# Sidelobe Reduction in Cognitive Radio Systems Using Hybrid Technique

Atif Elahi, Ijaz Mansoor Qureshi, Mehreen Atif, Noor Gul



***Abstract*—**Orthogonal frequency division multiplexing (OFDM) is one of the best candidates for dynamic spectrum access due to its flexibility of spectrum shaping. However, the high sidelobes of the OFDM signal that result in high out-of-band radiation, introduce significant interference to the users operating in its vicinity. This problem becomes more critical in cognitive radio (CR) system that enables the secondary users (SUs) users to access the spectrum holes not used by the primary users (PUs) at that time. In this paper, we present a generalized OFDM framework that has a capability of describing any sidelobe suppression techniques, despite of whether one or a number of techniques are used. Based on that framework, we propose cancellation carrier (CC) technique in conjunction with the generalized sidelobe canceller (GSC) to reduce the out-of-band radiation in the region where the licensed users are operating. Simulation results show that the proposed technique can reduce the out-of-band radiation better when compared with the existing techniques found in the literature.

***Keywords*—**Cognitive radio, cancellation carriers, generalized sidelobe canceller, out-of-band radiation, orthogonal frequency division multiplexing.

## I. Introduction

IN order to fulfill the increasing demand for high data rate and wireless services and at a same time coming up with the enhanced spectrum utilization, researches from all over the world have given a suggestion to utilize the spectrum resources efficiently [1], [2]. Spectrum policy task force (SPTF) appointed from Federal Communication Commission (FCC) in its report has shown that spectrum in use of licensed user also called as PUs is most of the time idle. The idea of CR which was first given by Mitola and Maguire [3] in 1999, is the solution to the above mentioned problem. The key issue in CR is dynamic spectrum sensing (DSS) used for the activation and deactivation of the spectrum. So, efficient use of spectrum results in the precise DSS. OFDM technique [4], [5] is a high performance modulation scheme for CRs due to its ability of dividing the available bandwidth into multiple narrow band orthogonal channels, insusceptibility to frequency selective fading, efficient use of spectrum by overlapping of subcarriers, and support for high data rate. The main challenge faced by OFDM is its sidelobes that result in high out-of-band radiation that is a cause of significant interference to the neighboring users. This is more crucial in CR systems where the un-licensed user is allowed to use the spectral hole which is not used by the licensed user at that time.

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There are many techniques found in literature to tackle the problem of out-of-band radiation that are classified into two main categories: time domain and frequency domain. Time domain techniques include windowing [6], [7], filtering [8], while frequency domain techniques include CCs [9]-[11], advanced CCs [12], advanced subcarrier weightings [13], constellation expansion [14], [15], precoding techniques [16]-[18], and GSC [19].

In this paper, we present the generalized OFDM framework that is capable of describing any out-of-band radiation technique, and a new tachnique has been proposed that is a combination of CCs and GSC to reduce the out-of-band radiation effectively. The effectiveness and reliability of the proposed technique is compared with the existing techniques found in the literature, which shows that the proposed techniques show better results.

The rest of the paper is organized as follows: in Sections II and III, we will discuss the system model and proposed technique, while in Sections IV and V simulations and results and conclusion of the paper are given.

## II. System Model

Consider that $M$ SUs opportunistically utilize the available spectral band identified with the help of DSS, which is un-occupied by un-licensed user. This available spectral band may be contiguous or non-contiguous in nature and can be divided into group of subcarriers. $\zeta = \left[n_0, n_1, \ldots, n_{N-1}\right]$. Consider $r$th SU employing the subgroup of subcarriers $\zeta_r \in \zeta$ where $\zeta_r = \left[n_0^r, n_1^r, \ldots, n_{N_r-1}^r\right]$, i.e. total number of subcarriers employed by $r$th SU is $N_r$. Also, consider that $g_n$ is the transmitted PSK modulated symbol over the nth subcarrier. The baseband signal over the $n$th subcarrier with one symbol duration is given as:

$$x_r\left(t\right) = \sum_{n=0}^{N_r-1} g_n \exp\left(j2\pi \frac{n}{T_S} t\right) I\left(t\right) \quad (1)$$

where $T_s$ is the duration of symbol, and $I$ ($t$) represents the windowing function defined as:

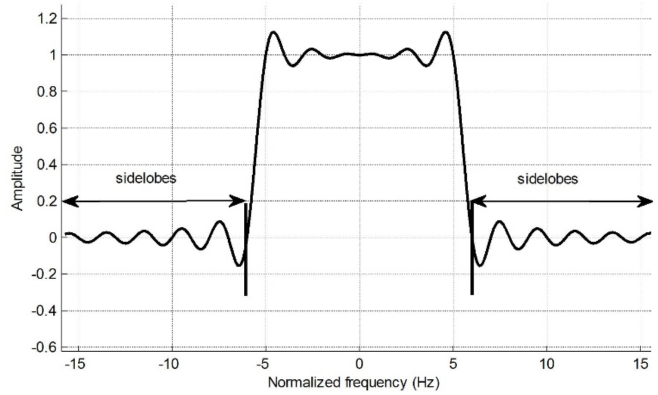


Fig. 1 Transmitted OFDM signal

$$I(t)=\begin{Bmatrix}1 & -T_g\le t\le T_s\\ 0 & otherwise\end{Bmatrix} \quad (2)$$

Here, $T_g$ represents the length of guard interval to eliminate the effect of intersymbol interference (ISI).

Frequency domain representation of a signal given in (1) as shown in Fig. 1 is obtained by taking its fast Fourier transformation:

$$X_r(f)=\sum_{n=0}^{N_r-1} g_n s_n(f) \quad (3)$$

where $s_n(f)=T\exp\left(-j\pi\left(T_s-T_g\right)\left(f-\frac{n}{T_s}\right)\right)\sin c\left(T\left(f-\frac{n}{T_s}\right)\right)$ and T represents OFDM symbol duration.

Power spectral density of the transmitted OFDM signal given in (3) of $r$th SU is given as:

$$P_r(f)=\frac{1}{T}E\left\{\left|X(f)\right|^2\right\}=\frac{1}{T}\mathbf{s}^T(f)E\left(\mathbf{gg}^H\right)\mathbf{s}^*(f) \quad (4)$$

Here, $\mathbf{g}=\left[g_0,g_1,...,g_{N_r-1}\right]^T$ and $\mathbf{s}(f)=\left[s_0(f),s_1(f),...,s_{N_r-1}(f)\right]^T$, respectively. As shown in Fig. 1, the sidelobes of the transmitted OFDM signal of $r$th SU are a cause out-of-band radiation which gives severe interference to the neighboring users including **PUs** and SUs. To protect the neighboring users from such an interference, the sidelobe should be suppressed effectively.

## III. Proposed Techniques

In this section, the proposed technique that consists of CC in conjunction with GSC based on our proposed generalized OFDM framework is presented as shown in Fig. 2.

Suppose that the input bit stream $\mathbf{a}_r=\left[a_0,a_1,...,a_{N_r-1}\right]^T$ of $r$th SU is first modulated with Phase shift keying (PSK), $\mathbf{g}=\left[g_0,g_1,...,g_{N_r-1}\right]^T$ is passed through serial to parallel (S/P) block.

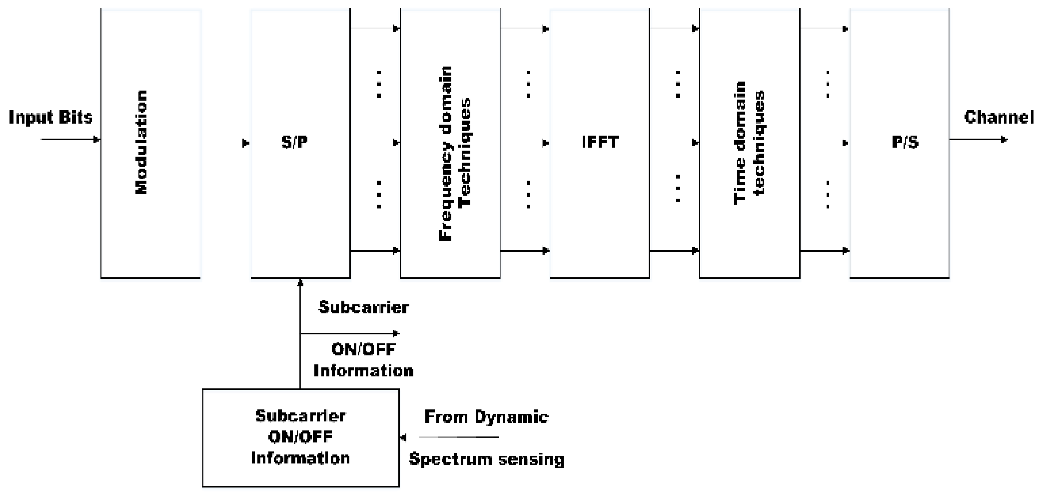


Fig. 2 Generalized OFDM Framework

These modulated symbols are supposed to be identically and independently distributed (iid), i.e.

$$E\left[\mathbf{gg}^H\right]=\mathbf{I}_{N_r\times N_r} \quad (5)$$

where **I** represents the identity matrix having dimension $N_r\times N_r$. After S/P, the symbols are then passed through frequency domain block whose output is given by:

$$\mathbf{d}=\mathbf{Qg} \quad (6)$$

where **d** represents the pre-coded symbol vector of $r$th SU having dimension $M_r \times 1$ and $M_r > N_r$ where $L = (M_r - N_r)$ represents the number of CCs inserted on either sides of the OFDM signal of the $r$th SU, while **Q** can be treated as precoding matrix having dimension $M_r \times N_r$ representing CCs technique defined as:

$$\mathbf{Q} = \begin{bmatrix} \mathbf{A}_{\frac{M_r}{2} \times N_r} \\ \mathbf{I}_{N_r \times N_r} \\ \mathbf{B}_{\frac{M_r}{2} \times N_r} \end{bmatrix} \quad (7)$$

Here, in (7), the identity matrix **I** represents the weights of the data subcarriers, while the two matrices **A** and **B** represent the optimized weights of the CCs. The resulting signal of $r$th SU will then be given by:

$$T_r(f) = \sum_{j=1}^{\frac{M_r}{2}} d_j s_j(f) + \sum_{n=1}^{N_r} d_n s_n(f) + \sum_{j=\frac{M_r}{2}+1}^{M_r} d_j s_j(f) \quad (8)$$

The signal given in (8) has a suppressed sidelobe. For further suppression, the signal is then sampled into $W_r$ samples and are collected in vector $\mathbf{y}_r$ with dimension $W_r \times 1$ and passed through GSC.

GSC is the straightforward form of linearly constraint minimum variance (LCMV), which converts the minimiztion problem having some constraint into an unconstraint [20]. It consists of two branches, the upper one and the lower one. The upper one contains a vector called as quiescent weight vector represented by $\mathbf{w}_q$ that preserves the incoming signal while the lower branch consists of blocking matrix **C** followed by adaptive weight vector $\mathbf{w}_a$. The blocking matrix **C** blocks the wanted portion of the signals and allows the un-wanted portion, i.e. allows the sidelobes while blocking the rest of the signal, and the adaptive weight vector $\mathbf{w}_a$ adjusts the amplitudes of the sidelobes such that when the signal from the upper branch and lower branch are subtracted, we get a signal with a suppressed sidelobe.

The output of the GSC is given by:

$$Z_r(f) = (\mathbf{w}_q^H - \mathbf{w}_a^H \mathbf{C})\mathbf{y}_r \quad (9)$$

Here, in (9), the term $\mathbf{w}_a$ is the adaptive weight vector whose function is to minimize the sidelobe that is a cause of out-of-band radiation. This adaptive weight vector modifies the amplitudes of the sidelobes such that, when the signals from the upper and lower branch subtract from each other, it will result in a signal with reduced sidelobes. The expression for $\mathbf{w}_q$, $\mathbf{w}_a$ and **C** is found in [19] is given by:

$$\mathbf{w}_q = \mathbf{C}_a \left(\mathbf{C}_a^H \mathbf{C}_a\right)^{-1} \mathbf{f}$$
$$\mathbf{C} = null\left(\mathbf{C}_a^H\right) \quad (10)$$

The optimized adaptive weight vector $\mathbf{w}_{a(opt)}$ is the one that minimizes the cost function given by:

$$J(\mathbf{w}_a) = \left(\mathbf{w}_q - \mathbf{C}\mathbf{w}_a\right)^H \mathbf{R}_\mathbf{y} \left(\mathbf{w}_q - \mathbf{C}\mathbf{w}_a\right) \quad (11)$$

i.e. $\min_{\mathbf{w}_a} \left(\mathbf{w}_q - \mathbf{C}\mathbf{w}_a\right)^H \mathbf{R}_\mathbf{y} \left(\mathbf{w}_q - \mathbf{C}\mathbf{w}_a\right)$ and on solving gives:

$$\mathbf{w}_{a(opt)} = \left(\mathbf{C}^H \mathbf{R}_\mathbf{y} \mathbf{B}\right)^{-1} \mathbf{C}^H \mathbf{R}_\mathbf{y} \mathbf{w}_q \quad (12)$$

Finally, we get:

$$\mathbf{w}_{GSC} = \mathbf{w}_q - \mathbf{C}\mathbf{w}_{a(opt)} \quad (13)$$

## IV. Simulations and Results

In this section, we consider that single SU operating in a spectrum hole detected with the help of DSS. Suppose that this SU divides the available spectrum holes into 16 sub-channels also called as subcarriers, in which e.g. a 64 – point FFT is applied for OFDM modulation. Each sub-channel is BPSK modulated whose power is normalized to 1. Here we are considering two CCs each on the left and right side of the data subcarriers. 20 sidelobes are reserved on both sides of the spectrum with one frequency sample taken in the middle of every sidelobe, resulting in $K_l = K_r = 10$ samples. For GSC, 301 samples of the signals are collected in vector **y**. Figs. 3-5 show the performance comparison of our proposed technique with different existing techniques found in the literature in terms of PSD that shows that our proposed technique gets better reduction of sidelobes as compared to the exiting techniques.

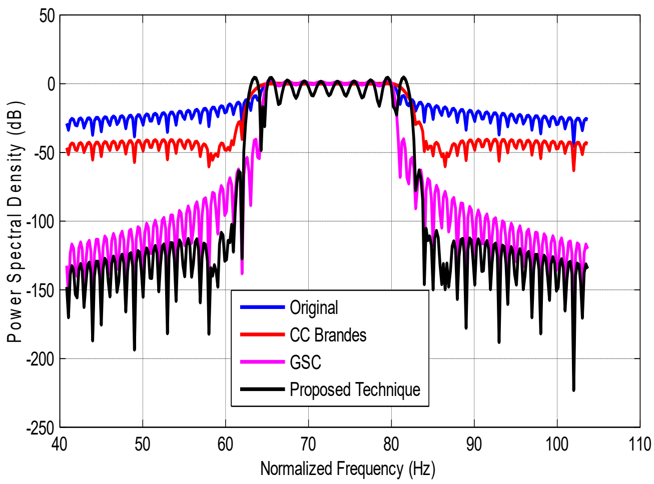


Fig. 3 Comparison of proposed technique with existing techniques

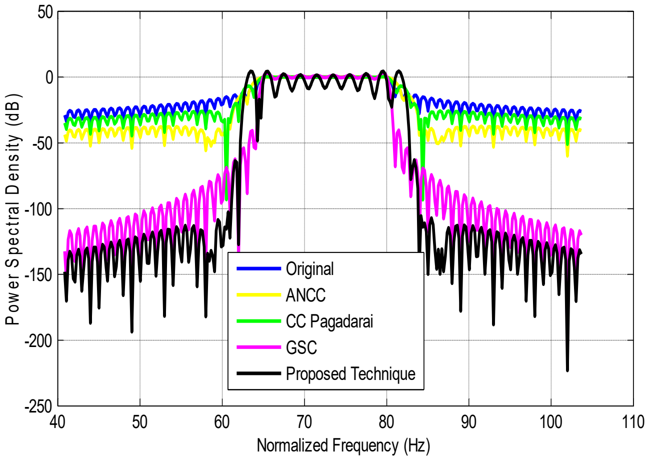


Fig. 4 Comparison of proposed technique with existing techniques

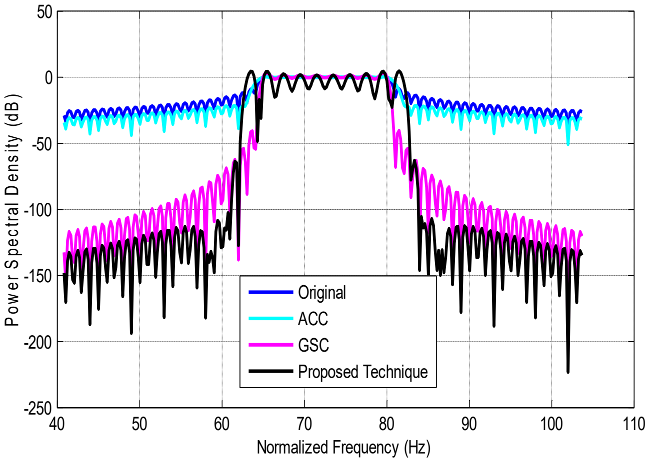


Fig. 5 Comparison of proposed technique with existing techniques

## V. Conclusion

In this paper, we have given a generalized OFDM framework that has an ability of describing any out-of-band radiation reduction techniques whether we are using single or multiple techniques. Based on that framework, we have proposed a technique that is a combination of CCs' technique which can also be represented with pre-coding matrices with GSC. The usefulness and reliability of the proposed technique in term of power spectral density is compared with the other techniques found in literature, which shows that our proposed technique gets better reduction of sidelobes.

## References

[1] B. Wang and K. J. R. Liu, "Advances in cognitive radio networks: A survey," *IEEE Journal of selected topics in signal processing*, vol. 5, no. 1, pp. 5–23, 2011.

[2] A. Goldsmith, S. A. Jafar, I. Maric, and S. Srinivasa, "Breaking spectrum gridlock with cognitive radios: An information theoretic perspective," *Proceedings of the IEEE*, vol. 97, no. 5, pp. 894–914, 2009.

[3] J. Mitola and G. Q. Maguire, "Cognitive radio: making software radios more personal," *IEEE personal communications*, vol. 6, no. 4, pp. 13–18, 1999.

[4] J. A. C. Bingham, "Multicarrier modulation for data transmission: An idea whose time has come," *IEEE Communications magazine*, vol. 28, no. 5, pp. 5–14, 1990.

[5] J. G. Proakis and M. Salehi, *Salehi Digital Communications*. New York, NY: McGraw-Hill, 2008.

[6] A. Sahin and H. Arslan, "Edge windowing for OFDM based systems," *Communications Letters, IEEE*, vol. 15, no. 11, pp. 1208–1211, 2011.

[7] J. Luo, W. Keusgen, and A. Kortke, "Optimization of time domain windowing and guardband size for cellular OFDM systems," in *Vehicular Technology Conference, 2008. VTC 2008-Fall. IEEE 68th*, 2008, pp. 1–5.

[8] D. Noguet, M. Gautier, and V. Berg, "Advances in opportunistic radio technologies for TVWS," *EURASIP Journal on Wireless Communications and Networking*, vol. 2011, no. 1, pp. 1–12, 2011.

[9] S. Brandes, I. Cosovic, and M. Schnell, "Reduction of out-of-band radiation in OFDM systems by insertion of cancellation carriers," *IEEE communications letters*, vol. 10, no. 6, pp. 420–422, 2006.

[10] S. Brandes, I. Cosovic, and M. Schnell, "Sidelobe suppression in OFDM systems by insertion of cancellation carriers," in *Vehicular Technology Conference, 2005. VTC-2005-Fall. 2005 IEEE 62nd*, 2005, vol. 1, pp. 152–156.

[11] A. Elahi, I. M. Qureshi, F. Zaman, and F. Munir, "Reduction of out of band radiation in non-contiguous OFDM based cognitive radio system using heuristic techniques," *J. Inf. Sci. Eng*, vol. 32, no. 2, pp. 349–364, 2016.

[12] A. Selim, I. Macaluso, and L. Doyle, "Efficient sidelobe suppression for OFDM systems using advanced cancellation carriers," in *Communications (ICC), 2013 IEEE International Conference on*, 2013, pp. 4687–4692.

[13] A. Selim and L. Doyle, "Real-time sidelobe suppression for OFDM systems using advanced subcarrier weighting," in *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, 2013, pp. 4043–4047.

[14] S. Pagadarai, R. Rajbanshi, A. M. Wyglinski, and G. J. Minden, "Sidelobe suppression for OFDM-based cognitive radios using constellation expansion," in *Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE*, 2008, pp. 888–893.

[15] D. Li, X. Dai, and H. Zhang, "Sidelobe suppression in NC-OFDM systems using constellation adjustment," *Communications Letters, IEEE*, vol. 13, no. 5, pp. 327–329, 2009.

[16] X. Zhou, G. Y. Li, and G. Sun, "Multiuser spectral precoding for OFDM-based cognitive radio systems," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 3, pp. 345–352, 2013.

[17] R. Xu and M. Chen, "A precoding scheme for DFT-based OFDM to suppress sidelobes," *IEEE Communications Letters*, vol. 13, no. 10, pp. 776–778, 2009.

[18] M. Ma, X. Huang, B. Jiao, and Y. J. Guo, "Optimal orthogonal precoding for power leakage suppression in DFT-based systems," *Communications, IEEE Transactions on*, vol. 59, no. 3, pp. 844–853, 2011.

[19] A. Elahi, I. M. Qureshi, Z. U. Khan, and F. Zaman, "Sidelobe Reduction in Non-Contiguous OFDM-Based Cognitive Radio Systems Using a Generalized Sidelobe Canceller," *Applied Sciences*, vol. 5, no. 4, pp. 894–909, 2015.

[20] A. Elahi, I. M. Qureshi, F. Zaman, F. Munir, and A. Umar, "Techniques for the suppression of sidelobes in a non-contiguous orthogonal frequency division multiplexing framework," *Applied Informatics Springer Berlin Heidelberg*, vol. 3, no. 1, p. 6, 2016.