EE678-Application Assignment
Discrete Wavelet Multitone Modulation

Group Members:

Chirag Jain	chiragjn@ee.iitb.ac.in	01D07018
Abhijeet Bhorkar	bhorkar@ee.iitb.ac.in	01D07014
Namita Dalmia	namita@ee.iitb.ac.in	01D07004

Abstract

The idea of breaking the channel into a number of subchannels for transmitting the data is not a new concept in the sphere of analog or digital communication. In fact, it has been used in various forms in transmitting data over the channel. The multicarrier modulation uses the same concept, but in a more elegant and refined manner. Multi-Carrier Modulation (MCM) is the principle of transmitting data by dividing the data stream into several parallel bit streams. Orthogonal Frequency Division Multiplexing (OFDM) is a special form of MCM with densely packed subcarriers having overlapping spectra which are orthogonal to each other. The DMT circumvents the same concept by using a single IDFT and DFT blocks which elegantly achieves the modulation and the demodulation of the message signal. The main challenge lays in designing a good filter bank for this purpose. The wavelet based DWMT exactly promises a better performance on the account of the spectral containment features of the filter responses. This report studies the wavelet based MCM and the advantages it offers.

Index Terms

MCM, OFDM, DMT, DWMT, Wavelet, ICI, ISI

I. Introduction

A multicarrier system uses a transmission band effectively by dividing it into number of subchannels that are totally independent and spectrally isolated. In practice, implementations of multicarrier systems use orthogonal digital transformations on block of data, a process called subchannelization, in an attempt to achieve the frequency partitioning. Also the modulation technique in each subchannel can be adjusted according to the response of the channel. OFDM time domain waveforms are chosen such that the mutual orthogonality is ensured even if subcarrier spectrums overlap. However, the process of creating so many subcarriers at the transmitting end and again the need for generating so many subcarriers at the receiving end was far from being attractive. But with the progress in digital signal processing and features like the discrete Fourier transform (DFT) using FFT, implementation of such system became feasible. The DFT though improved the elegance of the system with its reduced complexity, had its own demerits. Amongst many, the main disadvantage was its considerable overlapping with the adjoining subchannels which gave rise to inter channel interference (ICI). The discrete wavelet multitone modulation, with its better spectral containment properties, promised a better performance due to reduced ICI. In the following section, we will discuss discrete multitone modulation (DMT) and discrete wavelet multitone modulation (DWMT) with a comparison which emphasizes the upper hand of DWMT over DMT by virtue of its superior immunity to narrow band interference.

II. Background Theory

Ideally, the channel is assumed to possess infinite bandwidth with a constant gain and phase delay. However, the practical channels are noisy and bandlimited. As a result the received sequence is usually an attenuated and distorted version of the transmitted sequence (mainly due to noise introduced by the channel). Further there are distortions caused due to inter symbol interference (ISI), crosstalk noise, narrow band interference, etc., which are likely to affect a particular subchannel more than others. Thus, at the very outset the signal to noise ratio is not the same for all

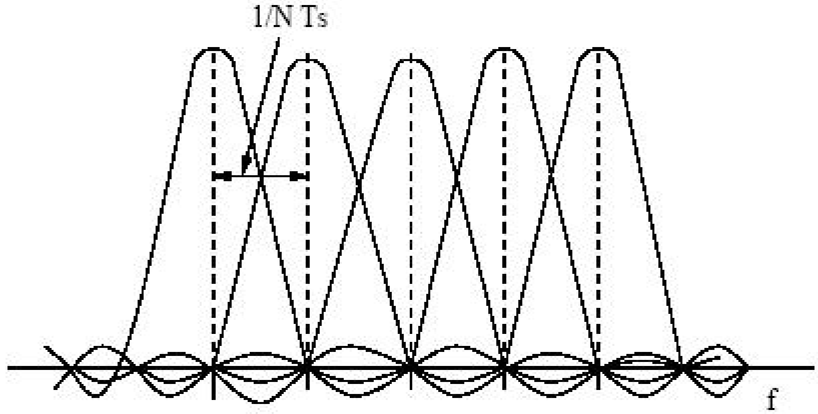

Fig. 1. Frequency Spectrum of an Orogonal Frequency Domain Multiplexing Symbol

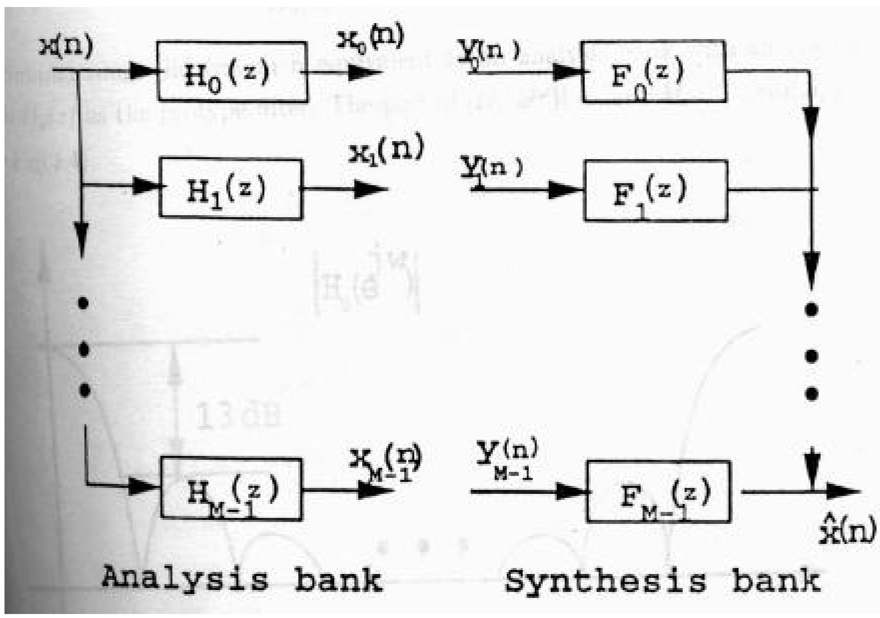

Fig. 2. Block Diagram of Analysis and Synthesis Filter Bank

the subchannels over the entire bandwidth. The multicarrier modulation precisely underscores this fact and deviates from the transmultiplexer by optimally allocating the bits tailored to the signal to noise ratio (SNR) of the respective subchannels, while in the transmultiplexer all the subchannels are allocated the same number of bits, irrespective of their SNR.

In DMT, we use densely packed subcarriers having overlapping spectra which are orthogonal to each other. In this, the sub-carrier pulse used for transmission, is chosen to be a truncated sine wave. This has slight advantage because the task of pulse forming and modulation can be performed by a simple IDFT, which can be implemented efficiently using IFFT and accordingly in the receiver, we only need a FFT to reverse this operation. According to the theorems of the Fourier Transform, these pulses will lead to a sinc(x) type of spectrum of the sub-carriers as shown in Figure 1. Figure 2 represents a conceptual method of generating OFDM, where for $0 \leq t \leq T$, $\phi_n(t)$ can be thought of sinusoids or exponentials of the form

$$\phi_n(t) = \frac{1}{\sqrt{T}} e^{j2\pi \frac{W}{N} kt} \tag{1}$$

These exponentials are spaced W/N Hz apart, where W is the available bandwidth. Each carrier is scaled by a complex constellation value x_{nm} from the input data. The subscript n corresponds to the index number of the carrier and m is the index of the entire symbol. The constellation points are generally taken from M-ary Quadrature Phase Shift Keying (QPSK) or M-ary Quadrature Amplitude Modulation (M-QAM). The scaled carriers are then summed to yield the time waveform to be transmitted over the channel.

III. Merits and Demerits of DMT

Having discussed the modus operandi of DMT we will now discuss the advantages and disadvantages of the DMT system.

Advantages

1) One of the obvious advantages of the DMT system over the QAM system is its elegant implementation by using FFT as a single block which obviated the need for multiple sub-carriers.
2) The computational complexity was also greatly reduced due to fast FFT algorithms.
3) The digital nature of DFT allowed for cost effective programmable transmitter and receiver combinations and also for modification/alteration of function through soft-ware changes.

Disadvantages

1) As we saw in the first section of this chapter viz. DFT filter banks there was considerable overlap amongst the neighboring channels leading to inter-channel interference (ICI).
2) The large spectral overlap necessitated the use of guard band to preclude the spectral overlap in the form of cyclic prefix (CP). However, the CP reduced the net data rate by a factor corresponding to the length of the CP.
3) The use of CP also necessitated the use of a pre-equalization filter to accurately maintain the length of the transmission channel to that of the CP. But, in the event of any slight changes or the deviations of the filter tapping it drastically effected the performance of the system and decoding of the encoded signals.

IV. Wavelet Transform

The wavelet transform is a very powerful transform, used in different branches of science. In most of the applications, the power of the transform comes from the fact that the basis functions of the transform are localized in time and frequency and their different resolutions in time and frequency. These different resolutions often correspond to the natural behavious of the process one want to analyze, hence the power of the specturm. The wavelet transform has been proposed as a possible transform to generate subchannels in a multi carrier system. The expression for the wavelet transform is given by

$$WT_{\psi} = \frac{1}{\sigma_0} \int x(t) \overline{\psi(\frac{t-b_0}{\sigma_0})} dt \tag{2}$$

V. Discrete Wavelet Multi-tone Modulation (DWMT)

In the previous sections, we discussed how a DMT system is implemented and also studied its pros and cons. While it undoubtedly offered many advantages over the conventional QAM, it also had many demerits, the prominent being the considerable overlapping amongst the sub-channels which led to ICI and hence, the degradation of the system. The challenge therefore, lay in designing a better filter bank which could take care of these short-comings. The DWMT exactly promises a better performance on the account of the spectral containment features of the filter responses. The present section is devoted to a study of this new implementation method viz. DWMT.

A. Basic Transceiver Structure

The Figure 3 depicts the block level diagram for a DWMT transceiver. As shown, the transmitter accepts data in serial form and converts into several low rate sequences of channel symbols, which appear at the constellation encoder outputs. The several sequences of channel symbols are then frequency multiplexed (FDM) to form a single signal sequence for transmission, which passes to a DAC, and then onto the communication channel. The FDM incorporates multi-carrier modulation, implemented with an inverse fast wavelet transform (IFWT). At the DWMT receiver, shown in the bottom part of Figure 3, multi-carrier demodulation is performed with the forward fast wavelet transform (FWT). Each of the several sequences of detector (demodulator) outputs undergoes equalization before decisions are made for the channel symbols. The decoded data sequences are then converted back to a single TDM stream.

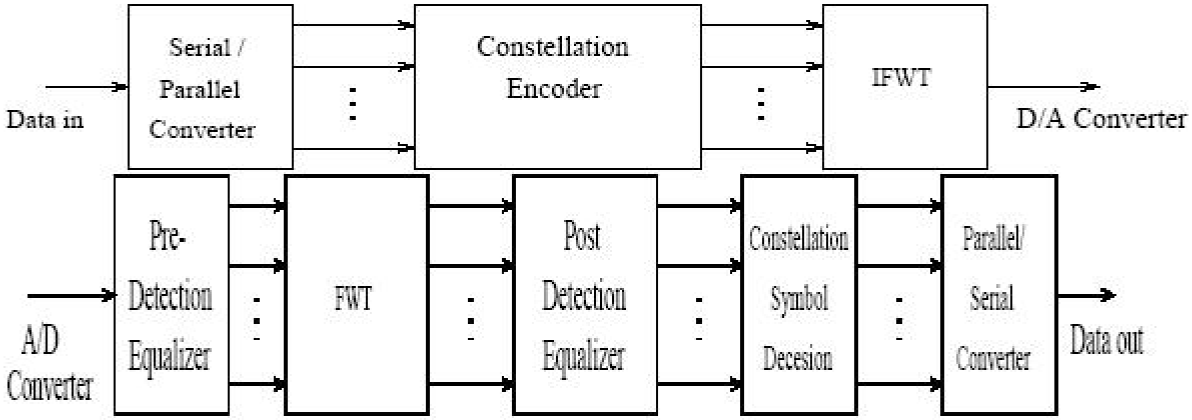

Fig. 3. Block Diagram of the DWMT Transmitter and Receiver

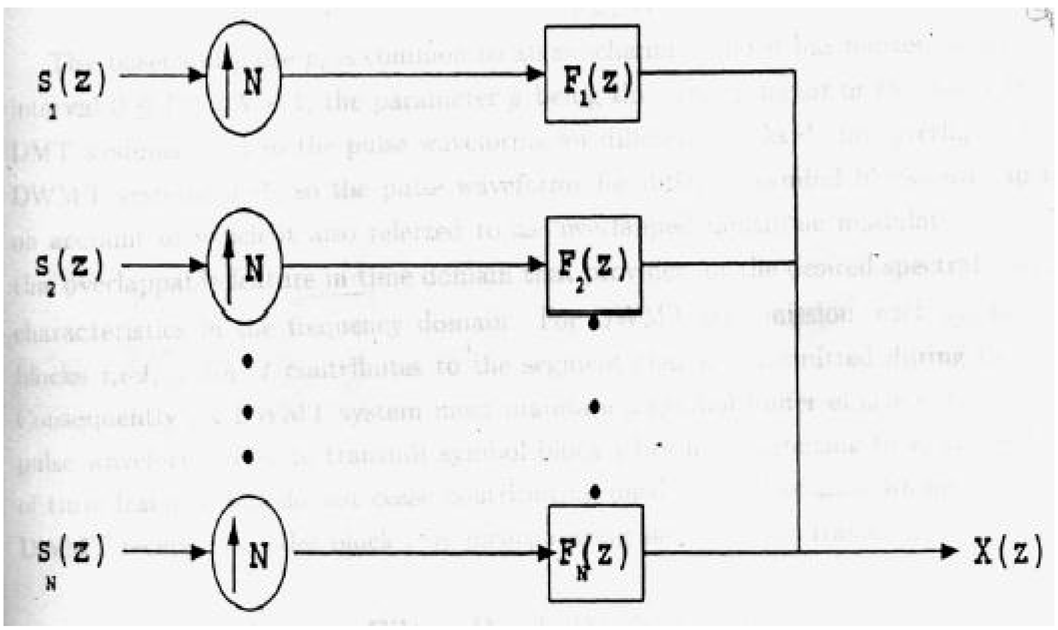

Fig. 4. Modulation

For either DWMT or DMT transmission, the output of the serial-to-parallel converter/constellation encoder combination effectively is in blocks, with each block comprising M symbols. Time is partitioned into contiguous, non-overlapping, equal length intervals, referred to as frames, and for each integer i, transmission for symbol block i is initiated at the beginning of time frame i. The M symbols in a block are transmitted simultaneously, with each symbol assigned to a different one of M sub-channels; each sub-channel employs pulse amplitude modulation (PAM) with a bandpass pulse. The symbol alphabet size for a given sub-channel is defined by the bits allocated to that frequency band.

B. Modulation

The Figure 4 depicts a modulation filter bank. Let f_l^m represents the bandpass pulse for the sub-channel m (with Z-transform as $F_m(z)$) and s_i^m represents the symbol in symbol block i that is transmitted on sub-channel m. As illustrated conceptually in Figure 5, modulation in a sub-channel is performed digitally, and the resulting sub-channel signals are added together to produce a single sequence x_l for transmission. This sequence is used to excite at the rate of f_s samples per second, the composite channel which consists of the transmitter D/A system, the channel and the receiver front end. As depicted in figure, each frame, each sub-channel modulator accepts a new symbol, and produces a length-N segment of x_l that is transmitted during the frame. The frame duration is N/f_s. For DWMT transmission,

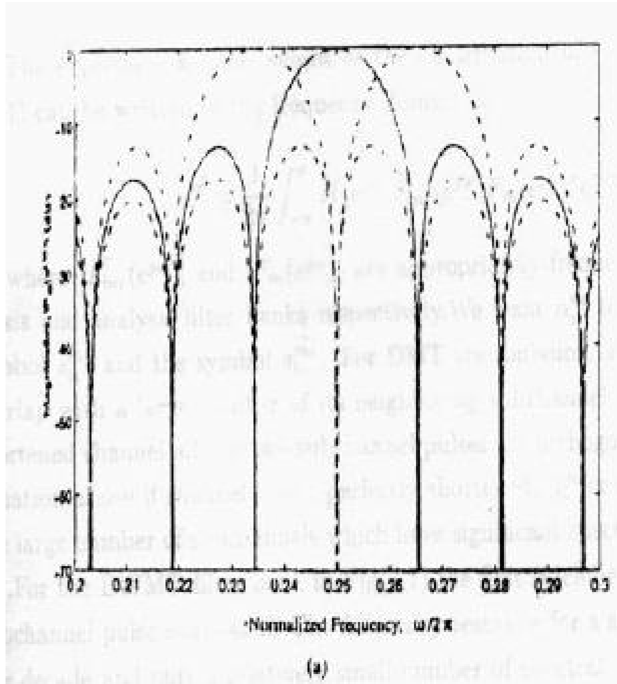

Fig. 5. Frequency response of six spectrally contiguous sub-channel pulse sequences: DMT transmission

$N = M$. For DMT transmission, $N = M + k$, where k is the length of the cyclic prefix.

A DWMT system incorporates careful pulse design to achieve a high level of spectral containment without sacrificing the Nyquist properties of the set of sub-channel waveforms. The sub-channel generation and modulation techniques used for DWMT are basically the same as applicable to DMT transmission. The difference however lies in the implementation of the filter bank. In generation of the sub-channel pulses in both the systems, the sub-channel m is centered at the normalized radian frequency w_m and the bandpass pulse is given as

$$f_l^m = p_l cos(w_m l + \phi_m) \quad (3)$$

The frequencies w_m for DWMT are given by

$$w_m = 2[\frac{m}{2}]\frac{\pi}{N} \quad (4)$$

The baseband pulse p_l is common to all sub-channels and it has nonzero samples for the interval $0 \leq l \leq gN - 1$; the parameter g being the overlap factor or the genus factor. For DMT systems $g = 1$, so the pulse waveforms for different blocks do not overlap in time. For DWMT systems $g > 1$, so the pulse waveforms for different symbol blocks overlap in time, on account of which it also referred to as "overlapped multi-tone modulation". It is in fact this overlapping feature in time domain that provides for the desired spectral containment characteristics in the frequency domain. For DWMT transmission, each symbol in the g blocks $i, i-1, ..., i-g+1$ contributes to the segment that is transmitted during time frame i. Consequently, a DWMT system must maintain a symbol buffer of size gM. Note that the pulse waveforms used to transmit symbol block i begin contributing to x_l at the beginning of time frame i, but do not cease contributing until the end of time frame $i + g - 1$. Thus, a DWMT receiver decodes block i by incorporating samples from frames $i, ...i + g - 1$.

C. Condition on Filter Bank Basis Functions

For particular choices for g and the tone phases ϕ_m, and with the frequencies w_m specified, the baseband pulse p_l used in a DWMT system is designed to minimize stop band energy with the constraint that the set of bandpass pulses f_l^m, $1 \leq m \leq M$, and their time shifts by integer multiples of N, provide a set of orthonormal waveforms (a Nyquist set) for transmission of the sequences of symbol blocks, i.e.

$$\sum_l f_l^{m_1} f_{l-iN}^{m_2} = \beta \delta_i \delta_{m_1 - m_2} \quad (5)$$

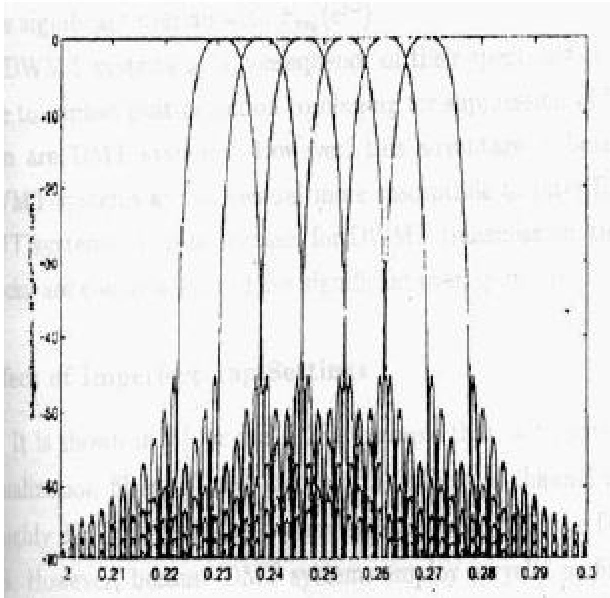

Fig. 6. Frequency response of six spectrally contiguous sub-channel pulse sequences: DWMT transmission

for some $\beta > 0$, where δ_l is the Kronecker delta function.

As discussed in previous sections, the frequency tones for DMT were obtained using DFT, while in the case of the DWMT they could be obtained using M-band wavelet transforms.

VI. Advantages of DWMT

The greatest advantage of DWMT over DMT is its spectral containment. Basically, DWMT owes its superiority over DMT due to this spectral containment property.

A. Comparison of Different Bases

The amplitude responses of the Fourier transform of the real and imaginary parts of the DFT bases differ significantly in both the passband and stop band. On the other hand, in the case of wavelet packet bases, the amplitude responses corresponding to the real and imaginary parts are almost same in the passband. In the case of DMT, the side lobes are just 13 dB below the main lobe whereas, in the case of DWMT the side lobes are as low as 55 to 60 dB below the main lobe. Thus the temporal overlap of the sub channel filters in the time domain translates into brick wall filtering or in other words better spectral containment. The Figu5 and Figure 6 give an illustration of frequency responses for six spectrally contiguous sub-channels both for DMT and DWMT.

B. Effect of Spectral Containment

The better spectral containment obviates the need for cyclic prefix which as we saw in the case of DFT was responsible for reducing the data rate. This in turn implies that receiver complexity would also be reduced as there would be no necessity of a pre-detection equalization filter. In DFT implementation if there were any deviations in the filter taps, the performance was drastically affected.

C. Computational Complexity

The total number of operations required per sample to implement the modulation and demodulation for a DWMT system is $4(1 + g + log_2 M)$, where g is the degree of overlap in DWMT transmission and M is the transform size and for DMT it is $5 log_2 M$. In a fixed transmission bandwidth, when choosing M to be same for DMT and DWMT systems, the two systems will have same frame rate but not the same sub-channel bandwidth. It is possible to select the transform size, so that the sub-channel spacings are the same. In this case, the frame rate for the DWMT system is twice that of the DMT system and the transform size M required to implement DWMT modulation/demodulation is half that for the DMT system. The increase in frame rate of the DWMT system over the DMT system reduces the latency of the DWMT system, an important issue in many applications.

REFERENCES

[1] T.Pollet and M.Moeneclaey. Synchronisation of OFDM signals in Proc Globecom volume 3. pages 2054-2058 Singapore Nov 1995.
[2] P.H.Moose. A technique for orthogonal frequency division multiplexing frequency offset correction. IEEE Trans. Comm., 42(10):2908-2914, October 1994.
[3] Flavio Daffara and Ottavio Adami. A new frequency detector for orthogonal multi-carrier transmission techniques. In Proc. VTC'95, volume 2, pages 804-809, Chicago, Illinois, USA, July 1995. IEEE.
[4] Magnus Sandell, Jan-Jaap van de Beek, and Per Ola Brjesson. Timing and frequency synchronization in OFDM systems using the cyclic prefix. In 1995 International Symposium on Synchronization, pages 16-19, December 1995.
[5] M. Alard and R. Lassalle. Principles of modulation and channel coding for digital broadcasting mobile receivers. EBU Review Technical, (224): 168-190, August 1987.
[6] Symbol time offset estimation in coherent OFDM system (daniel Landstorm Sarah Kate wilson Jan-Ja