Performance evaluation of high SLFOR fixed windows in ECG signal compression using optimized Cosine modulated filter bank

Shilpa Datar, Ashutosh Datar, Alok Jain

Samrat Ashok Technological Institute (Engg. College)
Vidisha (M.P.) India

Abstract: In this paper, data compression performance of high SLFOR fixed windows based cosine modulated filter banks is presented. Three fixed windows with high SLFOR (decay greater than or equal to −24 dB/octave) are selected for this study. The designed prototype filters are optimized and respective filter banks are developed. These filter banks are used for compression of ECG signal data. LZW algorithm, which is a dictionary based scheme, is used for sub band coding of the signal. Popular error measures are computed for quantitative assessment of reconstructed ECG signal.

Keywords: Cosine-modulated filter banks, SLFOR, Filter banks, Compression Ratio, LZW algorithm.

I. Introduction

Electrocardiogram (ECG) signal represents the electrical activity of heart and is vital in several clinical diagnoses. The need for ECG data compression arise in various applications like ambulatory ECG monitoring, patient databases in hospitals, medical education systems, ECG telemetry, etc. [1]. The digitized ECG generates massive volume of data, hence requires an effective compression technique scheme for transmission/ storage. The main goal of any compression technique is to achieve maximum data reduction while preserving the significant signal morphology features upon reconstruction. There are three approaches for ECG data compression: direct methods, transform methods and parameter extraction methods. Direct methods like TP, AZTEC, CORTES, FAN, SAPA, etc. are sometime domain based schemes which utilizes correlation of neighboring samples to reduce the redundancy [2-4]. The transformational compression methods apply a transform to analyze the energy distribution of the signal. The compression strategy is to minimize the number of coefficients, which can represent the input signal. These selected coefficients, compactly representing the input ECG signal, are transmitted/ stored, while other redundant samples are discarded. Some of the transformational compression methods are Fourier transform, discrete cosine transform (DCT), Walsh transform, Karhunen- Loeve transform (KLT), wavelet transform and filter banks [5]. The parameter extraction methods are prediction based coding, where near prediction behavior of ECG signals are used to develop subset auto regression (SAR) model for long term prediction [6].

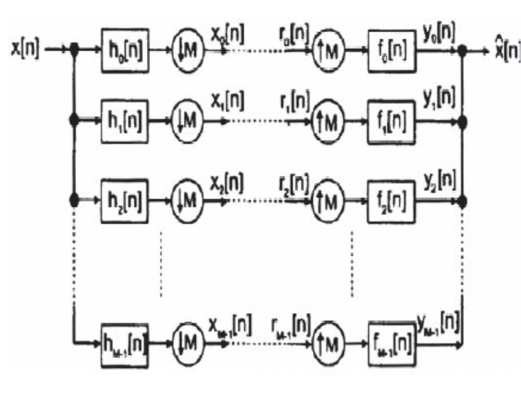


Fig. 1. M-Channel maximally decimated filter bank.

Multirate filter banks (Fig. 1) find variety of applications in sub band coding, trans multiplexing, image and video or audio compression, spectral estimation, bio signal processing, and adaptive signal processing. The fundamental block in implementation of such applications is cosine modulated filter banks (CMFBs), where analysis and synthesis filter banks are derived by cosine modulating the low pass prototype filter. Hence the entire design of the filter banks is reduced to design the prototype filter. Therefore, during the design phase, it is required to optimize the coefficients of prototype filter only. This significantly reduces the complexities and computational overheads.

To obtain high quality reconstruction, the linear phase low pass prototype filter $P(e^{j\omega})$ must satisfy following two conditions as much as possible [7]-[8]:

$$\left|P(e^{j\omega})\right| = 0 \; for \; |\omega| > \pi/M \qquad (1)$$

$$\left|T(e^{j\omega})\right| = 1 \; for \; 0<\omega<\pi/\mathrm{M};$$

$$\text{where } T(e^{j\omega}) = \sum_{k=0}^{2M-1}\left|P(e^{j(\omega-k\pi/M)})\right|^2 \qquad (2)$$

M is the number of channels.

If (1) is satisfied exactly, there is no aliasing between nonadjacent bands, while if (2) is satisfied, all amplitude distortion is eliminated in the combined analysis/synthesis filter bank system. Aliasing between the adjacent bands is eliminated by selecting appropriate phase factor in the modulation. Hence the filter bank that provide approximate or near-perfect reconstruction (NPR), is designed, that approximately satisfies the constraints laid down in (1) and (2). Design approaches involve linear optimization [7]-[9] as well as nonlinear optimization [10] of different objective functions.

II. Filter Bank Design

The prototype filter $p(n)$ are designed with windowing technique, using high SLFOR fixed windows. High side lobe fall-off rate (SLFOR) is a spectral parameter, which is important in many applications. In beam forming applications, a high SLFOR ensures a better rejection of far end interference [11]. Superior far end attenuation for stop band energy may be achieved in filters, designed with high SLFOR window function [12]. In speech and signal processing applications, it minimizes the energy leaks from one band to another [13].

Nutgall [14] proposed some 3-and 4 non-zero term windows with high SLFOR characteristics. These windows exhibit rapid decay in response and have some higher derivative continuous for all t. These windows $w(n)$ are defined for the DFT by:

$$w(n) = a_0 - a_1 \cos(\frac{2\pi}{N}n) + a_2 \cos(\frac{2\pi}{N}2n) - a_3 \cos(\frac{2\pi}{N}3n);$$
$$with \; n = 0,1,\ldots,N-1, \qquad (3)$$

The coefficients of these windows are given in Table-I.

Table I. Window Parameters and Coefficients

Window	Max Sidelobe attenuation	SLFOR dB/ octave	Coefficients
4-term with continuous fifth derivative (4TC5D)	-60.95	-42	a_0=10/32, a_1 =15/32, a_2= 6/32, a_3=1/32
4-term with continuous third derivative (4TC3D)	-82.60	-30	a_0= 0.338946, a_1= 0.481973, a_2= 0.161054, a_3= 0.018027
3-term with continuous third derivative (3TC3D)	-46.74	-30	a_0= 0.375, a_1= 0.5, a_2= 0.125, a_3= 0.00

For prototype filter $p(n) = hid(n) \cdot w(n)$, where $hid(n)$ is the shifted impulse response of ideal low pass filter. Cutoff frequency w^c is $(w_s + w_p)/2$ and transition bandwidth is $(w_s - w_p)$ are calculated.

The cutoff frequency w_c of low pass prototype filter is taken as the variable parameter, which is optimized in such a way so as to yield the minimum value of objective function. The same objective function as in [7] is used and the algorithm evaluates w_c such that the 3-dB cutoff point of optimized prototype filter is located approximately at $2M$.

$$\phi = \max_{\omega} \left| \left|P(e^{j\omega})\right|^2 + \left|P(e^{j(\omega-\pi/M)})\right|^2 - 1 \right| \quad for \ 0 \le \omega \le \pi / M \tag{4}$$

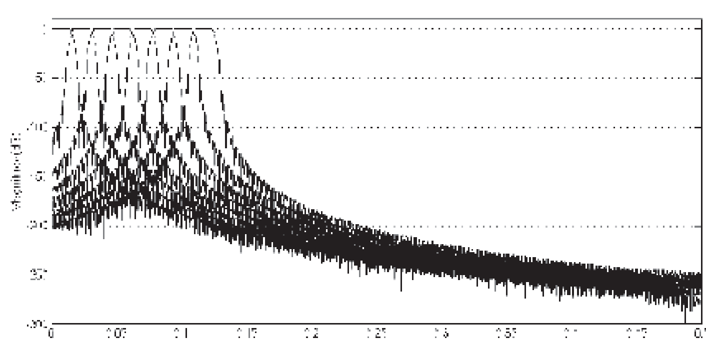
The golden section search method [15] is used to minimize the objective function by adjusting the cutoff frequency w_c of prototype filter [16].

The impulse responses of the analysis filter banks $hk(n)$ and synthesis filter banks $fk(n)$ are the cosine modulated versions of the optimized prototype filter $p(n)$ [17]-[19].

$$\left.\begin{aligned} h_k(n) &= 2p(n)\cos((2k+1)\frac{\pi}{2M}(n-\frac{N-1}{2})+(-1)^k\frac{\pi}{4}), \\ f_k(n) &= 2p(n)\cos((2k+1)\frac{\pi}{2M}(n-\frac{N-1}{2})-(-1)^k\frac{\pi}{4}) \end{aligned}\right\}$$

$$0 \le n \le N-1, \ 0 \le k \le M-1 \tag{5}$$

Fig 2. Frequency response of optimized 32-channel cosine modulated



analysis filter bank, with prototype filter designed using 3-term with continuous third derivative (3TC3D) window. Only first eight bands are shown to highlight the high fall-off rate of the designed filter banks.

III. Sub Band Coding Scheme

A subband coder splits the input signal into a collection of approximately disjoint frequency bands. If the resulting subbands have the same extent in the frequency domain, the subband decomposition is said to be uniform. Since the bandwidth of each subband is reduced by an amount corresponding to the number of subbands, - say M, each subband, can be subsamples by a factor of M. Thus, the number of signal samples in the critically sampled subbands is the same as in the input signal. Since the critical information of various subbands is unequal, compression is obtained by representing (quantizing) the lesser informatic subband with a small number of bits. In case of ECG signals, normally, the signal energy is concentrated in the lower frequency subbands, implying that the higher frequency subband can be represented
with a small number of bits or may even be discarded (Fig. 3).

LZW (Lempel-Ziv-Welch) algorithm is a general compression algorithm capable of working on almost any type of data. It is generally fast in both compressing and decompressing data and does not require the use of floatingpoint operations. LZW is often referred to as a substitutional or dictionary-based encoding algorithm. The algorithm builds a

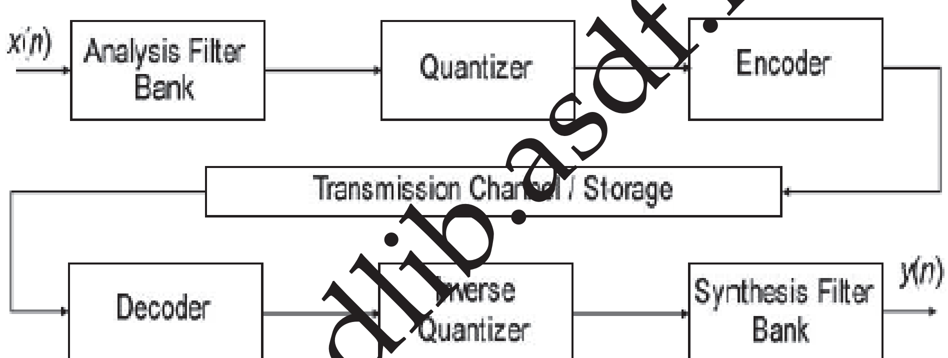


Fig. 3. Subband codec system.

data dictionary (also known as translation table or string table) of data occurring in an uncompressed data stream. Patterns of data (substrings) are identified in the data stream and are matched to entries in the data dictionary. If the substring is not present in the dictionary, a code phrase is created based on the data content of the substring, and it is stored in the dictionary. The phrase is then written to the compressed output stream. When a reoccurrence of a substring is identified in the data, the phrase of the substring already stored in the dictionary is written to the output. Because the phrase value has a physical size that is smaller than the substring it represents, data compression is achieved.

Decoding LZW data is the reverse of encoding. The decompressor reads a code from the encoded data stream and adds the code to the data dictionary if it is not already there. The code is then translated into the string it represents and is written to the uncompressed output stream. The dictionary based compression schemes are normally faster than entropybased schemes, adaptive, and does not use any statistical model [20]-[21].

IV. Error Measures

The quality of retrieved signal is measured using the Percentage Root Mean-square Difference (*PRD*), which is defined as [22]

$$PRD = \sqrt{\frac{\sum_{n=1}^{L}(x[n]-y[n])^2}{\sum_{n=1}^{L}(x[n])^2}} \times 100 \qquad (6)$$

Where *x*[*n*] is the original ECG signal and *y*[*n*] is the reconstructed ECG signal and *L* its length.

As *PRD* is heavily dependent on the mean value of signal, it is more appropriate to use the modified criteria:

$$PRD1 = \sqrt{\frac{\sum_{n=1}^{L}(x[n]-y[n])^2}{\sum_{n=1}^{L}(x[n]-\overline{x}[n])^2}} \times 100 \qquad (7)$$

Where *x*[*n*] is the mean value of the signal.

If the value of *PRD1* is between 0% to 9%, the quality of reconstructed signal is either very good or good, where as if the value is greater than 9%, its quality group cannot be determined. In this paper, it is ensured that the *PRD1* value of reconstructed ECG signal is equal to or less than 9%.

The Signal to Noise Ratio (*SNR*) and *PRD1* are related as [23]:

SNR = – 20log10 (0.01*PRD1*) (8)

Mean Square Error (*MSE*) is also one of the important parameter to evaluate the quality of reconstructed signal [24].
It is expressed as:

$$MSE = \frac{1}{L}\sum_{n}\left|x(n)-y(n)\right|^2 \qquad (9)$$

The measure of the maximum differences gives an idea about the local effects. This can be achieved by means of the maximum amplitude error (*MAX*) and is defined as [22]

$$MAX = \max_{n}\{\left|x[n]-y[n]\right|\} \qquad (10)$$

Compression ratio (*CR*) can be expressed as [25]

$$CR = \frac{\text{The number of bits in original 1-D ECG signal}}{\text{The total number of bits in the compressed data}} \qquad (11)$$

However, the clinical acceptability of the reconstructed signal should always be determined through visual inspections.

V. Design Examples and Results

In first example, 32 channel cosine modulated filter banks are developed using optimized prototype filter. The prototype filter is designed with high SLFOR fixed window using windowing technique. The stopband frequency and passband frequency are chosen. Here is the roll off factor, influencing the overlap of subbands. Keeping the roll-off factor at 1.88, results in *N*= 380. Two ECG signal (records no. 100 and record no. 117) from ECG Arrythmia Database of MIT-BIH ECG database [25] are used for compression and decompression with LZW algorithm . These signals have been sampled at 360 Hz with 11 bits/sample. The 1024 baseline is removed prior to subband coding of the signal.

In second design, 16-channel cosine modulated filter banks are developed. The same Roll-off factor ? is at kept at 1.88, to obtain *N*= 190. In each case, a block of 1024 samples are used in the experiment. The results of both designs are given in Table – II. The original and reconstructed waveforms from filter banks designed with different high SLFOR fixed windows, are shown in figure 4.

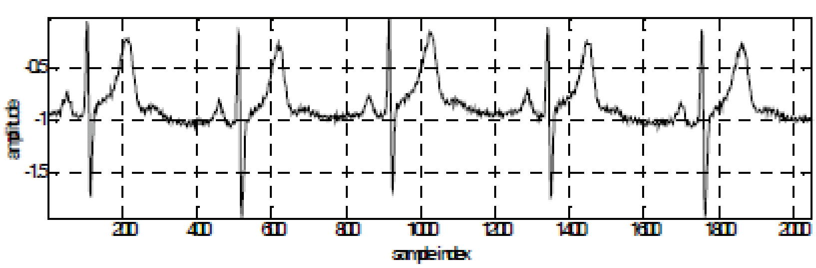
Results from Table–II show that Nuttall's rapidly decaying window (4TC5D window) offered superior signal compression performance than others. This is due to its high SLFOR of -42 dB/octave. However, the window has slightly lower sidelobe attenuation level of -60.95 dB, compared to -82.60 dB of 4TC3D.

VI. Conclusion

Performance of some high SLFOR fixed window functions based filter bank is evaluated for ECG signal compression. It is evident, that the sidelobe fall-off rate and sidelobe attenuation level are two important parameters that greatly influence the signal compression. As discussed, window with high SLFOR

Table II. Signal Reconstruction Error Measures

Window	*M*	ECG signal Record No.	*PRD1*	*MSE*	*MAX*	*CR*
4TC5D	16	117	8.96	4.24E-04	0.11	**11.37**
		100	8.96	2.38E-04	0.09	**7.49**
	32	117	9.00	4.29E-04	0.13	**12.27**
		100	8.93	2.45E-04	0.08	**7.83**
4TC3D	16	117	8.94	4.24E-04	0.11	11.21
		100	8.91	2.38E-04	0.09	7.34
	32	117	8.95	4.25E-04	0.12	12.19
		100	8.92	2.45E-04	0.08	7.76
3TC3D	16	117	8.98	4.28E-04	0.11	11.25
		100	8.95	2.40E-04	0.09	7.18
	32	117	8.92	4.22E-04	0.11	11.98
		100	8.93	2.48E-04	0.09	7.53



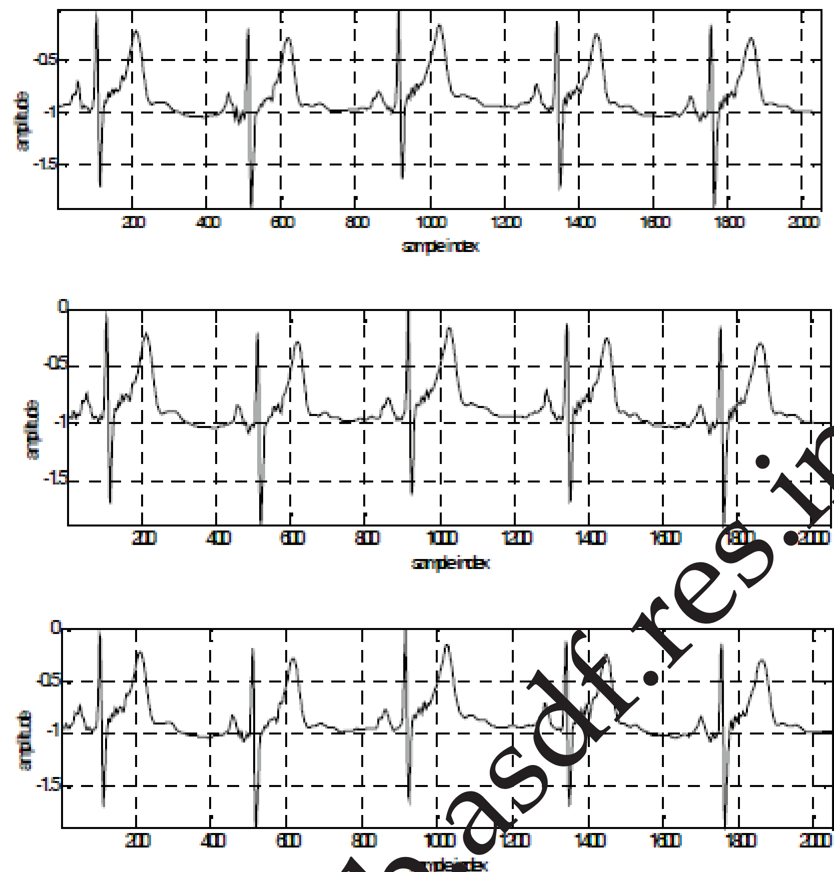


Fig. 4. Signal Reconstruction. (From top to bottom) Original ECG, Reconstructed signal using: 4TC5D window; 4TC3D window; 3TC3D. M=32 (only 2048 samples of ECG record no. 117 are shown)

and high sidelobe attenuation level can be an excellent candidate in design of filter bank based data compression scheme. The fixed windows offer good performance in general but, has a drawback of inflexibility to provide desired sideband attenuation level. It can be concluded that high SLFOR property and good sidelobe attenuation level are desirable in achieving a good signal compression ratio.

References

1. Z. Lu, D.Y. Kim, A. Pearlman, Wavelet compression of ECG signals by the set partitioning in hierarchical trees algorithm, IEEE Transactions on Biomedical Engineering 47 (7) (July 2000) 849–856.
2. S.M.S. Jalaleddine, C.G. Hutchens, R.D. Strattan, W.A. Coberly, ECG data compression techniques A unified approach, IEEE Transactions on Biomedical Engineering 37 (4) (1990) 329–343.
3. M. Ishijima, S.B. Shin, G.H. Hostetter, J. Sklansky, Scan along polygon approximation for data compression of electrocardiograms, IEEE Transactions on Biomedical Engineering BME-30 (November 1983) 723–729.
4. W.J. Tompkins, Biomedical Digital Signal Processing, Prentice-Hall of India, New Delhi, India, 1999.
5. M. Pooyan, A. Teheri, M. Moazami-Goudarzi, I. Saboori, ECG Signal using SPIHT algorithm, WASET Journal 2 (2005) 212–215.
6. G. Nave, A. Cohen, ECG compression using long-term prediction, IEEE transactions on Biomedical Engineering 40 (1993) 877– 885.

7. C.D. Creusere, S.K. Mitra, A simple method for designing high-quality prototype filters for M-band pseudo QMF banks, IEEE Transactions on Signal Processing 43(4) (April 1995) 1005–1007.
8. Y.-P. Lin, P.P. Vaidyanathan, A Kaiser window approach for the design of prototype filters of cosine modulated filterbanks, IEEE Signal Processing Letters 5(6) (June 1998) 132–134.
9. A. Jain, R. Saxena and S.C. Saxena, An improved and simplified design of cosine-modulated pseudo QMF filterbanks, Transactions on Digital Signal Processing 16 (2000) 225–232.
10. A.V. Oppenheim, R.W. Schafer, Digital Signal Processing, Prentice- Hall of India, New Delhi, India, 2004.
11. S.W.A. Bergen, A. Antoniou, Design of ultraspherical window functions with prescribed spectral characteristics, EURASIP J. Appl. Signal Processing 2004 (13) (2004) 2053–2065.
12. S.W.A. Bergen, A. Antoniou, Design of nonrecursive digital filters using ultraspherical window function, EURASIP J. Appl. Signal Processing 2005 (12) (2005) 1910–1922.
13. A. Jain, R. Saxena, S.C. Saxena, A simple Alias-free QMF system with Near-perfect reconstruction, J. of Indian Inst. Sci. 86 (January-February 2005) 1–10.
14. A. H. Nuttall, Some windows with very good sidelobe behavior, IEEE Transactions on Acoustics, Speech, and Signal Processing ASSP–29 (1) (February 1981) 84–91.
15. A. Antoniou, W.S. Lu, Practical Optimization: Algorithms and Engineering Applications, Springer, NY, 2007.
16. A. Datar, A. Jain, P.C. Sharma, Design of Kaiser window based optimized prototype filter for cosine modulated filter banks, Signal Processing 90 (5) (May 2010) 1742–1749.
17. P.P. Vaidyanathan, Multirate Systems and Filter Banks, Prentice-Hall, Englewood Cliffs, NJ, 1993.
18. S.K. Mitra, Digital Signal Processing, Tata-McGraw-Hill, New Delhi, 2006.
19. T.Q. Nguyen, Near-perfect-reconstruction pseudo-QMF banks, IEEE Transactions on Signal Processing 42 (1) (January 1994) 65–76.
20. K. Sayood, Introduction to Data Compression, Elsevier, Noida, India, 2009.
21. I. M. Poo, Fundamental Data Compression, Elsevier, Oxford, UK, 2006.
22. M. Blanco-Velasco, F. Cruz-Roldán, J.I. Godino-Llorente, J. Blanco-Velasco, et al., On the use of PRD and CR parameters for ECG compression, Medical Engineering & Physics 27 (2005) 798–802.
23. Y. Zigel, A. Cohen, A. Katz, The weighted diagnostic distortion (WDD) measure for ECG signal compression, IEEE Transactions on Biomedical Engineering 47 (11) (November 2000) 1422–1430.
24. B. Kwan, R. Paramesran, Comparison between Legendre moments and DCT in ECG compression IEEE (2004) 167–170.
25. H.H. Chou, Y.J. Chen, Y.C. Shiau, T.S. Kuo, An effective and efficient compression algorithms for ECG signals with irregular periods IEEE Transactions on Biomedical Engineering 53 (6) (June 2006) 1198– 1205.
26. MIT-BIH ECG database, (online) http://www.physionet.org/physiobank/databank/mitdb/