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Advanced Filter-Bank Multicarrier System for QAM Signal Transmission and Reception: A Survey

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Abstract— **Multicarrier modulations attract a lot of attention among researchers working in the field of telecommunications. One specific form of multicarrier modulation referred to as OFDM has been the dominant technology for broadband multicarrier communications. In spite of their many advantages, OFDM systems have a few, but important drawbacks. Filter bank multicarrier (FBMC) is an evolution with many advantages over the widespread OFDM multicarrier scheme. Filter banks are an evolved form of subband processing based on Fast Fourier Transforms and addressing some of its shortcomings, at the price of a somewhat increased implementation complexity. In this paper, a review of FBMC and its concept is presented, emphasizing its benefits over OFDM in applications such as Cognitive Radio(CR), Multiple access networks, TVWS, PLC and MIMO communication systems.**

Index Terms— **Filter-Bank Multicarrier (FBMC), Bit Error Rate (BER), FBMC/OQAM, Multicarrier. OFDM, CMT, SMT, Cognitive Radio.**

I. INTRODUCTION

Multicarrier modulation has marked its importance over the past several decades for the realization of broadband communication systems. Based on sending parallel streams of information in the frequency domain on different center frequencies, multicarrier modulation has exhibited its potential to transmit large amounts of data across a channel while improving the robustness of communication system against various impairments.

Among the existing multicarrier modulation systems, OFDM (orthogonal frequency division multiplexing) is the most widespread. OFDM has attracted a lot of attention because each subcarrier signal can be demodulated in the absence of inter carrier interference (ICI) and inter symbol interference (ISI) which is achieved by transmitting redundancy in the form of a cyclic prefix (CP). However, this is associated with the reduction in the spectral efficiency and also in certain applications such as cognitive radio and uplink of multicarrier systems; OFDM may be an undesirable solution [1]. One solution to this problem is to employ a multicarrier system referred to as FBMC [2].

In FBMC, a set of synthesis and analysis filters are designed such that they have both adequate spectral selectivity and bandwidth efficiency. Although each filter could be designed on an individual basis, a more efficient approach is to design a single prototype low pass filter and modulate it to several specified center frequencies to generate the synthesis and analysis filters

$$g^{(k)}(n) \text{ and } f^{(k)}(n), \text{ where } k = 0, 1, 2 \ldots\ldots(N-1)$$

Usually the filters are uniformly spaced, designed to be highly spectrally selective to minimize cross-talk with adjacent subcarriers, can either be odd stacked or even stacked; which implies, no center frequency at $\omega = 0$ rad/s[3].

II. ADVANCEMENT OF FBMC TECHNIQUES

Prior to OFDM, the first multicarrier methods that were developed, were based on filter bank. The first proposal came from Chang in the 1960s, who presented the conditions required for signalling a parallel set of Pulse amplitude modulated (PAM) symbol sequences through a bank of overlapping vestigial side band (VSB) modulated filters[4]. Saltzberg extended the idea and showed how the Chang's method could be modified for transmission of Quadrature amplitude modulated (QAM) symbols[1]. In 1980s, Hiroshaki progressed more on FBMC and proposed an efficient polyphase implementation for the Saltzberg method[5]. The method proposed by Saltzberg is referred to as OFDM based on offset QAM or OFDM-OQAM. This method is also referred to as staggered modulated multitone (SMT).

In the 1990s, the evolution in digital subcarrier line (DSL) technology led to more work on two classes of FBMC communication systems, namely filtered multitone (FMT) and discrete wavelet multitone (DWMT) modulation [6]. More recently, in [7] it has been shown that DWMT is essentially using cosine modulated filter banks. Therefore, DWMT was renamed to cosine modulated multitone (CMT).

Filtered Multitone (FMT) is another multicarrier communication scheme which has been proposed for DSL applications [8].In this scheme, the adjacent subcarriers do not overlap as they are separated by guard bands. Hence, FMT is less bandwidth efficient than the FBMC methods.

Multicarrier modulation, MCM is a technique for transmitting data by sending the data over multiple carriers. Multicarrier modulation operates by dividing the data stream to be transmitted into a number of lower data rate data streams. Each of the lower data rate streams is then used to modulate an individual carrier.

When the overall transmission is received, the receiver has to then re-assembles the overall data stream from those received

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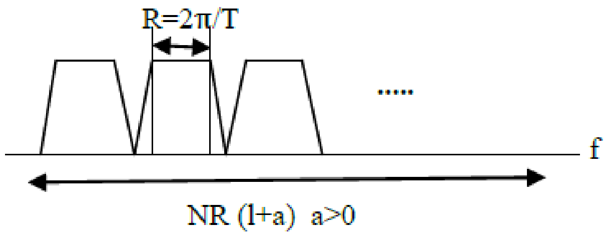
on the individual carriers. It is possible to use a variety of different techniques for multicarrier transmissions.

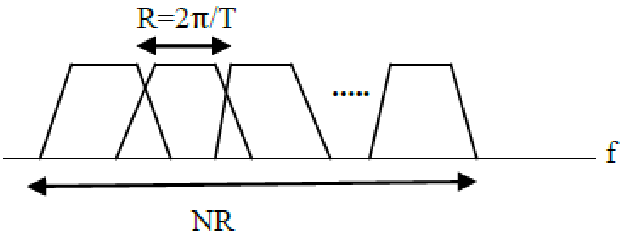
III. FMT, OFDM-OQAM & CMT TECHNIQUES

In OFDM-OQAM, each subcarrier band is double sideband modulated and carries a sequence of QAM symbols. Whereas, in CMT, subcarrier modulation is vestigial sideband which carries a sequence of PAM symbols. Therefore, assuming identical symbol duration and number of subcarriers, the CMT signal occupies half the bandwidth of OFDM-OQAM, hence providing only half of its data rate.
However, FMT introduces guard bands between adjacent subcarriers which are complex modulated. Hence, FMT requires more bandwidth compared to SMT and CMT [9].The relationship between the three techniques are given in figure 1.

Filtered Multitone (FMT):



OFDM-OQAM:



CMT:

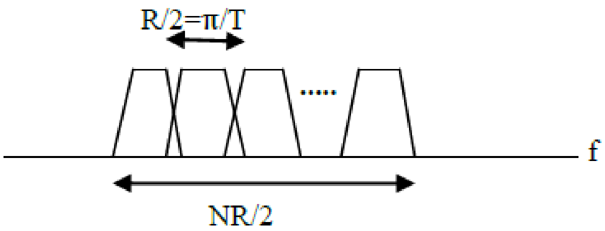


Figure 1: FMT, OFDM-OQAM & CMT

Filtered multitone (FMT) is a multichannel modulation scheme in which the subchannels are synthesized using a modulated filterbank structure. The high level of spectral containment achieved by FMT enables independent processing of the subchannels by the receiver, and makes it a potential candidate for broadband communication systems in which there is a need to mitigate the impact of frequency selectivity, narrowband interference, crosstalk, or regulatory spectral masks; e.g., digital subscriber lines (DSL) [2]. Indeed, it has been shown [1] that for long DSL cables, the achievable rate of FMT is larger than that of discrete multitone (DMT) modulation. FMT system works similar to a conventional frequency division multiplexing method. There is no overlap between adjacent subcarriers and thus there is no ICI. The reconstruction properties on each subcarrier can be derived similarly to single carrier communication systems. Therefore, a square-root Nyquist filter can be used for pulse shaping. As such, FMT may be seen as a multicarrier communication technique that follows
the principle of the legacy frequency division multiplexing (FDM) methodology to separate a high-rate data stream into a number of disjoint frequency bands.
However, we note that in order to keep the subcarrier bands nonoverlapping, excess bandwidth has to be reserved to allow for a transition band for each subcarrier. Hence, there is some bandwidth loss due to the guardbands in FMT communication systems.

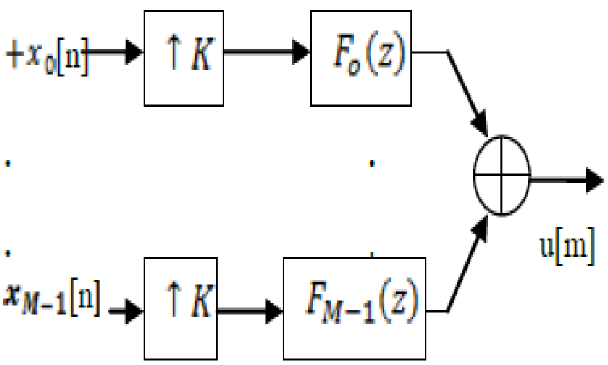
The classic OFDM employing baseband quadrature amplitude modulation and rectangular pulse shape, denoted OFDM/QAM, is most commonly used in today's applications which refers to OFDM. In an ideal channel where no frequency offset is induced, intercarrier interference (ICI) can be fully removed by orthogonality between sub-carriers. Intersymbol interference (ISI), which is caused by multipath propagation, can also be eliminated by adding a guard interval, which is longer than the maximum time dispersion. On the other hand, such guard interval (cyclic prefix) costs a loss of spectral efficiency and increases power consumption. In order to achieve better spectral efficiency and meanwhile reducing combined ISI/ICI, another OFDM scheme using offset QAM for each sub-carrier, denoted OFDM/OQAM, is of increasing importance over OFDM/QAM in time and frequency dispersive channels. Contrary to OFDM/QAM which modulates each sub-carrier with a complex-valued symbol, OFDM/OQAM modulation carriers a real-valued symbol in each sub-carrier and consequently allows time-frequency well localized pulse shape under denser system.

OFDM or, more precisely, (CP-OFDM) [6, 14, and 18] is a family of multicarrier transmission techniques enriched with many inherent properties. Efficient use of spectrum, robustness against frequency-selective fading, resistance to both ISI and ICI (with the aid of guard intervals and cyclic prefixes) and capability of being implemented using Fast Fourier Transform (FFT) techniques can be highlighted as some of the key merits of it. The critical and limiting drawbacks of OFDM, however, include higher peak-to-average power ratio (PAPR), higher sensitivity for carrier frequency offset (CFO) errors, larger number of side lobes with non negligible power levels, inevitable overhead due to cyclic prefixes (or guard intervals) and extra time consumed due to guard intervals. Due to these considerations, OFDM is still a commendable and impressive topic where any sort of discussion on transmission techniques takes place. FBMC, which is also known as orthogonal frequency division multiplexing / offset quadrature amplitude modulation (OFDM / OQAM) [11], [19]-[21] is a result of endeavors to overcome the inherent demerits associated with OFDM. Neither guard intervals nor cyclic prefixes are needed by design. Comparatively higher throughput is expected to be maintained with a continuous and efficient transmission. Another main advantage is much more efficient use of spectrum with lower spectral leakages or reduced amount of power associated with side lobes, where the robustness against ICI is increased due to that. FBMC is supported by some theories of multirate techniques [22], [23] and theories of well-localized filter design [19], [24]-[28]. Therefore, the success of this particular category of communication techniques is strongly dependent on aforementioned associated technologies. For this reason, it is very important to study their developments while exploring how to integrate them to FBMC.

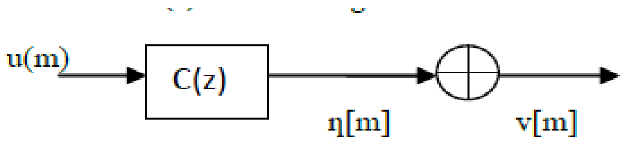
In a Cosine Modulated Multitone (CMT) multicarrier system, parallel streams of real data symbols are transmitted using a set of vestigial side-band (VSB) subcarrier channels. Each carrier conveys a stream of pulse amplitude modulated (PAM) symbols. This scheme also has the maximum possible bandwidth efficiency. In a CMT system, in order to transmit N complex symbols on each multicarrier symbol, a system with 2N subcarrier is implemented where each carrier conveys a real symbol, while, in an SMT system the transceiver would have N subcarriers that convey N complex symbols. If SMT symbols are transmitted at the rate of 1/T complex symbols on each subcarrier with a bandwidth of 1/T , an equivalent CMT system with the same data rate, would have a rate of 1/T real symbols on each subcarrier with the bandwidth of 1/2T. Therefore, the same bandwidth is divided into twice as many subcarriers in case of CMT to achieve the same data rate.

IV. CONCEPT OF A FILTER BANK TRANSCEIVER

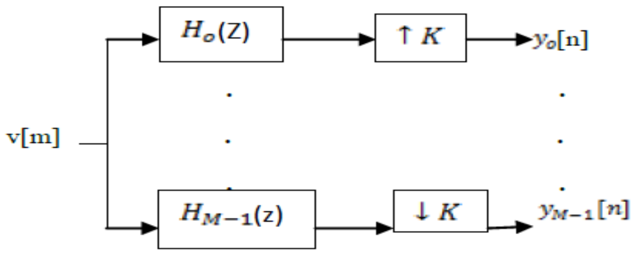
A filter bank transceiver consists of two filter banks, one at the transmitting end (termed as synthesis filter) and the other at the receiving end (termed as analysis filter). A filter bank contains M digital filters arranged in a parallel configuration. These filters are employed with K-fold digital upsamplers at the transmitter denoted by K, and with K-fold decimators at the receiver, denoted by K.To emphasize the multirate nature of the system, two time indices, n and m are used to denote the time samples corresponding to the low sampling rate(symbol rate) and the high sampling rate (channel rate), respectively. There exist many types of filter banks depending on how the filters are designed. In fig.2, the input bit stream is assumed to have already partitioned appropriately and mapped to constellation symbols $X_0(n)$ …………… $X_{M-1}(n)$. In practical implementations, to combat intersymbol interference (ISI) due to the presence of a frequency selective channel, the symbols at the output of the receiving filter bank, $Y_0(n)$ …………… $Y_{M-1}(n)$, needs equalization.



(a)Transmitting filter bank



(b) Communication Channel



(c)Receiving filter bank

Figure 2: Filter bank Transceiver

The additional complexity brought by the filter bank in the FBMC receiver can be expressed by taking the FFT of the OFDM receiver as the reference. It depends on the number M of the subchannels in the system and the overlapping factor K. The relationship between M and K is important. Three cases can occur [10].

1) K = M. The transceiver is minimally interpolated,i.e., non-redundant.
2) K > M. The transceiver is over-interpolated,i.e., redundant.
3) K < M. The transceiver is under-interpolated. In this case, some information will be lost. This case is not suitable for practical application.

In case of OFDM transceiver, it utilizes redundancy to equalize an FIR channel. In case FBMC, since the subchannels are well separated, high level narrowband disturbing signals or jammers affect only a few subchannels. Therefore, efficient subchannel equalizer can be used and constraints on synchronisation are relaxed. The subchannel equalizer can be implemented in frequency domain or in the time domain, depending on the receiver filter bank implementation.

V. COMPLEXITY AND COMPATIBILITY OF OFDM-FBMC

FBMC systems are complex when compared to OFDM. The increase in complexity is due to the exchange of the IFFT/FFT by the filter banks. The number of real multiplications per modulation symbol as meausre are used to compare OFDM and FBMC. With OFDM, when applying the Split-Radix algorithm we have,

$$C_{FFT/IFFT} = M*(\log(M) - 3) + 4$$

With FBMC, the number of real multiplications per complex symbol can be calculated approximately for the synthesis(SFB) and analysis filter bank(AFB) as follows:

$$C_{SYNTHESIS} = \log_2(M/2) - 3 + 4K$$
$$C_{ANALYSIS} = 2(\log_2(M) - 3) + 4K$$

Since OFDM and FBMC are multicarrier techniques based on the FFT operation, a high degree of compatibility can be obtained if the frequency pattern is the same for both approaches, particularly at initialization. They have a common core, and software defined transmitters and receivers can be efficiently implemented. However, due to the presence of the cyclic prefix in OFDM, the streaming of the signals is different.

Esentially,filter banks offfer more degrees of freedom which can be exploited to mitigate certain issues associated with OFDM. For instance, OFDM sufers from poor spectral selectivity since the frequency response of adjacent subchannels overlap significantly with each other.

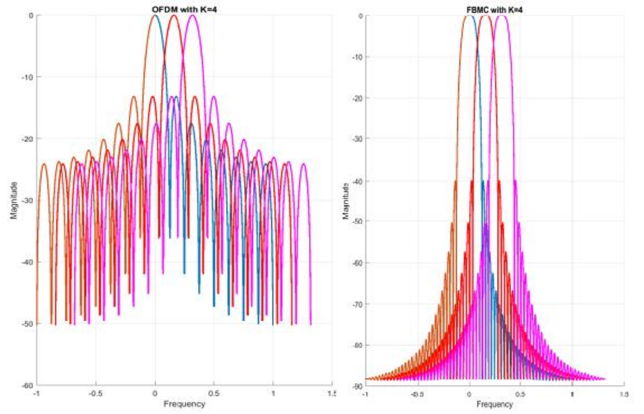


Figure 3: Spectrum of OFDM and FBMC subchannels

The poor spectral selectivity may pose problems in the presence of narrowband noise because subchannels adjacent to the narrowband noise will provide a rather poor attenuation which can severely affect the performance of OFDM. In this case, filter banks can be designed to provide much better spectral selectivity. At a more fundamental level, the problem of selecting the optimal transformation that minimizes the bit error rate for a given transmitted power can be considered using the filter bank framework. Figure 3 shows the spectra of OFDM and FBMC subchannels and concludes that consumption of power is less in FBMC than OFDM.

VI. ADVANTAGES AND CHALLENGES

Advantages

1) Efficient usage of the allocated spectrum: FBMC technique, cyclic prefix is not required and also exploits the totality of the symbol period.

2) The same filter bank can be used for receiver data signal processing and flexible, high resolution spectrum sensing with high dynamic range.

3) High performance spectrum sensing and transmission: Due to the spectral subchannel separation, the functions of spectrum analysis and data transmission can be mixed and performed simultaneously. This serves as a remarkable facility for efficient opportunistic communications.

4) Robustness to narrowband jammers and impulse noise.

5) Spectral protection of neighboring users: The out of band attenuation curve of the prototype filter sets the level of spectral protection to the users.

Challenges

1) High computational complexity is associated with FBMC implementation when compared to OFDM. The time domain overlap of subcarrier symbols in filter bank introduces overhead in tightly time multiplexed operation.

2) Analog RF performance is critical for implementing generic spectrum sensing with wide bandwidth and high dynamic range.

3) The development of MIMO-FBMC system is nontrivial and may be very limited.

VII. APPLICATIONS

Cognitive Radio*:* Compared to OFDM, FBMC offers higher spectral efficiency and is more applicable for the CR network with small size of spectrum holes and also the performance of FBMC is close to that of the perfectly synchronized case because of its frequency localization.

Multiple Access Networks: In the multiuser context, the uplink of an OFDM network employs a method called multiple access interference (MAI) cancellation in order to meet its basic operational requirements i.e. tight time and carrier synchronization which increases implementation complexity of the system. On the other hand FBMC avoids MAI without any need to perform synchronization.

Access to Television White Space (TVWS): For opportunistic access to the TVWS, flexibility, low adjacent leakage power ratio (ACLR), frequency agility and sharp spectrum roll off are important factors. In OFDM, implementing filter for avoiding non agile RF filters dramatically increases system complexity. Moreover, OFDM does not have the flexibilty to address TVWS fragmented spectrum while FBMC can met the ACLR co-existence requirements and its performance is significantly better than OFDM.

Power Line Communication: The intrinsic properties of FBMC makes it well suited for broadband power line communication. In addition to its capability of fully exploitating the time and the channel bandwidth, they also offer high level of protection for the tones and are robust to jammers.Due to the absence of cyclic prefix, the streaming of data is regular in case of FBMC.

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. So far, in adopting the various MIMO techniques, only FMT-based FBMC can offer the same flexibility as OFDM.

VIII. CONCLUSION

In this paper, a multicarrier modulation technique, FBMC evolved from OFDM, the most widely deployed technique for multicarrier communication is presented. FBMC outclasses OFDM in terms of spectral efficiency, robustness and spectral protection at a cost of somewhat increased complexity. These superior qualities of FBMC make it an ideal choice for CR communications, multiple access networks, TVWS and PLC. Whereas FMT is the only FBMC system that can be efficiently extended for transmission over MIMO channels so far.

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