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Enhancing Spectrum Efficiency of Cognitive Radio waveforms Using SD-SMSE Framework

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***Abstract* – Spectrum overcrowding continues to present is a fundamental challenge for both military and commercial communications. Recent studies suggest that spectrum congestion is primarily due to inefficient usage rather than spectrum availability. Dynamic Spectrum Access (DSA) and Cognitive Radio (CR) are two techniques being considered to improve spectrum efficiency and utilization. Interest in Cognitive Radio (CR) remains strong as the communications community strives to solve the spectrum congestion problem. In conventional CR implementations, interference to primary users is minimized using either overlay waveforms that exploit unused (white) spectrum holes or underlay waveforms that spread their power density over an ultra-wide bandwidth. In general, underlay approaches use more spectrum than overlay approaches and operate below the noise floor of primary users. We proposed a hybrid overlay/underlay waveform that realizes benefits of both waveforms and demonstrated its performance in frequency selective fading channels. This was done by extending the original Spectrally Modulated Spectrally Encoded (SMSE) framework to enable soft decision CR implementations that exploit both unused (white) and underused (gray) spectral areas. We analyze and evaluate performance of the overlay, underlay and hybrid overlay/underlay waveforms in frequency selective fading channels is presented and benefits discussed.**

Keywords—Software defined radio, cognitive radio, overlay waveform, underlay waveform, dynamic spectrum access.

I. INTRODUCTION

Fundamental challenge for both military and commercial communications is spectrum crowding. As demand for higher data rates grows and the number of wireless applications and users increases, then spectrum overcrowding continues to increase. Recent studies suggest that spectrum congestion is mainly due to inefficient spectrum usage rather than spectrum scarcity [1]. A number of Dynamic Spectrum Access (DSA) models have been proposed to enhance the spectrum efficiency. Under the hierarchical DSA model, interactions between primary and secondary users are considered to achieve spectrum efficiency [2], [3]. Thus, hierarchical DSA model is synonymous with Cognitive Radio (CR) technology. In current CR research, the secondary user may use either an overlay waveform to harness unused spectrum holes (white areas) and avoid interference to the primary users, or an underlay waveform to spread its energy across a very wide bandwidth with very low power spectral density such that interference to primary user is minimized.

The original Spectrally Modulated Spectrally Encoded (SMSE) framework [5]-[7] provides a unified expression for generating and implementing a host of multicarrier waveforms (e.g., OFDM [10], MC-CDMA [11], CI/MC-CDMA [12], [13], TDCS [14], [15], etc) and satisfies current CR goals of exploiting unused spectral bands. How ever, the original work did not explicitly exploit underused spectrum.

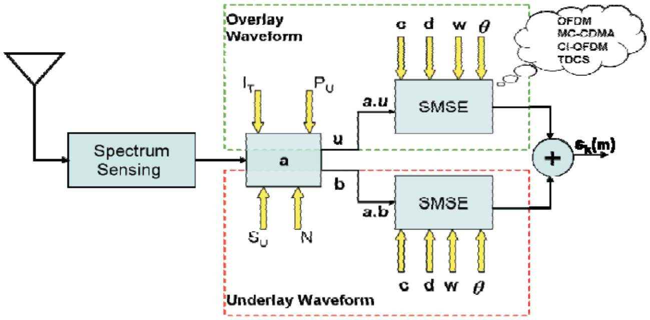

Fig.1 Block diagram representation of SD-SMSE framework [8].

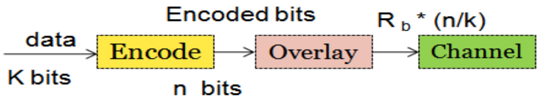

Fig.2 Block diagram representation of overlay with channel coding.

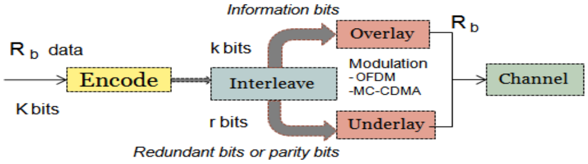

Fig. 3. Hybrid overlay/underlay technique using channel coding [4].

We extended the original SMSE framework into a soft decision SMSE (SD-SMSE) [4], [8] framework in Fig.1 by relaxing conditions on the binary (hard decision) spectrum availability variable ‘a’ to allow for assignment of real values (soft decision), i.e.,

$$a = [a_0, a_1, ...a_{N-1}], 0 \le a_m \le 1 . \quad (1)$$

A new design variable, ‘b’, was also introduced to allow exploitation of underused spectrum, $b = [b_0, b_1, ...b_{N-1}]$, (2)

Where $$b_m = \begin{Bmatrix} 0 & a_m = 1 \\ a_m & a_m \neq 1 \end{Bmatrix} \quad (3)$$

Accounting for unused spectrum through vector ‘u’ and underused spectrum through vector ‘b’, the discrete time domain waveform for a general soft decision CR waveform can be expressed as:

$$s_k[n] = \frac{1}{N}\mathrm{Re}\{\sum_{m=0}^{N-1} a_m\, c_m\, d_{m,k}\, \omega_m \quad .e^{j(2\Pi f_m t_n + \theta_{d_{m,k}} + \theta_{c_m} + \theta_{\omega_m} + \theta_{0_{m,k}})} \tag{4}$$

$$\begin{aligned} s_k[n] = {} & \frac{1}{N}\mathrm{Re}\{\sum_{m=0}^{N-1} u_m c_m d_{m,k} \omega_m \\ & .e^{j(2\Pi f_m t_n + \theta_{d_{m,k}} + \theta_{c_m} + \theta_{\omega_m} + \theta_{0_{m,k}})} \\ & + \frac{1}{N}\mathrm{Re}\{\sum_{m=0}^{N-1} b_m c_m d_{m,k} \omega_m \\ & .e^{j(2\Pi f_m t_n + \theta_{d_{m,k}} + \theta_{c_m} + \theta_{\omega_m} + \theta_{0_{m,k}})} \end{aligned} \tag{5}$$

Where terms in the first summation of (5) account for unused frequency components and terms in the second summation account for underused frequency components.

As shown in Fig.2 and Fig.3, the hybrid overlay/underlay approach is combined with systematic channel coding where the information bits are transmitted via overlay waveform (over unused frequency bands), and the redundant bits are transmitted via underlay waveform (over underused frequency bands). This way both the unused and the underused frequency bands are utilized. Compared to pure overlay systems, the new overlay/underlay system exploits channel coding gain without sacrificing data rate. More importantly, the overlay/underlay system possesses an increased degree of flexibility in receiver design. If preferred, no channel decoding need to be implemented and the receiver simply demodulates the data from the overlay transmission. On the other hand, with a channel decoder present the overlay/underlay receiver can improve the performance significantly.

II. PERFORMANCE ANALYSIS IN FLAT-FADING CHANNELS

Analytic BER performance of non-contiguous overlay and underlay waveforms in flat fading channels is first considered. The total signal in a CR scenario is given by

$$r(t) = \sum_{k=1}^{K} r_{p_k}(t) + \sum_{l=1}^{L} r_{s_l}(t) + n(t) \tag{6}$$

Where K is the total number of primary users, L is the total number of secondary users, $r_{pk}(t)$ represents the received signal of the k^{th} primary user, $r_{sl}(t)$ is the received signal of the l^{th} secondary user, and $n(t)$ represents AWGN with a two-sided power spectrum density of $N_0/2$. It is assumed here that the received primary user’s signals are not passed through a fading channel and are given by

$$r_{p_k}(t) = s_{p_k}(t)\ , \tag{7}$$

Where $s_{pk}(t)$ represents the k^{th} primary user’s transmitted signal. The received secondary user signals are passed through a fading channel and given by

$$r_{s_l}(t) = \alpha s_{s_l}(t) \tag{8}$$

Where α is the channel fading gain factor and $s_{sl}(t)$ is the l^{th} Secondary user’s transmitted signal. We assume that the k^{th} primary user user transmits an OFDM signal with BPSK modulation over M_k subcarriers. Thus, the received signal in (7) for the k^{th} primary user corresponds to:

$$r_{Pk}(t) = \sqrt{\frac{E_{b_k}}{T}}\,\mathrm{Re}\left\{\sum_{i=0}^{M_k-1} b_i^{(k)} e^{j2\pi f_{k_i} t} g(t)\right\} \tag{9}$$

Where E_{b_k} is the k^{th} user’s average bit energy, $b_i^{(k)}$ is the k^{th} user’s i^{th} symbol value, f_{k_i} is the i^{th} subcarrier frequency for the k^{th} user, $g(t)$ is a rectangular waveform of unity height which time-limits the code to one symbol duration T, and the subcarrier bandwidth $\Delta f = f_{ki} - f_{ki-1} = 1/T$.

A. Performance Analysis of Overlay waveforms

When the secondary user employs an overlay waveform for transmission, only the spectrum holes are used. Here it is assumed that one secondary user is transmitting over all available spectrum holes. The corresponding received signal for a secondary user employing NC-OFDM can be written as

$$r_s(t) = \alpha\sqrt{\frac{E_{b_s}}{T}}\,\mathrm{Re}\left\{\sum_{i=0}^{M_h-1} b_i^{(s)} e^{j2\pi f_{h_i} t} g(t)\right\} \tag{10}$$

Where E_{b_s} is the secondary user’s average bit energy, $b_i^{(s)}$ is the secondary user’s i^{th} symbol value, f_{h_i} is the i^{th} subcarrier frequency that corresponds to the i^{th} spectrum hole, and M_h is the total number of subcarriers/spectrum holes.

Similarly, the received signal for a secondary user employing NC-MC-CDMA can be written as

$$r_s(t) = \alpha\sqrt{\frac{E_{b_s}}{M_h T}}\,\mathrm{Re}\left\{b^{(s)} \sum_{i=0}^{M_h-1} \beta_i . e^{j2\pi f_{h_i} t} g(t)\right\} \tag{11}$$

Where β_i is the i^{th} component of the spreading code for the secondary user.

Since the secondary and primary user’s transmissions are assumed to be synchronized in time, and the secondary user only transmits within spectrum holes, there is no interference from the secondary user to primary users and vice versa. In this case, the BER performance of the secondary and primary users is simply given by [16]

$$p(e) = \frac{1}{2}\left(1 - \sqrt{\frac{\bar{\gamma}/2}{1 + \bar{\gamma}/2}}\right) \tag{12}$$

Where $\bar{\gamma}$ is the average signal-to-noise (SNR) ratio defined as:

$$\bar{\gamma} = \frac{E_b}{N_0} E[\alpha^2] \tag{13}$$

With *E[.]* being the expected value operator.

B. Performance Analysis of Underlay Waveforms.

When underlay waveforms are employed by secondary users their transmissions occupy the entire available bandwidth instead of just the spectrum holes. Here, multiple secondary users can be accommodated using MC-CDMA with the composite secondary user's signal corresponding to:

$$r_s(t)=\alpha\sqrt{\frac{E_{b_s}}{NT}}\mathrm{Re}\left\{\sum_{l=1}^{L}b^{(l)}\sum_{i=0}^{N-1}\beta_i^{(l)}.e^{j2\Pi(f_c+i\Delta f)t}g(t)\right\} \quad (14)$$

Where N is the total number of subcarriers spanning the entire available bandwidth and $\beta_i^{(l)}$ is the i^{th} component of l^{th} user's spreading code.

At the receiver, the received signal in (14) is first decomposed into N subcarrier components and then recombined to create the final decision variable for the desired secondary user. Specifically, the n^{th} secondary user's decision variable is:

$$R^{(n)}=\sum_{i=0}^{N-1}r_i^{(n)} \quad (15)$$

When one subcarrier exists in a spectrum hole, there is no primary user signal contribution at that subcarrier and the secondary user's signal becomes,

$$r_i^{(n)}=\alpha\sqrt{\frac{E_{b_s}}{N}}b^{(n)}+\alpha\sqrt{\frac{E_{b_s}}{N}}\sum_{l=1,l\neq n}^{L}b^{(l)}\beta_i^{(l)}\beta_i^{(n)}+n_i \quad (16)$$

Where the first term is the desired signal, the second term is due to multiple access interference (MAI), and the third term represents the AWGN contribution.

However, if at least one secondary user subcarrier is not within a spectrum hole, the secondary users' signal spectrally coexists with one primary user's signal and becomes:

$$r_i^{(n)}=\alpha\sqrt{\frac{E_{b_s}}{N}}b^{(n)}+\alpha\sqrt{\frac{E_{b_s}}{N}}\sum_{l=1,l\neq n}^{L}b^{(l)}\beta_i^{(l)}\beta_i^{(n)}+\sqrt{E_{b_k}}b_i^{(k)}+n_i \quad (17)$$

When orthogonal spreading codes are employed for secondary users, the n^{th} secondary user's decision variable after recombining corresponding to:

$$R^{(n)}=\sum_{i=0}^{N-1}r_i^{(n)}=N\alpha\sqrt{\frac{E_{b_s}}{N}}+\sum_{k=1}^{K}\sqrt{E_{b_k}}\sum_{i=0}^{M_k-1}b_i^{(k)}+\sum_{i=0}^{N-1}n_i \quad (18)$$

Where the first term in (18) is the desired signal, the second term represents interference from primary users to the secondary user and the third term is the noise contribution in the final decision variable due to the orthogonality among spreading codes.

Using a Gaussian approximation with the second term in (18), the interference power from the primary user on the secondary user is given by

$$E\left[\left(\sum_{k=1}^{K}\sqrt{E_{b_k}}\sum_{i=0}^{M_k-1}b_i^{(k)}\right)^2\right]=\sum_{k=1}^{K}M_kE_{b_k} \quad (19)$$

If all primary users have the same bit energy E_{b_p}, the right-hand expression in (19) reduces to:

$$\sum_{k=1}^{K}M_k\,E_{b_k}=ME_{b_p} \quad (20)$$

Where M is the total number of subcarriers occupied by primary users. It is relatively straightforward to show that the average signal-to-interference-plus-noise ratio (SINR) $\overline{\gamma}'$ is given by:

$$\overline{\gamma}'=\left\{N\,E[\alpha^2]\,E_{b_s}\right\}\Big/\left\{\sum_{k=1}^{K}M_kE_{b_k}+N\frac{N_0}{2}\right\} \quad (21)$$

This is used to establish the corresponding BER for the secondary user in a flat fading channel.

$$p(e)=\frac{1}{2}\left(1-\sqrt{\frac{\overline{\gamma}'/2}{1+\overline{\gamma}'/2}}\right) \quad (22)$$

III. PERFORMANCE ANALYSIS IN MULTIPATH FADING CHANNELS

The analytic expression to evaluate the BER performance of overlay and underlay waveforms in multipath fading channels is derived here. As reintroduced from (6) for completeness, the total received signal in a CR scenario is

$$r(t)=\sum_{k=1}^{K}r_{p_k}(t)+\sum_{l=1}^{L}r_{s_l}(t)+n(t) \quad (23)$$

Without loss of generality, it is assumed that each primary user experiences different, independent channel fading. Hence, the kth primary user's signal goes through a frequency selective fading channel with impulse response $h_k(t)$ and is given by:

$$r_{p_k}(t)=h_k(t)*s_{p_k}(t) \quad (24)$$

Where * represents convolution and $s_{pk}(t)$ represents the k^{th} primary user's transmitted signal. Note that if the k^{th} primary user's signal is not transmitted through a fading channel, the channel response in (24) simply reduces to $h_k(t) = \delta(t)$.

After transmission through a multipath fading channel impulse response h(t), the received secondary user signals are given by:

$$r_{s_l}(t)=h(t)*s_{s_l}(t) \quad (25)$$

Where s_{sl} is the l^{th} secondary user's transmitted signal.

Assuming that the k^{th} primary user transmits an OFDM signal with BPSK modulation over M_k subcarriers, the transmitted signal in (24) for the k^{th} primary user corresponds to:

$$s_{p_k}(t)=\sqrt{\frac{E_{b_k}}{T}}\mathrm{Re}\left\{\sum_{i=0}^{M_k-1}b_i^{(k)}e^{j2\pi f_{k_i}t}g(t)\right\} \quad (26)$$

Where Eb_k is the k^{th} user's average bit energy, $b_i^{(k)}$ is the k^{th} user's i^{th} symbol value, f_{k_i} is the i^{th} subcarrier frequency for the k^{th} user, $g(t)$ is a rectangular waveform of unity height which time-limits the code to one symbol duration T, and the subcarrier bandwidth $\Delta f = f_{k_i} - f_{k_{i-1}}$ = 1/T.

A. *Performance Analysis of Overlay Waveforms*

When the secondary user employs an overlay waveform for transmission, only spectrum holes are used. Here, it is assumed that one secondary user is transmitting over all the available spectrum holes. The received signal corresponding to the secondary user waveform employing NC-OFDM [17], [18] can be written as:

$$r_s(t) = \sqrt{\frac{E_{b_s}}{T}}\,\mathrm{Re}\left\{ \sum_{i=0}^{M_h-1} \alpha_i b_i^{(s)} e^{j(2\pi f_{h_i} t + \theta_i)} g(t) \right\} \tag{27}$$

Where α_i is the channel fading gain on the ith subcarrier, θ_i is the phase offset introduced by the fading channel on the bi(s) is the secondary user's i^{th} symbol value, f_{h_i} is the i^{th} and M_h is the total number of subcarriers.

Similarly, the received signal of a secondary user employing NC-MC-CDMA [19] can be written as:

$$r_s(t) = \sqrt{\frac{E_{b_s}}{M_h T}}\,\mathrm{Re}\left\{ b^{(s)} \sum_{i=0}^{M_h-1} \alpha_i \beta_i e^{j(2\pi f_{h_i} t + \theta_i)} g(t) \right\} \tag{28}$$

Where β_i is the i^{th} component of the spreading code for the secondary user.

Given that primary and secondary user transmission are assumed to be synchronized in time, and the secondary user only transmits within spectrum holes, there is no interference from the secondary user to primary users and vice versa. Without frequency diversity, the NC-OFDM BER performance of secondary and primary users in the same as what occurs for a flat fading channel and is given by (12) and (13). However, the signal is recombined across all NC-MC-CDMA subcarriers to exploit frequency diversity. After frequency combining, the final decision variable corresponds to:

$$R^{(n)} = \sum_{i=0}^{N-1} W_i . r_i^{(n)} \tag{29}$$

$$= \sum_{i=0}^{M_h-1} W_i \alpha_i \sqrt{\frac{E_{b_s}}{M_h}} b^{(n)} + \sum_{i=0}^{M_h-1} W_i \alpha_i \sqrt{\frac{E_{b_s}}{M_h}} \sum_{l=1, l\neq n}^{L} b^{(l)} \beta_i^{(l)} \beta_i^{(n)} + \sum_{i=0}^{M_h-1} W_i n_i$$

Where the first term is the desired signal, the second term is MAI and the third term is the noise contribution. It is relatively straight forward to show that the corresponding instantaneous SINR is:

$$SINR = \frac{P_{signal}}{P_{MAI} + P_{Noise}} \tag{30}$$

$$= \frac{E_{b_s}}{M_h} \left(\sum_{i=0}^{M_h-1} W_i \alpha_i \right)^2 \Bigg/ \left\{ (L-1) \frac{E_{b_s}}{M_h} \sum_{i=0}^{M_h-1} W_i^2 \alpha_i^2 + \frac{N_0}{2} \sum_{i=0}^{M_h-1} W_i^2 \right\}$$

The corresponding average BER *P(e)* is calculated using

$$P(e) = \int_0^{\infty} Q\left(\sqrt{SINR}\right) p(SINR)\, d(SINR), \tag{31}$$

Where *p(SINR)* is the probability density function of SINR.

B. Performance Analysis of underlay waveforms

When underlay waveforms are employed by secondary users their transmissions occupy entire available bandwidth instead of just the spectrum holes. Here multiple secondary users can be accommodated using MC-CDMA with the composite secondary user's signal corresponding to:

$$r_s(t) = \sum_{l=1}^{L} r_{s_i}(t) \tag{32}$$

$$= \sqrt{\frac{E}{NT}} R\mathrm{e}\left\{ \sum_{l=1}^{L} b^{(l)} \sum_{i=0}^{N-1} \alpha_i \beta_i^{(l)} e^{(j2\pi(f_c + i\Delta f)t + \theta_i)} g(t) \right\}$$

Where N is the total number of subcarriers spanning the available bandwidth and $\beta_i^{(l)}$ is the i^{th} component of lth user's spreading code.

At the receiver, the received signal is first decomposed into N subcarrier components and then recombined to create the final decision variable for the desired secondary user. Specifically, the nth secondary user's decision variable is:

$$R^{(n)} = \sum_{i=0}^{N-1} W_i . r_i^{(n)} \tag{33}$$

When one subcarrier exists in a spectrum hole, there is no primary user signal contribution at that subcarrier and $r_i^{(n)}$ becomes:

$$r_i^{(n)} = \alpha_i \sqrt{\frac{E_{b_s}}{N}} b^{(n)} + \alpha_i \sqrt{\frac{E_{b_s}}{N}} \sum_{l=1,\, l\neq n}^{L} b^{(l)} \beta_i^{(l)} \beta_i^{(n)} + n_i \tag{34}$$

Where the first term is the desired signal, the second term is due to MAI, and the third term represents the AWGN contribution. However, if at least one secondary user subcarrier is not within a spectrum hole, the secondary user's signal spectrally coexists with one primary user's signal and $r_i^{(n)}$ becomes:

$$r_i^{(n)} = \alpha_i \sqrt{\frac{E_{b_s}}{N}} b^{(n)} + \alpha_i \sqrt{\frac{E_{b_s}}{N}} \sum_{l=1, l\neq n}^{L} b^{(l)} \beta_i^{(l)} \beta_i^{(n)} + \alpha_i^{'} \sqrt{E_{b_k}} b_i^{(k)} + n_i \tag{35}$$

Where $\alpha_i^{`}$ is the fading gain of the k^{th} primary user's fading channel.

It is relatively straightforward to show that the instantaneous SINR is given by:

$$SINR = \frac{p_{signal}}{p_{MAI} + p_{PUI} + p_{Noise}} = \tag{36}$$

$$\frac{E_{b_s}}{N} \left(\sum_{i=0}^{N-1} W_i \alpha_i \right)^2 \Bigg/ \left\{ (L-1) \frac{E_{b_s}}{N} \sum_{i=0}^{N-1} W_i^2 \alpha_i^2 + \sum_{k=1}^{K} \sum_{i \in P_k} W_i^2 \alpha_i^{'2} E_{b_k} + \frac{N_0}{2} \sum_{i=0}^{N-1} W_i^2 \right\}$$

With the corresponding BER determined (calculated) via numerical methods using (31).

IV. SIMULATION RESULTS

Simulation analysis of overlay-CR, underlay-CR and hybrid overlay/underlay waveforms is demonstrated via simulation over a frequency selective fading channel. Perfect time synchronization is assumed between primary and secondary users.

Analytic and simulated $P_{(e)}$ versus E_b/N_0 is used as performance metrics to validate waveform performance. To model a realistic wireless channel, a Rayleigh fading channel is employed in the simulations to induce frequency selectivity across the available bandwidth BW. However, only flat fading is induced on each individual subcarrier. The simulations assume a channel model with coherence bandwidth of Δf_c being eight times the subcarrier bandwidth, i.e. $\Delta f_c = 8\Delta f$. Hence, a primary user that transmits over N_p=32 subcarriers observes 4-fold diversity and in the overall CR bandwidth of 64 subcarriers the frequency selectivity is 8 folds. To mitigate multipath fading effects and take maximum advantage of the diversity, a minimum mean square error combining (MMSEC) diversity approach is used.

A. Simulation Analysis of Overlay waveform in Multipath Fading

In this section, performance of overlay-CR waveforms in frequency selective fading channel is demonstrated. The overlay spectrum allocation scenario is assumed to have N=64 total available subcarriers, with N_p=32 subcarriers allocated to the primary user and N_{CR}=32 allocated to the overlay-CR user at any given time. Even though the multi-carrier overlay-CR waveforms are suitable for a multi-carrier scenario, the scope of the simulations is limited to include only a single primary and single secondary user. It is also assumed that the primary user signals, which are modeled as OFDM-BPSK, are not passing through a fading channel. As previously noted, the primary and secondary users are perfectly time synchronized.

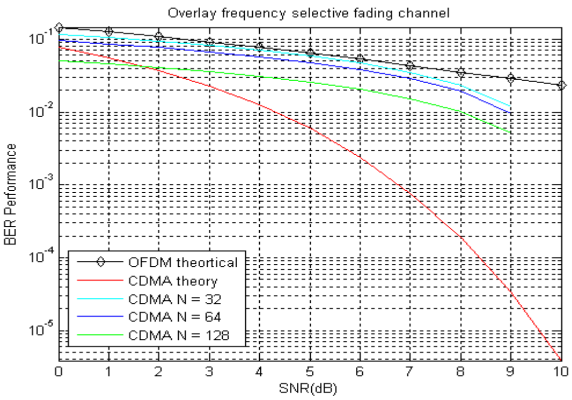

Fig. 4. Analytic performance of OFDM-BPSK and MC-CDMA BPSK due to diversity combining in frequency selective fading channel.

Results in Fig. 4 illustrate frequency selective fading channel performance of OFDM with BPSK and MC-CDMA with BPSK, respectively, as obtained using the MMSEC diversity combining technique for MC-CDMA system. The performance of OFDM system in frequency fading channel is the same as in flat fading channel, which matches with the analysis BER performance in (12). It is clearly evident in the figure that as the number of subcarriers increases, the performance gain for MC_CDMA system due to frequency diversity also increases.

B. Simulation Analysis of Underlay Waveform in Multipath Fading

Simulation results are presented to demonstrate underlay-CR waveform performance in a frequency selective fading environment. The underlay-CR waveform employed by the secondary user either occupies the entire CR bandwidth or some less amount of bandwidth depending up on the data rate and interference requirements set forth by the primary users. In overlay-CR waveform implementation and analysis, perfect time synchronization was assumed between primary and overlay-CR secondary users. However, in underlay-CR analysis primary and secondary waveforms overlap temporally and spectrally which effectively increases SINR in both systems. To minimize the mutual interference, underlay waveforms perform similar to UWB and spread spectrum signals and are expected to operate under the noise floor of primary user signals.

Result in Fig. 5 illustrates performance for an underlay-CR waveform employing MC_CDMA with BPSK modulation. The underlay-CR waveforms are assumed to be operating at -20dB relative to the primary user. Each of the primary users is modeled as using N_p=32 subcarriers with OFDM and BPSK modulation. MMSEC combining technique is employed in these systems. It is obvious that the BER performances match the analytic results in (30) perfectly.

The BER performance for different number of secondary users. There are N=128 subcarriers and one primary user occupying N_p=32 subcarriers. The comparison results show that the increasing of the number of secondary users degrades the BER performance due to the MAI.

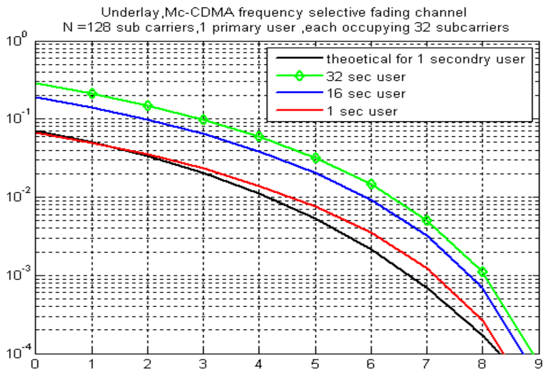

Fig. 5 Performance of underlay waveform using MC-CDMA BPSK in

frequency selective fading channel for different number of secondary users.

C. Simulation Analysis of Hybrid Overlay/Underlay Waveform in Multipath Fading

Simulation results are presented here for the hybrid overlay/underlay waveforms by combining channel coding in multipath fading channels. Two popular block codes, namely a (7, 4) Hamming code with t=1 error correction capability and a (15, 5) BCH code with t=3 error correction capability were chosen for demonstration purposes.

Results in Fig.6 illustrate performance of a hybrid overlay/ underlay waveform that employs NC-OFDM BPSK as an overlay-CR waveform, MC-CDMA BPSK as an underlay-CR waveform, and a Hamming H (7, 4) code for encoding. Underlay spreading lengths of N=256 and N=512 subcarriers were considered. The top solid line represents "OFDM (7, 4)" represents coded OFDM and the labels "H (7, 4) N=256" and "H (7, 4) N=512" represent overlay/underlay waveforms with spreading lengths of N=256 and N=512 subcarriers. It is evident from the simulation results that the hybrid overlay/underlay not only offers performance improvements over uncoded overlay-CR, but also outperforms overlay-CR with channel coding. Moreover, the hybrid performance improvement does not come at the expense of reduced throughput as is the case with coded overlay-CR systems.

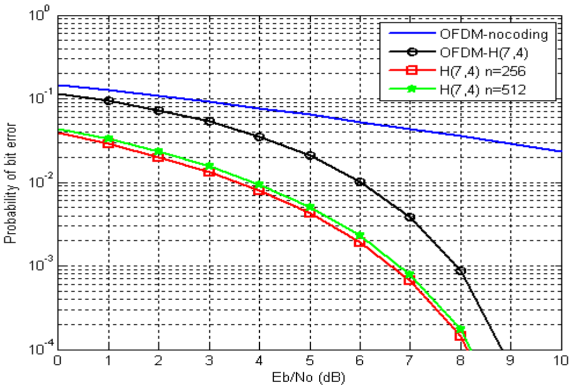

Fig.6 Performance of hybrid overlay/underlay waveform using Hamming codes in Frequency Fading channel. Overlay is implemented using NC-OFDM BPSK and underlay is implemented using NC-MC-CDMA BPSK.

V. CONCLUSION

Using a previously developed SMSE framework based on hard decision spectrum usage, we have proposed an extended soft decision SMSE framework (SD-SMSE) to support soft decision CR applications. We demonstrated for Rayleigh faded channels, the SD-SMSE CR implementation is capable of dynamically generating spectrally efficient overlay, underlay and hybrid overlay/underlay waveforms based on user requirements. Performance is evaluated here for all three SD-SMSE waveform types in the CR context over frequency selective fading channels. We demonstrated that the hybrid overlay/underlay-CR waveform can be used to improve spectrum efficiency.

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