We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900
Open access books available

185,000
International authors and editors

200M
Downloads

Our authors are among the

154
Countries delivered to

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



7

Cognitive Radio Dynamic Access Techniques for Mutual Interference Reduction and Efficient Spectrum Utilization

I. Budiarjo, M.K.Lakshmanan and H. Nikookar
International Research Centre for Telecommunications and Radar
Department of Electrical Engineering, Mathematics and Computer Science
Delft University of Technology, Mekelweg 4 2628CD, Delft,
The Netherlands

1. Introduction

A Background

Advances in wireless technologies have spawned the development of a host of new and innovative wireless applications and services. With each passing day there is demand for more wireless services even when the popularity of existing applications is on the rise. As a result the clamor for valuable resources such as transmission spectrum has reached a shrill note. Paradoxically studies after studies conclude that large swathes of licensed frequency bands remain unused for most of the time and that spectrum congestion is more due to inadequate access techniques rather than non-availability (Brodersen et al., 2004); (Haykin, 2005). This has sparked a debate in the Telecommunications circles on the need to revamp existing spectrum regulatory policies and introduce newer approaches. One such initiative is the idea of Cognitive Radio, a new paradigm that promises opportunistic utilization of unused spectrum and efficient spectrum management. In (Haykin, 2005) Haykin has defined Cognitive Radio as an intelligent wireless communication system that is cognizant of its environment, learns from it and adapts its internal states to statistical variations in the incoming RF stimuli by making changes in certain operating parameters in real time with objectives of highly reliable communications whenever and wherever needed, and efficient utilization of the radio spectrum. Modulation scheme, transmit power, channel coding, and carrier frequency are examples of parameters to be exploited in cognitive radio. The modulation scheme is chosen in such a way that the data is transmitted reliably using the least possible spectrum; in other words the modulation method must be spectrally efficient. Spectral efficiency is influenced by the noise and propagation condition. The latter varies with time due to environmental changes, hence the modulation scheme should be able to adapt to the channel propagation variation. It should also support multi node communication, as several nodes exist in the Cognitive Radio network. Spectral utilization is

optimized by allowing rental (i.e., unlicensed) users to transmit and receive data over portions of spectra when primary (i.e., licensed) users are inactive. This is done in a way that the rental users (RUs) are invisible to the licensed users (LUs). In such a setting, the LUs are ordinary mobile terminals and their associated base stations. They thus do not possess much intelligence. The RUs, on the other hand, should possess the intelligence of sensing the spectrum and use whatever resources are available when they need them. At the same time, the RUs should give up the spectrum when an LU begins transmission.

Among several modulation schemes, Orthogonal Frequency Division Multiplexing (OFDM) is a suitable scheme that fulfils the requirements (Moseley, 2004). The cyclic prefix is inserted before the transmitted data that makes the scheme resistant to multipath fading, hence equalization is not required at the receiver. Multiple access can be applied by frequency division multiple access (FDMA) due to the carriers orthogonality, by time division multiple access (TDMA) where each node can access different OFDM symbols in a time frame, and multi carrier CDMA where node access is differentiated by otrthogonal codes.

Recently a method called Spectrum Pooling is reported (Weiss et al., 2004). In spectrum pooling public access to spectrum is provided without sacrificing the transmission quality of the actual license users. Multicarrier communication for CR has been suggested in (Weiss et al., 2004). The rationale is that any CR system needs to sense the spectrum, and this involves some sort of spectral analysis. Since FFT can be used for the spectral analysis (Cabric et al., 2004) and at the same time it can act as the demodulator of an OFDM, it has been suggested as a proper candidate for multicarrier-based CR systems. A number of short-comings of OFDM in its application in CR have been noted in (Weiss et al., 2004) and solutions to them have been proposed. The carriers located at the LU's band are deactivated, The sidelobes are reduced by deactivating more carriers adjacent to LU's band. Further sidelobes reduction is attained by applying windowing to the OFDM signal in time domain. If the number of available carriers for RU transmission is inadequate, due to lot of deactivations, then frequency hopping to another band is applied (Hoeksema et al., 2005). In (Jamin & Mahoenen, 2004) and (Negash & Nikookar, 2000) an interest of replacing Fourier transform by wavelet transform in multicarrier OFDM system is presented. The scheme gives better intercarrier interference (ICI) and inter symbol interference (ISI) reduction. Single carrier CR method using adaptive waveform is proposed in (Chakravarthy et al., 2005) and (Lee, 2002). In this method the transmitted signal is shaped in a way that its band does not contain the frequencies occupied by the LUs. The method takes the advantage of Fourier or wavelet transform.

B Theme and Organization of the Chapter

Adaptive OFDM and its combination with spectrum pooling for improving the quality of service (QoS) and efficient use of the spectrum are reviewed. Wave shaping and beamforming as alternative methods of efficient utilization of the spectrum are addressed and their importance in CR is stressed. MIMO system as an added value to enhance the QoS of CR is described. The chapter is structured as follows: Multi carrier adaptive OFDM with Fourier and Wavelet basis functions and its combination with spectrum pooling are analyzed in section 2. Wave Shaping with single carrier modulation for CR is explained in Section 3. Section 4 shows the role of MIMO transmission in enhancing the CR performance.

Beamforming as spatial interference avoidance technique in CR is discussed in Section 5. A summary of the chapter is given in Section 6.

2. Cognitive Radio with Adaptive Multicarrier Modulation and Spectrum Pooling

A strategy which is called *spectrum pooling* is proposed in (Weiss et al., 2004) where the public access is enabled to these bands without giving significant interference to the actual license owners. Spectrum pooling enables public access to spectral ranges of licensed frequency bands which are seldom used by overlaying a secondary rental user (RU) to an existing licensed user (LU). The LUs are radio systems authenticated to operate under licensed spectral bands. The RUs are intelligent CR systems that actively scan the landscape and opportunistically utilize available and unused resources. The RU relinquishes control over the resources (here spectrum) as and when the LU starts using them. To identify and utilize unused bands, the frequency bands of various radio systems (including licensed and rental users) are combined to obtain a common spectral pool. Cohabitation of LU and RU systems is actualized by shaping the transmission waveform of the RU in a way that it utilizes the unoccupied time-frequency gaps of the LU.
The pioneering work on the subject was conducted in (Weiss et al., 2004) which devised a spectrum pooling scheme using multi-carrier modulation (MCM) where individual sub-carriers adjacent to the occupied licensed user spectrum are deactivated for frequencies which are occupied by a licensed user. Fig. 1 illustrates a typical scenario. The combination of adaptive MCM and spectrum pooling can serve as a robust method to achieve a good quality of communication and efficient use of the spectrum. In the next subsections Fourier based (OFDM) and Wavelet based MCM with its application in Spectrum Pooling are explored.

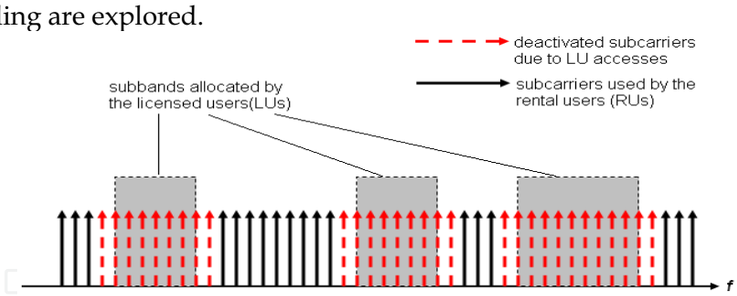


Fig. 1. Illustration of Spectrum pooling block diagram.

A Fourier Based Multicarrier OFDM

An obvious MCM candidate for CR systems is OFDM. With advantages of flexibility, ease of implementation and elegance in operation, OFDM is naturally suitable for CR system design. The short-coming of the OFDM solution is the large sidelobes of the frequency response of filters that characterize the channel associated with each of subcarrier. The sidelobes amplitude of the Fourier based OFDM can be observed from its power spectral density (PSD),

$$PSD(f)=\frac{1}{N_{FFT}}\left|\sum_{m=0}^{N_{FFT}-1}\sqrt{p_m}\,X_m\int_{-(1+\alpha)\frac{T_u}{2}}^{(1+\alpha)\frac{T_u}{2}}g(t)e^{-j2\pi(f-f_m)t}dt\right|^2 \quad (1)$$

where N_{FFT} is the FFT point, T_u is the useful signal duration, $g(t)$ is the window function, a is the roll off factor of the window, f_m is the frequency on carrier m. p_m and X_m are the allocated power and the symbol from QAM or PSK mapping on subcarrier m, respectively.
The large side lobes result in significant interference among the subcarriers that originate from different RUs and between LUs and RUs. Equation (1) shows that parameters like allocated power (p_m), symbol (X_m) amplitude and window ($g(t)$) can be set to resolve this problem. Other elements which can be varied to improve the performance of RUs are the channel coding parameters and carrier frequency. The utilization of the parameters to reduce the PSD in the LU's band and elements to improve the quality of service (QoS) of RUs will be further explored in the next following sub subsections.

A.1 Spectrum Shaping by Time Domain Windowing

In (Weiss et al., 2004) extension of each OFDM block with long cyclic prefix and suffix samples and application of some windowing to reduce the side-lobes of the subcarrier channels are suggested. Obviously, this solution is at the cost of bandwidth loss because excessive time should be allocated to cyclic extensions that otherwise could be used for data transmission. Further in (Weiss et al., 2004), interference reduction method is extended by deactivating subcarriers located adjacent to the licensed system (LS) which provides a kind of shield to the LUs. Due to the channel propagation influence, in OFDM bit errors are typically concentrated in a set of severely faded subcarriers. This fact indicates that there is possibility that the quality of service can not be maintained. Meanwhile, as mentioned before, the carriers resource is limited due to deactivation of RU carriers on the occupied LU band. Having adaptive OFDM in CR is thus a solution. The heavily faded and noisy subcarriers are excluded from transmission to improve the overall bit error rate (BER) of the system, and the loss of throughput is counteracted by applying higher order modulation modes to the subcarriers which have better signal to noise ratios (SNR) or BER.
Commonly used window type is the raised cosine window, which is defined as (Weiss et al., 2004):

$$g(t)=\begin{cases}\dfrac{1}{T_u} & 0\le|t|\le\dfrac{T_u(1-\alpha)}{2}\\ \dfrac{1}{2T_u}\left\{1+\cos\left[\dfrac{\pi}{\alpha T_u}\left(|t|-\dfrac{T_u(1-\alpha)}{2}\right)\right]\right\} & \dfrac{T_u(1-\alpha)}{2}\le|t|\le\dfrac{T_u(1+\alpha)}{2}\\ 0 & Otherwise\end{cases} \quad (2)$$

where a is the roll off factor, and T_u is the useful OFDM symbol interval (without guard interval). The shape of the window in the region of $\frac{T_u(1-\alpha)}{2}\le|t|\le\frac{T_u(1+\alpha)}{2}$ determines how rapid the OFDM spectrum goes down to zero. The PSD will hit zero on the frequencies in the interval of $1/T_u$. Bartlett window is defined by equation (3), (Nikookar & Prasad, 1997b)

while *Better than Raised Cosine* (BTRC) Window which gives the lowest sidelobes among the three windows is defined by equation (4) (Tan & Beaulieu, 2004).

$$g(t)=\begin{cases}\dfrac{1}{T_u} & 0\le|t|\le\dfrac{T_u(1-\alpha)}{2}\\ \dfrac{1}{2T_u}-\dfrac{1}{T_u}\left[\dfrac{|t|}{\alpha T_u}-\dfrac{1}{2\alpha}\right] & \dfrac{T_u(1-\alpha)}{2}\le|t|\le\dfrac{T_u(1+\alpha)}{2}\\ 0 & Otherwise\end{cases} \tag{3}$$

$$g(t)=\begin{cases}\dfrac{1}{T_u}, & 0\le|t|\le\dfrac{T_u(1-\alpha)}{2}\\ \dfrac{1}{T_u}e^{\left(-2\ln 2/\alpha T_U\right)\left[|t|-(T_U(1-\alpha)/2)\right]} & \dfrac{T_u(1-\alpha)}{2}\le|t|\le\dfrac{T_u}{2}\\ \dfrac{1}{T_u}\left[1-e^{\left(\frac{-2\ln 2}{\alpha T_u}\right)\left[|t|-\frac{T_u(1-\alpha)}{2}\right]}\right], & \dfrac{T_u}{2}\le|t|\le\dfrac{T_u(1+\alpha)}{2}\\ 0 & Otherwise\end{cases} \tag{4}$$

A window with lower sidelobes than BTRC which is called the *Flipped- Inverse Hyperbolic Secant* (farcsech) window is proposed in (Assalini & Tonello, 2004). The window is designed according to (5),

$$g(t)=\begin{cases}\dfrac{1}{T_u}, & 0\le|t|\le\dfrac{T_u(1-\alpha)}{2}\\ \dfrac{1}{T_u}\left[1-\dfrac{1}{\alpha T_u\gamma}arcsech\left(\dfrac{1}{\alpha T_u}\left(\dfrac{T_u(1+\alpha)}{2}-|t|\right)\right)\right], & \dfrac{T_u(1-\alpha)}{2}\le|t|\le\dfrac{T_u}{2}\\ \dfrac{1}{T_u}\left[\dfrac{1}{\alpha T_u\gamma}arcsech\left(\dfrac{1}{\alpha T_u}\left(|t|-\dfrac{T_u(1-\alpha)}{2}\right)\right)\right], & \dfrac{T_u}{2}\le|t|\le\dfrac{T_u(1+\alpha)}{2}\\ 0 & Otherwise\end{cases} \tag{5}$$

where $\gamma=2\ln(\sqrt{3}+2)/(\alpha T_u)$. According to (Muschalik, 1996) the duration of OFDM signal should be $2T_u$ in order to complete a total $2N_{FFT}$ samples to preserve the orthogonality, and zeros are added on the region outside the window $g(t)$. The window designs by equations (2)-(5) affect the transmitted signal, as the consequence an error floor will be formed. Fig. 2(a) shows an example Bartlett window design according to (3) which affects the transmitted signal.

It is emphasized in (Witrisal, 2002) that the applied window must not influence the signal during its effective period to avoid error floor. In order to fulfil this requirement the window forms are expanded, i.e., new T_u is becoming $2T_u$, and α is restricted in the range of $0 \le \alpha \le (1- T_{GI}/ T_u)/2$, where T_{GI} is the guard interval duration. The orthogonality is preserved since the PSD hits zeros in the interval of $1/(2T_u)$ at the cost of longer duration of OFDM signal ($2T_u$ (α +1)). As a solution the window is truncated to fit $2T_u$ OFDM duration,

as depicted in Fig. 2(b). The orthogonality is preserved by applying the rectangular receiver filter with duration T_u , implemented by DFT (Witrisal, 2002). In this way there is more freedom in choosing window in the region of $T_u(1-\alpha) \le |t| \le T_u$ as long as its PSD on the symbol boundaries is low, e.g Gaussian window or half sine window (Nikookar & Prasad, 1997(a)).

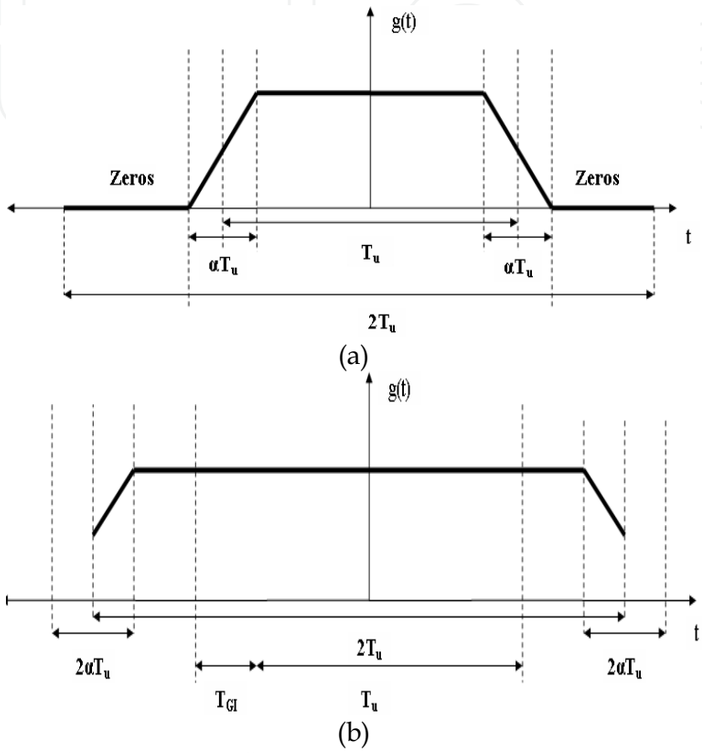


Fig. 2. (a) Window design with influence to the transmitted signal (b) Window design without influence to the transmitted signal.

It should be emphasized that applying only windowing is not enough to reduce interference to LU. A more powerful technique to suppress OFDM sidelobes is carriers deactivation. Deactivation of carriers adjacent to the licensed band provides flexible guard bands which will make the PSD sidelobes of RU's OFDM signal on the licensed band lower. Applying only one of the methods may not be sufficient, therefore combining both methods (windowing and adaptive deactivation of carriers adjacent to licensed bands) is suggested to make the PSD sidelobes even lower in the region of LU's band. The loss of throughput due to carriers deactivation and long OFDM symbol duration can be compensated by applying adaptive bits allocation. The next subsubsection will explore the application of adaptive bit allocation in CR system including its available algorithms.

Recently in (Harris & Kjeldsen, 2006) overlapped OFDM symbol transmission with long symbol duration is proposed to counteract the throughput loss. The scheme is described in Fig. 3 . The delay between one OFDM symbol to another should be designed in such a way that no intersymbol interference occurs, which means the next OFDM symbol should start after the end of the previous useful data part of an OFDM symbol. If zeros are inserted at

the prefix of suffix (outside the T_{GI} and T_U area as depicted in Fig. 2(b)), the useful data of the next OFDM symbol should start after the last useful data of the previous OFDM symbol.

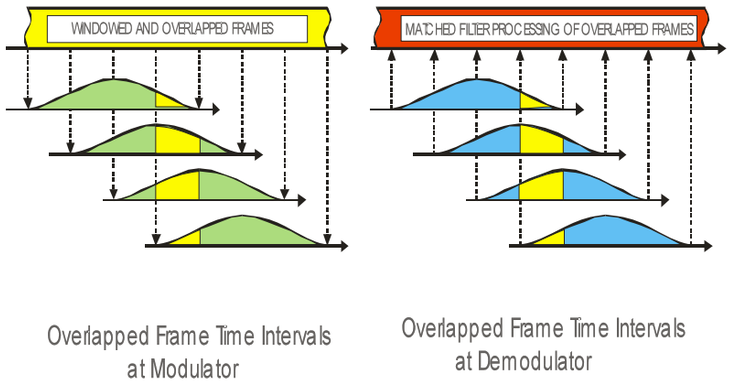


Fig. 3. Overlapped OFDM symbol with zero ISI.

A.2 OFDM Sidelobes Reduction Techniques

In this section a technique to reduce sidelobes by manipulating the composition of X_m in (1) is described. The results in (Yamaguchi, 2004); (Brandes et al., 2005a); (Brandes et al., 2005b); (Brandes et al., 2006); (Berthold et al., 2007); (Cosovic et al., 2005); (Cosovic et al., 2006); (Cosovic & Mazzoni, 2006); (Cosovic and Mazzoni, 2007); (Mahmoud & Arslan, 2008); (Padagarai et al., 2008a); (Padagarai et al., 2008b) show that a significant sidelobes reduction gain can be obtained.

A.2.1 Sidelobe Suppression by Cancellation Carriers Insertion

In (Yamaguchi, 2004);(Brandes et al., 2005a);(Brandes et al., 2006) instead of having deactivated carriers adjacent to the LU band, these carriers are used to cancel out the sidelobes on the LU band. The concept is to find the proper amplitude of the cancellation carriers in such a way that the resulting sidelobes be as low as possible. The optimization can be formulated as:

$$|X(f)|^2 = \frac{1}{N_{FFT}} \left| \sum_{\substack{m=1 \\ m \neq cc}}^{N_{FFT}} \sqrt{p_m}(X_m) \int_{-(1+\alpha)T_u}^{(1+\alpha)T_u} g(t) e^{-j2\pi(f-f_m)t} dt + \sum_{\substack{cc=cc1 \\ cc \neq m}}^{ccN} \sqrt{p_{cc}}(Xc_{cc}) \int_{-(1+\alpha)T_u}^{(1+\alpha)T_u} g(t) e^{-j2\pi(f-f_{cc})t} dt \right|^2 \quad (6)$$

$$subject \quad to \quad |X(f_{LLI})|^2 < P_{Threshold}, \quad and \quad \sum_{m=1}^{N_{FFT}} p_m = P_T$$

where ccN is the total number of sidelobes cancellation carriers, and Xc_{cc} is the symbol on the cancellation carrier position with the range within $cc1,\ldots,ccN$. The power constraint for all subcarriers including the cancellation carriers remains thus, no extra energy is added. The possible high power required by the cancellation carriers can be compensated from the unused power due to the carriers deactivation.

We introduce an alternative optimization problem by simplifying it to set of ccN linear equations to solve ccN cancellation carrier amplitude values. Fig. 4 provides a simple example of how the cancellation carriers with this new optimization problem work. The

spectrum is derived from 9 subcarriers (including the cancellation carriers) and uses a rectangular window which produces a spectrum from the sum of the sinc functions. One cancellation carrier is located at the left edge of the RU band adjacent to the LU band and another one is at the right edge. They are signed by the dark vertical arrows. If we take a look at the OFDM spectrum with carriers deactivation (one carrier at the left and one carrier at the right edge) denoted by the solid curve, we can see that the maximum sidelobe occurs at the frequency point half of carrier spacing from the deactivated carrier which, in Fig. 4 is indicated by the coordinate position (X:-4.5,Y:-0.1564). The cancellation carriers can be weighted in such a way that the sum of their spectras will nullify the OFDM spectrum at that particular coordinate position (e.g. by having a cancellation carrier spectrum coordinate (X_{c1}=X_{c2}=-4.5, Y_{c1}=0.1477, Y_{c2}=0.0087)).

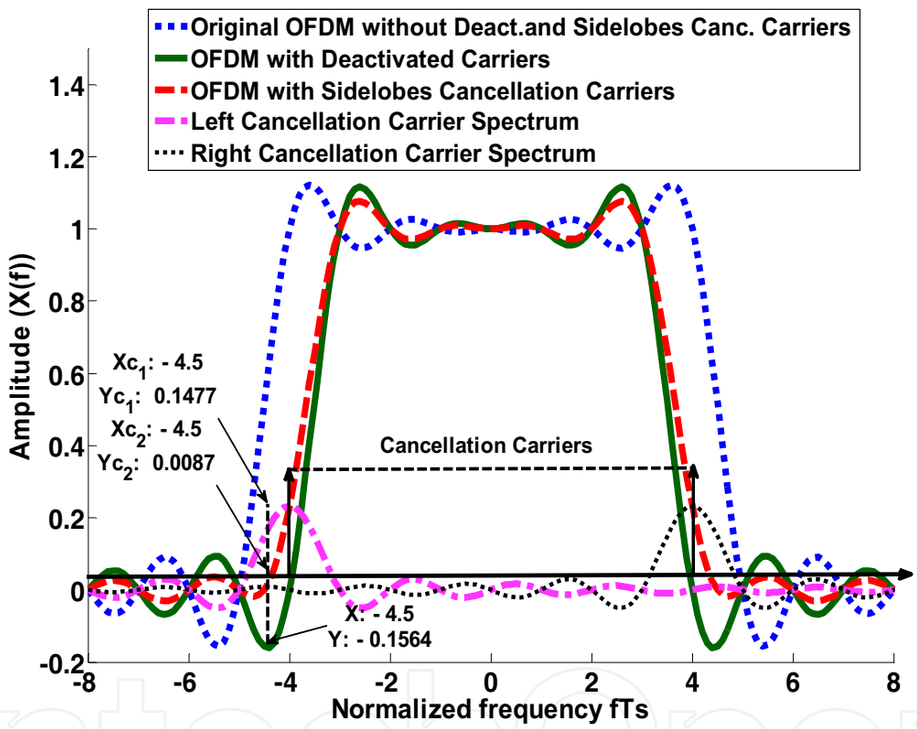


Fig. 4. The OFDM spectrum amplitude with the effect of the deactivated carriers or cancellation carriers.

The same technique is also applied to the sidelobes reduction on the right side. The resulting spectrum derived from using the cancellation carriers technique is depicted by the dashed lines. The sidelobes are lower than the sidelobe of the OFDM with the deactivated carriers.
The cancellation carriers can be combined with windowing (Brandes et al., 2005b);(Berthold et al., 2007);. Different windows provide different sidelobe levels. Combining a window that gives very low sidelobes (e.g. the farchsech window) with the cancellation carriers technique will lead to a very significant sidelobe (interference) reduction in the LU band. The results in (Brandes et al., 2005b) have shown that the combination of 2 cancellation carriers on each

side adjacent to LU band and raised cosine window with roll off factor (a) 0.2 gives more than 30 dB sidelobes reduction compared to the conventional OFDM.

A.2.2 Sidelobe Suppression by Subcarrier Weighting

Subcarrier weighting is introduced in (Cosovic et al., 2005); (Cosovic et al., 2006);. The weighting can be seen as varying the allocation power p_m on each carrier m which, obviously, according to (1) will affect the spectrum amplitude. By selecting the appropriate weight for each of the carriers the desired low sidelobes can be obtained. The sidelobe reduction by means of carriers weighting is attained at the expense of the bit error rate (BER) versus signal to noise ratio (SNR) degradation (Nikookar & Prasad, 2000), since the weighting will give unequal amounts of transmission power on each of the OFDM carriers. The weighting method was originally used in (Nikookar & Prasad, 2000) to counteract the high peak to average power ratio (PAPR) problem in OFDM.

A.2.3 Sidelobe Suppression by Multiple Choice Sequence

In (Cosovic & Mazzoni, 2006) a multiple choice sequence is introduced, where the multiple choice sequence abiding by the symbol constellation approach, the interleaving approach and the phase approach are discussed. The symbol constellation approach is applied by mapping the symbol X_m in (1) into $X'_m(l)$ which is still derived from one of the symbols set after the QAM or PSK mapping that was previously used to produce X_m . The index l ranges from $l=1,2,\ldots,L$, where L is the number of possible alternative values. This means that the bits can be mapped into L possible symbols. By putting the N_{FFT} symbols of $X'_m(l)$ into (1), and observing from all L possible PSDs, the one with the lowest sidelobe is then chosen for the transmission. An example of simple mapping from X_m into $X'_m(l)$ is given in (Cosovic and Mazzoni, 2006). The CS points of QAM or PSK are numbered as 0,1,….,CS-1, hence the symbol X_m is assigned to the number I_m ($I_m \in \{0,1,...,CS-1\}$) according to its point position. The $X'_m(l)$ will be the symbol value on the new number $I_m(l)$ which is derived from the addition of the assigned number I_m with the random number $D_m(l)$ which has L different possible values (Cosovic & Mazzoni, 2006),

$$I_m(l) = I_m + D_m(l) \tag{7}$$

By transmitting the information about the set index information l, the receiver can decode the received signal and reconstruct the original X_m symbol. By means of the interleaving approach, the N_{FFT} X_m symbols are interleaved by L different interleaver rules,

$$\boldsymbol{X'}(l)=\boldsymbol{\Pi}(l)\boldsymbol{X}, \tag{8}$$

where $\boldsymbol{\Pi}(l)$ is the permutation matrix that will do the interleaving, $\boldsymbol{X}$ is the symbol vector, and $\boldsymbol{X'}$ is the symbol vector after interleaving. The matrix $\boldsymbol{\Pi}(l)$ has L different possible matrix values. The permutation matrix $\boldsymbol{\Pi}(l)$ will be available at the transmitter and the receiver. Among L different possible OFDM spectrum using a set of symbols $\boldsymbol{X'}(l)$, the one with the lowest sidelobes is chosen for the transmission. The receiver will use the deinterleaver permutation matrix $\boldsymbol{\Pi}^{-1}(l)$ to recover the transmitted data upon receiving the side information index l. In the phase approach each phase of symbol X_m is shifted by random

phase $\theta_m(l)$ with L different possible values. The phase shifted symbol $X'_m(l)$ becomes (Cosovic & Mazzoni, 2006),

$$X'_m(l) = X_m e^{j\theta_m(l)} \tag{9}$$

where $\theta_m(l)$ is in the range of between 0-2π. In the vector notation, the phase shifted signal $\boldsymbol{X}'(l)$ is derived from point to point multiplication between the original signal $\boldsymbol{X}$ and the complex number vector derived from $e^{j\boldsymbol{\theta}(l)}$. As in the constellation and interleaver approach, in the phase approach, among L possible sets of vector $\boldsymbol{\theta}(l)$, the one that produces the lowest sidelobes is chosen and applied to the symbol vector $\boldsymbol{X}$. The index information l is transmitted so that the receiver can reconstruct the symbol vector $\boldsymbol{X}$. Apart from the random shift, random amplitude shift can also be applied, but in such cases the BER performance will be affected. Another approach is to only apply the multiple choice sequence technique to the carriers adjacent to the LU band, since these carriers mostly affect the sidelobes magnitude (Cosovic & Mazzoni, 2006),.

A.2.4 Sidelobe Suppression by Adaptive Symbol Transition

Sidelobes Suppression by time domain approach has been introduced in (Mahmoud & Arslan, 2008). Time domain symbol transition is inserted between two OFDM symbol, and the symbol transition value is obtained in such a way that the signal spectrum or the Fourier transform of the two consecutive time domain OFDM symbol (including the symbol transition) will have low sidelobes. The objective is to minimize the spectrum resulting from two consecutive time domain OFDM symbol without the symbol transition added by the spectrum contributed from the symbol transition on the LU band (Mahmoud & Arslan, 2008). If the OFDM based cognitive radio signal contribution on the LU is described as :

$$\mathbf{I} = \mathbf{F}_{LU} \begin{bmatrix} \mathbf{y}^{n} \\ \mathbf{a}^{n} \\ \mathbf{y}^{n+1} \end{bmatrix} \tag{10}$$

where $\boldsymbol{I}$ is the signal part of the cognitive radio signal in LU band, $\boldsymbol{F_{LU}}$ is the Fourier transformation matrix for the signal in LU band, $\boldsymbol{y}^n$ is the nth time domain OFDM symbol including the guard interval, $\boldsymbol{a}^n$ is the additive symbol transition, and $\boldsymbol{y}^{n+1}$ is the following OFDM symbol, then the optimization problem will be to find the vector $\boldsymbol{a}^n$ in such a way that $\boldsymbol{I}$ will be as small as possible. The symbol transition scheme is depicted in Fig. 5.

The symbol transition will not introduce any inter symbol interference (ISI) but the transmission duration becomes longer, which means that the bit rate is reduced. The search for the time domain symbol transition values are applied by the linear least squares problem with a quadratic inequality constraint.

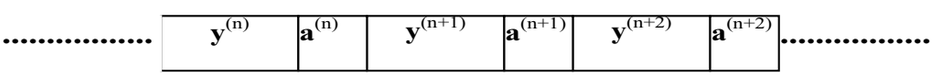


Fig. 5. Adaptive symbol transition scheme.

A.2.5 Sidelobe Suppression by Frequency Domain Additive Signal

In (Cosovic & Mazzoni, 2007) sidelobe suppression for OFDM based cognitive radio can be achieved by mapping the data symbol using QPSK modulation mode and add the frequency domain symbol vector $\boldsymbol{X}$ with random values vector $\boldsymbol{d}$ in such a way that the resulting PSD in the LU region be as small as possible. The optimization problem becomes as described in (11),

$$|X(f)|^2 = \frac{1}{N_{FFT}} \left| \sum_{m=1}^{N_{FFT}} \sqrt{p_m} (X_m + d_m) \int_{-(1+\alpha)T_u}^{(1+\alpha)T_u} g(t) e^{-j2\pi(f-f_m)t} dt \right|^2 \quad (11)$$

$$subject \quad to \quad |X(f_{LU})|^2 < P_{Threshold}, \quad and \quad \sum_{m=1}^{N_{FFT}} p_m = P_T$$

where d_m is the additive signal on subcarrier n. If $X'_m = X_m + d_m$ then in order not to destroy the cognitive radio BER performance and keep the total allocated power constant, the value of d_m is restricted to a circle with magnitude $|d_m| \leq 0.7$ (Cosovic & Mazzoni, 2007). In this way, according to the QPSK gray mapping, the value of X'_m will not give decision error at the receiver, except in the severely noise and faded channel. Simulation results in (Cosovic & Mazzoni, 2007) have shown about 15 dB sidelobes reduction could be achieved with the cost of 2.8 dB SNR degradation as the upper limit value of $|d_m|$ is 0.7.

A.2.6 Sidelobe Suppression by Constellation Expansion

The most recent technique in OFDM sidelobe suppression has been proposed in (Padagarai et al., 2008a), where the M-PSK modulation mapping is expanded to 2xM-PSK mapping in order to have lower OFDM sidelobe. The original symbol after M-PSK mapping which is located at point a of M available PSK symbol points is transformed into two possible new points a_1 and a_2, where a_1=-a_2. By combining all possible new OFDM symbol set on the 2x M-PSK points through all OFDM carriers, the one set which gives the smallest sidelobes will be chosen for the transmission. No additional information is required by the receiver for data detection, since the receiver has the knowledge of all possible a_1 and a_2 positions. Therefore, the receiver can detect the data by calculating the minimum Euclidean distance between the received symbol and the reference points on 2xM- PSK mapping, and accordingly translates the result to the M PSK mapping. Fig. 6 shows an example on how the points from QPSK are expanded to 8-PSK mapping. In this way there are two possibilities of mapping a data symbol, and accordingly the constellation expansion will add extra randomness to X_n in (1) with various possible sidelobes magnitude.

The one which gives the smallest sidelobes will be chosen to be transmitted. The simulation results in (Pagadarai et al., 2008a) have shown that the sidelobes suppression technique by the constellation expansion from QPSK to 8-PSK gives only slight BER degradation. With Constellation Expansion technique about 9 dB sidelobes suppression can be attained (Padagarai et al., 2008a). The work has been extended in (Padagarai et al., 2008b) by combining the constellation expansion technique with the cancellation carriers inserted on the carriers adjacent to the LU band. Extra sidelobes reduction has been achieved without having high value of cancellation carrers magnitude, due to prior sidelobes reduction by the constellation expansion technique. According to (Padagarai et al., 2008b) the combination

between constellation expansion and one sidelobes cancellation carrier on each side adjacent to LU band gives around 16 dB sidelobes reduction.

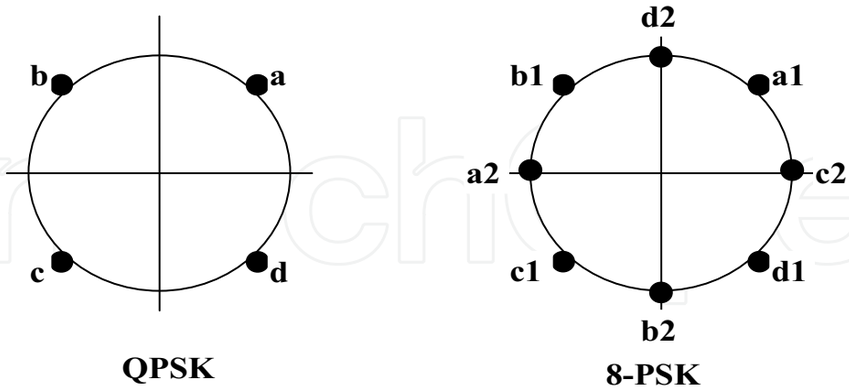


Fig. 6. Constellation Expansion from QPSK to 8-PSK mapping.

A.3. Adaptive Bit Allocation (Bit Loading)

Referring to (1) the sidelobes to LU's band can be lowered by applying the low constellation size (e.g BPSK) to the symbols adjacent to LU's band. Another advantage of the low constellation size is its resistance to noise and interference compared to high constellation size. Hence, although the sidelobes of LU to RU's band exists, the BER of the RU's carriers adjacent to LU's band can be better preserved.

Adaptive bit loading is one of adaptive OFDM methods which allocates bits to subcarriers efficiently by taking estimated channel fading and noise variance information, and accordingly selecting the subcarriers modulation modes By utilizing the unused power due to carriers deactivation on the subband occupied by the LUs and allocating them to some of the other carriers intelligently, according to the adaptive bit loading algorithms, reliable communications without sacrificing the legacy system can be achieved. Transmitting more bits on a carrier requires more power. This power can be derived from the unallocated ones.

As a consequence of applying adaptive bit loading, the receiver needs information about the number of bits allocated on each carrier in order to decode the signal properly. This information can be derived blindly by examining the received signal (Hanzo et al., 2002); (Reddy et al., 2003); or from dedicated signaling symbols. An example of the signaling symbol is depicted in Fig. 7, where the allowable constellation size is restricted to the set of {0, 2,4,16 and 64}, (Budiarjo et al., 2007a). The inner rectangle which is the decision area for 0 modulation mode (no symbol is transmitted) can be made smaller up to a distance of about *3d/4* from the other reference symbols, where *d* is the distance between outer points and the no symbol point shown in Fig. 7. This is due to the fact that a decision error (e.g no symbol transmitted but BPSK or other modulation mode is decided) is only caused by the noise (no contribution from channel fading). Fischer-Hueber algorithm allocates the bits with the intention to minimize the BER on each carrier. It tries to guarantee equal SNR on every carrier. The bits are assigned as (Barreto and Furrer, 2001):

$$R_m = \frac{1}{K}\left[R_T + \log_2\left(\prod_{n=0}^{K-1}\frac{\sigma_n^2}{\Phi_n}\right) - K\log_2\left(\frac{\sigma_m^2}{\Phi_m}\right)\right], \tag{12}$$

where R_m is the number of allocated bits on carrier m, K is the number of active carriers, and R_T the total target bits per OFDM symbol. In the beginning value of K is equal to N_{FFT}, after applying (12) on each carrier the nonpositive values of R_ms are replaced by zeros, and the number of active carriers K is substracted by the number of carriers with nonpositive R_m values. The loop of calculating (12) continues until all R_ms are nonnegative. Each of the R_m is quantized into an integer number R_{Qm}. If the sum of the R_{Qm} is not equal to the target rate, addition or subtraction of bit is applied. It starts from the carrier with the lowest deviation of R_{Qm} to its R_m (for the addition) or the carrier with the highest deviation (for the subtraction). The addition or subtraction is iteratively applied bit per bit until the target rate is fulfilled. Another adaptive bit allocation algorithm is the Chow algorithm introduced in (Chow et al., 1995). The goal is to maximize the allowable noise margin while the minimum desired BER is still achieved. The bits are assigned as follows (Chow et al., 1995):

$$R_m = \log_2\left[1 + \frac{p_m \Phi_m}{\sigma_m^2 \cdot (\Gamma + \gamma_{m\,\mathrm{arg}\,in})}\right], \tag{13}$$

where γ_{margin} is the additional amount of noise (in dB) that the system can tolerate, while still achieving the minimum desired bit error rate requirement.

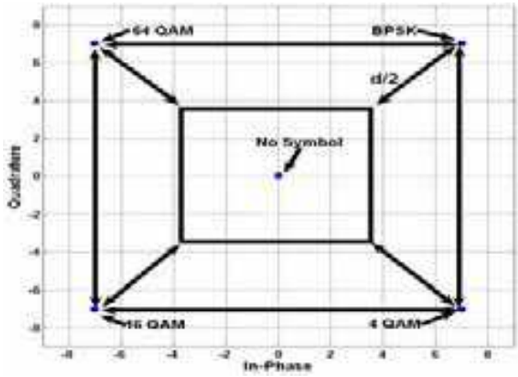


Fig. 7. An example of signaling symbol points for adaptive bit loading with allowable M= {0, 2, 4, 16, and 64} (Budiarjo et al., 2007a).

The SNR gap Γ is a constant which estimates the difference between channel capacity and the actual capacity usage by the transmission scheme, which is defined as:

$$\Gamma = \frac{1}{3}\left[Q^{-1}\left(\frac{SER}{4}\right)\right]^2. \tag{14}$$

SER is the expected symbol error rate, and $Q(x)$ is the function $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{\frac{-t^2}{2}}dt$.

Besides allocating the bits carrierwise, the bits can be allocated groupwise according to the average channel gain of the carriers within a certain group. This method reduces the

signaling symbols required to determine the modulation mode on each carrier, as the required modulation information of a group of N_{cg} carriers is the same in a signaling symbol.

A Simple Blockwise Loading Algorithm (SBLA) is proposed in (Gruenheid et al., 2001). The algorithm divides the subcarriers into N_B blocks of N_{cb} adjacent subcarriers. The same modulation level is assigned to subcarriers within one block. The SNRs of neighboring sub carriers are highly correlated; hence no significant performance degradations are expected by introducing blocks of subcarriers, which are smaller than the coherence bandwidth of the channel. The choice of the modulation level for the specific block of subcarriers is based on the mean SNR of the block. Initially, the SNR grid is predetermined as e.g depicted in Fig. 8 (Gruenheid et al., 2000). The grid contains a list of differences of the SNR thresholds, required to switch between the modulations levels of the supported PSK/QAM modulation alphabets for a specific block. The middle point (center of 8-PSK) is placed on the overall SNR average of OFDM frame.

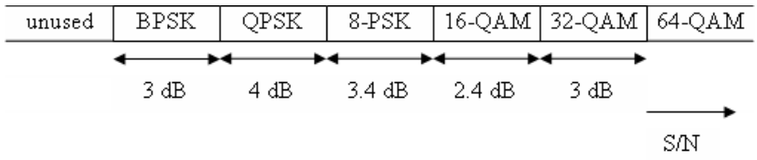


Fig. 8. SNR grid for Simple Blockwise Loading Algorithm (SBLA) (Gruenheid et al., 2000).

In (Lei and Zhang, 2003) the Fischer Hueber algorithm is modified to determine the allocated bits on a block of subcarriers. The bits are distributed as:

$$R_i = \frac{R_T}{N'_B} + \frac{1}{N'_B}.\log_2\left(\frac{\left(|H_i|^2\right)^{N'_B}}{\prod_{k\in\psi}|H_k|^2}\right) \tag{15}$$

where R_i is the allocated bits to carriers block i, N'_B is the number of active blocks, H_i is the average channel gain in block i, and ψ is the set of active carriers block.

Like in the subcarrierwise Fischer –Hueber algorithm, after several iterations, the value of all bit allocations are non negative, but if the target rate is not yet achieved, the addition or substraction of bit to each carrier based on the deviation between the quantized bit allocation and unquantized bit allocation for Chow, SBLA and groupwise Fischer algorithm, is applied until the target rate is satisfied.

In (Budiarjo et al., 2005) these bit loading algorithms are evaluated and compared by utilizing the 2x1-D Wiener filter as the channel estimation technique (Budiarjo et al., 2006a). In (Budiarjo et al., 2006b) the performance of combination of adaptive bit loading algorithms and windows with the design according to Fig. 2.b are evaluated. Simulation results in (Budiarjo et al., 2006a) and (Budiarjo et al., 2006b) show that carrierwise bit loading outperforms the groupwise bit loading, since the method maps the bit allocation to each carrier more accurately. If throughput is a critical issue, the groupwise bit loading is a better candidate than carrierwise bit loading. This is because in adaptive OFDM, the signaling symbols required by the receiver to recognize the modulation mode of each carrier, reduces the throughput.

A.4. Adaptive Coding and Frequency Hopping

An element which does not influence the level of interference to LU's band but is needed to boost or improve the quality of service (QoS) of CR system is the channel coding. As it can be noticed, none of the parameters shown in (6) refers to channel coding element. Most of references such as (Mutti et al., 2004); (Jetlund et al., 2002); (Vucetic, 1991); (Keller et al., 2000); discuss the adaptation of channel coding by varying the rate according to the estimated channel gain. The coding rate level is decreased as the channel fading power is increased (Mutti et al., 2004).

In the situation where due to LU's access and bad channel condition, too many carriers are deactivated, and therefore the frequency hopping is suggested. The scanning module will give information to the front end to switch transmission to a certain carrier frequency where available spectrum in that region is adequate to achieve the target quality of service (QoS). The performance of OFDM based CR using Wiener filter channel estimation with frequent frequency hopping at GSM 900 MHz channel model is evaluated in (Budiarjo et al., 2007c), where the channel models are based on ETSI GSM specification for rural area and urban area power delay profiles.

B. Wavelet Based Multicarrier OFDM

In traditional implementations of Multicarrier OFDM (MC-OFDM), the generation and modulation of the sub-channels are accomplished digitally using Fourier bases. In this subsection another modulation technique is introduced. The conventional Fourier-based complex exponential carriers of OFDM are replaced with orthonormal wavelet packet (WP) bases for use in cognitive radio environments. The WP bases are derived from perfect reconstruction two-band FIR filter bank solutions (Jamin and Mahoenen, 2004); (Negash & Nikookar, 2000); (Bouwel et al., 2000); (Jensen & Harbo, 2001).

Cohabitation of the WP-MCM based CR systems with existing licensed users is actualized by shaping its transmission waveform and by adaptively activating or deactivating sub-carriers in a way that it utilizes the unoccupied time-frequency gaps of the LU. The idea is to dynamically sculpt the transmission signal so that it has no or very little time-frequency components competing with the LU. This way the CR can seamlessly blend with the LU operation. The steps to generate the WP-MCM transmission signal are elucidated in Fig. 9. The level and the number of bases generated is given as $M = 2^J$. A level 3 tree structure generates up to 8 wavelet packet carriers and duals each.

B.1. Generation of Wavelet Packet Bases and Their Duals through Two Channel Filter Bank Analysis

The WP-MCM transmission is realized by replacing orthonormal complex exponential basis functions, as used in OFDM systems, with orthonormal wavelet packet basis functions. The wavelet packet bases and their dual bases are derived from perfect reconstruction two-band FIR filter bank solutions from multistage tree-structured paraunitary filter banks derived by cascading 2-channel filter banks.

B.1.1 Generation of Wavelet Packet Sub-Carrier Bases

The wavelet packet sub-carriers (to be used at the transmitter end) are generated through a multichannel filterbank consisting of cascaded two-channel filterbanks applying the

synthesis filters (H' and G'). The process known as the synthesis procedure consists of binary interpolation (up-sampling) by 2, filtering and recombination at each level.

To demonstrate the process of generation of wavelet packet bases, here we consider a cascaded level-3 tree structure as shown in Fig. 10(a). Such an arrangement can give rise to eight wavelet packet bases. This procedure is simplified further by applying the identities shown in Fig. 10(b). These expressions called the noble identities are popularly applied in the implementation of multi-rate systems. And in Fig. 10(c) the equivalent eight-channel system after the application of the noble identities is shown. In general, to generate M bases or sub-carrier waveforms, a level-J tree has to be constructed.

B.1.2 Generation of Wavelet Packet Dual Bases

The wavelet packet duals (to be used at the receiver end) are obtained from multichannel filter bank analysis too, though the processes are reversed. The duals are obtained from the analysis filters (H and G) through the analysis procedure which consists of filtering, decimation (downsampling) by 2 and decomposition at each stage. Fig. 11 illustrates the generation of 8 wavelet packet duals from a level-3 tree cascaded filter bank.

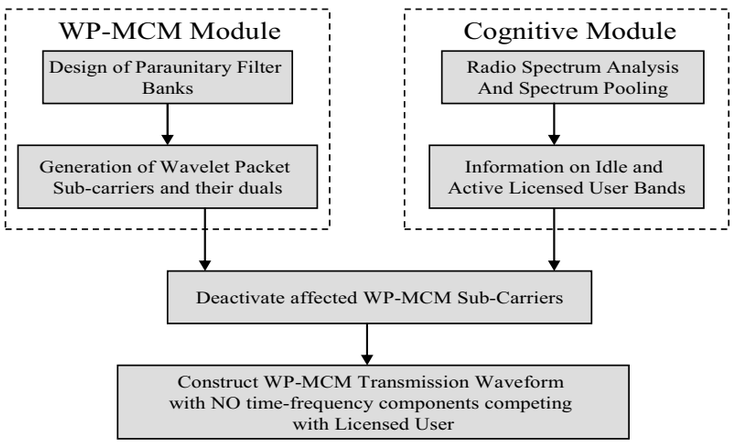
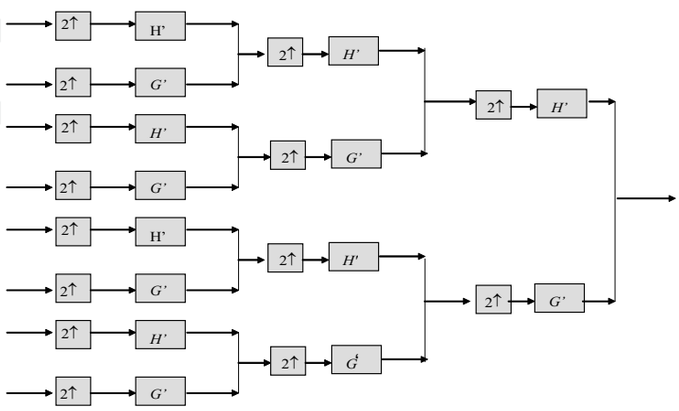
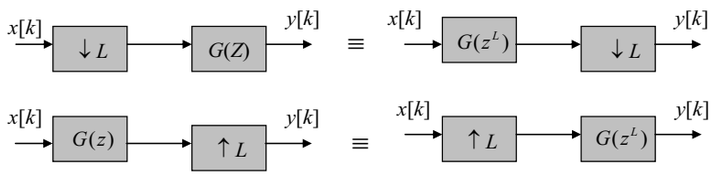


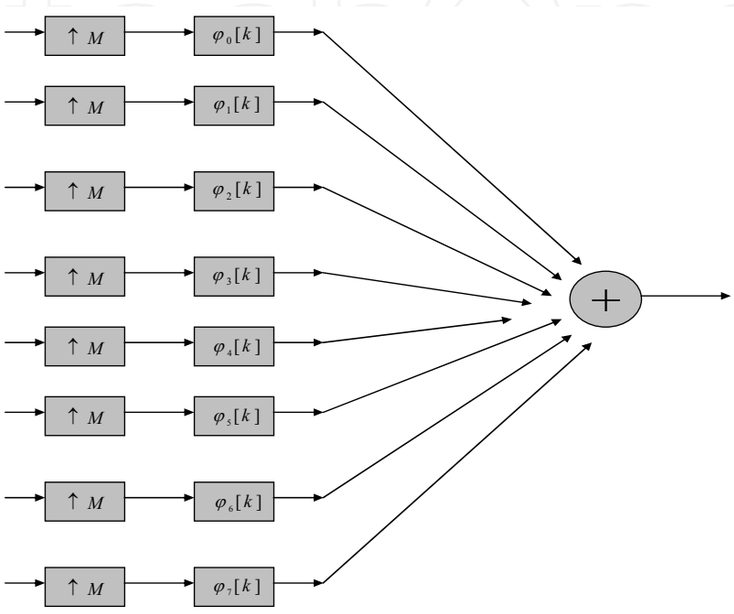
Fig. 9. Fundamental Blocks of WP-MCM based Cognitive Radio system.



(a)



(b)



(c)

Fig. 10. Generation of wavelets. (a) A level-3 tree gives 8 wavelet packet bases. The up arrows represent interpolation by 2. H' and G' denote the frequency responses of the low and high pass reconstruction filters, respectively; (b) Noble identities; (c) Equivalent 8-channel system after applying the noble identities, where φ' is equivalent reconstruction filter as results of the convolution combination H' and G' according to the tree lines. M=8 for the considered example.

B.1.3 Wavelet Design Considerations for WP-MCM application

Choosing the right wavelet is a delicate and at times even an overwhelming issue. In theory any time and frequency limited function can be utilized. However in practice, the wavelet bases cannot be arbitrarily chosen and instead have to satisfy a number of requirements.
With regard to the applicability to WP-MCM systems, the desirable properties may be listed as follows:

- The bases must be time and band limited
- The bases and their duals must be orthogonal to one another to enable perfect reconstruction.
- The bases must be orthogonal to one another in order to have unique demodulation.

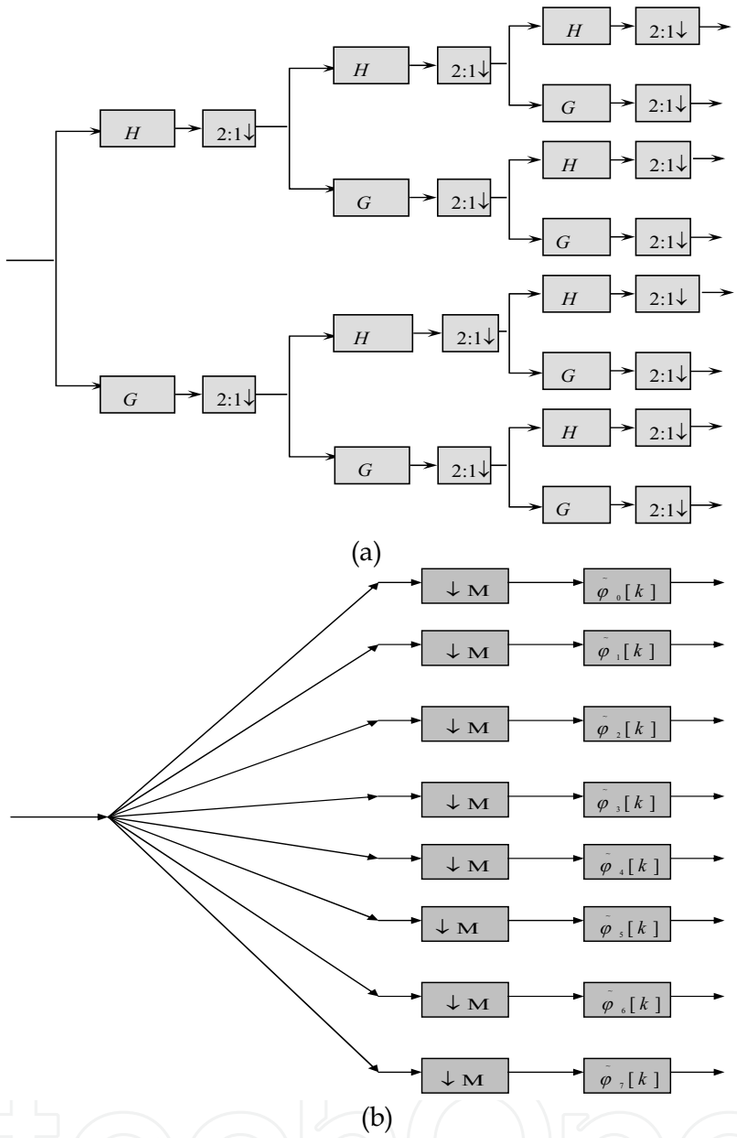


Fig. 11. Generation of wavelet Duals. (a) A level-3 tree gives 8 wavelet packet dual bases. The down arrows represent decimation by 2. *H* and *G* denote the frequency responses of the low and high pass decomposition filters, respectively; (b) Equivalent 8-channel system after applying the noble identities, where φ is equivalent decomposition filter as results of the convolution combination *H* and *G* according to the tree lines *M*=8 for the considered example.

Considering these requirements, among several available wavelet such as: Coifflets, Daubechies, Haar, Symlets, the most suitable wavelet is the family of maximally frequency filter banks derived using a modified Remez exchange algorithm. It provides degree of freedom to shape its sidelobes by varying its regularity order, transition bandwidth and the filter length. The longer the filter length, the more degree of freedom is available in

designing the frequency selectivity and also the regularity order of the signal. The smaller the transition bandwidth the more frequency selective the filter will be. The regularity order corresponds to the smoothness of the signal sidelobes. The higher the regularity order, the smoother or the lower the sidelobes of the signal will be. More on this subject can be found in (Rioul and Duhamel, 1994).
In (Lakshmanan et al., 2007) WP-MCM with Remez exchange algorithm as CR system is evaluated and compared with Fourier based MC-OFDM CR system in the presence of LU signal in Additive White Gaussian Noise (AWGN) channel. The results show within a certain Remez parameters value, WP-MCM outperforms the Fourier based MC-OFDM.

C. Interpolated Tree Orthogonal Multiplexing

In the WP-MCM technique the filter banks perform the dual role of shaping the spectrum as well as interpolating in time series. A more intuitive method is to separate the two processes to have a greater control over the characteristics of the carriers. This method called the Interpolated Tree Orthogonal Multiplexing (ITOM) was introduced in (Harris & Kjeldsen, 2006) by constructing a binary wavelet packet tree and performing the spectral shaping external to the tree structure. The procedure is depicted in Fig. 12 from which we can notice that up-sampled shaping filters precede the input ports of the wavelet packet tree structure. Notching over the desired spectral interval is achieved by vacating one or more of the input branches.
Fig. 13 shows an example of the ITOM mechanism. We may note from Fig. 13(a) and (b) that the enabled and disabled carries neatly fit into the spectral gaps of one-another illustration the superiority of the ITOM procedure towards spectrum shaping.

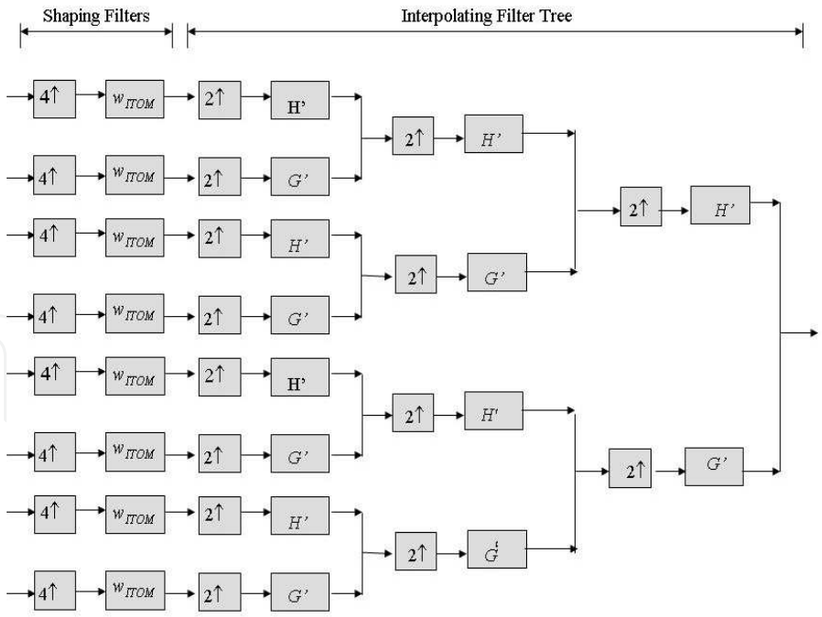
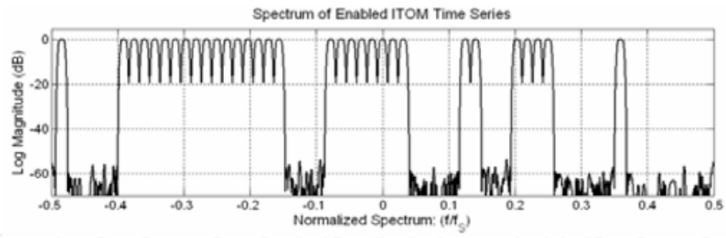
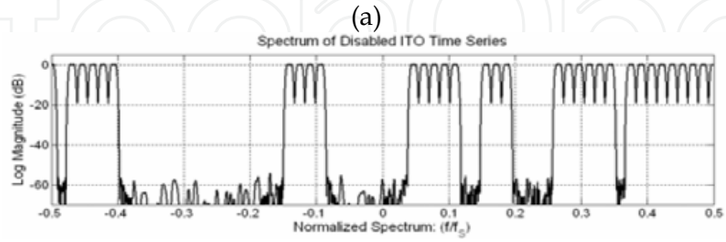


Fig. 12. Modulator of ITOM Interpolated Tree Structure (Harris & Kjeldsen, 2006). In the figure w_{ITOM} is the ITOM shaping filters.



(a)



(b)

Fig. 13. Illustration of ITOM operation: (a) Spectra of Enabled Spectral Bands of 64-point ITOM; (b) Spectra of Disabled Spectral Bands of 64-point ITOM (Harris & Kjeldsen, 2006).

3. Single Carrier Cognitive Radio with Adaptive Waveform

Another method of utilizing the spectrum efficiently is shaping of the waveform of the transmitted signal dynamically over a spectral region, in order not to interfere with the occupied spectrum. Transform Domain Communication System (TDCS) is introduced in (Chakravarthy et al., 2005) as a candidate technique for Cognitive Radio. In principle the transmitted signal is shaped in such a way that its bandwidth does not contain the LUs band. In (Lee, 2002) the Fourier transform as a tool in shaping the spectrum in TDCS is replaced by the wavelet basis function. The technique is called Wavelet Domain Communication System. The two techniques will be further explored in the following subsections.

A Transform Domain Communication System (TDCS)

The TDCS transmitter system is described in Fig. 14(a) where single carrier is used. A clean spectrum information is derived from $\boldsymbol{A}$= $\{A_1, A_2, \ldots, A_{NFFT}\}$, where amplitudes of interfering frequency components exceeding a threshold are set to zero, while the others are set to one. Multi-valued complex pseudorandom phase vector ($e^{j\theta}$) is multiplied element by element with $\boldsymbol{A}$ to produce the spectral vector $\boldsymbol{B}_b$. By multiplication with the scaling factor C, a vector $\boldsymbol{B}$ is produced. After IFFT operation, a time domain basis function $b(t)$ is derived, which subsequently is stored and modulated by using pulse amplitude modulation (PAM), pulse position modulation (PPM) or cyclic code shift keying (CCSK) where the bits are represented by the cyclic shifted pulse in time. The impact of this zeros insertion can be described from the power spectrum density (PSD) equation of TDCS,

$$PSD(f) = \left| \frac{1}{N_{FFT}} \sum_{m=0}^{N_{FFT}-1} A_m e^{j\theta_m} \int_{-(1+\alpha)\frac{T_u}{2}}^{(1+\alpha)\frac{T_u}{2}} p(t) e^{-j2\pi(f-f_m)t} dt \right|^2 \tag{16}$$

where T_u is the useful signal duration, $p(t)$ is the window function, a is the roll off factor of the window, and θ_m is the phase on subband m produced by the random phase module. If $p(t)$ is a rectangular window and α is zero, the area within the integral can be replaced by $T_u sinc(\pi f - \pi f_m)T_u)$. Zero amplitude at the carrier m will make the PSD on that carrier position becoming zero, and due to the orthogonality among carriers the power contributions from the other carriers are also zero. The equation is almost similar to (1), the differences are the power p_m and symbol amplitude A_m in (1) are replaced by the spectrum information A_m and the random phase θ_m.

TDCS gives more degree of freedom in choosing window $p(t)$ to lower the sidelobes of its spectrum. Unlike OFDM, the spectrum sidelobes of the window of TDCS do not have to be zero on the frequency spacing interval (in OFDM this is described as the orthogonality between carriers), as long as its sidelobes are very small. Since data detection at the receiver is performed by correlating the received signal with reference signal, as described in Fig. 14(b), the designed non-orthogonal spectrum of the transmitted signal will not affect the data detection.

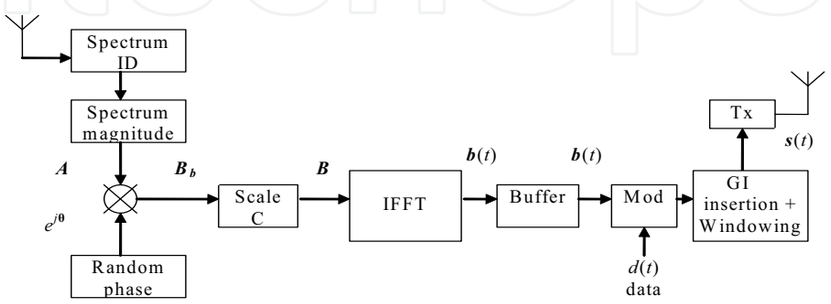
In an attempt to increase the bit rate of TDCS, in this section we describe the proposed embedded symbol to TDCS-CCSK. The embedded symbol can be derived from PAM, QAM or PSK modulation. The proposed transmitter and receiver architectures of the system are depicted in Fig. 15.

There are two bit sources available. The first one is for the embedded symbol, and the second one is for the CCSK modulation. At the transmitter one embedded symbol will be multiplied with the vector from the point to point multiplication between the vector produced by the random phase $\boldsymbol{\theta}$ and the vector produced by the spectrum magnitude $\boldsymbol{A}$. Further, the legacy processes in producing TDCS signal are applied. At the receiver, the CCSK data detection is applied first. After removing the fading effect in frequency domain, the CCSK data detection is applied by de-correlating the time domain received signal with the time domain reference signal. De-correlation can be simplified by taking the maximum absolute value of inverse Fourier transform of the product of the frequency domain conjugate received signal and reference signal.

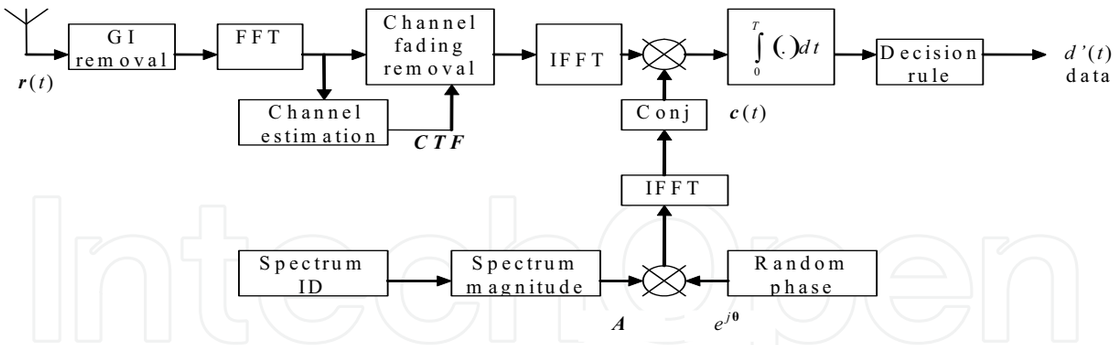
The new TDCS bit rate becomes:

$$R_{NEWTDCS} = \frac{\log_2 CS \cdot CS_{EM}}{T_s'} \tag{17}$$

where CS_{EM} is the embedded symbol constellation size.



(a)



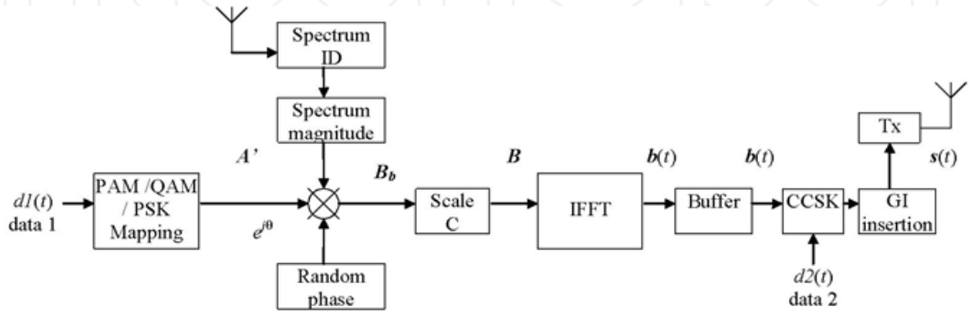
(b)

Fig. 14. TDCS (a) Transmitter and (b) Receiver.

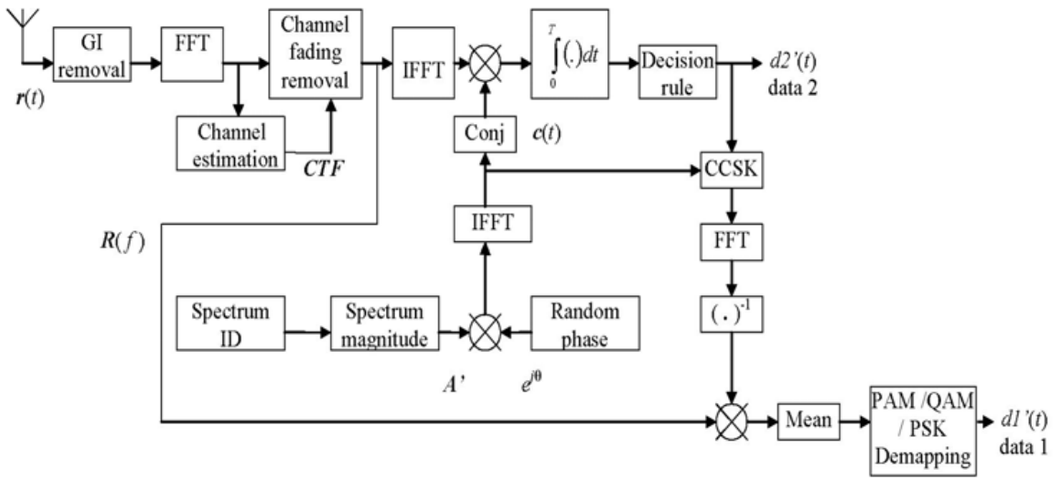
From the spectrum point of view, the PSD of TDCS-CCSK with extra embedded symbol becomes (Budiarjo et al., 2008a); (Budiarjo et al., 2008b) :

$$PSD(f) = \left| \frac{1}{N_{FFT}} S e^{j\varphi} \sum_{k=0}^{N_{FFT}-1} A_k e^{j\theta_k} \int_{-(1+\alpha)\frac{T}{2}}^{(1+\alpha)\frac{T}{2}} p(t) e^{-j2\pi(f-f_k)t} dt \right|^2 \quad (18)$$

By observing (18) it is reasonable to consider PSK as the most appropriate embedded symbol modulation mode among the three mapping types (PSK, PAM, and QAM). The PSK symbols are spread in a unit circle with magnitude of one. Therefore embedding the PSK symbol to the TDCS with CCSK modulation will not change the TDCS transmission power, while embedding PAM and QAM requires more power. The extra amount of power required will depend on the constellation size of the PAM/QAM embedded symbol. Moreover, the embedded symbol will affect the sidelobes of the proposed TDCS. Because PSK symbol magnitude is one, according to (18), the sidelobes amplitude of the proposed TDCS will not be changed. The PAM and QAM symbols with constellation size bigger than 2 have average magnitude larger than one therefore the sidelobes amplitude of the proposed TDCS will be affected. The PAM modulation in this case will be the worse option since for the same constellation size (larger than 2) its maximum amplitude is bigger than the QAM mode. Increasing the embedded symbol's constellation size will enhance the symbol- to-noise ratio on each of the TDCS subband, and symbol-to noise ratio enhancement will lead



(a)



(b)

Fig. 15. (a) Transmitter and (b) Receiver architecture of TDCS with extra embedded symbol (Budiarjo et al., 2008a); (Budiarjo et al., 2008b).

to the symbol probability of error improvement and eventually to the bit error rate improvement. Increasing the constellation size means allocating more bits to the transmitted signal and as the consequence more energy is practically allocated. The amount of allocated energy is linearly comparable with the number of allocated bits. Therefore, the SNR gain obtained by increasing the CS_{EM} compared to the conventional TDCS-CCSK corresponds to

$$SNR_{Gain} = 10\log_{10}\left(\log_2(CS_{EM})\right)dB \tag{19}$$

where $\log_2(CS_{EM})$ refers to the number of bits allocated to the embedded symbol.

B Wavelet Domain Communication System (WDCS)

An offshoot of TDCS is the wavelet domain communication system (WDCS) (Lee, 2002) where the Fourier transform operation in TDCS is replaced by wavelet transformation. Wavelets are used in this scheme to identify and establish an interference-free spectrum. The advantages of using wavelet are (Lee, 2002):

1. Increased adaptation over a larger class of interfering Signals,
2. Finer high-frequency resolution,
3. Allow implementation of *CS*-ary orthogonal signaling

The WDCS uses a packet-based transform to estimate the electromagnetic spectrum (Lee, 2002). Through the use of adaptive thresholds and notches, sub-bands containing the interference are effectively canceled. From this estimate, a unique communication basis function $\boldsymbol{A}$ in the transform domain is generated so that no (or very little) energy-bearing information is contained in the areas occupied by primary users. These functions are then multiplied with a pseudo random(PR) phase vector $e^{j\boldsymbol{\theta}}$ to generate $\boldsymbol{B}_b$. The PR code is used to randomize the phase of the spectral components. The resulting complex spectrum is then

scaled C to provide the desired energy in the signal spectrum. A time domain version $b(t)$ of the basis function is then obtained by performing an inverse wavelet transfom. The wavelet basis function can be Coifflets, Daubechies, Haar, Symlets or Remez filter as also be applied in WP-MCM. Finally, the basis function is modulated with data using PAM, or PPM, or CCSK modulation and then transmitted. The block diagram of the WDCS transmission process is shown in Fig. 16.

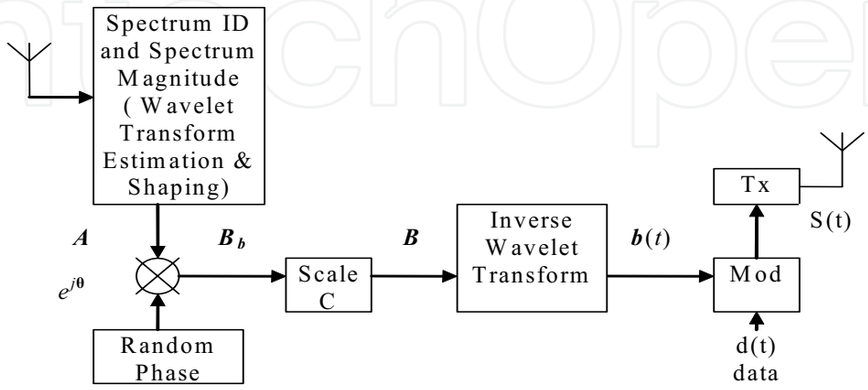


Fig. 16. WDCS Transmitter blocks (Lee, 2002).

At the receiver the detection is preceded by correlating the received signal with the reference signal in time domain. The receiver structure of WDCS is almost similar to the TDCS, the differences are the FFT and IFFT modules in TDCS that are replaced by discrete wavelet transform (DWT) and inverse discrete wavelet transform (IDWT), respectively.

4. MIMO for Cognitive Radio

Due to deactivation of carriers and long windowing duration upon the LU's occupancy, the CR bit rate is decreased. Multiple transmit antennas can be applied to CR for the purpose of transmitting different data on different antennas to increase the bit rate. The resource loss due to carriers deactivation on LU's band and bit rate loss due to long symbol duration are compensated. The transmitted power is distributed uniformly among the transmit antennas, so the total power is kept constant. In (Budiarjo et al., 2007b) CR with MC-OFDM and SC – TDCS on MIMO system using V-BLAST Receiver architecture has been evaluated. The results show the bit rate increases with the trade_off of more required pilots to estimate the channel transfer function of each transmit (Tx) and receive (Rx) antenna link. The composition of larger number of receive antenna compared to transmit antenna boosts the BER performance of the CR system. Especially for the TDCS the performance gain is even more significant than MC-OFDM for high SNR. Interesting results of (Budiarjo et al., 2007b) show that more SNR gain can be achieved by having more Rx antennas when compared to Tx antennas. Furthermore, this SNR gain is more significant when compared to the adaptive bit loading applied to OFDM with spectrum pooling (Budiarjo et al., 2006b).

5. Beamforming

Beamforming is formerly a multi access technique in mobile communications that takes the advantage of the position and angle of the other communications partners (nodes). This technique can increase the range between communications nodes, since the signal beam is concentrated (focused) on the intended communication partner hence no energy is wasted to the other direction. In CR system two scenarios can be considered in the application of beamforming: first is the interference avoidance to the LUs by not directing the signal beams to the LUs while occupying the LUs frequency, and second is the communications to multiple CR nodes without interference to each other (no multiple access interference).
In the case where no beamforming is applied, the RU can only occupy the LU's band if its distance to the licensed user is far so that it will not interfere with the LU's signal decoding process. Fig. 17(a) shows how the scenario should be when LU base station (BS) transmits data to LU mobile station (MS) which is located on the border of decodability region (dashed line). The RU can only transmit outside the "no talk zone" (solid line). The shaded region is called "protected region" where the signal decodability of the LUs is guaranteed (Sahai et al., 2004). Fig. 17(b) depicts the case when beamforming is applied by the RUs, the beams are directed to the intended RU partner, where communication to several RU nodes does not interfere to each other, and beams to the direction of LUs are nullified.
The important process in beamforming is the direction of arrival (DOA) estimation of the incoming signals. DOA estimation with Multiple Signal Classification (MUSIC) is introduced in (Schmidt, 1986), while Estimation of Signal Parameters by Rotational Invariance Techniques (ESPRIT) is proposed in (Paulraj et al., 1986). These DOA techniques give the angle directions from where the LUs signals are coming. An antenna array as well as a baseband model to estimate the direction of the intended partner is shown in Fig. 18 (a) and (b), respectively. If the plane wave incident on the array is from an angle (θ,ϕ) relative to the axis of the array, where θ is the angle of the wave incident with respect to the z axes, while ϕ is the angle between the x axis and the map of the wave incident on the x-y plane. If the array elements have uniform gain in all directions, and the spacing between array elements (Δx) is small, there will be no amplitude variations between signals received at different elements. All incident fields can be decomposed into a discrete number of plane waves. Other assumptions are well defined in (Liberti & Rappaport, 1999). The received signal will update the weights of the linear array elements and accordingly the maximum main beam of the array will be directed to the desired direction. By pointing the beam to specific angle where the LU signal comes and taking the Fourier transform of the received signal on that direction then the CR node with beamforming capability will have the information regarding the spectrum occupied on specific spatial direction. Accordingly this information is used for transmission of the CR system signal without interfering the LUs within spatial directions and certain frequency band. Investigation in (Liberti and Rappaport, 1999) shows that the utilization of beamforming by the LUs can enhance the coverage area of the CR system, and the propagation condition between the LUs and CR system affects the CR system's coverage area size. According to (Nishimori et al., 2006) for reusable CR coverage area greater than 70%, a signal to Interference Ratio (SIR) gain of about 14 dB is achieved by the CR system where the LU's beamwidth is 10 degrees in vertical plane compared to omni directional beam.

6. Summary

In this tutorial chapter techniques for CR were discussed. Spectrum sensing as the crucial element of cognition in terms of spectrum awareness was reviewed. Adaptive OFDM with Fourier and wavelet basis functions and the combination with spectrum pooling as well as the single carrier modulation with wave shaping technique using Fourier and wavelet transform were explained. MIMO technique as a QoS enhancement scheme for CR system was explained and beamforming as a spatial awareness technique in CR was studied.

Spectrum Pooling enables the access to spectrum without giving significant interference to the actual license owners. The high sidelobes of OFDM in spectrum pooling can be counteracted by deactivating carriers adjacent to the LUs (non contiguous OFDM), and applying a proper window to the signal in time domain. The loss due to carrier deactivation and long windowed symbol duration can be compensated by adaptive bit loading so the system still can achieve the target bit rate. Spectrum pooling provides a high degree of freedom in choosing the window to suppress the sidelobes of the signal since the signal orthogonality can be preserved at the receiver by applying the rectangular window implemented by DFT. If target bit rate is the main concern in adaptive bit loading, then groupwise bit loading is the choice, while if target error rate is the constraint, then carrierwise bit loading will be the solution.

Overlapping OFDM symbol transmission is another method in counteracting the loss of bit rate due to the long OFDM window duration. However the starting point of the consecutive OFDM symbols should be taken care of in order to avoid the ISI. Frequency hopping is the solution in very harsh channel environments where propagation condition and LU's access is very severe. Frequency hopping is only conducted when it is necessary.

Wavelet transform is considered to be a better modulation method compared to the Fourier transform method due to its flexibility in shaping the spectrum and its better ICI and ISI suppression. With the proper basis functions in the wavelet transform, the spectrum can be used efficiently; hence bit rate can be maintained or even increased. Furthermore, no guard interval is needed for the wavelet which is another boost for the throughput. A practical utilization of wavelet in CR system is by representing the RU signal as wavelet packet coefficients and by selectively removing those coefficients whose spectra footprint lies in the LU band. In all these techniques, the reliable information from the spectrum sensing unit is essential.

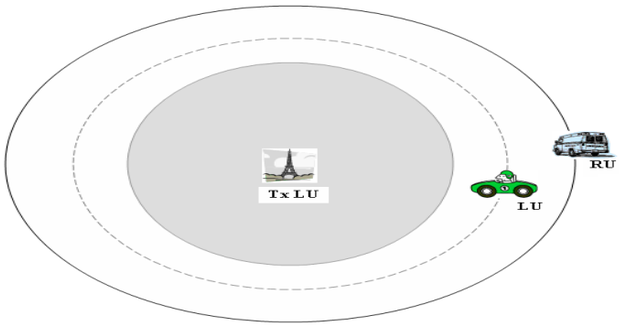
TDCS and WDCS are single carrier transmission techniques in utilizing the spectrum efficiently. The technique provides a degree of freedom in reducing its sidelobes which also directly reduces the interference to LU's band. In TDCS unlike in OFDM, the transmitted signal inter frequency orthogonality is not necessary since the data detection at the receiver is conducted by correlating the received signal with the reference signal. The drawback of the single carrier approach is the achievable data rate which is lower compared to OFDM.

MIMO system boosts the bit rate of CR system with additional computational costs of estimating all of the Tx and Rx channel links. For the improvement of BER of CR system, the usage of more receive antennas (than transmit antennas) is suggested.

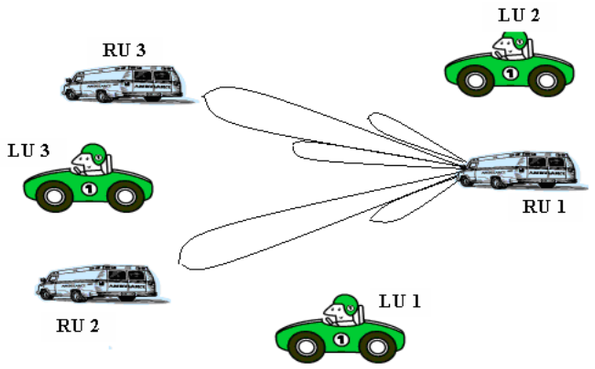
Beamforming gives spectrum sharing capability to a wireless system. It also enhances the multiple access capability of the CR system. As beamforming technique can be used by the scanning module to detect the spectrum occupancy in a specific direction, it will also enhance the coverage area of a CR system.

7. Acknowledgement

The authors acknowledge the support of Dutch Adaptive Adhoc Freeband (AAF) project in this research.

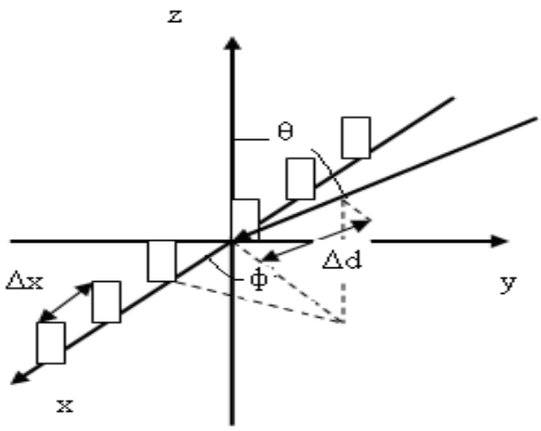


(a)

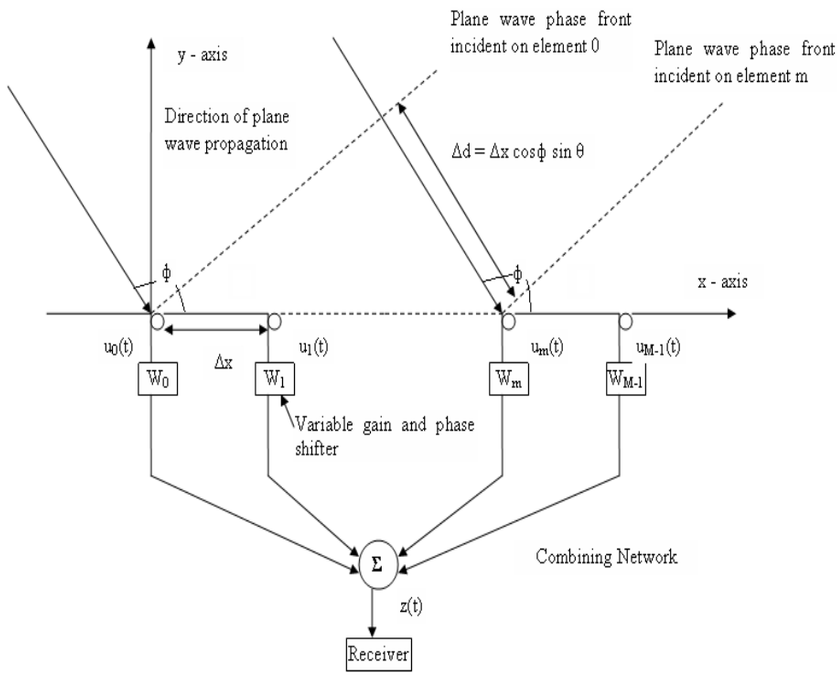


(b)

Fig. 17. (a) CR without beam forming (Sahai et al., 2004) (b) CR with beamforming.



(a)



(b)

Fig. 18. (a) A linear equally spaced array antenna (b) Baseband model of a linear equally spaced array for estimating Direction of Arrival of a plane wave incident on the antenna elements (Liberti & Rappaport, 1999).

8. References

Assalini, A. & Tonello, A. M. (2004). "Improved Nyquist Pulses", *IEEE Communicaions Letters,* Vol. 8, No.2, (February 2004) pp 87-89

Barreto, A. N. & Furrer, S. (2001). " Adaptive Bit Loading for Wireless OFDM Systems", Proceedings of *IEEE International Symposium on Personal, Indoor, Mobile Radio Communications*, pp. 88–92, San Diego California, USA, October 2001

Berthold, U.; Jondral, F. K.; Brandes, S. & Schnell, M. (2007). OFDM Based Overlay Systems: A Promising Approach for Enhancing Spectral Efficiency, *IEEE Communications Magazine*, Vol. 45, No. 12, (Dec. 2007) pp. 52-58

Bouwel, C.V.; Potemans, J.; Schepers, S.; Nauwelaers, B. & Capelle, A.V. (2000). Wavelet Packet Based Multicarrier Modulation, *Proceedings of IEEE Benelux Symposium on Communications and Vehicular Technology*, Leuven, Belgium, October 2000

Brandes, S.; Cosovic, I. & Schnell, M. (2005a). Sidelobe Suppression in OFDM Systems by Insertion of Cancellation Carriers, *Proceedings of 62nd IEEE Vehicular Technology Conference (VTC)*, pp. 152-156, Dallas, USA, September 2005

Brandes, S.; Cosovic, I. & Schnell, M. (2005b). Reduction of Out-of-Band Radiation in OFDM Based Overlay Systems, *Proceedings of First IEEE International Symposium New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, pp. 662 – 665, Baltimore Maryland, USA, November 2005

Brandes, S.; Cosovic, I. & Schnell, M. (2006). Reduction of Out of Band Radiation in OFDM Systems by Insertion of Cancellation Carriers, *IEEE Comunications Letters*, Vol. 10, No. 6, (June 2006) pp. 420-422

Brodersen, R.W.; Wolisz, A.; Cabric, D.; Mishra, S. M. & Wilkomm, D. (2004). CORVUS: A Cognitive Radio Approach for Usage of Virtual Unlicensed Spectrum, White Paper, Dept. of Electrical Engineering and Computer Science University of Berkeley, July 2004

Budiarjo, I.; Nikookar, H. & Ligthart, L. P. (2005). An Overview of Adaptive OFDM in the Context of Cognitive Radio, *Proceedings of 12th IEEE Symposium on Communications and Vehicular Technology (SCVT),* pp. 1-6, Enschede, the Netherlands , November 2005

Budiarjo, I.; Nikookar, H. & Ligthart, L. P. (2006a). Performance Evaluation of Adaptive Bit Loading For OFDM With Channel Estimation Using 2x1-D Wiener Filter, *Proceedings of Int. Sym. on Wireless Personal and Multimedia Communications*, pp. 1138-1142, San Diego CA, USA, September 2006

Budiarjo, I.; Nikookar, H. & Ligthart, L. P. (2006b). Combined Spectrum Pooling and Adaptive Bit loading for Cognitive Radio OFDM Based System, *Proceedings of 13th IEEE SCVT*, pp. 73-76,Liege, Belgium, November 2006

Budiarjo, I.; Heskamp, M.; Zhang, Q.; Nikookar, H. & Kokkeler, A. J. (2007a). *D.3.41 Radio system: Second Phase Verification andAdvances in Architecture and Algorithms*", Adaptive Ad-hoc Freeband (AAF), The Netherlands, July 2007

Budiarjo, I.; Nikookar, H. & Ligthart, L. P. (2007b). Cognitive Radio with Single Carrier TDCS and Multicarrier OFDM Approach with V-BLAST Receiver in Rayleigh Fading Channel, *Proceedings of 2nd International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom)*, pp. 140-146, Orlando, USA, August 2007

Budiarjo, I.; Nikookar, H. & Ligthart, L. P. (2007c). Performance Evaluation of OFDM Based Cognitive Radio System with Wiener Filter Channel Estimation Using Frequency Hopping GSM Channel Model at 900 MHz, *Proceedings of 10th European Conference on Wireless Technology (ECWT)*, pp. 74-77, Munich, Germany, October 2007

Budiarjo, I.; Nikookar, H. & Ligthart, L. P. (2008a). On the Utilization of Embedded Symbol for CCSK BER Improvement in TDCS Dynamic Spectrum Access, *Proceedings of IEEE European Wireless Technology Conference*, pp. 123-126, Amsterdam, The Netherlands, October 2008

Budiarjo, I.; Nikookar, H. & Ligthart, L. P. (2008b). Cognitive Radio Modulation Techniques: Reducing Mutual Interference, *IEEE Signal Processing Magazine*, Vol. 25, No. 6, (November 2008) pp. 24-34

Cabric, D.; Mishra, S. M. & Brodersen, R. W. (2004). Implementation Issues in Spectrum Sensing for Cognitive Radios, in *Proceedings of Asilomar Conference on Signals, Systems, and Computer*s, pp. 772 – 776, November 2004, Pacific Grove CA, USA

Cabric, D. & Brodersen, R. W. (2005). Physical Layer Design Issues Unique to Cognitive Radio Systems", *Proceedings of IEEE Personal Indoor and Mobile Radio Communications (PIMRC)*, pp. 759-763, September 2005, Berlin, Germany

Cabric, D.; Tkachenko, A. & Brodersen, R.W. (2006). Spectrum Sensing Measurements of Pilot, Energy, and Collaborative Detection, *Proceedings of IEEE Military Communications Conference (MILCOM)*, pp. 1-7, October 2006, Washingthon D.C., USA

Chakravarthy, V.; Shaw, A. K.; Temple, M. A. & Stephens, J. P. (2005). Cognitive Radio -An Adaptive Waveform with Spectrum Sharing Capability, *Proceedings of IEEE Wireless*

Communications and Networking Conference (WCNC), pp. 724-729, March 2005, New Orleans, USA

Chow, P. S., Cioffi, J. M. & Bingham, J. A. C. (1995). A Practical Discrete Multitone Transveiver Loading Algorithm for Data Transmission over Spectrally Shaped Channels, *IEEE Transactions on Communications,* Vol. 43, No.2, (February 1995) pp. 773–775

Cosovic, I.; Brandes, S & Schnell, M. (2005). A Technique for Sidelobe Suppression in OFDM System, *Proceedings of IEEE GLOBECOM*, pp. 204-208, St. Louis Missouri, USA, November 2005

Cosovic, I.; Brandes, S. & Schnell, M. (2006). Subcarrier Weighting : A Method for Sidelobe Suppression in OFDM Systems, *IEEE Communications Letters*, Vol. 10, No. 6, (June 2006) pp. 444-446.

Cosovic, I. & Mazzoni, T. (2006). Suppression of Sidelobes in OFDM systems by multiple choice sequences, *European Transactions on Telecommunications Special Issue on Multi carrier – Spread Spectrum Wiley InterScience*, Vol. 17, No. 6, (June 2006) pp. 623-630.

Cosovic, I. & Mazzoni, T. (2007) "Sidelobe Suppression in OFDM Spectrum Sharing Systems via Additive Signal Method", *Proceedings of 65th IEEE Vehicular Technology Conference (VTC)*, pp. 2692-2696, Dublin, Ireland, April 2007

Gruenheid, R.; Bolinth, E.; Rohling, H. & Aretz, K. (2000). Adaptive Modulation for the HIPERLAN/2 Air Interface, *Proceedings of 5th International OFDM Workshop*, Hamburg, Germany, September 2000

Gruenheid, R.; Bolinth, E. & Rohling, H. (2001). A Blockwise Loading Algorithm for The Adaptive Modulation Technique in OFDM Systems, *Proceedings of Vehicular Technology Conference*, pp. 948–951, Atlantic City New Jersey, USA, October 2001

Hanzo, L.; Wong, C. H. & Yee, M.S. (2002). *Adaptive Wireless Transceivers*, John Wiley and Sons Ltd, Chichester,England, 2002

Harris, F. & Kjeldsen, E. (2006). A Novel Interpolated Tree Orthogonal Multiplexing (ITOM) Scheme with Compact Time-Frequency Localization: an Introduction and Comparison to Wavelet Filter Banks and Polyphase Filter Banks", *Proceedings of Software Defined RadioTechnical Conference and Product Exposition*, Orlando, USA, November 2006

Haykin, S. (2005). Cognitive Radio: Brain Empowered Wireless Communications. *IEEE Journal on Selected Areas In Communications,* Vol. 23, No. 2, (February 2005) pp. 201–220

Hoeksema, F.W.; Heskamp, M.; Schiphorst, R. & Slump, C.H. (2005). A Node Architecture for Disaster Relief Networking, *Proceedings of* 1*st IEEE Int. Symposium on new Frontiers in Dynamic Spectrum Access Networks (DySPAN'05)*, pp. 577–584, November 2005, Baltimore Maryland, USA

Jamin, A. & Maehoenen, P. (2004). Wavelet Packet Modulation for Wireless Communications, *Wireless Communications and Mobile Computing magazine Wiley Interscience*, Vol. 5, Issue 2, (December 2004) pp 123-137

Jensen, A. & Cour-Harbo, A.L. (2001). *Ripples in Mathematics: The Discrete Wavelet Transform*, Springer, Heidelberg, 2001

Jetlund, O.; Oien, G. E.; Hole, K. J. & Markhus, V. (2002). Rate - Adaptive Coding and Modulation with LDPC Component Codes, *Proceedings of COST 273 TD(02) -108, 5th*

Management Committee Meeting COST Action 273, Towards Mobile Broadband Multimedia Networks, Lisbon, Portugal, September 2002

Kaemarungsi, K. & Krishnamurthy, P. (2003). On the Use of Adaptive OFDM to Preserve Energy in Ad Hoc Wireless Networks, *Proceedings of 13th MPRG / Virginia Tech Symposium on Wireless Personal Communications*, June 2003, Blacksburg Virginia, USA

Keller, T.; Liew, T. H. & Hanzo, L. (2000). Adaptive Rate RRNS Coded OFDM Transmission for Mobile Communication Channels, *Proceedings of 51 st IEEE Vehicular Technology Conference*, pp. 230-234,Tokyo, Japan, May 2000

Krongold, B. S.; Ramchandran, K. & Jones, D. L. (2000). Computationally Efficient Optimal Power Allocation Algorithms for Multicarrier Communications Systems, *IEEE Transactions on Communications,* Vol. 48, No. 1, (January 2000) pp. 23–27

Lakshmanan, M.K.; Budiarjo, I. & Nikookar, H. (2007). Maximally Frequency Selective Wavelet Packets Based Multi-Carrier Modulation Scheme for Cognitive Radio Systems, *Proceedings of 50th IEEE Global Communications Conference (Globecom)*, pp. 4185-4189, Washingthon DC, USA, November 2007

Lee, M. J. (2002). *Wavelet Domain Communication System (WDCS): Packet-Based Wavelet Spectral Estimation And M-ary Signaling*. Master thesis, Air Force Institute of Technology, Ohio, USA, March 2002

Lei, M. & Zhang, P. (2003). Subband and Power Loading for Adaptive OFDM, *Proceedings of Vehicular Technology Conference*, pp. 1482–1486, , Orlando Florida, USA, October 2003

Liberti Jr, J. C.; & Rappaport, T. S. (1999). *Smart Antennas For Wireless Communications*, Prentice Hall, NJ, USA, 1999

Mahmoud, H. A. & Arslan, H. (2008). "Sidelobe Suppression in OFDM –Based Spectrum Sharing Systems by Using Adaptive Symbol Transition", *IEEE Communications Letters*, Vol. 12, No. 2, (February 2008) pp. 133-135

Moseley, N. A. (2004). *Radio Resource Discovery for Ad-hoc Wireless Networking*, M.Sc Thesis, University of Twente, Enschede, Netherland, August 2004

Muschalik , C. (1996). Improving An OFDM Reception Using An Adaptive Nyquist Windowing, *IEEE Transactions on Consumer Electronics,* Vol.42, No.3, (August 1996) pp. 259-269

Mutti, C.; Dahlhaus, D. & Destefanis, D. (2004). Adaptive Coding based on LDPC Codes for OFDM Systems with HD Decoding, *Proceedings of 13th IST Mobile & wireless Communications Summit*, Lyon, France, June 2004

Negash, B. G. & Nikookar, H. (2000). Wavelet Based Multicarrier Transmission over Multipath Wireless Channel, *IEE Electronic Letters*, Vol. 36, No. 21, (October 2000) pp. 1787-1788

Nikookar, H. & Prasad, R. (1997a). Optimal Waveform Design for Multicarrier Transmission Over a Multipath Channel, *Proceedings of 47th IEEE Vehicular Technology Conference*, pp. 1812-1816, Phoenix Arizona, USA, May 1997

Nikookar, H. & Prasad, R. (1997b). Wave shaping of Multicarrier Signal for Data Transmission Over Wireless Channels, *Proceedings of 6th IEEE International Conference on Universal Personal Communications Record (ICUPC)*, pp 173–177, San Diego California, USA, October 1997

Nikookar, H. & Prasad, R. (2000). Weighted OFDM for Wireless Multipath Channels, *IEICE Transactions on Communications*, Vol. E83-B, No. 8, (August 2000) pp. 1864-1872

Nishimori, K.; Bottega, E.; Yomo, H.; Popovski, P.; Takatori, Y.; Prasad, R. & Kubota, S. (2006). Spatial Availability for Cognitive Radio System Under Directional Interference, *Proceedings of Int. Sym. on Wireless Personal and Multimedia Communications*, pp. 44-48, San Diego CA, USA, September 2006

Pagadarai, S.; Rajbanshi, R.; Wyglinski, A. M. & Minden, G. J. (2008a). Sidelobe Suppression for OFDM-Based Cognitive Radios Using Constellation Expansion, *Proceedings of IEEE Wireless Communicaitons and Networking Conference (WCNC)*, pp. 888-893, Las Vegas Nevada, USA, April 2008

Pagadarai, S.; Wyglinski, A. M. & Rajbanshi, R. (2008b). A Novel Sidelobe Suppression Technique for OFDM-Based Cognitive Radio Transmission", *Proceedings of IEEE Symposia on New Frontiers Dynamic Spectrum Access Networks (DySPAN)*, pp. 1-7, Chicago, USA, October 2008.

Paulraj, A.; Roy, R. & Kailath, R. (1986). A Subspace Rotation Approach to Signal Parameter Estimation, Proceedings *of IEEE* , Vol. 74, No. 7, (Jul. 1986) pp. 1044-1046

Reddy, S. B.; Yucek, T & Arslan, H. (2003). An Efficient Blind Modulation Detection Algorithm for Adaptive OFDM Systems, *Proceedings of IEEE Vehicular Technology Conference (VTC)*, pp. 1895–1899, Orlando, USA, October 2003

Rioul, O. & Duhamel, P. (1994). A Remez Exchange Algorithm for Orthonormal Wavelets, *IEEE Transactions on Circuits Systems - II*, Vol. 41, No. 8, (August 1994) pp. 550-560

Sahai, A.; Hoven, N. & Tandra, R. (2004). Some Fundamental Limits on Cognitive Radio, *Proceedings of 42nd Allerton Conference on Communication, Control, and Computing,* Monticello IL, USA, October 2004

Schmidt, R. O. (1986). Multiple Emitter Location and Signal Parameter Estimation, *IEEE Transactions on Antennas and Propagation*, Vol. 34, No. 3, (March 1986) pp. 276-280

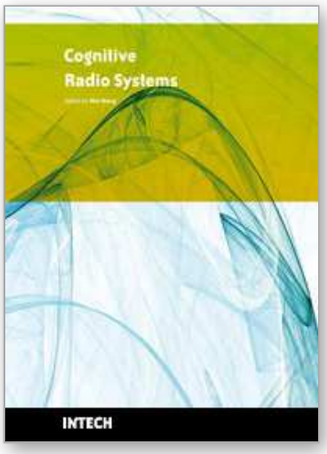
Tan, P. & Beaulieu, N. C. (2004). Reduced ICI in OFDM Systems Using the Better than Raised – Cosine Pulse, *IEEE Communications Letter,* Vol. 8, No. 3,(March 2004) pp. 135-137

Vucetic, B. (1991). An Adaptive Coding Scheme for Time Varying Channels, *IEEE Transactions on Communications*, Vol. 39, No. 5 , (May 1991) pp 653 – 663

Weiss, T.; Hillenbrand, J.; Krohn, A. & Jondral, F. K. (2004). Mutual Interference in OFDM based Spectrum Pooling Systems, *Proceedings of IEEE Vehicular Technology Conference (VTC)*, pp. 1873- 1877, Milan, Italy, May 2004

Witrisal, K. (2002). OFDM Air Interface Design for Multimedia Communications, *Ph.D. Thesis,* Delft University of Technology, The Netherlands, April 2002

Yamaguchi, H. (2004). Active Interference Cancellation Technique for MB-OFDM Cognitive Radio, *Proceedings of 34th European Microwave Conference*, pp. 1105-1108, Amsterdam, The Netherlands, October 2004



Cognitive Radio Systems
Edited by Wei Wang

ISBN 978-953-307-021-6
Hard cover, 340 pages
Publisher InTech
Published online 01, November, 2009
Published in print edition November, 2009

Cognitive radio is a hot research area for future wireless communications in the recent years. In order to increase the spectrum utilization, cognitive radio makes it possible for unlicensed users to access the spectrum unoccupied by licensed users. Cognitive radio let the equipments more intelligent to communicate with each other in a spectrum-aware manner and provide a new approach for the co-existence of multiple wireless systems. The goal of this book is to provide highlights of the current research topics in the field of cognitive radio systems. The book consists of 17 chapters, addressing various problems in cognitive radio systems.

How to reference
In order to correctly reference this scholarly work, feel free to copy and paste the following:

I. Budiarjo, M.K.Lakshmanan and H. Nikookar (2009). Cognitive Radio Dynamic Access Techniques for Mutual Interference Reduction and Efficient Spectrum Utilization, Cognitive Radio Systems, Wei Wang (Ed.), ISBN: 978-953-307-021-6, InTech, Available from: http://www.intechopen.com/books/cognitive-radio-systems/cognitive-radio-dynamic-access-techniques-for-mutual-interference-reduction-and-efficient-spectrum-u

INTECH
open science | open minds

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

© 2009 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike-3.0 License, which permits use, distribution and reproduction for non-commercial purposes, provided the original is properly cited and derivative works building on this content are distributed under the same license.

IntechOpen

IntechOpen