Spectral Sculpting for OFDM Based Opportunistic Spectrum Access by Extended Active Interference Cancellation

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Abstract— **To enable coexistence between an OFDM based opportunistic spectrum access system and a primary user, we proposed two novel methods called EAIC (Extended Active Interference Cancellation) and EAIC-H (EAIC-Hybrid) for spectral sculpting of OFDM signal. In EAIC and EAIC-H, cancellation signals are added to OFDM signal to cancel interference in target spectrum band caused by data tones, so that interference perceived by primary user can be limited. The cancellation signal (EAIC tones) has longer time duration than that of OFDM symbol, which enables a better notching capability than that of most existing methods. Optimal weights of EAIC tones have been analyzed and given in this paper. Simulation results show that the proposed methods can obtain very deep spectral notches of about 80 dB. Although the EAIC tones cause certain interferences to OFDM data tones, the SNR degradation of OFDM system is very limited and it can be acceptable for high order modulation such as 64QAM. Compared with EAIC, EAIC-H provides a better tradeoff between notching performance and SNR degradation for high order modulation.**

Keywords-OFDM; opportunistic spectrum access; cognitive radio; interference cancellation; out-of-band radiation

I. INTRODUCTION

To meet the ever-growing need for spectrum resources, cognitive radio and dynamic spectrum access have been proposed [1][2] in recent years. One approach to share spectrum between primary and secondary spectrum users is opportunistic spectrum access (OSA), in which secondary user is allowed to identify and exploit local and instantaneous spectrum white space where the prime user is not present. Since secondary users may need to transmit over noncontiguous frequency bands, OFDM is an attractive candidate for modulation in OSA networks [3]–[5]. In OFDM based OSA system, to enable coexistence with primary user, the constituent tones/subcarriers can be turned off at the prime user's channel, creating spectrum notches to limit interference perceived by primary user. The concept of the coexistence between an OFDM based OSA system and a primary user is illustrated in Fig. 1.

A method called active interference cancellation (AIC) was proposed to create deeper notches [6]. In addition to turning off the tones overlapped with primary user's channel, AIC actively transmit certain signals on these tones and edge tones to cancel the interference caused by data tones. With five AIC tones, this method can create a notch of about 40 dB for target spectrum band within three OFDM tones. Although deeper notches can be created with more AIC tones, more reduction in system throughput is also resulted because data can not be transmitted on these AIC tones.

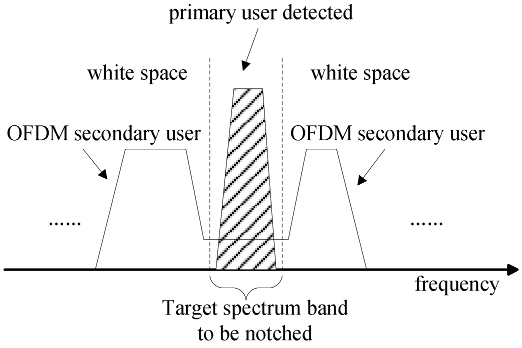

Fig. 1. OFDM based OSA secondary user coexist with primary user

To reduce the out-of-band radiation of the OFDM signal, the insertion of so-called cancellation carriers at the borders of the OFDM spectrum was proposed in [7] [8]. This technique can be directly applied to spectral sculpting of OFDM based OSA system and achieves similar performance as AIC. Subcarrier weighting was proposed in [9] and [10], which multiples the data subcarriers with subcarrier weights that were chosen such that sidelobes of OFDM signal were suppressed. This method avoided using additional spectral resources such as AIC tones and cancellation carriers. Another method referred to as additive signal, which was based on the addition of a complex-valued sequence to the original signal, was proposed in [11]. An optimization algorithm was used to determine the complex-valued sequence. Modified adjacent frequency coding was proposed in [12] for spectral sculpting problem in MB-OFDM WiMedia and the achievable notch

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depth was about 22 dB. Taking guard interval and windowing of OFDM signal into account leads to further reduction of out-of-band radiation. Proper combination of cancellation carriers and windowing was presented in [13]. Simulation results in [13] showed that spectral notches of more than 50 dB can be created. However windowing expands the signal in the time domain and results in further reduction of system throughput.

Through briefly reviewing technologies that can be applied to spectral sculpting for OFDM based OSA communications, it is noted that how to create deeper spectral notches with minimum sacrifice of spectrum resources is still an open research problem.

In this paper, we propose two novel methods called extended active interference cancellation (EAIC) and EAIC-Hybrid (EAIC-H), which are extended versions of AIC technique [6]. In EAIC and EAIC-H, to cancel interferences caused by data tones more effectively, AIC tones are extended to longer time duration and new EAIC tones in the frequency domain are introduced. Shortcoming of these methods is that the EAIC tones will cause certain interferences to the data tones and SNR degradation in OFDM systems. Simulation results show that the proposed methods can create very deep spectral notches of about 80 dB, and the SNR loss caused by EAIC tones is very limited and it can be acceptable for high order modulation such as 64QAM.

Throughout this paper, bold letters denote matrices and column vectors. $[\bullet]^T$ and $[\bullet]^H$ denote transpose and complex conjugate transpose, respectively.

The rest of this paper is organized as follows. System model and EAIC/EAIC-H method are presented in Section II. Optimal weights of EAIC tones are calculated in Section III. To demonstrate the effectiveness of the proposed methods simulation results are given in Section IV. The paper is concluded with a summary in Section V.

II. SYSTEM MODEL AND EAIC METHOD

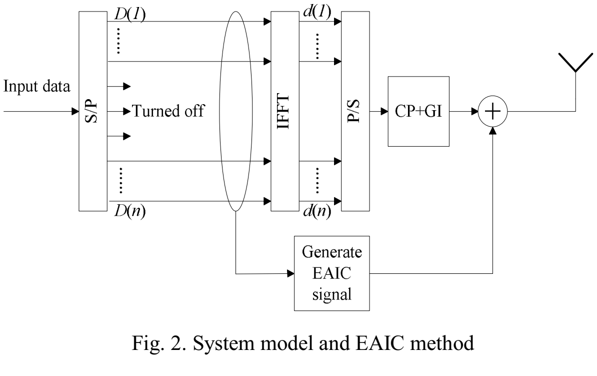

Fig. 2. System model and EAIC method

The complex envelope of one N-subcarrier OFDM symbol is expressed as

$$d(t)=\frac{1}{N}\sum_{k=0}^{N-1}D(k)\exp(j2\pi\times k\Delta f\times t)\qquad 0\le t<T \tag{1}$$

where Δf is the frequency interval between subcarriers, $D(k)$ is the data symbol modulated on subcarrier k, and T is the time duration of one OFDM symbol. Sample $d(t)$ with frequency $f_s=N\Delta f$, the OFDM signal in the discrete time domain is

$$\begin{aligned} d(n)&=\frac{1}{N}\sum_{k=0}^{N-1}D(k)\exp(j2\pi\times k\Delta f\times\frac{n}{f_s}) \\ &=\frac{1}{N}\sum_{k=0}^{N-1}D(k)\exp(\frac{j2\pi kn}{N})\qquad n=0,1,\cdots,N-1 \end{aligned} \tag{2}$$

For OFDM system with non-zero cyclic prefix (CP) and/or guard interval (GI), the length of $d(n)$ should be longer to include samples of CP and GI.

In OFDM based OSA system, the constituent tones/subcarriers are turned off at the prime user's channel, creating spectrum notches to limit interference perceived by primary users, i.e. $D(k)$s for certain k are set to zero in (2). To actively cancel the interference within the target spectrum band coursed by data tones, in this paper, an Extended AIC signal $c(n)$ of length MN is added to $d(n)$, where M is an integer larger than 1. The system model and EAIC method are illustrated in Fig. 2. Then the transmitted signal for one OFDM symbol is described as

$$t(n)=c(n)+d_e(n)\qquad n=0,1,\cdots,MN-1 \tag{3}$$

where $d_e(n)$ consists of $d(n)$ and equal number of zeros before and after $d(n)$

$$d_e(n)=\begin{cases}0 & 0\le n\le a-1\\ d(n-a) & a\le n\le b-1\\ 0 & b\le n\le MN-1\end{cases} \tag{4}$$

For $d(n)$ of length N, i.e. OFDM signal without CP and GI or OFDM signal with all-zero CP and/or all-zero GI, $a=(M-1)N/2$, $b=a+N$, where a denotes the number of zeros inserted before $d(0)$.

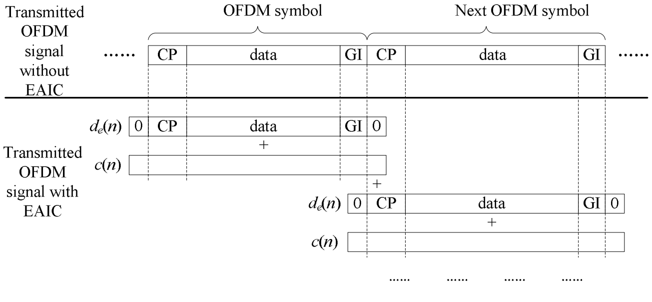

Fig. 3. OFDM symbols with EAIC signals in the time domain

Fig. 3 depicts OFDM symbols with EAIC signals in the time domain. It is noted that EAIC signal causes interference to adjacent OFDM symbols since it has the time duration longer than its corresponding OFDM symbol. In the frequency domain, EAIC signal consists of l EAIC tones around the target spectrum band. The frequency of these EAIC tones are

$k_1\Delta f, k_2\Delta f, \cdots, k_l\Delta f$, where $k_i = k_i'/M$ and k_i' has an integer value.

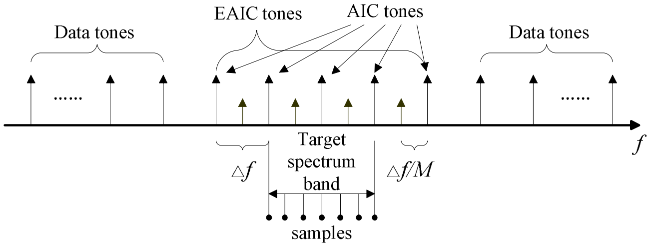

Fig. 4. EAIC tones in the frequency domain

The EAIC tones in the frequency domain are shown in Fig. 4. Since EAIC tones are spaced with smaller frequency interval and extended to longer time duration than AIC tones in [6], it can be anticipated that EAIC should have a better interference cancellation performance than AIC. Also note that EAIC tones spaced $\Delta f/M$ cause interference to data tones. Simulation results in Section IV show that with properly designed EAIC signal, the interference to data tones and adjacent OFDM symbols is very limited and acceptable.

Based on above proposal, $c(n)$ is given by

$$c(n) = \frac{1}{N}\sum_{i=1}^{l} C(i)\exp(\frac{j2\pi k_i n}{N}) \qquad n = 0,1,\cdots,MN-1 \tag{5}$$

where $C(i)$ is the weight of EAIC tone i.

The second method proposed in this paper is EAIC-H, which is a hybrid version of EAIC and AIC. In EAIC-H, EAIC tones with frequency $k_i\Delta f$ and $k_i \in \mathbb{Z}$ have the same time duration as $d(n)$, where $\mathbb{Z}$ denotes the set of all integers. $c(n)$ in EAIC-H is given by

$$\begin{aligned} c(n) = c_e(n)\frac{1}{N}&\sum_{\{k_i|k_i\in\mathbb{Z}\}} C(i)\exp(\frac{j2\pi k_i n}{N}) \\ +\frac{1}{N}&\sum_{\{k_i|k_i\notin\mathbb{Z}\}} C(i)\exp(\frac{j2\pi k_i n}{N}) \end{aligned} \tag{6}$$

where $c_e(n) = \begin{cases} 0 & 0 \le n \le a-1 \\ 1 & a \le n \le b-1 \\ 0 & b \le n \le MN-1 \end{cases}$ is used to shorten the time duration of EAIC tones with frequency $k_i\Delta f$ and $k_i \in \mathbb{Z}$. The shortened EAIC tones are actually AIC tones in [6], and they do not cause any interference to the data symbol. In this way EAIC-H causes less interference to the data symbol than EAIC method does.

III. CALCULATE WEIGHTS OF EAIC TONES

In this section, optimal weights of EAIC tones that cancel out the most of the interference caused by data tones are to be determined. The interference power in the target spectrum band is measured by the sum of the interference power at sample points $\{f_1, \cdots, f_m\}$ depicted in Fig. 4. The interference at frequency f_j caused by data tones is given by

$$E_d(j) = \sum_{n=0}^{MN-1} d_e(n)\exp(\frac{-j2\pi n f_j}{f_s}) \quad j = 1,\cdots,m \tag{7}$$

Using (4) and (2), $E_d(j)$ is obtained as

$$\begin{aligned} E_d(j) &= \sum_{n=a}^{b-1} d(n-a)\exp(\frac{-j2\pi n f_j}{f_s}) \\ &= \sum_{n=a}^{b-1}\left[\sum_{k=0}^{N-1} D(k)\exp(\frac{j2\pi k(n-a)}{N})\right]\exp(\frac{-j2\pi n f_j}{f_s}) \\ &= \sum_{k=0}^{N-1} D(k)P_d(j,k) \end{aligned} \tag{8}$$

Then the interference at $\{f_1, \cdots, f_m\}$ is given by

$$\mathbf{E}_d = \mathbf{P}_d\mathbf{D} \tag{9}$$

where $\mathbf{D}$ is the vector of data symbols

$$\mathbf{D} = \begin{bmatrix} D(1) & D(2) & \cdots & D(l) \end{bmatrix}^T$$

and $\mathbf{E}_d$ is interference at all sample points

$$\mathbf{E}_d = \begin{bmatrix} E_d(1) & E_d(2) & \cdots & E_d(m) \end{bmatrix}^T$$

and the element of $\mathbf{P}_d$ at j-th row and k-th column is $P_d(j,k)$.

Similarly, cancellation signal at frequency f_j by EAIC/EAIC-H signal is given by

$$E_c(j) = \sum_{n=0}^{MN-1} c(n)\exp(\frac{-j2\pi n f_j}{f_s}) \tag{10}$$

Using (5), $E_c(j)$ is obtained as

$$\begin{aligned} E_c(j) &= \sum_{n=0}^{MN-1}\left[\sum_{i=1}^{l} C(i)\exp(\frac{j2\pi k_i n}{N})\right]\exp(\frac{-j2\pi n f_j}{f_s}) \\ &= \sum_{i=1}^{l} C(i)P_c(j,i) \end{aligned} \tag{11}$$

Then, the cancellation signal at $\{f_1, \cdots, f_m\}$ is given by

$$\mathbf{E}_c = \mathbf{P}_c\mathbf{C} \tag{12}$$

where $\mathbf{C}$ is the weights of EAIC tones

$$\mathbf{C} = \begin{bmatrix} C(1) & C(2) & \cdots & C(l) \end{bmatrix}^T$$

and $\mathbf{E}_c$ is the cancellation signal at all sample points

$$\mathbf{E}_c = \begin{bmatrix} E_c(1) & E_c(2) & \cdots & E_c(m) \end{bmatrix}^T$$

and the element of $\mathbf{P}_c$ at j-th row and k-th column is $P_c(j,k)$.

To minimize the total interference power of transmitted signal with EAIC/EAIC-H, the following optimization problem has to be solved

$$\mathbf{C} = \arg\min_{\tilde{\mathbf{C}}} \left\|\mathbf{E}_d + \mathbf{E}_{\tilde{c}}\right\|^2 = \arg\min_{\tilde{\mathbf{C}}} \left\|\mathbf{P}_d\mathbf{D} + \mathbf{P}_c\tilde{\mathbf{C}}\right\|^2 \qquad (13)$$

This problem is a typical linear least square problem, and the answer is

$$\mathbf{C} = -\mathbf{P}_c^{+}\mathbf{P}_d\mathbf{D} = -(\mathbf{P}_c^{H}\mathbf{P}_c)^{-1}\mathbf{P}_c^{H}\mathbf{P}_d\mathbf{D} \qquad (14)$$

where $[\bullet]^+$ is known as Moore-Penrose generalized inverse.

IV. SIMULATION RESULTS

In this section, the performance of EAIC technique is illustrated via computer simulations. For all the following simulations, a 128-subcarrier OFDM system is considered. Each OFDM symbol has an all-zero CP of length 32 at the head and an all-zero GI of length 5 at the tail. These parameters are selected according to [14]. In the simulations, M is selected to be 2, so the EAIC signal for each OFDM symbol is of length $2N$, i.e. its time duration is $2T$. In order to get power spectrum density of the transmitted signal, 10000 OFDM symbols were simulated and Welch method with Blackman window was adopted.

Fig. 5 shows the normalized power spectrum of the OFDM signal with EAIC and EAIC-H. In Fig. 5, the target spectrum band is from $85\Delta f$ to $87\Delta f$, the sampling points are $85\Delta f$ to $87\Delta f$, spaced $0.25\,\Delta f$. Nine EAIC tones with frequencies from $84\Delta f$ to $88\Delta f$ spaced $0.5\Delta f$ are applied. Data tones are QPSK modulated. Performances of AIC with tones from $84\Delta f$ to $88\Delta f$ and simply turning off these tones are also simulated to give comparisons. Fig. 5 shows that notch depth achieved by EAIC is greater than 80 dB, 40 dB better than AIC. For EAIC-H, the notch depth is greater than 70 dB. Simply turning off five tones only creates a 13 dB notch. It should be noted that for all these methods, same number of OFDM data tones are turned off for notching purpose, so that the spectrum efficiencies are equal. OFDM signals with 64QAM modulation have the similar performances.

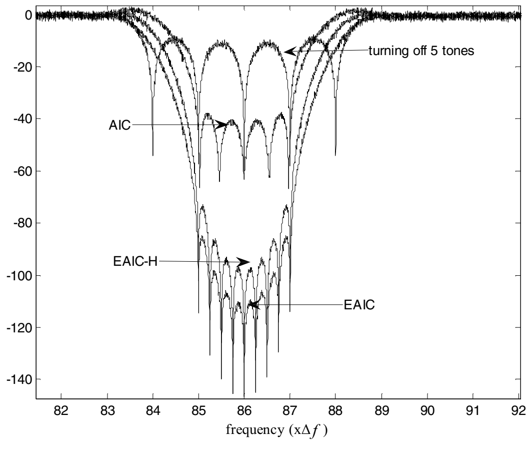

Fig. 5. Spectrum of OFDM signal with EAIC, EAIC-H, AIC, and five tones turning off; target spectrum band $85\Delta f$ to $87\Delta f$.

Symbol error rate (SER) performances of EAIC-H and EAIC methods are simulated and presented in Fig. 6 and Fig. 7. As a reference the performance of simply turning off five tones is given. Unlike simply turning off five tones and AIC method, EAIC and EAIC-H cause certain interferences to data tones. Fig. 6 shows that for a target SER of 10^{-2} to 10^{-3}, SNR loss of EAIC-H method is below 0.2 dB for 64QAM modulation. While for EAIC, the SNR loss is larger. In Fig. 7, it is about 0.8 dB for 64QAM modulation. For 16QAM modulation, the SNR loss of EAIC method is below 0.2 dB.

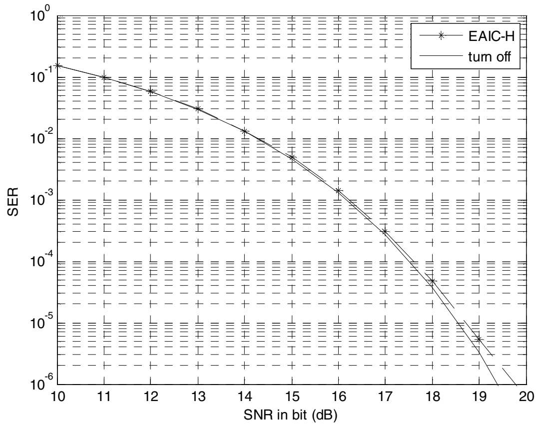

Fig. 6. SER of EAIC-H; 64QAM modulation.

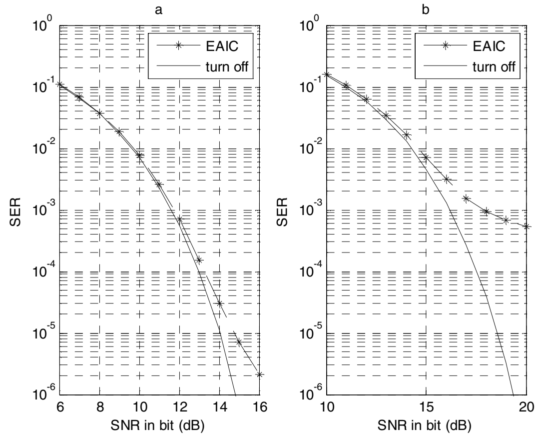

Fig. 7. SER of EAIC; (a) 16QAM modulation, (b) 64QAM modulation.

For a wider target spectrum band, from $83\Delta f$ to $89\Delta f$, the simulation results are shown in Fig. 8 to Fig. 10. The sampling points for this band are $83\Delta f$ to $89\Delta f$, spaced $0.25\,\Delta f$. 13 EAIC tones with frequencies from $82\Delta f$ to $90\Delta f$ spaced $0.5\Delta f$ are applied. Data tones are QPSK modulated. It can be seen from Fig. 8 that, while notching performances of all AIC-based methods get poorer, EAIC and EAIC-H still create notches deeper than 60 dB. For SER performances, the simulation results in Fig. 9 and 10 are similar to Fig. 6 and 7.

It is observed from above simulation results that EAIC method gives the best notching performance, but its interference to data tones may not be acceptable for high-order modulation such as 64QAM. For high-order modulation, EAIC-H is more preferred, since EAIC-H provides a perfect tradeoff between notching performance and SNR degradation.

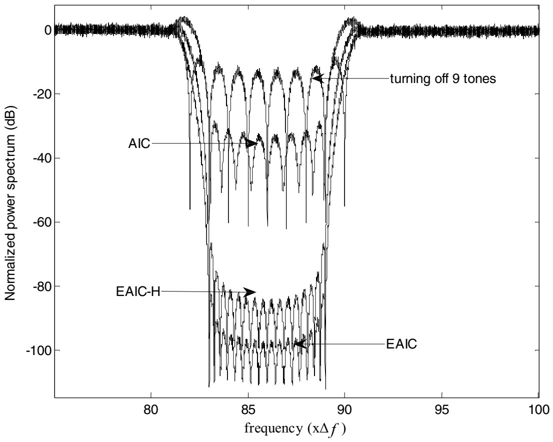

Fig. 8. Spectrum of OFDM signal with EAIC, EAIC-H, AIC, and nine tones turning off; target spectrum band $83\Delta f$ to $89\Delta f$

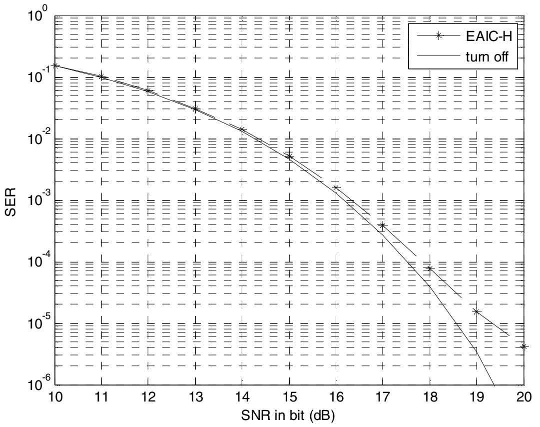

Fig. 9. SER of EAIC-H; 64QAM modulation; wider target spectrum band

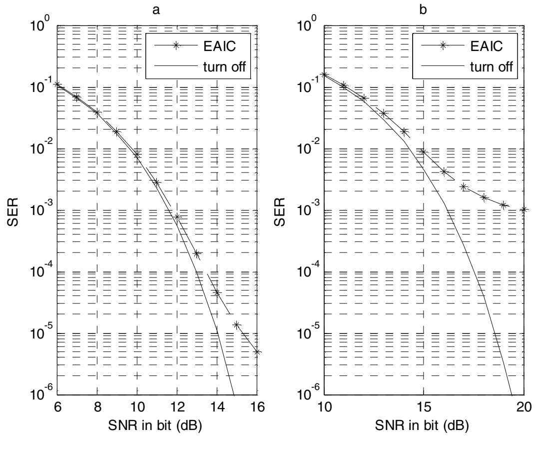

Fig. 10. SER of EAIC; (a) 16QAM modulation, (b) 64QAM modulation; wider target spectrum band.

V. CONCLUSION

In this paper, two novel methods called EAIC and EAIC-H have been proposed to create very deep notches in spectrum of OFDM signal. These methods can be applied to OFDM based OSA system to enable coexistence with primary users. The proposed EAIC method creates spectral notches of more than 80 dB, 40 dB better than AIC method, while maintaining equal spectrum efficiency as AIC method. Although the proposed methods cause some interference to OFDM data tones, simulation results show that the interference of EAIC is limited and acceptable. For high-order modulation such as 64QAM, EAIC-H is more preferred, since EAIC-H provides a perfect tradeoff between notching performance and SNR degradation.

REFERENCES

[1] J. Mitola, “Cognitive radio for flexible mobile multimedia communications,” in Proc. IEEE Int. Workshop Mobile Multimedia Communications, 1999, pp. 3-10.

[2] Frederick W. Seelig, “A Description of the August 2006 XG Demonstrations at Fort A. P. Hill,” New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on 17-20 April 2007, pp. 1-12.

[3] T. Weiss and F. Jondral, “Spectrum pooling: An innovative strategy for enhancement of spectrum efficiency,” *IEEE Commun. Mag.*, vol. 42, pp. 8–14, Mar. 2004.

[4] U. Berthold and F.K. Jondral, “Guidelines for designing OFDM overlay systems,” in Proc. 1st IEEE Symp. New Frontiers Dynamic Spectrum Access Networks, Nov. 2005, pp. 626-629.

[5] H. Tang, “Some physical layer issues of wide-band cognitive radio systems,” in Proc. 1st IEEE Symposium New Frontiers Dynamic Spectrum Access Networks, Nov. 2005, pp. 151-159.

[6] H. Yamaguchi, “Active interference cancellation technique for MB-OFDM cognitive radio,” Microwave Conference, 2004. 34th European, Volume 2, 13 Oct. 2004, pp. 1105-1108.

[7] S. Brandes, I. Cosovic, and M. Schnell, “Sidelobe Suppression in OFDM Systems by Insertion of Cancellation Carriers,” Vehicular Technology Conference, 2005. VTC-2005-Fall. 2005 IEEE 62nd Volume 1, 28-25 Sept., 2005, pp. 152 – 156.

[8] 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. JUNE 2006

[9] I. Cosovic, S. Brandes, and M. Schnell, “Subcarrier Weighting: A Method for Sidelobe Suppression in OFDM Systems,” *IEEE Communications Letters*. VOL. 10. NO. 6. JUNE 2006.

[10] I. Cosovic, S. Brandes, and M. Schnell, “A Technique for Sidelobe Suppression in OFDM Systems,” Global Telecommunications Conference, 2005. GLOBECOM '05. IEEE Volume 1, 28 Nov.-2 Dec. 2005.

[11] I. Cosovic, and T. Mazzoni, “Sidelobe Suppression in OFDM Spectrum Sharing Systems Via Additive Singal Method,” Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th 22-25 April 2007, pp. 2692-2696 .

[12] K. A. Shelby, J. Chiang, J. Lansford, “Modified Adjacent Frequency Coding for Increased Notch Depth in MB-OFDM under DAA/Spectral Sculpting,” Cognitive Radio Oriented Wireless Networks and Communications, 2006. 1st International Conference, pp. 1-5.

[13] S. Brandes, I. Cosovic, and M. Schnell, “Reduction of out-of-band radiation in OFDM based overlay systems,” New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on 8-11 Nov. 2005, pp, 662 – 665.

[14] IEEE P802.15-03/268r3, “Multi-band OFDM Physical Layer Proposal for IEEE 802.15 Tast Group3a”, April 2004.