Performance Comparison of Modulation Techniques for Underlay Cognitive Radio Transceivers

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Abstract— **In this paper, we present a quantitative comparison of two agile modulation techniques employed by cognitive radio transceivers operating in a dynamic spectrum access (DSA) network. One of the modulation techniques is single carrier frequency division multiple access (SC-FDMA). The other modulation technique under study is a variant of multicarrier code division multiple access (MC-CDMA). Although several studies comparing conventional OFDM and MC-CDMA has been conducted in literature to justify robust error performance of MC-CDMA, a quantitative performance evaluation of these schemes has not been performed when employed in a DSA network. In this paper we show that their performances can be significantly different from the conventional setup. Analytical expressions for the error probability of an SC-FDMA transceiver have been derived and compared with computer simulation results. The results show that the error robustness of SC-FDMA is relatively better then MC-CDMA in underlay communication.**

I. INTRODUCTION

SPECTRUM crowding will continue to increase as the demand for higher data rates grows and the number of wireless applications and users increases. From an assigned spectrum perspective, a cursory glance at the FCC's spectrum allocation chart can lead one to believe that spectrum is scarce [1]. With advances in software-defined radio (SDR) technology, where the baseband processing is performed entirely in software, current radio transceivers are sufficiently agile to operate in a DSA networking environment due to their ease and speed of programming baseband operations. SDR units that can rapidly and autonomously reconfigure operating parameters due to changing requirements and conditions are known as cognitive radios [2]. With recent developments in cognitive radio technology, it is now possible for these systems to simultaneously respect the rights of incumbent license holders while providing additional flexibility and access to spectrum. The choice of physical layer transmission technique is a very important design decision when implementing a cognitive radio. To support high data-rate transmissions, the technique should be sufficiently agile to enable users to use a large bandwidth without interfering with incumbent users. Single Carrier frequency division multiple Acess (SC-FDMA) and multicarrier code division multiple access (MC-CDMA) are two high-speed modulation techniques previous is proposed for 3GPP-LTE(4-G System) and latter is employed in conventional Transmission systems. SC-FDMA has been shown to be an effective transmission technique for high data rate for uplink communication. SC-FDMA has similar throughput performance and essentially the same overall complexity as OFDMA. A principal advantage of SC-FDMA is the peak-to-average power ratio (PAPR), which is lower than that of OFDMA. On the other hand, MC- CDMA is capable of mitigating the effects of multiuser interference. Several studies have justified superior error performance of MC-CDMA system over OFDM system. In underlay system, communication is done under restriction of power in the presence of primary (licensed) user. So that it will not get interfered by secondary (unlicensed) user.

In this paper, we conduct a quantitative comparison of SC-FDMA and MC-CDMA transmission techniques within the context of underlay communication in cognitive radio. The analytical expressions for the probability of error of an SC-FDMA transceiver are presented and validated using computer simulations. Then, we compare SC-FDMA and MC-CDMA, in terms of error robustness. The paper is organized as follows: In Section 2, brief introduction to the MC-CDMA and SC-FDMA transmission techniques are presented. In Section 3, AWGN channel model for BER performance analysis is presented. Theoretical SNR analysis of the SC-FDMA system is presented in Section 4. Finally, Section 5 presents the BER performance comparison between MC-CDMA and SC-FDMA techniques in underlay data transmissions.

II. SYSTEM MODEL

When portions of the target licensed spectrum are occupied by primary users, multicarrier techniques can provide the necessary agile spectrum usage. Multicarrier based transceivers can transmit in low power transmission in that region of spectrum providing high data rates at an acceptable level of error robustness . Both SC-FDMA and MC-CDMA are popular multicarrier transmission techniques. In this section, we present a brief overview of SC-FDMA and MC-CDMA transmission frameworks.

A. *MC-CDMA* FRAMEWORK

The structure of MC-CDMA was devised in order to overcome the high sampling rates required by direct sequence CDMA (DS-CDMA) transmission, where spreading is performed in the time domain.

This high sampling rate makes DS-CDMA very susceptible to performance degradation caused by multipath propagation [8]. To avoid any interference to existing transmissions, power of subcarriers that interfere with occupied portions of spectrum are decreased upto threshold. The MC-CDMA system begins by taking the high data rate input, $x(n)$, and feeding it into an MPSK or MQAM modulator prior to serial-to-parallel (S/P) conversion into L streams. Each of these streams has a data rate less than $x(n)$ by a factor of L. Following the S/P conversion, each stream is replicated into N parallel copies, with copy m of stream k being multiplied by chip m of spreading code C_k, for $k = 0, \ldots, L-1$ and $m = 0, \ldots, N-1$ [9]. This is referred to as spreading in the frequency domain. Note that all the spreading codes used must be orthogonal with each other. After the frequency domain spreading, copy m of all the streams are added together, for $m = 0, \ldots, N-1$, yielding N subcarrier inputs to the IFFT block, which converts these subcarriers into the time domain. The resulting normalized complex envelope of an MPSK-modulated MC-CDMA signal is given as,

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{L-1} \sum_{m=0}^{N-1} b_k C_{k,m} e^{j2\pi mn/T} \qquad (1)$$

where b_k is the MPSK-modulated symbol from k_{th} stream, and $C_{k,m}$ is chip m of spreading sequence k. Following the P/S conversion, the baseband MC-CDMA signal, $s(n)$, is then passed through the transmitter RF chain, which amplifies the signal and upconverts it to the desired center frequency.

The receiver performs the reverse operation of the transmitter, where the received baseband signal $r(n)$ undergoes S/P conversion, time-to-frequency conversion via FFT, and equalization. Each of the equalizers outputs are then replicated into L parallel copies, with each copy allocated to one of L streams, where despreading is performed using C_k, for $k = 0, \ldots, L-1$. An integrate-and-dump procedure is then performed per stream, followed by P/S conversion and demodulation. This results in a reconstructed version of the original high data rate input signal, $\hat{x}(n)$.

B. *SC-FDMA* FRAMEWORK

The transmitter of an SC-FDMA system converts a binary input signal to a sequence of modulated subcarriers[6]. To do so, it performs the signal processing operations as shown in fig.1. At the input to the transmitter, a baseband modulator transforms the binary input to a multilevel sequence of complex numbers x_n in one of several possible modulation formats including binary phase shift keying (BPSK), quaternary PSK (QPSK), 16 level quadrature amplitude modulation (16-QAM) and 64-QAM. The system adapts the modulation format, and thereby the transmission bit rate, to match the current channel conditions of each terminal.

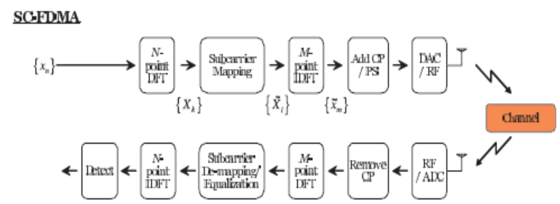

Fig.1 Transmitter and receiver structure of SC-FDMA

The transmitter next groups the modulation symbols, x_n into blocks each containing N symbols. The first step in modulating the SC-FDMA subcarriers is to perform an N-point discrete Fourier transform (DFT), to produce a frequency domain representation X_k of the input symbols. It then maps each of the N DFT outputs to one of the *M(>N) orthogonal* subcarriers that can be transmitted. A typical value of M is 256 subcarriers and $N = M/Q$ is an integer submultiple of M. Q is the bandwidth expansion factor of the symbol sequence. If all terminals transmit N symbols per block, the system can handle Q simultaneous transmissions without cochannel interference. The result of the subcarrier mapping is the set $\tilde{X}_l$ $(l = 0, 1, 2, \ldots, M-1)$ of complex subcarrier amplitudes, where N of the amplitudes are non-zero. As in OFDMA, an M-point inverse DFT (IDFT) transforms the subcarrier amplitudes to a complex time domain signal $\tilde{X}_m$. Each $\tilde{X}_m$ then modulates a single frequency carrier and all the modulated symbols are transmitted sequentially.

The other part of the block performs same operation as in normal OFDMA structure except two additional block of pulse shaping which reduces the out of band energy and subcarrier mapping Several approaches to mapping transmission symbols X_k to SC-FDMA subcarriers are currently under consideration. They are divided into two categories; *distributed* and *localized* as shown in Figure 2. In the distributed subcarrier mapping mode, DFT outputs of the input data are allocated over the entire bandwidth with zeros occupying the unused subcarriers resulting in a non-continuous comb-shaped spectrum. As mentioned earlier, *interleaved* SC-FDMA (IFDMA) is an important special case of distributed SC-FDMA. In contrast with IFDMA, consecutive subcarriers are occupied by the DFT outputs of the input data in the localized subcarrier mapping mode resulting in a continuous spectrum that occupies a fraction of the total available bandwidth.

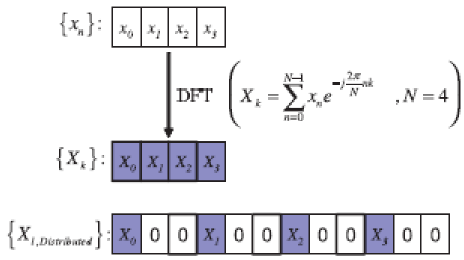

Fig.2 Subcarrier mapping in SC-FDMA

III. Channel Model

This section begins by considering application of the general frameworks to typical modulations including SC-FDMA and MC-CDMA. It has been shown that these modulations can be readily adapted to a non-contiguous spectrum environment by deactivating undesired subcarriers that are interfering with primary user bands.

Here, the BER performance of overlay-CR and underlay- CR waveforms is evaluated. The total received signal in a CR environment under AWGN channel conditions is given by[4]

$$r(t) = \sum_{k-1}^{K} S_{p_k}(t) + \sum_{l=1}^{L} S_{S_l}(t) + n(t) \qquad (2)$$

where K is the total number of primary users, L is the total number of secondary users, $S_{pk}(t)$ represents the kth primary user's signal, $S_{sl}(t)$ is the lth secondary user's signal, and $n(t)$ represents the additive Gaussian noise. Figure 4 illustrates such a dynamic spectrum access scenario containing two primary users occupying two non-contiguous frequency bands and two spectrum holes that are available for secondary user transmissions. Assuming the kth primary user transmits an OFDM signal with BPSK modulation over M_k subcarriers, the kth primary user's signal corresponds to

$$S_{p_k}(t) = \sqrt{\frac{E_{b_k}}{T}} Re\left\{\sum_{i=0}^{M_k-1} b_i^{(k)}\, e^{j2\pi f_{k_i}} g(t)\right\} \qquad (3)$$

where E_{bk} is the kth user's bit energy, $b(k)\ i$ is the kth user's ith bit, f_{ki} is the ith subcarrier of the kth user, $g(t)$ is a rectangular waveform of unity height which time-limits the code to one symbol duration T, and the subcarrier bandwidth

$\Delta f = f_{ki} - f_{ki-1} = 1/T$.

When underlay waveform is employed by the secondary users for transmission, the transmission occupies the entire bandwidth instead of only the spectrum holes. Here, multiple secondary users can be accommodated using MC-CDMA & SC-FDMA. The total secondary users' signal corresponds to:

$$S_s(t) = \sum_{l=1}^{L} S_{s_i}(t) \qquad (4)$$

$$= \sqrt{\frac{E_{b_s}}{N_f T}} Re\left\{\sum_{l=1}^{L} b^{(l)} \sum_{i=0}^{N_f-1} \beta_i^{(l)} e^{j2\pi(f_c+i\Delta f)t} g(t)\right\}$$

N_f is the total number of subcarriers over the entire bandwidth, $(l)\ i$ is the ith component of lth user's spreading code.

III. Signal-To- Noise Ratio Analysis

Assuming a wide sense stationary uncorrelated scattering (WSSUS) channel, the SNR of the received signal in Eq. (2) is given by[5]:

$$\gamma_i^f = \frac{|X_i\,.\,H_i|^2}{|\tilde{n}_i|^2} = \frac{|X_i|^2.\,|H_i|^2}{|\tilde{n}_i|^2} \qquad (5)$$

Therefore, the mean SNR can be given by [15]:

$$E(\gamma_i^f) = \frac{E(|X_i|^2.\,|H_i|^2)}{E(|\tilde{n}_i|^2)} = \frac{E(|X_i|^2.\,E|H_i|^2)}{E(|\tilde{n}_i|^2)} \qquad (6)$$

Where $E(\cdot)$ denotes an expectation operator. In the following two subsections, we present the SNR analysis for the SC-FDMA system over additive white Gaussian noise (AWGN) channel.

AWGN Channel

Consider an AWGN channel with noise spectral density N_0 and bandwidth B, the noise power is given by:

$$E(|\tilde{n}_i|^2) = \sigma_N^2 = N_0 B \qquad (7)$$

While the SNR is given by:

$$\gamma_1 = 10\log_{10}\left(\frac{E(|X_i|^2)}{\sigma_N^2}\right) = 10\log_{10}\left(\frac{E(|X_i|^2)}{N_0 B}\right) \qquad (8)$$

Suppose the incumbent spectral occupancy (ISO) is α, then the total available bandwidth would be $(1-\alpha)B$. Since the channel response is assumed to be flat, the signal power would remain constant, irrespective of the available bandwidth. However, the effective noise power would be:

$$\sigma_N^2 = N_0(1-\alpha)B \qquad (9)$$

with the SNR given by:

$$\gamma_2 = 10\log_{10}\left(\frac{E(|X_i|^2)}{\sigma_N^2}\right) = 10\log_{10}\left(\frac{E(|X_i|^2)}{N_0(1-\alpha)B}\right) \quad (8)$$

Therefore, the SNR gain is:

$$SNR_{gain} = -10\log_{10}(1-\alpha) \quad (9)$$

However, the total throughput would also be reduced to $(1-\alpha)NR_b$, where R_b represents the bit rate over an individual subcarrier.

IV. SIMULATION RESULTS

SIMULATION SETUP

Performance of the overlay-CR, underlay-CR and hybrid underlay waveforms is demonstrated via simulation under AWGN channel conditions. Perfect synchronization is assumed between the primary and secondary user. Analytic versus simulated (e) versus E_b/N_o is used as a performance metric to validate these waveforms. When the secondary user is perfectly synchronized with the primary user, there is no interference from the secondary user to primary user. The primary user and secondary underlay user will be interfering with each other causing mutual performance degradation. Two scenarios are considered to get some insight and understanding of the mutual interference in which we examine an underlay-CR waveform with a primary user as the interference

In the first scenario, the primary user is modeled as OFDM with BPSK modulation using a contiguous N = 32 subcarrier spectrum. The underlay waveform is modeled as MC-CDMA & SC-FDMA with BPSK modulation. The underlay waveform uses much lower power and will spread its spectrum while maintaining its own performance requirements and minimizing its interference to the primary user. Figure 1 & Figure 2 illustrates the performance of an underlay secondary user under AWGN channel conditions with primary user interference. In Fig. 3 the underlay waveform is operating at -30 dB transmission power relative to that of the primary user. It can be seen that as the underlay waveform spectrally spreads its performance improves and approaches to the theoretical baseline at N = 1024.

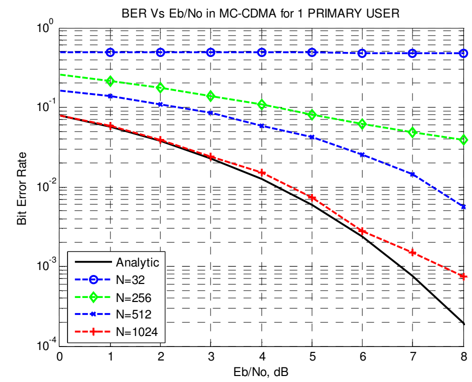

Fig.3 Performance of Underlay MC-CDMA BPSK as a secondary user. Primary to secondary user power ratio is 30 dB.

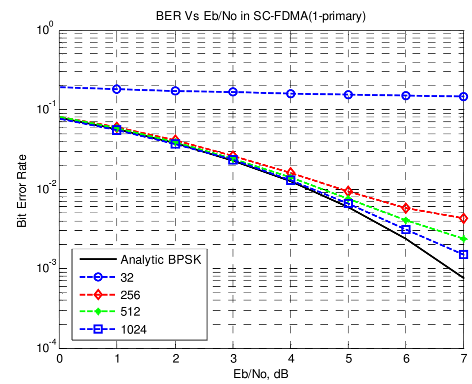

Fig.4 Performance of Underlay SC-FDMA BPSK as a secondary user. Primary to secondary user power ratio is 30 dB.

The second scenario also models the primary user as OFDM-BPSK consisting of N = 32 contiguous subcarriers. In this case, the underlay spread length is fixed to N = 512 and the secondary to primary power ratio is set at -20 dB.

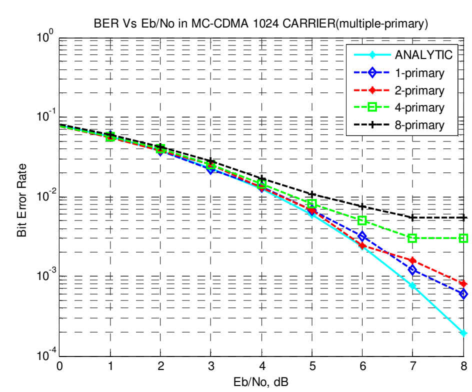

Fig.5 Performance of underlay MC-CDMA BPSK as a secondary user in the presence multiple primary users.

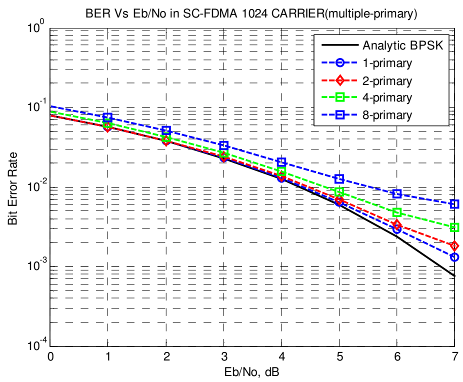

Fig.6. Performance of underlay SC-FDMA BPSK as a secondary user in the presence multiple primary users.

In the previous scenario there was just one single primary user in the entire underlay spread bandwidth, where as in this case the entire bandwidth is populated with multiple primary users, each operating over 32 subcarriers. It is evident from Fig. 6 that as number of primary users increases underlay performance goes down, prompting the underlay to use other means such as spread further or add channel coding to improve the performance.

V.CONCLUSION

In this paper, we presented two candidates for agile modulation in cognitive radio transceivers. We evaluated and compared the error robustness of SC-FDMA and MC-CDMA transceivers (both analytically and through simulations) operating in an AWGN. From the SNR analysis, it is observed that BER performance of SC-FDMA is superior to the MC-CDMA system, when the available transmission is UNDERLAY.

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