Comparative Study of Frequency Agile Data Transmission Schemes for Cognitive Radio Transceivers

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Abstract – In this paper, we present a comparative study of two frequency agile data transmission schemes employed by cognitive radio transceivers for use in dynamic spectrum access (DSA) networks. The transmission schemes under study, *non-contiguous orthogonal frequency division multiplexing* **(NC-OFDM) and a modified form of** *multicarrier code division multiple access* **(MC-CDMA), are based on conventional OFDM and MC-CDMA schemes. Besides providing a degree of error robustness while yielding large data throughputs, the schemes under study are designed to avoid interference with incumbent user transmissions via subcarrier deactivation, i.e.,** *nulling***, in order to operate within a DSA network. Although several studies comparing conventional OFDM and MC-CDMA have been conducted in the literature, and the relative performance of NC-OFDM and the variant of MC-CDMA schemes is intuitive, there has not been a quantitative performance evaluation of these schemes when used within a DSA network. The quantitative evaluation corroborates with the intuitive assessment that NC-OFDM exhibits a greater degree of error robustness when avoiding incumbent transmissions relative to the variant of MC-CDMA.**

1 Introduction

With the demand for additional bandwidth increasing due to existing and new services, new solutions are sought for this apparent spectrum scarcity. Although, measurement studies have shown that licensed spectrum is relatively unused across time and frequency [1], current government regulatory requirements prohibit unlicensed transmissions in these bands, constraining them instead to several heavily populated, interference-prone frequency bands. To provide the necessary bandwidth required by current and future wireless services and applications, the Federal Communications Commission (FCC) has already started working on the concept of unlicensed users "borrowing" spectrum from spectrum licensees [2, 3], known as *dynamic spectrum access* (DSA).

Simultaneously, the development of *software-defined radio* (SDR) technology, where the radio transceivers perform the baseband processing entirely in software, which made them a prime candidate for DSA networks due to their ease and speed of programming baseband operations. SDR units that can rapidly reconfigure operating parameters due to changing requirements and conditions[1] are known as *cognitive radios* [4]. 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 a physical layer data transmission scheme is a very important design decision when implementing a cognitive radio. Specifically, the technique must be sufficiently agile to enable unlicensed users the ability to transmit in a licensed band while not interfering with the incumbent users. Moreover, to support throughput-intensive applications, the technique should be capable of handling high data rates. One technique that meets both these requirements is a variant of orthogonal frequency division multiplexing (OFDM) called *non-contiguous OFDM* (NC-OFDM) [5–7]. Although there are several other candidate transmission techniques, including multicarrier code division multiple access (MC-CDMA), no study has been conducted that quantitatively assesses the relative performance of these techniques when employed within a DSA scenario.

In this paper, we present a comparative study of NC-OFDM and a variant of MC-CDMA employed by cognitive radio transceivers for use in a DSA network. A qualitative comparison is performed highlighting the advantages and disadvantages of these candidate transmission technologies. Furthermore, the error robustness of these techniques is quantitatively assessed using computer simulation and compared against each other. This paper is organized as follows: Section 2 presents the

This work was supported by NSF grants ANI-0230786 and ANI-0335272.

[1]These requirements and conditions can be at the physical, network, and/or application layers of the system.

framework for the NC-OFDM and MCCDMA variant studied in this work. Section 3 presents a qualitative comparison between NC-OFDM, MC-CDMA, and conventional OFDM. An evaluation of NC-OFDM and MC-CDMA with respect to error robustness is presented in Section 4. Finally, several concluding remarks are made in Section 5.

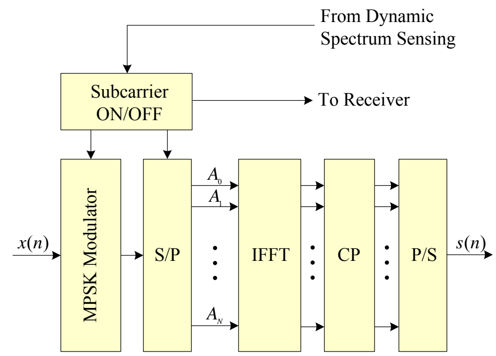
2 Agile Modulation Techniques for Cognitive Radios

To achieve the agility necessary for transmission within a licensed frequency band occupied by incumbent users, multicarrier-based transceivers are an appropriate choice [6, 8]. Besides being able to deactivate, or "null", subcarriers that could potentially interfere with other users, multicarrier-based transceivers are also capable of providing high data rates at an acceptable level of error robustness [9, 10]. Although there are several multicarrier-based transceiver implementations available, the two most popular choices are OFDM and MC-CDMA [11]. When an OFDM transceiver deactivates several subcarriers in order to avoid incumbent users, we refer to this transceiver implementation as NC-OFDM [5, 6]. In this section, we provide an overview of the NC-OFDM and MC-CDMA frameworks employed in this work.

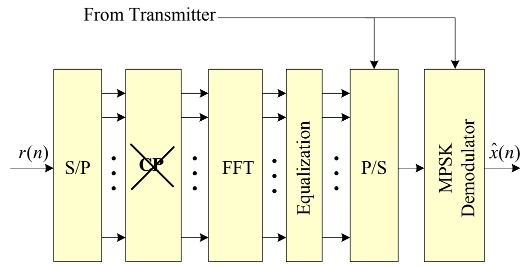
2.1 NC-OFDM Framework

A schematic of an NC-OFDM transceiver is shown in Fig. 1. The transceiver splits a high data rate input, $x(n)$, into N lower data rate streams. Unlike conventional OFDM, not all the subcarriers are active in order to avoid transmission in occupied frequency bands[2]. The remaining active subcarriers can either be modulated using M-ary phase shift keying (MPSK), as shown in the figure, or M-ary quadrature amplitude modulation (MQAM). The inverse fast Fourier transform (IFFT) is then used to transform these modulated subcarrier signals into the time domain. Prior to transmission, a guard interval, with a length greater than the channel delay spread, is added to each OFDM symbol using the cyclic prefix (CP) block in order to mitigate the effects of intersymbol interference (ISI). Following the parallel-to-serial (P/S) conversion, the baseband NC-OFDM signal, $s(n)$, is then passed through the transmitter radio frequency (RF) chain, which amplifies the signal and upconverts it to the desired center frequency.

The receiver performs the reverse operation of the transmitter, mixing the RF signal to baseband for processing, yielding the signal $r(n)$. Then the signal is



(a) NC-OFDM Transmitter.



(b) NC-OFDM Receiver.

Fig. 1 Schematic of an NC-OFDM transceiver.

converted into parallel streams, the cyclic prefix is discarded, and the fast Fourier transform (FFT) is applied to transform the time domain data into the frequency domain. After the distortion from the channel has been compensated via per subcarrier equalization, the data on the subcarriers is demodulated and multiplexed into a reconstructed version of the original high-speed input, $\hat{x}(n)$.

2.2 MC-CDMA Framework

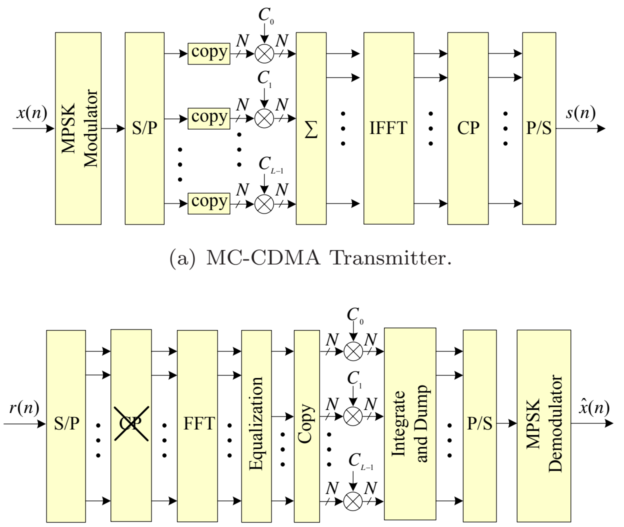
The structure of MC-CDMA was devised in order to overcome the high sampling rates required by direct sequence (DS)-CDMA transmission, where spreading is performed in the time domain. This high sampling rate makes DS-CDMA very susceptible to performance degradation caused by multipath propagation [11].

Referring to the MC-CDMA schematic in Fig. 2, we observe that a high data rate input, $x(n)$, is fed into an MPSK modulator[3] 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 using the copy function[4], with copy m of stream i being multiplied by chip m of spreading code C_i, for $i = 0, \ldots, L-1$ and $m = 0, \ldots, N-1$ [17]. The result is having all the streams being spread in the frequency

[2] The location of occupied spectrum and the identification process of either incumbent or other unlicensed transmissions is performed through channel sounding and spectrum analysis [12–16].

[3] Other forms of digital modulation, including MQAM, can also be employed by the transceiver.

[4] The data rate of the stream and its copies are identical.



(a) MC-CDMA Transmitter.

(b) MC-CDMA Receiver.

Fig. 2 Schematic of an MC-CDMA transceiver.

domain. Note that all the spreading codes used must be orthogonal with each other in order for the MC-CDMA transceiver to work. 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:

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

where b_i is the MPSK-modulated symbol from stream i, and $C_{i,m}$ is chip m of spreading sequence i. A guard interval, with a length greater than the channel delay spread, is then added to each symbol using the CP block in order to mitigate the effects of ISI. 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, CP removal, time-to-frequency conversion via FFT, and per subcarrier equalization. Each of the equalizers outputs are then replicated into L parallel copies using the copy function, with each copy allocated to one of L streams, where despreading is performed using C_i, for $i = 0, \ldots, L-1$. An integrate-and-dump procedure is then performed per stream, followed by P/S conversion and MPSK demodulation. This results in a reconstructed version of the original high data rate input signal, $\hat{x}(n)$.

To implement a non-contiguous version of MC-CDMA[5], subcarriers that interfere with occupied portions of spectrum are deactivated, in much the same way as is done in NC-OFDM. However, in order to compare with NC-OFDM, it is necessary that both implementations employ identical data rates. Therefore, the number of streams, L, must also be reduced. Note that when all of the subcarriers are active, $L = N$.

3 Qualitative Comparison

Thus far, we have presented the transceiver frameworks for NC-OFDM and MC-CDMA. To understand the advantages and disadvantages of employing NC-OFDM in a cognitive radio transceiver, we start with a qualitative comparison between this transmission technique and both MC-CDMA (employing non-contiguous subcarriers) and conventional OFDM. A summary of the qualitative comparison is shown in Table 1.

3.1 Conventional OFDM, MC-CDMA and NC-OFDM

Several discrete Fourier transform (DFT)-based modulation techniques are very sensitive to frequency and timing offsets [11]. However, there exist a number of synchronization techniques that make use of regularly-spaced pilot subcarriers in the frequency domain. Although conventional OFDM can exploit the pilot subcarriers since its transmission bandwidth is contiguous, both NC-OFDM and MC-CDMA cannot use these pilot subcarriers, since they might be located in occupied spectrum and are deactivated [8]. As a result, this solution is unavailable to these two techniques, which must resort to more complex approaches to obtain synchronization.

Both NC-OFDM and MC-CDMA are very agile with respect to spectrum usage, "filling in" the available spectral gaps within a transmission bandwidth partially occupied by other users (incumbent and other unlicensed). All that conventional OFDM can do is transmit in the largest unoccupied portion, if its transmission bandwidth fits in the first place. However, the spectrum agility for NC-OFDM and MC-CDMA comes at the cost of increased transmission overhead, where the activity status of each subcarrier must be shared between the transmitter and receiver. Moreover, if the occupied spectrum changes rapidly, frequent updates are required.

Since NC-OFDM is based on conventional OFDM, it has a potentially serious problem with peak-to-average power ratio (PAPR), while this problem is less pronounced in MC-CDMA since it employs frequency domain spreading [17]. Although PAPR is an issue with NC-OFDM, there are several techniques that can be employed to reduce the PAPR of a transceiver.

[5]Throughout this paper, only the non-contiguous version of MC-CDMA is employed.

Table 1 Qualitative comparison MC-CDMA, OFDM and NC-OFDM system, where '√' denotes the transceiver with best performance.

Characteristics	MC-CDMA	OFDM	NC-OFDM
Synchronization		√	
Spectrum Agility	√		√
Throughput	√		√
Overhead		√	
Error Robustness		N/A	√
PAPR	√		

With respect to the nulling of subcarriers within the vicinity of occupied spectrum, NC-OFDM can accomplish this task without any degradation in its error robustness since the subcarriers are relatively independent of each other given a sufficient cyclic prefix length and adequate equalization techniques. However, the subcarriers of an MC-CDMA transceiver are not independent due to the spreading in the frequency domain. As a result, the error robustness of an MC-CDMA system decreases as subcarriers are nulled, as we will see in the following section.

4 Error Robustness of NC-OFDM

It has been shown that when all subcarriers are available to the cognitive radio transceiver, MC-CDMA outperforms conventional OFDM with respect to error robustness [18]. Nevertheless, when several subcarriers are deactivated, we will show in this section that the error performance of a cognitive radio transceiver is better when NC-OFDM is employed relative to MC-CDMA.

4.1 Simulation Setup

For the simulations of the NC-OFDM and MC-CDMA transceivers, $N = 64, 128$, and 256 BPSK-modulated subcarriers were employed. Comparisons were performed when both systems deactivated 0%, 5%, 10%, 15%, 20%, and 25% of the N available subcarriers, modeling the effects of incumbent user spectral occupancy within the transmission bandwidth. A three-path Rayleigh multipath channel model with an exponential power delay profile was used [19], where each of the multipath components is an independent and identically distributed (i.i.d.) zero-mean Gaussian random variable. The rms delay spread, τ_{rms}, was assumed to be equal to $0.1T_s$, where T_s is the NC-OFDM and MC-CDMA symbol period. The cyclic prefix length for both transceivers was three samples long (2.5% of the symbol). Channel distortion compensation was performed using per tone equalization for each subcarrier [9]. The transceivers for both systems were assumed to be perfectly synchronized, the channel fading was considered to be pseudo-stationary, i.e., do not vary over a long period of time,

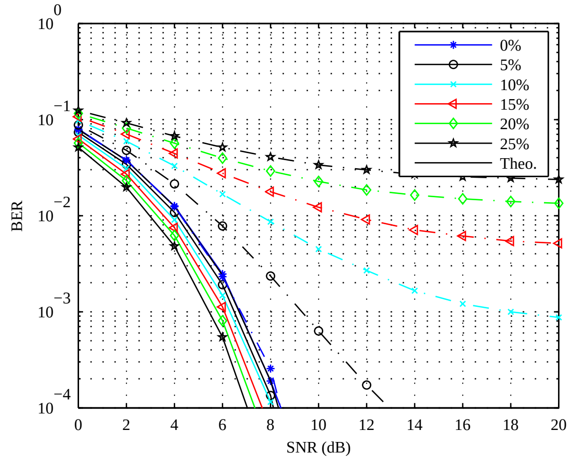


Fig. 3 BER performance of NC-OFDM (solid lines) and MC-CDMA (dashed lines) transceivers employing $N = 256$ subcarriers and operating in an AWGN channel.

and no coding was performed for the purpose of straightforward comparison. For each SNR point, the simulations continued until 100 bit errors were recorded, and each BER point was averaged over 200 channel realizations.

4.2 BER Performance Analysis

The BER results for an NC-OFDM and an MC-CDMA transceiver operating in an AWGN channel for different percentages of deactivated subcarriers are shown in Fig. 3. When 0% of the subcarriers are deactivated, both transceivers have the exact same performance when operating in the AWGN channel. Moreover, their curves in this case also match the theoretical BER curve for a single carrier BPSK-modulated transceiver operating in an AWGN channel, which is true for both transceivers. On the other hand, when the percentage of deactivated subcarriers increases, the performance of the two transceivers begins to differ. The BER performance of the NC-OFDM transceiver slightly improves relative to the 0% curve as power of nulled subcarrier can be redistribued to active subcarriers to improve signal SNR. However, the BER performance of the MC-CDMA degrades as the number of deactivated subcarriers increases. This is due to the fact that the subcarriers are dependent on each other since the information from the original L streams have been spreaded across them all. Thus, the deactivation of a subcarrier will result in the loss of some information, which would have been used at the receiver to reconstruct the original streams.

Given a three-path Rayleigh multipath channel, the BER results for an NC-OFDM and an MC-CDMA transceiver for different percentages of deactivated subcarriers are shown in Fig. 4. Generally, the performance

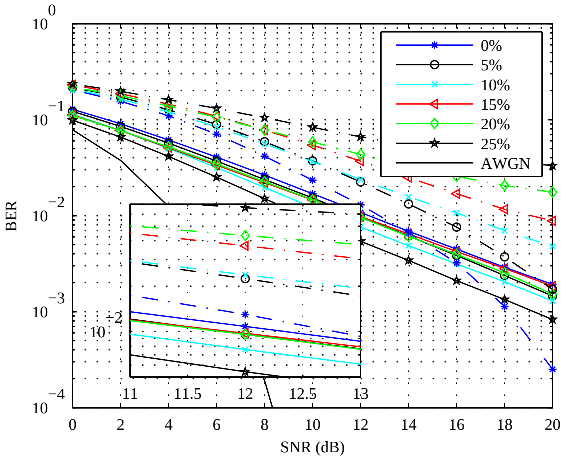
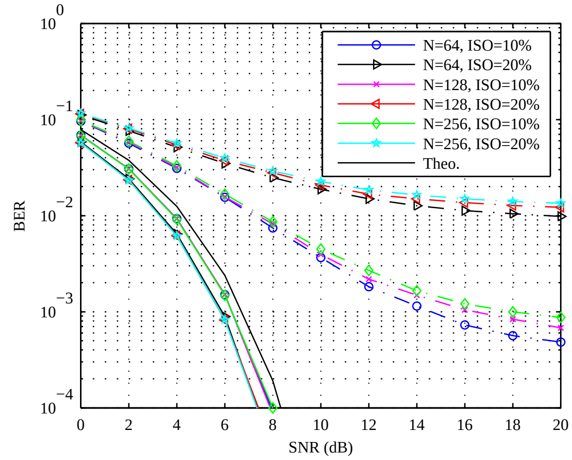
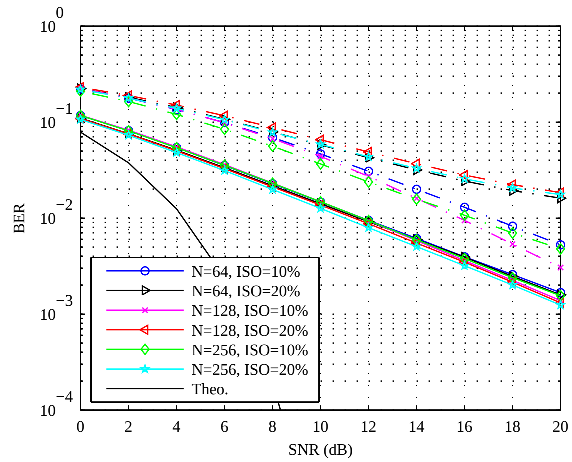


Fig. 4 BER performance of NC-OFDM (solid lines) and MC-CDMA (dashed lines) transceivers employing $N = 256$ subcarriers and operating in a 3-path Rayleigh fading channel.



(a) AWGN Channel.



(b) 3-path Rayleigh channel

Fig. 5 BER performance of NC-OFDM (solid lines) and MC-CDMA (dashed lines) transceivers for several ISO values and N subcarriers.

of the NC-OFDM transceiver is better than that of the MC-CDMA transceivers. In particular, as the percentage of deactivated subcarriers increases, the BER performance of the MC-CDMA system worsens while the BER performance of the NC-OFDM transceivers improves slightly.

The BER results for an NC-OFDM and an MC-CDMA transceiver for $N = 64$, 128, and 256 subcarriers are shown in Fig. 5 for different incumbent spectral occupancy[6] (ISO) values. We observe that the BER performance for a given ISO remains relatively constant, irrespective of number of subcarriers. Although there are slight fluctuations in BER performance for the MC-CDMA transceiver, which may be due to the random nature of the channel, the choice of deactivate subcarriers, and the loss of orthogonality between the spreading codes.

These results show that NC-OFDM is a suitable transmission technology for cognitive radio transceivers operating in DSA networks, since they do not suffer from an error performance penalty when avoiding incumbent user transmissions. Moreover, NC-OFDM can employ its active subcarriers to achieve an aggregate throughput that is greater than other candidate implementations requiring a contiguous bandwidth for transmission.

5 Conclusion

In this paper, we presented NC-OFDM as a viable transmission technology for cognitive radio transceivers operating in DSA networks. NC-OFDM was evaluated and compared, both qualitatively and quantitatively, with other candidate transmission technologies. The results show that NC-OFDM is sufficiently agile to avoid spectrum occupied by incumbent user transmissions, while not sacrificing its error robustness. Thus, NC-OFDM should be considered for use in cognitive radio transceivers to provide high data rates, spectral agility and acceptable error robustness.

[6] *Incumbent spectral occupancy* is defined as the fraction of the intended transmission bandwidth occupied by incumbent user transmissions.

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