Paper No. 83136
IEEC & E '83

Session No. 13

# PERFORMANCE OF A 60-CHANNEL DIGITAL TRANSMULTIPLEXER

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SUMMARY

The performance of a digital per-channel transmultiplexer system based on the analytic signal method is discussed, with application to the conversion between two 30-channel PCM groups and one 60-channel FDM supergroup. The system structure, the digital filter design and realization, and the overall computational complexity are considered, showing the suitability of the system implementation by presently available integrated digital circuits.

## 1. INTRODUCTION

The conversion of a set of telephone channels from the time-division-multiplexing (TDM) format to the frequency-division-multiplexing (FDM) format and viceversa at the multiplex signal level (transmultiplexer) represents a particularly interesting and challenging application of the digital signal processing techniques to communication systems. The very stringent requirements of telecommunications equipment needed to guarantee the high level of signal quality (set, for example, by the relevant Recommendations of CCITT) can be achieved by exploiting many of the theoretical and practical properties of the digital signal processing. The processing techniques involved, though sophisticated, appear well matched to the present state and the future trend of high-density integrated digital circuits, and are attractive from an implementation point of view.

Many approaches have been proposed in the last decade and up-to-date developments have been reported in the recent literature[1]. Here we consider the application of the analytic signal method[2] to the conversion between two 30-channel PCM groups and the 60-channel FDM supergroup of the standardized multiplexing hierarchy.

In Sect. 2 the structure of the conversion system is briefly recalled and discussed, pointing out the specific implementation requirements for the 60-channel application. In Sect. 3 the digital filter design and realization are presented, in order to meet the CCITT transmultiplexer specifications, and the overall conversion system computational complexity is evaluated.

## 2. STRUCTURE OF THE CONVERSION SYSTEM

The principle of operation of the transmultiplexer, analytically explained in[2], and depicted in the block diagram of Fig. 1 for the TDM to FDM conversion, is briefly recalled in the following. Each (decommutated) TDM signal is supplied to the input of a different channel. At the odd-numbered channels an alternate sign inversion of the signal samples is present. For the i-th channel the method generates a discrete analytic signal at the TDM sampling rate $1/T = 8$ kHz (baseband SSB signal) by means of the complex filter $\bar{G}_i(e^{j\omega T})$. The output complex signal has a spectrum bandlimited in 0 to $1/2T$ for the even channels and in $-1/2T$ to 0 for the odd channels. Successively, it is allocated in the SSB format in one of the FDM channels at the rate $L/T$ by means of the interpolating bandpass complex filter $\bar{H}_i(e^{j\omega T/L})$. For the 60-channel case the FDM supergroup occupies the frequency range 312-552 kHz. An appropriate sampling frequency for this application is therefore $L/T = 576$ kHz. This choice of the output sampling frequency assures the correct allocation of the first replica of the sampled signal spectrum in one of the FDM bands and allows for sufficiently wide guard-bands (48 kHz) for the final extraction of the composite analog FDM signal by means of an analog bandpass filter with passband from 312 to 552 kHz. This output sampling frequency gives rise to an interpolation factor

$$L = 72 \tag{1}$$

The index i in the previous filters, ideally, should run from 1 to 72. However, in practice, due to the presence of the guard-bands, it is limited to the number of channels, i.e. $i = 1,\dots,60$.

The high value of the interpolation factor L makes impractical the implementation of the sampling frequency increase in one step. A more convenient approach[3] is to split the interpolation process in two steps with interpolation factors $L_1$ and $L_2$ respectively, provided that

$$L = L_1 L_2 \tag{2}$$

Consequently, each high-rate complex interpolation filter must be realized, according to the relation

$$\bar{H}_i(e^{j\omega T/L}) = \bar{H}_{1i}(e^{j\omega T/L_1})\, \bar{H}_{2i}(e^{j\omega T/L}) \tag{3}$$

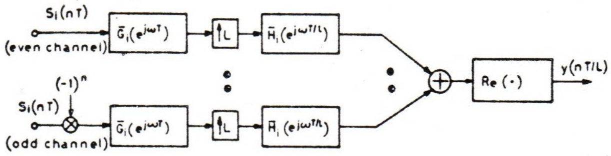


Fig. 1 - Block diagram illustrating the principle of the transmultiplexer operation.

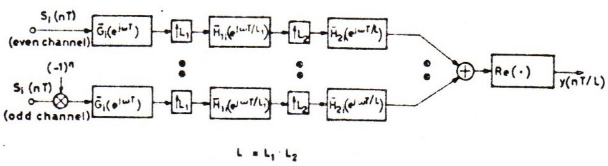


Fig. 2 - Block diagram with two interpolation stages.

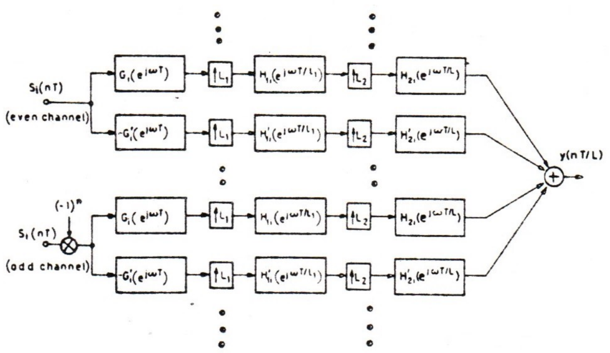


Fig. 3 - Implementation structure of the transmultiplexer.

as the cascade of the filter $\bar{H}_{1i}(e^{j\omega T/L_1})$, interpolating by the factor $L_1$, and of the filter $\bar{H}_{2i}(e^{j\omega T/L})$, further interpolating by the factor $L_2$, as shown in Fig. 2.

Moreover, as shown in[2], the complex-type processing required by the block diagram of Fig. 2 followed by the extraction of the signal real part, is not necessary to the conversion system operation. Indeed, by expressing

$$\bar{G}_i(e^{j\omega T}) = G_i(e^{j\omega T}) + j\,G'_i(e^{j\omega T}) \qquad (4)$$

$$\bar{H}_{1i}(e^{j\omega T/L_1}) = H_{1i}(e^{j\omega T/L_1}) + j\,H'_{1i}(e^{j\omega T/L_1}) \qquad (5)$$

$$\bar{H}_{2i}(e^{j\omega T/L}) = H_{2i}(e^{j\omega T/L}) + j\,H'_{2i}(e^{j\omega T/L}) \qquad (6)$$

where at the right hand side the first term is the conjugate symmetric part and the second term is the conjugate antisymmetric part of each complex filter, it is possible to verify that an equivalent implementation structure for the transmultiplexer is that shown in Fig. 3, involving only processing of real signals by means of real filters.

This conversion system allows wide transition bands to the high-rate filters, whose realization more heavily influences the overall system computational complexity.

## 3. FILTER DESIGN AND REALIZATION AND SYSTEM PERFORMANCE

The conversion system requires the design of the complex filters $\bar{G}_i(e^{j\omega T})$, $\bar{H}_{1i}(e^{j\omega T/L_1})$ and $\bar{H}_{2i}(e^{j\omega T/L})$ or equivalently of the three couples of real filters $G_i(e^{j\omega T})$, $G'_i(e^{j\omega T})$, $H_{1i}(e^{j\omega T/L_1})$, $H'_{1i}(e^{j\omega T/L_1})$ and $H_{2i}(e^{j\omega T/L})$, $H'_{2i}(e^{j\omega T/L})$, for $i = 1,\dots,60$. As explained in[2], the preferred approach is the design of the complex filters, because it assures well-matched filter responses in the passband and, mainly, in the transition bands, which is a specific requirement of the proposed conversion method. Moreover a little insight in the method shows that the actual required number of filters to be designed is: i) two low-rate filters $\bar{G}_i(e^{j\omega T})$, i.e. one for the even channels and the other for the odd channels; ii) $L_1$ first-stage interpolation filters $\bar{H}_{1i}(e^{j\omega T/L_1})$; iii) L (theoretically) or 60 (in practice) final-stage interpolation filters $\bar{H}_{2i}(e^{j\omega T/L})$. The $L_1$ first-stage interpolation filters and the 60 final-stage interpolation filters can be obtained by means of a frequency translation, respectively, of two appropriate lowpass-type complex prototypes, according to the filter design technique reported in[2]. The two low-rate filters are related by a frequency translation of 1/2T. Therefore, only one filter design at each sampling rate is required.

These three prototypes, say $\bar{G}(e^{j\omega T})$, $\bar{H}_1(e^{j\omega T/L_1})$

and $\bar{H}_2(e^{j\omega T/L})$, have to comply with the specifications for transmultiplexer systems (CCITT Recommendations G791, G792, G793): the sums of their in-band deviation must not exceed 0.3 dB and their stopband attenuation must be individually not less than 65 dB.

A FIR filter design is a convenient choice for both the interpolating prototypes $\bar{H}_1(e^{j\omega T/L_1})$ and $\bar{H}_2(e^{j\omega T/L})$ and the low-rate prototype $\bar{G}(e^{j\omega T})$, because of the higher noise immunity and the absence of limit cycles and of stability problems.

The filter design was carried out by means of a program able to deal with complex conjugate impulse responses, according to the technique proposed in[4].

Many choices are possible for the interpolation factors $L_1$ and $L_2$. They are indicated in Table 1. For each combination of $L_1$ and $L_2$, Table 1 shows the coefficient numbers $N_1$ and $N_2$ of the designed filters $\bar{H}_1(e^{j\omega T/L_1})$ and $\bar{H}_2(e^{j\omega T/L})$ respectively, their in-band (I.B.) deviation (dB) and stopband (S.B.) attenuation (dB).

| $L_1$ | $L_2$ | $N_1$ | I.B. | S.B. | $N_2$ | I.B. | S.B. |
|---|---|---|---|---|---|---|---|
| 8 | 9 | 39 | 0.032 | 68.6 | 27 | 0.043 | 66.11 |
| 6 | 12 | 29 | 0.034 | 68.11 | 47 | 0.014 | 76.02 |
| 3 | 24 | 15 | 0.023 | 71.55 | 119 | 0.034 | 68.25 |
| 4 | 18 | 19 | 0.036 | 67.56 | 71 | -0.036 | 67.78 |
| 12 | 6 | 59 | 0.03 | 69.19 | 23 | 0.0033 | 88.38 |
| 18 | 4 | 89 | 0.029 | 69.58 | 11 | 0.042 | 66.35 |

Table 1 - Results for the interpolation filters.

The multiplication rate $R_{Mp}$ of each signal path in Fig. 3 is given by the relation

$$R_{Mp} = N/T + \sum_{k=1}^{K} \lceil N_k/L_k \rceil \prod_{j=1}^{k} L_j/T \qquad (7)$$

where N is the number of the coefficients of the low-rate filter, $N_k$ is the number of the coefficients of the k-th stage filter interpolating by the factor $L_k$, K is the number of interpolation stages and $\lceil x \rceil$ indicates the smallest integer equal to or greater than x.

Following the results of Table 1, the following combination was chosen as the most convenient for the three prototypes to meet the transmultiplexer frequency response constraints: N = 35 for $\bar{G}(e^{j\omega T})$, $N_1$ = 39 for $\bar{H}_1(e^{j\omega T/L_1})$ with $L_1$ = 8 and $N_2$ = 27 for $\bar{H}_2(e^{j\omega T/L})$ with $L_2$ = 9. The overall multiplication rate for each signal path amounts to

$$R_{Mp} = 2328 \ 10^3 \text{ mults/s} \qquad (8)$$

This filter design procedure with infinite-precision coefficients was followed by the determination of the minimum wordlengths for the coefficients of all the low-rate filters $\bar{G}_i(e^{j\omega T})$ and the

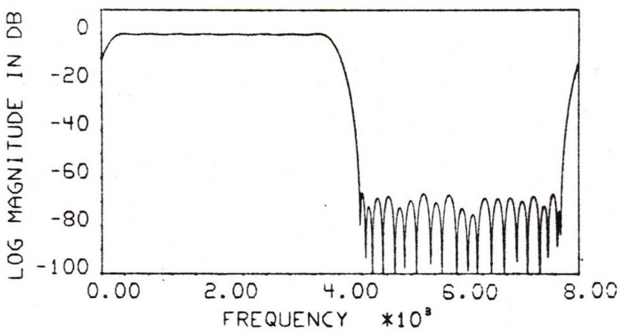


Fig. 4 - Frequency response of $\bar{G}_i(e^{j\omega T})$ (even channels).

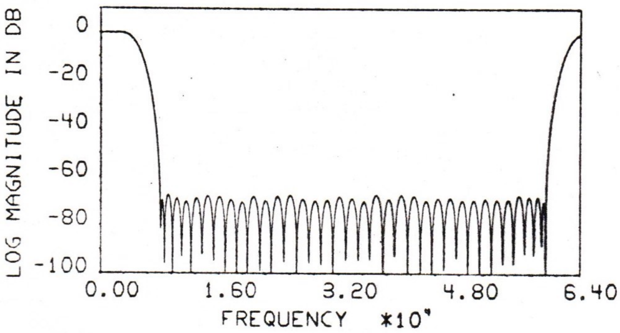


Fig. 5 - Frequency response of $\bar{H}_{11}(e^{j\omega T/L_1})$.

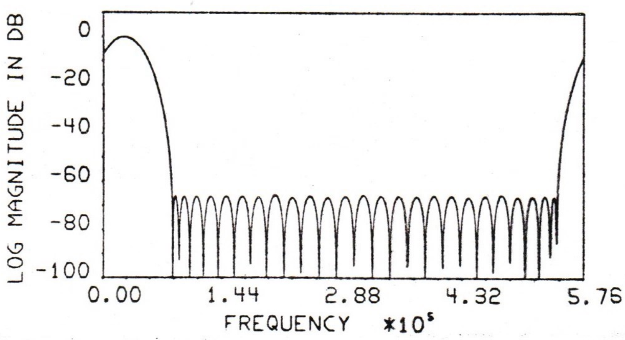


Fig. 6 - Frequency response of $\bar{H}_{21}(e^{j\omega T/L})$.

interpolation filters $\bar{H}_{1i}(e^{j\omega T/L_1})$ and $\bar{H}_{2i}(e^{j\omega T/L})$, that still satisfied the overall system requirements. They turned out to be 15 bits for the low-rate filters, 14 bits for the first-stage interpolation filters and 15 bits for the final-stage interpolation filters (all wordlengths include the sign bit).

This filter design produces an overall in-band maximum deviation of .24 dB and a minimum stop-band attenuation of 65.5 dB for one conversion (e.g. TDM to FDM), that assure a certain margin with respect to the CCITT specifications. It should also be pointed out that the designed filters are of the linear-phase type. This approach can be considered a kind of worst-case analysis. Indeed, as shown in[2] and [5], if one should design minimum-phase filters to meet the CCITT specifications on the overall conversion system group delay, a comparable, and even better, filter response is obtained with a smaller number of coefficients.

As examples of the obtained filters Fig. 4 shows the frequency response of $\bar{G}_i(e^{j\omega T})$ for the even channels, Fig. 5 shows the frequency response of $\bar{H}_{11}(e^{j\omega T/L_1})$, the first of the eight first-stage interpolation filters, and Fig. 6 shows the frequency response of $\bar{H}_{21}(e^{j\omega T/L})$, the first of the sixty final-stage interpolation filters. In each figure the filter coefficients have been rounded to the appropriate bit number previously indicated.

## 4. CONCLUSIONS

A transmultiplexer structure for directly interfacing two 30-channel PCM groups with a 60-channel FDM supergroup has been discussed, based on the analytic signal method. The results reported here show the feasibility of this method for the implementation of the 60-channel transmultiplexer.

The system computational complexity allows the use of the presently available low-cost digital integrated circuits. Other advantages of this approach are the system structure modularity and the use of FIR digital filters, with their inherent high noise immunity, the absence of limit cycles and of stability problems and their simple hardware realization throughout the whole conversion system.

Further improvements of this structure are expected to be obtained from a minimum-phase design of both low-rate and interpolation filters.

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