EFFICIENT FILTERBANK CHANNELIZERS FOR SOFTWARE RADIO RECEIVERS

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ABSTRACT

For cellular software radio receivers, this paper presents a computationally efficient algorithm for extracting individual radio channels from the output of the wideband A/D converter. In a software radio, the extraction of individual channels from the output of the wideband A/D converter is by far the most computationally demanding task; hence, it is very important to devise computationally efficient algorithms for this task. Our algorithm is obtained by modifying the DFT filter bank structure that is well known in the multi-rate signal processing literature [8, 5]. We show that the complexity of the proposed algorithm is significantly less (2X-50X) than the complexity of the conventional channelizers.

1. INTRODUCTION

Software radios can significantly reduce the cost and complexity of today's cellular radio base stations. Software radios architectures center on the use of wideband A/D converters and D/A converters as close to the antenna as possible , with as much radio functionality as possible implemented in the digital domain [1]. For cellular software radio receivers, this paper presents a computationally efficient algorithm for extracting individual radio channels from the output of the wideband A/D converter.

Currently, each cellular radio base station contains 20 or more narrowband receivers, and each of these receivers has its own set of analog mixers, local oscillators, analog filters, analog to digital converters (ADC), and baseband processing unit. The cost of today's radio base station receivers is a linear function of the number of received channels, and this cost is dominated by the cost of the analog components. In a radio base station with a software radio receiver, a single analog front end can be used to receive all channels; hence, the cost of the analog part of the resulting receiver is a constant function of the number of received channels.

The analog front end of a software radio receiver contains a wideband ADC for digitizing the entire frequency band allocated to the cellular radio base station. The output of this ADC goes to the IF processing block which contains a bank of digital bandpass filters for extracting individual radio channels from the output of the ADC (e.g. 30KHz channel in IS-54 standard [2]).

Practical cellular radio base stations require that wideband receivers be efficient in their use of resources such as power, hardware cost, and computational resources. In a wideband radio receiver, the IF processing block is by far the most computationally demanding block; since, this block operates at the highest sampling rate [1]. Computationally efficient algorithms for the implementation of the IF processing block are essential for widespread deployment of software radios. Digital down-converter chips dedicated to extraction of one radio channel are currently available [3, 4]; however, the complexity of the digital part of the resulting receiver is still a linear function of the number of received channels.

A computationally efficient structure, the filter bank channelizer, for implementing the IF processing block is presented in this paper. Complexity of this structure is a constant function of the number of received channels. Specifically, the complexity of this structure is approximately twice the complexity of implementing a digital bandpass filter that extracts only one radio channel from the output of the ADC. If the radio base station conforms to a regular frequency reuse pattern, the complexity of the filter bank channelizer can be further reduced (by a factor of 2) resulting in what we call the subsampled filter bank channelizer. Expressions for the exact complexity of the filter bank channelizer, in terms of number of real multiplications/second, are presented.

2. CHANNELIZERS

A generic wideband receiver is depicted in Fig. 1. In this receiver, the entire frequency band of interest (e.g. 10MHz) is digitized using a pair of wideband ADCs. In the wideband receiver of Fig. 1, the final frequency/channel selection is performed digitally by the block labeled "Digital Channelizer" whose input x[n] is the complex-valued output of the ADCs. Each output of the channelizer is fed to a baseband processing block. The channelizer performs bandpass filtering followed by sample rate reduction from the very high sampling rate of the ADCs to the relatively low sampling rate expected by the baseband processing units.

Discrete channelizers and filter bank channelizers are the two most commonly proposed structures for implementing the channelizer. A discrete channelizer with M received channels essentially consists of M narrowband digital filters running in parallel; hence, this channelizer is the digital equivalent of implementing M narrowband analog receivers in parallel. More importantly, the complexity of a discrete channelizer is a linear function of the number of received channels [3].

2.1. Filter Bank Channelizers

An alternative to the discrete channelizer is a filter bank channelizer. Using multi-rate signal processing concepts, the filter bank channelizer can extract every channel between $\left[-\frac{-F_s}{2}, \frac{F_s}{2}\right]$, where F_s is the sampling frequency of the wideband ADCs. Using the fast Fourier transform, computationally efficient algorithms for implementing the filter bank channelizer have been developed [5]. The complexity of a filter bank channelizer is a constant function of the number of received channels; hence, when a large number of channels are needed in a receiver, the filter bank channelizer can be a very computationally attractive choice. In this paper we focus on the design and analysis of filter bank channelizer for wideband receivers.

Functionally, the channelizer is a bank of digital, complexvalued, bandpass filters where the output of each filter is followed by a mixer and downsampler (see Fig. 2). In Fig. 2, each bandpass filter, $H_i(w)$, is centered around the carrier frequency of a particular radio channel. Each mixer in the channelizer converts the bandpass output of the corresponding filter to a baseband signal. Since the bandwidth of the output of each filter is much less than the bandwidth of x[n], it is logical to decimate the output of each filter by N.

2.2. Classical Filter Bank Channelizer

Provided that $H_i(z)$'s satisfy certain conditions, an FFT can be used to implement the channelizer of Fig. 2 efficiently. This implementation is presented in this section. In the next section, we show how the complexity of this channelizer can be further reduced by taking advantage of the frequency reuse pattern commonly used in cellular networks.

Let $H_0(z)$ be a real, causal, lowpass filter with finite impulse response $h_0[n]$. Assume there are M equally spaced channels between $\left[-\frac{F_s}{2}, +\frac{F_s}{2}\right]$, and let f_{cs} denote the frequency separation between any two consecutive channels, i.e.

$$F_s = M \times f_{cs} \quad . \tag{1}$$

Furthermore, assume that each bandpass filter in the filter bank channelizer, $H_i(z)$, is a modulated version of $H_0(z)$, i.e.

$$H_i(w) = H_0(w - \frac{2\pi}{M}i)$$
 $0 \le i \le M - 1.$ (2)

Note that the center frequency of the i - th filter, $H_i(z)$, is $\frac{2\pi}{M}i$ ($\frac{F_s}{M}i$ in continuous time). In Fig. 2, the single input/Moutput system with input x[n] and outputs $\{c_i[n]\}_{i=0}^{M-1}$ is called a DFT filter bank [5]. Finally, assume that M is an integer multiple of the downsampling factor, N, i.e.

$$M = K \times N \qquad \text{for some integer } K. \tag{3}$$

If conditions (1) and (3) are satisfied, polyphase decomposition of $H_0(z)$ can be used to implement this DFT filter bank efficiently [5]. To this end, express $H_0(z)$ in polyphase form as:

$$H_0(z) = \sum_{l=0}^{M-1} z^{-l} E_l(z^M), \qquad (4)$$

where

$$e_l(n) = h_0(nM+l)$$
 $0 \le l \le M-1,$ (5)

and $E_l(z)$ is the z-transform of $e_l(n)$. Using the polyphase filters $E_l(z)$, it can be shown [5] that the structure in Fig. 3 is equivalent to the filter bank channelizer of Fig. 2 as long as constraint (1) and (3) are met.

The complexity of the channelizer in Fig. 3 is dominated by the complexity of the *M*-point IDFT. Note that Fig. 3, an *M*-point IDFT is performed every $\frac{N}{F_s}$ seconds. Next, we show that this M-point IDFT can be replaced with an $\frac{M}{L}$ -point IDFT, where L is the frequency reuse factor of the cellular system.

2.3. Subsampled Filter Bank Channelizer

Most radio base stations conform to some sort of frequency reuse pattern which restricts the set of channels received by the base station [6]. For example, with a 7/21 frequency reuse pattern, each base station only receives every 7-th radio channel; hence, only every 7-th channel needs to be extracted by the filter bank channelizer. More generally, assume that the filter bank channelizer needs to extract only every L-th channel between $\left[-\frac{F_s}{2}, +\frac{F_s}{2}\right]$. In this case, we show that the M-point IDFT in the opened filter bank channelizer of Fig. 3 can be replaced with an $\frac{M}{L}$ -point IDFT resulting in a channelizer with lower overall complexity. Naturally, for an $\frac{M}{L}$ -point IDFT to be defined, M must be an integer multiple of M, i.e.

$$M = Q \times L \qquad \qquad \text{for some integer } Q. \quad (6)$$

Referring to Fig. 3, if only every L-th output channel is needed, we will only need to compute

$$\{r_{iL}(n)\}_{i=0}^{Q-1} = \{r_0(n), r_L(n), r_{2L}(n), r_{3L}(n), \dots, r_{M-L}(n)\}$$
(7)

Since $\{r_i(n)\}_{i=0}^{M-1}$ are the IDFT coefficients of $\{s_i(n)\}_{i=0}^{M-1}$, the sequence in equation (7) is obtained by subsampling, by a factor of L, the IDFT coefficients $\{r_i(n)\}_{i=0}^{M-1}$. The subsampled IDFT coefficients in (7) can be computed by taking a Q-point IDFT instead of an M-point IDFT. The key step is to form a Q-point tor 1 instead of an M-point in 1. The key step is to form a Q-point sequence $\{z_i(n)\}_{i=0}^{Q-1}$, from the M-point sequence $\{s_i(n)\}_{i=0}^{M-1}$, in such a way that the Q-point IDFT of $\{z_i(n)\}_{i=0}^{Q-1}$ is the sequence in (7). The desired sequence $\{z_i(n)\}_{i=0}^{Q-1}$ is obtained [7] from $\{z_i(n)\}_{i=0}^{M-1}$ according to

 $\{s_i(n)\}_{i=0}^{M-1}$ according to

$$z_i(n) = \sum_{r=0}^{L-1} s_{i+Qr}(n) \qquad 0 \le i \le Q-1.$$
 (8)

The sequence $\{z_i(n)\}_{i=0}^{Q-1}$ is typically referred to as the "time-aliased" version of $s_i(n)$ [7]. The block diagram of the resulting subsampled DFT filter bank is depicted in Fig. 4. A simple way to visualize the construction of the sequence $\{z_i(n)\}_{i=0}^{Q-1}$ from the sequence $\{s_i(n)\}_{i=0}^{M-1}$ is to think of $\{s_i(n)\}_{i=0}^{M-1}$ as a vector of length M, and break this vector into L vectors of length Q. The vector $\{z_i(n)\}_{i=0}^{Q-1}$ is the vector sum of these L vectors (each of length Q).

To be able to use a filter bank channelizer with reduced size IDFT, restrictions (1), (3), and (6) must be met. Combining these restrictions, we see that F_s must be divisible by f_{cs} , by N, and by L. The smallest F_s that satisfies these three conditions is the Least Common Multiple of (f_{cs}, N, L) , denoted by $LCM(f_{cs}, N, L)$.

Example: Let us consider the IS-54 cellular system [2] which uses a 7/21 frequency reuse pattern, i.e. L=7. Recall that the channel spacing for IS-54 is $f_{cs} = 30KHz$. Considering restrictions (1) and (6), we see that F_s must be divisible by $LCM(L, f_{cs}) = LCM(7, 30 \times 10^3) = 210KHz$. To digitize the entire cellular band, approximately 10MHz wide, F_s can be chosen to be 26.88MHz corresponding to M = 896. The down sampling factor can then be chosen as N = 224. The size of the IDFT in the classical filter bank channelizer of Fig. 3 will be 896, and the size of the IDFT in the subsampled filter bank channelizer of Fig. 4 will be 128; since, $Q = \frac{M}{L} = 128$. The sampling frequency of the output of the decimators in this case will be $\frac{F_s}{N} = 120KHz$, i.e. exactly four times the channel spacing frequency.

2.4. Complexity of Filter Bank Channelizers

The complexity of the classical filter bank channelizer and the complexity of the subsampled filter bank channelizer are compared next. For each 'n', we need to compute $\{s_i[n]\}_{i=0}^{M-1}$, and we need to compute an *M*-point IDFT or an $\frac{M}{L}$ -point IDFT. Let $\Psi(P)$ denote the number of real multiplications needed to compute $\{s_i[n]\}_{i=0}^{M-1}$ for each 'n', where *P* is the number of real non-zero coefficients of the lowpass filter prototype $h_0[n]$. Similarly, let $\Phi(X)$ denote the number of real multiplications needed to implement an *X*-point IDFT. Since x[n] is complex-valued, and each $e_i(n)$ is real-valued:

$$\Psi(P) = 2 \times P. \tag{9}$$

Noting that these computations need to be repeated every $\frac{N}{F_s}$ seconds, we see that the total number of real multiplications/second for the classical filter bank channelizer with a full-size IDFT is

$$\mu(M, P) = \left[\Psi(P) + \Phi(M)\right] \times \frac{F_s}{N}.$$
 (10)

The total number of multiplications/second for a subsampled filter bank channelizer that extracts every L-th channels is

$$\mu(M, P, L) = \left[\Psi(P) + \Phi(\frac{M}{L})\right] \times \frac{F_s}{N}.$$
 (11)

Equation (10) implies that the complexity of a filter bank channelizer is equal to sum of the complexity of one low-pass digital filter and the complexity of one *M*-point IDFT; hence, at an additional cost of one *M*-point IDFT, the opened filter bank channelizer can extract every radio channel between $\left[-\frac{F_s}{2}, \frac{F_s}{2}\right]$. The subsampled filter bank channelizer extracts every *L*-th radio channel at the additional cost of one $\frac{M}{L}$ -point IDFT. Since computationally efficient algorithm for implementing the IDFT exist, i.e. FFT algorithms, this additional complexity due to the IDFT can be quite low. Most importantly, complexity of a filter bank channelizer is always a constant function of the number of received channels.

Example: Let us again consider the IS-54 case with $F_s = 26.88MHz$, N = 224, and M = 896. Considering typical numbers for the peak passband ripple and peak stopband ripple for the lowpass prototype filter would indicate that the order of this lowpass filter is at least 1450.

Assuming that the order of the lowpass prototype filter is P=1450, the complexity of a filter bank channelizer with a full-size IDFT (i.e. 896-pt IDFT) will be, using equation (10), 826×10^6 real multiplications/second. A Cooley-Tuckey FFT algorithm is assumed for efficiently computing the 896-pt IDFT. For the same example, let us consider a system in which only every 7-th channel is needed, i.e. L=7. In this case, the size of the IDFT will be $128 = \frac{896}{7}$. The complexity of a subsampled filter bank channelizer with this reduced-size IDFT will be , using equation (11), 410×10^6 real multiplications/second.

For this example, Fig. 5 depicts the complexity of various channelizers as a function of the number of extracted channels. The discrete channelizer in Fig. 5 refers to a channelizer that uses separate digital bandpass filters to extract each radio channel [3]. The complexity of each of these bandpass filters is the same as the complexity of the lowpass prototype filter in the filter bank channelizer, i.e. the complexity of $h_0(n)$. From Fig. 5, we see that if two or more channels need to be extracted, it is more efficient to use a filter bank channelizer that extracts every channel than to use two or more digital filters to extract these channels individually.

3. SUMMARY

For a cellular software radio receiver, a computationally efficient channelizer that extracts individual radio channels from the output of the wideband ADC was presented in this paper. This channelizer is closely related to the DFT filter bank used in transmultiplexers [8]. If the cellular system conforms to a regular frequency reuse pattern, a subsampled DFT filter bank channelizer can be used instead of the classical DFT filter bank channelizer resulting in a factor of 2 reduction in the complexity of the channelizer.

4. REFERENCES

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5. FIGURES



Figure 1: Generic wideband receiver



Figure 2: Filter Bank view of a Wideband Channelizer.



Figure 3: Classical Filter Bank Channelizer.



Figure 4: Subsampled Filter Bank Channelizer.



Figure 5: Complexity of Various Channelizers.