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A Generalized Transmultiplexer and its Application to Mobile Satellite Communications

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ABSTRACT

This paper presents a generalization of the digital transmultiplexer technology. The proposed method can realize a transmultiplexer (TMUX) and a trans-Demultiplexer (TDUX) filter banks whose element filters can have bandwidths greater than the channel spacing frequency. This feature is useful for many applications in communications fields. As an example, a satellite switched (SS) FDMA system is proposed for spot beams satellite communications in particular for mobile satellite communications.

1. INTRODUCTION

The transmultiplexer based on FFT and Digital polyphase concept was proposed in 1974[1]. Since then extensive applications have been made to FDM/TDM transmultiplexers for General Switched Telephone Networks[2,3]. Another interesting area of its application is to the onboard processing circuit for satellite switched (SS) FDMA systems[4], which will be quite effective for mobile satellite communications. An exhaustive summary and prospect of the technology is given in the literature[5].

The conventional transmultiplexer method has an inherent limitation that the bandwidth of the element filter of the filter bank is bounded by the channel spacing frequency. This limitation is too restrictive for general SS/FDMA systems which must be able to provide transparent transmission paths for any portion of the assigned frequency ranges.

This paper presents a generalization of the transmultiplexer which can provide such filter banks.

2. CONVENTIONAL TRANSMULTIPLEXER

A block diagram of the trans multiplexer is given in Figure 1. In the figure (A) shows a multiplexer (TMUX) and (B) a demultiplexer (TDUX). The TMUX output Y (Z) is given by

$$Y(Z) = \sum_{i=0}^{N-1} Z^{-i} G_i(Z^N) \sum_{k=0}^{N-1} e^{j\frac{2\pi}{N}ki} X_k(Z^N) \qquad (2\text{-}1)$$

where

$$Z = e^{j2\pi fT} = e^{j2\pi f/fs} \qquad (2\text{-}2)$$

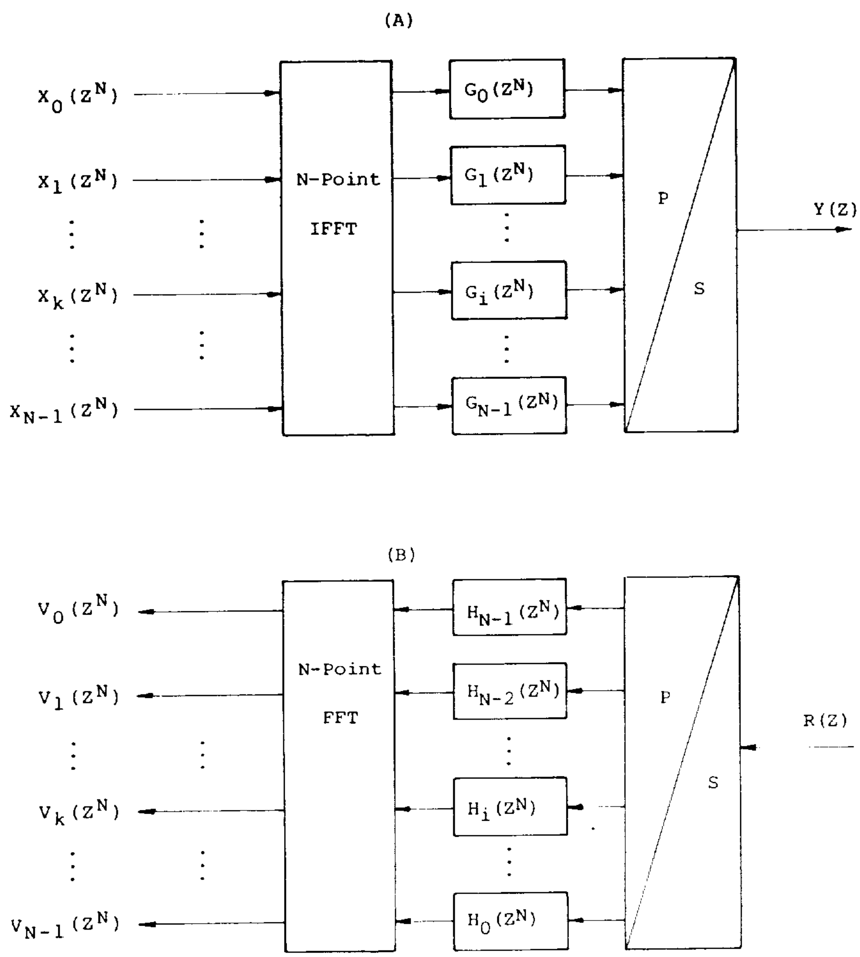
$$fs = 1/T \text{ ; Sampling frequency} \qquad (2\text{-}3)$$

$$X_k(Z^N) = \sum_n x_k(n) Z^{-nN} \qquad (2\text{-}4)$$

Those $G_i(Z^N)(i=0,1,2, \ldots, N-1)$ in eq(1) are the subfilters which constitute the basic LPF G(Z) as

$$G(Z) = \sum_{\ell=0}^{L-1} g(\ell) Z^{-\ell} = \sum_{i=0}^{N-1} Z^{-i} G_i(Z^N) \qquad (2\text{-}5)$$

$$G_i(Z^N) = \sum_{\ell=0}^{L/N-1} g(\ell N+i) Z^{-\ell N} \qquad (2\text{-}6)$$



(A) Multiplexer (MUX)
(B) Demultiplexer (DUX)

Figure 1 Conventional Digital FDM Circuit

The output of the k-th channel of TDUX is given by

$$V_k(Z^N) = \sum_{i=0}^{N-1} e^{-j\frac{2\pi}{N}ki} H_{N-1-i}(Z^N) R_i(Z^N) \tag{2-7}$$

where the receive signal R(Z) is decomposed into subsequences $R_i(Z^N)$ as follows

$$R(Z) = \sum_n r(n) Z^{-n} = \sum_{i=0}^{N-1} Z^{-i} R_i(Z^N) \tag{2-8}$$

$$R_i(Z^N) = \sum_n r(n \cdot N+i) Z^{-Nn} \tag{2-9}$$

It is apparent from Figure 1 that the TMUX and TDUX are mutualy inverse operations.
It should be noted that because sampling frequencies for the signals $X_k(Z^N)$ or $V_k(Z^N)$ are

$$\Delta f = \frac{1}{NT} = \frac{fs}{N} \tag{2-10}$$

the bandwidth of each multiplex or demultiplex filter can not exceed Δf.

3. GENERALIZED TRANSMULTIPLEXER

The structure of the generalized TMUX and TDUX is given in Figure 2.

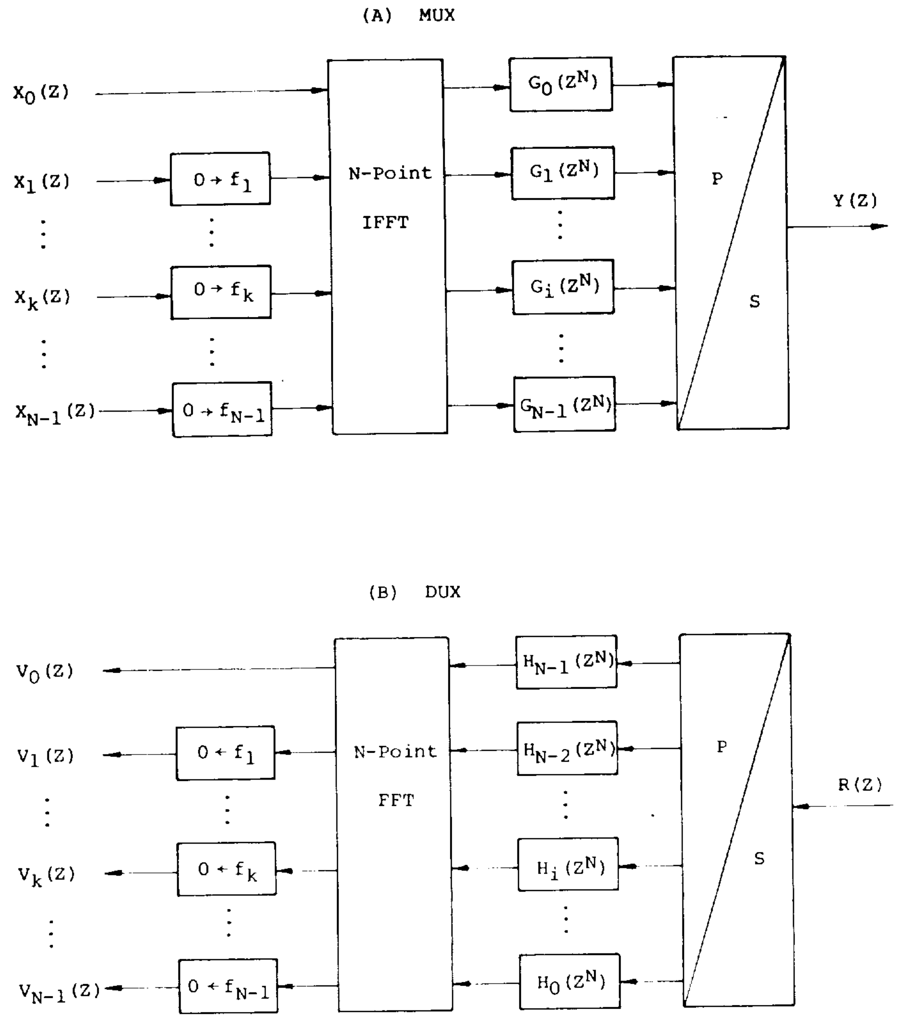


Figure 2 Generalized Digital FDM Circuit

3.1 TMUX

In general the k-th input $X_k(Z)$ is expressed as

$$X_k(Z) = \sum_n x_k(n) Z^{-n} \tag{3-1}$$

This signal is to be frequency converted to f_k;

$$f_k = k \cdot \Delta f = k \cdot \frac{fs}{N} \tag{3-2}$$

The conversion is made by the variable transform;

$$Z \to e^{-j2\pi f_k T} Z = e^{-jk\frac{2\pi}{N}} Z \tag{3-3}$$

Hence;

$$X_k(Z;k) = \sum_n e^{j\frac{2\pi}{N}kn} x(n) Z^{-n} \tag{3-4}$$

In the same manner the original LPF $G(Z)$ is also frequency converted to f_k in order to select $X_k(Z;k)$;

$$G(Z;k) = \sum_{i=0}^{N-1} e^{j\frac{2\pi}{N}ki} Z^{-i} G_i(Z^N) \tag{3-5}$$

Thus the output of the TMUX will be

$$\begin{aligned} Y(Z) &= \sum_{k=0}^{N-1} G(Z;k) \cdot X_k(Z;k) \\ &= \sum_{i=0}^{N-1} Z^{-i} G_i(Z^N) \sum_{k=0}^{N-1} e^{j\frac{2\pi}{N}ki} \cdot X_k(Z;k) \end{aligned} \tag{3-6}$$

Eq (3-6) is depicted in (A) of Figure 2. The figure and eq (3-6) tell that the generalized TMUX is basically of the same structure as the conventional TMUX including it as a special case as shown below. From eq (3-4)

$$X_k(Z;k) = \sum_n e^{jk\frac{2\pi}{N}n} x_k(n) Z^{-n}$$

If the input signal $X_k(Z)$ has data only for every N samples, then

$$X_k(Z;k) = \sum_{n'} x_k(n'N) Z^{-n'N} = X_k(Z^N)$$

Thus the generalized TMUX reduces to the conventional TMUX.
If the input $X_k(Z)$ has data for every N/2 samples, then

$$X_k(Z;k) = \sum_n (-1)^{kn} x_k(n\tfrac{N}{2}) Z^{-n\frac{N}{2}} \quad (3\text{-}7)$$

Eq (3-7) can be expressed in another form;

$$X_k(Z;k) = X_k(Z^N;e) + (-1)^k Z^{-N/2} X_k(Z^N;O) \quad (3\text{-}8)$$

where

$$X_k(Z^N;e) = \sum_n x_k(nN) Z^{-nN} \quad (3\text{-}9)$$

$$X_k(Z^N;O) = \sum_n x_k(nN+\tfrac{N}{2}) Z^{-nN} \quad (3\text{-}10)$$

Because the sampling frequency is $2\Delta f$, the bandwidth of the input signal can be greater than Δf up to $2\Delta f$.

3.2 TDUX

The receive signal R(Z) is first frequency converted from f_k to 0(Hz), and then selected by the LPF H(Z). The frequency conversion is made by the variable transform

$$Z \to e^{j\frac{2\pi}{N}k} \cdot Z \quad (3\text{-}11)$$

Hence;

$$R(Z;-k) = \sum_n r(n) e^{-j\frac{2\pi}{N}kn} Z^{-n} \quad (3\text{-}12)$$

Then the low pass filter output is given by

$$V_k(Z) = H(Z)R(Z;-k)$$

$$= Z^{-(N-1)} \sum_{i=0}^{N-1} \sum_n Z^{(i-n)} H_{N-1-i}(Z^N) \cdot e^{-j\frac{2\pi}{N}kn}\, r(n)$$

$$= Z^{-(N-1)} \sum_m Z^{-m} e^{-j\frac{2\pi}{N}km} \sum_{i=0}^{N-1} e^{-j\frac{2\pi}{N}ki} H_{N-1-i}(Z^N)\, r(m+i) \quad (3\text{-}13)$$

The equation gives the structure (B) of Figure 2.
If we select one of every N samples, then we put m=nN to obtain

$$V_k(Z^N) = Z^{-(N-1)} \cdot \sum_n Z^{-nN} \cdot \sum_{i=0}^{N-1} e^{-j\frac{2\pi}{N}ki} H_{N-1-i}(Z^N)\, r(nN+i)$$

$$= Z^{-(N-1)} \sum_{i=0}^{N-1} e^{-j\frac{2\pi}{N}ki} H_{N-1-i}(Z^N) \cdot R_i(Z^N) \quad (3\text{-}14)$$

Thus the generalized TDUX includes the conventional TDUX as a special case.
If we select one of every N/2 samples, then we put m=nN/2 to obtain

$$V_k(Z^{N/2}) = Z^{-(N-1)} \sum_n Z^{-nN/2} (-1)^{kn} \cdot \sum_{i=0}^{N-1} e^{-j\frac{2\pi}{N}ki} H_{N-1-i}(Z^N)\, r(nN/2+i)$$

$$= Z^{-(N-1)} \{V_k(Z^N;e) + Z^{-N/2}(-1)^k \cdot V_k(Z^N;O)\} \quad (3\text{-}15)$$

where for even samples

$$V_k(Z^N;e) = \sum_{i=0}^{N-1} e^{-j\frac{2\pi}{N}ki} H_{N-1-i}(Z^N) R_i(Z^N) \quad (3\text{-}16)$$

and for odd samples

$$V_k(Z^N;O) = \sum_{i=0}^{N-1} e^{-j\frac{2\pi}{N}ki} H_{N-1-i}(Z^N) R'_i(Z^N) \quad (3\text{-}17)$$

where

$$R'_i(Z^N) = \sum_n r(nN+\tfrac{N}{2}+i) Z^{-nN} \quad (3\text{-}18)$$

$$(i=0,1,2,\ \ldots,\ N-1)$$

The generalized TDUX above gives the output with sample frequency $2\Delta f$. Therefore the bandwidth of the filter $H(Z)$ can be greater than Δf up to $2\Delta f$.

It is apparent from Figure 2 that the TMUX and TDUX are mutually inverse operations. If the output of TDUX is fed to the corresponding input of TMUX, then the total frequency response is given as follows.

$$\begin{aligned} Y(Z) &= \sum_{k=0}^{N-1} G(Z;k)V_k(Z;k) \\ &= \sum_{k=0}^{N-1} G(Z;k)H(Z;k)R(Z) \\ &= R(Z)\sum_{k=0}^{N-1} G(Z;k)H(Z;k) \qquad (3\text{-}19) \end{aligned}$$

Thus the whole transmission path is transparent if

$$\sum_{k=0}^{N-1} G(Z;k)H(Z;k) = 1 \qquad (3\text{-}20)$$

4. SATELLITE SWITCHED (SS) FDMA SYSTEM

The block diagram of a SS/FDMA system for mobile satellite system is given in Figure 3. The SS/FDMA system is very effective for mobile satellite communications systems with a number of spot beams. For example mobile to mobile links can be easily set up to avoid the double delay which would be incurred by double hops via feeder links. By adoption of spot beams for feeder links Very Small Aperture Stations (VSATs) can be easily set close to customer facilities and can reduce utility cost for terrestrial networks.

The proposed SS/FDMA system uses the generalized TDUX to divide incoming signals from each beam, put them into the Base Band Switch Matrix (BBSM) which executes the inter-beam switching.

The output of the BBSM is frequency multiplexed by the generalized TMUX to be sent to each downlink.

The total frequency response of the proposed system is depicted in Figure 4. The filters for TMUX and TDUX are designed to satisfy eq (3-20). Thus the proposed system can provide adaptive bandwidth SS/FDMA system with perfectly transparent transmission paths.

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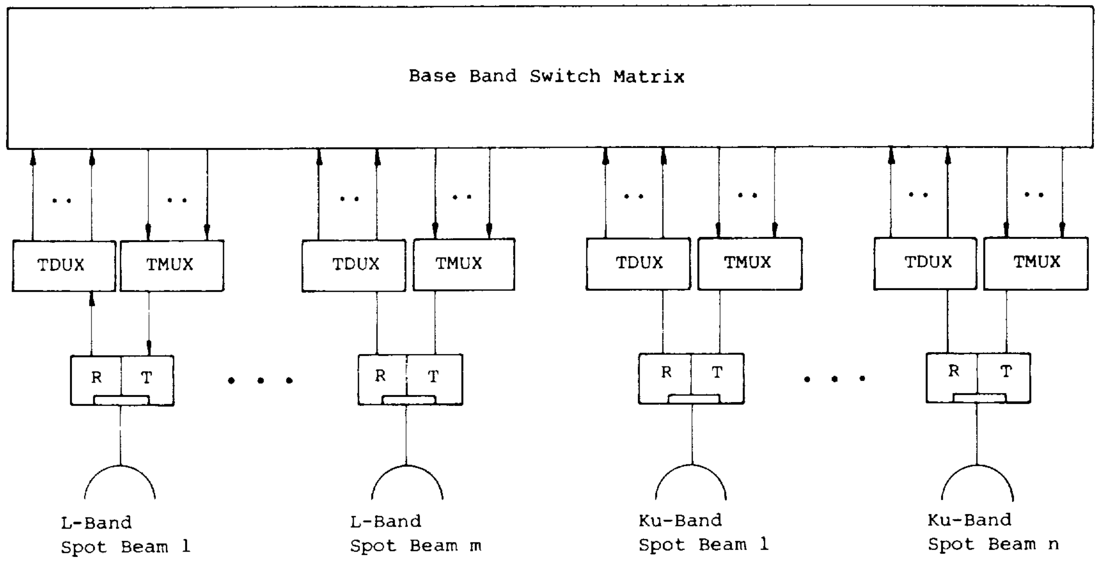
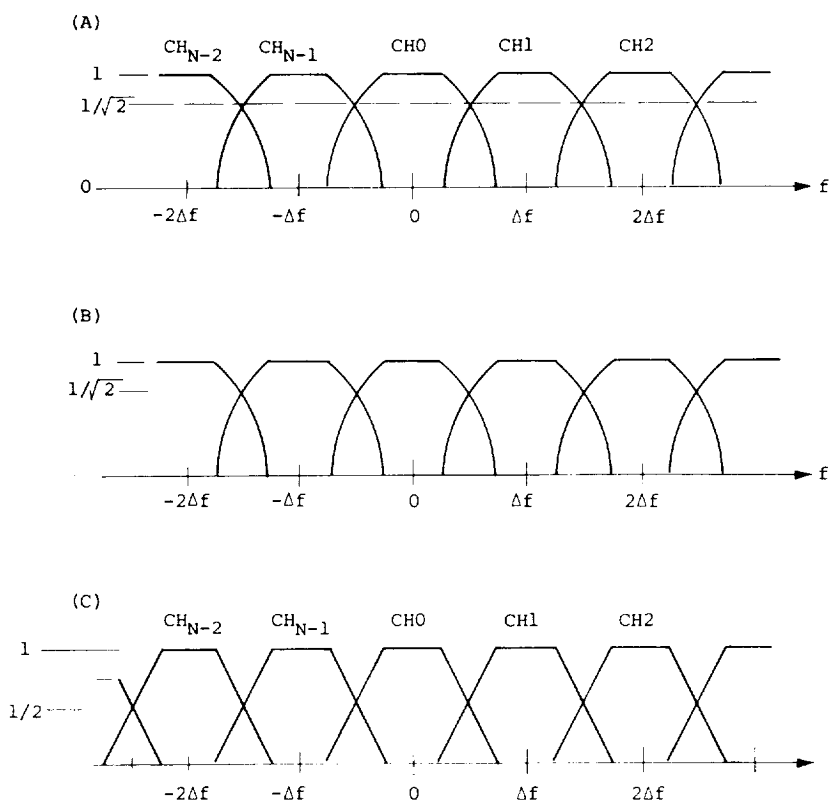


Figure 3 Satellite Switched FDMA System



(A) TDUX Filter Bank
(B) TMUX Filter Bank
(C) TDUX-TMUX Filter Bank

Figure 4 Satellite Switch Frequency Characteristics