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Reconfigurable Filter Bank Multicarrier Modulation for Cognitive Radio Spectrum Sharing - A SDR Implementation

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Abstract

Background/Objectives: Cognitive radio is used as promising technologies for dynamic spectrum access and optimization of wireless resources. Under dynamic spectrum access to provide the ability of working any band of frequency based on need, the reconfigurable cognitive radio is designed. **Methods/Statistical Analysis:** Multicarrier modulation is the feasible method to share the spectrum without interference. OFDM is one of the efficient multicarrier techniques available for the system design. One of the problems in OFDM for spectral sharing is the side band leakage that will inject interference from secondary radio sub carrier to primary radio sub carrier. To avoid this, in this work a Filter Bank based Multi Carrier (FBMC) modulation is used. **Findings:** Few simulation works are reported for the interference free spectrum sharing by using FBMC. But this work analyzes the real time practical implementation of the interference free dynamic spectrum sharing. Reconfigurable is another important aspect of the implementation which is provided by the Kintex 7 FPGA implementation of the reconfigurable filter bank multicarrier modulation using NI USRP 2943R SDR platform. This FBMC based Transceiver is implemented by using fast Xilink IP cores of FFT and systolic array based FIR filter IP core. The transceiver is realized to produce output for every clock after a fixed latency 240 clocks or 6 microsecond for 40Mz clock rate. This performance is achieved using single clock loop architecture of LABVIEW FPGA tool and the parallel, pipelined architecture realization of IP cores and other building blocks. **Applications/Improvements:** Experimental study shows that the BER of primary user for the implemented system is better than the OFDM system by the factor of 10^{-1}.

Keywords: Cognitive Radio, Dynamic Spectrum Sharing, Multi Carrier Modulation, OFDM Reconfigurable, SDR

1. Introduction

Reconfigurable communication system is required for the next generation of wireless system to support wide variety of waveforms on demand. Reconfigurability can be easily realizable in function level by using intelligent radio system of cognitive radio. Cognitive radio is intelligent radio that will sense the electromagnetic environment and select and set the radio parameter based on current environment condition for the target performance or spectrum sharing objective[1,2]. Since the spectrum is a fixed resource which can't be able to meet for the ever increasing wireless network and its subscriber. So spectrum sharing is the main research issue for the cognitive radio. Interference free spectrum sharing is challenging one and always there is gap between simulation and practical results. Under spectrum sharing application of cognitive radio another important need of the radio is it must switch multiple frequency band on the fly to utilize the vacant spectrum, practical implementation of such a system is challenging one. So this work present a multiband reconfigurable interference free spectrum sharing by using filter bank based implementation on Universal Software Radio Peripheral Reconfigurable Input and Output (USRP-RIO) Software Defined Radio (SDR) platform and practical analysis of it. Multicarrier modulation like OFDM will be the efficient choice for the dynamic spectrum sharing because spectrum can be allocated and shared by subcarrier level systematically by using the underlying FFT technique. But spectrum leakage is one of the main

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issues in OFDM based spectrum sharing especially at high data rate. This spectrum leakage injects interference to nearby channel of primary user and effects the performance of it. Handling this kind of interference is challenging one under dynamic spectrum sharing. There are few simulation works of filter bank modulation in literature but practical real time implementation of filter bank modulation technique for cognitive radio spectrum sharing is not addressed much in literature. An efficient on-the-fly reconfigurations implementation and analysis of a cognitive transceiver for opportunistic network by using Orthogonal Frequency Division Multiplexing (OFDM) with Interference Alignment (CIA) is proposed[3] as a practical implementation based on the Universal Software Radio Peripheral (USRP) Software-Defined Radio (SDR) and GNU Radio. The spectral leakage problem of OFDM is handled by interference alignment by the work. But interference alignment requires the channel state of the primary radio to be available at secondary radio which is practically not feasible. OFDM is require guard interval and cyclic prefix that reduces the spectral efficiency of the system which are avoided in the filter bank based proposed system.

Filter bank based multicarrier modulation is proposed as another candidate solution for implementation of dynamic spectral access with less interference between primary and secondary user. Maliatsos et al.[4] proposed a simulation work of filter-bank-based spectrum sensing with optimum detectors based on the Neyman-Pearson theorem by using Discrete Fourier Transform (DFT). This work focuses on accurate spectrum detection but not addressing interference free sharing of the detected free spectrum. In order to reduce interference and to make more confined subcarrier without leakage an overlapped discrete multitone or Discrete Wavelet Multitone (DWMT) transmission scheme is proposed[5]. A DWMT system uses efficient pulse design to achieve a high level of sub channel spectral containment and more accurate than DFT based system. The DWMT system is not suitable for the practical system implementation because of the computational complexity.

An efficient multicarrier technique than that of DWMT system is proposed by Cherubini[6] called Filtered Multitone (FMT) for very high-speed digital subscriber line. A DWMT structure based Cosine-Modulated Filter Banks (CMFBs) is presented[7] with reduced computational complexity which enable practical implementation of the multicarrier system. Since the prototype filter design is important one for realize filter bank based multicarrier system a prototype filter with excellent frequency selectivity and fast side lobe fall-off rate is presented by Mirabbasi et al.[8] which can be used any filter bank multicarrier system. For efficient implementation of filter bank based multicarrier modulation Offset Quadrature Amplitude Modulation (OQAM) scheme is proposed as right candidate[9].

In this paper a reconfigurable implementation of filter bank based multi carrier modulation technique is implemented for dynamic spectrum sharing and the performance is analyzed practically in real time wireless channel. The main reconfigurable parameter under this implementation are: the no. of subcarrier N from 64 to 1024, frequency bands and dynamic allocation of subcarriers between primary and secondary user.

2. System Model

The proposed work used three USRP-RIO 2943R to implement the transmitter and receiver of cognitive radio. USRP RIO 2943 has 2x2 MIMO RF transceivers with independently tunable options from 50 MHz to 6 GHz and has configurable DSP-oriented Xilinx Kintex-7 (410T) FPGA[10–11]. USRP RIO-1 is configured as cognitive transmitter with two channels and uses some of the subcarrier for its transmission and leaving subcarrier that are used by the primary transmitter. USRP RIO-2 is configured as primary transmitter with FBMC modulation. Both the primary and secondary transmitter uses same transmission signal processing that is given in Figure 1.

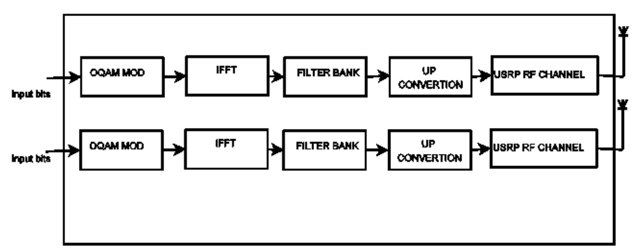

Figure 1. Transmitter signal processing block diagram.

The base band information bits are modulated by using OQAM modulation. OQAM gives efficient pulse shaping, which solve the frequency offset problem and spectral leakage problem in some extend. The OQAM modulated symbols are given to IFFT block to generate multicarrier modulation signal. This IFFT block is made to work as reconfigurable one to accommodate any number of subcarrier on the fly based on the user demand. The LABVIEW FPGA tool pipelined FFT block function is used to generate multicarrier modulation. The 1024 stage of pipe line is introduced to compute the 1024 point IFFT operation in one cycle clock. This fast computation is must for the cognitive radio in order to switch to empty subcarrier very quickly. The IFFT output data is feed to the filter bank block in order to reshape the base band signal to avoid spectrum leakage and interference to the primary user. The combined filter banks with OQAM modulation allows the maximum bit rate, without a guard time or cyclic prefix as in OFDM.

For the filter bank design, the impulse response of the prototype filter is given as below:

$$h(n) = 1 - 2*H_1*\cos[(+2*H_2])*\cos(-2*H_3)*\cos\left(\pi*n*\frac{3}{2*N}\right) \tag{1}$$

Where $H_1 = 0.971960$; $H_2 = \frac{\sqrt{2}}{2}$ $H_2 = 0.235147$ are the filter coefficient of the prototype filter. This prototype filter is implemented by using Xilink IP (Intellectual Property) core which enable to realize the filter by means of systematic pipeline architecture of Systolic array of multiply accumulate units to increase the computation throughput without increasing memory bandwidth. The four order prototype filter systolic array filter architecture is presented in the Figure 2.

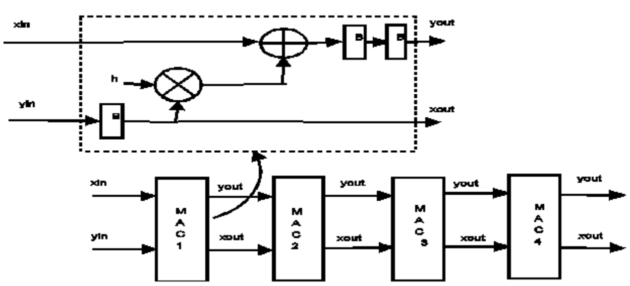

Figure 2. Systolic array based four tap filter.

Here, Offset Qadrature Modulation (OQAM) technique is used for modulating the information bits[8] under OQAM the symbol rate are made double and for each subchannel real and imaginary part of the IFFT is used alternatively. In effect the imaginary part of IFFT is delayed half the symbol duration.

The base band symbol output of filter bank is:

$$T_{tx} = S_{OQ} * F^{-1} * H_{FB} \tag{2}$$

Where S_{OQ} is the OQAM modulated symbol; F^{-1} is the inverse DFT matrix; H_{FB} is the filter bank impulse response matrix. The Xilink FFT IP core v9 complier is used to implement the IFFT and FFT operation in the transceiver. This base band signal is digitally up converted by LABVIEW FPGA tool function, converted to analog and fed to the RF hardware channel for the transmission in radio channel. Digital up conversion is another unique thing done on this work which will allow to reconfigure the RF channel on the fly.

USRP-RIO-3 is used as cognitive receiver and primary receiver. Since USRP-RIO-2943 has two channels, one of the channel is configured as primary receiver and another one is configured as cognitive receiver. In order to calculate the worst case interference reception by primary receiver due to secondary transmitter both the primary and secondary receiver is implemented in the same USRP–RIO on different RF channel. The signal processing of both the primary and cognitive receiver is given in Figure 3. The design parameters used at the transmitter and receivers of both the primary and secondary user is given in Table 1.

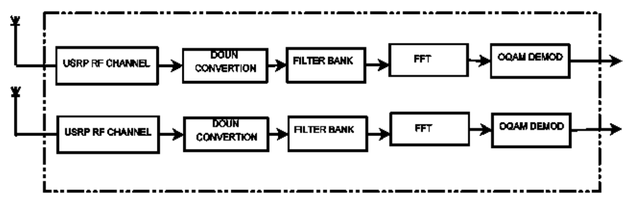

Figure 3. Receiver signal processing block diagram.

Table 1. Transmitter and receiver design parameters

Parameter	Transmitter value	Receiver value
Modulation	OQAM-4	OQAM-4
Carrier Frequency	1Ghz-6Ghz	1Ghz-6Ghz
Tx power	-20 to 0dBm	----------
FFT size N	64 to 1024	64 to 1024

On the receiver side, after getting the data from RF channel, the signal is converted into digital by the analog to digital converter present in the down converter. The down conversion is performed in digital domain in FPGA to enable the reconfigure feature in the signal reception.

The down conversion unit also correct the impairment and do the offset correction before to further process the base band data by means of lab view code. The base band signal after this correction is given to the base band signal processing block of the filter bank. The complex conjugate of the transmitter side impulse response is used on the receiver side filter bank in order to recover the original symbols. The filter bank produce the overlap less symbol to avoid interference which is fed to the FFT block and OQAM demodulator to recover the binary data. The demodulated bits are used to analyze the performance of the system.

The received base band signal is given below:

$$R_{Tx} = Y * H_{FB}^{*} * F \quad (3)$$

Where the Y is the received signal after down conversion; H_{FR}^{*} is the receiver side filter bank co efficient matrix (conjugate of the transmitter side filter); F is the DFT forward transform matrix.

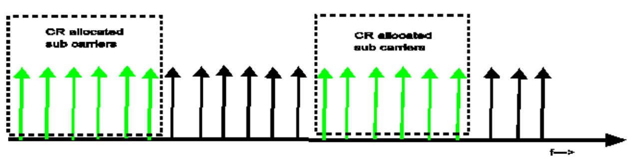

Figure 4. Sub carrier sharing between primary and cognitive user.

Subcarrier allocation between the primary user and secondary user will determine the performance of the primary and secondary system. Figure 4 illustrate a simple subcarrier allocation between the primary and secondary user to share the available subcarrier. Where ever the primary subcarrier is free it can be allocated to the secondary user. Since our intention is to show the efficient way of the spectrum sharing without leakage, under our system it is assumed that already spectrum sensing in done and free available subcarrier of the primary is known .The unused primary subcarrier is designed such that it will be interleaved between the used subcarrier in order to study how well the system share the spectrum without leakage to neighbor primary user. This implementation used 60% of subcarrier for the primary user and 40% of remaining interleaved subcarriers are used by secondary user for the testing and measurement purpose.

3. Result and Discussion

The entire transmitter and receiver for the primary user and the secondary user is implemented by using LABVIEW 2014 version and the bit files are generated for the Kintex-7 FPGA in the USRP RIO by using Xilinx complier tool 14.7. The filter bank for given number of subcarrier N is designed from the fourth order prototype filter. The designed filter impulse response for N = 64 is given in Figure 5. In order to analyze the space complexity to implement the FBMC system device utilization without the core blocks of FBMC (FFT and filter bank) and with the core blocks is analyzed. Table 2 provides the FPGA device utilization before the filter bank and FFT operation and after the introducing FFT and filter bank operation in a transceiver design.

Table 2. Device utilization and energy consumption of transceiver Design on Kintex 7 FPGA

Device resource	Without FBMC blocks	With FBMC blocks	Total available
LUT's	28512	35462	254200
Registers	52788	58004	508400
Block RAM	103	302	795
DSP48s	280	302	10540
Energy consumption at 40Mhz	0.267W	0.302W	----

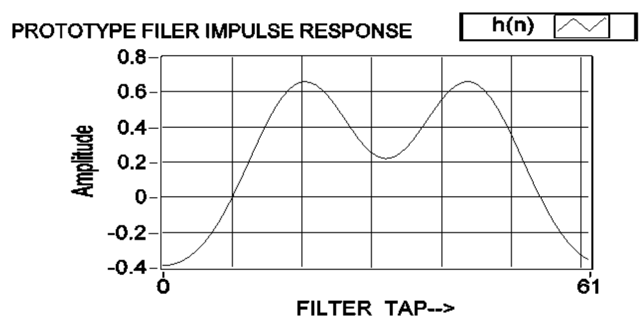

Figure 5. Impulse response of prototype filter.

From the Table 2 , it is observed that the added FBMC block increases LUT by the amount 6950 numbers i.e. 24% more required, similarly it requires 10% more registers, 7.8% more block RAMs, 7.8% more DSP48s. Total resource utilization wise on the device, normal receiver occupies 11% of LUT's but FBMC requires around 14%, register requirement increased from 10% to 11%, Block RAM requirement increased from 13% to 38% and DSP48s requirements increased from 2.6% to 2.8%. The energy consumption of the proposed transceiver design is calculated by using Xilink power estimator 2016.1. EA1 tool and tabulated in Table 2. The FBMC blocks consume additional 13% of normal transceiver consumption of 0.267W. The timing analysis is carried out to find the response time of the system. The system provides response by taking 0.025 microsecond for the 40Mhz clock after the initial latency of 240 clocks i.e. 6 microsec.

The implementation is tested in indoor environment of research LAB at 9th floor of ECE Department, SRM University. Three USRP is connected to PXIe high speed bus (1 Gbps) by using NI PXIe chassis 1075 with embedded controller NI 8108. The embedded controller is used to control the three USRP hardware's and supplies the reconfigurable parameters on fly when the hardware's are running. The high speed PXIe bus enables to acquire the data in real time.

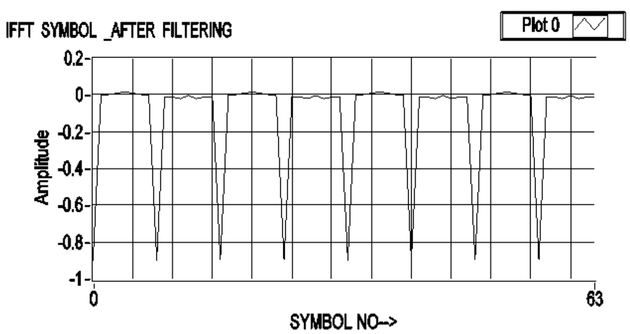

Figure 6. IFFT symbol after prototype filtering.

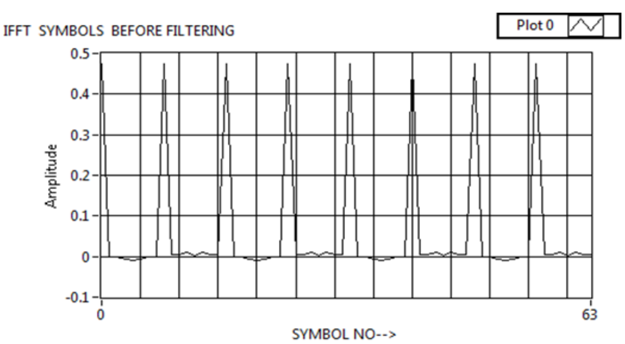

Figure 7. IFFT symbol before prototype filtering.

Figure 6 and Figure 7 shows the OFDM symbol after and before applying the filter bank filtering. From the filtered OFDM symbol it can be observed that the data rate is doubled with overlapping of symbol in order to improve spectral efficiency. The overlapping of adjacent symbol can be observed from the small up and down in the top of the filtered symbol.

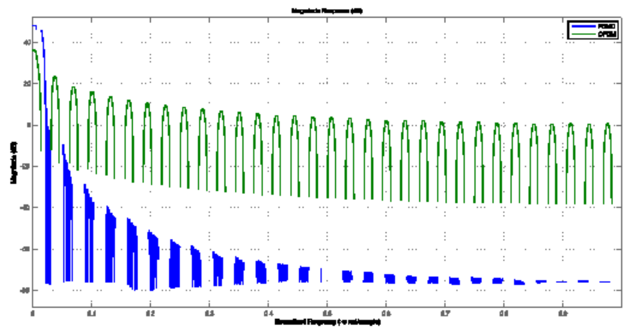

Figure 8. Spectrum of OFDM and FBMC system for N = 64.

The advantages of FBMC system can be observed by comparing its spectrum with OFDM which are given in Figure 8. From Figure 8 it is clear that FBMC side lobes attenuated very quickly but OFDM system side lobes are large in magnitude and it may spread to next symbol and introduce interference. So the FBMC system enables interference free subcarrier sharing but OFDM provide interference due to this spectral leakage.

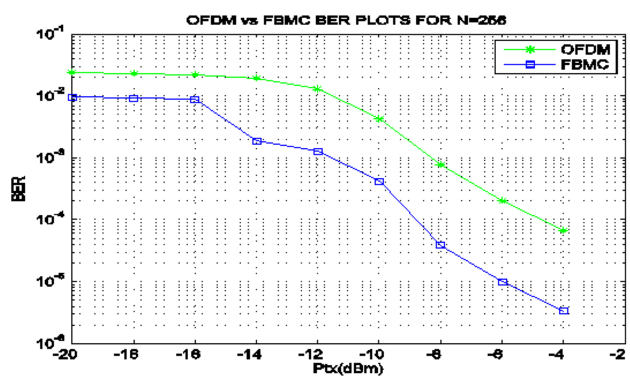

Figure 9. BER comparison between OFDM and FBMC.

The bit error rate of the primary user is computed for the conventional OFDM system and the FBMC system and plotted as shown in Figure 9. A fixed data binary streams of size 25600 are transmitted by using both the convention OFDM system and FBMC system and the computation of BER is carried out. The BER computation procedure is repeated for 10 times with various transmitter power from -20 dBm to -4 dBm and the average BER for various transmitter power is calculated and plotted in the graph. Since there is little side lobes leakage in FBMC comparing with OFDM, FBMC gives less BER comparing with the OFDM. Figure 8 provide the BER of OFDM and FBMC system for the transmit power of -20 dBm to -4 dBm. From the Figure 9 it is observed that FBMC out perform with OFDM system where the BER of primary user for the implemented system is better than the OFDM system by the factor of 10^{-1}.

4. Conclusion

Reconfigurable OQAM based filter bank multicarrier modulation system is implemented by using the National Instruments (NI) USRP RIO 2943 SDR. This LABVIEW software and USRP RIO SDR based implementation allows us to reconfigure the no. of subcarrier from 64 to 1024 and dynamic allocation of subcarriers between primary and secondary user. It is evident from the BER graph that the subcarriers are shared between primary and secondary user without much interference with each other. The results shows that the filter bank based multicarrier system outperform comparing the conventional OFDM system for the inference free spectrum sharing application. A fast efficient transceiver is realized which produces output for every clock after an initial latency of 240 clocks.

5. Acknowledgements

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