OFDM SIGNAL CLASSIFICATION AND SYNCHRONIZATION

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ABSTRACT

This paper presents an Orthogonal frequency division multiplexing (OFDM) signal classification and synchronization system design for a cognitive radio system that extracts key features from an incoming OFDM signal to accomplish classification, synchronization and demodulation, all without any prior knowledge of the signal characteristics. This system is combined with our previously implemented narrowband signal classification and synchronization system[2]. The combined system supports a variety of modulations, including digital OFDM, MPSK, FSK, QAM, as well as analog AM and FM. This system has been implemented and tested on a variety of platforms, including a Microsoft Windows-based Anritsu signal analyzer, and Linux-based GNU Radio with Universal Software Radio Peripheral (USRP) RF front end.

The system presented in this paper can be used for any WiFi or WiMAX standard waveform. It can also be used to classify and synchronize other non-standard or custom OFDM signals. Combined with other functions for narrow band signal classification and synchronization, the complete universal classifier and synchronizer system fully enables key cognitive radio functionality, including automation, cognition, and interoperation.

1. INTRODUCTION

OFDM has been demonstrated as an effective technique to combat multipath fading in wireless channels[1]. This technique has gained popularity in a number of applications including digital subscriber loops, WiFi and WiMAX. OFDM provides excellent benefits in the case of closely-spaced "orthogonal sub-carriers" by dividing the available bandwidth into a collection of narrow sub-bands, which makes efficient use of available spectrum, especially in a dynamic spectrum access (DSA) system[1]. An OFDM signal can occupy variable bandwidth channels by changing the symbol duration and number of subcarriers. A cognitive receiver incorporating an OFDM signal classification and synchronization system enables use of cognitive wideband and broadband communication.

A Cognitive Radio (CR) can be defined as "a radio that senses and is aware of its operational environment and can dynamically adapt to utilize radio resources in time, frequency and space domains on a real time basis, accordingly to maintain connectivity with its peers while not interfering with licensed and other CRs"[3]. The operational environment includes both channel conditions and the signal parameters. A cognitive radio that initializes a connection with its peers needs to observe channel conditions to find available spectrum and determine transmission settings for optimal utilization of spectrum and power. A cognitive radio that responds to a connection set up request should follow the modulation type that has been initiated. For cognitive radio and especially for DSA, modulation and other signal parameters commonly change in response to the varying channel conditions. Our system—which can automatically detect signal presence, determine center frequency and bandwidth, identify modulation type and extract information needed for demodulation—will allow the transmitting end of a communication link to change modulation settings freely without having to notify the receiver. The receiving end of the link can always pick up the signal and continue communication. In [2], we developed a narrowband cognitive receiver which can accommodate FM, AM, MPSK, and QAM. In this paper, we will explore the wideband modulation world and develop a system can detect, classify and synchronize wideband signals. The combination of narrowband and wideband subsytems will serve as the heart of a powerful cognitive receiver.

Two of the most popular wideband modulation technologies are code division multiple access (CDMA) and orthogonal frequency-division multiplexing (OFDM). Because the detection and demodulation of CDMA signal requires a spreading code, in this paper we will focus on OFDM. Our OFDM signal classification and synchronization algorithm will also benefit DSA research by exploiting the flexibility and spectral efficiency that characterizes OFDM.

In this paper, we focus on the cognitive receiver; specifically we cover tracking and detecting an OFDM signal, classifying it, and extracting all parameters needed for demodulation. These parameters include center frequency, OFDM symbol duration, CP length, and number of subcarriers.

In Section 2, we briefly introduce the application of OFDM in DSA and discuss the assumptions we make in our system design. In Section 3, we give a detailed description of the system. This section includes an overview of the system, coarse carrier frequency estimation, measurement of symbol duration and CP length, subcarrier scheme detection, and fine carrier frequency synchronization. In Section 4, we present simulation results and over the air (OTA) experiment performance. In Section 5, we conclude with a brief summary and discussion of future work.

2. APPLICATION OF OFDM IN DSA

A frequency agile cognitive radio should dynamically identify unused portions of spectrum in order to adapt and operate in the available band. In order to operate effectively in the available band, the cognitive radio has to adjust its signal bandwidth, reducing or increasing bandwidth and corresponding symbol rate accordingly. OFDM is able to change its symbol duration, and thus is particularly suited to this adaptive procedure. There are two schemes of changing OFDM symbol duration [4]. One method is to turn off certain subcarriers, which is the scheme applied in Orthogonal Frequency-Division Multiple Access (OFDMA). The other method reduces the subcarrier width and inter-subcarrier spacing, allowing the signal to adapt to variable available bandwidth while maintaining a constant number of subcarriers. The symbol rate adaption is controlled by the bandwidth of subcarrier. Both methods have the same effect regarding bandwidth and data throughput. For example, in Figure 1, the available bandwidth is decreased by 3/5 of the original bandwidth as show in Figure 1a. We can either use the first method, as shown in Figure 1b, or the second method, as in Figure 1c. We adopt the second method; keeping the number of subcarriers constant allows us to reduce computational complexity.

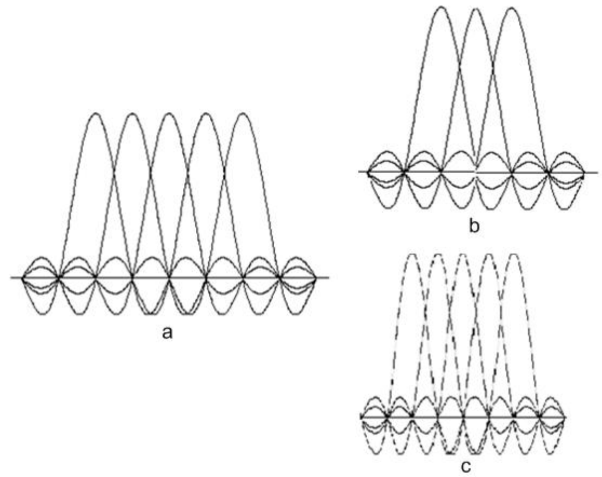

Figure 1: Original OFDM signal and two schemes for changing the bandwidth of an OFDM signal

3. SYSTEM DESCRIPTION

3.1. System Overview

In our system, we are able to detect a signal by spectrum scanning, and identify the signal as OFDM. Next we measure the length of a complete OFDM symbol and the length of the cyclic prefix (CP) and then resolve the number of sub-carriers and the frame information. After that, we extract the symbol rate and carrier synchronization information for each subcarrier. Finally, we are able to detect the modulation type used in each subcarrier. The extracted information is used to configure our cognitive radio receiver and enable demodulation. The process can be repeated as necessary, tracking signals and reconfiguring radios to adapt to a changing signal space.

Figure 2 shows an overview of our system. The system can be seen as three main parts. The down conversion block converts the signal to the IF band. The classification block is used to classify the signal, detect the start and end of a single OFDM symbol, and measure the length of the CP. The final block does synchronization by processing data based on the complete OFDM symbol. In the synchronization block, we estimate and compensate the frequency offset, adjust the symbol timing and analyze the subcarrier modulation type and settings. The output of the whole system will be several key parameters: accurate carrier frequency, OFDM symbol duration, length of CP, number of FFT points and modulation type of a subcarrier.

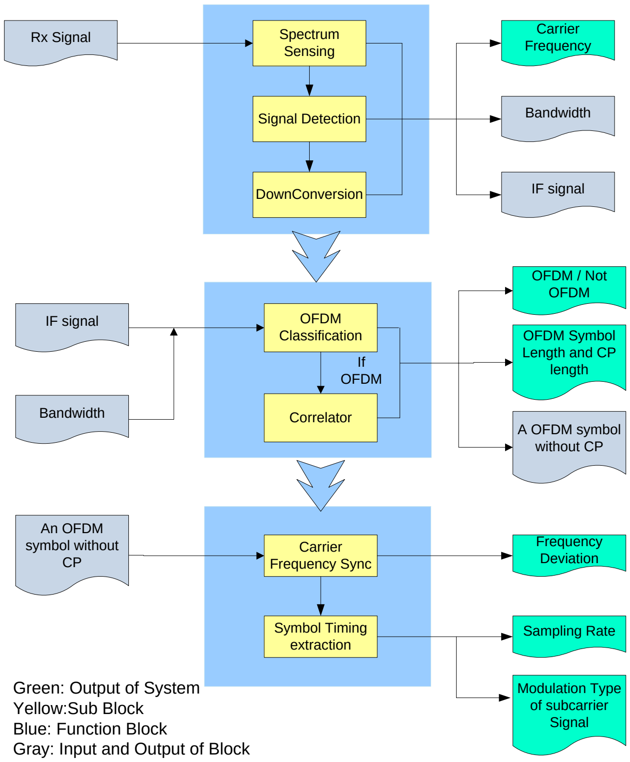

Figure 2: System Overview

3.2. Detection of OFDM signal and coarse carrier frequency estimation

Our first step is to scan the spectrum for the signal, and if the signal is present, detect and classify it. For identifying the signal as OFDM, we correlate the incoming signal with itself. We did OTA experiments for MPSK, analog FM and OFDM signal; the result is shown in Figure 3. The correlated output is different in the case of narrowband modulation and OFDM modulation. This difference is due to the cyclic prefix present in the OFDM signal, which gives us multiple peaks as opposed to a single peak in narrowband modulation.

Figure 4 shows the power spectral density of an OFDM signal. After we detect and identify the OFDM signal, the center frequency and bandwidth is estimated in the same way as described in [2].

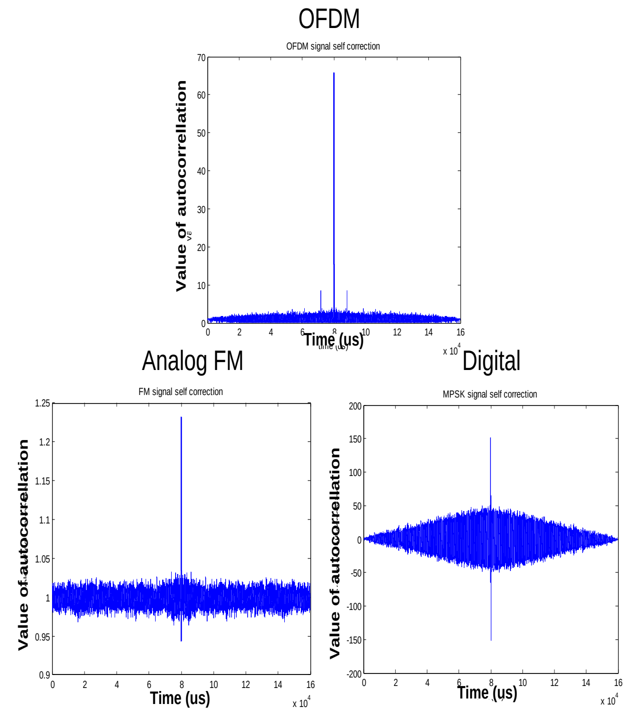

Figure 3: Autocorrelation to detect OFDM

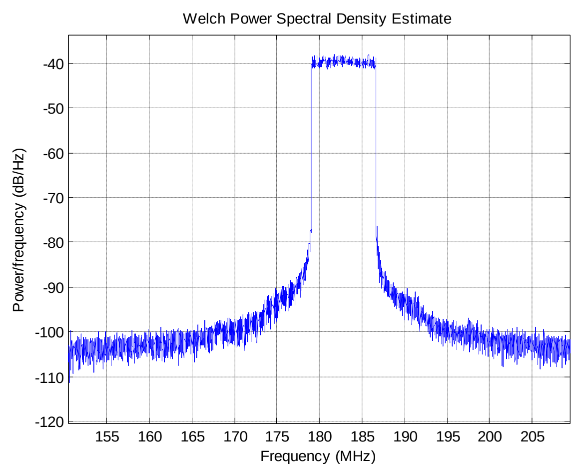

Figure 4: PSD of an OFDM signal

3.3. Estimation of Symbol length and CP length

For extracting the information from the incoming signal, it is necessary to separate out one symbol and the cyclic prefix. We remove the cyclic prefix and find the length of the actual symbol by correlating the incoming signal with itself. From Figure 3, we observe that the OFDM plot has three distinct peaks. The two smaller peaks are due to the presence of the cyclic prefix. The length of the actual symbol excluding the cyclic prefix is the difference between the highest peak and the smaller peak. Let the number of samples between these two peaks be n_{rx}.

If the sampling rate at the receiver is set as Rx samples per second, then the useful symbol length is $\frac{n_{rx}}{Rx}$ .We use this useful symbol length for carrier synchronization and symbol timing extraction.

For finding the CP length we convolve one useful symbol with the rest of the OFDM symbols as shown in Figure 5. The CP of the useful symbol will overlap with its copy in the rest of the OFDM symbol. This will result in a peak as shown in Figure 6. The position of the peak determines the length of the CP.

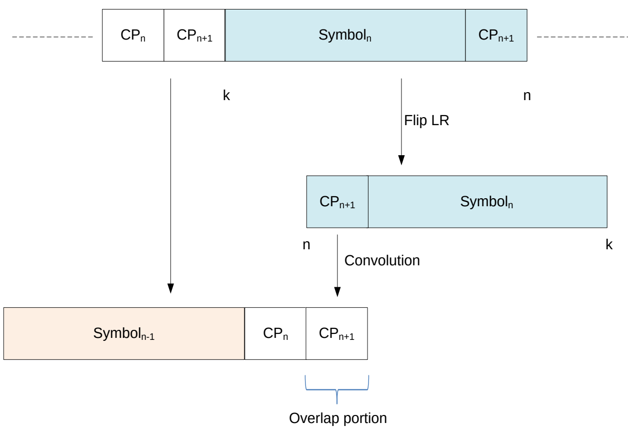

Figure 5: Estimation of CP length

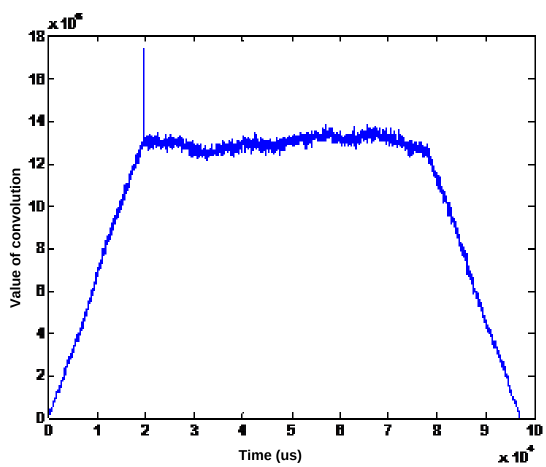

Figure 6: Convolution plot

However, we also get an OFDM symbol excluding the cyclic prefix. This OFDM symbol vector is called V_{rx}. When we use an OFDM symbol for carrier synchronization and symbol timing, it is necessary to have integer numbers of samples per symbol. "Symbol" in this case refers to the MPSK signal that is acquired after FFT and parallel-to-serial conversion. To meet the requirement of integer number of samples per symbol, we resample the OFDM symbol vector V_{rx}.

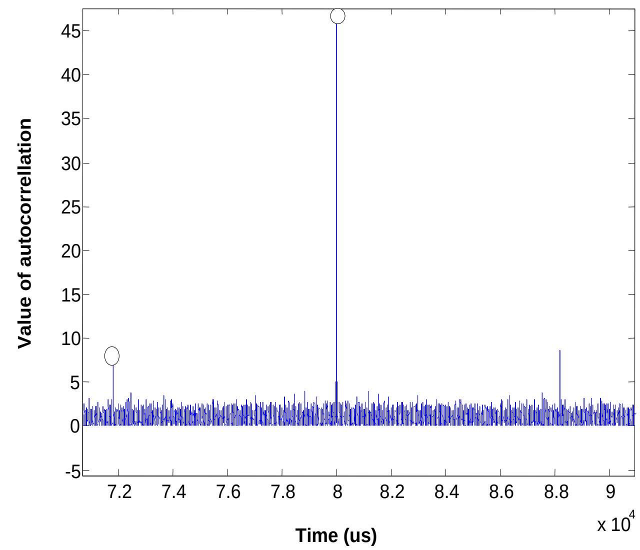

Figure 7: OFDM signal autocorrelation

Figure 8 shows the serial to parallel (S/P) processing at the transmitter side. t_{tx} is symbol duration before S/P, $t_{tx} = \frac{1}{R_t}$, and R_t is the symbol rate at the transmitter side. Fs is the number of subcarriers. Thus, the OFDM symbol duration is $t_{tx} \times Fs$.

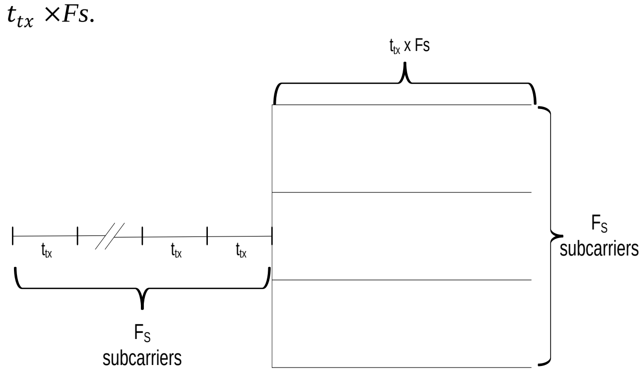

Figure 8: Serials to Parallel of OFDM in transmitter side

The OFDM symbol length at the transmitter side is the same as the OFDM symbol length as the receiver side. Thus, we have:

$$\frac{n_{rx}}{R_x} = \frac{F_s}{R_t}$$

$\frac{n_{rx}}{R_x}$ is determined by the value of R_x and R_t , and cannot be guaranteed an integer. Thus, we resample vector V_{rx} and the number of V_{rx} becomes $round(\frac{n_{rx}}{R_x})F_s$ after the resampling. Samples per symbol of V_{rx} after the FFT is $round(\frac{n_{rx}}{R_x})$. The new vector after resampling is $V_{resample}$.

3.4. Carrier Frequency Synchronization

The down conversion process converts RF to baseband, however there is still some error in the form of frequency offset. For an OFDM signal, the frequency offset has a completely different influence on symbol constellation as compared to the effect of frequency offset in a narrow band signal. In Figure 9, the effects of frequency offset on an OFDM signal and on an MPSK signal are compared.

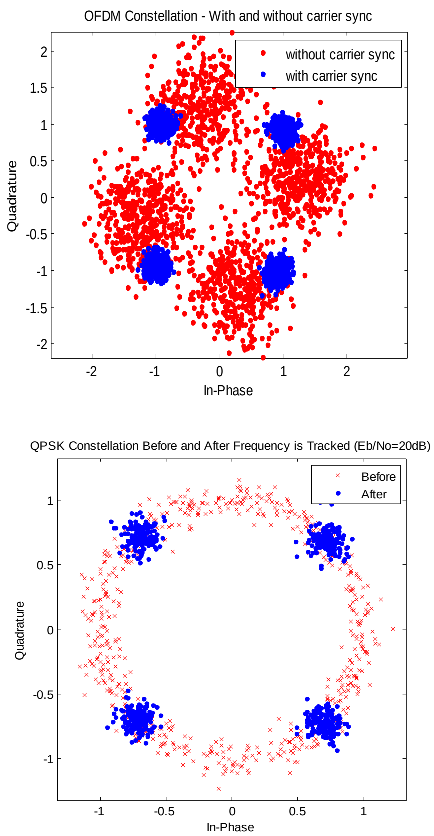

Figure 9: Comparison between the effect of frequency offset on OFDM signal and QPSK signal

In Figure 9, the comparison is based on the assumption that the symbol rate is correct. Frequency offset causes an OFDM constellation to spread; there is an error in both amplitude and phase. The frequency offset introduces only phase error in MPSK signals. The reason for this difference is because the frequency offset becomes a timing delay after the FFT at the OFDM receiver. This delay will lead to incorrect symbol timing, which will spread the signal constellation.

The frequency offset estimation algorithm is designed as follows. The step size of the frequency offset is defined as Δf, the range of the frequency offset estimated is defined as f_{range}. We search from $-f_{range}$ to f_{range} using step size Δf. As we compensate for frequency offset, the variance of the amplitude of the symbols changes. The minimal variance corresponds to the carrier frequency offset.

4. EXPERIMENT AND SIMULATION RESULT

As we mentioned in Section 3.1, the purpose of our system is to automatically detect the existence of the OFDM signal and extracting the parameters so that the signal can be demodulated without prior information from the transmitter side. In this section, we are going to give an example and the result, which is the set of output parameters. In Table 1, we give the parameter settings at the transmitter side in the first column and give the output of our system in the second column.

Transmitter Setting	Receiver Classification Result
Center frequency=450000018 Hz;	Center Frequency=45000000 Hz
Symbol rate=100k;	Symbol rate=100k
Number of FFT points = 4096 (known by both transmitter and receiver)	
CP length = ¼ OFDM symbol duration	CP length = ¼ OFDM symbol duration
Subcarriers occupied = 1706(known by both transmitter and receiver)	
SNR=10dB	

Regarding the occupied subcarriers, the number doesn't influence our classification and synchronization performance. In Figure 10, we show the final constellation plots with different number of occupied subcarriers.

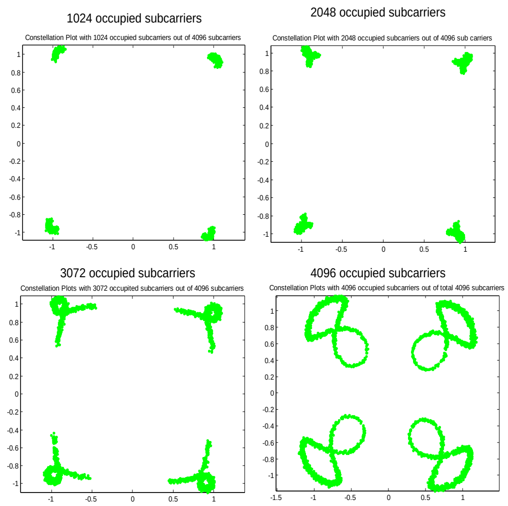

Figure 10: Constellation plots with Different Numbers of Occupied Subcarriers

5. CONCLUSION

In this paper, we put forward an OFDM classification and synchronization system for cognitive radio systems. The proposed scheme can successfully detect the presence of an OFDM signal and extract all the parameters necessary for demodulation of an OFDM signal without any prior knowledge of the transmitter. This classification and synchronization system, when integrated with the narrowband UCS system, will serve as a comprehensive cognitive receiver capable of detecting, classifying, and demodulating NB and WB signals.

6. ACKNOWLEDGEMENT

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