CHAPTER 1
INTRODUCTION AND LITERATURE SURVEY

1.0 Introduction

Telephones and telephone lines have been in place for more than a century. For several decades telephone lines were used only to carry voice, across the globe. Pure voice communication however, requires only a very small bandwidth, much smaller than the actual capacity of the telephone lines. Copper wires have a lot more room, to carry more than just telephonic conversations – they are capable of handling a much larger bandwidth than that demanded by voice communication. However the one serious limitation of this channel is that the high frequency regions suffer from high attenuation and noise. The challenge before communication engineers is to fully utilize the potential of the billions of kilometres of existing telephone cables by effectively transmitting and delivering vast amounts of information swiftly and accurately over them. Digital communication techniques and advances in Digital Signal processing have made high speed transmission on POTS (Poor Old Telephone Services) possible [1][2].

1.1 Multicarrier Modulation and DSL

Digital Subscriber Line (DSL) [3][7] is one technology that has in some ways tried to exploit the dormant capacity of the twisted copper wire pairs, the telephone lines. Multicarrier modulation (MCM) is chosen as a standard for high bit rate transmission over the twisted copper wires using DSL technology such as Asymmetric Digital Subscriber Lines (ADSL), High Speed DSL (HDSL) and Very High Speed DSL (VDSL). Multicarrier modulation is known to be optimal for time dispersive channels such as the copper wires used for the telephone systems when the number of subcarriers is large[2]. The basic principle of multicarrier transmission is to convert the problem of broadband transmission into a set of easily conquerable narrow band problems. Multicarrier modulation is the name given to the process of transmitting data by dividing it into several interleaved bit streams and using these to modulate several carriers[8]. MCM has the ability to efficiently access and distribute multiplexed data streams. It also offers improved resistance to impulse noise, and narrowband channel disturbances because of increased symbol duration. Modulation, the
The process of embedding information in a signal is one of the important aspects of digital transmission.

![Diagram](image)

**Fig. 1.1.1** Binary stream \( s(n) \) is divided into blocks of \( b \)-bits each of which is further subdivided into \( M \) blocks.

**Fig. 1.1.2** Basic Multicarrier Transmitter

In the Multicarrier modulation scheme is shown in Fig. 1.1.1 and Fig.1.1.2 Here the input data at MF bits are grouped into blocks of M bits at a block rate of \( F_s \). The M bits are
used, \( m_n \) bits for the carrier at \( f_{c,n} \) to modulate \( N_c \) carriers which are spaced \( \Delta f \) apart across any usable frequency band that is

\[
f_{c,n} = n\Delta f \quad \text{for } n = n_1 \text{ to } n_2
\]

\[
M = \sum_{n=n_1}^{n_2} m_n \quad N_c = n_2 - n_1 + 1
\]

(1.1.1)

(1.1.2)

The modulated carriers are summed for transmission and separated in the receiver before demodulation. MCM has been chosen as a way of transmitting data at high bit rates of the order of Mbits/sec over the digital subscriber loop.

Digital signal processing has played a significant role in the advancement of digital communication. In this work one such aspect of digital signal processing is considered namely that of filter banks. Originally filter banks were proposed for use in speech processing. Over the years however they have found application in the areas of image, video and audio processing. In the area of digital communications filter banks have been used in digital transmultiplexing\[9\]-[17], precoding for channel equalization\[18][19], discrete multitone modulation\[7\] and in high speed DSL services\[20][21]\.

For efficient performance every subchannel should be free of inter symbol interference (ISI) and inter channel interference (ICI). In order to avoid ICI there should be no spectral overlapping between the channels. This necessitates sharp cutoff filters which are not practical. In \[22\] Weinstein and Ebert suggested the use of IDFT and DFT for modulation and demodulation. However the adjacent filters of the DFT filterbank had large overlapping side lobes. This resulted in a considerable degradation in performance when used in the case of a highly dispersive channel\[23][24][25]\.

Peled and Ruiz\[26\] used a method of guard time to cope with the dispersive channel. Here the transmitted symbols are cyclically extended at the output of the IDFT.(inverse

Fig.1.1.3. Multicarrier modulation system using multirate filter banks
Discrete Fourier Transform) at the transmitter side. Extensions created redundancy, that is there is a time interval for which no new information is sent, thereby reducing the bandwidth efficiency of the transmission scheme. However multicarrier modulation using DFT basis functions

Most of the research work on multicarrier modulation is based on the DFT basis functions which as discussed have severe limitations in the context of our application which means therefore that alternate schemes have to be explored for implementing this modulation scheme. Fig. 1.1.3 shows the multicarrier modulation scheme implemented using filter banks for modulation and demodulation operations.

1.2 Literature Survey

xDSL a family of technologies that provides digital data transmission over the wires of a local telephone network are being investigated as a method of exploiting the dormant capacity of the telephone lines[4][5][6][7][8]. J.M. Cioffi in his paper investigates the very high speed digital subscriber lines (VDSL) which is the latest of these technologies for carrying high speed digital services on the digital twisted-pair phone lines[5]. VDSL allows speeds from a few hundred kilobits per second on long phone lines and tens of megabits per second on shorter lines, depending on the length of the twisted pair.

In [21] Cherubini, Eleftheriou, Olcer and Cioffi suggest that the method “divide and conquer”, could help make such high speed transmission possible. Further they suggest that since the tenet multicarrier modulation has been shown to divide the complex problem of wideband transmission into a set of easily conquerable narrow band problems it could be identified as the optimum method for transmission over dispersive channels.

Multicarrier modulation as a means of efficient transmission was highlighted in [2] by J.A.C Bingham. The reasons given in support of this scheme were, firstly, that the MCM signal could be processed in the receiver without the enhancement of noise or interference caused by linear equalization of a single carrier signal and secondly the longer symbol times used in MCM would provide greater immunity to impulse noise. The attention that MCM has received in the context of its application to DSL has been largely due to the fact that it allows optimized bit allocation over all the subchannels and the simplicity of the equalization process[4][5]. This scheme was initially implemented using analog filters. However when
the number of channels is large which is the case with an ideal multicarrier system the process of analog implementation becomes unreasonably expensive and complicated.

The use of fast signal processing algorithms such as FFT for the digital implementation of MCM scheme using DFT was proposed by Weinstein and Ebert in [3]. Interest in multicarrier modulation grew rapidly in the 80’s. This could be attributed to vast advances in digital signal processing technology. Most specifically the communication area that generated significant research activity in multicarrier modulation, initially was the DFT based DMT scheme[6],[11]. In the DMT scheme the channel was divided into subbands each with a different frequency band. Band separation is of utmost importance when the channel response is not flat, as it is in the case of the DSL channel. It was shown that very good transmission rates could be achieved using this scheme for channels such as the asymmetric digital subscriber line(ADSL) and the high bit rate digital subscriber line(HDSL). In this scheme the transmitting filters $H_k(z)$ and the receiving filter $F_k(z)$ are DFT filters. The filter lengths of the subchannel filters are very short being equal to the number of subchannels. The filter length constraint limits the level of stop band attenuation in DMT based transceivers.

It was shown by Peled and Ruiz in [27] that the only filter function that would allow time and frequency orthogonalities when modulated by the DFT function was the rectangular function. Therefore a given subchannel would have a significant overlap with a large number of neighbouring sub channels owing to sinc(f) – shaped spectral characteristic of the function. The large spectral overlap could lead to substantial leakage of power between subchannels and induce inter-channel interference. This leads to significant levels of ISI and ICI.

To compensate for the high degree of spectral overlap it was suggested by Weinstein and Ebert in [3] that a cyclic prefix be inserted at the beginning of each transmission segment. If the channel impulse response was shorter than the cyclic prefix or if the receiver was able to equalize the channel in such a way that the channel impulse response was shortened to have a length not greater than the cyclic prefix then subchannel isolation would be achieved. When the channel response is shorter than the cyclic prefix the channel linear convolution is mapped into circular convolution. Hence on the receiver side after demodulation by the DFT the obtained symbols are only affected by a value equal to the
channel transmittance for the frequency of the tone being considered. However the drawback of this method is that the method creates a redundancy which corresponds to a time interval when no new information is sent. This reduces the bandwidth efficiency of the system. Also performance of the DMT system is very sensitive to changes in tap settings of the channel shortening equalizer.

It was shown in [23] by Sandberg and Tzannes that the performance of the system was severely affected by increase in ISI if the tap settings were changed by even a very small amount.

Sandberg and Tzannes [23] introduce in their work, the Discrete Wavelet Multitone (DWMT) where the DFT is replaced by Fast Wavelet Transform (FWT). In this case multicarrier modulation at the modulator is implemented using the inverse FWT. At the DWMT receiver demodulation is performed using the FWT. This method offers enhanced spectral containment with a result that there is increased robustness to ISI and narrowband interferences. Changes in taps settings do not result in severe performance degradation as was the case with cyclic prefix. The transceiver system is constructed as perfect reconstruction PR filter bank. In the case of the DWMT system the interpolation/decimation ratio N is equal to number of channels M and the filterbank is said to be maximally decimated. Good quality filter bank designs result in better band separation.

The connection between transmultiplexers and the filter banks was first observed by Vetterli [26]. The filter bank transceiver is called as a transmultiplexer. When the analysis and synthesis filter banks of a PR filter bank are interchanged the resulting structure is called a transmultiplexer. When the transmission channel is an ideal one then the use of a PR filter bank based transmultiplexer would result in the system being ISI free. However if the channel is highly dispersive as is being considered in this work then the PR property of the filterbank does not ensure that ISI is completely cancelled. Simpler designs for the filterbank can now be explored since designs will no longer be required to meet the stringent constraints imposed for perfect reconstruction.

G.W. Wornell [1] suggested that multirate systems and filter banks that were traditionally used in source coding and compression could find use in channel coding and modulation for several important classes of channels both wireless and wireline. Examples were given to show how filter banks and lapped transforms could be used effectively in
applications such as multicarrier modulation for channels that were subject to severe intersymbol and narrowband interference.

In [10] P.P. Vaidyanathan explores several issues relating to filter banks in digital communications with an emphasis on their application to discrete multitone modulation which has impacted high speed data communication on the twisted pair phone line. Filter bank precoders and their application to channel equalization problems was also highlighted.

In [11] Akansu, Duhamel, Lin and Courville have presented the emerging applications of transmultiplexers in communications. They have highlighted how the general concepts of filter bank theory can be tied to application specific requirements of different communication systems so as to boost research activity in the area of applications of filter bank theory to communications.

In [14] Ihalainen, Alhava and others have highlighted the efficiency of filter bank based multicarrier techniques. Equalisation issues involved in filterbank based multicarrier systems have been addressed.

The DFT based DMT was chosen as the working standard for ADSL. Very high speed digital subscriber line (VDSL) technology was explored by Cioffi in [5] is a copper wire based network-access technology that is considered to be an evolution of ADSL. It is the next step in DSL technology for two way broadband access. The envisaged data rates for asymmetric transmission are 52Mbits downstream and 6.4Mbits upstream. For symmetric transmission the data rates are 34Mbits. Interference to VDSL transmission is mainly the result of NEXT, FEXT and amateur radio frequency signals. Thus far we have explored the use of DFT basis functions for the implementation of the multicarrier modulation scheme. The DFT based scheme has its advantages and limitations and other schemes need to be explored for more efficient implementation of communication systems.

Cherubini, Eleftheriou, Olcer and Cioffi[21],[22] proposed the Filtered Multitone (FMT), as an alternative to the single carrier and multicarrier transmission. This scheme has been applied to data transmission for VDSL. It is a filter bank based modulation technique where the subchannel filters are frequency shifted versions of the prototype filter which provides a high degree of spectral containment, so that inter-channel-interference (ICI) is negligible compared to the other noise signals. The prototype filter is not required to be
designed for perfect reconstruction. Since perfect reconstruction with an affordable complexity of filters requires a substantial overlap of the adjacent filters, by relaxing the perfect reconstruction condition a high degree of spectral containment is achieved.

Rizos, Proakis and Nguyen[24] suggested an alternate signaling scheme to the DFT filter bank for multicarrier transmission. This scheme employs in the synthesis/analysis part of the transmitter/receiver, a Cosine-Modulated Filter Bank (CMFB). In the CMFB the subchannel filters are obtained from the prototype filter by cosine modulation. The CMFB uses filters of greater length than the DFT resulting in much lower side lobe levels and hence reduced interference between carriers. Besides offering good frequency response characteristics, the CMFB is computationally efficient since all the filters are derived from a single prototype filter, and fast algorithms or cosine modulation are available. Also the filter banks are efficiently implemented using the polyphase representation. The length of filters was 2mM where m is any integer. Longer length filters mean that delay was greater. The method provides a simple efficient method of implementing the multicarrier modulation scheme and will be investigated in greater detail in this work.

Heller Karp and Nguyen[56] have presented a general formulation for modulated filter banks. Perfect reconstruction cosine modulated filter banks where the cosine modulation was based on the discrete cosine transforms DCT-I, DCT-II, DCT-III and DCT-IV were formulated.

Several designs and formulations for the perfect reconstruction cosine modulated filter banks and arbitrary length cosine modulated filter banks have been studied by Nguyen and Koilpillai in [59] and by Koilpillai and Vaidyanathan in [62].

One of the more important specifications in digital transmission is delay. A delay budget is allotted to a system and is shared between the various functions of the transmitter and the receiver. In the filter bank based multicarrier system most of the delay is due to the modulation and demodulation. Delay being dependent on the filter length there is pressure to keep filter length to a minimum. This would result in lesser attenuation in the stopband. Hence the selection of length of the filter would mean a tradeoff between filter performance and delay as highlighted by Bellanger in[17].
Biorthogonal cosine modulated filter banks, studied extensively by T. Karp and others [28]-[29] are a class of filter banks where the overall system delay can be chosen independently of the filter length. This feature is especially useful in transmultiplexer applications where both low delay and high stopband attenuation are desirable.

Govardhanagiri, Karp, Heller, and Nguyen [25]. Thus better stopband attenuation could be obtained than the DFT filter banks keeping the delay as a constant. In applications where the delay is not so crucial stopband attenuation was increased further, by increasing filter lengths and computational cost. The performance of the biorthogonal CMFB based transmultiplexer was compared with that of a DFT filter bank system, using a time domain equalizer along with a cyclic prefix. The signal to interference ratio SIR was determined by varying the number of channels M and the filter length. It was concluded that up to a certain point the SIR increases with and increase in the number of channels and the filter length. Beyond that the effect of ISI was predominant and there was no further improvement in the SIR with increased filter lengths. It was shown that the CMFB outperformed the DFT system without TDE and cyclic prefix. However the performance of the CMFB system was poor compared to the DFT with TDE and cyclic prefix. The use of oversampling to improve the CMFB performance was suggested.

In oversampled filter banks the number of sub channels M is greater than the downsampling/upsampling factor N. Oversampled filter banks with integer and rational oversampling factors have been studied by past researchers[29]-[42]. Recently oversampled filter banks have gained interest in the signal processing community. They have the advantage of better immunity to noise, subband signal redundancy and existence of nonunique PR synthesis filter banks, as compared to the maximally decimated filter banks.

In [42] Lin and Phoong have shown, in the case of a DFT based DMT system, that by introducing redundancy that is by having interpolation ratio more than the number of channels M in the system it is possible to cancel ISI completely. Oversampled filter banks are know to have higher attenuation in the stopband which would mean inter-channel interference ICI would be lower[31],[34],[37]. In the case of PR filter banks oversampling has been shown to give additional design freedom in the filter design process, which could be exploited to find FIR perfect reconstruction prototypes for the oversampled filter banks, with much higher stopband attenuation than maximally decimated filter banks. Also in the case
of oversampled filter banks for a given analysis prototype the synthesis prototype is not unique, if the filter bank is Perfect Reconstruction. Numerically efficient implementation of oversampled filter banks have been discussed in literature.

Labeau,F.[30] discusses methods based on decompositions of the polyphase matrix as well as structures based on maximally decimated filter banks. The design freedom in terms of availability of multiple structures of the synthesis filter bank for a given analysis filter bank in the case of perfect reconstruction were highlighted. The design methods were however limited to the case of complex modulated filter banks. In [31][35][37][39] oversampled cosine modulated filter banks were studied. The filter banks were studied for integer oversampling rates.

In [29] Reil, Shpak and Antoniou discussed the realization of a structure for the oversampled filter bank using a lifting scheme. The filter bank was designed as a PR filter bank with integer oversampling. The oversampled filter bank structure was derived by factorizing the polyphase matrices of the synthesis and analysis filter banks into lifting matrices. This lead to the simple and efficient designs of the oversampled filter bank.

In [31] an efficient design for the oversampled cosine modulated filter banks for variable delay, that is biorthogonal filter banks were presented by Kliewer and Mertins. The oversampled filter banks were derived from the polyphase representation of the maximally decimated filter banks. Though the designs were for the PR case their relation to the pseudo-qmf filter banks were highlighted. The improvements brought about in stopband energy, stopband attenuation over the maximally decimated filter bank were investigated in detail for different oversampling ratios. The effect of overall system on stopband energy was also discussed.

Efficient designs for the oversampled cosine modulated filter banks were suggested by Bolsckeai, and Hlawatsch in [37] and [39]. In [39] a new type of cosine modulated filter bank based on discrete time Wilson expansions was suggested. These filter banks were designed to satisfy PR conditions and their relation to PR DFT filter banks were highlighted.

In [38] Bolsckeai, Hlawatsch and Feichtinger studied FIR and IIR DFT filter banks in relation to oversampling. The relation to earlier designs for the oversampled CMFBs was investigated.
In case of ideal channels it is possible, using perfect reconstruction filter banks recover the signal completely. However in the case where the channel is dispersive the use of a perfect reconstruction filter bank would alone not ensure that the ISI-free property of the transmultiplexer system. Hence NPR based design structures for the construction of the filter bank based transmultiplexer were to be investigated[13]-[20].

In [13] S.Weiss, A.P. Millar, R.W.Stewart and M.D Macleod seek to address the problems associated with maximally decimated transmultiplexers through oversampling. It has been suggested that oversampling could lead to simplified transceiver structures. Transmultiplexer design developed using near perfect reconstruction, oversampled GDFT filter bank was used in the study.

During the course study of various existing transmultiplexer schemes the importance of design of the prototype filter was highlighted. A proper design of the prototype filter would ensure proper band separation of the subchannel filters. This would ensure low values of ICI and ISI.

An important point that was highlighted by Bellanger in [17] was the importance of choice of filter length. Both from the point of view of ensuring that the overall system delay was to be kept at a minimum level and to ensure reduced computational complexity an optimal filter length had to be chosen. So several prototype filter designs were investigated with respect to their suitability for the application considered in this work.

1.3 Objectives of this work

Based on the literature survey conducted it was felt that there was need for a new scheme that would be computationally more efficient and comparable in performance and that has been the objective of this work.

- The objective of this work is to investigate a multicarrier modulation scheme that is based on the discrete cosine transform.
- The CMFB is known to provide good spectral containment since longer length filters can be used. The next objective is to explore existing design methods for the prototype filters that could be suitable for our application.
• The filter bank is to be designed as an oversampled filter bank which means that there 
are more number of samples to deal with. So the filters must be designed to minimize 
computation costs. So existing methods needed to be explored and new methods to 
be investigated for the prototype filter designs.
• The objective function for the design of optimal filters was to be constructed. Since 
the application requires that attenuation in the stopband be very high and ripple in the 
pass band be very low the objective function is suitably derived.
• The oversampling ratio of the filter bank that will provide best possible system 
performance needs to be determined.
• An efficient cost effective implementation of the oversampled filter bank based 
transmultiplexer is to be derived.
• For studying the performance of the filter bank transmultiplexer for the DSL system 
the channel was to be modeled as IIR system and the coefficients of the transfer 
function were to be determined.
• Then the performance parameters of the system are to be obtained and compared with 
existing system to determine whether the proposed designs for the filters and 
filterbank provide the required savings in design and implementation costs while 
providing the high level of performance that earlier design have been known to 
deliver.

1.4 Plan of Work

This work aims to design an oversampled filter bank based on cosine modulation to 
exploit the inherent advantages of the CMFB based approach for the implementation of the 
multicarrier modulation scheme. The filters forming the analysis and the synthesis filter 
banks were derived from a single prototype filter by the process of cosine modulation of the 
prototype filter. Oversampling increases computation since there are more samples to deal 
with than in the critically sampled filter bank. The goal was to obtain an efficient MCM 
scheme with minimum increase in computational cost. The process involved the design of 
the prototype filter, where the basic filter is FIR, designed using the window method. The 
coefficients of the filter are optimized to satisfy certain criteria. The goal was to choose a 
method of design that would obtain filters with optimum characteristics at minimum 
computational cost while bearing in mind that the process of filter design would involve
nonlinear optimization of the filter coefficients. Next step was to design the filter bank. The oversampled filter bank is represented by a matrix of size $M \times N$, whereas in the maximally decimated case the matrix is $M \times M$. The oversampling factor $L = N / M$ was to be chosen. The design chosen was again based on the method that yielded greatest computational efficiency. Filter banks for different values of the oversampling factor were designed and their performances compared and the optimum value of $L$ the oversampling factor was chosen. As a criterion for system performance, the signal-to-interference ratio based on a theoretical estimation of the interference at the output of the receiver was chosen. Comparison of results with those obtained in the case of the maximally decimated filter banks was done and the computational costs of designing the oversampled cosine modulated filter bank were determined.

There are two main components of this work. One the design of the prototype filter and the other the design of the filter bank and the filter bank based transmultiplexer. In Chapter 2 the use of filter bank based multicarrier systems is studied. Then reasons for choice of the cosine modulated filter bank are put forth. Next multirate systems and filter banks are introduced. In Chapter 3 several designs for the prototype filter and are investigated and their performances as well as computational complexity are compared. Here two methods to simplify design and reduce the cost of computation are proposed. In Chapter 4 the structure of the oversampled filter banks are studied and its structure is developed from a similar structure for a maximally decimated filter bank. The matrix representation of the oversampled filter bank is derived as also the structure for the hardware implementation of the filter bank. In Chapter 5 the design of the oversampled filter bank is modified to obtain the structure of an oversampled transmultiplexer. The performance of the oversampled transmultiplexer is analysed in terms of the obtained inter-symbol-interference-ratio (ISI), inter-channel-interference ratio (ICI) when used with and ideal channel. In Chapter 6 the mathematical model for the DSL channel was derived and the performance of the oversampled filter bank transmultiplexer when used with a practical channel was studied and a comparison was drawn with earlier design methods.

Several publications come from this work. They mainly concern the design and performance analysis of the prototype filter[43]-[46] and the oversampled cosine modulated filter banks and transmultiplexer[47]-[49].