
A OQAM (Offset QAM) Based Filter Bank Multicarrier Modulation

(IJCST) International Journal of
Communication Systems and Network
Technologies

ISSN Number: 2053-6283

Volume 8, Issue No. 3, 122–133

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<https://journals.mirlabs.in/index.php/ijcsnt>

DOI-10.18486/ijcsnt/8.3.110



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Abstract

Filter bank Multicarrier Modulation techniques are new generation evolution and they are dominating the currently adopted Orthogonal Frequency Division Multiplex (OFDM) being used for the latest commercial mobile communication applications. FBMC i.e filter bank multicarrier modulations are implemented with the help of filter analysis and synthesis filter banks obeying the Nyquist criteria for pulse shaping. The offset quadrature modulation is advantageous in achieving better baud-rate by using in-phase and quadrature components of QAM symbols and recovering the information symbols with minimized intersymbol interference (ISI) and intercarrier interference (ICI). Better spectral efficiency and low out of band radiation is achieved as compared to OFDM modulation. In this paper we first analyse the offset quadrature modulation based FBMC model explore the Nyquist criteria used for pulse shaping and implementation of the polyphase structures of FBMC transmitter and receiver are discussed with various field applications of FBMC.

Keywords

Multicarrier Systems, FBMC, Nyquist-Filters, OFDM OQAM, Polyphase Structures

Received: 24 August 2019; **Revised:** 23 November 2019; **Accepted:** 18 December 2019;
Published: 31 December 2019;

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INTRODUCTION

Multicarrier modulation techniques are the current generation technology adopted for the implementation of broadband communication systems. Currently, Orthogonal Frequency Division Multiplex (OFDM) is being used for the latest commercial mobile communication applications. But OFDM, suffers from larger side lobe problem because of the use of the rectangular windowing technique which is performed after the Inverse Fast Fourier Transform (IFFT). These side lobes increase the interference in adjacent channels, which reduces the spectral efficiency and baud-rate of the communication systems. Also higher PAPR and strict orthogonality condition has led towards the drift of another multicarrier technique called FBMC (Filter bank Multicarrier) Modulation techniques.

For Filter bank approach, instead of using a Quadrature Amplitude Modulation (QAM) on each sub-carrier, offset QAM is used in which a time offset equal to half the QAM symbol duration is obtained between the real and imaginary component. The more precise name is given to this staggered multitone (SMT) as suggested in literature^[10]. This leads to the FBMC /OQAM orthogonal Quadrature Amplitude Modulation also known as OFDM/OQAM. The filter banks at the transmitter and receiver side are designed with the help of various kinds of prototype filter designing. The filter design is significant in determining various useful parameters of the system such as intersymbol interference(ISI), intercarrier interference(ICI)^[1,2] and stopband attenuation of the signal. Also output symbols recovered must be equivalent to the input symbols transmitted thus satisfying perfect reconstruction (PR) condition^[3]. Also various kinds of windowing techniques satisfying the Nyquist criteria in the filter analyses and synthesis filter banks have been formulated and they account for low out-of-band radiations. The FBMC transmitter and receiver are implemented with the help of various polyphase structures and evaluated on the basis of their computational complexity.

The sections of the paper are organised as follows. Section II focuses on Literature survey of the evolution of filter bank techniques in multicarrier systems. Section III focuses on the FBMC pulse shaping of the Square Root Nyquist filters based prototype filtering. Section IV provides the FBMC model details and Section V depicts the polyphase structures of SMT transmitter and receiver. Section VI focuses on the various field applications of FBMC and Section VII providing the concluding remarks.

LITERATURE REVIEW

Prior to OFDM, the multicarrier methods studied were filter bank based. The first research was formulated by Chang^[4] in 1960 s who evolved the set of conditions required to transmit the PAM symbols through the bank of overlapping vestigial sideband (VSB) modulated filters with minimum bandwidth. A year later Saltzberg^[5] presented to extend the ideas of Chang for transmission of QAM symbols in a double-sideband modulated (DSB) filters. Broadly three classes of Filter bank modulation (FBMC) have been studied. Saltzberg presented that using a half-symbol space delay between the in-phase and quadrature components of QAM symbols a perfect reconstruction FBMC system can be implemented. Bellanger^[6] and later Hirosaki^[7] used polyphase structures for digital implementation of Saltzberg's multicarrier system. Saltzberg's /Chang's method can be adopted to minimize ISI and ICI in doubly dispersive channels which can be significant improvement of FBMC over OFDM in mobile channels^[8]. The offset comes from the half symbol shift between the in- phase and quadrature of each QAM symbol with respect to each other which is referred as staggered modulated multitone (SMT) where staggered word implies that time staggering of QAM symbols with in-phase and out-phase components are evolved .

In 1990s, focus was moved to discrete multitone (DMT) over using OFDM in DSL literature. Sandberg and Tzannes, elaborated discrete wavelet multitone (DWMT)^[9]. Further studies suggested that DWMT is a resemblance to Chang's method^[4]. The more precise name given to DWMT in literature suggests cosine modulated multitone (CMT) as another class of filter bank modulation^[6]. Farhang - Boroujeny and Yuen^[10], provided the study of DWMT as equivalent to Chang's method. DWMT is best suitable in suppressing narrow-band interference as compared to OFDM^[9], but still due to complex equalizer structure its usage is limited over OFDM. Later researches focused on channel equalization in DWMT^[10] to reduce the complexity and to consider its adoption in standards e.g^[11].

Filtered multitone (FMT) is another multicarrier modulation technique that has been specifically developed for DSL applications^[12,13]. FMT follows the conventional method of frequency division multiplexing in which subcarrier bands are separated by guard band transitions whereas the original idea of Chang and Saltzberg laid over overlapping of adjacent subcarrier bands to maximize the bandwidth efficiency. Hence, FMT is less bandwidth efficient than the FBMC methods proposed by Chang and Saltzberg.

FBMC Pulse shaping

FBMC are analyzed with the help of filter banks which obey the Nyquist criteria. FBMC trans-receiver are implemented with the help of transmit and receive filters as fig 1.

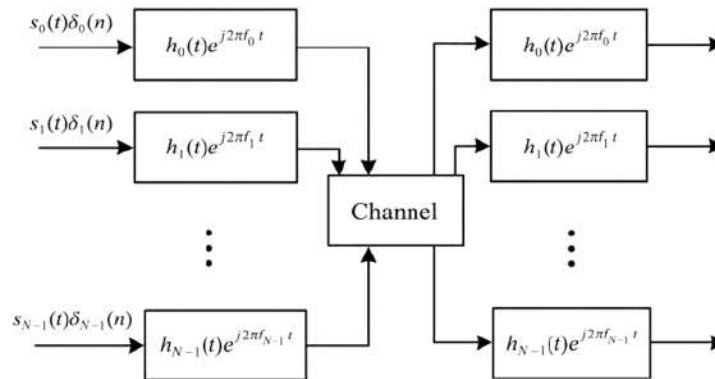


Figure 1. FBMC Transreceiver Block Diagram.

The transmitted signal is given as:

$$x(t) = \sum_{k \in K} s_k[n] h_t(t - nt) e^{j2\pi(t-nt)f_k} \quad (1)$$

where K is the set of active symbol indices, x(t) is obtained by summation of time-limited complex values with respect to every n value, in which $s_k[n]$ determines the magnitude and phase. These tones,

when passed through the channel, after the transient period of the channel response, will be the same tones modified by the channel gains at the respective frequencies.

On separating various sub carriers (1) is evaluated as

$$x(t) = \sum_{k \in K} x_k(t) \quad (2)$$

where

$$x_k(t) = \sum_{n \in K} s_k[n] h_t(t - nT) \quad (3)$$

$$h_{T,K}(t) = h_t(t) e^{j2\pi t f_k} \quad (4)$$

The $h_{T,K}(t)$ filter response is described by modulating the prototype filter $h_t(t)$.

Also (2) is written as

$$x(t) = \sum_{k \in K} s_k[n] h_t(t - nT) \quad (5)$$

Also the received signal $y(t)$ would be same as that the transmitted signal $x(t)$ under ideal channel conditions. The data symbol values will be separable if

$$\langle h_{T,K}(t - mT), h_{R,l}(t - mT) \rangle = \delta_{kl} \delta_{mn} \quad (6)$$

The above refers to the orthogonality condition.

Where

$$\langle h_{T,K}(t - mT), h_{R,l}(t - mT) \rangle = \int_{-\infty}^{\infty} h_{T,K}(t - mT), h_{R,l}^*(t - nT) dt \quad (7)$$

The ambiguity function of $h(t)$ can be defined as

$$A_p(\tau, v) = \int_{-\infty}^{\infty} h\left(t + \frac{\tau}{2}\right), h^*\left(t - \frac{\tau}{2}\right) e^{-j2\pi v t} dt \quad (8)$$

Where τ is a time delay and v is a frequency shift.

$$\begin{aligned} \langle h_{T,K}(t - mT), h_{R,l}(t - mT) \rangle &= \int_{-\infty}^{\infty} h_{T,K}(t - mT), h_{R,l}^*(t - nT) e^{-2\pi l F t} dt \\ &\alpha A_p((n - m)T, (l - k)F), \end{aligned} \quad (9)$$

Due to the delays mT and Nt phase shift produces a proportionate factor. Hence ambiguity function is defined as

$$A_p(nT, lF) = 1 \text{ for } n = l = 0, \text{ Else } 0 \quad (10)$$

For $v=0$, the function is written as:

$$A_p(\tau, 0) = \int_{-\infty}^{\infty} h(t + \frac{\tau}{2}), h^*(t - \frac{\tau}{2}) dt \quad (11)$$

which minimizes the nyquist constraint

$$A_p(nT, 0) = 1 \text{ for } n = 0 \quad (12)$$

The right-hand side integral of (12) is equal to the convolution of $h(t)$ and its matched pair $h(-t)$, at $t=\tau$. Thus $A_p(t, 0) = h(t) * h(-t)$ and hence shows $h(t)$ a nyquist pulse and follow the generalization of nyquist constraints.

Transmit and receive filters are used for sub-carriers separation. Square Root Nyquist filters specifically are designed for pulse shaping purposes. Square root cosine function is used for designing of filters.

Sensitivity to phase and timing error^[10] is same for both FBMC and OFDM ,but using square root nyquist pulse FBMC avoids intersymbol interference^[4]. Both in frequency domain exhibit spectral components at every point. Using the rectangular pulse signals results in higher spectral leaks in the adjacent bands due to sinc pulses obtained in frequency domain. While designing an FBMC signal does not leak significant power into adjacent sub carrier bands in the channel. As a result of using a longer non-rectangular shape window in FBMC, it does not only creates Inter Carrier Interference (ICI) but also Inter Symbol Interference (ISI).

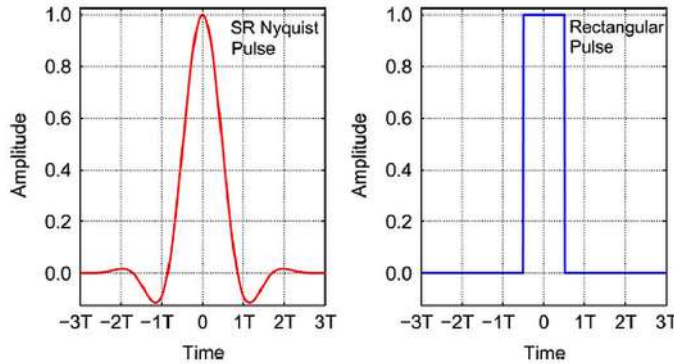


Figure 2. FBMC and OFDM pulse shaping^[10].

To satisfy the orthogonality conditions^[15] various kinds of filters are employed ,also Heisenberg-Gabor uncertainty lower bounds^[10] as close as possible have been evolved and design methods have been developed^[16,18]. The isotropic orthogonal transform algorithm prototype filter design is the widely used method^[16]. IOTA design/algorithm was introduced by Alarad and was put in journals by Le Floch et al^[16]. The algorithm starts with the Gaussian pulse and converts it to the orthogonalized pulse. IOTA yields optimally-concentrated function when there are no restrictions on filter length and bandwidth. It also fulfils Nyquist criterion after matched filtering.

$$h(t) = F^{-1} Q_{\tau O} F Q_{V O} g(t) \quad (13)$$

F and F^{-1} denote fourier and inverse transforms , Q_a is an orthogonalization operator defined as

$$y(u) = \frac{x(u)}{\sqrt{a \sum_{-\infty}^{\infty} ||x(t - ka)x(t - ka)||}} \quad (14)$$

The above operation would also depict the orthogonalization process in^[19].The constructed prototype filter fulfils the Nyquist criterion and may yield isotropic response in time and frequency.

FBMC MODEL

Offset quadrature amplitude modulation (OQAM) is a variation of quadrature amplitude modulation(QAM). Saltzberg used root-Nquist filter with symmetric impulse response for pulse – shaping at the transmitter and using the same for match filtering at the receiver in a multichannel QAM system.The offset quadrature modulation is advantageous in achieving better baud-rate by using in-phase and quadrature components of QAM symbols and recovering the information symbols with minimized intersymbol interference (ISI) and intercarrier interference (ICI).This method is better than orthogonal frequency division multiplexing (OFDM) as it does not require the use of cyclic prefix and works under asynchronous mode. OQAM multicarrier, thus, is more bandwidth efficient than the conventional OFDM.

The in-phase and quadrature components are then staggered in time by half a symbol period, $T/2$. The outputs of these filters are modulated using N subcarrier modulators whose carrier frequencies are $1/T$ -spaced apart.

$$S_k[n] = s_k^I[n] + j s_k^Q[an] \quad (15)$$

where $s_k^I[n]$ and $s_k^Q[n]$ are the real and imaginary parts ofb the nth symbol of the kth subcarrier. These are defined as:

$$s_k^I[t] = \sum s_k^I[n] \delta(t - nT) \quad (16)$$

$$s_k^Q[t] = \sum s_k^Q[n] \delta(t - nT) \quad (17)$$

where $s(t)$ is the dirac delta .The modulated signal is defined as:-

$$x(t) = \sum_{m=0}^{N-1} x_m(t) \quad (18)$$

where

$$x_m(t) = \sum_{l=-\infty}^{\infty} (s_m^I[l]h(t - lT) + j s_m^Q[l] h(t - lT - T/2)) e^{jm(2\pi/T+\pi/2)} \quad (19)$$

The output of the receiver can be written as

$$\hat{s}_k^I[n] = \text{real} [h(-t) * y_k(T)|_{t=nT}] \quad (20)$$

$$\begin{aligned}\hat{s}_k^I[n] &= \text{real} \int_{-\infty}^{\infty} y_k(\tau) h(-(nT - \tau)) d\tau \\ &= \text{real} \int_{-\infty}^{\infty} h(\tau - nT) y_k(\tau) d\tau\end{aligned}\quad (21)$$

where * denotes convolution and demodulated signal before matching.

$$y_k(\tau) = e^{-jk(\frac{\pi}{2} + \frac{2\pi}{T})} x(\tau) \quad (22)$$

substituting (18) in (22), we obtain

$$\hat{s}_k^I[n] = \text{real} \int_{-\infty}^{\infty} h(\tau - nT) \sum_{M=0}^{N-1} x_m(\tau) = e^{-jk(\frac{\pi}{2} + \frac{2\pi}{T})} d\tau \quad (23)$$

Futhermore ,substituting (18) in (23),

$$\begin{aligned}\hat{s}_k^I[n] &= \sum_{m=0}^{\infty} \sum_{l=0}^{N-1} \int_{-\infty}^{\infty} \text{real}[h(\tau - nT)] s_m^I[l] h(t - lT) \\ &\quad + j s_m^Q[l] h(t - lT - T/2) e^{jm(2\pi/T + \pi/2)} d\tau\end{aligned}\quad (24)$$

Further rearranging

$$\begin{aligned}\hat{s}_k^I[n] &= \sum_{-\infty}^{\infty} \sum_{m=0}^{N-1} \int_{-\infty}^{\infty} s_m^I[l] h(\tau - nT) h(\tau - lT) \cos((m - k) (\frac{2\pi\tau}{T} + \frac{\pi}{2})) \\ &\quad - s_m^Q[l] h(\tau - nT) h(\tau - lT - T/2) \sin((m - k) (\frac{2\pi\tau}{T} + \frac{\pi}{2})) d\tau\end{aligned}\quad (25)$$

Changing the variable $(\tau - nT)$ to τ and taking into account that l varies $-\infty$ to $+\infty$, (11) is rearranged as

$$\begin{aligned}\hat{s}_k^I[n] &= \sum_{-\infty}^{\infty} \sum_{m=0}^{N-1} \int_{-\infty}^{\infty} s_m^I[n + l] h(\tau - nT) h(\tau) \cos((m - k) (\frac{2\pi\tau}{T} + \frac{\pi}{2})) \\ &\quad - s_m^Q[n + l] h(\tau - lT - T/2) h(\tau) \sin((m - k) (\frac{2\pi\tau}{T} + \frac{\pi}{2})) d\tau\end{aligned}\quad (26)$$

Similarly the imaginary part $\hat{s}_k^Q[n]$ can be written as:

$$\hat{s}_k^Q[n] = \text{imag}[h(t + T/2) * y_k(t)|_{t=nT}] \quad (27)$$

$$\begin{aligned}\hat{s}_k^Q[n] &= \sum_{-\infty}^{\infty} \sum_{m=0}^{M-1} \int_{-\infty}^{\infty} s_m^I[n + l] h(\tau - nT) h(\tau) \sin((m - k) (\frac{2\pi\tau}{T} + \frac{\pi}{2})) \\ &\quad - s_m^Q[n + l] h(\tau - lT - T/2) h(\tau + T/2) \cos((m - k) (\frac{2\pi\tau}{T} + \frac{\pi}{2})) d\tau\end{aligned}\quad (28)$$

Under ideal transmission system, received signal equals to the transmitted signal

$$\begin{aligned}\hat{s}_k^I[n] &= s_k^I[n] \\ \hat{s}_k^Q[n] &= s_k^Q[n]\end{aligned}\quad (29)$$

For the design of the matched filter $h(t)$ is selected such that the above identities are satisfied :

$$\int_{-\infty}^{\infty} h(\tau - lT)h(\tau) \cos\left((m - k) \left(\frac{2\pi\tau}{T} + \frac{\pi}{2}\right)\right) d\tau = \delta[m - k, l] \quad (30)$$

$$\int_{-\infty}^{\infty} h(\tau - lT - T/2)h(\tau) \sin\left((m - k) \left(\frac{2\pi\tau}{T} + \frac{\pi}{2}\right)\right) d\tau = 0 \quad (31)$$

$$\int_{-\infty}^{\infty} h(\tau - lT)h(\tau + T/2) \sin\left((m - k) \left(\frac{2\pi\tau}{T} + \frac{\pi}{2}\right)\right) d\tau \quad (32)$$

$$\int_{-\infty}^{\infty} h(\tau - lT + T/2)h(\tau + T/2) \cos\left((m - k) \left(\frac{2\pi\tau}{T} + \frac{\pi}{2}\right)\right) d\tau = \delta[m - k, l] \quad (33)$$

where $\delta[m - k, l]$ is the Dirac delta function. $\delta[m - k, l]$ is one if $m - k = 0$ and $l = 0$ and it is zero otherwise. τ is a real and even function of time, τ .

The integrand in (32) is antisymmetric around $\tau = lT/2 + T/4$ and the integrand in (33) is anti-symmetric around $\tau = lT/2 - T/4$. It is assumed that only adjacent subcarrier bands may overlap. When this is the case only instances of m and k where $m - k = 0; +1; -1$. Values of m and k where $|m - k| > 1$ are related

To non adjacent subcarrier bands, and thus, their multiplication in (32) results in values close to zero. Also, for

$m - k = 0$, and if $h(\tau)$ is a root-Nyquist filter, (32) equates to

$$\int_{-\infty}^{\infty} h(\tau - lT)h(\tau) d\tau = \delta[0, l] = \delta[l] \quad (34)$$

For $m - k = +1, -1$ it reduces to

$$\int_{-\infty}^{\infty} h(\tau - lT)h(\tau) \sin\left(\frac{2\pi\tau}{T}\right) d\tau = 0 \quad (35)$$

The integrand in (35) under same conditions comes out to be anti-symmetric since, $h(\tau)$ is a symmetric filter and sine is odd with respect to origin. In precise, FBMC transceiver (SMT system) is realized following nyquist condition in (34) and designing $h(\tau)$ as even and real.

POLYPHASE STRUCTURE

Polyphase structures are commonly used to the FBMC transceiver. One polyphase structure per each set of real symbols, equivalent to two polyphaser structures per each pair of real symbol sets, should be implemented [20]. These are carried with the help of polyphase Analysis and Synthesis Filter Banks for SMT structures.

A. SMT transmitter

It is obtained by separating the phase and quadrature components of the filter banks, combining the phase shifts at different points in the structure and adding the combined results to the real data symbols, $s_k^I[n]$ and $s_k^Q[n]$.

The structure involves two separate polyphaser networks. In short they are modulated versions of two real vectors:

$$s_k^I[n] = [s_0^I[n] \ s_1^I[n] \ \dots \ s_{N-1}^I[n] \ 0 \ \dots 0]^T$$

$$s_k^Q[n] = [s_0^Q[n] \ s_1^Q[n] \ \dots \ s_{N-1}^Q[n] \ 0 \ \dots 0]^T$$

The corresponding delay of $T/2$ in the quadrature paths has been shifted to the corresponding filter bank output. Computational complexity of various types of Polyphase structures for SMT transmitters have been studied by the authors and have been implemented in order to reduce the complexity.

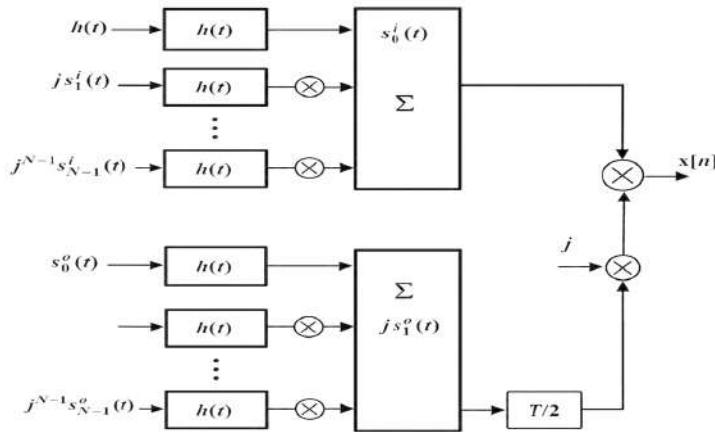


Figure 3. A polyphase SMT transmitter.

B. SMT Receiver

SMT Receiver action is used to extract the real-valued data symbols; the analyzed signals are the pre-equalized ones and, hence, are complex-valued^[21]. Various types of implementation structures are studied and evaluated in terms of reducing the complexity.

APPLICATION

A. Cognitive-radio systems

Up till now OFDM is the potential candidate for the physical layer in cognitive radio systems. But due to out of band radiation, high spectral leaks, low bandwidth rate due to implication of cyclic prefix and strict orthogonality conditions have drifted the technology towards multicarrier filter banks systems.

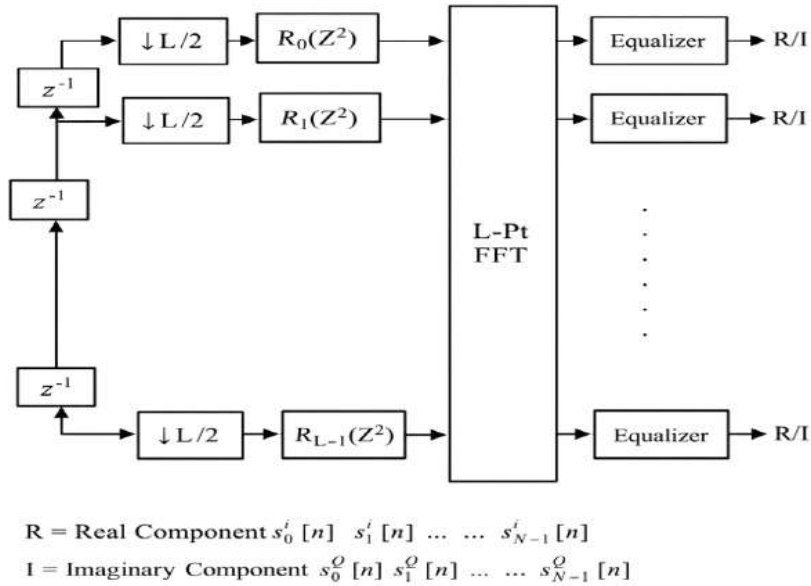


Figure 4. A SMT Receiver.

FBMC transceiver emphasis on efficient cognitive radio networks. All the unnecessary zero operations are eliminated at the transmitter by transform decomposition method. Whereas at the receiver analysis filter provides the spectrum sense algorithm. Cognitive radio systems work on the principle of primary (non-cognitive nodes) and secondary (cognitive nodes) transmitting independently which is implemented with the filter banks. Sensing algorithms are designed using synthesis and analysis filter and optimization is obtained with various filtering algorithm.

B. DSL and PLCs

In power line communications (PLC) community, wavelet OFDM has been adopted with the IEEE P1901 standard. To eliminate ingress and egress noises in DSL and PLC the use of DWMT is considered, since both DSL and PLC use unshielded copper lines that are subject to strong radio interference. Further in 1999, FBMC method with non-overlapping subcarrier bands was proposed as a solution for filtering the narrow-band interferences in very high-speed DSL (VDSL) channels. The studied technique was called as filtered multitone (FMT). This technique that was included as in the initial draft documents of VDSL was used for researchers in multicarrier communications.

C. Multiple-access communications

Access to OFDM is useful for downlink of a base station where all the sub carriers are transmitted from same point i.e. from base station and are easily synchronized. The synchronization issues arise in the uplink of OFDMA network. Here the sub carriers from all the mobile nodes arrive at the base station synchronously in terms of timing and frequency offset. After several reviews it is analysed that the timing and carrier frequency offset problems can be resolved using bank of filters that separate different users.

D. MIMO communications

Multicarrier transmissions particularly OFDM combine easily with MIMO techniques. Whereas in MIMO-FBMC systems, for moderate and highly frequency selective channels, received signals are corrupted by ISI, ICI and IAI(inter antenna interference) and equalization techniques adopted to mitigate the above is not an easy task. Also with imperfect channel state information(CSI), additional significant ICI/ISI terms appear in FBMC and not in OFDM. Out of the widely used three techniques CMT, SMT, FMT so far, in adopting the various MIMO techniques, only FMT-based FBMC can offer the same flexibility as OFDM.

E. Access to Television White Space(TVWS)

For opportunistic access to the white spaces, high flexibility, low adjacent leakage power ratio (ACLR), frequency agility, low out of band radiations and sharp spectrum roll off are important factors. In OFDM, implementing filter with various kinds of filtering technique drastically increases system complexity. Moreover, OFDM does not have the flexibility to address TVWS fragmented spectrum while FBMC can met the low spectrum leaks problems with adequate requirements and its performance is significantly better than OFDM.

CONCLUSION

FBMC excels from OFDM in terms of spectral leaks and better out of band radiations. By building FBMC systems based on well-designed prototype filters, the spectrum of each subcarrier can be obtained within a limited bandwidth. OQAM modulation where provides better spectral efficiency. The in-phase and quadrature components are then staggered in time by half a symbol period, $T/2$. Various kinds of polyphase structures for filter analysis and synthesis bank are used for FBMC transceiver which satisfy the Nyquist criteria for ideal filtering. This, in turn, allows transmission over non-contiguous bands, a property that makes FBMC an ideal choice for many applications, including the uplink of multiuser multicarrier networks and cognitive radios.

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