End To End Latency Analysis of FBMC using FPGA

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Abstract— **Different multi carrier communication techniques are being developing in the recent years. By assigning unlicensed users to the subcarriers that coincide with the portions of the spectrum not used by licensed users, multicarrier methods provide much flexibility to fill in the spectral holes and thus to best utilize the available resources. Orthogonal Frequency-Division Multiplexing (OFDM) is the most popular multicarrier method. In certain applications such as cognitive radios and uplink of multiuser multicarrier systems, where a subset of subcarriers is allocated to each user, OFDM may be an undesirable solution. So Filter Bank Multicarrier (FBMC) systems which use a filtering approach for transmitting signals is a more effective solution. FBMC is a multicarrier transmission method that do not use cyclic prefix and thus improves the efficiency. Combination of filter banks with Orthogonal Quadrature Amplitude Modulation (OQAM) leads to maximum data transmission speed. Latency analysis is required for the efficient implementation of FBMC on SoC for the mass production. Hence, analysis of latency of the FBMC technique is essential for communication systems.**

Keywords— *FBMC; cognitive radios; latency.*

I. INTRODUCTION

Multimedia wireless applications have been increasing tremendously in recent years and studies show that this trend will remain the same in the future. The large demand for radio spectrum makes it no room to accommodate new wireless applications. On the other hand, studies have shown that large portions of the licensed spectra are rarely used. This has initiated the idea of cognitive radio (CR) introduced by Joseph Mitola. In a cognitive radio, secondary users are allowed to transmit and receive data over portions of spectra when primary users are inactive, demanding that the secondary users be invisible to the primary users. Then the segments will be used optimally without causing harmful interference to licensed users. This technology is called spectrum pooling. In spectrum pooling, multicarrier transmission techniques can be used as the baseband transmission schemes. Actually, the cognition is achieved by nullifying the subcarriers which cause interference to licensed users. The remaining frequency segments are used optimally by Cognitive Radio.

Multicarrier modulation technique is an efficient transmission scheme, where the available channel bandwidth is divided into several parallel sub channels, each with its own associated carrier. A transmitter efficiently combines several low rate input signals into a single high rate signal, which is then transmitted over a communication channel, and the receiver should be able to reconstruct at least good approximations of the low rate input signals. Multicarrier methods are identified as important candidates for the physical layer of cognitive radio systems. These methods provide much flexibility to fill in the spectrum holes by allotting secondary users to the subcarriers that coincide with the portions of the spectrum not used by the primary users and thus help to make use of the available resources in the best way.

In the spectrum sensing perspective, multicarrier modulation technique has many advantages. It allows flexible multiplexing of silent sensing windows within the data symbols in secondary transmission for spectrum monitoring purposes. It also allows flexible means for constructing decision statistics from basic observations within the sensing window. It provides high spectral resolution and commonality of sensing and communication functions.

II. RELATED WORK

There are different multicarrier communication methods [1] for the physical layer of cognitive radio systems. Fast Fourier Transform (FFT) as part of the OFDM modulator can be used for channel sensing. Filter banks can be used for multicarrier communication and spectral analysis in a Cognitive Radio setting. A review of the classical works on FBMC communication systems [2] shows that some of the more recent developments are, actually reinventions of multicarrier techniques that have been developed prior of the era of OFDM.

A scheme called FFT FBMC [3] transforms the FBMC system into an equivalent system formulated as OFDM regardless of some residual interference. Thus, any OFDM transmission technique can be performed straightforwardly to the proposed FBMC scheme with a corresponding complexity growth compared to the classical FBMC. The Universal Software Radio Peripheral (USRP), which is a Software Defined Radio (SDR) platform, can be used for the implementation of a Filter Bank Multicarrier (FBMC) prototype transmission link [4]. The proposed system consists of a conventional FBMC transmitter and receiver using time stamped synchronization and shared system clock.

A packet format can be used for the implementation of multicarrier systems that operate based on filter banks [5]. An improved partial transmit sequence (PTS) scheme called as MBJO-PTS scheme [6] is implemented by employing multi-block joint optimization (MBJO) for the PAPR reduction of FBMC-OQAM signals,. In PTS scheme, one data block is divided into several sub blocks and each sub block is multiplied by a phase rotation factor for the sub block. For FBMC/OQAM, the IFFT outputs present properties that can be exploited by a pruned IFFT implementation [7]. In some cases, a reduction of the computational complexity can be operated at the filtering stage.

III. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation scheme with densely spaced sub carriers. OFDM technique uses Frequency Division Multiplexing (FDM) of orthogonal sub-carriers, each modulating a low bit rate digital stream. In other multichannel methods using FDM, the total bandwidth available is divided into a number of non-overlapping frequency sub-channels. Each sub-channel is modulated using a separate symbol stream and then all the sub-channels are frequency multiplexed. This leads to an inefficient use of the spectrum although the prevention of spectral overlapping of the subcarriers reduces or even eliminates inter channel interference. Actually, the guard bands on either side of each sub-channel are a waste of precious bandwidth. In order to overcome the problem of this bandwidth wastage, a number of overlapping and orthogonal subcarriers can be used, each carrying a baud rate of 1/T and spaced 1/T apart. The sub carriers are all mathematically orthogonal to each other because of the frequency spacing selected. This allows the proper appropriate demodulation of the symbol streams without the usage of non-overlapping spectra. Each sub-carrier should have exactly integer number of cycles in the interval at T. This is another condition for sub-carrier orthogonality. Inverse Fourier Transform can be used to represent the modulation of the orthogonal subcarriers. The DFT operation followed by low pass filtering can be used to generate the OFDM signal. OFDM can be used either as a modulation or a multiplexing technique.

Fig. 1 illustrates the basic block diagram of an OFDM scheme. At the source encoder, the data is usually an image, wave or text which is converted into binary data bits. These binary bits are then padded with zeroes to form group of bits which is used to create the symbols based on the modulation scheme. At the decoder section, these bits are put back to get back the original source data. In mapping of symbols, the bits are grouped together based on the modulation technique opted by the user to form symbols ready for modulation. In case of multicarrier transmission signals, the bits are appended with zeroes to make it a multiple of sub-carriers. These bits can be recovered from the symbols by unpacking the symbols. The symbols are then modulated and demodulated using different modulation methods.

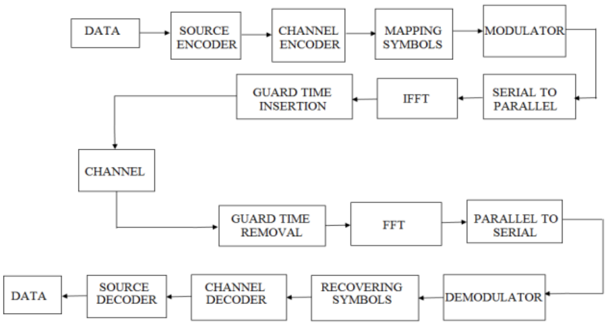

Fig. 1: OFDM Block Diagram

The subcarriers in an OFDM scheme should remain orthogonal to each other in order to perform carrier interference free demodulation; otherwise degradation of the system performance will occur. So OFDM is very sensitive to the frequency offset originating from the mismatch of the local oscillators of the transmitter and receiver sections. The time domain OFDM signal is the sum of a number of complex sinusoids. So according to central limit theorem, the amplitude distortion tends to be Gaussian, which leads to high peak-to-average-power ratio (PAPR) of the signal. So a power amplifier with a relatively large linear range is required, or else the non-linear effects will affect the system performance.

IV. FILTER BANK MULTI CARRIER SYSTEM

Inter Symbol Interference (ISI) occurs in wireless channels due to multipath fading. ISI is usually mitigated using channel equalizers. But channel equalizers are very complex to implement and difficult to adapt in practical situations when one has to deal with fast varying wireless channels. Moreover, a channel equalizer enhances the noise over the portions of the frequency band where the channel gain is small. This leads to prominent degradation. The occurrence of inter symbol interference across the data symbols is directly proportional to the delay spread of the channel and inversely proportional to the symbol period. Thus, the inter symbol interference can be decreased by increasing the symbol period which is equivalent to decreasing the data rate.

In a multicarrier communication system, a data stream is multiplexed into N parallel sub streams each having a rate N times slower. Thus, the effect of inter symbol interference is reduced proportional to N. These parallel streams are modulated at N subcarriers and added together at the transmitter. At the receiver section, the N sub-streams are separated and de-multiplexed to the original higher data rate stream. OFDM, the most popular multicarrier method is implemented over a variety of communication products. FBMC are alternative methods for OFDM systems. An OFDM system uses cyclic prefix or guard interval to reduce channel distortion while FBMC system mitigates the problem of channel distortion through filtering techniques. When proper filter design is used in FBMC, adjacent sub-carriers are only sub-carriers that overlap, and so there is almost no interference from the non adjacent sub-carriers. Thus, FBMC techniques are better suited for systems with high mobility and high Doppler Effect, since in such systems, orthogonality among sub carriers will be destroyed and the Inter Channel Interference (ICI) creates distortion. Moreover, for asynchronous multicarrier communications in cognitive radio networks and multiuser systems, big side lobes of OFDM sub- carriers result in interference and thus lead to loss of performance.

In cognitive radio scenarios, the spectral disturbance of the incumbent users should be minimized and the available spectral regions must be aggregated and used as efficiently as possible. So the property of FBMC systems to fulfill the extremely strict out-of-band radiations makes it very suitable in Cognitive Radio scenarios. A specially designed filter bank structure is used by FBMC systems. In an FBMC system, the complex modulation values are spread over different sub carriers and are then filtered by a prototype filter. Thus, a larger FFT is necessary to construct the signal to be transmitted. The spectral band efficiency will be more efficient than the OFDM signal due to the properties of the prototype filter bank. In an offset-QAM modulation, the real and the imaginary data values are offset by half symbol duration. So there will be no data rate loss. The filter banks are designed to satisfy Nyquist criterion to minimize the inter symbol interference. Because of this fact, before transmission, the symbols are overlapped in such a way that they can be separated at the receiver side. Even though the symbols duration is longer compared to the OFDM symbols and they overlap, there will be no data rate loss. FBMC systems do not use cyclic prefix to eliminate the channel induced inter symbol interference. But more complex signal processing is applied in FBMC systems and also the channel equalization in the receiver chain will be more complex than any other multicarrier techniques. This complex signal processing requirement can be reduced by using poly phase filter bank.

Thus in a FBMC system, a set of parallel data symbols are transmitted through a bank of modulated filters and the transmitted signal is synthesized. The difference between OFDM system and FBMC system is mainly in the choice of the prototype filters. OFDM uses a rectangular pulse as the prototype filter while FBMC uses a general prototype filter which is modulated on each sub carrier. The selected prototype filter must satisfy the Nyquist ISI criterion in order to demodulate the signal efficiently.

V. STAGGERED MODULATED MULTITONE

Staggered Modulated Multitone (SMT) is used to refer a FBMC system that uses OQAM modulation. OQAM, Offset Quadrature Amplitude Modulation, is a variation of Quadrature Amplitude Modulation (QAM).In SMT, a root Nyquist filter with symmetric impulse response is chosen for pulse shaping at the transmitter. The same filter is used for match filtering at the receiver section in a multichannel QAM system. OQAM multicarrier does not need any cyclic prefix samples for resolving Inter Symbol Interference and Inter Channel Interference. Thus, OQAM multicarrier is more efficient in case of bandwidth than the OFDM. This is the main advantage of OQAM multicarrier over the conventional OFDM. In Staggered Modulated Multitone (SMT) transmission, N parallel complex data signals are made to pass through N subcarrier transmission filters. Fig. 2 below presents the block diagram of a SMT transmitter. The data signals represented as $S_0(t)$ through $S_{N-1}(t)$ are continuous time signals associated with transmit symbol sequences. They are defined as:

$S_K(t)=\sum S_K[n]\ \delta(t-nT)$
(1)

where k= 0,1,2….. N-1 and $S_K[n]$ are complex-valued (either QAM or PSK) data symbols which can be represented as:

$S_K[n]= S_K^I[n]+j S_K^Q[n]$
(2)

The superscripts "I" and "Q" in (2) refer to the in-phase and quadrature components, respectively.

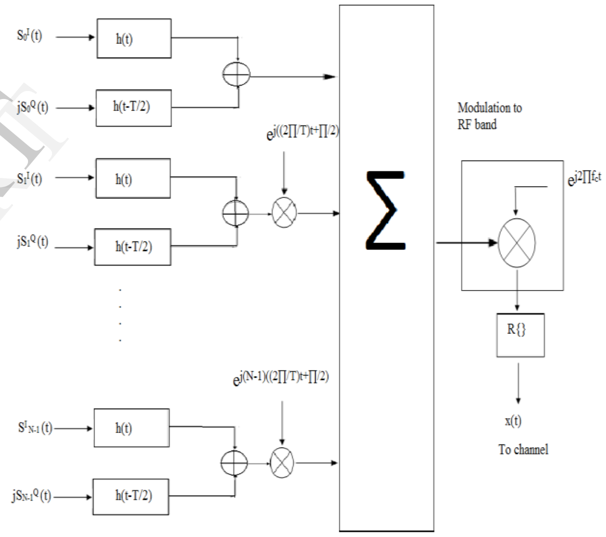

Fig. 2: Block Diagram of a continuous-time SMT Transmitter

At each subcarrier channel, the real part and the imaginary parts of $S_k[n]$ are separated and time staggered by half symbol duration, that is by T/2. This is done using pulse shaping filters h(t) which is shifted in time to the right on the quadrature branches of all the sub-carrier channels. The same pulse shaping filter is used at both the transmitter and receiver sections of a SMT system. This is done to satisfy the symmetry condition h(-t)= h(t) to assure a matched filter pair at both the transmitter and the receiver. Moreover, the multiplications by 1, $e^{j((2\pi/T)t+\pi/2)}$,…., $e^{j(N-1)((2\pi/T)t+\pi/2)}$ are effectively modulators that arrange the subcarrier channels at the center frequencies 0, 2π/T, ..., 2π(N − 1)/T. This shows that the spacing between the adjacent subcarriers is 1/T which is twice of that of the CMT.

The detected data symbols at the receiver side are denoted as $S_k[n]$. The block diagram of SMT receiver is shown in fig. 3. At the receiver side, the filter h(t) should be designed in such a way that when the channel is perfect, that is, when there is no multipath and no noise, the transmitted and the detected symbols should be the same.

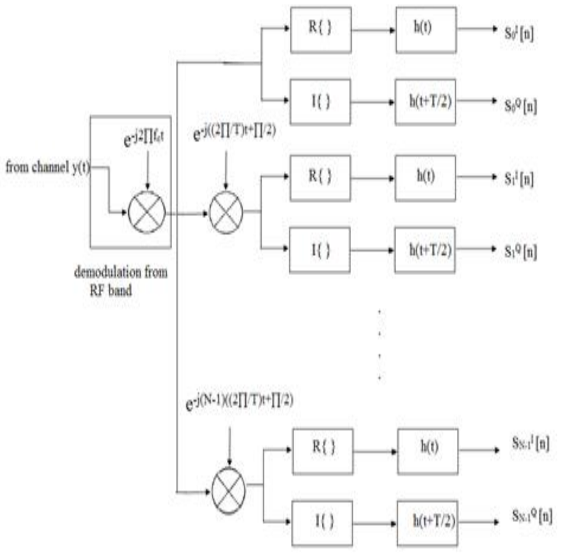

Fig. 3: Block Diagram of a continuous-time SMT Receiver

Here, only adjacent bands overlap. So the possible interference from non-adjacent bands can be ignored. Thus interference in SMT transceiver can happen only in three different ways. They are:

- Inter Symbol Interference can occur across each in-phase or quadrature part of the sub- carrier channel, that is, the successive values of $S_k^I[n]$ may interfere with one another and similarly for $S_k^Q[n]$.
- Cross interference can occur between the sequences $S_k^I[n]$ and $S_k^Q[n]$.
- Inter Channel Interference can occur between the adjacent subcarrier signals.

In order to analyze the inter symbol interference and the cross interference mentioned above, consider the specific branches from figure 2 and fig. 3 that connects $S_k^I(t)$ and $S_k^Q(t)$ to $S_k^I[n]$ and $S_k^Q[n]$. In the absence of channel, these branches can be represented as shown in fig. 4 below.

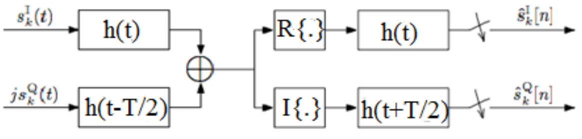

Fig. 4: The kth subcarrier channel in an SMT system

From the fig. 4, it is evident that the sub carrier modulator $e^{jk((2\pi/T)t+\pi/2)}$ and the demodulator $e^{-jk((2\pi/T)t+\pi/2)}$ and also the modulator to RF, $e^{j2\pi f_c t}$, and the demodulator from the RF, $e^{-j2\pi f_c t}$, cancel each other. The output of filter represented as h(t) on the top-left of figure 5.3 is a real function of time, and the output of filter delayed by T/2, represented as h(t−T/2) on the bottom-left of fig. 4 is an imaginary function of time. Thus the blocks in fig. 4 can be separated into two different channels as shown in fig. 5 below.

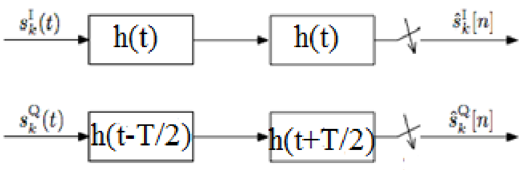

Fig. 5: The kth subcarrier in two separate channels

From fig. 5 above, it is clear that there is no cross interference between the in-phase and quadrature components of each sub-carrier channel in SMT system. The filter h(t) should be chosen in such a way that the combined response h(t)*h(t) should be a Nyquist pulse. This condition avoids the inter symbol interference in the upper branch of fig. 5. This condition also assures inter symbol interference free transmission in the lower branch of fig. 5, since h(t−T/2) * h(t+T/2) = h(t) * h(t). This shows that the lower channel also has a Nyquist response.

In SMT systems, the same prototype filter h(t) is used at both the transmitter and receiver sections. This results in inter channel interference cancellation between the adjacent sub carrier channels in both the systems. In order to satisfy the condition the combined response h(t)*h(t) be a Nyquist pulse, h(t) should be an even symmetric square root Nyquist filter. This avoids ISI. The filter h(t) should be band limited in order to reduce the inter channel interference among non-adjacent subcarrier channels. Thus, various types of interferences are reduced or eliminated.

VI. IMPLEMENTATION

The basic block diagram of Staggered Modulated Multitone (SMT) transmitter and receiver are implemented using Simulink System Generator. FBMC System divides the transmission channel associated with the bandwidth into a number of sub channels which is in contrast to OFDM, which exploits a given frequency bandwidth with a number of carriers. In FBMC, a set of parallel data symbols are transmitted through a bank of modulated filters. A 1000 KHz signal is divided into 10 signals of 100 KHz each. Thus, 10 sub carriers are used as the input. In the transmitter section, the first input signal is passed through Rectangular QAM block to modulate the signal using M-ary Quadrature Amplitude Modulation. The complex output obtained is passed through Complex to Real-Imag block which produces the real and imaginary parts of the complex signal. The real part of the signal is then passed through a Nyquist filter designed using FDATool and the imaginary part is sent through the same Nyquist filter designed, but after half the symbol duration. The fig. 6 below depicts the Simulink model for the first sub-carrier channel.

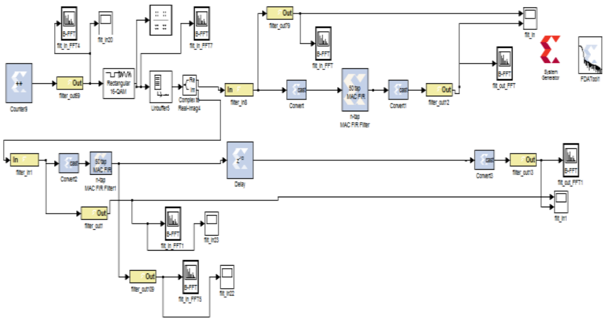

Fig. 6: Simulink Model For The First Subcarrier Channel In The Transmitter

In the second sub-carrier channel, DDS Compiler and Complex Multiplier blocks are used. The 2MHz sine wave and cosine wave generated using DDS compiler is multiplied with the in-phase and quadrature parts of the signal obtained after passing through the Nyquist filter using Complex Multiplier. Thus, the complex multiplier has two complex signals as inputs. The first signal is from in-phase and quadrature parts of the input signal and the second one is from the DDS Compiler. Cosine wave generated from the DDS Compiler is given as the real input of the second complex signal and the sine wave generated from the DDS Compiler is given as the imaginary input of the second complex signal of Complex Multiplier. The fig. 7 below illustrates the model designed for the second sub carrier.

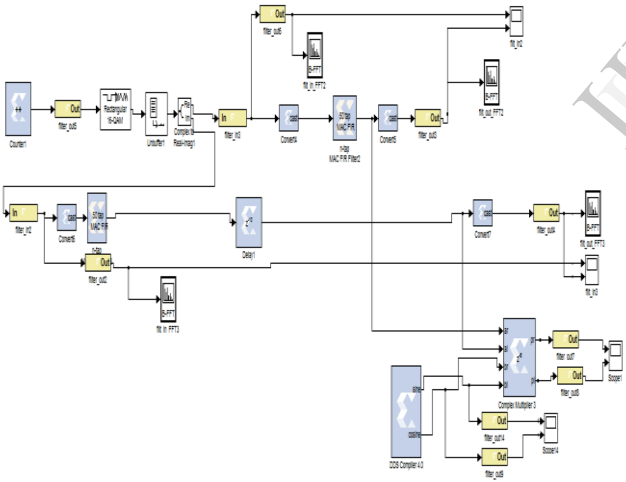

Fig. 7: Simulink model for the second subcarrier channel in the transmitter

Since ten subcarriers are considered for the design, the same design is used till the tenth subcarrier. DDS Compiler is used in all the subcarrier channels to generate sine and cosine waveforms of 2MHz, 4MHz, 6MHz and so on up to 18MHz. The real and the imaginary outputs from each subcarrier channel are added separately using AddSub block and the outputs from the AddSub blocks are taken as transmitter outputs. These signals are sent to the receiver section.

In the receiver section, the inverse of transmitter action occurs. The first channel in the receiver section is designed as the Simulink model given below in fig. 8.

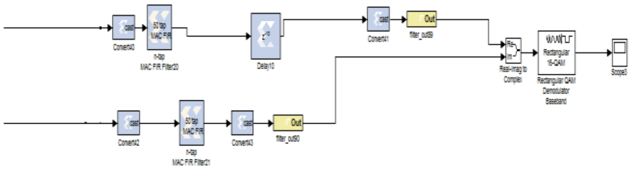

Fig. 8: Simulink model for the first subcarrier channel in the receiver

Here, the real part of the signal is delayed by half the symbol duration than the imaginary part after passing through the Nyquist filters and the outputs obtained are passed through the Real-Imag to Complex block and then through the Rectangular QAM Demodulator block. For the second subcarrier channel through the tenth subcarrier, DDS Compiler and the Complex Multiplier blocks are used as in transmitter section. In order to compute the negative sine wave, Negate block is used. The design of the Simulink model for the second subcarrier channel is depicted below in fig. 9 below. The same design is used till the tenth subcarrier like in the transmitter. The difference lies in the DDS Compiler block which is used to generate sine and cosine waveforms of different frequencies from 2MHz to 18 MHz.

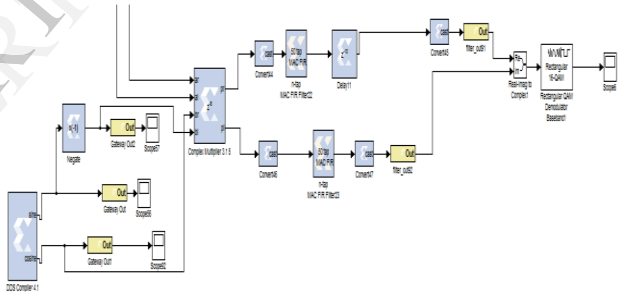

Fig. 9: Simulink model for the second subcarrier channel in the receiver

VII. EXPERIMENTAL RESULTS

After designing the Simulink model, VHDL code is generated using Simulink System Generator and synthesized using Xilinx ISE Design Suite 14.7 for Artix 7 FPGA board. Fig. 10 shows the simulated waveform of post place and route model. Post-route simulation, which is very close to real hardware, uses back-annotated timing information that is exact for the design. Latency is calculated as 9,195.100 ns from the post route simulated waveform.

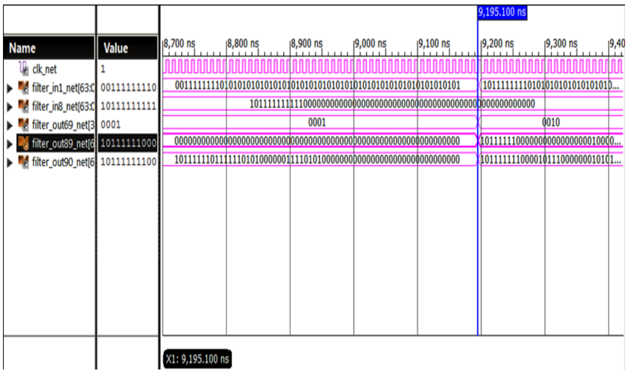

Fig. 10: Simulated waveform of FBMC System

VIII. CONCLUSION

FBMC Transmitter and Receiver are designed in Simulink System Generator. The VHDL code generated is used to synthesize in Xilinx ISE Design Suite 14.7 and latency is analyzed. The hardware used for implementation is Artix 7 FPGA board. While OFDM offers a lower complexity and is more robust to timing offset, FBMC offers a number of other advantages that makes it a more efficient technology for many upcoming and future communication systems. The poor frequency spectra of subcarrier signals in OFDM are the main source of problems that limits the application of OFDM in some present and future development of broadband communication systems. FBMC, on the other hand, is an efficient method that resolves most of these problems by taking a filtering approach to multicarrier communications. Latency problems can affect SoC performance and even delays the time to market for the design. SoC architects strive to create architectures that deliver optimum latency for efficient applications. In the future, polyphase implementation of FBMC can be done to reduce the latency since it requires less number of resources.

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REFERENCES

[1] Behrouz Farhang-Boroujeny and Roland Kempter, “Multicarrier Communication Techniques for Spectrum Sensing and Communication in Cognitive Radios”, IEEE Communications Magazine, pp.80-84, April 2008.

[2] Behrouz Farhang-Boroujeny and Chung Him(George) Yuen,“ CosineModulated and Offset QAMFilter Bank Multicarrier Techniques: A Continuous-Time Prospect” , EURASIP Journal on Advances in Signal Processing, 2010.

[3] Rostom Zakaria and Didier Le Ruyet, “A Novel Filter-Bank Multicarrier Scheme to Mitigate the Intrinsic Interference: Application to MIMO Systems”, IEEE Transactions On Wireless Communications, Vol. 11, No. 3, pp. 1112-1123, March 2012.

[4] Balint Horvath and Peter Bakki, “Implementation of FBMC Transmission Link Using SDR”, 23rd Conference on Radioelektronika ,April 2013.

[5] Peiman Amini and Behrouz Farhang Boroujeny, “Packet Format Design and Decision Directed Tracking Methods for Filter Bank Multicarrier Systems”, EURASIP Journal on Advances in Signal Processing, 2010.

[6] Daiming Qu, Shixian Lu, and Tao Jiang, “Multi-Block Joint Optimization for the Peak-to Average Power Ratio Reduction of FBMC-OQAM Signals”, IEEE Transactions On Signal Processing, Vol. 61, No. 7, pp.1605-1613,April 1, 2013.

[7] Youssef Dandach and Pierre Siohan, “FBMC/OQAM modulators with half complexity”, IEEE Communications Society.