DESIGN OF M-BAND COMPLEX-VALUED FILTER BANKS FOR MULTICARRIER TRANSMISSION OVER MULTIPATH WIRELESS CHANNELS

Yuhong Wang and Xiao-Ping Zhang
Department of Electrical and Computer Engineering
Ryerson University, 350 Victoria Street
Toronto, Ontario, Canada, M5B 2K3

Email: xzhang@ee.ryerson.ca

ABSTRACT

The orthogonal M-band complex-valued filter banks have more flexibility in terms of frequency response. In this paper, a new general design method for orthogonal M-band complex-valued filter banks is presented for multicarrier (MC) transmission to reduce intersymbol and interchannel interference (ISI and ICI). The design includes three procedures. First, a parameterization method is used to design the baseband scaling filter. Then the *M*-1 bands wavelet filters are deduced based on the scaling filter by a Gram-Schmidt algorithm. Thirdly, a numerical optimization method is developed to determine the free parameters and coefficients of the filter banks based on an objective to minimize the intersymbol and interchannel interference power for a multipath wireless channel. Simulation results demonstrate that the MC system based on the designed M-band complex-valued filter banks has superior performance to that of discrete Fourier transform (DFT) based orthogonal frequency division multiplexing (OFDM) and discrete wavelet multitone (DWMT) in terms of the interference power over a multipath channel.

1. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is the most commonly used multiplexing method in a multicarrier (MC) system, since it is desired that the modulation filters in a MC system form a set of orthogonal basis function. The conventional OFDM uses discrete Fourier transform (DFT) to achieve the desired orthogonality of modulation filters. DFT based OFDM has significant spectral overlaps among subchannels since it employs rectangular pulse as data modulation [1]. Hence, it may exhibit significant intersymbol and interchannel interference (ISI and ICI) over communication channels. The M-band wavelet transform is a good candidate to modulation filters of OFDM because of the inherent orthogonality among its bases [2-4] and the flexibility to design filter banks in the modulator and demodulator to reduce ISI and ICI over channels. Orthogonal wavelet filter banks based OFDM, also known as discrete wavelet multitone (DWMT), has proved to have more flexibility in terms of the spectral shape of the prototype filters [1]. In DWMT system, filter banks are designed to minimize the ICI by decreasing the side lobe energy of the filter banks in the modulator and demodulator. While DWMT system has more flexibility in filter design and appears to be able to achieve better ICI deduction, the ISI over channels are not considered and so far only real-valued filter banks are used.

In this paper, we present a new OFDM system based on orthogonal M-band complex-valued filter banks associated with M-band wavelet transform. Unlike real-valued filters, complex-valued filters can have asymmetric frequency response and are more suitable to deal with complex-valued signals which are often present in a wireless system. In this system, the scaling filter of M-band wavelet transform is formulated according to the parameterization algorithm introduced by [2], and then the *M*-1 wavelet filters are obtained by a Gram-Schmidt process based on the scaling filter such that the filter bank is orthogonal. Since Gram-Schmidt process can be done in more than one way for a given scaling vector, there is flexibility in choosing wavelet filter vectors according to specific applications. Moreover, because of the existence of free parameters, the design of wavelet transform can be optimized through numerical methods towards various objective functions. In this paper, simulation is done by taking the power of ISI and ICI introduced by a wireless multipath channel as the objective function. The simulation results show that the designed OFDM scheme based on complex-valued filter banks can significantly reduce the power of interference compared to DFT-based OFDM and DWMT.

2. DESIGN OF M-BAND COMPLEX-VALUED WAVELET FILTER BANK

A typical communication system based on multirate filter banks is shown in figure 1 [6]. There are different realizations for the transmitting filter bank $[f_0(n), f_1(n), \cdots, f_{M-1}(n)]$ and receiving filter bank $[h_0(n), h_1(n), \cdots, h_{M-1}(n)]$. These realizations include DFT matrix, extended orthogonal transform and M-band wavelet transform. The M-band complex-valued wavelet filter bank is used in this paper because of its flexible frequency response and advantages to process complex-valued signals.

2.1 Parameterization of the Scaling Filter

The parameterization of the scaling filter $h_0(n)$ for M-band complex-valued wavelet filter bank can be summarized as following [5]. The z-transform of $h_0(n)$ can be formulated in polyphase form as:

$$H_0(z) = \sum_{k=0}^{M-1} z^{-k} H_{0,k}(z^M). \qquad (1)$$

The polyphase vector is defined as:

$$h_0(z) = [H_{0,0}(z), H_{0,1}(z), ..., H_{0,M-1}(z)]^T. \qquad (2)$$

It can then be decomposed as:

$$h_0(z) = V_{J-1}(z) V_{J-2}(z) .... V_1(z) V_0, \qquad (3)$$

where

$$V_n(z) = I - v_n v_n^H + z^{-1} v_n v_n^H \qquad (4)$$

and

$$V_0 = e^{j\varphi_0} \cdot \left[\frac{1}{\sqrt{M}}, \frac{1}{\sqrt{M}}, ..., \frac{1}{\sqrt{M}} \right]^T, \qquad (5)$$

where J-1 is McMillan degree of vector polynomial $h_0(z)$ and v_n, $n = 1,2,\cdots,J-1$ are $M \times 1$ unit vectors. Each v_n can be further factorized as:

$$v_{n,j} = \left[\prod_{k=0}^{j-1} \sin(\theta_{n,k}) \right] \cos(\theta_{n,j}) \exp(j\varphi_{n,j})$$

when j=0,…,M-2, and

$$v_{n,M-1} = \prod_{k=0}^{M-2} \sin(\theta_{n,k}), \qquad (6)$$

i.e., v_n can be determined by $2(M-1)$ angle parameters and therefore, scaling filter h_0 is determined by 2(J-1)(M-1)+1 angle parameters φ_0, $\theta_{n,j}$ and $\varphi_{n,j}$, $j = 0,1,\ldots,M-2$, $n = 0,1,...,J-1$. The length of h_0 is $N=JM$.

2.2 Design of Wavelet Filters by Gram-Schmidt Algorithm

The design of M-band wavelet transform includes design of scaling filter h_0 and design of wavelet filters $h_1, h_2, \cdots, h_{M-1}$. For any given scaling filter, the only requirement for M-1 band wavelet filters is that wavelet filters and scaling filter together form a unitary filter bank [2, 3], i.e., if we take coefficients of each filter as a row vector then M vectors from scaling and wavelet filters form a unitary matrix. One way to generate wavelet filters for a given scaling filter is to find M-1 unitary orthogonal vectors which are also orthogonal to the scaling filter. This can be done by a Gram-Schmidt process in $\binom{M-1}{2}$ ways.

We propose to design M-band wavelet filters using the DFT matrix. Construct a (M-1)×N matrix

$$R = \left[\Phi, \mathbf{0}_{(M-1)\times(N-M+1)} \right]$$

where Φ is an (M-1)×(M-1) DFT matrix with element

$$\Phi_{nk} = \sqrt{\frac{1}{M-1}} e^{-j2\pi(k-1)\cdot(n-1)}, k, n = 1,2,\ldots,M-1.$$

Since matrix R is a full-rank matrix and its rows are independent with the scaling vector (filter) h_0, the following Gram-Schmidt procedures are used to obtain the wavelet filters h_l:

$$h_l = \frac{r_l - \sum_{i=0}^{l-1} \langle r_l, h_i \rangle \cdot h_i}{\left\| r_l - \sum_{i=0}^{l-1} \langle r_l, h_i \rangle \cdot h_i \right\|}, \quad l=1,\ldots,M-1,$$

where r_l, $l = 1,2,\ldots,M-1$, are row vectors of R. The operator $\langle \cdot \rangle$ means inner product and $\|\cdot\|$ means absolute value.

To make the filter bank in figure 1 a perfect reconstruction filter bank, the transmitting filters and receiving filters should satisfy the biorthogonality property [6]. In the case of M-band wavelet transform, the biorthogonality property is maintained with the following formula:

$$f_k(n) = h_k^*(-n).$$

3. OPTIMIZATION OF FILTER BANKS FOR MULTIPATH CHANNELS

3.1 Optimization of M-Band Wavelet Filter Bank

The non-uniqueness in the generation of wavelet filters provides flexibility in the design of M-band wavelet transform. The choice of wavelet filters for different applications is an optimization process. Moreover, the free parameters introduced by (6) provide the possibilities to optimize the design of modulator and demodulator filter banks towards specific objective functions using numerical methods.

A conjugate gradient method is used for filter bank optimization. Note that the optimization may fall into a local minimum. Some global optimization methods such as adding random interference and simulated annealing may be used. However, in practice, a local minimum may be satisfactory as well.

3.2 Numerical Simulations for a Multipath Wireless Channel

In this section, we take power of interference caused by multipath wireless channels as the objective function. Without loss of much generality, we assume the impulse response of a two-path channel is $h_{ch} = \delta(n) + \beta \cdot \delta(n-p)$. The second path is a reflected path with positive integer delay p, and β is the reflection parameter. Without considering channel noise, the normalized ISI and ICI powers for subchannel j are:

$$P_{ISI_j} = \beta \cdot \sum_{m=-\infty}^{\infty} \left| h_{jjp}(Mm) \right|^2 \quad (7)$$

and

$$P_{ICI_j} = \beta \cdot \sum_{\substack{k=0 \\ k\neq j}}^{M-1} \sum_{m=-\infty}^{\infty} \left| h_{jkp}(Mm) \right|^2 , \quad (8)$$

respectively, where $h_{jkp}(n) = f_k(n-p) * h_j(n)$. We take the weighted sum of ISI and ICI power averaged over M subchannels as our objective function, which is defined as:

$$P_{AV} = \frac{1}{M}\left(\alpha \cdot \sum_{j=0}^{M-1} P_{ISI_j} + (1-\alpha) \cdot \sum_{j=0}^{M-1} P_{ICI_j} \right), \quad (9)$$

where $\alpha \in [0,1]$ is a constant weight parameter and can be chosen according to the predominance of ISI or ICI of different digital channels.

Figure 2 shows the simulation results of P_{AV} for the DFT-based OFDM, DWMT and the OFDM based on M-band complex-valued filter bank which is designed according to the method described above with $\alpha = 0.5$, $\beta = p = 1$. The length of filters, N, for DFT-based OFDM, DWMT and M-band complex-valued filter banks are M, $2M$ and $2M$, respectively. When $\alpha = 0.5$, DFT-based OFDM and DWMT have identical performance because filters of both systems are generated by equally shifting real prototype filters and both have unit energy. According to (7)-(9), P_{AV} is power of the downsampled filters which is a constant. Figure 3 shows simulation results for $\alpha = 0.8$, where DWMT displays better results than DFT-based OFDM. In both experiments, the M-band complex-valued filter bank demonstrates superior performance in interference reduction than DFT-based OFDM and DWMT.

It is noted that when increasing the filter length, the M-band complex-valued filter bank has better performance in case of average power of interference. Table 1 and 2 show the change of average power of interference with the increase of filter length N. Parameters α, β and p are the same as they are in Figure 2 and 3, respectively.

4. CONCLUSIONS

In this paper we presented a general design method for a new OFDM system based on orthogonal M-band complex-valued filter banks, which have more flexible frequency response and are more suitable to deal with complex-valued signals present in wireless systems. This method provides flexibility in choosing OFDM subchannel carriers for different applications by optimizing filter banks towards required objective functions. Simulation was done by minimizing ISI and ICI power in a multipath wireless channel. Simulation results show that the designed filter bank has better performance over DFT-based filter bank and DWMT systems in case of average power of interference. It is also shown that average power of interference can be further reduced by using longer filters in the proposed M-band complex-valued filter banks.

5. REFERENCES

[1] S.D. Sandberg and M.A. Tzannes, “Overlapped discrete multitone modulation for high speed copper wire communication,” IEEE Journal on Selected Areas in Communications (JSAC), vol. 13, no.9, pp. 1571-1585, Dec 1995.

[2] H. Zou and A.H. Tewfik, “Discrete orthogonal m-band wavelets decompositions,” Proc. Of ICASSP’92, vol. 4, pp 605 -608, May 1992.

[3] P. Steffen, P. Heller, R. Gopinath, and C.S. Burrus, “Theory of regular m-band wavelet bases,” IEEE Trans. Signal Processing, vol. 41, no.12, pp. 3497 -3511 Dec 1993.

[4] H. S. Malvar, “Extended lapped transforms: properties, applications, and fast algorithms,” IEEE Trans. Signal Processing, vol.40, no.11, pp. 2703-2714, Nov 1993.

[5] X.-P. Zhang, M. Desai and Y.-N. Peng, “Orthogonal complex filter banks and wavelets: some properties and design,” IEEE Trans. Signal Processing, vol.47, no. 4, pp. 1039 -1048, Apr. 1999.

[6] P.P. Vaidyanathan, “Filter banks in digital communications,” IEEE Circuits and Systems Magazine, vol.1, no. 2, pp. 4-25, 2000.

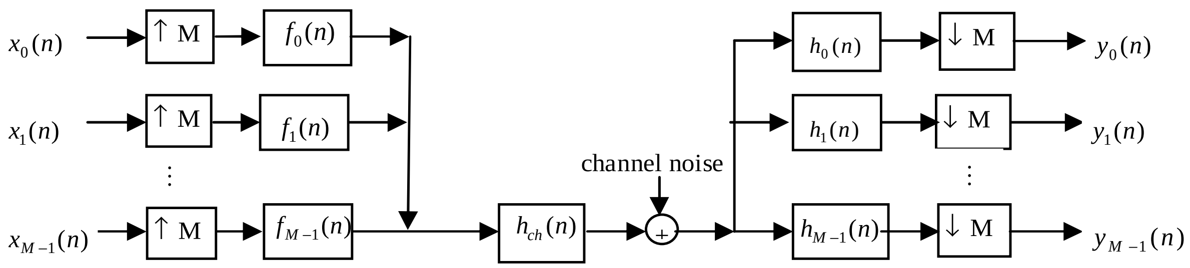

Figure 1. M-band Multirate filter bank based communication system

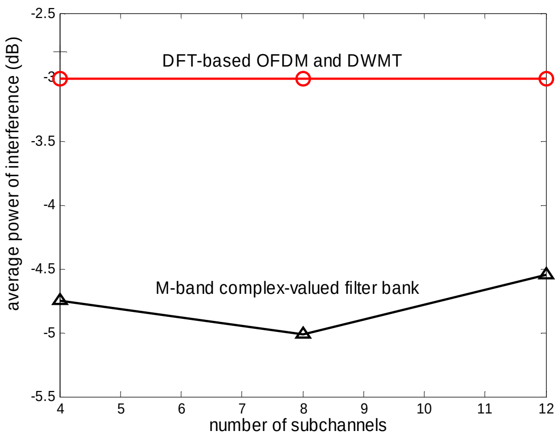

Figure 2. Average power of interference for DFT-based OFDM, DWMT and the new OFDM system based on M-band complex-valued filter bank $(\alpha = 0.5)$.

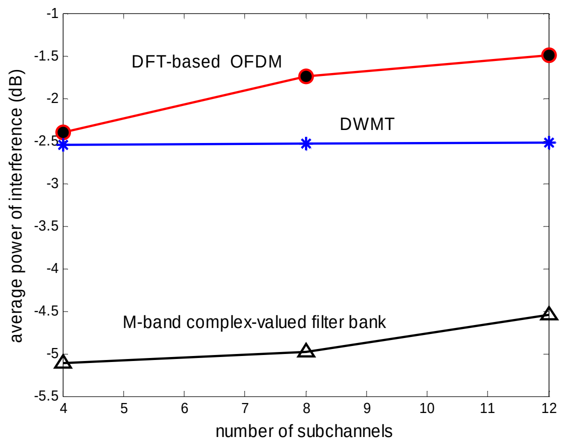

Figure 3. Average power of interference for DFT-based OFDM, DWMT and the new OFDM system based on M-band complex-valued filter bank $(\alpha = 0.8)$.

Table 1 Average power of interference (in dB) $(\alpha = 0.5, \beta = p = 1)$

Filter bank	Filter length	Number of subchannels		
		M=4	M=8	M=12
M-band Complex-Valued	2M	-4.7472	-5.0143	-4.5507
	3M	-5.3087	-5.4212	-5.5921
	4M	-5.8135	-6.1306	-5.7335
DFT-based	M	-3.0103	-3.0103	-3.0103
DWMT	2M	-3.0103	-3.0103	-3.0103

Table 2 Average power of interference (in dB) $(\alpha = 0.8, \beta = p = 1)$

Filter bank	Filter length	Number of subchannels		
		M=4	M=8	M=12
M-band Complex-Valued	2M	-5.1195	-4.9812	-4.4841
	3M	-5.6978	-5.9702	-4.7431
	4M	-5.9439	-6.5103	-5.1542
DFT-based	M	-2.4036	-1.7409	-1.4983
DWMT	2M	-2.5438	-2.5312	-2.5204