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On Performance of Bi-directional Cognitive Radio Networks

Amir Ligata
Communication Department
IPSA Institute
Sarajevo, Bosnia and Herzegovina
amir.ligata@ipsa-institut.com

Haris Gacanin†
Motive Division
Alcatel-Lucent Bell N.V.
Antwerp, Belgium
haris.gacanin@alcatel-lucent.com

Fumiyuki Adachi
Graduate School of Engineering
Tohoku University
Sendai, Japan
adachi@ecei.tohoku.ac.jp

***Abstract*—Future wireless Internet services require a broadband frequency spectrum with high data rates. Cognitive radio (CR) concept is a novel approach to improve the spectrum efficiency. The CR is based on the opportunistic usage of frequency spectrum, which is not occupied by the primary users. Conventional multi-user access in bi-directional CR network may be done by using either time division multiple access (TDMA), frequency division multiple access (FDMA) or code division multiple access (CDMA). Without adaptive or dynamic frequency reuse, TDMA and FDMA have lower spectrum efficiency in comparison with CDMA. However, the problem of CDMA in a multipath channel is a multi-user interference (MUI). In this paper, we present a bi-directional CR network with wireless network coding (WNC) in a multipath channel. Unlike the conventional multi-user bi-directional CR network, where the users access the spectrum holes in different time-slot or frequency, the proposed method allows secondary users (SUs) to access the spectrum holes simultaneously. The performance of bi-directional CR network with WNC is theoretically analyzed in terms of spectrum efficiency and the maximum number of SUs. The numerical results show that the spectrum efficiency and the maximum number of SUs of the proposed method increases in comparison with conventional CR network.**

***Index Terms*—Cognitive radio, wireless network coding, NC-OFDM, spectrum efficiency.**

I. Introduction

A limited frequency spectrum is becoming a major problem to accommodate demands of new broadband wireless Internet services such as video streaming, video conferencing, network gaming, etc. [1]. Governmental agencies regulate and assign available frequency spectrum (henceforth spectrum) based on fixed spectrum assignment policy. However, this does not guarantee that the allocated spectrum is efficiently utilized (utilization of the spectrum variates from 15% to 85% [2]). To solve this problem a cognitive radio (CR) network was proposed [3], where the frequency bands which are not used by the primary users (PU) are refer to as spectrum holes [2].

Recently, orthogonal frequency division multiplexing (OFDM) has been widely recognized as the most promising candidate for CR because of its efficient spectrum utilization and high degree of flexibility as coding, constellation and power assignment can be adaptively controlled per subcarrier according to the user's requirements and/or changes of communication environment [4]. A variant of OFDM called non-contiguous OFDM (NC-OFDM) for CR applications was proposed [5]-[7], where the available spectrum holes may be shared among different users. The CR users may access the available spectrum hole by time division multiple access (i.e., TDMA), frequency division multiple access (i.e., FDMA) or code division multiple access (i.e., CDMA). In the case of bi-directional CR system based on TDMA or FDMA the spectrum efficiency degrades since the users access the spectrum holes separately. Using CDMA, the multi-user interference (MUI) arises, which may severely limit the transmission performance of bi-directional CR system in a multipath (i.e., frequency-selective) channel and consequently degrades the spectrum efficiency.

Network coding has been introduced for two-way relaying in [8]-[9]. Wireless network coding (WNC) [10]-[12] has been proposed for bi-directional relay-assisted communication between a pair of users. WNC scheme is divided into two stages; (*i*) first a pair of users transmit to an access point and then, (*ii*) the access point broadcasts the received signal to both users using amplify-and-forward protocol. During the first stage the MUI arises between a pair of users, but in WNC the interference is "*friendly*" and its exploited to increase the spectrum efficiency (i.e., network capacity) in comparison with conventional multi-user relay-assisted communications [10]-[12]. To the best of the authors knowledge a potential of WNC in CR networks has not been fully investigated yet.

In this paper, we present a bi-directional CR network using two-way relaying. We consider NC-OFDM radio access in a multipath (i.e., frequency-selective) wireless channel. In the presented CR network model, WNC-enabled CR-BS listens to the spectrum and if idle informs a pair of CR users to initiate a bi-directional communication using WNC. Unlike the conventional multi-user CR network where the users access the spectrum holes in different time-slot or frequency, the proposed method allows CR users to utilize the spectrum holes simultaneously. The performance of bi-directional CR network with WNC is theoretically analyzed in terms of spectrum efficiency and the maximum number of CR users. Spectrum efficiency is defined as the information rate that can be transmitted over a given bandwidth. Our numerical results show that the presented method may be used to increase the spectrum efficiency and the maximum number of CR users in comparison with CR network without WNC

†H. Gacanin is the acting Head of the Communication Group at Energy and Communication Department, IPSA Institute, Sarajevo, Bosnia and Herzegovina.

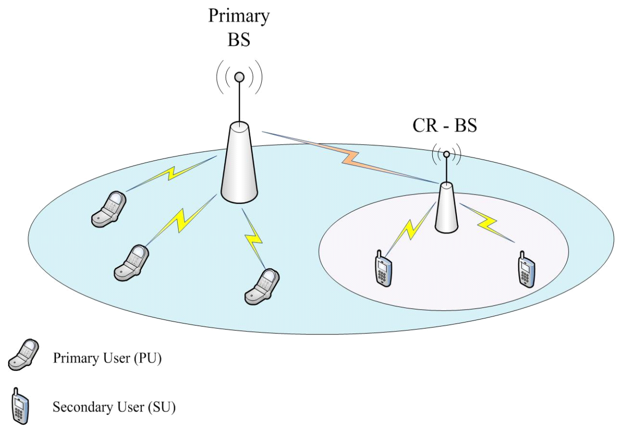

Figure 1. Conventional CR network.

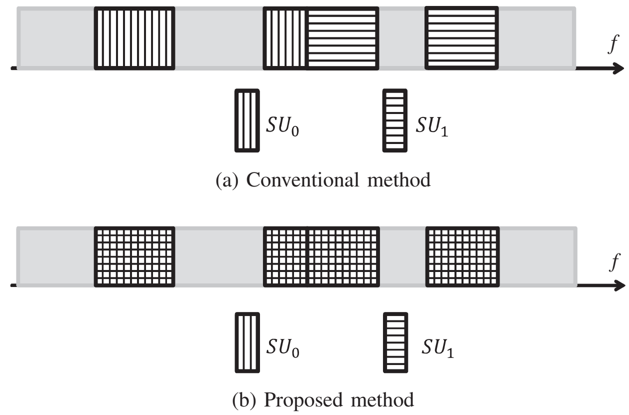

Figure 2. Spectrum allocation.

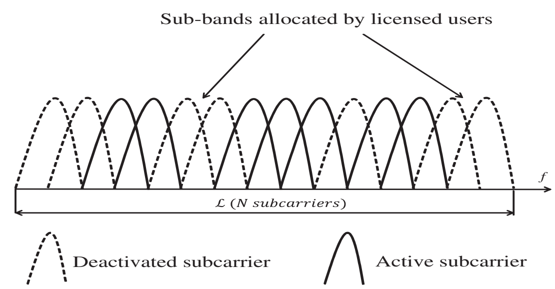

Figure 3. Subcarrier distribution over wideband spectrum.

(henceforth conventional CR network). We note that imperfect time and frequency synchronization may affect the network performance, but, however, it is out of scope of this paper.

The reminder of the paper is organized as follows. Section II gives an overview of CR network model. The application of WNC in CR system is presented in Section III, while the performance analysis is given in Section IV. Numerical results are given in Section V. Section VI concludes the paper.

II. Cognitive Radio Network Model

A. Radio access

The CR network consists of a primary system and the CR system, where the primary system has a higher priority [13]. The PUs communicate over a primary base station using an assigned spectrum, while the secondary users (SUs) access the network through the CR base station (CR-BS) whenever PUs are not active.

Conventional CR network is illustrated in Fig. 1. CR-BS allocates available spectrum for each SU, and then they communicate with each other using the unoccupied spectrum of the primary network accessing through the CR-BS. In the conventional approach [14]-[15] two users communicate in CR network based on NC-OFDM radio access, while splitting the total available spectrum as illustrated in Fig. 2a. The cross-channel interference between PUs and SUs is reduced by deactivating (i.e., nulling) their neighboring subcarriers as shown in Fig. 3. It has been shown that NC-OFDM can support a high aggregate data rate with the remaining subcarriers and simultaneously maintain an acceptable level of error robustness.

B. Problem Statement

In conventional multi-user CR network, SUs may access the spectrum holes by using TDMA, FDMA or CDMA. However, in case of TDMA and FDMA, the SUs occupy spectrum holes separately (either in different time-slots or frequency and do not allow common use of the spectrum holes). Higher spectrum efficiency can be achieved by using CDMA. However, increased MUI may significantly degrade the network performance in a multipath (i.e., frequency-selective) channel. To increase the spectrum efficiency and eliminate MUI between a pair of SUs, we present an application of WNC in a bi-directional CR system.

III. Bi-directional Cognitive Radio Network with WNC

We note here that the total spectrum $\mathcal{L}$, over which the spectrum sensing is applied, is divided into N subcarriers ($\mathcal{L}=\{1,...N\}$). As a result of spectrum sensing a set of subcarriers $\xi\,(\subset\mathcal{L})$ unoccupied by licensed users is detected. Henceforth, a set of subcarriers ξ we will denote as the white subcarriers. Then, a bi-directional CR communication with WNC between a pair of SUs is done over the set of white subcarriers. Without loss of generality we assume that the CR system consists of CR-BS and the two SUs (SU_0 and SU_1). We will then further extend our theoretical analysis for $U=2M$ SUs, where U is divided into M pairs, where each of the pairs utilize equal number of subcarriers. We note here that in this paper, path loss and shadowing loss are not taken into consideration.

A. Communication Protocol

The coverage area of the SUs includes the CR-BS, but they are out of each others transmission range as shown in Fig. 4.

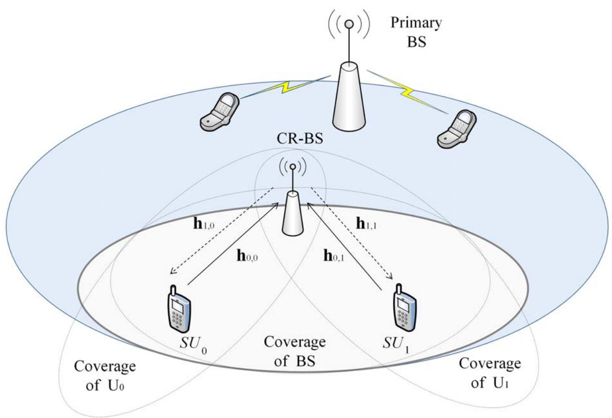

Figure 4. Wireless network coding.

Unlike the conventional approach, where SU_0 and SU_1 share the available set of white subcarriers ξ, in the CR system with WNC, the SU_0 and SU_1 utilize all white subcarriers in ξ at the same time. CR-BS continuously monitors occupation of available frequency band using one of the spectrum sensing techniques [2]. We note that in this work we consider perfect spectrum sensing. Then, a bi-directional CR communication is performed through three time stages as shown in Table I. In the first stage, a CR-BS identifies white subcarriers and allocate them to different pairs of SUs. During the second stage SUs transmit their signals simultaneously to the CR-BS, while at the third stage, the received signal at the CR-BS is broadcasted toward the users with amplify-and-forward protocol and finally the detection is done.

B. Wireless Network Coding in CR Network

In the following subsection, application of WNC in a bi-directional CR network is presented for a pair of SUs. The jth user (SU_j) data-modulated symbol sequence is represented by $\mathbf{d}_j = [d_j(1)\, d_j(2)...d_j(N)]^T$ for $j \in \{0, 1\}$. Subcarriers belonging to the set of white subcarriers are kept active, while the rest subcarriers (corresponding to active PU spectrum) are deactivated.

Then, the sequence $\tilde{\mathbf{d}}_j = [\tilde{d}_j(1)\, \tilde{d}_j(2)...\tilde{d}_j(N)]^T$, where

$$\tilde{d}_j(k) = \begin{cases} d_j(k) & \text{if } k \in \xi \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

for $k = 1 \backsim N$, is fed to an N-point inverse fast Fourier transform (IFFT) and then N_g-sample guard interval (GI) is inserted. Finally, the signal is transmitted over a multipath (i.e., frequency-selective) channel.

The signal received at the CR-BS during the second stage can be expressed as

$$\mathbf{R}_r = \sqrt{P}\sum_{j=0}^{1} \mathbf{H}_{0,j}\tilde{\mathbf{d}}_j + \mathbf{N}_r, \quad (2)$$

where $P\,(= E_s/T_c N), \mathbf{H}_{m,j} = \mathrm{diag}[H_{m,j}(1)\, H_{m,j}(2)... H_{m,j}(N)]^T$ and $\mathbf{N}_r = [N_{m,j}(1)\, N_{m,j}(2)...N_{m,j}(N_c)]^T$,

Table I: CR system communication protocol.

First stage	$CR-BS \rightarrow SU_0,\, SU_1$	Spectrum sensing
Second stage	$SU_0,\, SU_1 \rightarrow CR-BS$	Wireless network coding
Third stage	$CR-BS \rightarrow SU_0,\, SU_1$	

respectively, denote the transmit signal power, the channel gain matrix between the jth user SU_j and the CR-BS and the noise vector whose elements are modeled as a zero-mean Gaussian variables with the variance $2\sigma_n^2 = 2N_0/T_c$. E_s, N_0, T_c, N and m denote the data modulated symbol energy, single-sided noise power spectrum density, the fast Fourier transform sampling period, the total number of OFDM subcarriers and the transmission stage, respectively.

At the third stage, the signal received at CR-BS during the second stage is normalized by a factor of $\sqrt{1/E[|\mathbf{R}_r|^2]}$. Then, it is amplified with factor $\sqrt{P}$ and broadcasted ($\widetilde{\mathbf{R}}_r = \sqrt{P}\mathbf{R}_r$). After GI removal and N- point FFT, the signal received at the jth user U_j is given as

$$\mathbf{R}_j = \mathbf{H}_{1,j}\widetilde{\mathbf{R}}_r + \mathbf{N}_j, \quad (3)$$

where $\mathbf{H}_{1,j}$ represents channel gain matrix between the jth user SU_j and the CR-BS during the third stage. The jth user U_j removes its self-information as

$$\widetilde{\mathbf{R}}_r = \mathbf{R}_j - \mathbf{H}_{1,j}\mathbf{H}_{0,j}\tilde{\mathbf{d}}_j. \quad (4)$$

Then, one-tap zero forcing frequency domain equalization (ZF-FDE) is applied to obtain the decision variables given by [12]

$$\hat{\mathbf{R}}_j = \mathbf{W}_j\widetilde{\mathbf{R}}_j, \quad (5)$$

where $\mathbf{W}_j$ denote the equalization weight matrix for the jth user.

IV. Performance analysis

In the following section, performance analysis of bi-directional CR network in terms of spectrum efficiency with WNC is presented. The analysis is performed for U secondary users.

First, let us define the set of occupied white subcarriers sensed by the jth $\{j = 1 \sim U\}$ user determined through spectrum sensing process as

$$\Psi_j = \{i \in \xi;\, P_{\bar{j}}(i) \neq 0\}, \quad (6)$$

where i and $P_{\bar{j}}(i)$, denote the ith white subcarrier and the power allocated by the $\bar{j}$th $\{\bar{j} \in \{1, ..., U\} \setminus j\}$ user on ith subcarrier, respectively. Ψ_j obeys the following properties [16]

$$\begin{cases} \Psi_1 \neq \varnothing, \\ \bigcup_{j=1}^{U} \Psi_j \subset \mathcal{L}, \\ \bigcap_{j=1}^{U} \Psi_j \neq \varnothing. \end{cases} \quad (7)$$

The channel capacity of the jth user in bits/s/Hz for a given number of subcarriers N is given as [16]

$$C_{j,N} = \frac{1}{\text{card}(\Omega_j)} \sum_{i \in \Omega_j} \log_2\left(1 + \frac{P_j(i)\,|h_j(i)|^2}{N_0}\right), \quad (8)$$

where $\mathbf{h}_j = \text{IFFT}\{\mathbf{H}_{0,j}\}$ with the instantaneous channel impulse response $\mathbf{h}_j = \text{diag}[h_j(1)\, h_j(2) ...\, h_j(N)]^T$. In above expression card(.) denotes the cardinal number (i.e., the number of elements in a finite set) and Ω_j denotes a set of the remaining unoccupied white subcarriers sensed by jth user and can be described as

$$\Omega_j = \left\{ \xi \bigcap \overline{\bigcup_{k=\overline{1,U}} \Psi_k} \right\}. \quad (9)$$

Now, expression for the spectrum efficiency per band of the jth user can be derived as [14]

$$\Phi_{j,N} = \frac{1}{N} \sum_{i \in \Omega_j} \log_2\left(1 + \frac{P_j(i)\,|h_j(i)|^2}{N_0}\right), \quad (10)$$

where the instantaneous signal-to-noise ratio (SNR) for the ith subcarrier is defined as ${P_j(i)|h_j(i)|^2}/{N_0}$. Using (8) above expression for spectrum efficiency can be obtained as

$$\Phi_{j,N} = \frac{\text{card}(\Omega_j)}{N} C_{j,N}. \quad (11)$$

We assume that using sensing algorithm W ($W = \text{card}(\xi)$) subcarriers is allocated for bi-directional communication in CR network. Following notation is used in respect to access type to primary network:

$$W = \begin{cases} W^{NC-OFDM} & \text{Conventional method} \\ W^{WNC} & \text{Proposed method} \end{cases}. \quad (12)$$

The analysis will be conducted for the same number of the SUs (i.e., U) for both cases. Using previous expressions, aggregated spectrum efficiency of a system with N subcarriers per user is given by

$$\Phi_N = \sum_{j=1}^{U} \Phi_{j,N}. \quad (13)$$

A. Conventional method

The total of $W^{NC-OFDM}$ subcarriers will be equally split among U users so that each user will get the same number of subcarriers $W^{NC-OFDM}/U$. We note here that we are not considering how spectrum holes are distributed in terms of contiguity. Thus, set of unoccupied white subcarriers for SUs transmission allocated for the jth user can be expressed as

$$\bigcup(\Omega_j^{NC-OFDM}) = W^{NC-OFDM}(1 - \frac{j-1}{U}) \quad (14)$$

for $j = 1, ..., U$. Using (13), we obtain expressions for capacity and spectrum efficiency per subcarrier of jth user as

$$C_{j,N}^{NC-OFDM} = \frac{1}{\text{card}(\Omega_j^{NC-OFDM})} \times \sum_{i \in \Omega_j} \log_2\left(1 + \frac{P_j(i)|h_j(i)|^2}{N_0}\right) \quad (15)$$

Table II: Numerical parameters.

Transmission technique	OFDM	
Frequency-domain equalization	ZF-FDE	
Number of subcarriers	N	64, 128, 256
Number of secondary users	U	2, 4, 8

and

$$\Phi_{j,N}^{NC-OFDM} = \frac{\text{card}(\Omega_j^{NC-OFDM})}{N} C_{j,N}^{NC-OFDM}. \quad (16)$$

B. Proposed method

With proposed method, total number of U users will be split into pairs and each pair will receive the same number of subcarriers $W^{NC-OFDM}/U$ for bi-directional communications. Thus, set of white subcarriers for the SUs with WNC can be expressed as

$$W^{WNC} = \frac{U}{2} \frac{W^{NC-OFDM}}{U} = \frac{1}{2} W^{NC-OFDM}. \quad (17)$$

In this case, a set of unoccupied white subcarriers sensed by the jth user is given as

$$\bigcup(\Omega_j^{WNC}) = W^{WNC}\left(1 - \frac{2(j-1)}{U}\right) \quad (18)$$

for $j = 1, ..., U$. Now, we obtain expressions for capacity and spectrum efficiency per subcarrier of jth user as

$$C_{j,N}^{WNC} = \frac{1}{\text{card}(\Omega_j^{WNC})} \sum_{i \in \Omega_j} \log_2\left(1 + \frac{P_j(i)\,|h_j(i)|^2}{N_0}\right) \quad (19)$$

and

$$\Phi_{j,N}^{WNC} = \frac{\text{card}(\Omega_j^{WNC})}{N} C_{j,N}^{WNC}. \quad (20)$$

V. Numerical Results and Discussions

The numerical parameters are given in Table II. We note that in the proposed method, the maximum number of SUs is split into pairs and each pair receives corresponding set of white subcarriers. In this way, two users access the same unoccupied white subcarriers and communicate using WNC protocol. Same principle is used for other pairs within the group. Moreover, the shared spectrum is divided into N subcarriers.

Figure 5 illustrates the aggregated spectrum efficiency of the CR network as a function of the average SNR and a number of the SUs as a parameter. We can see that as the number of the SUs increases a gap between conventional and proposed method in terms of the spectrum efficiency becomes greater. In the low SNR region this ratio variates around two but for 8 SUs in high SNR region it claims over three.

A maximum number of SUs as a function of the average SNR and the number of sub-bands as a parameter is illustrated in Fig. 6. As transmitted power arises, interference between SUs due to multi-user transmission access becomes higher.

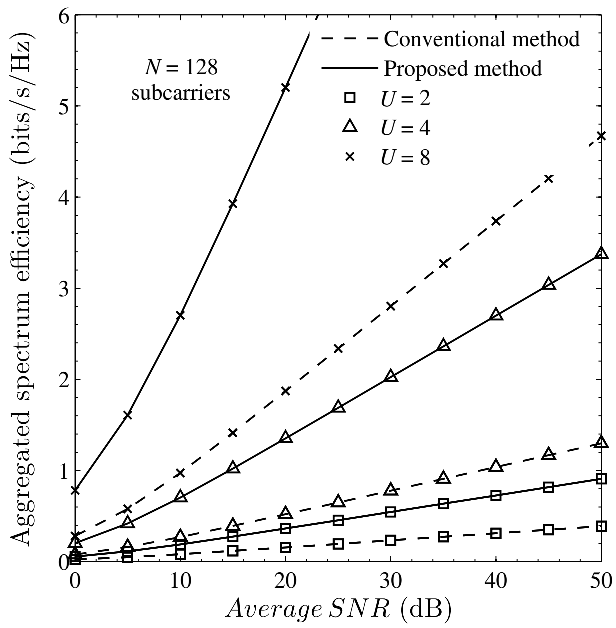

Figure 5. Spectral efficiency of CR network.

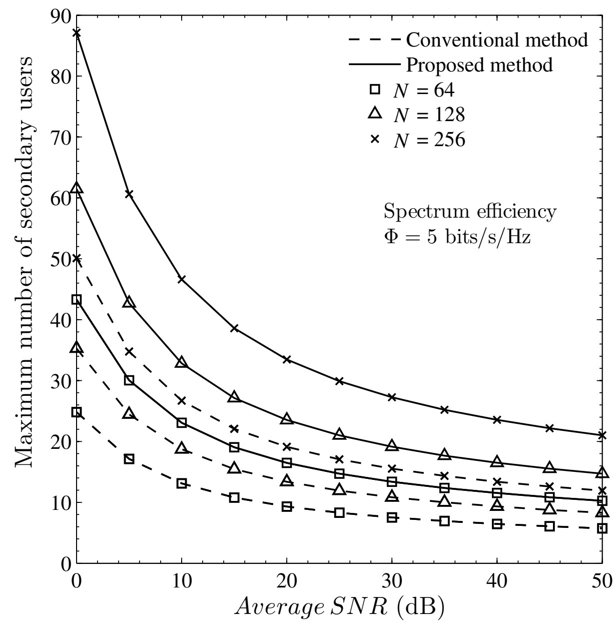

Figure 6. Maximum number of secondary users in CR network.

This leads to reduced number of the SUs allowed to access CR network at specific aggregated spectrum efficiency of the CR system. Thus, using proposed method more SUs are allowed to access the CR network in comparison to the conventional approach.

VI. Conclusion

In this paper, we presented a bi-directional CR network with WNC in a multipath fading channel. In the conventional multi-user CR network the spectrum efficiency degrades since the users utilize the spectrum holes separately. We introduced WNC in a CR system to enable a bi-directional communication between a pair of the SUs with increased spectrum efficiency. The performance of bi-directional CR network in terms of spectrum efficiency and the maximum number of SUs was theoretically evaluated. Our numerical results show that the spectrum efficiency and the maximum number of SUs of the proposed method increase in comparison with conventional CR access due to higher spectrum efficiency.

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References

[1] H. Berndt, "Towards 4G Technologies: Services with Initiative," *Wiley*, 2008.

[2] K-C.Chen and R.Prasad, "Cognitive radio networks," *Wiley*, 2009.

[3] J. Mitola and G. Q. Maguire, "Cognitive radio: Making software radios more personal," *IEEE Personal Commun*. Mag., Vol. 6, No. 4, pp. 13–18, Aug. 1999.

[4] H. Arslan, "Cognitive Radio, Software Defined Radio, and Adaptive Wireless Systems," *Springer*, 2007.

[5] J.D. Poston, W.D. Horne, "Discontiguous OFDM considerations for dynamic spectrum access in idle TV channels," *2005 First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks DySPAN*, pp. 607-610, Baltimore, MD, USA, Nov. 2005.

[6] H. Tang, "Some physical layer issues of wide-band cognitive radio systems," *2005 First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks DySPAN*, pp.151-159, Baltimore, MD, USA, Nov. 2005.

[7] M.P. Wylie-Green, "Dynamic spectrum sensing by multiband OFDM radio for interference mitigation," *2005 First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks DySPAN*, pp. 619-625, Baltimore, MD, USA, Nov. 2005.

[8] Y. Wu, P. A. Chou, and S. Y. Kung, "Information exchange in wireless networks with network coding and physical layer broadcast," Tech. Rep. MSR-TR-2004-78, Microsoft Research, Redmond, Wash, USA, 2004.

[9] P. Larsson, N. Johansson, and K.-E. Sunell, "Coded bi-directional relaying," *IEEE Vehicular Technology Conference 2006. VTC 2006-Spring*, pp. 851 - 855, Melbourne, Australia, May 2006.

[10] P. Popovski and H. Yomo, "Wireless network coding by amplify-and-forward for bi-directional traffic flows," *IEEE Communications Letters*, Vol. 11, No. 1, pp. 16-18, 2007.

[11] S. Katti, S. S. Gollakota, and D. Katabi, "Embracing wireless interference: Analog network coding," *ACM SIGCOM 2007*, Kyoto, Japan, Aug. 2007.

[12] H. Gacanin, and F. Adachi, "Broadband analog network coding," *IEEE Transactions on Wireless Communications*, Vol. 9, No. 5, pp. 1577-1583, 2010.

[13] A. M. Wyglinski, M. Nekovee, Y. T. Hou, "Cognitive radio communications and networks," *Academic Press*, 2010.

[14] G. Bansal, Z. Hasan, M. J. Hossain, V. K. Bhargava, "Subcarrier and power adaptation for multiuser OFDM-based cognitive radio systems," *2010 National Conference on Communications (NCC)*, pp. 1-5, Chennai, Jan. 2010.

[15] Y. Zhang, C. Leung, "Subcarrier, Bit and Power Allocation for Multiuser OFDM-Based Multi-Cell Cognitive Radio Systems," *VTC 2008-Fall. IEEE 68th Vehicular Technology Conference*, pp. 1-5, Calgary, Sept. 2008.

[16] M. Haddad, A. Hayar, M. Debbah, "Spectral efficiency of spectrum-pooling systems," *IET Communications*, Vol. 2, No. 6, pp. 733-741, 2008.