Scalar Wavelet packet based multi-user Cognitive Radio Transceiver

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***Abstract*— A multi-user Cognitive Radio (CR) network resolves the problem of spectrum under utilization and enables the deployment of new wireless applications in the fast growing wireless communication area. Hence a multi-user CR network using scalar wavelets is considered in this paper for evaluating the performance characteristics. Both mathematical and experimental analysis of the proposed system are given in detail. Spectrum efficiency, sidelobe suppression, error performance and complexity analysis of the system are analyzed.**

***Index Term*— Wavelet Transform, spectrum sensing, carrier allocation, reconfigurability.**

I. INTRODUCTION

CRis envisioned as the most promising wireless technology for optimizing the usage of radio frequency spectrum and for insuring reliable communication [1]. Even though OFDM based systems have been proposed to be the most promising candidate for CR transmission [2]-[5], recent research work propose wavelet based schemes to be an alternative modulation technique in terms of flexibility, adaptivity, and spectrum efficiency [6]-[11]. The efficacy of scalar wavelet packets for CR based systems has been explored and various results are discussed in [12] - [16]. Both analytical and experimental results show that scalar wavelet based schemes insures better flexibility, sidelobe suppression and reconfigurability at moderate complexity but the research has been limited to single user environment. As WPM is a generalization of Time Division Multiplexing (TDM) and Frequency Division Multiplexing (FDM) it can be considered in a multiuser network with necessary modifications. Hence a Wavelet Packet based Multi Carrier Multiple Access scheme (WP-MC-MA) for CR applications is first proposed in [17]. In this paper the detailed uplink and downlink system models and signal representations are explained. The performance of the system is evaluated using standard orthogonal wavelet basis functions and is compared with OFDMA. The bit error rate under multi-path fading is simulated which is crucial in wideband wireless links. Effect of phase and frequency offset in both uplink and downlink channels are evaluated. The spectrum efficiency and computational complexity of the proposed system are analyzed.

II. WP-MC-MA SYSTEM FOR CR

The basic difference between OFDM and wavelet packet modulation is the replacement of IFFT and FFT blocks of OFDM scheme by Inverse Discrete Wavelet Packet Transform (IDWPT) and Discrete Wavelet Packet Transform (DWPT) [10]. As in OFDM the inverse transform (Synthesis) is used in generating the transmitted signal and the direct transform (Analysis) in retrieving the symbol [9]. The transmitted signal in discrete time domain $x[k]$, is the sum of successive modulated symbols, each of which is constructed as the sum of M waveforms$\psi_m[k]$individually amplitude modulated.This can be expressed as

$$x[k] = \sum_{s} \sum_{m=0}^{M-1} a_{s,m} \psi_m[k - sM] \quad (1)$$

where "$a_{s,m}$" is the s^{th}baseband data symbol modulating the m^{th}waveform and "ψ" is the modulating waveform. Better error performance is achieved in this scheme by choosing the waveforms $\psi_m[k]$that are mutually orthogonal. Such a system can be extended to a multi-user network since the waveforms are orthogonal which is exploited in our proposed scheme. Thebasic multi-user CR network is assumed with a number of CR nodes communicate with a central CR base station (BS). Theconcept is adopted from the already existing IEEE 802.22 standard of CR. This simplifies the downlink transmission andinsures reliable spectrum sensing of the RF environment.

A. *Uplink System Model*

The basic uplink model of the proposed WP-MC-MA system can be described with the help of block diagram shown in Fig. 1. It is based on 2 assumptions.

1) The spectrum sensing block in each CR node gives the exact information regarding the free bands.

2) CR nodes within a cell have Channel State Information (CSI) of their neighboring nodes

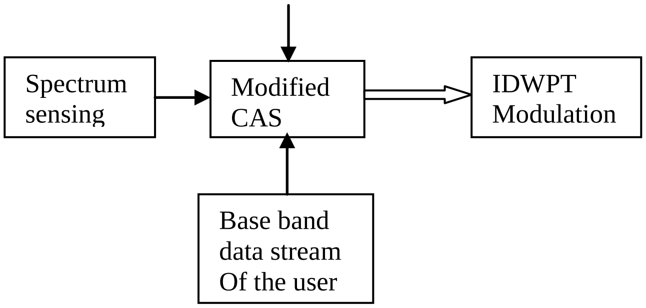

Fig. 1. Uplink Schematic of WP-MC-MA system

The spectrum sensing scheme considered is a wavelet packet based spectrum sensing as given in [18]. The CR node scansits band of interest (BOI) and generates a wavelet packet coefficient vector $C_v(n)$. Based on the value of $C_v(n)$ a preliminary decision of free spectrum is taken. The final spectrum decision and allocation block for CR in this scheme is a modified form of generalized Carrier Assignment Scheme (CAS). There are 3 different types of CAS to allocate subcarriers among active users in OFDMA based networks [19]. In fixed CAS each subchannel is assigned a group of R/M adjacent subcarriers where R is total number of free subbands and M is the number of users. The method is simple but because of lack of flexibility this scheme is rarely used. The second method is the interleaved CAS where the subcarriers within a subchannel are spaced by a distanceequal to the number of subchannels. This scheme is more flexible compared to fixed CAS and the retrieval of the information at the receiver is possible with moderate complexity. To completely exploit the frequency diversity of available subcarriers and to incorporate dynamic frequency allocation the generalized CAS is used in most of the applications where each user is assigned subcarriers with the highest signal to noise ratio that are currently available [19]. The modified form of generalized CAS will have the cognitive capability to incorporate more parameters to assign the subcarriers among CR nodes. The user’s data are baseband encoded, channelled through *P* parallel streams where *P* is the number of subcarriers allotted for each user. The data stream is fed into CAS, which will allocate subbands to the selected user based on the spectrum measurement vector $C_v(n)$ and CSI of the users within the given cell. The symbol stream is allocated to *P* subbands within available *R* subcarriers and by inserting (R-P) zero arrays an *R* dimensional vector is obtained as in OFDMA [19]. Mathematically it can be expressed as

$$d_m(n) = \begin{cases} c_m(n) \text{if } n \in I_m; \\ 0 \qquad \text{otherwise} \end{cases} \tag{2}$$

where$c_m(n)$ represents the constellation of encoded data stream of the user and $I_m$is the set of the indices of m^{th}subchannel assigned to m^{th}user. The vector $d_m$generated is input to the Inverse Discrete Wavelet Packet Transform (IDWPT) block for waveform modulation and the serial data stream $s_m$is obtained. The subbands generated by wavelet packet transform in a multiple access scheme should be orthogonal so as to ensure minimum Multiple Access Interference (MAI) and hence orthogonal wavelet bases are to be chosen. In addition to orthogonality, wavelet bases should have compact support, regularity and frequency localization. Hence, an arbitrary choice of wavelet bases for multi-user CR applications will lead to undesirable results. The standard wavelets used in performance evaluation are tabulated below.

Table I
Wavelet Specifications

Name	Filter Length	Compact Support	Orthogonality	Notation
Daubechies	20	Yes	Yes	db10
Symlet	20	Yes	Yes	sym10
Coiflet	18	Yes	Yes	coif3
Discrete Meyer	102	Yes	Yes	dmey

B. *Modified CAS*

The Carrier Assignment Scheme acts as the spectrum manager or spectrum decision block within a CR node and at BS.As in OFDMA the best scheme to be used is generalized CAS which provides dynamic frequency allocation. CAS in theuplink generates the subcarrier index set of each user based on the spectrum measurement vector and CSI. The modified CASfunctions are shown in the flowchart and various steps included are as described by the accompanying algorithm.

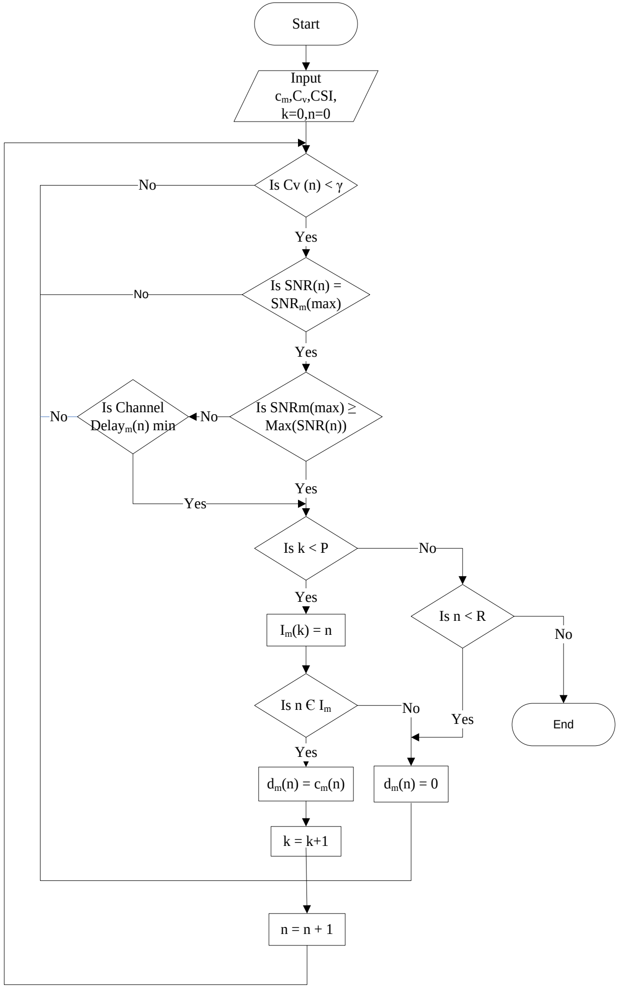

Fig. 2. Flow chart of Modified CAS

Algorithm:

1: The received spectrum measurement vector $C_v(n)$ is compared with a predefined threshold to determine the available free bands.

2: CSI of each free subband available within the BOI is input to CAS.

3: CSI of the CR node under consideration along with the neighboring nodes are obtained.

4: Based on the information obtained, CAS assigns subbands for the considered CR node. The subband with maximum SNRis the primary choice.

5: If the specified CR as well as a competing neighbor has maximum SNR at the k^{th}subband, other CSI factors such aschannel delay, phase offset will be taken into consideration to make the final decision.

6: Once the subband is fixed, final decision is made and that subband index is included in the spectrum index vector $I_m$andthe n^{th}data stream of the user is mapped onto that subband.

7: The process is repeated until all the P data streams of the user are mapped accordingly. The remaining subcarriers carry no data and are padded with zeros.

C. Uplink Signal Model

The signal transmitted from the m^{th}user can be written as

$$s_{wpm}(k) = \sum_{p=0}^{R-1}\sum_{n} d_p^m(n)\psi_m^{syn}(k-nR) \qquad (3)$$

Signal received at the base station will be the composite of N user waveforms summed up which are subjected to individualfrequency, phase and timing offset along with their corresponding fading components. Received signal is given as

$$r(k) = \sum_{m=1}^{N} \acute{s}_{wmp}(k)h^m(k) + n(k) \qquad (4)$$

where$n(k)$ is the noise and $\acute{s}_{wmp}(k)$ is wavelet packet modulated component of the m^{th}user and $h^m(k)$ is the impulse response (IR) of the corresponding fading channel and N is the total number of users. The signal component can be expressed as

$$\acute{s}_{wpm}(k) = e^{j\phi_m(k)}\sum_{p=0}^{R-1}\sum_{n} d_p^m(n)\psi_m^{syn}(k-nR-\tau_m) \qquad (5)$$

where$d_p^m(n)$ is the symbol stream mapped onto the subchannel of the m^{th}user as given before and $\psi_m^{syn}$is the wavelet packetsynthesis waveform for the m^{th}user subchannels. The term $e^{j\phi_m}$corresponds to the frequency and phase offset of the m^{th}userand is defined as

$$\phi_m(k) = \frac{2\pi\varepsilon_m k}{R} + \theta_m(k) \qquad (6)$$

where$\theta_m$is the phase noise component and $\varepsilon_m$is the relative frequency offset of the m^{th}user. R is the total number ofsubcarriers. The frequency offset is normalized to the inter carrier spacing. The integer timing offset $\tau_m$is expressed insampling periods. After channel equalization the signal is retrieved through DWPT and the demodulated signal will be

$$\tilde{r}(k) = \left(\sum_{m=1}^{N} \acute{s}_{wpm}(k) + n(k)\right)\psi_m^{anal}(k-nR)$$

$$= \left(\sum_{m=1}^{N} e^{j\phi_m(k)}\sum_{p=0}^{R-1}\sum_{n} d_p^m(n)\psi_m^{syn}(k-nR-\tau_m) + n(k)\right)\psi_m^{anal}(k-nR) \qquad (7)$$

When the frequency, phase and timing offsets are nulled this expression can be simplified as

$$\tilde{r}(k) = \left(\sum_{m=1}^{N}\sum_{p=0}^{R-1}\sum_{n} d_p^m(n)\psi_m^{syn}(k-nR)\right)\psi_m^{anal}(k-nR) + n(k)\psi_m^{anal}(k-nR) \qquad (8)$$

$$= \sum_{m=1}^{N}\sum_{p=0}^{R-1}\sum_{n} d_p^m(n) + n(k)\psi_m^{anal}(k-nR)$$

since the wavelet basis used is orthonormal. It is evident that to maintain orthogonality among subcarriers during detectionprocess proper timing and frequency estimation are required at the base station. The channel index set $I_m$is received at theBS through the control channel. This will help channel assignment for downlink.

D. Downlink Systems

The downlink transmitter and receiver of the proposed system is shown in Fig. 3 and Fig. 4 respectively. The downlinktransmission is almost equivalent to basic wavelet packet modulation scheme but each transmitted block carries data stream of multiple users. The data stream of each user is divided into blocks after symbol mapping. The i^{th}block of the m^{th}user is denoted as $b_{m,i}$. Similar to uplink, CAS unit maps the P data symbols of each block onto subcarriers assigned to the corresponding user. The final R dimensional vector will have data stream of all the N users summed up and hence the i^{th}block is given as

$$d_i = \sum_{m=1}^{N} d_{m,i} \qquad (9)$$

Each data block is fed to IDWPT modulator and the serial data stream obtained is input to Digital to AnalogCoverter(D/A)and then to RF modulator. At the receiver the A/D output will be the composition of data blocks of all users. Frequency andtiming errors are present in the signal received at the user terminal, similar to that in the BS. Hence the coarse frequency and timing estimation units employ the received sequence r(k) to compute estimates of frequency and timing error denoted by $\epsilon$and £ respectively. The frequency error estimate can be used to counter rotate r(k) by an angle of $\frac{2\pi\epsilon}{R}$and the timing error estimate for correct positioning of DWPT window. After the correction process, the data stream is input to DWPT block where the serial stream is decomposed into R subbands. The channel equalization block will compensate for channel impairments and fractional timing errors. For data detection, from the available R subbands, P subbands of the particular user are considered. For brevity, the estimation techniques at the receiver for uplink and downlink are excluded in the simulation study. In practical, frequency and phase estimation can be done using higher order statistics.

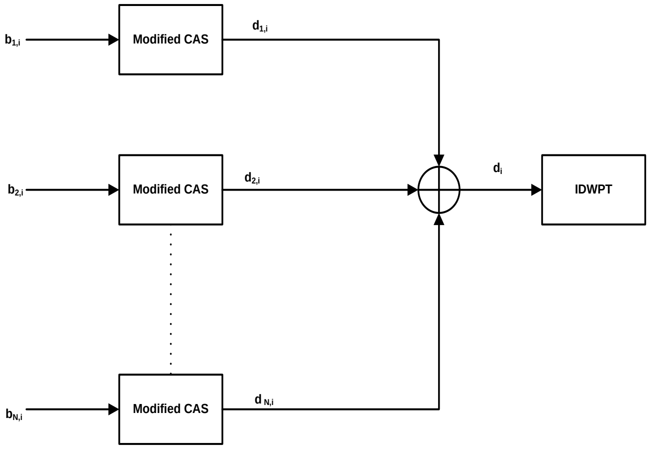

Fig. 3. Downlink transmitter of WP-MC-MA

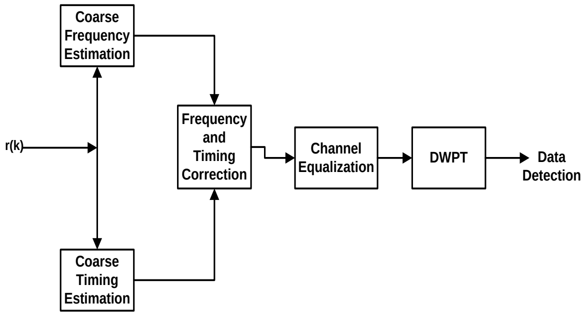

Fig. 4. Downlink receiver of WP-MC-MA

III. PERFORMANCE EVALUATIONS

To evaluate the performance of the proposed system, a multi-user CR environment with 4 users is considered. It is assumedthat the BOI is scanned with wavelet packet transform and total frequency band of 16 subcarriers is found vacant. Equal number of subcarriers for all users is considered. Hence there are 4 subchannels with 4 subcarriers for each user in the simulated system. The user data stream is base band encoded, converted from serial to 4 parallel streams and is mapped onto 16 subcarriers at the CAS. In IDWPT block, the data stream undergoes 4 iterations of upsampling and filtering to generate the serial data stream. It is assumed that there is perfect synchronization between the users and base station (BS). The channel index set $I_m$generated is known at the user end in order to separate the required data streams. The different user signals embedded in noise is demodulated, passed through the DWPT block for successive iterations of filtering and downsampling. Thus 16 parallel streams are recovered and using the knowledge of subband index vector, the user data stream is extracted and detected. The results obtained for WP-MC-MA are compared with an OFDMA system of 4 users and 16 subcarriers. The BER curves simulated in this work correspond to downlink scenario of WP-MC-MA and OFDMA.

A. *Error Performance in single path fading Channels*

To incorporate the effects of flat fading, the channel gain is modeled as complex normal distribution $CN(0,1)$, with variance 1 such that its real and imaginary parts are normally distributed with half the variance. That is the channel response h can be expressed as

$$h = \mathit{normal}(0,0.5) + j \times \mathit{normal}(0,0.5) \tag{10}$$

Fig. 5 shows the BER in flat fading channel for downlink scenario of both wavelet and OFDMA system. The results arecomparable with a basic QPSK or QAM baseband modulation scheme. It is assumed that the channel information is knownat the receiver and is compensated. The different wavelets simulated in the work show similar performances. In Fig. 6 theeffect of a single path Rayleigh fading channel with a maximum Doppler shift of 55 rad/sec is plotted. The channel model is generated based on Jakes model and zero forcing equalization algorithm is used at the receiver. Error performance does not show significant change with different wavelets used. The BER of OFDMA and WP-MC-MA is almost similar.

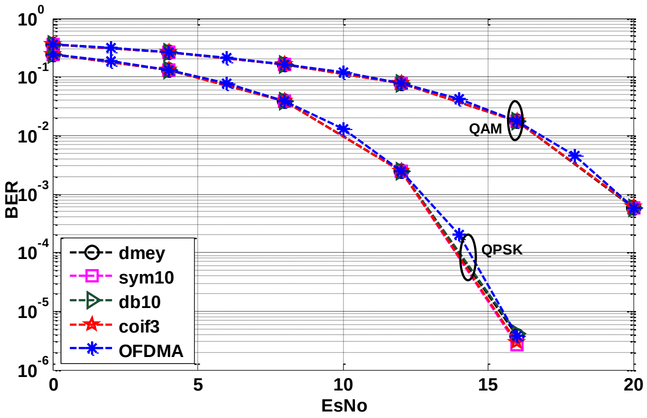

Fig. 5. BER in single path flat fading channel

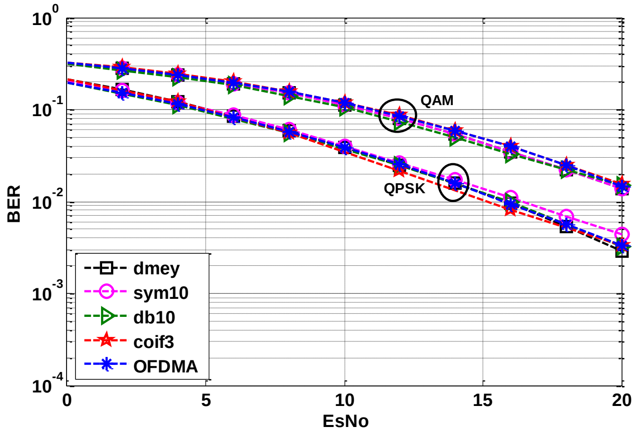

Fig. 6. BER in single path Rayleigh fading channel

B. *Error Performance in multipath fading Channels*

To evaluate the capability of the system to mitigate multi-path fading channel impairments, three path fading channel withfixed and Gaussian fading coefficients are considered. OFDMA system with and without CP is plotted as the latter system will have spectrum efficiency equivalent to that of proposed wavelet based system. The Cyclic Prefix (CP) of the simulated OFDMA system is equal to the channel delay. At the receiver, the wavelet based scheme uses a time domain zero forcing equalizer with three taps per sample as given in [20] and OFDMA uses a frequency domain zero forcing equalizer with one tap per subcarrier since the demodulated OFDM signal is in the frequency domain. The fixed channel impulse response used for simulation is h = [0.407 1 0.407]. These coefficients are chosen such that the frequency response of the channel represents low pass filter characteristics. The error curves of both systems are plotted in Fig. 7 and 8. In both cases OFDMA without CP gives high error rate as one tap frequency domain equalizer is not sufficient for nullifying multi-path channel distortions. When the channel coefficients are fixed the wavelet based system performs nearly as OFDMA system with CP since the equalizer weights of the wavelet scheme can be designed such that the combined channel and equalizer impulse response will be zero at all sample points except the desired sample point. But when the channel coefficients are normally distributed Gaussian random variables the proposed scheme gives a very poor performance since there is random frequency nulls in the channel by which the noise enhancement is very high. OFDMA system with CP gives a fairly good performance. As CP cannot be incorporated with wavelet systems it is required to design a better equalization technique in order to improve the error performance in a multi-path Rayleigh fading channel.

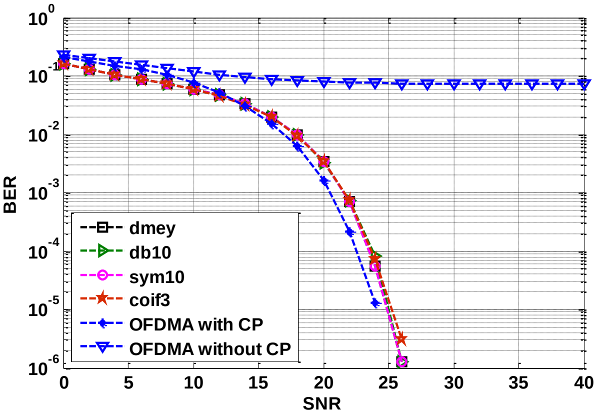

Fig. 7. BER in multi path fading channel with fixed fading coefficients

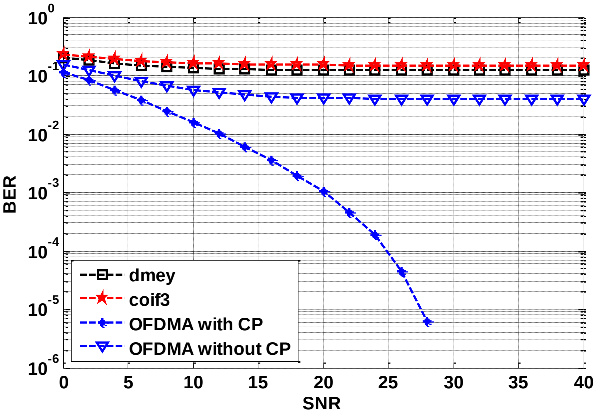

Fig. 8. BER in multi path fading channel with gaussian fading coefficients

C. *Effect of phase Offset*

In any multi carrier modulation it is important to consider the effect of frequency, phase and timing offset. A brief study onthe effect of frequency , phase and timing offset in wavelet packet modulation is given in [13]- [14]. In this work the effect of phase, frequency and time offset in a multiuser environment is considered and for the simulation study, each one is taken independently. The presence of phase noise will affect the multicarrier modulation in two ways. Firstly it will rotate all the constellation symbols by the same angle which is approximately equal to the average phase noise. Secondly it will introduce ICI due to the spread of subcarriers with a larger bandwidth around the carrier frequency [13]. To simulate the effects of phase noise in a multi user environment the phase noise is expressed as a zero mean Gaussian noise. If the channel is assumed to be AWGN and relative frequency error $\varepsilon_m$to be zero the received signal at the base station can be given as

$$r(k) = \sum_{m=1}^{N} \acute{s}_{wpm}(k) e^{j\theta(k)} + w(k) \qquad (11)$$

where$e^{j\theta(k)}$is the phase noise component. When the phase noise is too small this can be simplified as

$$e^{j\theta(k)} = 1 + j\theta(k) \qquad (12)$$

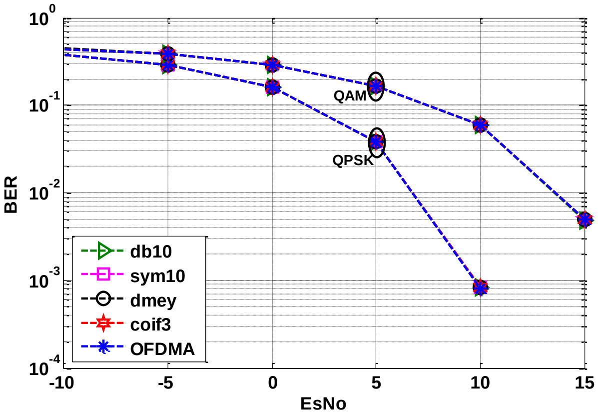

Fig. 9. BER with phase noise variance=0.001 (DownLink Channel)

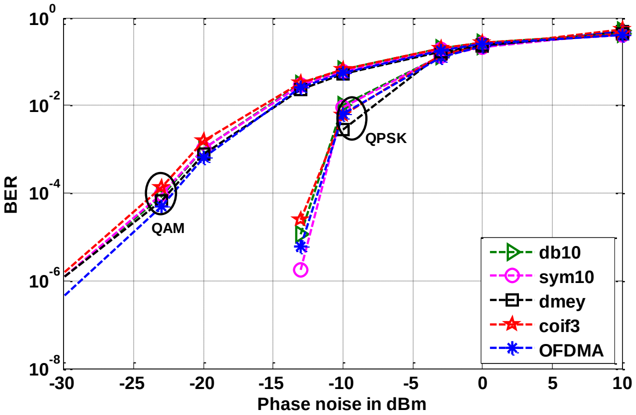

Fig. 10. BER with phase noise expressed in dBm (DownLink Channel)

Fig. 9 and 10 shows the effect of phase offset for downlink in WP-MC-MA system. In Fig. 9 the BER of the system using different wavelets is plotted as a function of SNR, corresponding to a small phase noise with a variance of 0.001 so that equation (12) will be satisfied. In Fig. 10 the phase noise power is expressed in dBm and its effect on BER is plotted corresponding to SNR of 15dB. Fig 11 shows the BER for uplink channel when different users are subjected to distinct phase offsets but all users employ QPSK modulation. BER is plotted for user 1 affected by a phase noise variance of 0.01 and user 3 with 0.05. The proposed system and OFDMA shows similar results.

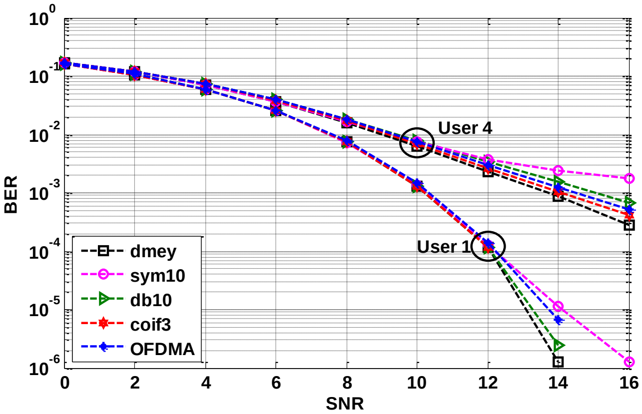

Fig. 11. BER with phase noise (Uplink Channel)

D. Effect of frequency and timingOffset

Frequency offset can occur due to Doppler shift or by misalignment between the transmitted carrier frequency and the locallygenerated carrier frequency at the receiver. It destroys orthogonality among subcarriers and hence causes severe ICI. To simulate the effect of frequency offset, the channel is assumed to be AWGN and the phase and timing offsets are assumed to be zero. The graphs are plotted for both WP-MC-MA and OFDMA. Fig. 12 shows the effect of frequency error on performance. BER is plotted as a function of relative frequency offset for a constant symbol energy of 15dB and no error compensation is done at the receiver. From the plots it is evident that both systems are severely affected when the relative frequency offset is increased to 0.2 or more. OFDMA and WP-MC-MA results are comparable and the type of wavelet has no impact on performance. Fig. 13 shows the uplink channel with frequency offset. Each user experience different frequency offsets and no compensation is done at BS. Relative frequency offset considered for user1 is 0.05 and that for user 3 is 0.1. QPSK modulation is adopted for all users. Similar to downlink, as frequency offset increases, performance of the system degrades drastically. So frequencyestimation and correction techniques are essential at the receiver to improve the performance of the system.

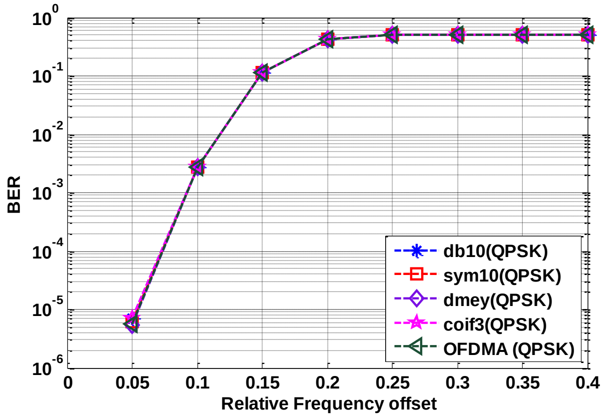

Fig. 12. BER with relative frequency offset (Downlink Channel)

Multicarrier systems are always vulnerable to time synchronization errors. Latency in timing will appear as phase shift andwill rotate the constellation symbols at an angular speed of $\frac{-2\pi\tau k}{R}$where k is the subcarrier index and τ is the timing offset.That is, the subcarriers of higher indices will be subjected to greater phase shifts [14]. Besides phase shift, timing offset cancause ICI and ISI. Fig. 14 shows the effect of timing offset on BER. Timing offset is simulated as phase shift proportionalto subcarrier index and both systems show similar degradation in performance. In practice, use of CP in OFDMA system canreduce ICI and ISI effects of timing offset.

E. Spectrum Efficiency and Sidelobe Suppression

As CR makes secondary usage of spectrum their transmitting waveform should possess maximum spectrum efficiency andminimum sidelobes. It is well known that OFDM is more spectrally efficient than conventional FDM because of overlap oforthogonal subcarriers. But to mitigate multi-path distortions of wireless channels, OFDM signals incorporate a cyclic extensionof the symbol in its transmission which is known as Cyclic Prefix (CP). The length of CP is usually determined by the channeldelay spread and as a thumb rule it should be 25 percent of the total symbol duration. The insertion of CP will result in poorbandwidth efficiency compared to WP-MC-MA system where it is not included. Moreover as mentioned in the earlier chapters,OFDMA as its prototype inherits large sidelobes for its transmitting waveform. Fig. 15 gives the Power Spectral Density ofWPM and OFDM and verifies that the sidelobe suppression capability of wavelet based systems. For “coif3” wavelet withfilter length 18 the sidelobes are much lower compared to OFDM and for “discrete Meyer” with filter length 102 sidelobesare almost absent. It is evident that in WP-MC-MA systems the sidelobes can be controlled by adjusting the inherent filterlength. Thus the proposed system insures lower harmful interference to adjacent primary users and higher spectral efficiencyby eliminating CP.

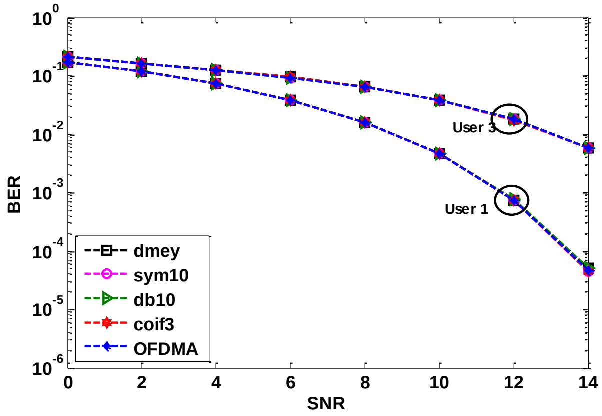

Fig. 13. Effect of Frequency Offset in Uplink

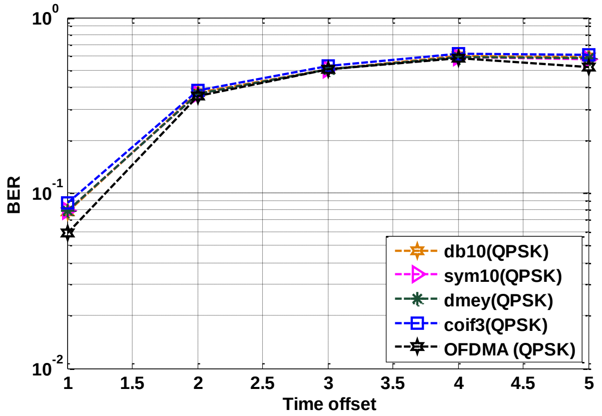

Fig. 14. BER with time offset

F. Complexity Analysis

The Fast Wavelet Transform (FWT) is asymptotically faster than Fast Fourier Transform (FFT) requiring only *O(N)* stepsinstead of *O(Nlog N)* where N is the transform size [21]. In general, for a transform size N and filter length L the total numberof multiplications required for wavelet packet transform is always less than $2NL$. A table showing the required number ofmultiplications for the different wavelet systems and OFDM system for a transform size of 64 is given in Table II. The numberof multiplications for smaller transform size is higher for wavelet based system. But due to the iterative nature of WPT theoverall complexity can be reduced. To implement N stage WPT it is only required to run a single occurrence of the elementaryblock at a clock speed of $N2^{N-1}$ times the symbol rate. Moreover, the transform size in WPT can be changed by changing thenumber of iterations and hence adaptive change in number of subbands is possible without increasing the complexity. As thefilter length of wavelet base does not affect error performance the complexity can be reduced by using filters of lower numberof coefficients. FFT transform size is usually fixed and implementation of programmable FFT is especially difficult [10]. Itcan be concluded that for CR type of applications where flexibility and reconfigurability are crucial, WP-MC-MA can be apromising scheme than OFDMA.

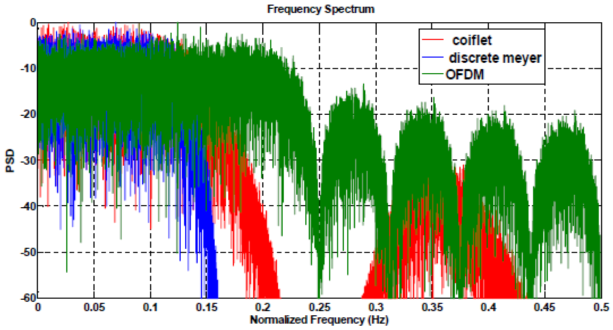

Fig. 15. PSD of WPM and OFDM

IV. CONCLLUSION&FUTURE WORK

In this work, a new multiple access scheme for CR using wavelet packet modulation is considered. The WP-MC-MA systemincorporates both the flexibility and orthogonality of wavelet packet modulation and the multi-user support of OFDMA. Amodified CAS unit is described for proper free channel assignment in CR. The proposed system outperforms OFDMA in termsof flexibility, spectrum efficiency, sidelobe suppression and reconfigurable transform size. The error performance in single pathflat and frequency selective fading are equivalent to that of OFDMA. But the proposed system fails to mitigate multi-pathchannel impairments effectively. Hence low complex efficient equalizer technique is essential for the proposed system.

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Table II
Complexity Analysis

Name	Filter Length	Transform Size	Number of Multiplications
Daubechies	20	64	2560
Symlet	20	64	2560
Coiflet	18	64	2304
Discrete Meyer	102	64	12816
OFDM	-	64	1024