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OFDM for Cognitive Radios: An overview Present Solutions and Future Directions

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Abstract: Spectrum efficiency, high speed data transmission and security are the major requirements for new generation wireless communications. By integrating OFDM into physical layer of cognitive radio, we can achieve high speed data transmission with high spectrum utilization. In this article, we investigate the impediments for use of OFDM with cognitive radios. We discuss some of the solutions to overcome these problems and identify the need for further exploration taking into account the practical issues of synchronization errors between the transmitter and the receiver. We also discuss security issues related to cognitive radio networks and suggest some future research directions.

Keywords: Cognitive Radio, OFDM, PAPR, Out of Band Radiation

1. Introduction

Radio spectrum is becoming scarcer day by day with the ever increasing use of wireless devices. On the other hand, measurements performed on licensed bands show that the spectrum usage of some of the bands is heavy while for others it is low [1]. These underutilized bands cannot be used by other users, as they are licensed. This creates a need for a novel technology to increase the spectrum utilization of the unused/underutilized bands. The devices using this technology should be capable of sensing spectrum opportunities and utilizing them either in an opportunistic manner or with least interference to the legacy systems. Cognitive Radio (CR) can provide a solution to this problem with its intelligent wireless system that can sense the spectrum opportunities and adjust the radio parameters accordingly [2]. Another problem that arises with the growing demand for wireless access, is the requirement for high data rate [3]. The higher data rate implies a decrease in symbol duration and thereby an increase in the chances of inter symbol interference (ISI). ISI can be eliminated at the receiver by using equalization. However, for frequency selective channels the distortion due to ISI cannot be removed by single tap equalizer [3]. This increases the receiver complexity. One of the solutions to overcome the problems associated with frequency selective channels is to divide a wideband channel into a number of frequency flat channels and use multi-carrier modulation for transmitting data over these channels. Thus by using cognitive radio with multi-carrier techniques, we can increase both spectrum utilization and the data rate. One of the popular and widely used multi-carrier technique is the Orthogonal Frequency Division Multiplexing (OFDM). It is a suitable candidate for physical layer of CR systems, owing to its inherent capabilities like spectrum agility, spectrum analysis, scalability and robustness to narrowband interference [4]. However, OFDM suffers from major drawbacks like high out of band radiation (OOBR) and high peak to average power ratio (PAPR). Both OOBR and PAPR degrade the performance of OFDM and limit its practical applications. To address these drawbacks a number of schemes exist in the literature. Some of these proposed schemes address the two problems separately while some others take a joint view of the two problems. These schemes are described in this article.

In this paper, we investigate the use of OFDM for physical layer of cognitive radios. Existing literature contains some survey papers on the two major drawbacks of OFDM i.e. OOBR and PAPR [5], [6]. However, this study differs from the existing surveys in several respects. First, in the existing survey papers, the two problems have been discussed separately and we have taken a joint view of the two problems, after discussing them separately. Second, we also discuss the need of incorporation of synchronization errors in OOBR and PAPR problems. This has not been well studied, to the best of our knowledge and thus needs further investigation. Third, we

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also discuss the security issues related to cognitive radio networks.

This paper is organized as follows. In Section 2, we discuss suppression techniques for OOB radiation. Sections 3 discusses the PAPR problem. In Section 4, we discuss OOB and PAPR problems jointly. In Section 5, the effect of synchronization errors on OFDM performance is discussed. In Section 6, we discuss the security issues related to cognitive radio networks. Finally, in Section 7, we give conclusions and some future research directions.

2. Out of Band Power Radiation

OFDM transmits a number of modulated subcarriers simultaneously. These modulated subcarriers have overlapping spectrum but are coherently orthogonal, which facilitates the demodulation of data symbols at the receiver. To overcome the adverse channel effects, guard interval in the form of either zero padding or cyclic prefix, is inserted between useful data blocks. Thus in OFDM transmission, each useful data block is followed by a redundant block. In practice, these blocks of data need to be represented by a pulse shape and the rectangular pulse shape is a suitable choice. Moreover, rectangular pulse shape is also suitable for FFT processes in practical OFDM systems [7]. Rectangular pulses, however, transform to a sinc function in the frequency domain, with a spectrum decay of f^2 [8]. This leads to high spectral side lobes in OFDM signals, which causes severe interference to users in the adjacent channels. This problem is of paramount importance if the users in adjacent channels are primary users. Thus in OFDM based CR, OOB power reduction gains more importance. A number of techniques have been proposed to reduce OOB interference [8]-[22]. These can be broadly classified as: Time domain techniques, Frequency domain techniques and Precoding Techniques.

A. Time Domain Techniques

Spectrum side lobes are created by rectangular pulse shape of the OFDM symbol. One of the simplest ways to address the problem of side lobes is to smoothen the transitions at the symbol boundaries. This can be done by extending the OFDM symbol and multiplying it with a window function. In practice, this is done after passing the signal through Inverse Fast Fourier Transform (IFFT) block and thus these techniques can be classified as Time domain techniques. Various types of time windows proposed include raised cosine (RC), Bartlett, Better than RC and flipped inverse secant hyperbolic [9]. Time domain windowing smoothens the transition of signal waveform between two OFDM symbols and thus leads to suppression of sidelobes [8]. The time domain windowing however, extends the OFDM symbol period, which in turn leads to reduction in throughput [8]. In [10], authors propose a technique termed as Adaptive Symbol Transition (AST), similar to time windowing technique. In this technique, instead of a predefined window shape, an adaptive method is used to calculate the symbol extension based on center frequency and bandwidth of the licensed user [10]. Using this technique significant side lobe suppression (around 50 dB) in comparison to other windowing techniques is achieved. Moreover, there is no increase in PAPR and SNR loss is also less [10]. In all of these time domain techniques, there is a loss in useful data throughput as the OFDM symbol is extended in time. To overcome the limitation of decrease in data throughput, a phase adjustment approach was recently proposed in [11]. In this technique, phase of each OFDM symbol is adjusted to minimize the OOB radiation in the band of interest. The authors carry out the phase computation for single antenna and multiple antenna cases. In single antenna case, the phase is computed on the basis of previous symbols, and all subcarriers of m consecutive symbols are rotated by the same phase. Since all subcarriers of a symbol are rotated by the same phase, thus relative location of symbols in the constellation does not change. Thus there is no increase in BER [11]. The phase rotation introduced in all subcarriers can be compensated in a manner similar to common phase error (CPE) due to channel effects, in a practical OFDM system. In multiple antenna case, the phase is computed on the basis of symbols transmitted from the other antennas. Phase adjustment technique does not suffer from decrease in useful throughput or increase in BER [11].

B. Frequency Domain Techniques

In this class of techniques, subcarriers, also termed as tones, are multiplied by optimal weights to suppress interference. In this class of techniques, symbols are processed before performing IFFT operation and hence these are termed as frequency domain techniques. In this sub-section, we will discuss some of the commonly used frequency domain techniques. In Subcarrier Weighting technique [12], all data tones are multiplied by an optimal set of weights to minimize the interference in the band of interest. This technique, however, suffers from increased bit error rate (BER), due to perturbation in the data tones. Further its applicability is limited to systems using constant envelope modulation. In Active Interference Cancellation (AIC) technique [13], some of the tones are reserved for transmitting cancellation signals and are termed as cancellation tones. These cancellation tones lie in and around the band of interest (e.g. primary users' band in a CR system). The signals transmitted on these tones cancel the interference caused by data tones in the victim band. A notch depth of 40 dB for target spectrum of three tones can be achieved using five AIC tones. This

TABLE I. RELATIVE COMPARISON OF OUT OF BAND RADIATION REDUCTION TECHNIQUES

OOBR Reduction Technique	Advantages	Disadvantages
Time Windowing	• Simplest technique • No degradation in error performance • No increase in PAPR • No need for subcarrier reservation	• Throughput reduction • Needs guard interval to maintain orthogonality
Adaptive Symbol Transition	• No degradation in error performance • No increase in signal PAPR • No need for subcarrier reservation	• Throughput reduction • High complexity • Data dependent design
Active Interference Cancellation	• No degradation in error performance • No extension in OFDM symbol duration • Deeper spectral notches in desired band	• High complexity • Data dependent design • Spectrum efficiency loss • Increase in PAPR
Multiple Choice Sequences	• No degradation in error performance • Provision for joint reduction of OOBR and PAPR by designing suitable sequences • No extension in OFDM symbol duration • No need for subcarrier reservation	• Requirement of signaling information (leading to Throughput reduction) • High complexity
Constellation Expansion	• No throughput reduction • No need of subcarrier reservation	• Requirement of signaling information • Increase in bit error rate (BER) • Slight increase in PAPR
Phase Adjustment	• No degradation in error performance • No throughput reduction	• Data dependent design • Slight increase in complexity
Precoding	• High decay rate for sidelobe power • No extension in symbol duration	• Slight increase in BER • Spectral efficiency loss

notch depth can be increased by increasing AIC tones, but that would reduce spectrum efficiency as no data is transmitted on AIC tones. A modified version of AIC, termed as Extended AIC (EAIC) has also been reported in the literature [14], [15]. In EAIC, deeper notches of around 80 dBs, can be achieved by reducing the spacing between cancellation tones in the frequency domain and extending the symbol duration in the time domain. As a downside, it can result in self-interference to the data tones. This can be avoided by computing the optimal weights with self-interference constraint [15].

It is seen that deeper notches can be achieved with Frequency domain techniques without increasing the symbol duration in contrast to windowing techniques, but some tones need to be reserved for cancellation signals. This in turn reduces the system throughput. Further, high power of cancellation carriers increases PAPR and may lead to inter-carrier interference (ICI), if Doppler spread or receiver frequency offset occurs [10].

Two other types of techniques which also use symbol mapping are multiple choice sequence (MCS) and constellation expansion (CE). In MCS [16], the original data sequence is transformed into a set of sequences and the sequence with the lowest side lobe power is chosen for transmission. This technique however, needs to convey some amount of signalling information to the receiver, to recover back the original data sequence. In CE [17], the number of constellation points is increased, so that each signal point can be mapped to a point in the expanded constellation. The combination of the new signal points that minimizes OOB radiation is chosen for transmission. Like MCS technique, the receiver should be informed about remapping the signal points to the original sequence. Since there is an increase in the number of signal constellation points (e.g. QPSK mapped to 8 PSK), the minimum distance between the signal points decreases, which is expected to increase BER. This technique also suffers from a slight increase in PAPR, as the symbols from a higher order constellation are used for signal transmission.

C. Joint Time Frequency Techniques

Among the interference reduction methods proposed in the literature, AIC [13] and AST [10] are the most efficient methods in frequency and time domain respectively. Both methods use least squares (LS) optimization to find weights of cancellation carriers (in case of AIC) and symbol extension (in case of AST). Both methods result in almost same decrease in system throughput [18]. To study the trade of between number of cancellation carriers and the symbol extension, on the system throughput, at a fixed level of interference, a joint time frequency method is proposed in [18]. In this method, interference reduction is studied as a joint optimization problem over the symbol extension and the number of cancellation carriers, for a given level of interference. It is shown that adding a pair of cancellation carriers reduces interference by about 4 dBs, whereas there is a marginal interference reduction when an extra pair of extension samples is added beyond the first extension sample pair. Thus using one sample extension and several cancellation carriers gives the best trade-off between complexity, throughput and interference reduction [18]. However, if the interference reduction is desired over multiple narrow bands (e.g. multiple spectrum holes in a CR system) than a single wideband, using several CCs will reduce throughput by 2m times in comparison to single wideband case, where m is the number of narrow bands. This is because each narrowband will need CCs at its edge. Thus it would better to increase number of extension samples than the number of CCs in multiple narrowband case [18].

D. Precoding Techniques

In Precoding techniques, data of each OFDM block is multiplied by a predefined matrix called precoding matrix. This multiplication thus, introduces correlation between the data symbols in the time domain, which in turn reduces the sidelobe power. For an L-th order correlatively coded OFDM signal, the decay rate for sidelobe power is $f^{-2(L+1)}$ at the band edges in comparison to f^{-2} for a rectangular pulsed OFDM. However, the error performance of correlatively coded OFDM degrades because the correlative coding breaks the orthogonality among modulated waveforms [7], [19]. Several other precoder designs to reduce the spectral sidelobes in OFDM have been proposed [20]-[23]. One of the common limitations of the precoding based techniques is the spectral efficiency loss, as some of the tones are not used for transmitting data symbols.

3. PEAK TO AVERAGE POWER RATIO

An OFDM signal being a sum of many independent modulated subcarriers, has large signal envelope variations. This gives rise to a large peak to average power ratio (PAPR) for an OFDM signal. The complex baseband representation of an OFDM signal with N subcarriers is given as [5]

$$x(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n\, e^{j2\pi n \Delta f t},\ 0 \le t < NT \qquad (1)$$

where Δf is the subcarrier spacing, X_n is n^{th} data symbol and NT denotes the useful data period.

The PAPR of the transmit signal given in equation (1) is defined as [5]

$$\mathrm{PAPR} = \frac{\max_{0\le t<NT} |x(t)|^2}{1/NT.\int_0^{NT} |x(t)|^2 dt} \qquad (2)$$

Thus PAPR of the signal depends on envelope variations. A large PAPR has many disadvantages like increased complexity in analog to digital and digital to analog converters, reduced efficiency for RF power amplifier, and spectral regrowth. In the context of Cognitive radios, PAPR problem needs to be addressed because the large envelope variations, when passed through final RF power amplifier, will cause intermodulation among subcarriers and out of band radiation. This can be prevented by operating the amplifier in its linear region, which leads to inefficient power conversion and low battery lifetime for mobile applications [5]. To reduce PAPR, various techniques proposed in the literature, can be broadly classified into following categories:

A. Signal Distortion Techniques

These techniques reduce the peaks by non-linearly distorting the signal at or around the peaks, e.g. clipping, peak windowing, peak cancellation and companding techniques. Amplitude clipping causes in-band and out of band distortion. To remove OOB problem of clipping, the signal peaks can be multiplied with non-rectangular windows like Kaiser, Hamming, and Gaussian. These windows should be narrowband to minimize the OOB interference, but that would mean longer windows in the time domain, which would affect more samples and thereby lead to increased BER. Thus there is a trade-off between OOB interference reduction and BER minimization in signal distortion techniques [5], [24]. Companding transforms have been proposed for PAPR reduction in [25]. These transforms offer two advantages over clipping. Firstly, the clipped portion of the signal cannot be recovered back at the receiver, whereas companded signal is recoverable at the receiver by applying inverse transformation. Secondly, unlike clipping, nonlinear companding enlarges smaller signals and compresses large signals which results in better immunity for smaller signals from noise besides a reduction in peak to average values [6].

B. Coding Techniques

The peak power during an OFDM symbol period depends on the data word modulated onto the subcarriers. It has been shown in [26], that different combinations of 4 bit word produce different peak powers. To reduce PAPR, only those data words should be transmitted that produce low peak powers. This can be done by mapping a 3 bit data word onto a 4 bit word by simple coding, and selecting the code words with minimum peak powers. Thus coding is one of the ways of reducing PAPR. In [26], it has been shown that PAPR reduces to 2.48 dB from 6.02 dB for the uncoded OFDM with 3/4 rate block code. In later works, some other coding techniques like modified simple block coding, complement block coding and cyclic coding has been used to reduce PAPR [27].

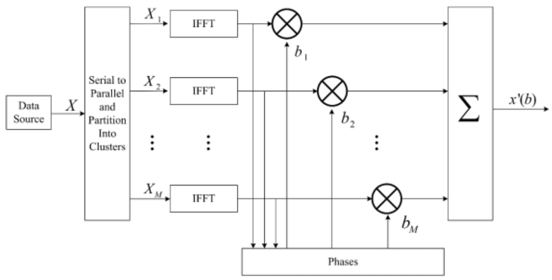

Figure 1. Block diagram of PTS Technique [5]

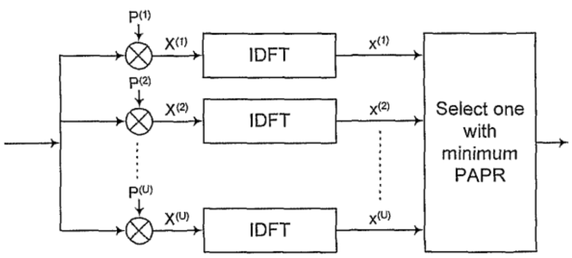

Figure 2. Block diagram of Selective Mapping (SLM) Technique [5]

C. Scrambling Techniques

In these techniques, each OFDM symbol is scrambled with different sequences and the sequence with least PAPR is chosen for transmission. On the basis of generation of new data sequence, scrambling techniques can be classified as partial transmit sequence technique (PTS) [28], selected mapping technique (SLM) [29], and interleaving technique [30], [31]. PTS technique divides the input data block (for each OFDM symbol)into M disjoint sub blocks and performs inverse discrete Fourier transform (IDFT) over each sub block as shown in Figure 1. Output of each IDFT unit is multiplied by a phase factor b_i (i=1 to M) and added to generate the transmit sequence. The output sequence thus depends on the phase factors b_i's. The values of the phase factors are optimized to minimize the PAPR of the combined output signal. Increasing the number of subcarrier blocks and the number of phase factors, reduces the PAPR. This also increases the search complexity and the amount of side information that needs to be transmitted to the receiver to recover the original data.

In SLM technique multiple copies (say U) of the original data are generated, by multiplying the original data with U phase sequences as shown in Figure 2. To retain the original data, one of the phase sequences can be taken as all 1's. Each of these U copies is then passed through separate IFFT units. The output of the IFFT unit with least PAPR is chosen for transmission. In this technique any type of modulation and any number of subcarriers can be used. The amount of PAPR reduction depends upon the phase sequence design and may vary from data block to data block. The side information needs to be transmitted to the receiver for the original data recovery. In interleaving technique, the baseband data block is permuted by a device termed as interleaver. To generate U data blocks, U interleavers are needed. The original and the permuted data blocks are then passed through IFFT blocks and the data block with least PAPR is chosen for transmission. To recover the original data block, the information about the interleaver used at the transmitter needs to be conveyed to the receiver.

D. Tone Reservation Technique

In this technique [32], a data dependent time domain signal ‘c’ is added to the original OFDM signal 'x' to reduce its peaks. Since IDFT is a linear operation, so we can write x + c= IDFT (X+C). Thus addition of time domain signal is equivalent to adding a frequency domain vector C to the original data block X; with X and C lying in disjoint frequency subspaces. The positions in subspace ‘C’ are termed as peak reduction carriers as their time domain equivalent is used for peak reduction. The addition of these PRC's does not cause distortion to the data bearing carriers, as the two sets are orthogonal. This technique is an effective solution to PAPR reduction, but the computation of an optimized data dependent signal adds to the complexity of the system.

E. Constellation Modification Techniques

In these techniques original signal constellation is either expanded or extended in the signal space. In the expansion technique, each constellation point can be mapped onto one among several constellation points in the expanded space. Since replacing a constellation point with a new one is equivalent to injecting a tone of appropriate frequency and phase, this technique is termed as tone injection technique [5]. For example, a signal point X_n can be modified to $X_n + pD + j.qD$, where p and q are integers and D is a real positive number. By choosing appropriate values of p and q, the real and imaginary parts of the baseband modulated signal can be changed. Since the PAPR of the signal depends on real and imaginary parts of the signal, modified signal constellation with a lower PAPR, can thus be designed. Tone injection technique, however, may degrade the BER performance if D is not properly chosen. The value of D should be at least $d\sqrt{M}$ [5] in order not to increase BER, where d is minimum distance between original constellation points and M is number of signalling levels. In constellation extension technique, some of the outer constellation points are extended outwards to reduce the PAPR of the original data sequence [5]. Moving the outer constellation points has an added advantage of reducing the BER as the distance from the decision boundary increases. For MPSK signal any set of points can be relocated but for MQAM constellation only signal points from the outermost set of signal points can be selected for relocation. In this technique no side information needs to be transmitted to the receiver, as the modified points lie in their decision regions and as such there is no data loss. However, this performance improvement is achieved at the cost of slight increase in transmit power.

F. Correlation based Techniques

The variations in a signal depend on the correlation between its samples. It has been shown in [33] that the N samples of every OFDM block are independent identical Gaussian distributed random variables. This correlation characteristic makes the OFDM signal highly variable and thus increases the PAPR. To reduce the signal variations and thus the PAPR, one of the solutions is to create some sort of correlation between the samples of each OFDM block. Following two ways can be used to introduce this correlation [33]:

Pulse shaping: In this technique, each modulated subcarrier is transmitted using a different pulse shape; derived from the same pulse shape (i.e. cyclic shifts of the same pulse). The PAPR of the resultant transmitted OFDM signal will have a reduced PAPR because the peak amplitudes of different shapes will never occur at the same time instant unless a rectangular pulse is used. This method is bandwidth efficient as no separate subcarriers are needed for transmitting side information.

Precoding: In this technique, the baseband modulated data of each OFDM block is multiplied by a predefined matrix (called precoding matrix) before OFDM modulation. Using the same matrix for all OFDM blocks reduces the processing complexity in comparison to the block based optimization methods. Since the precoding matrix is predefined so no side information needs to be conveyed to the receiver, thus making the technique bandwidth efficient as well [34]. For an N symbol block, a precoding matrix of L x N is used, where $L \geq N$. Thus there is slight overhead in terms of subcarriers in this technique. The precoding matrix reduces to N x N, when the original OFDM block (without precoding) needs to be processed.

4. JOINT PAPR AND OOB POWER REDUCTION

In the previous sections, we have discussed how the two major problems of OFDM, i.e. PAPR and OOB power radiation, have been addressed separately. It has been noted that certain common solutions address these two problems separately. These include MCS [16] and SLM [29], constellation expansion technique [17], precoding techniques [33] and phase adjustment technique [11]. This gives insight into proposing a joint solution for the two problems. In some recent works [35]-[40], joint approach has been used to address these problems. For example, both MCS and SLM create multiple sequences from the original data sequence. Whereas the former chooses the sequence that generates lowest side lobe power, the later chooses a sequence that has the lowest PAPR. In [35], the authors propose a method based on MCS and SLM techniques for joint reduction of PAPR and the OOB power. In this method, MCS generates a sequence with minimum OOB power and this sequence is then used to generate multiple SLM sequences for PAPR improvement. It has been shown to reduce PAPR with a decrease in bit error rate as well.

Tone reservation technique has been proposed for PAPR reduction in [32]. In this technique some of the tones (termed as reserved tones) are modulated by complex weights to reduce the PAPR of the resultant time domain signal. No side information needs to be conveyed to the receiver in this technique. In a similar manner authors in [36], propose a tone reservation technique for reducing OOB radiation. These tones lie at the edges of the band of interest and are modulated by complex factors to reduce radiation into the desired band [36]. Both the techniques [32] and [36] use the concept of tone reservation to address the two problems separately. In [37], authors propose a joint optimization technique based on tone reservation for reduction of PAPR and OOB radiation. A single set of tones is reserved for joint reduction of PAPR and OOB radiation.

In [38], a technique based on partial transmit sequences (PTS) is proposed for joint reduction of PAPR and OOB power. In this technique, the original data vector is partitioned into multiple blocks like in PTS technique. As discussed in previous section, this partitioning is done to reduce PAPR, ignoring the effects on OOB radiation due to edge sub-blocks. To reduce the OOB radiation, the technique proposes to further divide each edge block into sub-blocks and perform optimum phase rotations on them to reduce the spectral side lobes. These processed edge sub-blocks and the remaining blocks are then passed through PTS algorithm to reduce the PAPR. The output of PTS block (current OFDM symbol), is then passed through the adaptive phase shifter to smoothen the phase transition with respect to the previous symbol. This smoothening of phase transition will further reduce OOB radiation. In this technique, complexity of phase rotations and the size of side information is kept minimal, as the processing is done over blocks of subcarriers rather than individual subcarriers [38].

In the previous sections, we have discussed that precoding techniques have shown good performance in suppressing OOB power and in reducing PAPR separately. However, to the best of our knowledge, very little work [39], [40] exists on the design of precoding techniques for joint reduction of PAPR and OOB power. In [39], three precoding designs have been presented for joint suppression of PAPR and OOB power. It has been shown that all these designs show same OOB power reduction as that of SVD precoding approach. It has also been shown that two of the designs reduce PAPR as well. In [40], Zadoff-Chu precoding technique for PAPR reduction and SVD precoding technique for OOB radiation suppression, have been combined to study the joint reduction problem.

It can thus be summarized that most of the existing techniques address the two problems separately. Thus taking into consideration, the computational complexity, the spectral efficiency and the power efficiency, the two problems need to be addressed jointly as has been done in the recent past [35],[37]-[40].

5. Synchronization Problem

One of the limitations of OFDM systems is the sensitivity to synchronization errors. Since OFDM systems are designed on the basis of orthogonality of subcarriers, so any sort of mismatch with regard to frequency, phase or sample timing will lead to degradation in the performance. This performance degradation can be studied with respect to BER deterioration, increase in spectral side lobes and increase in PAPR. In this section we will discuss the effect of synchronization errors like frequency offset, phase noise and timing jitter on the performance of OFDM systems.

Frequency offset: In ideal OFDM system, local oscillator at the receiver is assumed to generate same frequency as the one at the transmitter. However, in practice, the mismatch between transmit-receive oscillators and Doppler shift leads to carrier frequency offset. This frequency drift destroys the orthogonality between the subcarriers, and thus the output of each subcarrier will contain interfering terms from other subcarriers. This is termed as inter-carrier interference (ICI). Another effect of frequency offset is the reduction in useful signal amplitude due to power leakage to other subcarriers [41].

Phase Noise: The output frequency of practical oscillators at the receiver is phase modulated by a random phase jitter. Thus the frequency, being a derivative of phase, is not perfectly constant. This effect is termed as phase noise and leads to ICI [24]. The effect of phase noise on BPSK, QPSK, Differential BPSK and Differential QPSK has been evaluated in [42]. It has been shown that BER performance degrades due to phase noise and this degradation is less severe in differential schemes than plain BPSK and QPSK schemes.

Timing Offset and Timing Jitter: Sampling instants in an OFDM receiver may be shifted from their desired instants. This shift may be constant from symbol to symbol or it may be random. In the former case it is termed as timing offset and in the latter case it is termed as timing jitter [43]. In [44], it is shown that the ICI power increases with the timing jitter. Oversampling can reduce this ICI power, but increasing oversampling increases the correlation between the adjacent samples, thereby limiting further decrease in ICI power.

In [45], the authors discuss the effect of timing jitter on high speed OFDM. The study is divided into white timing jitter and coloured jitter. It is shown that high frequency subcarriers cause more ICI power than low frequency subcarriers but for white jitter it is spread equally over all subcarriers unlike the coloured timing jitter, where it depends on the correlation between the jitter samples.

The effect of these synchronization errors on error performance is well investigated in [41]-[46]. However, the effect of these errors on OOB radiation and PAPR needs further attention because of the following reasons.

1. The synchronization errors destroy the orthogonality between subcarriers. This is expected to increase PAPR and OOB radiation.

2. The synchronization errors increase the ICI and as such will affect the radiation in the victim band.

6. Security Issues

Wireless networks are prone to security threats due to shared medium access [48]. The security threats in cognitive radio networks (CRNs) can be classified into two broad categories: General threats and CRN-specific threats [49]. General class of threats are similar to those of traditional wireless networks and have been well investigated in the literature e.g. See [50] and the references therein. CRN-specific threats can be attributed to the secondary (or non- prioritized) spectrum access of the CR nodes [49]. To realize this secondary spectrum access (SSA) paradigm, the CR nodes essentially operate in two phases: *spectrum sensing phase* and *transmit power control phase* (for interference management). From security point of view, adversaries can exploit the potential vulnerabilities of these phases to carry out attacks on a CR network. Following types of attacks have been reported in literature:

A. Jamming

In this type of attack, an adversary floods the sensed channel with white/coloured noise. This leads to an increase in the received SNR, thereby giving a false indication of the spectrum occupancy [49]. This type of attack is more likely to occur in energy detection based sensors, as the spectrum decision is made on the basis of local sensing.

In ad hoc CRN, nodes use a common control channel to identify their peers and coordinate resource access [49], [51]. The adversary can disrupt the CR network by jamming the control channel [49].

In another type of attack related to sensing, an adversary can intrude into the network as a legitimate node and influence the spectrum decision by reporting misleading local sensing data. Such type of attacks are termed as spectrum sensing data falsification (SSDF) attacks [52]-[54].

Unlike an intruding attacker, a legitimate CR node might turn greedy, to increase its chances of resource utilization, by misbehaving with MAC framework [49].

B. Primary User Emulation(PUE)

In this type of attack, the adversary disrupts CRN by transmitting a signal closely mimicking the primary's waveform [55]. This type of attack has more effect on feature detection based sensors, which make spectrum decision on the basis of primary signal characteristics such as pilot pattern, signal modulation or cyclostationary measures [56].

C. Conventional Attacks

Conventional attacking strategies also pose a threat to CRN operation. These include transmitting noise signal to degrade receiver SNR, eavesdropping to access and exploit the exchanged messages for future attacks, misusing the authentication information of CR nodes and transferring malicious codes during software upgradation of legitimate CR nodes [49].

D. Security Countermeasures proposed in the literature

To overcome the threats to CRNs, we discuss below some of the solutions proposed in the literature:

1) In cooperative spectrum sensing [57], the channel is sensed at multiple locations distributed in a region. Since it is unlikely that all the sensor nodes will lie in the jamming region at any given time, so reliable sensing data can be obtained to take spectrum decision. Thus this technique inherently guards against sensor jamming.
2) Spread spectrum techniques and error detection & correction coding can be potential solutions to control channel jamming and receiver jamming [3], [49].
3) Control channel hopping can also act as a safeguard against eavesdropping signalling information and also against control channel jamming [49]. Implementation of this approach is relatively easier in OFDM based CR by reserving a set of non-contiguous subcarriers.
4) References [58] and [59], discuss game theoretic approaches based on the channel availability, channel quality, utilization, power distribution and the jammer strategy to counter receiver jamming.
5) To combat primary user emulation (PUE) attack, *a priori* information about primary transmissions has been proposed to differentiate between real and fake transmitters [55].

The security issues discussed above, apply to all CR networks including OFDM based cognitive radio networks. However, for OFDM based CR, following issues need to be considered.

- Due to the structure of covariance matrix of OFDM signal, feature detection based sensors outperform energy detection based sensors [60]. Thus the attacks aimed at feature detectors need to be addressed.
- The radiation leakage to neighbouring channels due to OOB radiation and due to non-linear power amplifier, increases the interference power floor, thereby making the sensors and receivers more vulnerable to jamming attacks.

7. CONCLUSIONS AND FUTURE DIRECTIONS

Orthogonal Frequency Division Multiplexing is a popular technology for high speed data transmission over dispersive channels. It is a potential candidate for physical layer of Cognitive Radios due to its inherent advantages of spectrum shaping, spectral analysis, multiple access and interoperability. However, OFDM suffers from major drawbacks like out-of-band (OOB) radiation and peak to average power ratio (PAPR), which can limit its usefulness in newer technologies like cognitive radios. In this article, we classify and discuss some of the techniques used to reduce OOB radiation and the PAPR; separately and as a joint problem. We explore, that by assuming perfect transmitter-receiver synchronization, the existing techniques ignore the effects of synchronization errors like frequency offset, phase noise, and sampling time jitter, on the OOB radiation and the PAPR. However, in practice these errors are not uncommon and as such their effects on OOB radiation and PAPR need to be studied.

The effect of one of the synchronization errors i.e. sampling time jitter on OOB radiation has been very recently studied in [61]. The authors show that the performance of AIC technique for OOBR reduction degrades appreciably for practical jitter values. The work in [61] can be extended along following directions:

- Effect of sampling jitter has been considered only for active interference cancellation (AIC) technique: a frequency domain technique. The effect on other OOB radiation reduction techniques can also be investigated.
- The authors have only considered the effect of sampling time jitter and assumed perfect synchronization with respect to other errors. However, in practice all these errors can occur simultaneously and their cumulative effect needs to be studied.
- The effect of synchronization errors on PAPR needs to be investigated.
- The joint reduction methods of OOB radiation and PAPR are gaining popularity. However, all of these methods assume perfect synchronization with respect to frequency, phase and sampling time. The cumulative effect of synchronization errors in these methods, needs to be well investigated.

Security Issues:

The growing demand for security in wireless networks creates a need for secure CR networks especially when they have to coexist with traditional networks. The inherent features of OFDM can be exploited in the following manner, to increase the security of CR networks.

- Non-contiguous subcarriers can be reserved for hopping the common control channel from time to time. This can combat control channel jamming and also, make it difficult for the adversary to collect signalling information being exchanged between CR nodes.
- The wideband nature of the OFDM signal can be exploited to realize frequency diversity. This can be used to combat the effects of receiver jamming, as it is unlikely that all the versions of the information signal will be jammed at any given time.

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