# Implementation And Analysis Of Different Types Of Transmultiplexer Structures

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## ABSTRACT

**Multirate filter banks have become excellent solution for future wireless communication system. Filter bank based multicarrier system provides high spectral efficiency through removal of redundant information resulting in efficient use of available spectrum. In multicarrier communication system, filter bank based transmultiplexer (TMUX) having same analysis and synthesis filter bank is employed. The TMUX configuration which is core of any FBMC is of our interest here. This paper concentrates on implementation of filter bank based multicarrier/offset quadrature amplitude modulation (FBMC/OQAM). Different TMUX structures like maximally decimated, non-maximally decimated and partial TMUX have been implemented. In partial transmultiplexer, upsampling and downsampling factor is less than number of sub channels. Frequency sampling technique is used for design of prototype filter and other filters are complex modulated versions of prototype filter. For all the TMUX structures perfect reconstruction is observed with alias cancellation. Further, computation of Intersymbol interference (ISI), Interchannel interference (ICI) will support filter designs for two-band and four-band TMUX. The Optimization criterion is applied to frequency sampling technique and results are compared based on ISI, ICI performance of TMUX.**

**KEYWORDS-** *Transmultiplexer (TMUX), FBMC/OQAM, maximally decimated filter banks, non-maximally decimated filter banks, modified DFT filter banks, complex modulated filter banks, partial TMUX.*

## I. INTRODUCTION

Multicarrier modulation is default choice for high data rate wireless communication. In multicarrier modulation system available channel bandwidth is efficiently subdivided into several sub-channels; each has its associated subcarrier. In present scenario, most commonly used multicarrier modulation technique is orthogonal frequency division multiplexing (OFDM). Even though OFDM has numerous advantages it has certain shortcomings. It uses cyclic prefix (CP) which consumes certain amount of available bandwidth (critical in cognitive radio networks) and it uses rectangular prototype filter and IFFT/FFT blocks which results in less frequency selective sub-channel.

Filter bank based multicarrier system (FBMC) is widely used in present communication technology (e.g. cognitive radio) because of its inherent frequency selectivity and spectral efficiency [11, 12]. FBMC system provides certain advantages over conventional OFDM like improved frequency selectivity through use of longer and spectrally well shaped prototype filter and efficient use of available spectral bandwidth (spectral efficiency) by removal of CP [10]. Basic FBMC system consists of TMUX structure. A general TMUX consist of synthesis filter bank (SFB) at transmitter, analysis filter bank (AFB) at receiver. Corresponding filters in AFB and SFB are tuned so as to get desired response.

In this paper, we have implemented different TMUX Configurations namely maximally decimated TMUX and non-maximally decimated TMUX and partial TMUX. Frequency sampling technique is used to design prototype filter. Both AFB and SFB designed such that other filters in respective banks are complex modulated versions of prototype filter [3, 4].

## II. GENERAL TMUX STRUCTURE

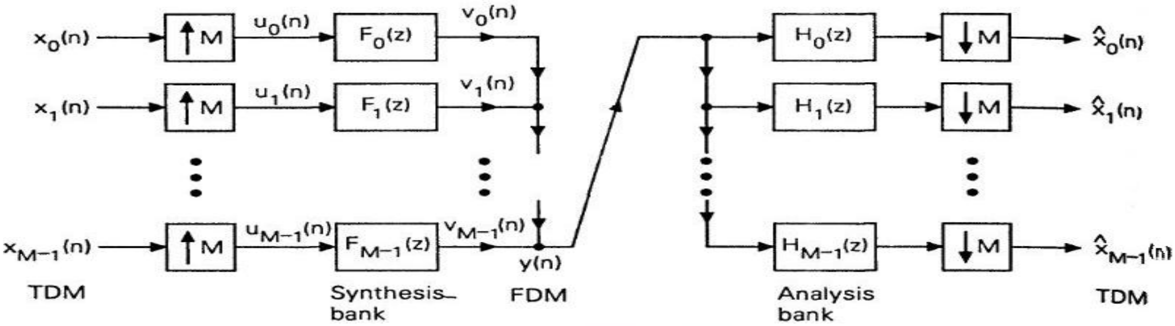


Fig. 1: General TMUX structure.

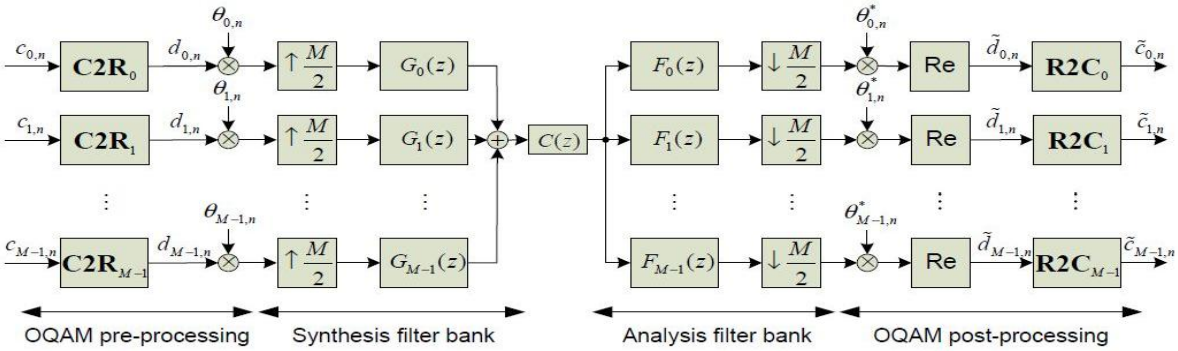


Fig. 2: Partial TMUX structure

The general TMUX structure consists of M sub-channels each having different input $x_k(n)$, where k is from 0 to M-1 i.e. time division multiplexed (TDM) data. After passing it through M fold expander as shown in Fig. it will create M-1 images of input signal, this operation is called upsampling. This upsampled data is passed through SFB having M different synthesis filters $F_k(z)$. Each filter will pass particular image out of M-1 images, which falls in its passband. Here $y(n)$ is interleaved version of filtered inputs, thus TDM data is converted into FDM data. This FDM data is passed through a communication channel. At receiver AFB is present which consist of M filters designed in such way that it will select FDM data corresponding to particular band of frequency of related filter. After passing this data through M fold decimators FDM data gets converted into TDM data $\hat{x}_k(n)$ which is either approximate or correct estimate of input data $x_k(n)$. The TMUX structure so implemented is called maximally decimated TMUX [5] i.e. upsampling and downsampling is performed by same factor M. In this structure perfect reconstruction, alias cancellation conditions can be achieved based on design of AFB and SFB. In case of non-maximally decimated TMUX, upsampling and downsampling factors are different [5, 6]. This will increase computational efficiency of overall structure and decreases computational complexity. Here perfect reconstruction is not guaranteed, as minimum two filters will have same pass band so distortion will be present but alias cancellation is guaranteed. Nearly perfect reconstruction can be achieved in non-maximally decimated TMUX. If we relax perfect reconstruction condition by allowing small amplitude and cross-talk (aliasing) distortion then we can use non-rectangular prototype filter which will in turn improve stop band performance of sub channel filters

## III. PARTIAL TMUX

The main processing blocks of partial TMUX [1] includes OQAM pre-processing, synthesis and analysis filter banks and OQAM post-processing. The transmission channel is $C(z)$, which can be modelled according to communication channel effects.

## IV. OQAM Pre-processing

The first operation is a complex-to-real conversion (C2R*k*), where the real and imaginary parts of a complex-valued symbol $C_{k,n}$ are separated to form two new symbols:

$$d_{k,2n} = \begin{Bmatrix} Re\,[c_{k,n}]\,;\ k\ even \\ Im\,[C_{k,n}]\,;\ k\ odd \end{Bmatrix} \quad (1)$$

and

$$d_{k,2n+1} = \begin{Bmatrix} Im\,[C_{k,n}]\,;\ k\ even \\ Re\,[C_{k,n}]\,;\ k\ odd \end{Bmatrix} \quad (2)$$

As mentioned above one complex symbol $C_{k,n}$ splitts into two real symbols one corresponds to real part and other corresponds to imaginary part. This means that the complex-to-real conversion increases the sample rate by a factor of 2.

## V. Synthesis and Analysis Filter Banks

In the SFB, input signals are upsampled by $(M/2)$ and then these are passed through respective filters $G_k(z)$ in order to obtain sub-signal for each sub channel. By adding all these sub-signals transmitted signal is formed. It is passed through channel model before given to receiver in order introduce channel effects. In the AFB, each filter will filter the input received signal based on its pass band and then these signals are downsampled by factor of $(M/2)$ to get recovered signal. This is critically sampled TMUX. AFB and SFB are designed based on the complex modified filter banks or modified filter banks where from the prototype filter $p(l)$ all other filters i.e. $f_k(l)$ and $h_k(l)$ can be designed. It can be shown as [4]:

$$g_k[l] = p[l]e^{j\left(\frac{2\pi k}{M}\right)\left(l-\frac{L_p-1}{2}\right)} \quad (3)$$

$$f_k[l] = g_k^*[L_p - 1 - l] = p[l]e^{j\left(\frac{2\pi k}{M}\right)\left(l-\frac{L_p-1}{2}\right)} = g_k \quad (4)$$

Where $k = 0,1, \dots . M-1$ and $l = 0,1, \dots L_p - 1$ and $L_p$ is length of prototype filter.

If $p(l)$ will have linear phase then due to modulation function, $f_k[l]$ and $g_k[l]$ will also have linear phase.

## VI. OQAM Post-processing

The second operation is real-to complex conversion (R2C*k*), in which two successive real valued symbols (with one multiplied by *j*) form a complex valued symbol $\tilde{c}_{k,n}$, i.e,

$$\tilde{c}_{k,n} = \begin{Bmatrix} \tilde{d}_{k,2n} + j\tilde{d}_{k,2n+1}\,; & k\ even \\ \tilde{d}_{k,2n+1} + j\tilde{d}_{k,2n}\,; & k\ odd \end{Bmatrix} \quad (5)$$

In this sense, the real-to-complex conversion decreases the sample rate by a factor 2.

## VII. PROTOTYPE FILTER DESIGN

The prototype filter can be designed in such a manner that the TMUX configuration guarantees perfect reconstruction (PR) or nearly perfect reconstruction (NPR) of the transmitted data at the receiving end. There are different methods of designing prototype filter like directly optimizing impulse response coefficients, windowing based method or frequency sampling technique.

In this paper, we are using frequency sampling technique to design prototype filter of odd length i.e. $L_p = KM - 1$, which can be given as [2]

$$p(l) = \frac{1}{KM}\left( A[0] + 2\sum_{k=1}^{U}(-1)^k A[k]\cos\left(\frac{2\pi k}{M}(l+1)\right)\right) \quad (6)$$

Where $k = 0,1, \dots . KM-2, U = \frac{(KM-2)}{2}$, $K$ is overlapping factor and $A[k]$ is frequency response values.

Frequency sampling technique can be summarized as:

Impulse response coefficients can be obtained from the desired frequency response by sampling $KM$ uniformly spaced points $\frac{2\pi k}{KM}$ is inverse Fourier transformed.

Generally prototype filter is low pass filter (LPF) only. LPF having requirements like Magnitude =1 at ω=0; Magnitude =0.707 at ω=$(\pi/M)$; and high stopband attenuation (>13dB), which can be achieved by:

- $A[0] = 1;$
- $A[l]^2 + A[K-l]^2 = 1\,; for\ l = 1,2, \dots, [K/2]$
- $A[l] = 0\,;\ for l = K, K+1, \dots U$

As mentioned above, very few adjustable parameters, like '$x$' are needed for this frequency sampling method of designing prototype filter.

- $K = 3: A[0] = 1, A[1] = x, A[2] = \sqrt{1-x^2}$
- $K = 4: A[0] = 1, A[1] = x, A[2] = 0.707, A[3] = \sqrt{1-x^2}$

Least square criterion [7, 8, 9] is applied to minimize stopband attenuation so that entire energy is concentrated only in passband. This will give optimized filter response.

## VIII. SIMULATION RESULTS

### 1. Maximally Decimated TMUX Structure: Four Channel TMUX

Fig. 3 shows results for four channels TMUX. It has four different inputs as shown. Perfect reconstruction is observed in Fig. 4 at output of four channels TMUX with amplitude reduction by a factor of 4 is because of following downsampling relation (M = 4). Similar structure can be implemented for two channel TMUX (M = 2).

$$Y(Z) = \frac{1}{M}\sum_{k=0}^{M-1} X\left(Z^{\frac{1}{M}} W_M^k\right) \quad (7)$$

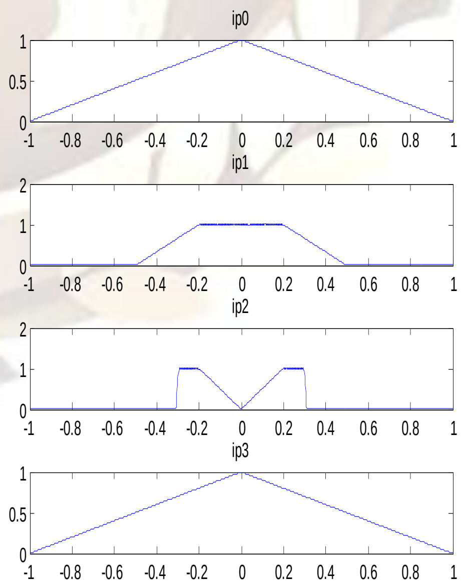



Fig. 3: Reconstructed output for four channel TMUX

## 2. Prototype filters for different Transmultiplexers

For M-band TMUX, prototype filter should have following design requirements

- Low pass frequency response.
- Cut-off frequency should be $\pi/M$
- Good transition band response
- Stop-band attenuation as minimum as possible

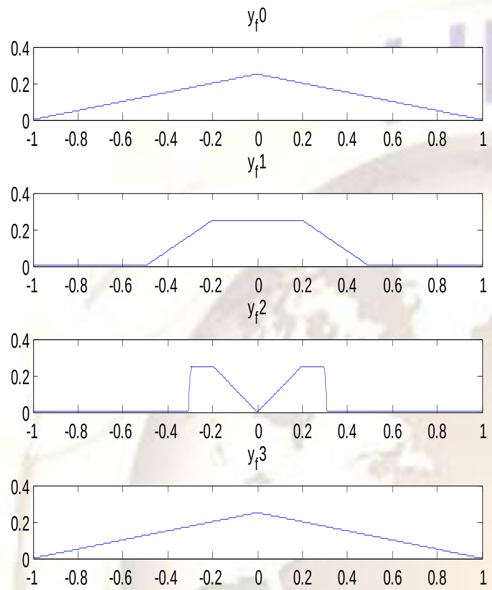
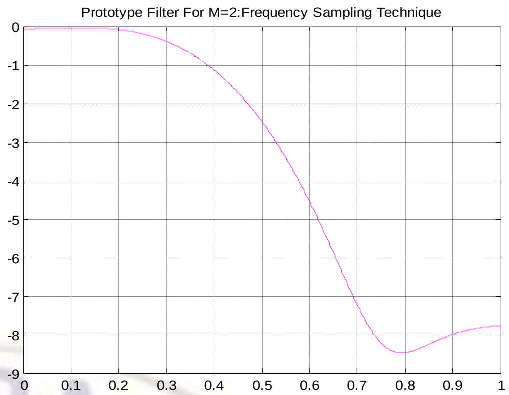



Fig. 4: Reconstructed output for four channel TMUX

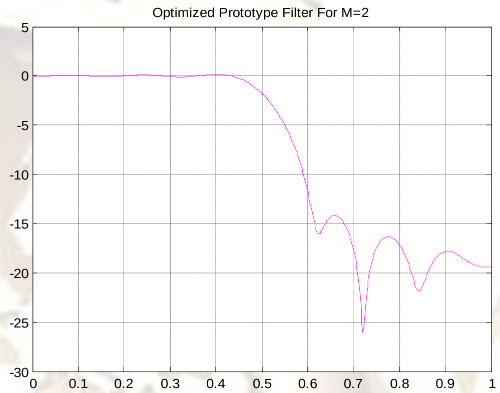
As per results from Fig. 5 (a), we have achieved some of the above requirements by selecting frequency sampling technique for this type of filter design. For two-band case, cut-off frequency we got is $\omega_c \cong 0.5\pi$, but still perfect stopband characteristics is not achieved (as seen from Fig. 15 (a), stopband attenuation is considered as practically very less).
So we minimized stopband energy using least square criterion [7]. This will give good prototype design for complex modulated filter banks, which can be clearly observed in Fig. 5 (b).

## 3. Non-Maximally Decimated TMUX:

The AFB and SFB for Non-maximally decimated TMUX are as shown in Fig. 6 and 7. Prototype filter is designed using frequency sampling technique having length $L_p = KM - 1$. Here K is overlapping factor and M is number of sub channels and $L_p$ is length of prototype filter.




**(a)**




**(b)**

Fig. 5: (a) Prototype filter frequency sampling technique for M=2 (b) Prototype filter using optimization technique for M=2

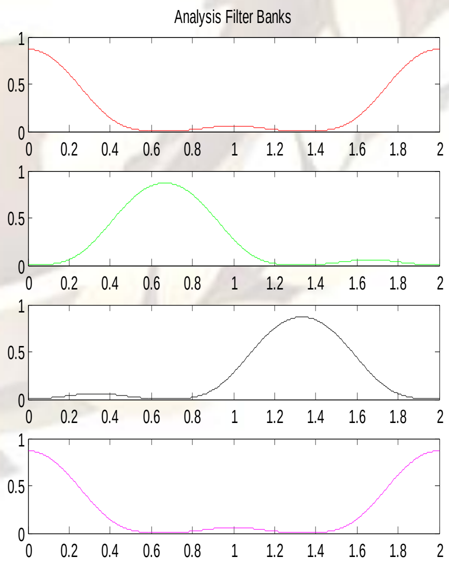
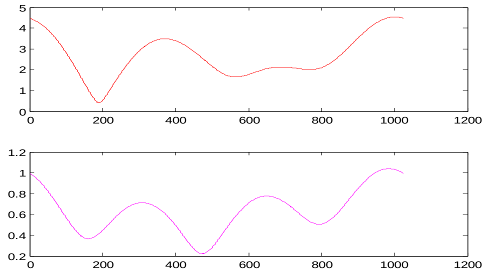



Fig. 6: Analysis Filter bank for Non-Maximally Decimated TMUX



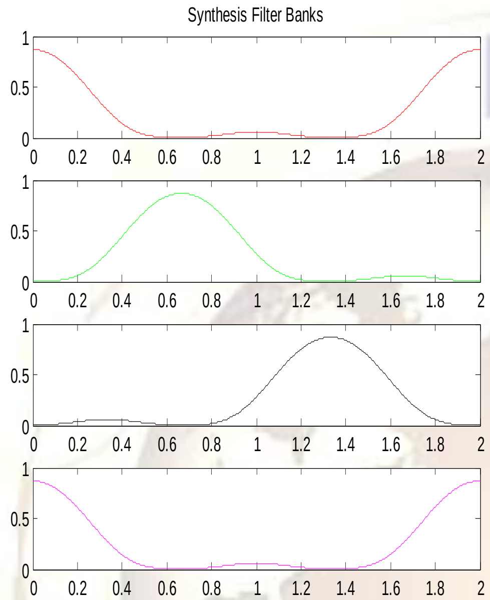



Fig. 7: Synthesis filter bank Non-Maximally Decimated TMUX

Here, upsampling and downsampling is performed by a factor of L which is less than number of sub channels M. (L=3 and M=4). From [5] and [6] implementation of this non-maximally decimated TMUX results in alias cancellation but perfect reconstruction is not gurranted which is observed in Fig. 8 .

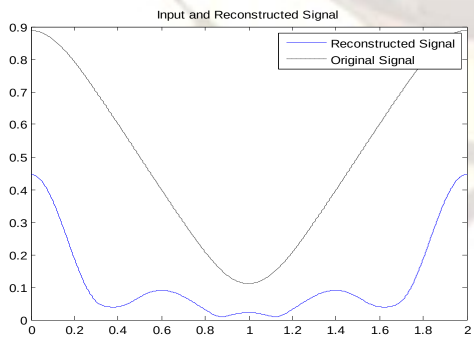
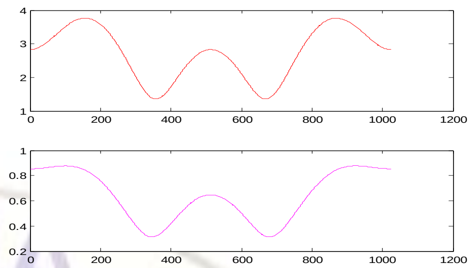



Fig. 8: Original and reconstructed signal for Non-maximally decimated TMUX

## 4. Partial TMUX

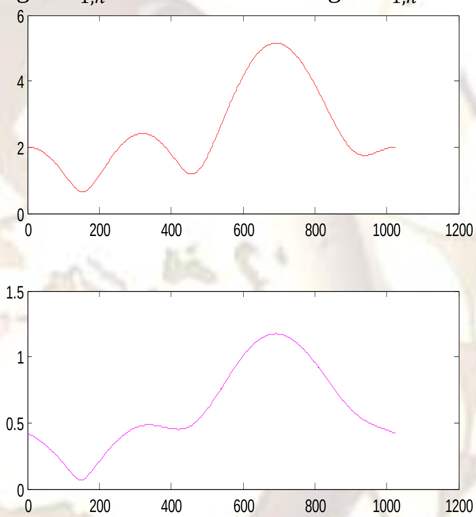
Implementation of partial TMUX where upsampling and downsampling is performed by factor of M/2. Frequency responses corresponding to four different users complex data shows nearly perfect reconstruction (some distortions are allowed).This implementation is shown in below Fig. 9 and 10.

(a)

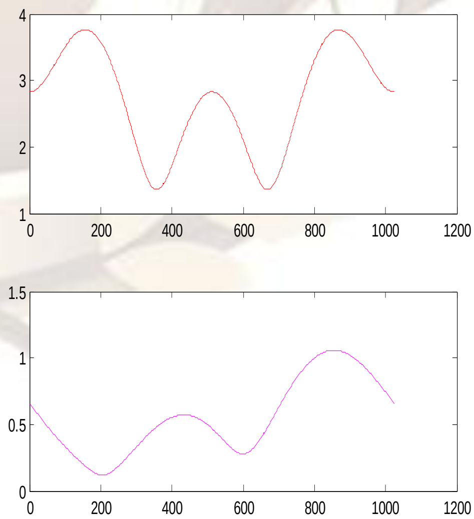


(b)

Fig. 9: (a) spectrum of original signal $c_{o,n}$ and reconstructed signal $\tilde{c}_{0,n}$ (b) spectrum of original signal $c_{1,n}$ and reconstructed signal $\tilde{c}_{1,n}$



(c)



(d)

Fig. 10: (c) spectrum of original signal $c_{2,n}$ and reconstructed signal $\tilde{c}_{2,n}$ (d) spectrum of original signal $c_{3,n}$ and reconstructed signal $\tilde{c}_{3,n}$

**5. ICI and ISI calculation**

There are two quality measures which decide performance of TMUX system.

1. Inter-channel Interference (ICI):-

It is nothing but $k$th input signal have effects on $l$th output signal for $k \neq l$ .The ICI in the $l$th output is the sum of effects of rest input signals $(k \neq l)$ on this output. For $l$th output ICI can be calculated from below relation [8]:

$$E_{ICI}(l) = \frac{1}{\pi}\int_0^{\pi}\left(\sum_{k=0,k\neq l}^{M-1} |T_{lk}(e^{jw})|^2\right)dw \quad (8)$$

Where, $T_{lk}(z)$ is transfer function of TMUX between $l$th output and $k$th output channel.

2. Inter-symbol Interference (ISI):-

Effect of $(N-1)$th symbol or any of total $N$ symbols on $N$th symbol will result in ISI. ISI can be measured using following relation [8]:

$$E_{ISI}(l) = \sum_n (t_{ll}[n] - \delta[n - [N/M]])^2 \quad (9)$$

Where, $t_{ll}[n]$ is impulse response between $l$th output and $k$th input $(k = l)$ and $\delta(n)$ is unit impulse response. Above equation in frequency domain is [9]:

$$E_{ISI}(l) = \frac{1}{\pi}\int_0^{\pi}\left(\sum_{k=0,k\neq l}^{M-1}|T_{lk}(e^{jw})|^2\right)dw \quad (10)$$

$$where\ l,k = 0\ to\ M-1$$

| TMUX Configuration | Filter design technique | ICI (dB) | ISI (dB) |
|---|---|---|---|
| Four band-partial TMUX | Frequency sampling | -34.82 | -29.52 |
| Two band-maximally decimated TMUX | Frequency sampling with optimization | -72.68 | -5.69 |
| Four band-maximally decimated TMUX | Frequency sampling | - 26.69 | -11.63 |
| Four band-maximally decimated TMUX | Frequency sampling | - 26.69 | -11.63 |

Table 1: ICI and ISI values for different TMUX structures

## IX. CONCLUSIONS

In this paper, different TMUX structures i.e. maximally, non-maximally decimated and partial structures have been implemented. In maximally decimated structure for two-channel TMUX and four-channel TMUX, perfect reconstruction of input signal is observed. Results obtained for non-maximally decimate TMUX for (L<M) shows that alias cancellation is achieved but perfect reconstruction is not guaranteed.

In case of partial TMUX, even after upsampling and downsampling factor is reduced to M/2, almost perfect reconstruction of complex input symbols is observed. The compensation of upsampling and downsampling factor by 2 is due to OQAM pre-processing and OQAM post-processing. In OQAM pre-processing, each complex QAM symbol is converted into two real symbols thereby increasing data rate by 2. Similarly, in OQAM post-processing, two real symbols are combined to form one complex QAM symbol, thereby decreasing sampling rate by 2. Frequency sampling technique is used to design prototype filter. Length of prototype filter can be controlled by overlapping factor (K). Proper design of prototype filter gives good TMUX performance, which is observed by comparing ICI, ISI values and reconstructed signals. for partial TMUX configuration will give good ICI and ISI results (i.e. low values) as compared to maximally decimated TMUX when for both the cases, frequency sampling technique is used. If we incorporate optimization criterion [7], then we get better ICI i.e. -72dB here. It is also observed that for ideal channel, ISI and ICI values are same which is very much expected.

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