

Flexible Frequency-Band Reallocation Network Based on Variable Oversampled Complex-Modulated Filter Banks

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ABSTRACT

An important issue in the next-generation satellite-based communication systems is the satellite on-board reallocation of information which calls for digital flexible frequency-band reallocation (FFBR) networks. This paper introduces a new class of FFBR networks based on variable oversampled complex-modulated filter banks (FBs). The new class can outperform previously existing ones when flexibility, low complexity and inherent parallelism, perfect frequency-band reallocation, and simplicity are considered simultaneously.

1. INTRODUCTION

The European Space Agency (ESA) outlines three major architectures for future broadband satellite-based systems [1]. Two of these are the *distributed access network* and *professional user network* which are to provide high-capacity point-to-point and multicast services for ubiquitous Internet access. The satellites are to communicate with user units via multiple spot beams. In order to use the limited available frequency spectrum efficiently, the satellite on-board signal processing must support frequency-band reuse among the beams and also flexibility in bandwidth and transmission power allocated to each user [2], [3]. Furthermore, dynamic frequency allocation is desired for covering different service types requiring different data rates and bandwidths. An important issue in the next-generation satellite-based communication system is therefore the *on-board reallocation of information*. In technical terms, this calls for digital *flexible frequency-band reallocation (FFBR) networks* (also referred to as frequency multiplexing and demultiplexing networks) which thus are critical components (see Fig. 1). In addition to flexibility, these future networks should have a *low complexity and inherent parallelism* and be able to approximate *perfect frequency-band reallocation (PFBR)* as close as desired. It is also desired that the network be as *simple* as possible regarding analysis, design, and implementation.

This paper introduces a new class of FFBR networks based on variable oversampled complex-modulated filter banks (FBs). The new technique can outperform the existing ones when all the aspects flexibility, low complexity and inherent parallelism, ability to approximate PFBR, and simplicity are considered simultaneously. Therefore, the new technique has potentials to become a standard solution for the next-generation satellite-based communications systems. Although the proposed technique primarily targets a problem present in satellite-based communication, as outlined in [1], it is a general technique that can be used in any communication environment that requires transparent (bentpipe) reallocation of information.

2. PROPOSED FFBR NETWORK

The section begins with a problem formulation and then continues with the proposed FFBR technique. Although a practical multicast system requires a multiple-input multiple-output (MIMO) network, it is beneficial to first understand and solve the single-

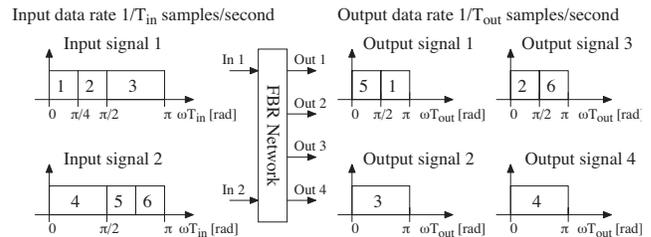


Figure 1. Illustration of frequency-band reallocation in the case of two input signals, four output signals, and six users.

input single-output (SISO) network case. The reason is that the SISO network case is simpler and a properly designed variable FB for a SISO network can be utilized in MIMO networks. In this way, the analysis and synthesis of MIMO networks are simplified. This paper will therefore concentrate on SISO networks, whereas MIMO networks will be considered in another paper.

2.1. Problem Formulation

The input signal is divided into Q fixed *granularity bands*. Any user can occupy one or several (at most Q) of these granularity bands. The input signal thus contains a *variable (adjustable) number of user subbands q* where $1 \leq q \leq Q$. In the extreme cases, $q = Q$ and $q = 1$, as illustrated for $Q = 6$ in Fig. 2(b) and (d) respectively. The case with $q = 3$ is illustrated in Fig. 2(c). It is stressed that q is *on-line variable* and, thus, can change its value during operation. Each value of q corresponds to a specific reallocation scheme which in practice is determined by an external controller. This means that the frequency-band reallocation network must be flexible in order to handle this variability. Furthermore, frequency guard bands (transition-bands) are assumed in order to ensure the network to be realizable in practice (see Fig. 2). Guard bands are only present between different user subbands, not within a user subband.

The function of the SISO FBR network is three-fold: it should 1) separate the input signal into the desired user subbands, 2) shift the user subbands in frequency to the desired positions, and 3) combine the frequency-shifted user subbands into the output signal.

2.2. SISO Network

The principle of the proposed SISO FFBR network is illustrated in Fig. 3. Like the existing multirate FB-based networks [4]–[5], it makes use of decimation and interpolation for generating the frequency shifts. However, there are several differences that distinguish the new method from the previous ones as outlined below.

The proposed network is based on a new class of variable oversampled complex-modulated N -channel FBs which makes use of decimation and interpolation by M and handles q input and

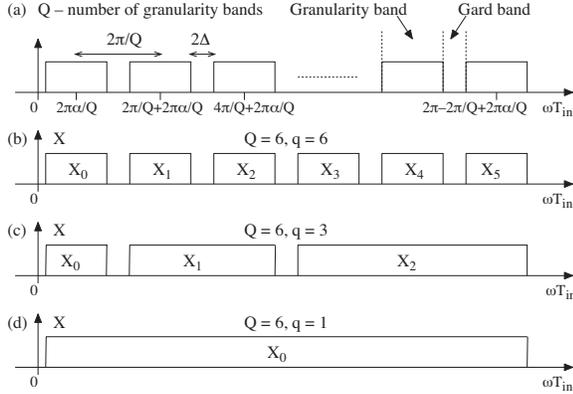


Figure 2. Granularity bands and typical input signals.

output user subbands. In the final implementation, M and N are fixed, whereas q is on-line variable satisfying $1 \leq q \leq Q$. By properly selecting N , M , and analysis and synthesis filters, given a maximum predefined value of Q , this new class of FBs can:

- 1) handle all possible frequency-shifts
- 2) handle all possible user subband widths
- 3) achieve as low complexity as in regular complex-modulated FBs
- 4) achieve as much parallelism as in any of the previously existing FFBR methods
- 5) approximate PFBR as close as desired via a proper design
- 6) easily be analyzed, designed, and implemented

Compared to previously existing frequency-band reallocation networks [4]–[6], the proposed one can: 1) outperform the regular modulated FB based network in terms of flexibility since that scheme is totally inflexible, 2) outperform the tree-structured FB based network in terms of flexibility and complexity because tree-structured FBs in our environment only offer partial flexibility (although the title of [5] suggests full flexibility) and require a substantially higher complexity than that of modulated FBs, and 3) outperform the overlap/save DFT/IDFT based network in terms of PFBR since it is not known how to approximate this as close as desired using that scheme. Furthermore, both tree-structured FB and overlap/save DFT/IDFT based networks appear more complicated to analyze and design.

In summary, the new technique can thus outperform the previously existing techniques when all the aspects flexibility, low complexity and inherent parallelism, PFBR, and simplicity are considered simultaneously. The ways in which these attractive features are obtained are as follows.

1) *Oversampled FB*: In the proposed technique, the outputs from the decimation filters are not maximally decimated. This is achieved by using an N -channel FB and a decimation factor of M , with $N > M$. The main advantage of this is that aliasing easily can be suppressed which allows one to combine smaller subbands into wider subbands *after* the synthesis FB, without introducing large aliasing distortion. In this way, full flexibility can be achieved.

2) *More FB channels than granularity bands*: The new technique makes use of more channels than granularity bands. This is necessary in order to be able to generate all possible frequency shifts, the reason being that a slight oversampling is employed. At first sight, this may seem to be a drawback, but it can in fact be shown that it is an advantage in that the complexity can be reduced by using more channels than granularity bands.

3) *Complex-Modulated FBs*: The new technique makes use of complex-modulated FBs resulting in very low complexity and simplicity in terms of analysis, design, and implementation.

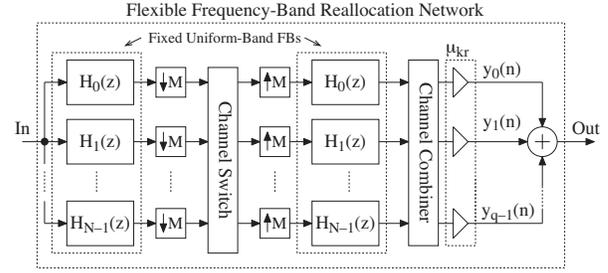


Figure 3. Proposed SISO FFBR network.

4) *Ability to approximate PFBR*: Because the proposed technique is based on oversampled complex-modulated FBs, one can easily control the performance of the FFBR network by properly designing one prototype filter.

3. PROPOSED CLASS OF ON-LINE VARIABLE OVER-SAMPLED COMPLEX-MODULATED FILTER BANKS

This section introduces the proposed class of variable oversampled complex-modulated FBs used in the new FFBR networks.

3.1. Problem Formulation

The point of departure is that the input signal consists of q adjacent user subbands where q is variable and $1 \leq q \leq Q$ with Q being the fixed number of granularity bands (see Fig. 2). It is further assumed that the input and output sampling rates are the same and the input as well as the output subbands have unique positions. Under the above assumptions, the problem reduces to that of reallocating the subbands in the input spectrum to the desired positions in the output spectrum. This problem can be solved by using the proposed multirate N -channel FB scheme in Fig. 4, provided that it satisfies certain requirements. To be precise, it is required that the FB should be able to:

- 1) handle a variable number, q , of user subbands where q can be any number between one and the number of the granularity bands, Q .
- 2) handle all possible combinations of user subbands that together cover the whole frequency region.
- 3) handle all frequency shifts that are integer multiples of $2\pi/Q$
- 4) approximate PFBR as close as desired via a proper design.

All these requirements can be met by using the scheme in Fig. 4 with properly selected filters and values of M and N . These issues will be treated in more detail in the following subsections.

3.2. Sampling Rate Change Factor M and number of FB Channels N

One can not choose $M = N = Q$, which corresponds to maximally decimated FBs [8], because then, variable subband widths and (approximately) zero-aliasing can not be achieved simultaneously. Aliasing is suppressed by properly selecting M , always with $M < N$ (see subsection 3.3). Through decimation and interpolation by the factor M , frequency shifts of $2\pi m/M$ radians for $m = 0, 1, \dots, M-1$ are generated [8]. It is required that one is able to generate all integer frequency shifts of the granularity frequency shift, i.e., all frequency shifts $2\pi q/Q$ for $q = 0, 1, \dots, Q-1$. It is therefore required that M is either equal to or a multiple of Q , i.e.,

$$M = BQ, B \geq 1, B \text{ integer} \quad (1)$$

Since $N > M$, this means that the number of uniform-band channels cannot equal the number of granularity bands. Instead, N must be a multiple of Q , as illustrated in Fig. 5. That is,

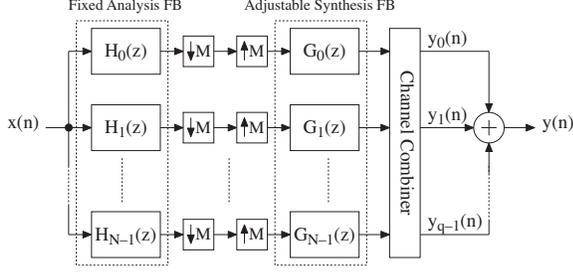


Figure 4. Proposed flexible frequency-band reallocation network using an adjustable (variable) synthesis FB. The synthesis part can be realized with fixed filters as indicated in Fig. 3.

$$N = AQ = \frac{AM}{B}, \quad A > B, \quad A \text{ integer} \quad (2)$$

In principle, one can choose any pair of values (M, N) satisfying (1) and (2). In practice, they are chosen as to minimize the overall complexity. For a fixed N , the complexity is minimized by selecting M as large as possible without introducing aliasing (see Section 3.3). From (1) and (2) it follows that B is selected as

$$B = A - K, \quad 1 \leq K \leq A - 1, \quad K \text{ integer} \quad (3)$$

whereby

$$M = N - KQ \quad (4)$$

with K being the smallest integer allowed without introducing aliasing.

3.3. Alias-Free Subbands

To satisfy Condition 4 in Section 3.1, we require (approximately) *alias-free subbands*. That is, aliasing emanating from the decimation process must be suppressed. In practice, aliasing components can not be completely eliminated but it must be possible to make them arbitrarily small which can be done if their magnitude is determined by the stopband attenuation of the analysis filters. To find out how to ensure this, we first observe that the filters are to extract spectra in accordance with Figs. 2 and 5. This is achieved by dividing each granularity band into a number of uniform-band FB channels with filter magnitude responses according to Fig. 6. The filters' bandwidth is thus $2\pi/N$ and their transition band is 2Δ wide. It is now required that passbands and transition bands of shifted terms caused by decimation do not overlap, because, with no overlap, the aliasing terms are attenuated by the filter's stopband attenuation. This is achieved when

$$M \leq N / \left(1 + \frac{N\Delta}{\pi} \right) < N \quad (5)$$

From (4) and (5), one obtains the minimum value of K as

$$K \geq \frac{N}{Q} \left(\frac{N\Delta}{N\Delta + \pi} \right) \quad (6)$$

3.4. Analysis Filters

The analysis filters are complex-modulated versions of a D th-order linear-phase FIR *prototype filter* $P(z)$ according to

$$H_k(z) = \beta_k P(zW_N^{k+\alpha}), \quad k = 0, 1, \dots, N-1 \quad (7)$$

where

$$W_N = e^{-j2\pi/N}, \quad \beta_k = W_N^{(k+\alpha)D/2} \quad (8)$$

and α is an arbitrary real-valued constant. The constants β_k compensate for the phase rotations that generally are introduced when replacing the D th-order linear-phase FIR filter $P(z)$ with $P(zW_N^{k+\alpha})$. In this way, all analysis filters become linear-phase

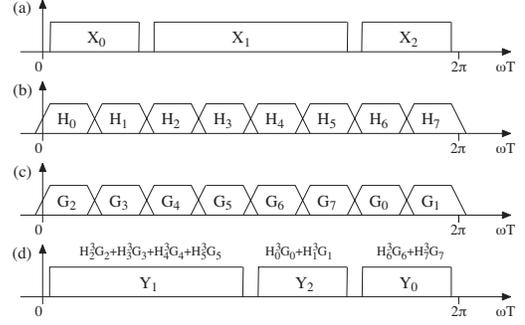


Figure 5. Illustration of frequency-band reallocation using the proposed class of FBs with $Q = 4$ and $N = 8$. H^3 stands for H shifted three granularity-band shifts to the right which amounts to one shift to the left when $M = 4$.

FIR filters with the same delay $(D/2)$ as the prototype filter.

3.5. Synthesis Filters

The synthesis filters must be chosen in such a way that the outputs $y_r(n)$, $r = 0, 1, \dots, q-1$ are frequency-shifted versions of the input subbands $x_r(n)$ according to

$$Y_r(z) = X_r(zW_Q^{s_r}) \quad (9)$$

where $W_Q = e^{-j2\pi/Q}$, $2\pi/Q$ is the granularity frequency shift (minimum allowed frequency shift), and s_r is an integer denoting the desired number of *granularity-band shifts* of subband r . For example, if it is desired to move X_0 (X_2) in Fig. 2 to X_2 's (X_0 's) position, then $s_r = 2$ ($s_r = -2$). Furthermore, it should be possible to approximate PFBR as close as desired (i.e., to approximate (9) as close as desired) for all values of q , $1 \leq q \leq Q$, by properly designing the FB. It can be shown that, with the analysis filters $H_k(z)$ in Section 3.4, together with the choices of M and N as given in Sections 3.2 and 3.3, both of these criteria are met by selecting the synthesis filters as

$$G_k(z) = \mu_{kr} H_{c_{kr}}(z), \quad k = i_r, i_r + 1, \dots, i_r + An_r - 1 \quad (10)$$

where i_r denotes the left-most granularity band included in $x_r(n)$, A is given by (2),

$$c_{kr} = k + s_r A, \quad \mu_{kr} = W_N^{(m_r N / M) D / 2}, \quad (11)$$

and

$$m_r = \begin{cases} Bs_r, & s_r \geq 0 \\ M + Bs_r, & s_r < 0 \end{cases} \quad (12)$$

where B is given by (1). It should be noted that only those combinations of k and r occur for which c_{kr} fall in the interval between 0 and $N-1$ which for obvious reasons must be ensured.

3.6. Synthesis FB Realization Using a Switch and Fixed Filters

A direct implementation of the synthesis filters as given by (10) would be very costly since they are variable. However, as seen in Fig. 3, the complexity can be reduced significantly by using instead a channel switch and a set of fixed synthesis filters, and possibly the adjustable phase rotations in (11). (With a proper selection of the filter order D , all μ_{kr} become one, which further reduce the complexity). This amounts to using the output from the analysis filter $H_k(z)$ as input to the fixed synthesis filter $H_{c_{k,r}}(z)$. In other words, the channel switch redirects its input at position k to its

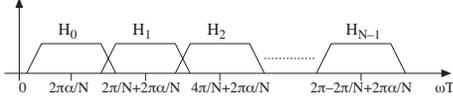


Figure 6. Principle magnitude responses of the analysis filters.

output at position c_{kr} . Further, the coefficients μ_{kr} are placed at the output of this switch.

3.7. Efficient FB Realizations

Each of the analysis and synthesis FBs can be realized with the aid of one filter part and an N -point discrete Fourier transform (DFT). Furthermore, by using polyphase decomposition [8], all the filtering operations can be moved to the lowest sampling rate involved. In this way, one can achieve as low complexity as in regular complex-modulated FBs, but with additional flexibility.

3.8. FB Design

The simplest way to design the FB is to use the prototype filter obtained when designing the FB to be a near-PR FB with channel filter requirements as to frequency selectivity. This corresponds to the simplest case with recombination but no reallocation. The advantage of using this design approach is that it offers an easily controlled performance of the FFBR network. The disadvantage is that it results in overdesigned filters. In order to reduce the filter orders, one can instead adopt more advanced design techniques that explicitly take care of all possible reallocation combinations during the design process.

4. EXAMPLE

This example illustrates the principle of the proposed FFBR network. The following parameters are assumed:

- Number of granularity bands: $Q = 4$
- Number of FB channels: $N = 8$
- Downsampling factor: $M = 4$
- Transition band width: $\Delta = 0.125\pi/Q = 0.125\pi/4$
- Frequency offset: $\alpha = 0.5$
- Prototype filter order: $D = 134$
- Number of subbands: $q = 3$
- Number of granularity bands in each input subband:
 - $n_0 = 1, n_1 = 2, n_2 = 1$
- First FB channel in each input subband:
 - $k_0 = 0, k_1 = 2, k_2 = 6$

The magnitude responses of the analysis filters are as shown in Fig. 7. The input spectrum is plotted in Fig. 8. The reallocation scheme shown earlier in Fig. 5 is assumed. This is realized by selecting the synthesis filters according to (10) with the following numbers of granularity-band shifts: $s_0 = 3, s_1 = -1, s_2 = -1$. These values imply that $m_r = 3$, for $r = 0, 1, 2$, which means that $\mu_{kr} = -j$ for all pairs of values kr of interest, i.e., for $kr = 00, 10, 21, 31, 41, 51, 62, 72$. These values of kr results in the following values of c_{kr} : $c_{00} = 6, c_{10} = 7, c_{21} = 0, c_{31} = 1, c_{41} = 2, c_{51} = 3, c_{62} = 4, c_{72} = 5$. This means that the switch in Fig. 3, which redirects its input at position k to its output at position c_{kr} in this example directs inputs 0 and 1 to outputs 6 and 7, respectively, and inputs 2–7 to outputs 0–5, respectively.

5. CONCLUDING REMARKS

This paper introduced the basic principle of a new type of FFBR network that can outperform existing ones when all the aspects flexibility, low complexity and inherent parallelism, PFBR, and simplicity are considered simultaneously. The paper also provided an example that demonstrated the functionality. More details about the new technique, as to filter bank design, complexity issues, etc., will be published elsewhere [7].

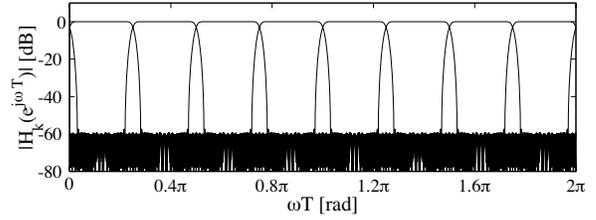


Figure 7. Analysis filters.

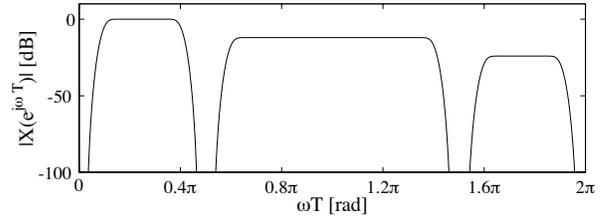


Figure 8. Input spectrum.

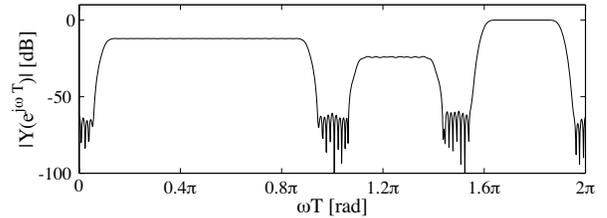


Figure 9. Output spectrum.

Finally, it is mentioned again that this paper only considered SISO networks despite the fact that MIMO networks are employed in practical multicast systems. The motivation behind this is that a properly designed variable FB in the proposed SISO network can be directly utilized in MIMO networks by making use of a number of instances of these FBs together with a switch that can redirect information from any input signal to any output signal. A thorough understanding of SISO networks is therefore crucial when designing MIMO networks. Details about the MIMO networks will be published in another paper.

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