Enhancement of SDR through FBMC Communication

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***Abstract*— As the fourth generation telecommunication is entering next generation, all the Radio communications are becoming software oriented. Software Defined Radio (SDR) is initially addressed followed by the technology of Orthogonal Frequency Division Multiplexing (OFDM). OFDM which is in the verge of replacement, is analysed and an alternate communication technology namely Filter Bank Multicarrier Communication (FBMC) is suggested. The technology and types of FBMC are discussed. OFDM and FBMC are compared. In this paper simple FBMC is implemented and the results are given.**

Key Words —SDR, OFDM, FBMC, ISI, ICI, Equalisation.

I INTRODUCTION

As the modern telecommunication is improving over each decade, two trends continue to persist. They are data rate and ability to send information independent of location and time. The software based radio communication enables the latest ICT devices a reconfigurable one. Data rate demand is increasing beyond 1 Gbps. The present 4G LTE [1] technology uses OFDM communication techniques. This has inherent problem of spectrum leakage and maintenance of Orthogonality among all sub-carriers. There is need for high data rate and low latency, as the world moves towards fifth generation Communication. Filter Bank Multicarrier Communication (FBMC) is very old FDM technology and due to complexity in implementation, this could not see the standards. With the advent of new fast processors, FBMC is suggested as next generation Communication layer. In order to implement the FBMC, in Section-II concept of Software Defined Radio (SDR), working of OFDM is described. Then Section-III deals with the concept of FBMC and its implementation. In Section – IV a comparison is brought out with OFDM and FBMC. Section-V gives the conclusion and future research work.

II CONCEPTS OF SDR AND OFDM

A. SDR[2]

The SDR Forum which is working alongwith IEEE P1900.1 group has defined SDR as "Radio in which some or the entire physical layer functions are software defined". Radio is a device which transmits and / or receives signals in the Electro-magnetic Spectrum to transfer information such as voice, music, and data. Scientifically the frequencies are grouped from 3 KHz to 300 GHz as Extremely Low Frequency (ELF) to Extremely High Frequency (EHF) under the various frequency bands.

In SDR-Transmitter the information is formatted into Digital input, m_i, in the form of message symbols. Then these symbols could be converted into bit stream, u_j, by source encoding, encrypting(for secrecy), channel encoding and multiplexing(for multi signals) process. Depending upon the source coding and multiplexing, the date rate of streams can be controlled. After that desired Pulse coding could be undertaken using modulation such as PAM, QAM, PSK, FSK, OFDM or its variants to form Electromagnetic waves suitable to antenna characteristics. After it travels thru' media, the signal is received at the receiver.

In SDR-Receiver, the received signal from Antenna is demodulated after carrier synchronization and automatic Gain control, using appropriate Demodulation techniques such as OFDM, QAM, FSK, PSK and its variants, to make the bit stream. From Bit Stream, after symbol synchronization and frame synchronization, the message is reconstructed successfully. The SDR Tx-Rx is given in the figue 1. below.

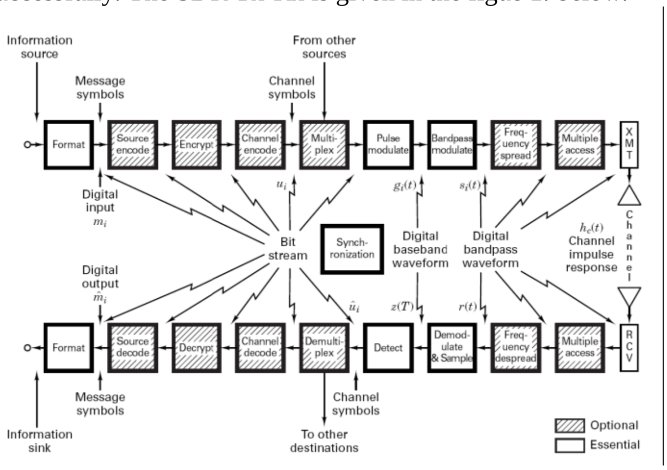

Figure . 1. Block diagram of SDR Tx and Rx.

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Most of the above functions can be executed in a Digital Signal Processor (DSP) or Field Programmable Gate Array (FPGA) or General Purpose processor (GPP) using Algorithms, middleware, Rate Convertor software. The SDR Forum has characterized this SDR architecture with the data flow mentioned in Figure. 2. given below.

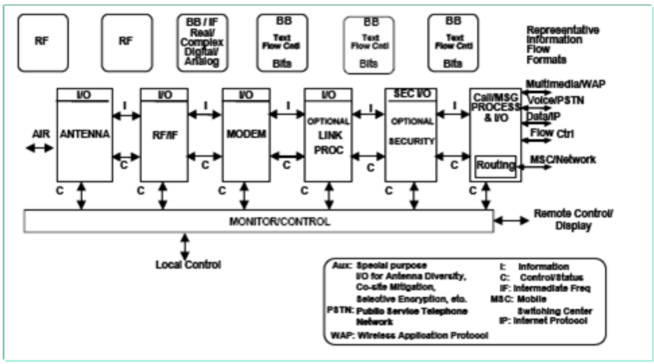

Figure. 2. SDR Forum's SDR Architecture with Data Flow.

Pure Software Radio is yet a distant dream due to high architectural Complexity and high Flexibility. Software Defined Radio (SDR) is the one which has medium architectural Complexity and more than medium Flexibility. These radios are reconfigurable one where in the software can be upgraded or added with other modes of radio or frequency of operation.

B. *OFDM [3] [4]*

Digital Modulation modulates fundamentally three parameters viz., Amplitude (A), Phase (θ_k) and Frequency (f_c) of sinusoidal signal. Mathematically, to represent ASK, PSK and FSK, this can be written as,

$$s(t) = A \cdot \cos(2\pi \cdot f_c \cdot t + \theta_k) \qquad (1)$$

OFDM uses a combination of ASK and PSK modulation such as QAM and PSK. By expanding and assigning, we obtain,

$$a_k = \cos\theta_k, \quad b_k = \sin\theta_k$$

$$s(t) = \mathrm{Re}[(a_k + jb_k)e^{j2\pi fc \cdot t}] \qquad (2)$$

$e^{j2\pi fc \cdot t}$ indicates carrier sinusoidal and $(a_k + jb_k)$ indicates Digital Modulation, by a complex number. OFDM is a multi-carrier amplitude modulation scheme where each carrier's amplitude is modulated. It uses DFT/FFT. Sin X / X spectra is used for sub-carriers. Available bandwidth is divided into many narrow-bands. Data is transmitted in parallel on these bands. The typical OFDM is shown as follows:-

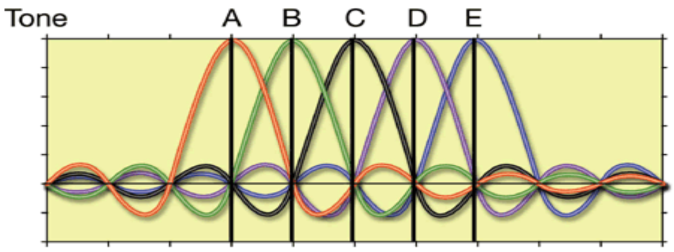

Figure . 3. OFDM Waveform.

Parallel data streams are sent. Data encoding is based on Amplitude Modulation. Multiple Carriers are combined through the Fourier series, which is computed by Inverse Fast Fourier Transform (IFFT). Pictorially an example of 4-QAM Modulation can be represented as below:-

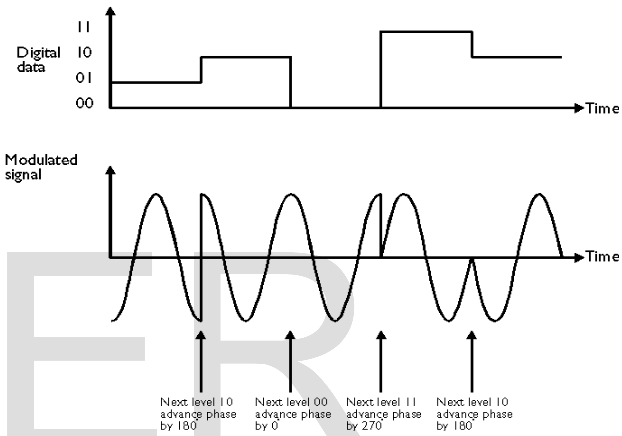

Figure. 4. 4-QAM Modulation.

Total Power spectrum of OFDM is almost like a rectangular pulse shape. Orthogonality in Frequency and Time domain is maintained. Overlap of frequency response is possible as against FDM where inter-carrier spacing is a must. Frequency responses of the carriers overlap at Zero Crossings avoiding Inter-Carrier-Interference (ICI). Frequency-Time Representation of an OFDM Signal can be depicted as follows:-

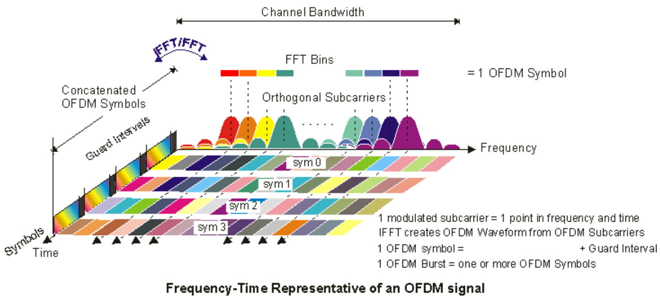

Figure. 5.

OFDM Modulator-Demodulator is designed as follows with Transmitter and Receiver:-

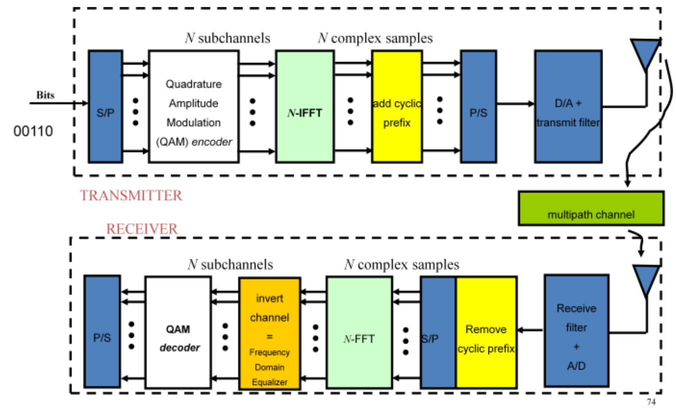

Figure. 6a. OFDM Modulator-Demodulator.

Defining the complex base-band signal u(t) in the following way for converting the OFDM signal into digital domain,

$$s_B(t) = \mathrm{Re}[u(t)]$$

$$u(t) = \sum_{n=0}^{N-1} d_n \cdot e^{j2\pi n f_0 t}, d_n = a_n + jb_n \qquad (3)$$

After performing N Times sampling in period T, we get,

$$u\left(\frac{k}{Nf_0}\right) = \sum_{n=0}^{N-1} d_n \cdot e^{j2\pi n f_0 \frac{k}{Nf_0}} = \sum_{n=0}^{N-1} d_n \cdot e^{j\frac{2\pi nk}{N}}$$

$$= \sum_{n=0}^{N-1} d_n \cdot \left(e^{j\frac{2\pi}{N}}\right)^{nk} \quad (k = 0,1,2,\cdots,N-1) \qquad (4)$$

$$u(k) = \mathrm{IFFT}(d_n) = \mathrm{IFFT}(a_n + jb_n) \qquad (5)$$

At Receiver mathematically following can be performed to get back the data symbol, d_n.

$$s(t) = \sum_{n=0}^{N-1} [a_n \cos\{2\pi(f_c + nf_0)t\} - b_n \sin\{2\pi(f_c + nf_0)t\}]$$

$$LPF[s(t)\cdot\cos(2\pi f_C t)] = \frac{1}{2}\sum_{n=0}^{N-1}\{a_n \cos(2\pi n f_0 t) - b_n \sin(2\pi n f_0 t)\} = \frac{1}{2}s_I(t)$$

$$LPF[s(t)\cdot\{-\sin(2\pi f_C t)\}] = \frac{1}{2}\sum_{n=0}^{N-1}\{a_n \sin(2\pi n f_0 t) + b_n \cos(2\pi n f_0 t)\} = \frac{1}{2}s_Q(t)$$

$$u(t) = s_I(t) + js_Q(t) = \sum_{n=0}^{N-1} d_n \cdot e^{j2\pi n f_0 t} \qquad (6)$$

$$d_n = \mathrm{FFT}(u(k)) \qquad (7)$$

The IEEE OFDM Standards, IEEE 802.11a is briefly listed below:-

- Sampling Rate : 20 MHz
- Chip Duration : 1/20 MHz = 50 nsec
- Number of FFT : 64
- FFT Symbol Period: 64 X 50 ns = 3.2 µsec
- Cyclic Period : 16 Chips X 50 nsec = 0.8 µsec
- OFDM Symbol Length: 80 Chips = 4 µsec
- Modulation Scheme
  - QPSK : 2 Bits / sample.
  - 16 QAM : 4 Bits / sample.
  - 64 QAM : 6 bits / sample.
- Coding rate ½ convolution code with constraint length 7

The BER curve Vs SNR implemented in SciLab software is given in figure.6b.

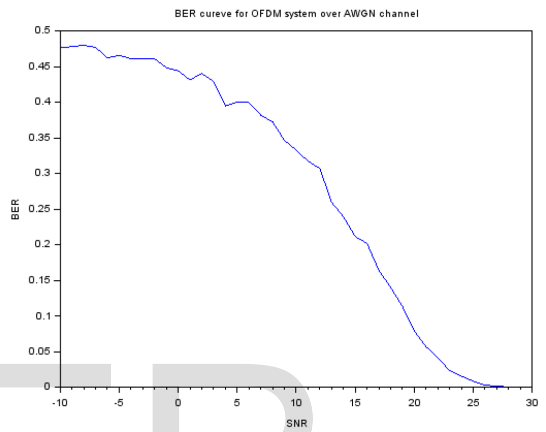

Figure. 6b. OFDM with AWGN Channel BER Curve Vs SNR

II CONCEPTS OF FBMC

Filter Bank Multi Carrier (FBMC) [5] [6] communication systems are a subclass of Multi-carrier Systems. This technique was first developed in the mid-1960s. Chang [7] and Saltzberg [8] have introduced PAM Symbol transmissions and QAM symbol Transmissions parallelly with filter-banks theory for efficient Bandwidth management. There are three major types of FBMC. They are suggested by different authors [6]. They are as follows:-

FMT. Filtered Multi Tone FBMC uses subcarrier bands with no overlap. Data symbols are QAM.

CMT. Cosine Modulated multi tone-FBMC uses subcarrier with maximum overlap.

SMT. Staggered Modulated Multi tone-FBMC uses subcarrier bands with maximum overlap. Data Symbols use PAM with VSB Modulation. It is also known as Offset QAM (OQAM).

FMT based FBMC is built on the conventional method known as Frequency Division Multiplexing (FDM). FMT-FBMC System is a filter bank modulation technique in which, N branch filters are frequency-shifted-baseband filters, called prototype filter, that achieves high level of spectral containment. ICI is resolved through use of well-designed filters with high stop-band attenuation. ISI may be compensated for by adopting the conventional method of square-root Nyquist filtering.

FBMC Technology

FBMC Communication uses Sample Rate Converters (UP and DOWN), Prototype Filter and Filter Banks as backbone element. The input-Output relation of Up Converter is given as

$$y_k[n] = \begin{cases} x[n/L], & n = mL,\ m \text{ is an integer} \\ 0, & \text{otherwise} \end{cases} \quad (8)$$

The input-Output relation of Down Converter is given as

$$y_D[n] = x[Mn],\ M \text{ is an integer} \quad (9)$$

Prototype Filter is designed to match the time and frequency spread of channel which is given below:-

Time spread

$$\sigma_t = \sqrt{\int_{-\infty}^{\infty} t^2 |h(t)|^2 dt}$$

Frequency spread

$$\sigma_f = \sqrt{\int_{-\infty}^{\infty} f^2 |H(f)|^2 df}$$

Choose h(t) so that H(f) = h(*l*f), for a constant scaling factor *l*.
Then one may find that $(T/\Delta\tau) = (F/\ \Delta\gamma)$
Or $T/F = \Delta\tau/\ \Delta\gamma\ = \sigma t/\sigma f = l$ (10)

The Gaussian pulse:

$$g(t) = e^{-\pi t^2}$$

The first property:

$$G(f) = g(f)$$

The second property: the Heisenberg-Gabor uncertainty principle states that for an arbitrary pulse h(t)

$$\sigma_t \sigma_f \geq \frac{1}{4\pi}$$

and equality holds when

$$h(t) = g(t)$$

Let p(t) be a prototype filter and with N sample points in the filter length $\beta N + 1$, where β is an integer greater than 1. Then β parameters are to be found for optimal design of prototype filter. p[n] is given as

$$= \begin{cases} \frac{1}{\beta N+1}\left(k_0 + 2\sum_{l=1}^{\beta-1} k_l \cos\left(\frac{2\pi l n}{\beta N+1}\right)\right), & 0 \leq n \leq \beta N, \\ 0, & \text{Otherwise.} \end{cases} \quad (11)$$

The best prototype filter, p[n], designed as part of PHYDYAS Filter[9] at Europe is given below:-

The impulse response is given as

$$p[m] = 1 + 2\sum_{k=1}^{K-1} (-1)^k P_k \cos\left(\frac{2\pi k}{MK} m\right)$$
$$p[0] = 0,$$
(12)

The frequency response is given as

$$P(f) = \sum_{k=-(K-1)}^{K-1} P_k \frac{\sin\left(\pi\left(f - \frac{k}{MK}\right)MK\right)}{MK \sin\left(\pi\left(f - \frac{k}{MK}\right)\right)}$$
(13)

$$m = 0, 1, \ldots, KM - 2$$
$$K = 4$$
$$\bar{P}[0] = 1$$
$$\bar{P}[1] = 0.97195983$$
$$\bar{P}[2] = 1/\sqrt{2}$$
$$\bar{P}[3] = 0.23514695$$

The above is pictorially given as follows:-

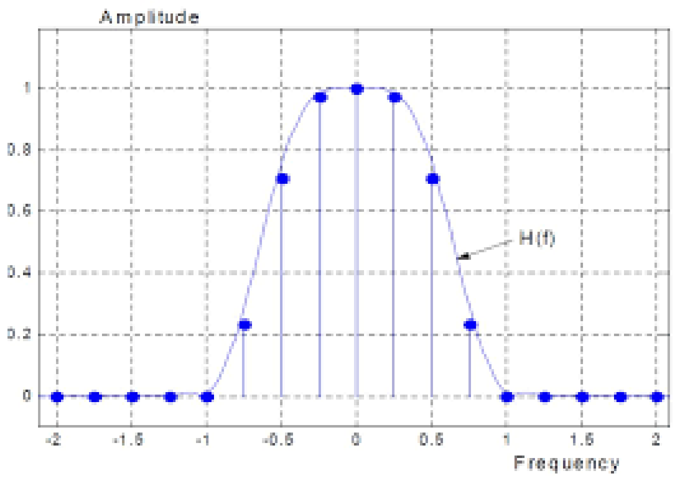

Figure. 7. Frequency Response

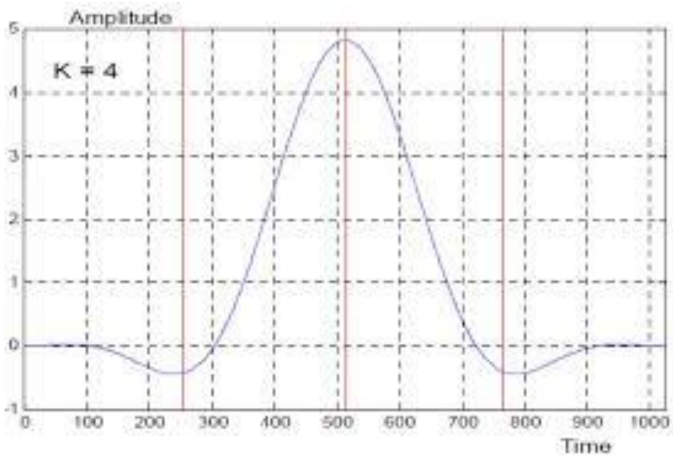

Figure. 8. Impulse Response

The same was simulated through MATLAB and the results are depicted below:-

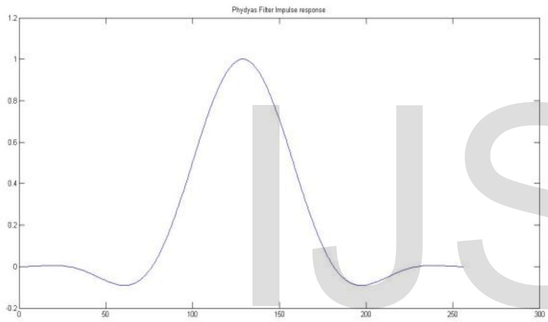

Figure. 9. PHYDYAS Filter Impulse Response

Filter Banks

Filter Bank is a system that comprises of a Group of Filters which processes a common input or result into a common output. Filter banks either break down an input signal to form sub-band component signals or combine the sub-band signals to form the output signal. There are two major types of Filter banks viz., Analysis Filter Bank (AFB) and Synthesis Filter Bank (SFB). AFB is used for analyzing the input signal according to characteristics of each filter. SFB is used to filter the individual signals and added to get combined new composite signal. For harnessing the real power of filter banks, it has to be used in pairs, either AFB-SFB combination as Sub-band Systems or as SFB-AFB pair as Trans-multiplexers. SFB-AFB combination is used in multicarrier communication as Tx-Rx pair. Decimation, i.e down conversion takes place at AFB and it consists of the filtering of the input signal (anti-aliasing Filtering) and subsequent down-sampling. Interpolation, i.e., takes place at SFB and it consists of an up-sampler and an interpolation filter (Anti-imaging filtering). Modulated Filter Banks are frequency shifted versions of Low Pass Prototype. It is achieved by multiplying the prototype with a modulation function. FMT-FBMC-Tx is implemented as follows with N number of Sub carriers, $s_k[n]$ data symol on the k^{th} subcarrier FMT Symbol, L= KN, symbol period, K oversampling factor and x[n] is the transmitted FMT- FBMC signal.

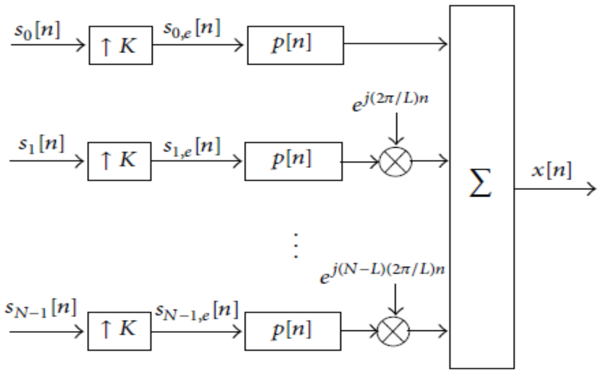

Figure. 10a. FBMC FMT Transmitter Block Diagram.

$$x[n] = \sum_{k=0}^{N-1} \left(\sum_{m} s_k[m]\, p[n-mK] \right) e^{j(2\pi kn/L)}$$

$$= \sum_{m} \left(\sum_{k=0}^{N-1} s_k[m]\, e^{j(2\pi kn/L)} \right) p[n-mK].$$

(14)

FMT-FBMC-Receiver is implemented as follows:-

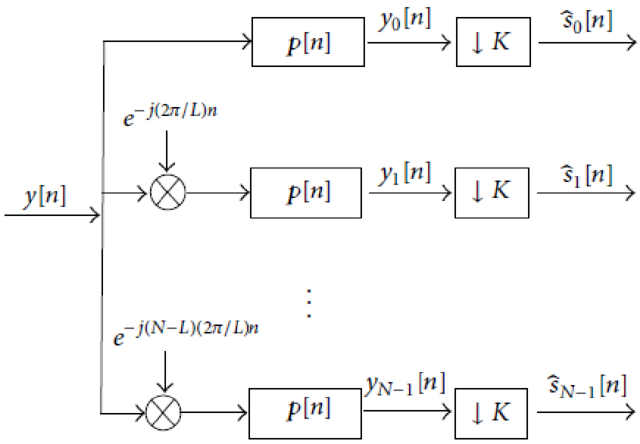

Figure. 10b. FBMC FMT Receiver Block Diagram.

$$y_k[n] = \left(y[n]\, e^{-j(2\pi kn/L)}\right) * p[n]$$
$$= \sum_m y[m]\, e^{-j(2\pi km/L)} p[n-m] \quad (15)$$

$$\hat{s}_k[n] = y_k[Kn] \quad (16)$$

With Polyphase network, FMT-FBMC system can be implemented with least complexity [4] [6].

Simplified FBMC Implementation and Results

A simple FBMC Tx-Rx is implemented by us using MATLAB. The block diagram of FBMC system is given in Figure.11.

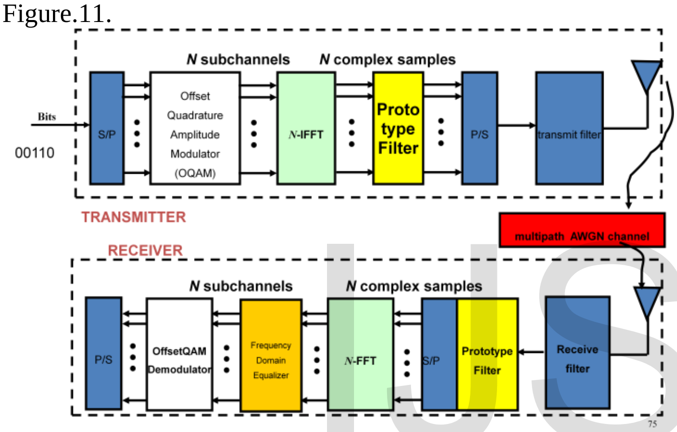

Figure. 11. Block diagram of Simple FBMC System.

The constellation diagram of above FBMC with 4 QAM symbols, 64 Subcarriers, 4 Frames and AWGN Channel is given in figure.12.

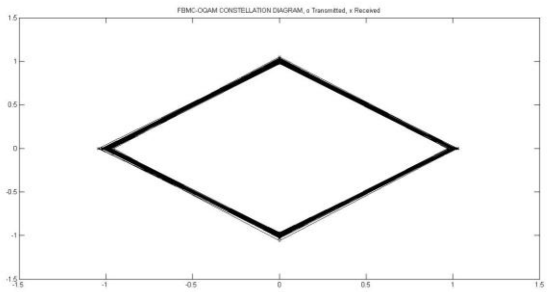

Figure.12. Constellation Diagram of 4-QAM- FBMC with AWGN Channel both transmitted and received symbols.

The Bit-Error-Rate for the above FBMC system in AWGN Channel is given at figure.13.

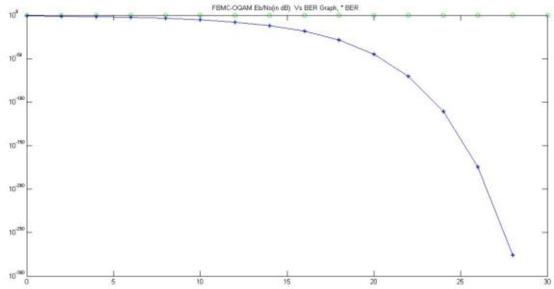

Figure.13. Constellation Diagram of 4-QAM- FBMC with AWGN Channel

The FBMC Transmitted pulse power is depicted at figure.14.

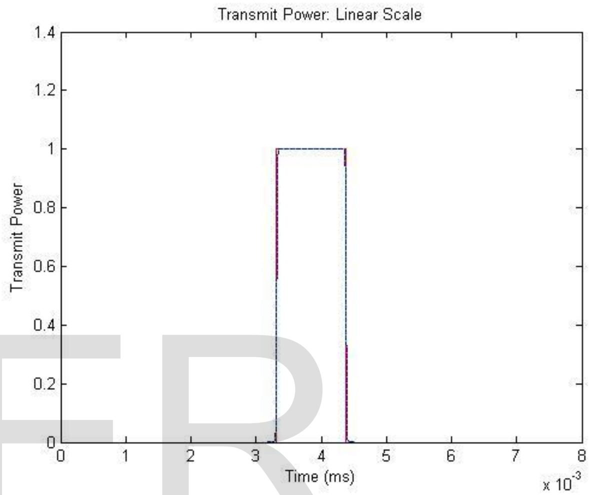

Figure.14. Transmitted Pulse of 4-QAM- FBMC.

IV – COMPARISIONS OF OFDM Vs FBMC

The OFDM and FBMC are analysed and discussed. The results are compared in the following Tables and figures.

•**All** sub-carriers are **Orthogonal** to each other. •Available BW is divided into many narrow-bands. •**Rectangular** pulse-shape increases susceptibility to **synchronisation errors**. Side-lobes cause signal **power leakage**. •Cyclic-Prefix used to avoid **ISI** and **ICI**. Hence significant **Overload** and reduction in Spectral efficiency. •**High PAPR** (Peak-to-Average-Power-Ratio). •Poor Spectrum Resolution •LessComplex.	•**Only** adjacent sub-carriers are **Orthogonal** to each other. •Complex data symbol is mapped to **real** symbols. •**Flexibility** to use different pulse-shape. Better Prototype Filter design. •**No CP**. Filter Banks are used. Side-lobes avoided. •Efficient Power **control** over leakage. •Prone to **Synchronisation** error, Time Offset(**TO**) and Frequency offset(**FO**). •High Spectrum Resolution. •More Complex.

Table.1. OFDM Vs FBMC Comparison

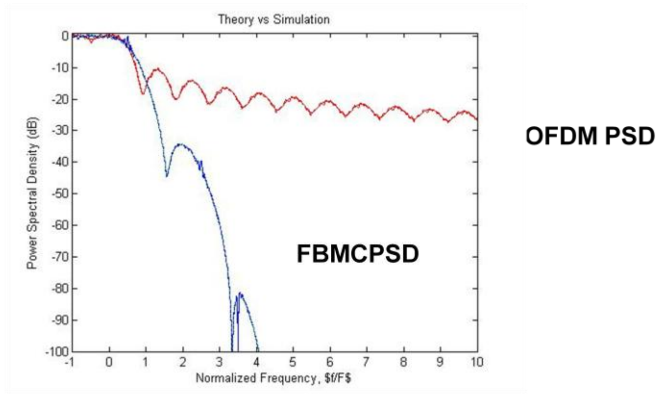

Figure. 15. Comparison of Power Spectral Density.

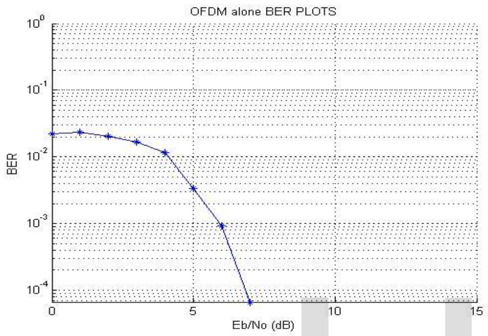

Figure.16. BER Vs Eb/No of OFDM

Type	Number of 'X'	Number of '+'
OFDM USING FFT OF LENGH N=2^K	**(N/2)LOG$_2$ N**	**NLOG$_2$ N**
FBMC OF ORDER N SYMMETRICAL	**N+1**	**N**
POLYPHASE REP WITH L UPSAMPLING FACTOR	**N/L**	**N**

Table.2. OFDM Vs FBMC Computation Comparison

With the above comparisons in Bit Error Rate, Spectrum Efficiency, Computations, FBMC is the best candidate in comparison with OFDM for 5G Communication.

V CONCLUSION AND FUTURE WORKS

The present 4 G Communication Technology based on OFDM is prone to spectrum leakage, strict Orthogonality conditions among entire sub-carriers. Its rectangular pulse-shape increases susceptibility to synchronisation errors. In order to mitigate the major drawbacks, new Communication technology based on FBMC techniques are suggested for future SDR. It has more spectrum efficiency, more flexibility to use different pulse shape and efficient power control. This FBMC Systems can also be susceptible to Synchronisation Errors, Time Offset and Frequency Offset. Though ICI (Interference of Symbols from other subcarriers in the same index) and ISI (Interference of Symbols in different time index from all subcarriers) depends upon Pulse-shape, Channel and Data, it can be mitigated through Channel Equalisation, Channel Estimation and Synchronisation techniques in the future.

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