PAPR Reduction and Sidelobe Suppression in Cognitive OFDM - A Survey

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Abstract— Cognitive radio (CR) is one of the key technology providing a new way to enhance the utilization of available spectrum effectively. The multicarrier modulation (MCM) technique which is widely used in Orthogonal Frequency Division Multiplexing (OFDM) system, is an excellent choice for high data rate application. The main two limitations of this technology is the high peak-to-average power ratio (PAPR) of transmission signal and large spectrum sidelobe. This article describes some of the important PAPR reduction techniques and sidelobe suppression techniques.

Index Terms— Cognitive Radio, Orthogonal Frequency Division Multiplexing, Peak-to-Average Power Ratio, Spectrum Sidelobe;

INTRODUCTION

Cognitive Radio (CR) is a developing technology that makes use of the available free spectrum, thus addressing the growing demand for high speed wireless access. The CR is an intelligent wireless communication system that is capable of detecting channels that are in use or not in use and thus moving into the vacant channels. Thus it reduces the scarcity of spectrum. CR Networks allows unlicensed users to access the spectrum opportunistically, so the network contains two types of users, they are Primary (license) users (PUs) and Secondary (unlicensed) users (SUs).

The recognized transmission technology for CR network is commonly preferred as multicarrier modulation (MCM) technique. The flexibility of the MCM technology is that it can dynamically adapt to spectral environment and allocate unused spectrum bands, resulting in the quick change of state of subcarriers in the radio spectrum. The best choice of MCM is Orthogonal Frequency Division Multiplexing (OFDM), which has many applications, including digital audio, video broadcasting, and so on [1]. The main advantages of using OFDM are: it provides high spectral efficiency, improves bandwidth efficiency, high power efficiency, multipath delay spread tolerance and immunity to the frequency-selective fading channels. However, the system suffers from two main bottlenecks: the high peak-to-average power ratio (PAPR) of transmitted signal and large spectrum sidelobe of the frequency bands. The large PAPR leads to both in-band distortion and out of band radiation. It increases the complexity of the analog-to-digital converter (ADC), digital-to-analog converter (DAC), also reduces the efficiency of the power amplifier [2], [3]. The large sidelobe spectrum introduces interference to the adjacent subcarriers; results in the performance degradation of the subcarriers [1], [2]. Therefore it is always better to reduce the PAPR and sidelobe spectrum in order to improve the system performance of an OFDM-based CR.

This paper organized as follows. Section II provides an overview of OFDM based CR system and challenges in section III. The section IV describes PAPR reduction techniques and the section V presents the Sidelobe Suppression techniques. Finally, the section VI concludes the article.

OFDM BASED CR SYSTEM

CR is capable of communicating with various radio access technologies in the environment, or it can improve the quality of communication, by simply changing the OFDM parameters and the radio frequency (RF) interface. Few advantages of OFDM are spectrum sensing, spectrum shaping and adapting to the environment. And these highlights are the main requirements to be fulfilled for a CR network. Thus OFDM becomes best transmission technique for CR network.

The most important features of CR are: the ability to measure, sense, learn, and should be aware of the operating conditions. CR should be able to identify and exploit the white spaces of the spectrum in a fast and efficient way. In OFDM system, conversion from time domain to frequency domain is achieved by using Fast Fourier Transform (FFT). Hence, all the points in the time-frequency grid of the OFDM systems operating band can be scanned without any extra hardware.

After scanning the spectrum, the CR is able to find the location of PUs, SUs, and opportunistic spectrum. Now, the next action to be performed is to shape the spectrum. By turning off some of the subcarriers where the PU exists. The spectrum can be easily shaped.

The key feature of CR is to adapt with the environment easily. i.e., the system can be easily adapt to the modulation order, coding, channel quality, transmit power and etc. Also, spacing between the subcarriers can be easily changed, thus PAPR can be easily reduced [3]. In total, it improves the performance in terms of system throughput, decreasing BER, increasing the battery life and coverage area.

Cognitive OFDM has the ability to support different multiple accessing techniques such as time division multiple access (TDMA), frequency division multiple accessing (FDMA) and carrier sense multiple accessing (CSMA) and many more. This feature enables greater flexibility for interoperability and accelerates the adoption of CR in future. In order to achieve interoperability, the best choice for signaling is considered to be OFDM. Since it is used in various technologies such as IEEE 802.11g Wireless LAN standards, digital video broadcasting (DVB), digital audio broadcasting (DAB), and WiMAX. Thus, a Cognitive OFDM can easily communicate with systems using other OFDM based technologies with much ease.

CHALLENGES TO COGNITIVE OFDM SYSTEM

CR is a promising wireless technology providing solutions to many problems in the area of communication. However, cognitive based OFDM has certain setbacks. The key challenges include high PAPR and large Spectrum Sidelobe.

Peak-To-Average Power Ratio

The presence of large number of orthogonally independent modulated subcarriers in an OFDM system, the peak value can be very high as compared to the average value of the whole system. This ratio of peak to average power value is defined as PAPR.

\[
PAPR = \frac{\max_{0 \leq t \leq T} |x(t)|^2}{1/N_T \int_{0}^{T} x(t) dt} (1)
\]

where the \(x(t)\) represents the transmitting signal and \(N_T\) is the duration of the OFDM data block. The principle aim is to reduce the value of \(\max|x(t)|\).
The major disadvantages of high PAPR are that, there is a reduction of power efficiency of RF amplifier and also increase the complexity of ADC and DAC [4]. Recently, various methods have been proposed in the literature for reducing the PAPR of the system such as clipping and windowing, Selective Signal Mapping (SLM), Partial Transmitting Sequence (PTS), Tone Reservation (TR), Tone Injection (TI) and Active Constellation Extension (ACE). These techniques effectively reduce the PAPR of the system but not the spectrum sidelobe.

The Cumulative Distribution Function (CDF) is an important parameter which is used to measure the efficiency of any PAPR technique. Usually, the Complementary CDF (CCDF) is used instead of CDF, which gives the probability that the PAPR of a certain data block exceeds the given threshold [5].

Spectrum Sidelobe

Other limitation of the cognitive OFDM system is the high sidelobe power. Spectrum sidelobe cause interference between the PUs and SUs. So for the CR-OFDM system, the constituent subcarriers are turned off at the PU’s channel to create spectrum notches to limit the interference faced by the PU’s [1]. Therefore, most of the researches have been done to create deep spectrum notches in the target spectrum band. Some of the schemes have been proposed by the researchers to suppress the large sidelobe power are Constellation Adjustment (CA), Active Interference Cancellation (AIC), Extended Active Interference Cancellation (Eaic), Pulse Shaping (PS) and Orthogonal Projection(OP), Adaptive Symbol Transition (AST).

**PAJR REDUCTION TECHNIQUE**

Clipping and Windowing

One of the simplest and easiest methods of reducing the PAPR of an OFDM based CR system is clipping. In this method, the high peak signal is clipped by setting a threshold value $A$. The clipped signal can be represented by:

$$\tilde{x}(n) = \begin{cases} x(n) & |x(n)| < A \\ A e^{j\Phi(x(n))} & |x(n)| \geq A \end{cases}$$

(2)

where $\Phi(x(n))$ represents the phase of the transmitting signal $x(n)$. The effect of clipping is that, it is capable of generating self-distortion and results in the degradation of bit error rate (BER). This may also result in the regrowth of high frequency components and thus affects the spectral efficiency badly. Because of these drawbacks, new methods were introduced in the literature.

Filtering is another scheme used for removing the out-of-band (OOB) radiation, but it can cause peak regrowth, i.e., the iterative clipping and filtering may decrease the appearance of OOB radiation but the signal may exceed the threshold value of the clipping operation [6]. However, this consumes long time and it will increase the computational complexity of the system. To eliminate the peak regrowth, iterative clipping is done many times. However clipping more will degrade the BER performance of the system [7], [8].

Peak windowing is an advanced technique to reduce the peak signals by multiplying the original signal with a correcting function. The correcting function used for this purpose is a window whose frequency spectrum is close to rectangular in the in-band frequency and in the time domain the window must be a narrow impulse response [9], [10]. The normally used windows are cosine filters, Kaiser, Gaussian windows to attenuate the high peak signals. Thus, windowing suppresses out-of-band radiation while attenuating peak signals.

**Selective Signal Mapping**

The SLM technique has relatively good PAPR reduction performance than the clipping and filtering method since it doesn’t introduce any kind of distortion to the transmitting signal. The key idea behind SLM is to generate many OFDM symbols as candidates signals by multiplying with a statistically-independent phase sequence $p_M$ and then select the one with the lowest PAPR and transmit it along with phase sequence as side information to the receiver [11]. The transmission of side information is needed so that the receiver can predict which candidate signal is selected for the transmission.

While implementing SLM, $U$ IFFT operations are required and the number of required side information is $\log_2 U$ for each data block. Therefore, the ability of SLM method for the PAPR reduction depends on the number of phase sequences and the design of the phase sequence. In this technique complexity involves in recovering the side information. The side information also reduces the data rate of the system because the side information is sent with the data blocks carrying information [5]. Many methods have been developed to reduce this side information such as Semi-Blind SLM portrayed in [12], known phase sequences like Hadamard, Chaotic, Riemann are mentioned in [13]-[15] to attenuate high peak signals.

![Fig. 1: Block diagram of SLM method.](image)

**Partial Transmitting Sequence**

The block diagram of PTS method is shown in Fig.2. In this, the N-point data is partitioned into non-overlapping sub-blocks. These non-overlapping sub-blocks are multiplied with an independent rotation factor. This rotation factor generates time domain data with lowest PAPR signal. This is actually a modification of SLM technique and offers better performance than SLM, since PTS doesn’t transmit any side information. However the technique is slightly complex in nature. The PTS technique requires $W$ IFFT operations on each block and the number of required side information bits is $\log_2 W^M$. The PAPR performance of PTS method is affected not only by the number of sub-blocks ($W$), also the number of allowed phase factors ($M$) as well as partition of the sub-blocks [16]. The method suffers from the complexity of searching for the optimum set of phase factor when the number of sub-blocks increases.

There’s also one more factor that affects the PAPR reduction: partitioning of the sub-block. i.e., subcarriers are
divided into multiple non overlapping sub-blocks. There are three different kinds of sub-block partitioning schemes: adjacent, interleaved, and pseudo-random partitioning. Pseudo-random partitioning has been found to be the best choice among the three schemes [5]. The PTS works with an arbitrary number of subcarriers and any modulation scheme.

![Block diagram of PTS method.](image)

**Tone Reservation**
This is an efficient method to reduce the PAPR of the system by reserving a certain number of tones to generate peak cancelling signal. These tones are used to minimize the peak values, sometimes called as peak reduction carriers (PRC’s) in the time domain. By adding these PRC’s, it won’t cause any distortion to the data bearing carriers, since these two are orthogonal to each other. The amount of PAPR reduction depends on certain factors such as total number of reserved tones, their location, allowed power of the tones. Thus adding tones may lead to the minimization of PAPR at the transmitter at reduced cost and complexity while recovery data at the receiver [17]. Though it seems to be a simple method to reduce the PAPR, the main task is to find an optimal value for the PRC’s. By solving convex optimization problem, it is able to determine the value of these tones [18]. It should be kept in mind that, the tones are not used for transmitting data.

**Tone Injection**
Another method to reduce the PAPR of multicarrier system is TI, which is an additive method without any loss of data rate. The basic idea behind this technique is to increase the constellation size, i.e. it makes use of the equivalent constellation points for original constellation points of the data. Then the original constellation points can be easily mapped on to the extended constellation points, this freedom of movement is utilized for PAPR reduction. The main thing is to inject tones at appropriate phase and frequency into the OFDM symbol since the injected signal occupies the same frequency band as the information bearing signal [5]. One of the demerits is that the injected signal occupies the same frequency band as the information bearing signal. Also this may cause an increase in the power of the transmit signal due the signal injection.

**Active Constellation Extension**
This is somewhat similar to TI method. This is a method which changes the constellation points to attenuate the peak power of the transmitting signal. The ACE method maps the original constellation point to an arbitrary point such that the minimum euclidean distance is maintained so as to minimize the PAPR of the cognitive OFDM. Constellation points can be of three types as: inner points, boundary points, and corner points.

From Fig. 3, it’s clear that the inner points of the 16-QAM (Quadrature Amplitude Modulation) cannot be extended. The boundary points can only be extended only in one direction whereas the corner points of 4-QAM and 16-QAM can be extended along the shaded region. For a CR OFDM system, moving into the shaded region is to add either sinusoidal or co-sinusoidal signal at a particular frequency to the transmitted signal. While extending the constellation points, the average power of the system increases [19]. Some of the advantages of ACE are: there is no loss of data, no degradation in system performance, lower BER as compared to other techniques and doesn’t bear side information just like SLM. The ACE method is best suited for small constellation size such as BPSK (Binary Phase Shift Keying), QPSK (QuadraturePhase Shift Keying), and 16-QAM. As the constellation size increases, the ability to reduce PAPR decreases linearly [5].

**SIDELOBE SUPPRESSION TECHNIQUE**

**Constellation Adjustment**
A new method called CA is used to reduce the sidelobe power of a cognitive OFDM signal without degrading the throughput or the error performances. This method iteratively adjusts the constellation points that are close to the bandwidth used by the subcarriers. Here, each data symbols have different levels of power and the subcarriers that are close to the PU’s induce the maximum sidelobe power. The constellation points of these subcarriers are adjusted such that the average power of these subcarriers is minimized. For every iteration, constellation points of two subcarriers are adjusted accordingly and the subcarriers corresponding to the lowest sidelobe power is chosen for data transmission. Thus the impact of high power PU’s are reduced. Even though, this method suppresses sidelobe it doesn’t account for PAPR reduction. The main plus points of this method are: they do not require any storage element at the transmitter and receiver section, also there is no degradation of BER performance [20].

**Active Interference Cancellation**
In this technique, instead of turning off a large number of tones, two special tones known as Active Interference Tones are defined at the edge of the interference band. These tones help in the cancellation of interference in that band. The value
of the tone can determined arbitrarily, without affecting the data tones due to the orthogonality relationship. Though, this technique can significantly suppress large spectrum sidelobes, but it results in an increase in PAPR of the system. The AIC is sensitive to cyclic prefix size and creates a small spectrum notch. Moreover, the use of high power may results in the spectral flatness of the transmitted signal and it can also increase the inter-carrier interference (ICI) in case of a Doppler spread or a frequency offset error at the receiver [21].

**Extended Active Interference Cancellation**

The main objective of the sidelobe suppression is to reduce the power spectral density (PSD) of the transmitted signal in allowed out-of-band ranges. The aim of EAIC technique is to add some extended active interference cancellation signals to minimize the large sidelobe. The cancellation signal consists of tones that are spaced closer than the cognitive OFDM subcarriers interval, thus eliminating the sidelobe power of the target spectrum. This method offers less implementation complexity and one of the efficient methods to reduce the sidelobe to an extent. Moreover, the EAIC scheme does not cause any interference to adjacent OFDM symbols and processing delay at the transmitter. Also it is capable of achieving good sideloop suppression without causing any noticeable symbol error rate (SER) degradation [22].

**Pulse Shaping**

For an OFDM spectrum, there will be a main lobe and a number of sideloops with reduced sideloop peak. At the peak of every carrier, there exist a spectral null because of this there won’t be any interference between the carriers since they are orthogonal to each other. The components of all other carriers are zero at spectral null. When the orthogonality of the system is lost, the spectral null does not coincide with the peak of individual carriers. Thus some sideloop power exists at the center of the individual carriers which is called ICI power. The ICI power shows a linear increase as the frequency offset increases. The ICI power needs to be suppressed by pulse shaping filter effectively. Several shaping-pulses have been introduced in the literature such as rectangular pulse, raised cosine pulse, double jump pulse, a family of pulse named as power of sech was used to reduce the effect of large spectrum sideloop of cognitive OFDM. Out of these pulses mentioned above, sech pulse has lower sideloop than the other pulses [23].

**Orthogonal Projection**

OP is an efficient method for sidelobe suppression. The implementation complexity is less in nature when compared to other schemes. This method uses OP matrix and employs few reserved subcarrier for recovering the distorted signal in the receiver. At some desired frequency points, zero emission can be obtained by the use of OP matrix, while suppressing emissions at neighboring frequencies. Inter symbol interference (ISI) between data symbols introduced by pre-distortion matrix can be eliminated by the use of reserved carrier. OP offers effective hardware implementation and is a flexible technique. It is possible to combine pre-processing techniques such as power loading under the condition that the OP should be implemented after the processing technique [24].

**Adaptive Symbol Transition**

The OFDM subcarriers are not able to generate spectrum nulls due to high spectrum sideloop. The OFDM symbols are extended in time domain. These extensions are used to reduce the symbol transition between the consecutive symbols. Based on the value of LU center frequency and bandwidth of the system it is possible to calculate value of the symbol extension. Thus, the symbol extension or transition signal is adaptively optimized based on transmitted data and detected LU bands to suppress the interference to LU. This method does not introduce any peaks to the signal, since the transition signal is optimized to smooth the symbol transition. Thus, the PAPR of the system is not affected by this method. This method achieves a significant amount of gain than the conventional method of suppressing the sideloop i.e., by the method of introducing guard bands [25].

**CONCLUSION**

Cognitive radio addresses spectrum crowding and OFDM is widely used as an effective transmission method for wireless communication systems. The requirements of CR are well satisfied by OFDM. This survey paper finds the two main limitations of Cognitive OFDM; high PAPR and large spectrum sideloop. Various techniques have been proposed to reduce PAPR and spectrum sideloop. The PAPR reduction methods effectively attenuate the PAPR; however, they don’t suppress sideloop. Also, there are many sideloop suppression methods that can suppress the sideloop power of an OFDM-based CR system, all of them do not consider PAPR reduction. As a future extension, combine PAPR reduction technique with sideloop suppression technique, thus jointly reducing PAPR and suppressing sideloop with better system performance.

**REFERENCES**


