Software Defined Radio Implementation of SMSE based Overlay Cognitive Radio in High Mobility Environment

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Abstract—A spectrally modulated spectrally encoded (SMSE) based overlay cognitive radio has been implemented and demonstrated in [1] via GNU software define radio (SDR). However, like most of the current cognitive radio implementations and demonstrations, this work does not consider the mobility between cognitive radio nodes. In a high mobility environment, the frequency offset introduced by Doppler shift leads to loss of the orthogonality among subcarriers. As a direct result, severe inter-carrier interference (ICI) and performance degradation is observed. In our previous work, we have proposed a new ICI cancellation method (namely Total ICI Cancellation) for OFDM [2] and MC-CDMA [3] mobile communication systems, which eliminates the ICI without lowering the transmission rate nor reducing the bandwidth efficiency. In this paper, we apply the total ICI cancellation algorithm onto the SMSE base overlay cognitive radio to demonstrate a high performance cognitive radio in high mobility environment. Specifically, we demonstrate an SMSE based overlay cognitive radio that is capable of detecting primary users in real time and adaptively adjusting its transmission parameters to avoid interference to (and from) primary users. When the primary user transmission changes, the cognitive radio dynamically adjusts its transmission accordingly. Additionally, this cognitive radio maintains seamless real time video transmission between the cognitive radio pair even when large frequency offset is introduced by mobility between CR transmitter and receiver.

I. INTRODUCTION

Cognitive radio (CR) [4] has been considered a strong candidate to solve the spectrum congestion problem [5]. In our previous work, we have proposed and demonstrated a cognitive centric overlay/underlay waveform design through a spectrally modulated spectrally encoded (SMSE) framework to improve the bit error rate (BER) performance and network throughput of a cognitive radio [6][7][8]. In [1], we have implemented a software defined radio (SDR) based cognitive centric overlay waveform in [6][7][8] and demonstrated an adaptive interference avoidance overlay cognitive radio.

Since most of the overlay cognitive radio employs multi-carrier transmission technologies such as non-contiguous OFDM and non-contiguous MC-CDMA to transmit over multiple spectrum holes, mobility and inter-carrier interference need to be addressed. It is well known that in mobile radio channels, the orthogonality among subcarriers of multi-carrier waveform is lost due to the frequency offset caused by mobility. Thus, inter-carrier interference (ICI) is observed on each and every subcarrier, leading to significant performance degradation.

In our previous work [2][3], a new ICI cancellation method called total ICI cancellation algorithm for multi-carrier transmission has been proposed. The total ICI cancellation scheme eliminates the ICI without lowering the transmission rate nor reducing the bandwidth efficiency by exploiting frequency offset quantization and orthogonality of the ICI matrix. As a direct result, the new scheme offers near perfect ICI cancellation and significant BER improvement at linearly growing complexity.

In this paper, we apply the total ICI cancellation scheme [2][3] onto SMSE base overlay cognitive radio [1] to demonstrate a high performance cognitive radio in high mobility environment. Using GNU SDR platform and universal software radio peripheral (USRP), we employ the SMSE framework to generate multi-carrier transmission waveforms over non-contiguous frequency bands. Combined with a spectrum sensing engine, the cognitive radio is capable of detecting the availability of each and every subcarrier in the operational bandwidth. By turning off those subcarriers occupied by the primary users and stitching all the available spectrum holes, the cognitive radio generates a non-contiguous SMSE transmission to avoid interference to (and from) the primary users. Integrated with total ICI cancellation algorithm, the overlay cognitive radio has the ability to eliminate the ICI due to the frequency offsets caused by mobility. In addition to the unique features of our cognitive radio implementation in [1], the cognitive radio node has the ability to dynamically adjust the parameters to maintain the real-time video transmission without interference to primary users, without interference from primary users, and without ICI through total ICI cancellation algorithm on every subcarrier in mobile environment. A flexible, agile, and robust cognitive radio node has been designed and implemented in the static as well as the mobile environment.

The rest of the paper is organized as following: part II describes the system setup, part III briefly explains the total ICI cancellation scheme, part IV implements and demonstrates the SMSE based overlay cognitive radio in mobile environment, and conclusion follows.

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II. SYSTEM SETUP

The innovation which makes engineers see cognitive radio (CR) a possible technology is the SDR where “the software meets the antenna”. We have chosen GNU SDR [9] as the platform for our overlay CR implementation since GNU radio is an open source architecture for building SDR projects and it has become very popular in recent years in both academia and commercial world. The universal software radio peripheral (USRP) [10] is the hardware solution for GNU Radio. USRP connects the computer and the real Radio Frequency (RF) world perfectly via flexible USB2.0 interface. The typical TX/RX path for GNU SDR is shown in Fig. 1. In the transmission path, waveforms are generated as sampled digital signals, converted from digital to analog via a digital-to-analog converter (DAC), and then upconverted from intermediate frequency (IF) to RF. Similarly, in the reception path, an analog-to-digital converter (ADC) is employed to capture all of the channels of the software radio node. The receiver then extracts, downconverts and demodulates the waveform using software on a general purpose processor [4].

In this implementation and demonstration, we use Ubuntu 10.04 operating system and gnuradio-3.3.0 as the platform. USRP motherboard, WBX and RFX2400 daughterboards are employed. Fig. 2 illustrates the system setup. Each USRP board is connected with a laptop via USB2.0 interface. We use two sets to mimic primary users, and two sets as the secondary based CR transmitter and receiver, respectively. An Agilent spectrum analyzer is employed to validate our demonstration.

A. Primary User

As shown in Fig. 2, we mimic a pair of primary users. PU_TX transmits an FM signal with bandwidth around 0.3 MHz. PU_RX receives what PU_TX transmits.

B. Secondary User

In Fig. 2, SU_TX and SU_RX are the secondary user’s transmitter and receiver, respectively. The SU CR employs the SMSE framework to generate multi-carrier transmission waveforms with 2 MHz bandwidth. SU_TX and SU_RX have the ability to communicate over contiguous and non-contiguous spectrum bands, resist the frequency offset, and transmit real-time seamless video.

III. TOTAL ICI CANCELLATION SCHEME

Multi-carrier transmission such as OFDM has been considered a strong candidate for next generation high-data-rate wireless communication systems [11]. However, multi-carrier transmission suffers from frequency offset introduced by Doppler shift in high mobility environment, so does the SMSE based waveform. With this frequency offset, the orthogonality among all the subcarriers is lost and inter-carrier interference (ICI) is observed.

Our previous work [2][3] has proposed a new approach, namely total ICI cancellation, to solve the ICI problem in mobile environment without estimating frequency offset through training symbols. Hence, the transmission rate and bandwidth efficiency are not reduced.

The ICI coefficient between $l^{th}$ subcarrier and $k^{th}$ subcarrier $S(l-k)$ is expressed as [2][3]:

$$S(l-k) = \frac{\sin(\pi(\varepsilon + l - k))}{N \sin(\frac{\pi}{N}(\varepsilon + l - k))} \cdot \exp\left(\frac{j \pi}{N}(1 - \frac{1}{N}) (\varepsilon + l - k)\right)$$

where $\varepsilon$ is the normalized frequency offset given by $\varepsilon = \frac{f_0}{\Delta f}$. $f_0$ is the frequency offset, $\Delta f$ is the subcarrier bandwidth of the OFDM system. It is reasonable to assume that $0 \leq \varepsilon < 1$. Hence, ICI coefficient $S(l-k)$ is simply the $l^{th}$ row and $k^{th}$ column of matrix $S$.

Obviously, the received signal $Y = X S + n$ can be viewed as a multi-carrier code division multiple access (MC-CDMA) signal with $N$ users and spreading code matrix $S$. It can be easily proven that $S$ is an orthogonal matrix. Therefore, the OFDM signal with ICI can be considered as an orthogonal MC-CDMA system with spreading code matrix $S$.

At the receiver side, normalized frequency offset $\varepsilon$ is unknown. By quantizing $\varepsilon$ into $M$ equally spaced values, one of $M$ quantized $\varepsilon_m = m \cdot \Delta \varepsilon, m = 0, 1, \ldots, M - 1$ is the closest to the true $\varepsilon$. The branch whose $\varepsilon_m$ is the closest to the true value of $\varepsilon$ should reproduce the received signal $Y_m = X_m S_m$ which is also the closest to the received signal.
vector $\vec{Y}$. Hence, we only need to calculate and compare the Euclidean distances between the $M$ reproduced received signal vectors $\hat{\vec{Y}}_m$ and the truly received signal vector $\vec{Y}$ and pick the one with the minimum distance to be the best branch and use that branch’s estimated data vector as the final decision. [2] states that $M = 8$ is good enough to provide near perfect ICI cancellation. In the following part, we integrate this total ICI cancellation scheme onto the SMSE based overlay cognitive radio, implement it via SDR, and demonstrate the SMSE based overlay CR in mobile environment.

IV. SMSE BASED OVERLAY COGNITIVE RADIO IMPLEMENTATION IN MOBILE ENVIRONMENT

A. Spectrum Sensing and Adaptation

By employing WBX USRP daughterboard, the designed CR is able to observe the band from 470 MHz to 806 MHz, which is UHF TV band. Because this CR applies the “Listen-before-talk” (LBT) concept, estimation of the power spectral density and some TV signal characteristics are useful for power/energy based spectrum sensing due to the low computation and implementation complexities [12][13]. We first sample the received signal, convert the samples to frequency domain by FFT, square the coefficients, and take the average to get the normalized value. The decision is made through comparing the received signal energy with the threshold.

The sensing engine with power/energy based algorithm first determines which TV channels are occupied, which are unoccupied, and what other transmissions are active, such as wireless microphones. Meanwhile, it decides a vacant band with at least 2 MHz bandwidth. We will perform our designed CR within this band. To employ energy based spectrum sensing algorithm sensing the ‘white space’, which is the term used by the FCC for unused TV spectrum, over ultra-high frequency (UHF) TV band, it is necessary to learn ATSC standard digital TV signal characteristics. In United States, 8-level vestigial sideband modulation scheme is applied in ATSC standard, and the modulated signal uniformly occupies almost the entire 6 MHz TV channel. A pilot tone is located at around 310 kHz above the lower edge of the channel.

After determining possible primary users by energy based fast spectrum sensing algorithm, a fine-tuned waveform based spectrum sensing is employed to find spectrum holes more accurately. A spectrum sensing result of the spectrum band from 470 MHz to 806 MHz is shown in Fig. 3 at a given time. TV Channel 26, 30, 41, 50, and 51 are active. There are other transmissions detected at 519.3 MHz, 576.0 MHz, 627.3 MHz, 640.1 MHz, 704.1 MHz, 716.6 MHz, and 768.3 MHz. Meanwhile, according to FCC’s Second R&O for White Spaces Order, all the ‘white spaces’ are determined, 512 MHz to 518 MHz, 524 MHz to 542 MHz, 548 MHz to 566 MHz, 584 MHz to 626 MHz, and 644 MHz to 686 MHz. Then, our cognitive radio adapts itself to the environment using unoccupied bands to communicate without any interference with the current users within the band.

B. SMSE Based Adaptive Transmission

To demonstrate an adaptive interference avoidance cognitive radio in mobile environment, we integrate total ICI cancellation scheme onto non-contiguous SMSE waveform, and implement an SMSE based overlay CR in mobile environment. Specifically, the spectrum sensing engine detects which subcarriers are occupied by the primary users. Next, by switching off those subcarriers and applying total ICI cancellation algorithm, we implement a non-contiguous SMSE waveform which only transmits over spectrum holes (or white space) in mobile environment.

The system block diagram of the adaptive interference avoidance CR is depicted in Fig. 4.

Fig. 4. Spectrum Sensing on UHF TV Band in US

Fig. 3. Spectrum Sensing on UHF TV Band in US

Fig. 4. SMSE Based Overlay CR Block Diagram

The webcam with a microphone captures the real-time video and audio signals. VLC is employed for data streaming. The spectrum sensing engine on SU_TX senses the spectrum, finds an unoccupied band, and adapts itself into the environment. Next, we employ a control channel to inform the receiver important parameters necessary to decode the data. Such parameters include center frequency, total number of subcarriers, subcarriers to be tuned off, etc. Last, we employ a SMSE waveform generator to generate contiguous multi-carrier waveform, as well as the non-contiguous multi-carrier waveform to carry the real-time seamless video data. It is reasonable to use package based sensing algorithm. SU_TX senses the spectrum when every 100 packages are transmitted. If any primary user (narrowband transmission or TV signal) becomes active in the band, SU_TX will adapt to the environment quickly, and turn
off the subcarrier that are occupied by narrowband emission, or switch to the next available white space.

Because this SMSE based overlay CR is in a mobile environment, we employ the total ICI cancellation scheme at the demodulation side. By calculating and comparing the Euclidean distances between the $M$ reproduced received signal vectors and the truly received signal vector, the minimum distance to be the best branch is chosen. Meanwhile, that branch’s estimated data vector is utilized as the final decision. Then, the demodulated data are fed into the VLC video decoder and play in real-time.

For this demonstration, the total transmission bandwidth is 2 MHz. The total number of subcarriers is 64. Hence, the frequency separation between adjacent subcarriers is $\Delta f = \frac{2M}{64} = 31.25KHz$. Fig. 5 is the spectrum captured by USRP, centered at 515MHz with 2MHz bandwidth. The spectrum in red is the one without frequency offset. The spectrum in blue is the one with normalized frequency offset $\epsilon$ at 0.3. Fig. 6 and Fig. 7 are spectrum captured by USRP, which demonstrate that PU and SU coexist without and with frequency offset, respectively. Obviously, the receiver needs to eliminate this frequency offset to perfectly demodulate the data.

We have conducted thorough test and experiments on the performance of our demonstration for both static and mobile environments. In static environment where no mobility and no ICI is involved, 98.13% of the transmitted packets are successfully received and 99.4% of the received packets are errorless. When mobility and ICI are introduced, no package can be received. After total ICI cancellation scheme is applied, 98.1% of the transmitted packets are received and 99.26% of the received packets are errorless. This vividly proves the effectiveness of the total ICI cancellation scheme.

Fig. 8 shows the setup of this SMSE based overlay CR. As can be seen on the two laptop screens, real-time video and audio transmission over the cognitive link is supported seamlessly.

The beauty of employing GNU radio and USRP as the software platform and hardware solution is making a very flexible, agile, and robust cognitive radio node. We also employ RFX2400 and Agilent Spectrum Analyzer to validate the transmission. Fig. 9, captured by Agilent spectrum analyzer, shows the result that SU, centered at 2.411 GHz, is occupying the entire 2 MHz band in mobility environment with normalized frequency offset at $\epsilon = 0.3$ when no PU is active. Fig. 10 and Fig. 11 show the results that PUs are avoided in mobility environment with normalized frequency offset at $\epsilon = 0.3$. The Agilent Spectrum Analyzer screen shows a 2
MHz span. SU employs SMSE framework to generate multi-carrier transmission waveforms. The subcarriers, which are occupied by PU_NB, are turned off. Hence, SU transmits over non-contiguous spectrum holes with lower power. No interference is caused from and to PU. Meanwhile, the interference caused by frequency offset is also eliminated at the receiver side, and the real-time video transmission is maintained.

V. CONCLUSION

In this paper, we extend our previous work to implement and demonstrate an SMSE based overlay CR in mobile environment via software defined radio. We employ the SMSE framework to generate multi-carrier transmission waveforms over non-contiguous frequency bands. Combined with a spectrum sensing engine, the cognitive radio can detect the availability of each and every subcarrier. The cognitive radio implements a non-contiguous SMSE transmission through turning off subcarriers occupied by the primary users. By integrating total ICI cancellation algorithm with the demodulator, the overlay cognitive radio is able of eliminating the ICI caused by mobility. The unique features of SMSE based overlay CR are maintained.

REFERENCES