CogWave: Open-source Software Platform for Cognitive Radio Waveform Design

Vincent Le Nir and Bart Scheers

***Abstract*—CogWave is a free and open-source software platform aiming at developing cognitive radio waveforms. Combining CogWave with USRP gives a rapid prototyping platform for physical layer design and algorithm validation through a real-time video, audio and text transmission. This paper presents the cognitive blind orthogonal frequency division multiplexing (OFDM) waveform implemented in the CogWave software. The cognitive blind OFDM waveform is an OFDM-based waveform divided into multiple sub-channels with a spectrum sensing algorithm to estimate the power spectral density and to determine the best sub-channel for transmission. A demonstration setup is described for the exchange of data between two computers using the CogWave software and running the cognitive blind OFDM waveform in the presence of a jammer sweeping the bandwidth used for transmission. It is observed that whenever the jammer perturbs the sub-channel used for transmission, the cognitive blind OFDM waveform is able to jump to another sub-channel while maintaining communication without a dedicated control channel.**

***Index Terms*—Cognitive radio, open-source software, cognitive waveform**

I. INTRODUCTION

CogWave is a free and open-source software platform aiming at developing cognitive radio waveforms [1]. The CogWave software allows the exchange of video, audio and text between two USRPs through a graphical user interface (GUI) developed in Qt4 and cognitive radio waveforms developed in IT++. The USRP products are computer-hosted software radio which connect to a host computer through a high-speed USB or Gigabit Ethernet link, which the host-based software uses to control the USRP hardware and transmit/receive data [2]. Some USRP models also integrate the general functionality of a host computer with an embedded processor that allows the USRP Embedded Series to operate in a standalone fashion. The goal of the USRP hardware driver (UHD) is to provide a host driver and application programming interface (API) for current and future USRP products. Qt4 is a cross-platform application framework that is widely used for developing application software with a graphical user interface (GUI) [3]. GStreamer is a pipeline-based multimedia framework which allows a programmer to create a variety of media-handling components, including simple audio playback, audio and video playback, recording, streaming and editing [4]. IT++ is a C++ library of mathematical, signal processing and communication classes and functions [5]. Its main use is in simulation of communication systems and for performing research in the area of digital communications. Combining CogWave with USRP gives a rapid prototyping platform for physical layer design and algorithm validation through a real-time video, audio and text transmission.

This paper presents the cognitive blind orthogonal frequency division multiplexing (OFDM) waveform implemented in the CogWave framework. The cognitive blind OFDM waveform is an OFDM-based waveform divided into multiple sub-channels with a spectrum sensing algorithm to estimate the power spectral density and to determine the best sub-channel for transmission. The cognitive blind OFDM waveform adjusts dynamically the sub-channel used for transmission to mitigate interference by sensing its operational electromagnetic environment. A complete OFDM blind receiver which does not require the use of pilot symbols is used for OFDM signal detection and time recovery, carrier frequency recovery, carrier phase recovery and amplitude gain control. First, a cyclic prefix based sliding window detects the presence of an OFDM signal and estimates its timing and frequency offsets. After correction, a two-dimensional carrier phase recovery based on the second/fourth power algorithms (BPSK/QAM constellations) adjusts the remaining frequency and phase offsets. Full-duplex mode is enabled by time division duplexing (TDD) mode. UHD timestamps and multi-threading allow precise time scheduling for the transmit and receive chains of the TDD mode. Multiple users are handled by orthogonal frequency division multiple access (OFDMA) in a decentralized ad-hoc network. The nodes automatically synchronize in time with an existing OFDM signal and use different sub-channels to allow concurrent OFDMA transmissions. Cyclic redundancy check (CRC) and forward error correction (FEC) are used to detect and correct errors between a frame's preamble and postamble. Once the frame's preamble is detected, the received timestamp is adjusted such that it coincides with the next frame's preamble.

A demonstration setup is described for the exchange of data between two computers using the CogWave software and running the cognitive blind OFDM waveform in the presence of a jammer sweeping the bandwidth used for transmission. It is observed that whenever the jammer perturbs the sub-channel used for transmission, the cognitive blind OFDM waveform is able to jump to another sub-channel while maintaining communication without a dedicated control channel.

The remainder of this paper is structured as follows. In Section II, the main functions of the cognitive blind OFDM waveform are described. These are the spectrum sensing, the OFDM signal detection and time recovery, the carrier frequency recovery, amplitude gain control and carrier phase recovery, and the frame structure. In Section III, a demonstration setup is described for the exchange of data between two computers using the CogWave software and running the cognitive blind OFDM waveform in the presence of a jammer sweeping the bandwidth used for transmission. Section IV concludes this paper.

II. MAIN FUNCTIONS OF THE COGNITIVE BLIND OFDM WAVEFORM

In this Section, the main functions of the cognitive blind OFDM waveform are described. These are the spectrum sens-

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This research work was carried out in the frame of the Belgian Defense Scientific Research & Technology Study C4/19 funded by the Ministry of Defense (MoD). The scientific responsibility is assumed by its authors.

ing, the OFDM signal detection and time recovery, the carrier frequency recovery, amplitude gain control and carrier phase recovery, and the frame structure.

A. Spectrum Sensing

The spectrum sensing algorithm of the cognitive blind OFDM waveform determines which sub-channel in the spectrum has the lowest energy to be used for transmission. Moreover, this information is communicated to the other nodes in the frame's preamble. The bandwidth of interest B is divided into a number of sub-channels S of width B/S. As there is no assumption about the type of the observed signals, a non-parametric method should be used. The method of averaged periodograms also known as the Barlett's method is used for power spectrum estimation [6]. We assume that the complex sampling rate equals the bandwidth of interest. The averaged periodograms for N sub-carriers of a complex baseband signal with K blocks of N samples $\mathbf{y} = [y(kN), \ldots, y((k+1)N-1)]$ with $k = [0, \ldots, K-1]$ is given by

$$E(i) = \frac{1}{KN} \sum_{k=0}^{K-1} |\sum_{n=0}^{N-1} y(kN+n) e^{-\frac{j2\pi in}{N}}|^2 \tag{1}$$

with $i = [0, \ldots, N-1]$ bins. The best sub-channel selection consists of integrating the estimated power spectrum of the frequency bins corresponding to the width B/S for all sub-channels and determine the sub-channel which have the lowest energy

$$S_{opt} = \min_{m} \sum_{i=\frac{mN}{S}}^{\frac{(m+1)N}{S}-1} E(i) \tag{2}$$

with $m = [0, \ldots, S-1]$.

B. OFDM Signal Detection and Time Recovery

The OFDM signal detection and time recovery of the cognitive blind OFDM waveform does not require the knowledge of pilot symbols nor the knowledge of noise variance but requires the knowledge of the OFDM parameters, i.e. number of subcarriers N, cyclic prefix size P, bandwidth of interest B and number of sub-channels S. A rectangular mask is applied in the frequency domain on the received samples for each sub-channel. A cyclic prefix based sliding window metric is calculated on the recomputed received samples for each sub-channel. The cyclic prefix based sliding window metric detects the presence of an OFDM signal and estimates its timing offset [7]. The detection threshold is based on the non-correlated part of the cyclic prefix based sliding window metric at the timing offset estimate instead of the noise variance [8]. This allows to detect the presence of an OFDM signal even in the presence of an unknown signal in the bandwidth of interest. We consider a complex baseband signal with K blocks of $N+P$ samples $\mathbf{y} = [y(k(N+P)), \ldots, y((k+1)(N+P)-1)]$ with $k = [0, \ldots, K-1]$. The cyclic prefix based sliding window metric is given by

$$\rho(\theta) = \frac{|\sum\limits_{k=0}^{K-2} \sum\limits_{j=\theta}^{\theta+P-1} y(k(N+P)+j) y^*(k(N+P)+j+N)|}{(K-1)P\sigma_y^2} \tag{3}$$

with σ_y^2 the variance of the received complex baseband signal. The absolute value in the metric is able to cope with frequency and phase offsets introduced by Doppler shifts and clock mismatches. The cyclic prefix based sliding window timing offset estimate is given by

$$\theta^{opt} = \underset{\theta \in \{0, \ldots, N+P-1\}}{max} \rho(\theta) \tag{4}$$

Assuming a channel delay spread spanning the entire cyclic prefix, the non-correlated part of the cyclic prefix based sliding window metric at the timing offset estimate is given by $\rho(mod(\theta^{opt} + 2P, N+P))$. Assuming that the non-correlated part is a Gaussian distribution with mean m_{nc} and variance σ_{nc}^2, the detection threshold η is given by

$$\eta = m_{nc} + \alpha \sigma_{nc} \tag{5}$$

with α an integer corresponding to the number of standard deviations necessary to discriminate between the cyclic prefix based sliding window metric at the timing offset estimate $\rho(\theta^{opt})$ and its non-correlated part $\rho(mod(\theta^{opt}+2P, N+P))$. The detector scheme is

$$\begin{array}{ll} \rho(\theta^{opt}) > \eta & \text{Presence of an OFDM signal} \\ \rho(\theta^{opt}) < \eta & \text{Absence of an OFDM signal} \end{array} \tag{6}$$

C. Carrier Frequency Recovery, Amplitude Gain Control and Carrier Phase Recovery

The cyclic prefix based sliding window timing offset estimate can also be used to estimate the frequency offset (ϵ^{opt})for carrier frequency recovery [9]

$$\epsilon^{opt} = -\frac{1}{2\pi N} \angle \rho(\theta^{opt}) \tag{7}$$

After time and frequency offset corrections, the OFDM symbols are transformed to the frequency domain by the discrete Fourier transform (DFT) operation. As there is no interference between two consecutive OFDM symbols, we obtain independent sub-carriers with the following channel model

$$Y(kN+i) = H(kN+i)X(kN+i) + N(kN+i) \tag{8}$$

with $k = [0, \ldots, K-1]$ and $i = [0, \ldots, N-1]$, in which $Y(kN+i)$, $H(kN+i)$, $X(kN+i)$, and $N(kN+i)$ are respectively the demodulated data, the channel frequency response, the transmitted symbol and the noise for the block k and sub-carrier i. Assuming the channel amplitude invariant over the K blocks, a blind estimate of the channel amplitude for amplitude gain control is given by

$$|H(i)^{opt}|^2 = \frac{1}{K} \sum_{k=0}^{K-1} |Y(kN+i)|^2 \tag{9}$$

The channel phase varies between sub-carriers due to an incorrect timing offset estimate and the channel frequency response. The channel phase also varies between blocks in time due to a remaining frequency offset or oscillator phase noise. The two-dimensional carrier phase recovery of the cognitive blind OFDM waveform uses the second-power estimator for the BPSK constellation ($M = 2$) and the fourth-power estimator for QAM constellations ($M = 4$) [10], [11]. A two-dimensional phase unwrapping algorithm is able to correct abrupt changes of the phase in the frequency domain and in the time domain due to the phase ambiguity introduced by the M-power estimators. A first estimate of the phase offset is performed in the frequency domain by the following expression

$$\phi(i)^{est} = \angle \frac{1}{K} \sum_{k=0}^{K-1} Y(kN+i)^M \tag{10}$$

A 1-D phase unwrapping is performed in the frequency domain to correct linear shifts of the phase in the frequency domain due to an incorrect timing offset as well as abrupt changes of the phase due to the phase ambiguity of the M-power estimators. After correction, a second estimate of the phase offset is performed in the time domain by the following expression

$$\phi(k)^{est} = \angle \frac{1}{N} \sum_{i=0}^{N-1} Y(kN+i)^M \tag{11}$$

Another 1-D phase unwrapping is performed in the time domain to correct a remaining frequency offset or oscillator phase noise. The carrier phase recovery with the M-power estimators is performed using the Algorithm 1.

Algorithm 1 Amplitude Gain Control and Carrier phase recovery with the M-power estimators

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$\phi(i)^{est} = \angle \frac{1}{K} \sum_{k=0}^{K-1} Y(kN+i)^M \ \forall i$
$\phi(0)^{opt} = \phi(0)^{est}$
for $i = 1$ to $N-1$
    if $|\phi(i)^{est} - \phi(i-1)^{est}| > \frac{\pi}{M}$
        $\phi(i)^{opt} = |\phi(i)^{est} - \phi(i-1)^{est}| - \frac{2\pi}{M}$
    else
        $\phi(i)^{opt} = \phi(i)^{est} - \phi(i-1)^{est}$
    $\phi(i)^{opt} = \phi(i)^{opt} + \phi(i-1)^{opt}$
end for
$Y(kN+i) = \frac{1}{|H(i)^{opt}|} Y(kN+i) e^{-j\phi(i)^{opt}} \ \forall k, i$
$\phi(k)^{est} = \angle \frac{1}{N} \sum_{i=0}^{N-1} Y(kN+i)^M \ \forall k$
$\phi(0)^{opt} = \phi(0)^{est}$
for $k = 1$ to $K-1$
    if $|\phi(k)^{est} - \phi(k-1)^{est}| > \frac{\pi}{M}$
        $\phi(i)^{opt} = |\phi(i)^{est} - \phi(i-1)^{est}| - \frac{2\pi}{M}$
    else
        $\phi(k)^{opt} = \phi(k)^{est} - \phi(k-1)^{est}$
    $\phi(k)^{opt} = \phi(k)^{opt} + \phi(k-1)^{opt}$
end for
$Y(kN+i) = Y(kN+i) e^{-j\phi(k)^{opt}} \ \forall k, i$
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The M-fold phase ambiguity can be mitigated using sync-words in the frame's preamble as described in the following Section.

D. Frame Structure

The frame structure of the cognitive blind OFDM waveform is shown in Figure 1. The frame size is set to be long enough to be able to carry the frame's preamble and postamble, a JPEG video image, several MP3 packets and several bytes of text. The frame consists of a preamble of 17 bytes, a payload of variable size, a postamble of 3 bytes, and dummy bytes of variable size. In the frame's preamble, two sync-words are used to mitigate the M-fold phase ambiguity and to find the start of the frame. A source address and a destination address are used to establish a communication link between two nodes. The node's best sub-channel is also transmitted to the other node as well as the transmitter timestamp of the frame in order to synchronize the two nodes. The payload may consist of a JPEG video image, several MP3 packets and several bytes of text which are CRC encoded, FEC encoded, and scrambled with a random seed which is known only to the two communicating nodes.

III. DEMONSTRATION OF THE COGNITIVE BLIND OFDM WAVEFORM

In this Section, a demonstration setup is described for the exchange of data between two computers using the CogWave software and running the cognitive blind OFDM waveform in the presence of a jammer sweeping the bandwidth used for transmission.

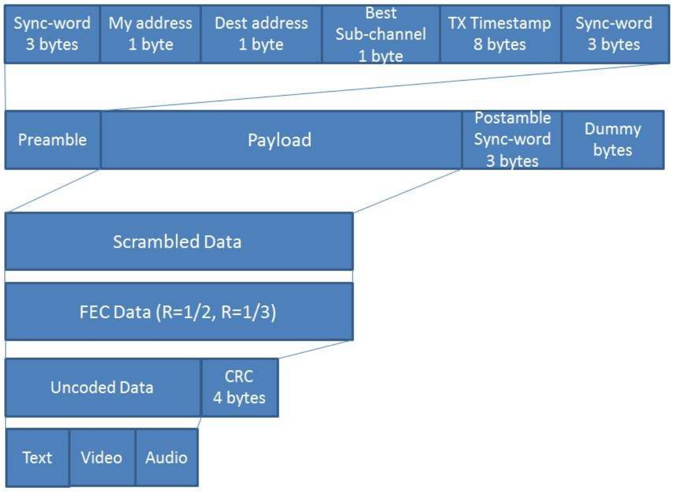


Fig. 1. Frame structure used for the cognitive blind OFDM waveform

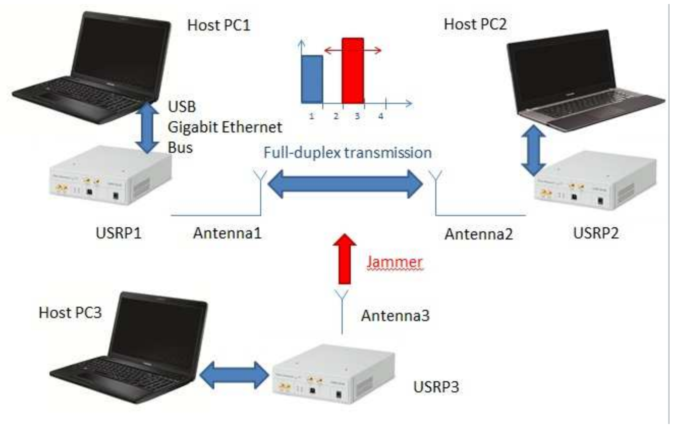


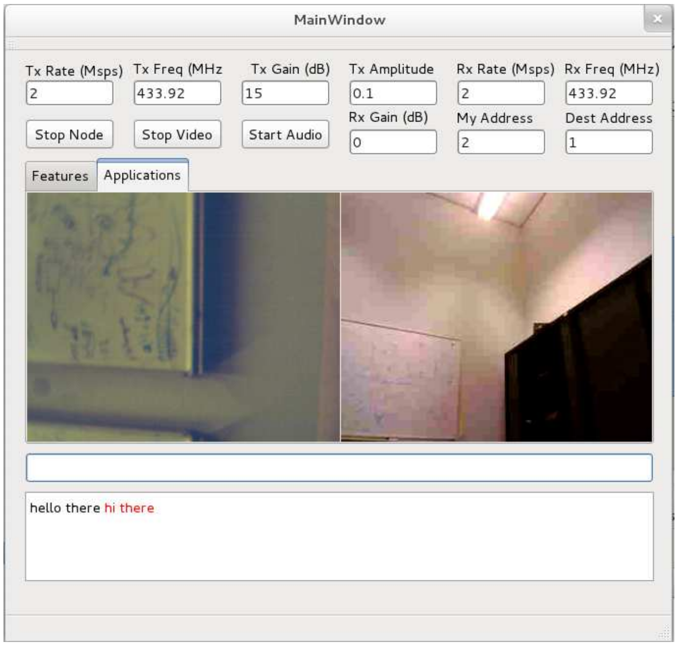
Fig. 2. Setup used for the demonstrator

CogWave is a free and open-source software platform aiming at developing cognitive radio waveforms [1]. CogWave allows the exchange of video, audio and text between two USRPs through a graphical user interface (GUI) developed in Qt4 and cognitive radio waveforms developed in IT++. Source coding is performed by Gstreamer [4]. Video streams are encoded in motion JPEG and audio streams are encoded in MP3. The encoded bytes are put into first in first out (FIFO) pipes. CogWave reads the FIFO pipes and the text, converts the bytes into bits, builds the frame according to Figure 1, modulates the frame by the cognitive blind OFDM waveform and sends the signal to the USRP. At the receive side, the USRP captures the signal, detects the presence of an OFDM signal, demodulates the frame, converts the bits into bytes, puts the bytes into FIFO pipes that are decoded by GStreamer.

Figure 2 shows the demonstration setup used for the cognitive blind OFDM waveform. In this setup, three host PCs are connected to three USRPs via USB, Gigabit Ethernet or via and internal bus depending on the USRP model [2]. Two host PC-USRP are used for exchanging data (video, audio, text) via the cognitive blind OFDM waveform of the CogWave software. Full-duplex transmission is enabled by the TDD mode of the cognitive blind OFDM waveform. A third host PC-USRP is used as a a jammer to sweep the transmission bandwidth and to perturb the communication between the two host PC-USRP. The number of sub-channels of the cognitive blind OFDM waveform is set to four sub-channels. The cognitive blind OFDM waveform adjusts dynamically the sub-channel used for transmission and mitigates interference by sensing its operational electromagnetic environment. Therefore, whenever the jammer perturbs the sub-channel used for transmission, the cognitive blind OFDM waveform is able to jump to another sub-channel while maintaining communication without a dedicated control channel.

Figure 3 shows the applications' GUI of the two host PC-USRP exchanging data. Some parameters are editable, such as the transmission rate “Tx Rate (Msps)”, the transmission frequency “Tx Freq (MHz)”, the transmission gain “Tx Gain (dB)”, the transmission signal amplitude “Tx Amplitude”, the reception rate “Rx Rate (Msps)”, the reception frequency “Rx Freq (MHz)”, the reception gain “Rx Gain (dB)”, the address of the node “My address” and the destination address “Dest Address”. There are also three buttons to start and to stop the node, the video transmission, and the audio transmission. There are two video windows showing the video transmitted (left) and the video received (right). There are also two text windows for text transmission and for text display. The text displayed in black is the transmitted text while the text displayed in red is the received text. The applications' GUI shows the exchange of data with the CogWave software using the cognitive blind OFDM waveform in TDD mode. The two nodes have transmission and reception rates set to 2 Msps. The carrier frequencies are set to 433.92MHz in the industrial, scientific and medical (ISM) radio band. The transmission gains transmission signal amplitudes, and reception gains are set to 15 dB, 0.1 and 0 dB respectively. The two nodes addresses are set to 1 and 2.

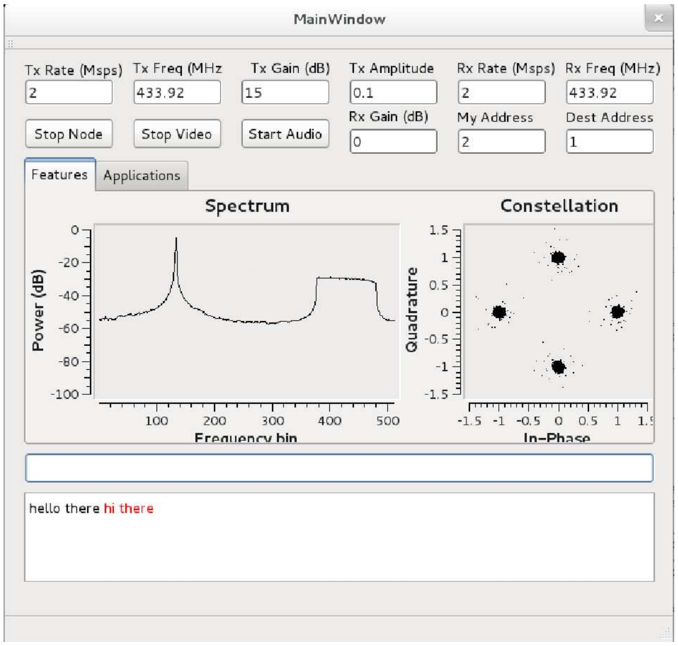
At the transmitter, the CogWave software takes some text, audio or video from keyboard, microphone or web-cam input sources. Cyclic redundancy check (CRC) and forward error correction (FEC) are used to detect and to correct errors between a frame's preamble and postamble. Using sensing information based on energy detection, the bit sequence is OFDM modulated on the best sub-channel. The resulting data is passed to the USRP via UHD for transmission at the selected carrier frequency, sampling rate, transmit gain and transmit timestamp. At the receiver, the received samples are captured by the USRP via UHD at the selected carrier frequency, sampling rate and receive gain and receive timestamp. UHD timestamps and multi-threading allow precise time scheduling for the transmit and receive chains of the TDD mode. The received buffer is set to the number of samples in a frame. First, a cyclic prefix based sliding window detects the presence of an OFDM signal, determines the sub-channel used by the transmitter and estimates its timing and frequency offsets. After correction, a two-dimensional carrier phase recovery based on the second/fourth power algorithms (BPSK/QAM constellations) adjusts the remaining frequency and phase offsets. Multiple users are handled by orthogonal frequency division multiple access (OFDMA) in a decentralized ad-hoc



Tx Rate (Msps) 2
Tx Freq (MHz 433.92
Tx Gain (dB) 15
Tx Amplitude 0.1
Rx Rate (Msps) 2
Rx Freq (MHz) 433.92
Rx Gain (dB) 0
My Address 2
Dest Address 1

hello there hi there

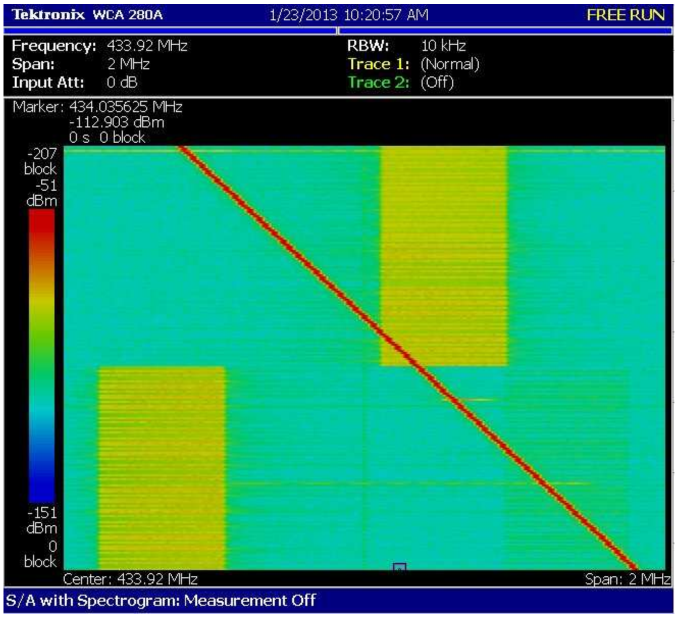
Fig. 3. Applications' GUI of the CogWave software



Tx Rate (Msps) 2
Tx Freq (MHz 433.92
Tx Gain (dB) 15
Tx Amplitude 0.1
Rx Rate (Msps) 2
Rx Freq (MHz) 433.92
Rx Gain (dB) 0
My Address 2
Dest Address 1

hello there hi there

Fig. 4. Features' GUI of the CogWave software



1/23/2013 10:20:57 AM FREE RUN

Frequency: 433.92 MHz
Span: 2 MHz
Input Att: 0 dB
RBW: 10 kHz
Trace 1: (Normal)
Trace 2: (Off)

Marker: 434.035625 MHz
-112.903 dBm
0 s 0 block

Center: 433.92 MHz
Span: 2 MHz

S/A with Spectrogram: Measurement Off

Fig. 5. Spectrogram showing the cognitive capability of the cognitive blind OFDM waveform

network. The nodes automatically synchronize in time with an existing OFDM signal and use different sub-channels to allow concurrent OFDMA transmissions. The hard bit sequence is then used to detect the frame's preamble and postamble, and within the frame to detect and to correct errors by CRC and FEC. Once the frame's preamble is detected, the received timestamp is adjusted such that it coincides with the next frame's preamble. Finally, the CogWave software puts some text, audio or video to the display or speaker output sinks.

Figure 4 shows the features' GUI of the two host PC-USRP exchanging data. The two features displayed are the spectrum plot and the constellation plot. The spectrum plot shows the spectrum power (dB) vs frequency bin for the whole bandwidth. The number of frequency bins corresponds to the the number of sub-carriers. The constellation plot shows the IQ samples of the received data for all sub-carriers after time recovery, carrier frequency recovery, carrier phase recovery and amplitude gain control. The number of sub-carriers is set to 512 and the cyclic prefix size is set to 128 samples. The reception bandwidth is set to 2MHz. Due to the Nyquist filter roll-off implemented in the FPGA and the carrier DC offset (peak at the center frequency) that might appear when the transmit frequency is not tuned with a local oscillator offset, the sub-carriers in the middle and at the edges are not used for transmission. There are 96 over 512 sub-carriers that are not used in total, 32 sub-carriers in the middle, 32 sub- carriers at the left edge and 32 sub-carriers at the right edge. The spectrum plot shows an OFDM transmission in the fourth sub-channel and a jammer that is present in the first and second sub-channels. The constellation plot shows a 4-QAM constellation used over all sub-carriers of the fourth sub-channel. The other constellations implemented in the cognitive blind OFDM waveform are BPSK, 16-QAM, 64-QAM and 256-QAM. A small text "hello there", "hi there" is exchanged between the two nodes on this fourth sub-channel as well as video transmission as shown on 3 in the presence of a jammer.

Figure 5 shows the spectrogram of the cognitive blind OFDM in demonstration. The jammer in red sweeps the whole bandwidth and the cognitive blind OFDM waveform in yellow automatically adapts its sub-channel whenever the jammer perturbs the transmission.

IV. CONCLUSION

This paper has presented the cognitive blind OFDM waveform implemented in the CogWave software. The cognitive blind OFDM waveform is an OFDM-based waveform divided into multiple sub-channels with a spectrum sensing algorithm to estimate the power spectral density and to determine the best sub-channel for transmission. A complete OFDM blind receiver which does not require the use of pilot symbols is used for OFDM signal detection, time recovery, carrier frequency recovery, carrier phase recovery and amplitude gain control. The cognitive blind OFDM waveform adjusts dynamically the sub-channel used for transmission to mitigate interference by sensing its operational electromagnetic environment. A demonstration setup is described for the exchange of data between two computers using the CogWave software and running the cognitive blind OFDM waveform in the presence of a jammer sweeping the bandwidth used for transmission. It is observed that whenever the jammer perturbs the transmission, the cognitive blind OFDM waveform is able to jump to another sub-channel while maintaining communication without a dedicated control channel. Future work will focus on the extension of the CogWave software to other cognitive waveforms.

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