IJICTR International Journal of Information & Communication Technology Research
CSRI

Volume 5- Number 2- Spring 2013 (19-26)

Deep Out-of-Band Radiation Reduction By Using Joint Filterbank and Cancellation Carriers in Cognitive Radios

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Received: August 24, 2012- Accepted: February 13, 2013

***Abstract*—A deep spectrum sculpting is necessary to enable coexistence between a cognitive radio (CR) user and a licensed user which has low dynamic range and is susceptible to interferences. In this paper, we propose to use joint filter-bank based multicarrier system and cancellation carriers to guarantee an almost free out-of-band interference transmission and keep the quality of services of licensed adjacent bands unchanged. We investigate the performance of the proposed method with different well-known existing methods from viewpoints of the average level of out-of-band power, spectral efficiency, and computational complexity.**

Keywords- Filter-bank; cancellation carrier; deep spectral mask; out-of-band radiation; cognitive radio.

I. INTRODUCTION

Due to emersion of new wireless standards and plethora of demands to access empty spectral resources, the tele-communication world has been faced an exhaustive challenge. The report of spectrum efficiency working group of federal communication commission (FCC) in 2002 revealed that a large amount of licensed spectrum are underutilized [1]. Recently, cognitive radios (CRs) are considered as a promising solution to the current low efficiency of the radio spectrum.CRs are intelligent and adaptive transcievers which can make opportunistic access to unused portions of spectrum by adapting the radio's operating parameters, while significant interferences are not introduced to the adjacent licensed bands [2].For example, IEEE 802.22 (WRAN) standard has been developed based on CR technology to provide broadband internet access for rural envirements by using white spaces in TV frequency spectrum [3].

An important feature of physical layer of CRs is provding almost free out-of-band (OOB) interference transmission. Therefore, the type of employed air interface technique should be such that the quality of service of licensed users (LUs) are kept unchanged while the spectral efficiency of CR user (CRU) is being maximized.Orthogonal frequency division multiplexing (OFDM) is a well-known candidate in physical layer of CR systems due to its flexibility in transmitting on non-contiguous frequency bands and ability to combat fading channels [4]. However, OFDM suffers from unwanted high OOB radiation due to its rectangular time domain symbol shaping [5]. Hence, beside the OFDM technique,a

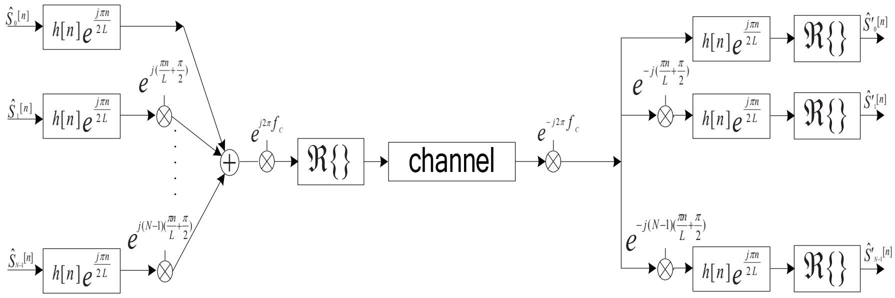

Figure.1. A CMT transceiver configuration [25]

supplementary spectrum shaping method should be considered in physical layer of CRs to satisfy mandatory spectral mask. These methods which are widely studied in literature, recently, include; guard bands in frequency domain, windowing [6-7],adaptive symbols transition (AST) [8], additive signal method (ASM) [9], cancellation carriers (CCs) [10-12], extended active intereference cancellation (EAIC) [13], subcarriers weighting (SW) [14], constellation expansion (CE) [15], multiple choice sequences (MCS) [16], coding techniques such as orthogonal projection (OP) [17], inside or cross mappings (IM or CM) [18], and etc [19]. Each method has its own pros and cons.

Using guard bands or nullifying those subcarriers at the edges of OFDM signal spectrum and extending the transmission symbol by windowing in time domain to smooth the symbols transition, sacrifice the spectral resources. The smoothing process in AST is done by adding an extension to the transmission symbols and in ASM, a complex-valued sequence is optimized and is added to the OFDM symbols. Both methods mitigate the OOB radiation through solving an optimization algorithm (OA) at the price of increasing the bit error rate (BER) of system. The CCs employ a few subcarriers at the edges of spectrum to be modulated by a complex-valued through an OA to cancel out the OOB radiation of data subcarriers. In this method, the BER increases and the system becomes more sensitive to inter-carrier interference and size of cyclic prefix (CP). In SW, the subcarriers are weighted through an OA under specific constraints such that the OOB power is minimized while the new achieved symbol and the original one remain in the same decision region. So this method is not suitable in high order constellation sizes (i.e. 16QAM, 64QAM ...) as the BER will increase significantly. In CE, the size of a constellation is doubled such that each point in the main constellation can be mapped into two different points. By using an iterative algorithm for mapping the symbols on new constellation and selecting the best point, the OOB power is minimized at the price of BER increasing. Similar to SW, CE is not applicable in high order modulation schemes. In MCS, the sequence of data-symbols is transformed into different sequences and one with the lowest OOB radiation is selected for transmission.

This method needs side information and has high computational complexity. OP is a precoder technique which uses signal predistortion to suppress OOB power. The performance of this method is very high in OOB rejection but it increases the BER of system, considerably. Moreover, IM and CM can mitigate OOB radiation at the cost of decreasing effective bit rate. Therefore, this scheme may not be preferred for ultra high data rates applications.Among all existed spectrum shaping techniques, CC outperforms than others due to its simplicity, reliability and high OOB interference suppression capability. Hence, recently, it has been proposed to be used in some draft of CR based IEEE standards [20].

As an alternative to OFDM, filter-bank based multicarrier (FBMC)systemsare another air interface candidate in physical layer of CRs which can solve the shortcomings of OFDM system. They include; wavelet packet multicarrier (WPM) [21], filtered multi-tone (FMT) [22], cosine modulated multi-tone (CMT) [23], and staggered modulated multi-tone (SMT) [24]. In these methods, a well-designed prototype filter is employed to shape spectrum of each subcarrier and guarantee a desired spectral containment.

CMT is the first FBMC system which is proposed by Chang in the 1960s [25]. With this system, transmitting a parallel set of pulse amplitude modulated(PAM) symbol sequences through a bank of overlapping vestigial side band (VSB) filters was implemented. CMT has same concept as the discrete wavelet multi-tone (DWMT) which is well-known in data transmission in digital subscriber line (DSL) [26]. Indeed, both techniques transmit real-valued modulated signals. However, the difference between two systems is originated from different structures employed at the receiver. An extension to CMT system is SMT which is proposed by Saltzberg [25]. In fact, SMT is used to transmit complex QAM symbols. It is shown that a perfect reconstruction FBMC based on QAM symbols can be implemented by creating half symbol shift between the real and imaginary parts of the QAM symbols when a time-frequency localized prototype filter is used as transceiver pulse shaping [24]. FMT is another FBMC system which is firstly designed for DSL applications. In this system a bank of filters which do not overlap with each other in frequency domain is used to transmit data. The concept of FMT is very similar to conventional frequency division multiplexing (FDM) methodology which separates a certain bandwidth to several small disjoint portions. Therefore, FMT is not bandwidth efficient compared to other FBMC schemes. In WPM systems, a multi stage tree structured interpolated finite impulse response (FIR) filters are used to decompose a channel into several orthonormal bases. At the receiver, the decimated match filters of the transmitter counterpart are employed to demodulate received data [20].

In fact, the principle of all FBMC systems is same; however the differences between various methods are originated from the types of employed prototype filter, being purely real or complex modulated symbols, and frequency channelization [27].Unlike OFDM systems, FBMC does not need guard bands. Furthermore, FBMC mitigates the problem of channel distortion by filtering of subcarriers instead of CP extending of time domain symbol. As a result, they are more spectrally efficient than OFDM systems. However being computationally expensive is the only shortcoming of FBMC systems [27].

CRUs should suppress the OOB radiation very deeply when LUs have low dynamic range and are susceptible to interference. In this paper, we introduce a new joint FBMC and CC scheme to guarantee an almost free OOB interference transmission in CRs. Here, we consider CMT as a FBMC system, because this scheme has the maximum possible bandwidth efficiency [25]. However, the proposed technique can also be applied to other mentioned FBMC schemes just with small modification.

We investigate the performance of a few well-known OOB suppression techniques in OFDM systems and compare them with joint CMT and CCscheme from viewpoints of suppression capability, system throughput, and computational complexity.

This paper is organized as follows: Section II presents efficient implementation of CMT system. In Section III, joint “CC and CMT” scheme is proposed and formulated.Finally, in Sections IV and V simulation results and conclusion are drawn.

II. EFFICIENT CMT IMPLEMENTATION

In a CMT system, a high-rate stream of PAM symbols is splitted into$N$ parallel low-rate real data streams and each is modulated on different VSB subcarriers [23, 25]. In order to transmit Ncomplex data symbols, i.e. QAM symbols, one may split the channel in$2N$ subcarriers such that each of which is modulated by a real data symbol corresponding to real or imaginary part of a QAM symbol.

According to Fig. 1, aCMT system is constituted of two main parts namely, synthesis filter-bank (SFB) and analysis filter-bank (AFB) that are corresponding to transmitter and receiver, respectively. The subcarriers are shaped by frequency shiftingof low pass prototype FIR filter $h[n]$which is centered at$f_0 = \frac{1}{4L}$, i.e.$h[n]e^{jk\frac{\pi n}{2L}}$, where L is the rate of symbol transmission. Suppose that a sequence of low-rate PAM symbols is described by:

$$\hat{S}_k[n] = \sum_{l} s_k[l]\,\delta[n-lL], \tag{1}$$

where $s_k[l]$, $k = 0,1,\dots,N-1$, are real PAM symbols. The baseband time-domain signal at the end of the transmission is obtained by:

$$x[n] = \sum_{k=0}^{N-1} x_k[n], \tag{2}$$

which$x_k[n]$ is the time-domain signal of kth subcarrier and is achieved by:

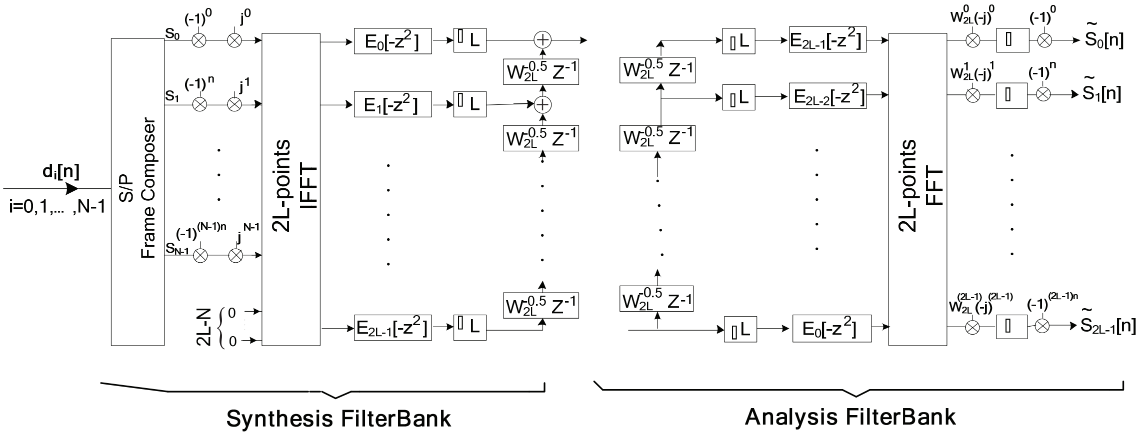

Figure. 2.An efficient CMT trans-multiplexer representation

$$x_k[n] = \left(\hat{S}_k[n] * h[n]e^{\frac{j\pi n}{2L}}\right)\left(e^{jk\left(\frac{\pi}{L}n+\frac{\pi}{2}\right)}\right) \quad (3)$$
$$= \sum_l (-j)^l j^k (-1)^{kl} s_k[l] h_k[n - lL] W_{2L}^{-\frac{n}{2}},$$

where$*$denotes convolution and$h_k[n] = h[n]W_{2L}^{-kn}$so that $W_L = e^{-j\frac{2\pi}{L}}$. The Z-transform of $x_k[n]$ is obtained by:

$$X_k(z) = \sum_n x_k[n]z^{-n}$$
$$= j^k H_k(z) \sum_l (-1)^{kl} s_k[l] z^{-lL}$$
$$= j^k H_k(z) S_k((-1)^k z^L), \quad (4)$$

where $H_k(z) = \sum_n h_k[n]Z^{-n}W_{2L}^{\frac{-n}{2}}$.

For efficient implementation of CMT, we use $2L$ poly-phaserepresentation [28] of $H_k(z)$ by transforming $n \rightarrow p + 2mL$ sothat $p \in [0, 2L-1]$, and $m \in (-\infty, \infty)$. We define $e_p[m] = h[2mL + p]$, therefore, we have:

$$H_k(z) = \sum_{p=0}^{2L-1} z^{-p} W_{2L}^{\frac{-p}{2}} \left(\sum_m (-1)^m e_p[m] z^{-2Lm} \right) \quad (5)$$
$$= \sum_{p=0}^{2L-1} E_p(-z^{2L}) z^{-p} W_{2L}^{\frac{-p}{2}} W_{2L}^{-kp}.$$

Finally, according to (2), we can write:

$$X(z) = \sum_{k=0}^{N-1} X_k(z)$$
$$= \sum_{p=0}^{2L-1} \left(\left(zW_{2L}^{0.5}\right)^{-p} E_p(-z^{2L}) \left(\sum_{k=0}^{N-1} j^k S_k((-1)^k z^L) W_{2L}^{-kp} \right) \right) \quad (6)$$

According to (6), and the properties of multi-rate systems [29], SFB in Fig. 2 is achieved. After similar derivations for receiver, one can implement AFB, effectively, as illustrated in Fig. 2. The computational complexity of CMT can be approximated by calculating the number of real multiplications which are necessary to evaluate one CMT symbol. Therefore, the number of real multiplications in SFB is the sum of the multiplications of $2L$-point inverse fast Fourier transform(IFFT), N branches of active poly-phase filters and Nmultiplicationsin parallel to serial converter. Hence, the computational complexity for each symbol transmission in CMT system is:

$$C_{SFB} = 2L(\log_2 2L - 3) + 4 + 2NK + 2N, \quad (7)$$

where$K$ is the overlapping factor and equals to the number of elements of each poly-phase branch. The trivial preprocessing before IFFT operation is assumed to be multiplication-free. Also the IFFT is considered to be implemented using Split-Radix algorithm [30].

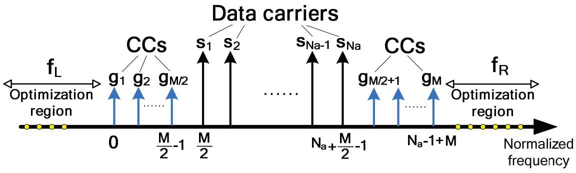

Figure. 3.Subcarriers arrangement in a CMT system

III. JOINT CANCELLATION CARRIER AND CMT

Assume that $N_a + M$ vestigial side-band subcarriers are available in a CMT system. $N_a$subcarriers areused for transmitting PAM symbols and M subcarriers are appendedat both edges of the signal spectrum to be weighted dynamically to suppress OOB radiation. According to Fig. 3, let$\boldsymbol{d}_n = [s_1[n], \dots, s_{N_a}[n]]$ consists of modulated data of N_a subcarriers at time index n, where $s_k[n]$ is a real symbol and modulate k-th subcarrier. Also $\boldsymbol{g}_n = [g_1[n], \dots, g_M[n]]$ consists of M auxiliary data at time index n, which modulate $M/2$ right- and left-hand side reserved subcarriers. Let $\boldsymbol{\omega}_d = [\frac{M}{2}, \dots, N_a+\frac{M}{2}-1]$ and $\boldsymbol{\omega}_g = [0, \dots, \frac{M}{2}-1, N_a+\frac{M}{2}, \dots, N_a+M-1]$ be the corresponding subcarrier indices of N_a data carriers and M CCs, respectively. Therefore the total spectrum of N_a data carriers at time index n is obtained by$S_d^n(f)$:

$$S_d^n(f) = \sum_{k \in \boldsymbol{\omega}_d} (-1)^{kn} j^k s_k[n] \, \mathcal{H}\left(f - \frac{K}{4L}\right), \quad (8)$$

where$\mathcal{H}(f - K/4L)$ is the spectrum of k-th VSB subcarriers and is achieved by fast Fourier transformof$h[n]e^{jk\frac{\pi n}{2L}}$. The spectrum of transmitted signal when $\boldsymbol{d}_n$ is sandwiched between CCs is obtained by$S_T^n(f)$:

$$S_T^n(f) = S_d^n(f) + \sum_{k \in \boldsymbol{\omega}_g} (-1)^{kn} j^k g_k[n] \, \mathcal{H}\left(f - \frac{K}{4L}\right) \quad (9)$$

The target is to find auxiliary values of $\boldsymbol{g}_n$ such that power of $S_T^n(f)$ in OOB regions is minimized. Let f_R and $f_L$be the frequency indices of right- and left-hand side of OOB regions, respectively. Hence, for simplicity, we take only y samples with equal distancefrompower spectrum of (9) in each of f_R and f_L region. Therefore, the optimization problem is formulated as the following least square problem with quadratic inequality:

$$\min_{g_k[n], k \in \boldsymbol{\omega}_g} \|S_T^n(f_i)\|^2 \quad subject\ to \quad \|\boldsymbol{g}_n\|^2 \leq \alpha, \quad (10)$$

where$\|.\|$ stands for Euclidean norm, and $f_i \subseteq f_L$ for $i = 1, .., y$ and $f_i \subseteq f_R$ for $i = y + 1, .., 2y$. The quadratic constraintlimits the maximum power of

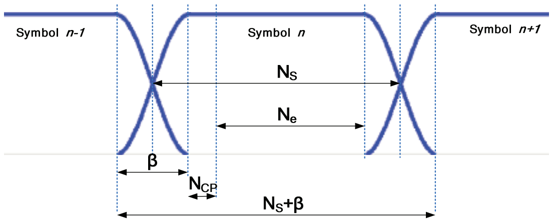

Figure. 4.Effect of windowing on OFDM symbols

CCs to α due to desired signal-to-noise ratio (SNR)loss. If the total active data symbol power is normalized to N_a at thetransmitter, the maximum SNR loss due to appending CCs is $\gamma_{max} = 1 + \frac{\alpha}{N_a}$ [10].

The computational complexity of CC method has been evaluated in [31], recently. The numbers of real multiplications per each symbol transmission either with a new system configuration (C_{config}) or without that (C_{Tx}) are estimated as follows:

$$C_{config} = 6M^3 + 8M^2y + 12M^2 + 8My + M \qquad (11)$$

$$C_{Tx} = 12M^2 + 8My + M. \qquad (12)$$

A system configuration is necessary when numbers of $N_a$or M are changed during transmission. However, when these parameters are kept unchanged, the complexity of system per each transmission is reduced to (12) due to saving by nonrecurring of some preliminary computations.

IV. SIMULATION RESULTS

Assume that $N_a + M = 64$ subcarriers with predefined subcarriers' spacing are available for transmitting 1000 randomly generated BPSK symbols in a CR scenario. Suppose that when CC method is not employed, all 64 subcarriers are used to transmit data. We consider an OFDM system with rectangular pulse shaping and $N_{CP} = N_e/4$, as a reference system, where N_e is duration of an OFDM symbol. Here, we investigate the performance of joint "CMT and CC" scheme with four types of transmission schemes including: OFDM;"OFDMandraised cosine windowing"; joint "OFDM,CC, and windowing"; and CMT. For designing theprototype filter of CMT scheme, the procedure of square-rootNyquist filter design which is developed in [32] is employed. In this paper, the length of prototype filter is equal to $2LK$, where $L = 64$and K can take different values between three up to six. In CC method, $y = 20$ samples per each OOB region are taken for optimization problem. We remind that in windowing the effective symbol duration of an OFDM symbol is increased from $N_e$to N_s by a raised cosine window defined in (13). Each symbol is extended by $N_{CP} + \beta$ cyclic prefix (CP) samples and βcyclic suffix samples and overlap with its adjacent symbols according to Fig. 4 [6]. In simulations, we fix $N_{CP} = N_e/4$ samples and vary β from $N_{CP}/8$to $N_{CP}/2$.Moreover, the computational complexity overhead due to windowing is estimated as4β.

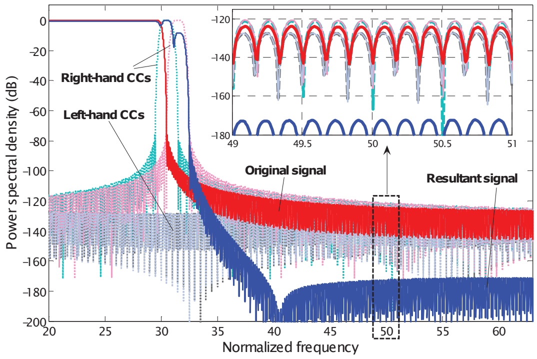

Figure. 5. The cancellation procedure of joint CMT and CC method

$$W(n) = \begin{cases} 0.5 + 0.5\cos\left(\pi + \frac{n\pi}{\beta N_s}\right) & 0 \le n < \beta N_s \\ 1 & \beta N_s \le n < N_s \quad (13) \\ 0.5 + 0.5\cos\left(\pi + \frac{(n-N_s)\pi}{\beta N_s}\right), & N_s \le n < (1+\beta)N_s \end{cases}$$

The suppression capability or the average level of OOB power (ϵ) which is measured by calculating the average of power spectral density (PSD) located in OOB regionsisdefined by (14), where N_t is the number of total PSDsamples of signal in OOB regions:

$$\varepsilon = 10\log\left(\frac{1}{N_t}\sum_{f_i \in \{f_L, f_R\}} |X(f_i)|^2\right). \qquad (14)$$

Fig. 5 depicts the effectiveness of joint "CMT and CC" scheme in deep OOB power suppressionwhen one CMT symbol with parameters; $\alpha = 0.2$, $K = 4$, $M = 4$ CCs is transmitted. In this demonstration, we consider all subcarriers convey $d_n = [1,..,1]$. Also Fig. 6 is brought to compare the suppression capability of joint "CMT and CC" scheme with other techniques.

It is clear that reference system cannot satisfy a good spectral containment, solely. Using two CCs at each side of the signal spectrum with $\alpha = 0.1$ can reduce almost 7dB OOB power compared to reference system. It is worth to mention that CC method is sensitive to CP size, however, when zero prefix is employed one can reduce more than 7dB OOB power [31]. Raised cosine windowing shows better suppression than CC method so that with $\beta = N_{CP}/2$can suppress almost 4dB more OOB power compared to CC ($\alpha = 0.1$) method. Furthermore, by increasingβ, more power reduction can be achieved at the cost of more redundancy in bandwidth efficiency. Using joint "windowing and CC" scheme can solve this problem and mitigate more OOB interferences so that with former assumptions of α and β more than 21dB suppression is achieved compared to raised cosine windowing. However, the latter investigated scheme cannot annihilate OOB power less than level of -60 dB. In some scenario, especially when dynamic ranges of adjacent users are noticeably different, more suppression is necessary to maintain the quality of service of LU [33].

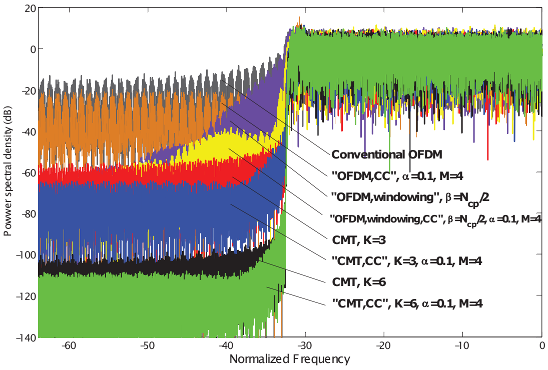

Figure. 6. PSD representation of different schemes

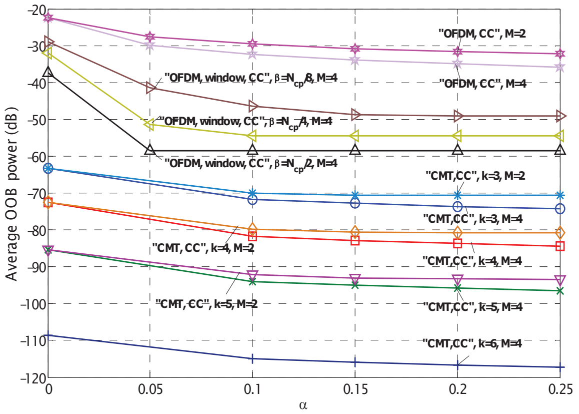

Figure. 7. Effect of ,M, α, and β on average level of OOB

Fig. 6 shows that CMT, ever with small overlapping factor, i.e. $K = 3$, can provide better suppression capability than other mentioned schemes. Moreover, when CC method is applied to CMT($K = 3$) almost10dB suppression can be seen compared to lattercase. Further suppression can be provided by increasing$K$, M, or α so that when they are assigned, respectively, 6, 4, 0.2, the level of OOB power is reduced up to $\varepsilon = -118$dBwhich is a noticeable rewardin OOB interference suppression of a CR system and provide deep spectrum mask.

Fig. 7 shows the effect of K, M, α, and βon average level of OOB power (ε). More detailed results and comparisons between different schemes from viewpoints of average OOB power level (ϵ), relative spectral efficiency, and relative variations in computational complexity per each symbol transmission or system configuration toward reference systemare collected in Table 1. Spectral efficiencyindicates the average bits which are sent in a unit of time per 1Hz of bandwidth. Also relative spectral efficiency is the ratio of spectral efficiency of a system toward reference system. Furtheremore, redundancy in computational complexity is defined by calculating the relative complexity of each system for transmitting each symbol toward our reference system.

Here, we put more emphasis on the computational complexity of different schemes per each symbol transmission, since the complexity for each system configuration is performed only once. When all 64 subcarriers in reference system are used for transmitting data, the spectral efficiency of 0.4 bit/s/Hz is achievedat the cost of using 516 real multiplications. Furthermore, when four CCs are appended to OFDM signal, only 60 subcarriers convey data, hence, the relative spectral efficiency is reduced to 0.937. In this case, the computational complexity for each symbol transmission increasesalmost 2.6 times.

In joint "OFDM and windowing" scheme, the specral efficiency is reduced when β is increased. However, this scheme can reduce more OOB power, compared to CC method, when β is more than $N_{CP}/2$. According to Table 1, this rewardis achieved at negligible increase in computational complexity. By using joint "OFDM, windowing, and CC" a considerable OOB suppression is achieved, at the prices of decreasing spectral efficiency and costing 2.74 times more computational complexity, compared to reference system.

As was mentioned before, CP extension is not employed in CMT, moreover, each symbol in time domain is overlaped with K adjacent symbols [23], therefore, superior increase in spectral efficiency of CMT system, compared to reference system,is achieved. By increasing the overlapping factor, K, from three up to six, throughput of system is degraded slightly and relative complexity is increased from 1.99 to 2.73 which are acceptable against the achieved 45dB reward in OOB power suppression.

Ever by employing CC in CMT system, the spectral efficiency of the scheme is more than reference system. By using four CCs in joint "CMT and CC" scheme and considering $\alpha = 0.1$, and $K = 6$, the average OOB power is reduced up to -118dB and more than 2.3 times throughput is acheived at the cost of 5.15 times more computational complexity per each symbol transmission, compared to reference system. It seems that this cost is rational for achieving the rewards of an almost free inrterference transmission and 2.3 times more throughput than refernce system.

We should note that the extracted relative spectral efficiencies in Table 1 is related to transmission ofPAM symbols. However, the number of subcarriers in CMT should be doubled in a certain bandwidth, when other modulation schemes, i.e. QPSK or QAM, are employed, since each subcarrier in CMT conveys real data. Still, our simulations show that relative spectral efficiency of CMT system with $K = 3$ is almost 1.237, when a complex constellation is employed. This amount of throughput is considerable, compared to other mentioned schemes.

In an overall comparison, an OFDM signal cannot provide a deep spectrum sculpting, singly. The well-known windowing method can improve its spectrum mask. However, more improvement is achieved by employing CC method, so that more OOB radiation is suppressed by using more cancellation carriers and dedicating more power to them.

TABLE.1.DETALED COMMPARISION OF DIFFERENT OOB POWER SUPPRESSION SCHEMES.

Method		Average OOB power level (ε) [dB]	Relative spectral efficiency	Relative computational complexity	
				Per System Config.	Per Symbol Tx.
OFDM+Window	$\beta = {}^{N_{CP}}/_{2}$	-36.3	0.909	1.12	1.12
	$\beta = {}^{N_{CP}}/_{8}$	-28	0.975	1.03	1.03
OFDM+4×CCs	$\alpha = 0.1$	-32.4	0.937	8.32	2.62
	$\alpha = 0.2$	-35.9	0.937	8.32	2.62
OFDM+ Window+4×CCs	$\beta = {}^{N_{CP}}/_{2}, \alpha = 0.1$	-58.5	0.852	8.45	2.74
	$\beta = {}^{N_{CP}}/_{2}, \alpha = 0.2$	-58.5	0.852	8.45	2.74
	$\beta = {}^{N_{CP}}/_{8}, \alpha = 0.1$	-46.5	0.914	8.35	2.65
	$\beta = {}^{N_{CP}}/_{8}, \alpha = 0.2$	-49.1	0.914	8.35	2.65
CMT	$k = 3$	-63.3	2.482	1.99	1.99
	$k = 6$	-108.6	2.467	2.73	2.73
CMT+4×CCs	$K = 3, \alpha = 0.1$	-72.8	2.327	9.31	3.61
	$K = 3, \alpha = 0.2$	-73.8	2.327	9.31	3.61
	$K = 6, \alpha = 0.1$	-115	2.312	10.92	5.15

Moreover, incorpoting CC method and windowing causes a deeper spectrum mask. But this amount of suppression does not always guarantee a safe coexistence of CRUs and LUs. FBMC techniques provide better spectrum shaping so that the depth of spectrum sculpting increases by increamenting overlapping factor. However, this reward is attained at the costs of increasing computational complexity, throughput loss, and system delay. Finally, the deepest spectrum mask is achieved in our proposed scheme (joint "CMT and CC") by costing more computational complexity compared to former case.

V. CONCLUSION AND FUTURE WORK

A joint "CMT and CC" scheme is proposed to provide deep spectrum sculpting for coexistence between a CRU and LUs. Simulation results shown thatwhen 60 subcarriers in a CMT system with $K = 6$ convey PAM symbols and four CCs with $\alpha = 0.1$ are appended at both sides of the signal spectrum, average OOB power level can be reduced up to-118dB. This amount of suppression is 10dB more than when a CMT is employed, solely. Also this scheme has another advantage which improves spectral efficiency almost 2.312 times more than corresponding OFDM system with CP size equals to $N_{CP} = N_e/4$. However, these rewards are achieved at the price of increasing 5.15 times computational complexity per each symbol transmission compared to an OFDM system.

The majority of computational effort in the proposed method is resulted from CC method and its optimization algorithm. Hence, for the future work, we can reduce the computational complexity by employing improved cancellation pulses instead of conventional sinc-shape OFDM subcarriers which have been recently proposed by authors in [30].

ACKNOWLEDGMENT

This work was supported in part by the CyberSpace Research Institute (ex ITRC).

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