-to-average-power ratio (PAPR) [9]; the data subcarrier interleaves to reduce BER [10] or even the used pilot patterns [11].

The adaptivity in OFDM systems can be performed either at the algorithm level or at the parameter level. In classical wireless systems, the algorithm parameters, for example, the coding rate, usually have been adapted to optimize the transmission. However, in cognitive OFDM systems, the algorithm type, for example, the channel coding type, also can be adapted to achieve interoperability with other systems and/or to fur-

CR requirements	OFDM's strength
Spectrum sensing	Inherent FFT operation of OFDM eases spectrum sensing in frequency domain.
Efficient spectrum utilization	Waveform can easily be shaped by simply turning off some subcarriers where primary users exist.
Adaptation/scalability	OFDM systems can be adapted to different transmission environments and available resources. Some adaptable parameters are FFT size, subcarrier spacing, CP size, modulation, coding, subcarrier powers.
Advanced antenna techniques	Techniques such as multiple-input multiple-output (MIMO) are commonly used with OFDM mainly because of the reduced equalizer complexity. OFDM also supports smart antennas.
Interoperability	With WLAN (IEEE 802.11), WMAN (IEEE 802.16). WRAN (IEEE 802.22), WPAN (IEEE 802.15.3a) all using OFDM as their physical layer techniques, interoperability becomes easier compared to other technologies.
Multiple accessing and spectral allocation	Support for multiuser access is already inherited in the system design by assigning groups of subcarriers to different users (i.e., OFDMA).
NBI immunity	NBI affects only some subcarriers in OFDM systems. These subcarriers can simply be turned off.

■ **Table 2.** *OFDM CR.*

ther optimize system performance. To achieve such adaptivity, a fully configurable hardware platform is required.

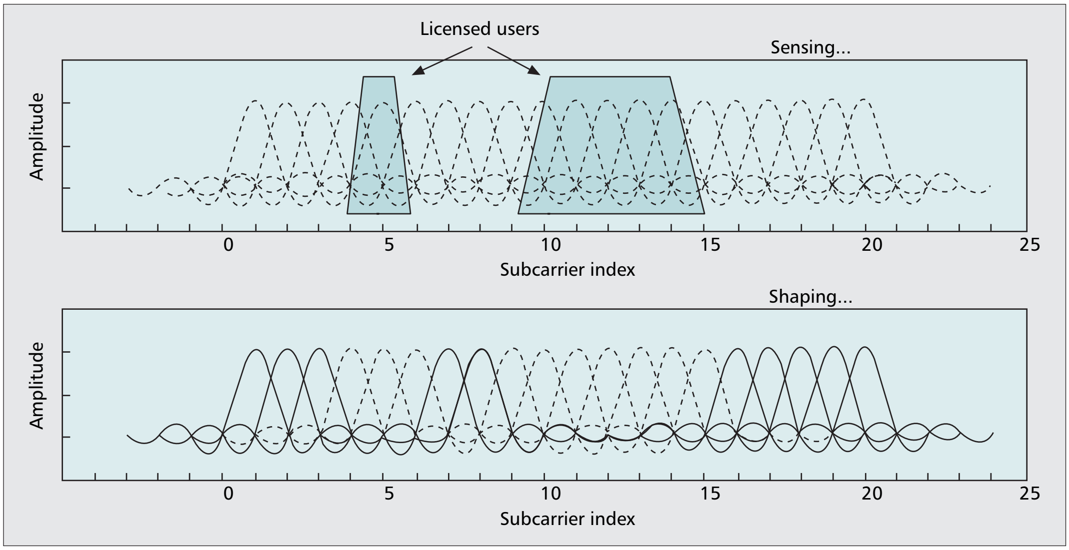
MULTIPLE ACCESSING AND SPECTRAL ALLOCATION

The resources available to a cognitive system must be shared among users. Several techniques can be used to accomplish this task. OFDM supports well-known multiple-accessing techniques such as time-division multiple access (TDMA), frequency-division multiple accessing (FDMA), and carrier-sense multiple accessing (CSMA). Moreover, code division multiple access (CDMA) can be used together with OFDM, in which case the transmission is known as multi-carrier code-division multiple access (MC-CDMA) or multi-carrier direct-spread code-division multiple access (DS-CDMA).

Orthogonal frequency-division multiple access (OFDMA), a special case of FDMA, gained significant 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 clustered subcarrier assignment schemes can be used. Therefore, OFDMA offers very flexible multiple accessing and spectral allocation capability for CR without extra hardware complexity. The allocation of subcarriers can be tailored according to the spectrum availability. The flexibility and support of OFDM systems for various multiple-accessing techniques enable interoperability and accelerate the adoption of CR in future wireless systems.

INTEROPERABILITY

Interoperability is defined as *the ability of two or more systems or components to exchange information and to use the information that was exchanged* [12]. Because CR systems may be required to deal with LUs, as well as other cognitive users, the ability to detect and encode existing users' signals can expedite the adoption and improve



■ **Figure 2.** *Spectrum sensing and shaping using OFDM.*

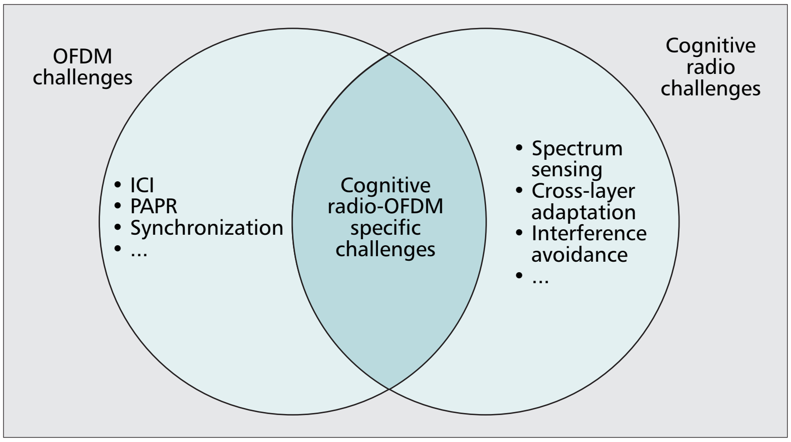


Figure 3. *Research challenges in CR and OFDM.*

the performance of CR systems. Furthermore, some recent and unfortunate disasters manifested the importance of interoperability of wireless communications for first responders. CR has the potential to improve disaster relief operations by developing coordination among first responders [13].

To achieve interoperability, OFDM is one of the best signaling candidates. OFDM signaling was successfully used in various technologies including IEEE 802.11a and IEEE 802.11g wireless local area network (LAN) standards, digital audio broadcasting (DAB), digital video broadcasting (DVB), and WiMAX. OFDM was used in both short-range and long-range communication systems. Hence, a CR system employing OFDM can communicate with systems using other OFDM-based technologies with great ease. The only requirement is knowledge of the signal parameters of the intended users (Table 1). However, for this task to be successful, the system must know all the standard, related information required to decode the signal, such as the data and pilot mapping to the frequency subcarriers, frame structure, and the coding type and rate. More importantly, the RF circuitry of the CR system must be flexible enough to accommodate different signal bandwidths and center frequencies. As a result, CR should be built around a software-defined radio architecture to provide the required flexibility to the system.

CHALLENGES TO COGNITIVE OFDM SYSTEMS

CR is an intelligent system with features such as awareness, adaptivity, and learning and represents the future of wireless systems with its promise of offering solutions to various communication problems. However, with new technology, new challenges appear that introduce interesting research topics. These challenges can be grouped into three categories as illustrated in Fig. 3. The first category includes the challenges that are unique to classical OFDM systems such as PAPR and sensitivity to frequency offset and phase noise. The second category includes problems faced by all CRs such as spectrum sensing, cross-layer adaptation, and interference avoidance. Our main focus in this article is on a third category: challenges that arise when the OFDM technique is employed by CR systems. In the following, we discuss major challenges to a practical system implementation, as well as some of the proposed approaches for solving these challenges.

MULTIBAND OFDM SYSTEM DESIGN

So far we have considered the more conventional, single-band systems. In single-band CR-OFDM systems, the available portion of the spectrum is occupied by a single OFDM signal. If LUs exist within the used band, the CR system shapes the OFDM signal so as to avoid interference to those users, as shown in Fig. 2. For systems utilizing wide bands of the spectrum, the multiband signaling approach — where the total bandwidth is divided into smaller bands — can prove to be more advantageous than using single-band signaling. This appears to be more significant if the detected, free parts of the spectrum are scattered over a relatively wide band. Whereas using a single band simplifies the system design, processing a wide-band signal requires the building of highly complex RF circuitry for signal transmission/reception. High-speed analog-to-digital converters (ADCs) are required to sample and digitize the wide-band signal. In addition, higher complexity channel equalizers are required to capture sufficient multipath signal energy for further processing. On the other hand, multiband signaling relaxes the requirements on system hardware because smaller portions of the spectrum are processed separately. Dividing the spectrum into smaller bands enables better spectrum allocation as well.

For OFDM-based CR, the question is 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 bandwidth, and the interference level are examples of what could affect the choice for a cognitive system.

It is worth mentioning that multiband OFDM (MB-OFDM) is employed in ultra-wide band (UWB) systems. Instead of using a single-band UWB signal, the spectrum is divided into subbands (of approximately 500-MHz bandwidth each), and OFDM signals are used to transmit data over each band [14]. However, although UWB is one of the applications of MB-OFDM, it is limited to a specific scenario where all subbands are of almost equal size, and OFDM signals used in the sub-bands have identical parameters such as CP size and subcarrier spacing.

From a practical point of view, designing a cost-effective, multiband transceiver with high performance has been studied in the literature [15–19]. On most proposed transceivers, direct conversion architecture is used to eliminate the requirement for image-rejection filters and to relax the bandwidth requirements for the baseband filters and converters [15, 16]. The challenges that face the implementation of a broadband, multiband OFDM system include the requirement for wide-range frequency synthesizers, broadband circuits, and matching the gain switch in the low-noise amplifier (LNA) without degrading the input match, broadband transmit/receive switch at the antenna, desensitization due to adjacent LU interferers, and fast-band hopping to avoid interference to occupied bands [17]. Frequency synthesizers that can operate in seven bands [18, 19], nine bands [16], and even 12 bands [17] were presented recently. If single-band transmission is employed, many subcarriers might be deactivated. In such a case, the efficiency of FFT algorithms can be increased, and the execution time can be decreased by removing operations on input values that are zero — a process known as pruning. Designing effective pruning algorithms, specific to CR-OFDM, is an important subject for achieving higher performance [20].

LOCATION AWARENESS

Geolocation information can be used to enable location-based services, optimize the network traffic, and adapt the transceiver to the environment. Applications utilizing location information can be grouped into four categories: location-based services, network optimization, transceiver algorithm development and optimization, and environment characterization. Although some existing wireless networks have a miniature utilization of location information, CR is expected to have a more comprehensive location information utilization [21, 22].

OFDM signaling can be used to obtain the geolocation information in CRs [23] without a requirement for external positioning systems. Pilot sequences (preambles), which are commonly used in OFDM systems for synchronization, can be used for acquisition and tracking of unit locations. In the literature, both time and frequency domain techniques are proposed to estimate the time of arrival (TOA) using the received OFDM signal. Existing wireless local area network (WLAN) systems are being studied for indoor positioning applications, whereas MB-OFDM-based UWB is proposed for high precision applications. Such positioning capabilities help OFDM to fulfill another requirement of CR.

SIGNALING THE TRANSMISSION PARAMETERS

In a CR system, communication units sense the surrounding environment and gather information that can be used to improve the communication link. Based on gathered information, the system selects transmission parameters such as LU bands, spectral mask, operating frequency, coding, and modulation. Although some of these parameters can be detected blindly by intended receivers, other parameters must be known prior to establishing a communication link. Distributing information among communication units, rather than using local sensing, reduces the complexity and improves the performance of the system. Thus, it is crucial for the success of CR to successfully distribute such information to other cognitive units.

One approach is to dedicate a communication channel to exchange measured information and transmission parameters among cognitive units. However, this requires that a channel be predefined (or licensed) for that purpose. As a result, the ability of cognitive units to operate adaptively within any given unlicensed band becomes dependent on the availability of such a channel. Moreover, as the number of units in the same cell increases, the amount of information that must be distributed increases as well. This can result in a huge overhead that the dedicated channel cannot handle.

Other approaches solve the distribution problem by either reducing the information overhead or by improving the performance of blind detectors. For example, in OFDM systems, based on the scanned channel, waveform is adjusted by turning off some subcarriers to exploit the available spectrum holes (Fig. 2). The receivers, however, should be informed about detected spectrum holes (or which subcarriers are deactivated). The overhead is reduced by sending a vector containing disabled subcarriers rather than by sending the spectrum sensing results. One method to further reduce the overhead is proposed in [24]. The activation/deactivation of subcarriers is performed over a block of subcarriers instead of individual subcarriers. Hence, the signaling overhead can be reduced by a factor of the block size. On the other hand, instead of sharing the spectrum-sensing information, tone-boosting can be used [25]. After a cognitive unit detects a LU signal within the band, it sends a tone with maximum power but with a very short time duration over the detected signal band. The purpose is to inform other users that a LU exists within this band. Thus, the probability of interference to LUs is reduced, which is one of the main purposes of spectrum sensing. Meanwhile, the short duration of these tones causes no interference to LUs.

SYNCHRONIZATION

Synchronization is an important issue that must be addressed in OFDM system design. With the introduction of CR, conventional synchronization methods become insufficient. The NBI, which can interfere with the preamble, is one of the problems [26]. Furthermore, the incomplete subcarrier set might be an issue for preambles. Pilots also can fall into unused subcarriers. Moreover, if multiple accessing is employed, subcarriers are assigned to different users. To keep the orthogonality between subcarriers and to avoid interference, all users should be synchronized to the receiver. In [26], it is shown that longer preambles are required in CR-OFDM systems compared to conventional systems. In addition, new preamble structures are introduced, and their performances for time and frequency synchronization are investigated.

MUTUAL INTERFERENCE

The side lobes of modulated OFDM subcarriers are known to be large. As a result, there is power leakage from OFDM signals to adjacent channels. In addition, used subcarrier power leaks to nulled subcarriers, which causes interference — known as mutual interference — to LUs. Various techniques are proposed in the literature to reduce this leakage and to enable co-existence of cognitive-OFDM systems with primary users. One technique is to window the time domain OFDM symbols. However, spectrum shape

Applications utilizing location information can be grouped into four categories: location-based services, network optimization, transceiver algorithm development and optimization, and environment characterization.

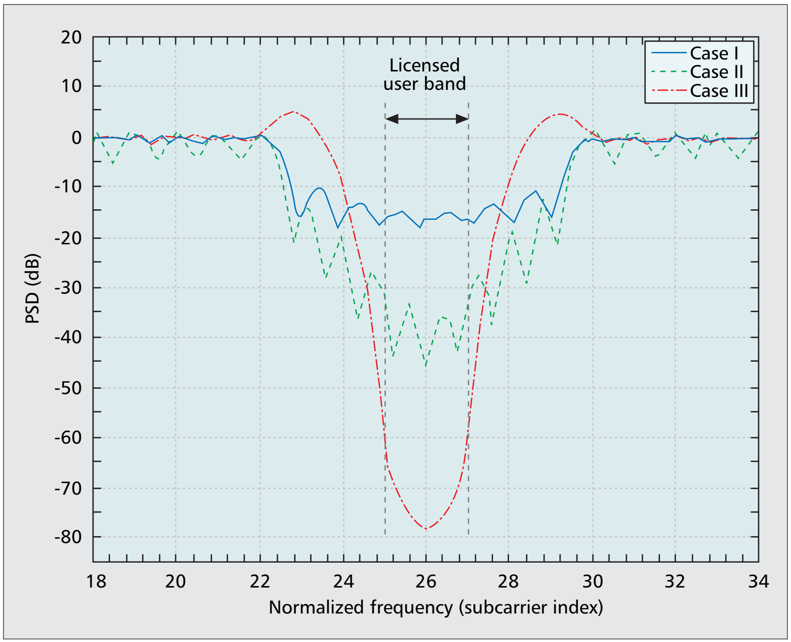


Figure 4. *PSD of cognitive system OFDM signal with a spectrum hole over LU band.*

improvement comes at the cost of longer OFDM symbol duration and thus reduces the spectrum efficiency of the system. Another approach is to increase the number of nulled subcarriers to achieve lower interference levels to LU bands because most of the interference is caused by neighboring subcarriers. However, the obvious disadvantage of this method is the reduction of spectral efficiency.

A method that reduces interference to spectrum holes while keeping high spectrum efficiency is proposed in [27, 28] and is referred to as active interference cancellation and cancellation carriers, respectively. Instead of disabling subcarriers adjacent to spectrum holes, a much smaller number of those adjacent subcarriers is used to reduce the interference leaked to spectrum holes. The cancellation subcarriers are pre-calculated to reduce subcarrier side lobes inside spectrum holes. This technique achieves significant reduction of adjacent channel interference. The disadvantage of this technique is the increase in overall system complexity due to the calculation of cancellation carrier values for each symbol. In addition, for larger spectrum holes, more cancellation carriers are required to maintain the desired interference level. Analog or digital filters also can be used to filter out the unwanted spectral components of the OFDM signal prior to transmission. However, because the spectrum mask on a CR signal must be adaptive, the use of analog filters is not practical. On the other hand, digital filters introduce an increase in the system computational complexity and processing delay. Other methods to reduce OFDM interference to adjacent channels are presented in [29, 30].

Figure 4 shows an example of a CR system that uses an OFDM signal with an FFT size of 256 subcarriers and a cyclic prefix of eight samples. A LU signal spanning three subcarriers, 25, 26, and 27, is detected. It is desirable to minimize the interference to the LU. In case I, the CR system disables subcarriers 23 through 29. A spectrum hole with a 15-dB depth is achieved. In case II, the OFDM symbols are windowed using a raised cosine window with a roll-off factor of 0.25 while subcarriers 23 through 29 are disabled. The cyclic prefix also is extended to 64 samples to preserve the orthogonality of the signal. In this case, the interference power is reduced to 30 dB of the original signal power. Finally, in case III, the CP is kept to eight samples, subcarriers 25 to 27 are disabled, and subcarriers 23, 24, 28, and 29 are used as cancellation subcarriers. In this case, a significant spectrum hole that is deeper than 70 dB is achieved.

A Step Toward Cognitive-OFDM: Standards and Technologies

Because the CR concept is attracting more interest every day, recently developed standards are considering more cognitive features. Dynamic frequency selection (DFS), transmit power control (TPC), and spectrum sensing are just a few examples of the features that are included in some of the current standards. These standards can be considered as a step toward the future implementation of a CR. In this section, examples of OFDM-based standards that utilize cognitive features are introduced.

IEEE 802.16

One of the technologies that is receiving interest lately — in both academia and industry — is IEEE 802.16 (WiMAX). The OFDMA PHY mode is probably the most interesting mode supported by WiMAX. In this mode, users can be assigned different bandwidths, time durations, transmit power levels, and modulation orders, based on various parameters, such as user carrier-to-interference-plus-noise ratio (CINR), received signal strength indicator (RSSI), or the available bandwidth. Moreover, OFDMA PHY offers multiple FFT sizes, CP sizes, and pilot allocation schemes. The FFT size can be selected as 128, 256, 512, 1024, or 2048 depending on the transmission bandwidth.[3] Similarly, the CP length can be set to 1/4, 1/8, 1/16, and 1/32 times the OFDM symbol length. The CP size can be changed depending on the environment characteristics. With all these adaptive features, WiMAX has the ability to adapt to various channel conditions and communication scenarios.

The WiMAX standard also is rich in terms of advanced antenna techniques. Available methods include adaptive antenna systems (AASs), space-time coding (STC), selected mapping (SM), collaborative SM, antenna selection, antenna grouping, multiple-input multiple-output (MIMO) precoding, STC sub-packet combining, frequency-hopping diversity combining (FHDC), and adaptive MIMO switch. The standard use of these techniques is not directly related to CR, but rather to increasing the spectral efficiency and increasing the overall throughput of the system. However, advanced antenna techniques could be used to achieve some of the CR goals as well. For example, the CR transmitter can exploit location awareness to focus its radiation only in

---

[3] *This is known as scalable OFDMA. Various FFT sizes are used to keep the subcarrier spacing constant for different transmission bandwidths.*

the direction of intended receivers using adaptive beamforming [31, 32]. On the other hand, the CR receiver can use the same technique to adaptively cancel the interference caused by unintended transmitters [33]. The goal is to achieve the coexistence of WiMAX devices in unlicensed bands. Furthermore, methods for coexistence with primary users also are developed.

IEEE 802.22

The IEEE 802.22 standard is known as the CR standard because of the number of cognitive features that are employed. These cognitive features include channel sensing, LUs detection, DFS, and TPC. Even though the IEEE 802.22 standard is not finalized yet, the current draft proposal is based on OFDM transmission, and it is anticipated that the final version will be the same. The IEEE 802.22 standard is designed for a fixed point-to-multipoint communication topology where the base station (BS) acts as the master, mandating all the operation parameters of users within the cell. And although the users (slaves) can share sensing information with the BS through distributed sensing, it is the responsibility of the BS to change a user transmit power, modulation, coding, or operating frequency.

One of the most distinctive features of the IEEE 802.22 standard is its sensing requirements, which is based on two stages: fast and fine sensing. In the fast-sensing stage, a coarse algorithm is employed, for example, an energy detector. The fine-sensing stage is initiated based on the previous stage results. However, more detailed and powerful sensing methods are used at this stage. A BS can distribute sensing load among subscriber stations (SS). The results are returned to the BS, which uses these results for managing transmissions.

Another challenge in designing the IEEE 802.22 standard is the initialization of new users who desire to communicate with the BS. Unlike current wireless technologies, the frequency and time duration of the initialization channel are not predefined. In other words, the initial users must scan parts (if not all) of the TV bands to find the BS operating frequency and time. In addition, users should be able to differentiate between incumbent signals and the BS signal. This could prove to be very challenging, especially if the BS is operating over a combination of multiple frequency bands.

IEEE 802.11

The WLAN standard, IEEE 802.11a/g, is probably the most commonly known OFDM-based standard. The main standard is upgraded to have cognitive features with the IEEE 802.11h and IEEE 802.11k standards. IEEE 802.11h is designed to allow the estimation of channel characteristics and DFS. In addition, TPC is incorporated, providing the system with more control over signal range and interference level. The purpose of the IEEE 802.11h standard is to allow WLAN systems to share the 5-GHz spectrum with primary users (e.g., military radar systems).

Note that the DFS proposed for the aforementioned standards can be considered as a channel-switching or frequency-hopping technique. Thus, it can be applied to any transmission technology and is not exclusive to OFDM. However, it also is worthy of mentioning that many recent published articles have proposed new methods to facilitate DFS use for OFDM systems. OFDM subcarriers are split into subchannels that can be disabled, enabled, or assigned to multiple users, according to sensing measurements. These recent studies can be divided into two categories: those that address the reduction of interference between different subchannels [28-30] and those that address the optimization of the subchannel allocation process [34, 35]. In following the progress of the amendments to wireless standards, we expect that the above, advanced OFDM-based techniques will be considered for DFS.

On the other hand, the IEEE 802.11k standard is proposed for radio resource management. It defines several types of measurements such as the channel-load report, noise-histogram report, and station-statistics report. The noise histogram report provides methods to measure interference levels that display all non-IEEE 802.11 energy on a channel as received by the subscriber unit. The access point (AP) collects channel information from each mobile unit and makes its own measurements. This data is then used by the AP to regulate access to a given channel.

Other features such as the tracking of hidden nodes and the sharing of client statistics are included in the standard. By applying both IEEE 802.11h and IEEE 802.11k standards to current IEEE 802.11-based WLAN systems, the performance and efficiency of wireless networking can be improved significantly. Adding cognitive features such as channel sensing and estimation, statistics distribution, DFS, and TPC to WLAN devices will be possible soon.

CONCLUSION

CR is an exciting and promising technology that offers a solution to the spectrum crowding problem. On the other hand, the OFDM technique is used in many wireless systems and has proven to be a reliable and effective transmission method. OFDM can be used for realizing the CR concept because of its inherent capabilities that are discussed in detail in this article. By employing OFDM transmission in CR systems, adaptive, aware, and flexible systems that can interoperate with current technologies can be realized. However, the challenges identified in this article must be researched further to address the open issues. Practical CR systems can be developed using two approaches: current wireless technologies can evolve to support more cognitive features over time, or new systems that support full cognitive features can be developed. In either case, we foresee that OFDM will be the dominant PHY technology for CR.

The IEEE 802.22 standard is known as the CR standard because of the number of cognitive features that are employed. These cognitive features include channel sensing, LUs detection, DFS, and TPC.

REFERENCES

[1] J. Mitola and G. Q. Maguire, Jr., "Cognitive Radio: Making Software Radios More Personal," *IEEE Personal Commun.*, vol. 6, no. 4, Aug. 1999, pp. 13–18.

[2] M. Wylie-Green, "Dynamic Spectrum Sensing by Multiband OFDM Radio for Interference Mitigation," *IEEE DySPAN*, 2005, pp. 619–25.

> By employing OFDM transmission in CR systems, adaptive, aware, and flexible systems that can interoperate with current technologies can be realized. However, the challenges identified in this article must be researched further to address the open issues.

[3] T. Weiss, J. Hillenbrand, and F. Jondral, "A Diversity Approach for the Detection of Idle Spectral Resources in Spectrum Pooling Systems," *Proc. 48th Int'l. Scientific Colloq.*, Ilmenau, Germany, Sept. 2003.

[4] J. Hillenbrand, T. A. Weiss, and F. K. Jondral, "Calculation of Detection and False Alarm Probabilities in Spectrum Pooling Systems," *IEEE Commun. Lett.*, vol. 9, no. 4, 2005, pp. 349–51.

[5] T. Yücek and H. Arslan, "Spectrum Characterization for Opportunistic Cognitive Radio Systems," *Proc. IEEE MILCOM*, 2006, pp. 1–6.

[6] H. Arslan and T. Yücek, "Adaptation of Wireless Mobile Multi-Carrier Systems," in *Adaptation Techniques in Wireless Multimedia Networks*, W. Li and Y. Xiao, Eds., Nova Science Publishers, 2006.

[7] T. Keller and L. Hanzo, "Adaptive Modulation Techniques for Duplex OFDM Transmission," *IEEE Trans. Vehic. Tech.*, vol. 49, no. 5, Sept. 2000, pp. 1893–1906.

[8] C. Y. Wong *et al.*, "Multiuser OFDM with Adaptive Subcarrier, Bit, and Power Allocation," *IEEE JSAC*, vol. 17, no. 10, Oct. 1999, pp. 1747–58.

[9] D. T. Harvatin and R. E. Ziemer, "Orthogonal Frequency Division Multiplexing Performance in Delay and Doppler Spread Channels," *Proc. IEEE VTC*, vol. 3, May 1997.

[10] S. W. Lei and V. K. N. Lau, "Adaptive Interleaving for OFDM in TDD Systems," *IEEE Proc. Commun.*, vol. 148, no. 2, 2001, pp. 77–80.

[11] A. Dowler, A. Doufexi, and A. Nix, "Performance Evaluation of Channel Estimation Techniques for a Mobile Fourth Generation Wide Area OFDM System," *Proc. IEEE VTC*, vol. 4, 2002.

[12] *IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries*, IEEE Comp. Soc. Press, 1990.

[13] SDR Forum, "Software Defined Radio Technology for Public Safety," approved doc. SDRF-06-A-0001-V0.00, Apr. 14, 2006.

[14] A. Batra *et al.*, "Design of a Multiband OFDM System for Realistic UWB Channel Environments," *IEEE Trans. Microwave Theory Tech.*, vol. 52, no. 9, 2004, pp. 2123–38.

[15] D. M. W. Leenaerts, "Transceiver Design for Multiband OFDM UWB," *EURASIP J. Wireless Commun. Net.*, vol. 2006, no. 2, 2006, p. 25.

[16] H. Zheng and H. C. Luong, "A 1.5 V 3.1-GHz8 GHz CMOS Synthesizer for 9-band MB-OFDM UWB Transceivers," *IEEE J. Solid-State Circuits*, vol. 42, no. 6, June 2007, pp. 1250–60.

[17] B. Razavi *et al.*, "Multiband UWB Transceivers," *Proc. IEEE Custom Integrated Circuits Conf.*, Sept. 2005, pp. 141–48.

[18] J. Lee and D. Chiu, "A 7-band 3-8 GHz Frequency Synthesizer with 1 ns Band-Switching Time in 0.18 m CMOS Technology," *Proc. IEEE Custom Integrated Circuits Conf.*, 2005, pp. 204–5.

[19] A. Ismail and A. Abidi, "A 3.1 to 8.2 GHz Direct Conversion Receiver for MB-OFDM UWB Communications," *Proc. IEEE Int'l. Solid State Circuits Conf.*, vol. 1, Feb. 2005, pp. 208–593.

[20] R. Rajbanshi, A. M. Wyglinski, and G. J. Minden, "An Efficient Implementation of NC-OFDM Transceivers for Cognitive Radios," *1st Int'l. Conf. Cognitive Radio Oriented Wireless Net. Commun.*, Mykonos Island, Greece, June 2006.

[21] H. Celebi and H. Arslan, "Cognitive Positioning Systems," *IEEE Trans. Wireless Commun.*, vol. 6, no. 12, 2007, pp. 4475–83.

[22] H. Celebi and H. Arslan, "Utilization of Location Information in Cognitive Wireless Networks," *IEEE Wireless Commun.*, vol. 14, no. 4, 2007, pp. 6–13.

[23] D. E. Breen, Jr., "Characterization of Multi-Carrier Locator Performance," Master's thesis, Worcester Polytechnic Inst., May 2004.

[24] A. M. Wyglinski, "Effects of Bit Allocation on Non-Contiguous Multicarrier-Based Cognitive Radio Transceivers," *Proc. IEEE VTC*, Sept. 2006.

[25] T. Weiss and F. K. Jondral, "Spectrum Pooling: An Innovative Strategy for the Enhancement of Spectrum Efficiency," *IEEE Commun. Mag.*, vol. 42, no. 3, Mar. 2004, pp. 8–14.

[26] T. Weiss *et al.*, "Synchronization Algorithms and Preamble Concepts for Spectrum Pooling Systems," *IST Mobile & Wireless TeleCommun. Summit*, June 2003.

[27] H. Yamaguchi, "Active Interference Cancellation Technique for MB-OFDM Cognitive Radio," *Proc. IEEE Euro. Microwave Conf.*, vol. 2, Oct. 2004, pp. 1105–8.

[28] S. Brandes, I. Cosovic, and M. Schnell, "Reduction of Out-of-Band Radiation in OFDM Systems by Insertion of Cancellation Carriers," *IEEE Commun. Lett.*, vol. 10, no. 6, 2006, pp. 420–22.

[29] H. A. Mahmoud and H. Arslan, "Sidelobe Suppression in OFDM-Based Spectrum Sharing Systems Using Adaptive Symbol Transition," *IEEE Commun. Lett.*, vol. 12, no. 2, Feb. 2008, pp. 133–35.

[30] S. Pagadarai *et al.*, "Sidelobe Suppression for OFDM-Based Cognitive Radios Using Constellation Expansion," *Proc. IEEE WCNC*, Apr. 2008, pp. 888–93.

[31] S. Haykin, "Cognitive Radio: Brain-Empowered Wireless Communications," *IEEE JSAC*, vol. 3, no. 2, Feb. 2005, pp. 201–20.

[32] T. S. Rappaport, *Smart Antennas: Adaptive Arrays, Algorithms, & Wireless Position Location*, IEEE Press, 1998.

[33] O. Hoshuyama, A. Sugiyama, and A. Hirano, "A Robust Adaptive Beamformer for Microphone Arrays with a Blocking Matrix Using Constrained Adaptive Filters," *IEEE Trans. Signal Process.*, vol. 47, no. 10, 1999, pp. 2677–84.

[34] G. Dong *et al.*, "Dynamic Frequency Selection (DFS) in IEEE802.16e OFDM System Working at Unlicensed Bands," *Int'l. Conf. Adv. Commun. Tech.*, vol. 2, Feb. 2007, pp. 1330-34.

[35] T. C. H. Alen, A. S. Madhukumar, and F. Chin, "Capacity Enhancement of a Multi-User OFDM System Using Dynamic Frequency Allocation," *IEEE Trans. Broadcast.*, vol. 49, no. 4, Dec. 2003, pp. 344–53.

BIOGRAPHIES

HISHAM ABDELAZIZ MAHMOUD (hmahmoud@mail.usf.edu) received his B.S. (with highest honors) degree in electrical engineering from Cairo University at Fayoum, Egypt, in 2002, and his M.S. degree in electrical engineering from Cairo University, Cairo, Egypt, in 2005. He is currently pursuing his Ph.D. degree at the electrical engineering department, University of South Florida, Tampa. His research interests include signal processing algorithms for the physical layer of wireless systems, OFDMA systems, spectrum sensing and shaping for cognitive radio, and channel coding.

TEVFIK YÜCEK [M] (yucek@mail.usf.edu) received his B.S. degree in electrical and electronics engineering from Middle East Technical University, Ankara, Turkey, in 2001, and his M.S. and Ph.D. degrees in electrical engineering from the University of South Florida in 2003 and 2007, respectively. He is currently working as a signal processing engineer at Atheros Communications Inc., Santa Clara, California. His research interests are in signal processing techniques for wireless multicarrier systems and cognitive radios.

HÜSEYIN ARSLAN [SM] (arslan@eng.usf.edu) received his Ph.D. degree in 1998 from Southern Methodist University, Dallas, Texas. Since August 2002 he has been with the Electrical Engineering Department of the University of South Florida. His research interests include advanced signal processing techniques at the physical layer, cross-layer design for networking adaptivity, and quality of service control. He is interested in many forms of wireless technologies including cellular, wireless PAN/LAN/MANs, fixed wireless access, and specialized wireless data networks like wireless sensor networks and wireless telemetry. His current research interests are UWB- and OFDM-based wireless technologies with emphasis on WIMAX and IMT-Advanced, and cognitive and software-defined radio. From January 1998 to August 2002 he was with the research group at Ericsson Inc., USA, where he was involved with several projects related to 2G and 3G wireless cellular communication systems. He has worked for the Anritsu Company in Morgan Hill, California, as a visiting professor during the summers of 2005 and 2006, and as a part-time consultant between August 2005 and August 2007. In addition, he worked for the Scientific and Technological Research Council of Turkey (TUBITAK) as a visiting professor during the summer of 2008. Since August of 2008 he remains involved with TUBITAK as a part-time consultant. He has served as technical program committee chair, technical program committee member, session and symposium organizer, and workshop chair at several IEEE conferences. He is a member of the editorial board for *Wireless Communication and Mobile Computing Journal* and *Research Letters in Communications*.