A Modified Ultraspherical Window and Its Application for Speech Enhancement

Aloui Noureddine[1*], Mohamed Boussif[2], Cherif Adnane[2]

[1] Centre for Research on Microelectronics & Nanotechnology, NANOMISENE laboratory, Sousse Technology Park, Sahloul BP 334, Sousse, Tunisia

[2] Laboratory of Analysis and Processing of Electrical and Energy Systems (A.P.E.E.S), Sciences Faculty of Tunis, University of Tunis El-Manar, El Manar PB 2092, Tunisia

Corresponding Author Email: noureddine.aloui@crmn.rnrt.tn

ABSTRACT

In this paper an improved ultraspherical window is developed for designing quadrature mirror filters banks (QMF) with the help of a real coded genetic algorithm (RCGA). In fact, the ultraspherical window is modified by adding a parameter (α) which to improve the spectral parameters. Then, RCGA is used to find optimal values of the adjustment parameters, the side-lobes ratio of ultraspherical window and the cut-off frequency of the low-pass prototype filter. This latter, is used to derive all the filters of QMF banks. When the developed QMF banks are exploited for speech enhancement algorithm based on wavelets techniques it gives good performances in terms of Perceptual Evaluation of Speech Quality (PESQ) and Signal to Noise Ratio (SNR). In addition to this, when compared to Dolph-Chebyshev, Kaiser and the original Ultraspherical windows the modified Ultraspherical window gives better performance referred to the obtained simulation results.

1. INTRODUCTION

In digital signal processing (DSP) the analysis window is a mathematical function that is zero valued outside of a given interval. It is widely used in many applications of DSP such as spectral analysis [1], digital filters design [2], beam forming techniques [3] and antenna design [4]. The window function can be classified into two types. The first type is known as fixed window function it has only one single parameter called window length, which is used to control the main lobe width. The Hanning, Hamming, Blackman, Triangular and Rectangular window are some examples of fixed window functions [5]. The second type, known as adjustable window function, it has one or more adjustment parameters besides the window length, which are used to improve spectral characteristics, among them is Kaiser [6], Dolph-Chebyshev [7], Cosh [8], ultraspherical [9] and Saramaki [10] windows. In fact, the Kaiser window approximates the discrete prolate spheroidal sequence function (DPSS), which have the particularity of maximum energy concentration in the main lobe. The Dolph-Chebyshev window is controlled by two parameters to produce minimum main lobe width for a specified maximum side-lobe. The ultraspherical window has three parameters that control the side lobes amplitude relative to the main lobe.

During the last decades a lot of effort has been made to design and optimize analysis window functions with desired specifications for different applications of signal processing. In fact, Kumar and Kuldeep [11] present an improved Dolph-Chebyshev window function by adding a third parameter (α) to improve the spectral characteristics in terms of smaller ripple ratio and the wider main lobe width. Then the developed window was exploited for designing QMF banks, and it gives better performance in term of computational time, amplitude

distortion and aliasing distortion compared to others modified Kaiser and Cosh window. A new window function is developed using the product of Hamming and Gaussian windows [12], it offers better spectral parameters in term of minimum side lobe peak. When it is exploited for FIR filters design it achieves minimum ripple ratio compared to the designed filters using the Hamming, Blackman, Gaussian, and Kaiser windows. Therefore, in this paper modified ultraspherical window function is developed and used for designing QMF banks. This latter, are exploited to enhance speech signals. The paper is organized as follows. Section 2 explains the principle of analysis and synthesis using QMF banks. Section 3, presents the optimized ultraspherical window. Section 4, discusses the QMF banks design using modified ultraspherical window and RCGA. The methodology of speech enhancement based on wavelet techniques is given in section 5. Section 6, depicts simulation results and comparative study of performances. Finally, a conclusion is given in section 7.

2. QUADRATURE MIRROR FILTER (QMF)

QMF is a two channel filter bank, which the principle consists of decomposing an input signal $x(n)$ into two sub-bands using a low-pass analysis filter $H_0(z)$ and a high-pass analysis filter $H_1(z)$. The obtained sub-bands are down-sampled by a factor of 2. After a processing stage, each sub-band is up-sampled by a factor of 2 and passing through a low-pass synthesis filter $G_0(z)$ and high-pass synthesis filter $G_1(z)$. Finally, to reconstruct the output signal $y(n)$ the sub-bands are recombined. Figure 1 shows the block diagram of QMF [13-17].
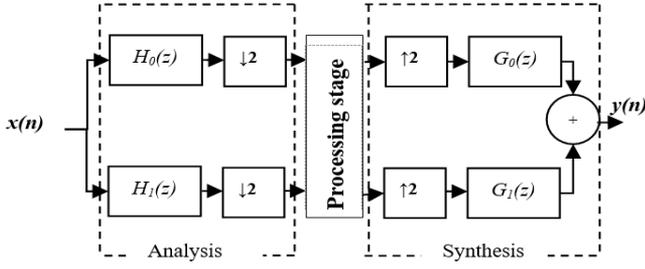
Figure 1. A general structure of two channels QMF bank

The relationship between the $x(n)$ and $y(n)$ signals in z-transform is expressed as:

$$Y(z) = \frac{1}{2}[H_0(z)G_0(z)+H_1(z)G_1(z)]X(z)$$
$$+\frac{1}{2}[H_0(-z)G_0(z)+H_1(-z)G_1(z)]X(-z) \tag{1}$$

For QMF banks design there are three types of distortion can be occurred; aliasing, phase and amplitude distortions. The aliasing distortion is due to the non-idealness of the designed filters, which can be eliminated by the use of a suitable design of the synthesis filters: $G_0(z)=H_1(-z)$ and $G_1(z)=-H_0(-z)$. The phase distortion is caused by the nonlinear phase response of the filter; it can be eliminated by the use of a linear phase FIR $(|H_0(e^{j\omega})|e^{-j\omega(N-1)/2})$ of even length (N). The amplitude distortion (or peak reconstruction error (PRE)), can never be eliminated completely. Then, the Eq. (1) becomes:

$$Y(z) = \frac{1}{2}[H_0^2(z)+H_0^2(-z)]X(z) \tag{2}$$

Let $F(z) = \frac{Y(z)}{X(z)}$, the Eq. (2) becomes:

$$F(z) = \frac{1}{2}[H_0^2(z)+H_0^2(-z)] \tag{3}$$

Then, the frequency response of the QMF filter bank can be expressed as follows:

$$F(e^{j\omega}) = \frac{Y(e^{j\omega})}{X(e^{j\omega})} = \frac{e^{-j\omega(N-1)}}{2}\left[|H_0(e^{j\omega})|^2 - (-1)^{N-1}|H_0(e^{j(\omega-\pi)})|^2\right] \tag{4}$$

where, $z = e^{j\omega}$ and $H_0(e^{j\omega}) = |H_0(e^{j\omega})|e^{-j\omega(N-1)/2}$.

The condition of perfect reconstruction implies that the QMF bank has a magnitude response $F(e^{j\omega})$ must be unity:

$$F(e^{j\omega}) = (|H_0(e^{j\omega})|^2 + |H_0(e^{j(\omega-\pi)})|^2 = 1 \tag{5}$$

If this equation is evaluated at frequency ($\omega=0.5\pi$), the perfect reconstruction condition reduces as follow: $|H_0(e^{j\frac{\omega}{2}})|=0.707$.

If this condition is not satisfied then a PRE is occurred, which can be expressed using the following equation [18]:

$$PRE = max\left\{20\,log\left(|H_0(e^{j\omega})|^2 + |H_0(e^{j(\omega-\pi)})|^2\right)\right\} \tag{6}$$

It can be remark from the above equation that the PRE function can be minimized by the use of appropriate prototype filter. Thus, for filter design using windowing techniques the choice of window function carefully allows for maximizing the prototype filter quality.

3. MODIFIED ULTRASPHERICAL WINDOW

The ultraspherical window of length N can be expressed as [19]:

$$W(n) = \frac{1}{N+1}\left[C_N^\mu(x_0) + \sum_{k=1}^{\frac{N}{2}} C_N^\mu\left(x_0 cos\left(\frac{k\pi}{N+1}\right)\right) cos\left(\frac{2nk\pi}{N+1}\right)\right] \tag{7}$$

where, $C_N^\mu(x)$ represents the ultraspherical polynomial or Gegenbauer polynomials, it can be expressed as follow:

$$C_N^\mu(x) = \frac{1}{N}[2(N+\mu-1)xC_{N-1}^\mu(x) + (N+2\mu-2)C_{N-2}^\mu(x)] \tag{8}$$

$$C_1^\mu = 2\mu x \tag{9}$$

$$C_2^\mu = -\mu + 2\mu(1+\mu)x^2 \tag{10}$$

The parameter μ controls the window Fourier transform side-lobe roll-off ratio and the parameter x_0 provides a trade-off between the ripple-ratio and a width characteristic. For $\mu\to0$ the Eq. (11) gives Dolph-Chebyshev window function, $\mu\approx3$-4 gives Hann window and for $0<\mu<-1$ the side lobes increase in magnitude with frequency.

For filter design using ultraspherical window these parameters must be chosen such that the filter specifications are satisfied [20].

In this work, the original ultraspherical window is modified by adding a parameter (α) which to improve the spectral characteristics in terms of the ripple ratio and side-lobe roll-off ratio. The modified ultraspherical window can be expressed as follow:

$$\omega(n) = \frac{1}{(N+1)^\alpha}\left[C_N^\mu(x_0) + \sum_{k=1}^{\frac{N}{2}} C_N^\mu\left(x_0 cos\left(\frac{k\pi}{N+1}\right)\right) cos\left(\frac{2nk\pi}{N+1}\right)\right]^\alpha \tag{11}$$

Figure 2 and the corresponding data given at Table 1 shows the effect of the adjustable parameter (α) on the ultraspherical window spectrum for constants values of $\mu=2$ at $x_0=1.005$ and window length N=51:

It is clear from Figure 2 and Table 1 that the increments of the adjustment parameter (α) implies an increase of the main lobe width decrease the ripple ratio and the side-lobe roll-off ratio for fixed values of $\mu=2$ and $x_0= 1.005$. Therefore, the adjustment parameter makes the modified ultraspherical window more flexible compared to the classical ultraspherical window.
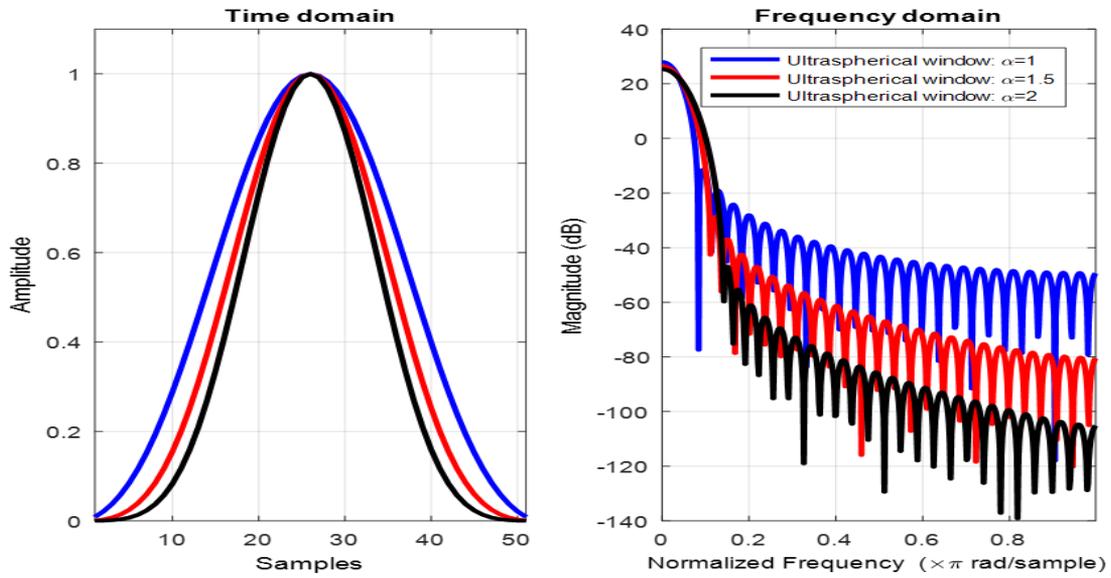
Figure 2. Effect of the adjustment parameter (α) on the ultraspherical window

Table 1. Comparison of the spectral parameters for different values of adjustment parameter (α)

Window	α	ω_R(rad/s)	Ripple ratio (dB)	Side-lobe roll-off ratio
Ultraspherical window	1	0.083	37.788	27.104
Modified ultraspherical window	1.5	0.111	55.173	51.485
Modified ultraspherical window	2	0.142	72.152	58.011

4. RCGA FOR QMF BANKS DESIGN USING MODIFIED ULTRASPHERICAL WINDOW

In this section, real coded genetic algorithm (RCGA) is exploited for finding the optimal spectral parameters (μ, x_0, α) of modified ultraspherical window and the cutoff frequency (ω_c) of the prototype filter, in order to develop efficient QMF banks.

Generally, genetic algorithms (GA) are optimization techniques inspired by natural evolution. They are used to generate efficient solutions to optimization problems by relying on biologically inspired operators such as: selection, crossover and mutation.

Figure 3 illustrates the flowchart of the RCGA used for optimizing the prototype filter parameters, which it is involves a number of different steps adapted for designing prototype filters.

Step 1. create a random initial population of chromosomes:
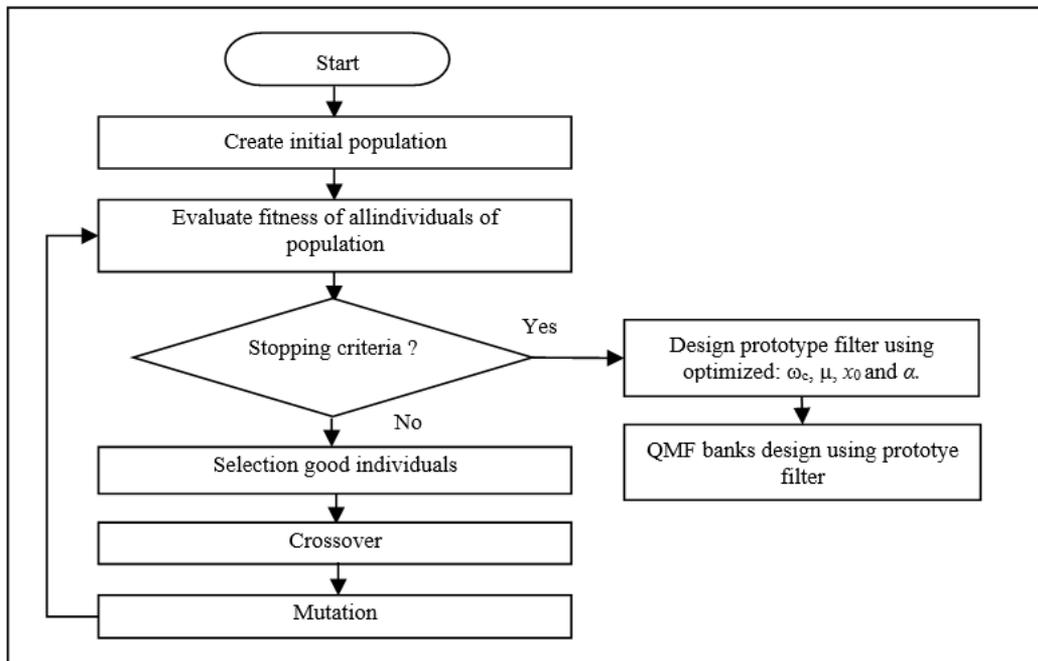
Figure 3. A flowchart of QMF banks design using GA

$$\text{initial population} = \begin{pmatrix} [\omega_{c1}\ \mu_1\ x_{01}\ \alpha_1]_1 \\ [\omega_{c2}\ \mu_2\ x_{02}\ \alpha_2]_2 \\ \vdots \qquad \vdots \\ [\omega_{cn}\ \mu_n\ x_{0n}\ \alpha_n]_n \end{pmatrix}_0$$

where, $\omega_{ci/i=1,2,\dots,n}$ represent the initial cutoff frequency values of the prototype filter and $\mu_{i/i=1,2,\dots,n}$, $x_{0i/i=1,2,\dots,n}$, $\alpha_{i/i=1,2,\dots,n}$ the initial parameters of the modified ultraspherical window function (usually $\mu \geq 1$ and $x_0 \geq 1$).

Step 2. Evaluate the fitness functions $f(\omega_{ci}, \mu_i, x_{0i}, \alpha_i)_{/i=1,2,\dots,n}$ for each individual and design the prototype filters based on modified ultraspherical window, then calculate the magnitude responses (*MRC*):

$$MRC_{i/i=1,2,\dots,n} = \left|e^{j\omega_{ci}}\right| \text{ at } \omega = \frac{\pi}{2} \qquad (12)$$

$$Er_{i/i=1,2,\dots,n} = |MRI - MRC_i| \qquad (13)$$

where, the magnitude response in the ideal condition (*MRI*) is equal to 0.707 and $Er_{i/i=1,2,\dots,n}$ is the fitness function.

Step 3. If the maximum number of generations is reached or $Er \leq Tol$ (*Tol*: tolerance) then RCGA algorithm stop. Otherwise RCGA algorithm repeats the following steps:
- Selection: consists in selecting individuals from the population for reproduction based on the relative fitness value of each individual. The selection can be performed by using Elitist function; the best individuals of each generation are guaranteed to be selected.
- Crossover: to apply the crossover operator, the chromosomes are randomly selected from the population. Then the chromosomes are chopped into parts at the crossover point and they exchange their parts.
- Mutation: randomly alters each gene with a small probability, usually less than 10%. This operator introduces innovation into the population and helps prevent premature convergence on a local maximum.
- Replace the current population with the new population.

$$\text{new population} = \begin{pmatrix} [\omega_{c1}\mu_1 & x_{01} & \alpha_1]_1 \\ [\omega_{c2}\mu_2 & x_{02} & \alpha_2]_2 \\ \vdots\ \vdots \\ [\omega_{cn}\mu_n & x_{0n} & \alpha_n]_n \end{pmatrix}$$

- Go to step 2.

Step 4. Stop and design prototype filter using the optimized parameters.

Table 2 illustrates tow optimized prototype filters using modified ultraspherical window and RCGA for different filters length (40 and 50). The optimal settings of the RCGA as shown in Table 3 and the associated QMF banks are given in Figures 4 and 5.

Table 2. Optimized prototype filters coefficients based on modified ultraspherical window

N	Modified Ultraspherical window: μ=2, x₀=3.552115681083168, α=1.880512388091985, ωc=0.552	Modified Ultraspherical window: μ=2, x₀=1.004381233990749, α=0.118292522778291, ωc=0.5068
1	0.000000000000000	0.007405125497528
2	0.000000000000000	-0.002474905928106
3	-0.000000000000000	-0.009420210751112
4	-0.000000000000002	0.003481007245895
5	0.00000000000000368	0.011163206985787
6	0.000000000000174	-0.004658644988645
7	-0.000000000344006	-0.012981123313748
8	0.000000001940887	0.006094563579390
9	0.000000074985647	0.015015805527867
10	-0.000000520182139	-0.007890395696965
11	-0.000004877296413	-0.017411232939896
12	0.000037401671299	0.010199912946942
13	0.000101446934606	0.020374492408386
14	-0.000991139297799	-0.013280669464605
15	-0.000420480334635	-0.024255874093758
16	0.011441470521815	0.017605631804231
17	-0.006493081366513	0.029726729536558
18	-0.068797041014316	-0.024151593722993
19	0.091129091166720	-0.038278959810925
20	0.485385977803475	0.035315986642234
21	0.485385977803475	0.054052516444313
22	0.091129091166720	-0.058976459541863
23	-0.068797041014316	-0.094431588343764
24	-0.006493081366513	0.145026402089081
25	0.011441470521815	0.454940713139490
26	-0.000420480334635	0.454940713139490
27	-0.000991139297799	0.145026402089081
28	0.000101446934606	-0.094431588343764
29	0.000037401671299	-0.058976459541863
30	-0.000004877296413	0.054052516444313
31	-0.000000520182139	0.035315986642234
32	0.000000074985647	-0.038278959810925
33	0.000000001940887	-0.024151593722993
34	-0.000000000344006	0.029726729536558
35	0.000000000000174	0.017605631804231
36	0.000000000000368	-0.024255874093758
37	-0.000000000000002	-0.013280669464605
38	-0.000000000000000	0.020374492408386
39	0.000000000000000	0.010199912946942
40	0.000000000000000	-0.017411232939896
41		-0.007890395696965
42		0.015015805527867
43		0.006094563579390
44		-0.012981123313748
45		-0.004658644988645
46		0.011163206985787
47		0.003481007245895
48		-0.009420210751112
49		-0.002474905928106
50		0.007405125497528

Table 3. Optimal RCGA parameters used for QMF banks design

Parameters	Values
Coding	Real
Population size	40
Maximum number of generations	30
Size of chromosome	2
Cutoff (ω_c)	0.49 - 0.57
μ	1 - 6
x₀	0-10
α	0-2
Tolerance (tol)	10^{-5}
Fitness Function	fitness =Minimize (|err-tol|)
Selection Technique	Elitist selection.
Probability of selection	0.5
Method of mutation	Random.
Mutation probability	pmut = 0.1
Method of crossing	One point crossover
Probability of crossover	pcross =0.5
Stopping criterion	Maximum number of generations or fitness ≤tol
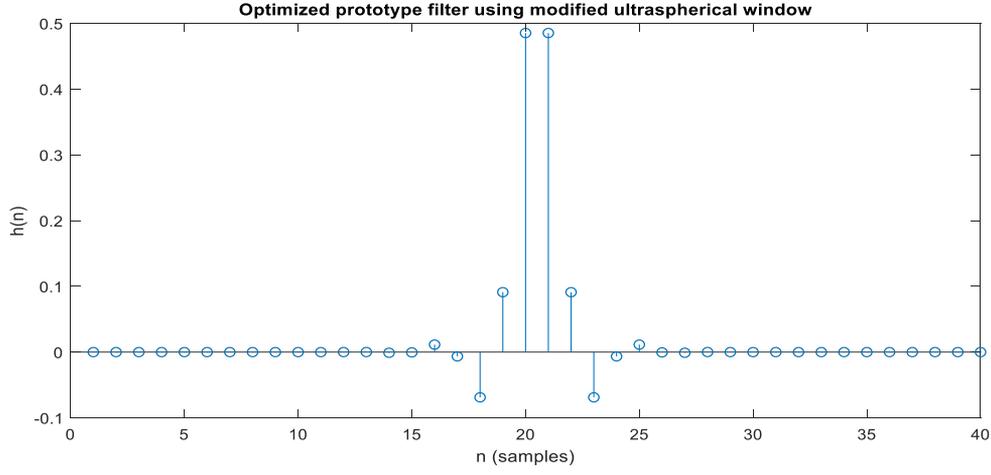
Figure 4. Optimized prototype filter using modified ultraspherical window and RCGA (N=40)
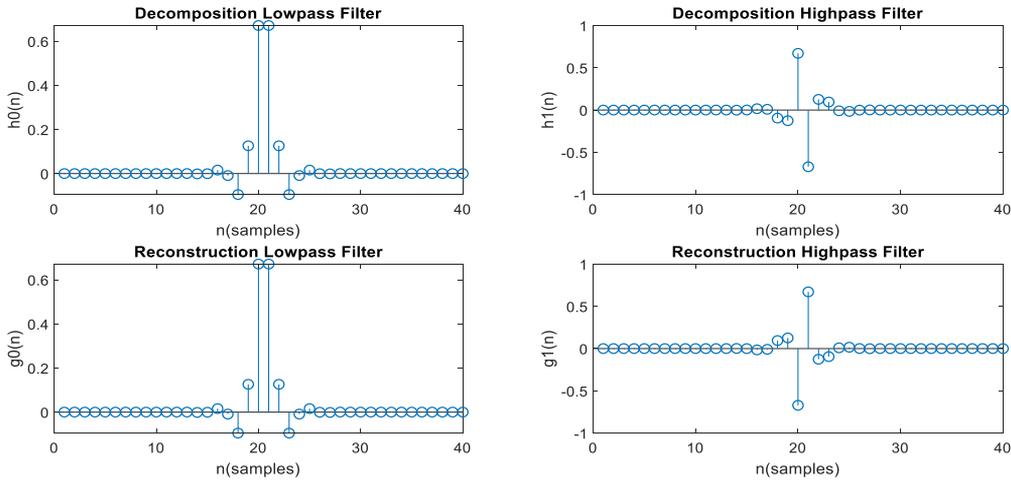
Figure 5. The associated QMF bank using modified ultraspherical window and RCGA (N=40)

5. SPEECH ENHANCEMENT USING OPTIMIZED QMF BANKS

In this work, the designed QMF banks using modified ultraspherical window and RCGA are exploited for speech enhancement based on discrete wavelet transform (DWT). In fact, the optimized analysis filters of two-channel QMF bank are used to decompose the noisy speech signals into sub-bands frequency. Then, the synthesis filters of two-channel QMF bank are applied to reconstruct the enhanced speech signals.

Generally, for speech enhancement based on DWT three steps most commonly used; decomposition using DWT, thresholding and reconstruction by applying inverse DWT [21-25]:

Step 1: consists in choosing the wavelet function, the decomposition level and compute the DWT in order to obtain approximation and detail coefficients of the noisy signal.

Step 2: in this step, the obtained wavelet coefficients ($w(n)$) are thresholded using hard thresholding or soft thresholding using the following formula:

Hard thresholding ($w_h(n)$):

$$w_h(n) = \begin{cases} w(n), |w(n)| \geq T \\ 0 \ otherwise \end{cases} \tag{14}$$

Soft thresholding ($w_s(n)$):

$$w_s(n) = \begin{cases} sign(w(n))(|w(n)| - T), w(n) > T \\ 0 \ |w(n)| \leq T \end{cases} \tag{15}$$

where, T represents the threshold value, which can be computed using many methods such as; level dependent threshold computation, global threshold computation or universal threshold computation. This latter, is most widely used due to its effectiveness and simpleness, which can be expressed as:

$$T_U = \delta\sqrt{2\,ln(N)} \tag{16}$$

where, σ and N are respectively the average variance of the noise and the signal length. σ can be calculated using the following formula:

$$\delta = \frac{median(|w_{1,i}|)}{0.6745} \tag{17}$$

$w_{1,i}$ represents all wavelet coefficients at scale one.

Step 3: in this steps IDWT is applied to reconstruct enhanced signal using original approximation coefficients and modified detail coefficients.

6. EXPERIMENTAL RESULTS AND COMPARATIVE PERFORMANCES

For the evaluation a MATLAB program has been written to implement the speech enhancement algorithm based on wavelets techniques, which exploit the optimized QMF banks based on modified ultraspherical window and RCGA.

A speech dataset token from the study [15] was used to evaluate the effectiveness of the optimized QMF banks. The noise signals were added to the speech signals at SNRs of 5dB and 10dB. The comparative study of performance was performed in terms of Perceptual Evaluation of Speech Quality (PESQ) and the Signal to Noise Ratio (SNR).

Tables 4, 5 and Figure 6 show the simulation results of SNR (dB) and PESQ score obtained using different window functions for QMF banks design. For speech enhancement algorithm using wavelet techniques, each selected test signal ("Babble.wav" and "Train.wav") is decomposed by using optimized QMF banks into 5 levels, soft thresholding is applied to the obtained coefficients using universal threshold value and a single estimation of noise level based on first level of wavelet coefficients.

Table 4. Comparison performances of the designed QMF banks for "Babble" test signal

Window	N	ω_c	SNR=5dB		SNR=10dB	
			SNR(dB)	PESQ	SNR(dB)	PESQ
Dolph-Chebyshev: As=60	40	0.5	4.786	1.817	8.849	2.072
Kaiser: β=8	40	0.5	4.806	1.816	8.726	2.068
Ultraspherical: μ=2, x_0=3	40	0.5	5.126	1.761	7.355	2.028
Modified ultraspherical: μ=2, x_0=3.552115681083168 α=1.880512388091985	40	0.552	5.556	1.882	9.661	2.095

Table 5. Comparison performances of the designed QMF banks for "Train" test signal

Window	N	ω_c	SNR=5dB		SNR=10dB	
			SNR(dB)	PESQ	SNR(dB)	PESQ
Dolph-Chebyshev: As=60	50	0.5	6.901	0.850	9.841	1.409
Kaiser: β=8	50	0.5	6.864	0.841	9.680	1.418
Ultraspherical: μ=2, x_0=1	50	0.5	6.974	0.838	10.293	1.435
Modified ultraspherical: μ=2, x_0=1.004381233990749, α=0.118292522778291	50	0.5068	7.156	0.921	10.869	1.541

Table 6. Speech quality obtained using SNR (dB) and PESQ for noisy "Babble" test signal

Algorithm	N	ω_c	SNR=5dB		SNR=10dB	
			SNR(dB)	PESQ	SNR(dB)	PESQ
Johnson ('db20') [25]	40	---	4.655	1.861	9.569	2.090
Xinmei ('sym20') [26, 27]	40	---	4.645	1.858	9.550	2.093
Proposed (μ=2, x_0= 3.552115681083168 α=1.880512388091985)	40	0.552	5.556	1.882	9.661	2.095

Table 7. Speech quality obtained using SNR (dB) and PESQ for noisy "Train" test signal

Algorithm	N	ω_c	SNR=5dB		SNR=10dB	
			SNR(dB)	PESQ	SNR(dB)	PESQ
Johnson ('db25') [25]	50	---	6.791	0.705	10.647	1.537
Xinmei ('sym25') [26, 27]	50	---	6.801	0.778	10.627	1.316
Proposed (μ=2, x_0=1.004381233990749, α=0.118292522778291)	50	0.5068	7.156	0.921	10.869	1.541
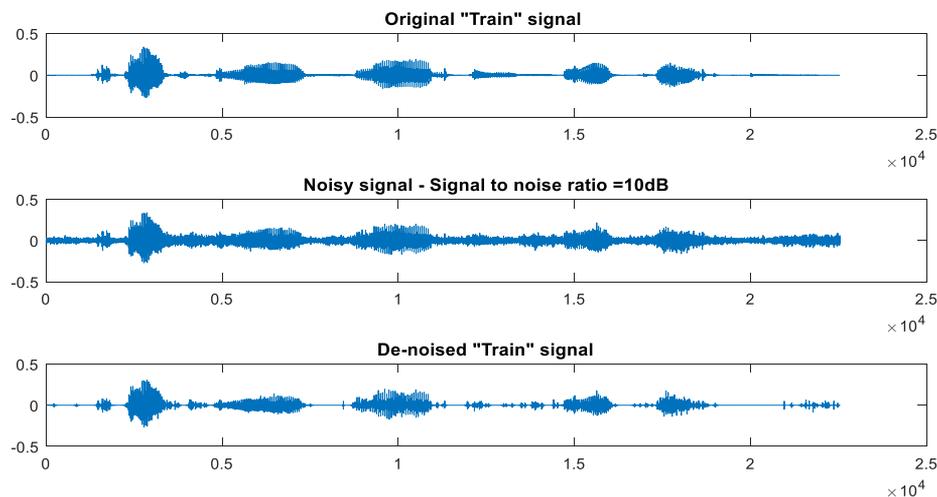
Figure 6. Time domain representation of clean, noisy and enhanced "Train" signals using modified ultraspherical window and RCGA

From the above tables, it is clear that the designed QMF banks using modified ultraspherical window and RCGA gives better performance in terms of PSNR and PESQ score compared to the Dolph-Chebyshev (As=60) and Kaiser (β=8) classical ultraspherical windows (μ=2, x_0=1). Moreover, from Table 6 and 7 it can be observed that developed QMF banks gives better performances while compared to the classical algorithm based on wavelet detailed in the studies [25-27].

Figure 6 shows the time plot of clean test signal "Train.wav", the noisy version corrupted by additive real noise and the denoised version using optimized QMF banks based on modified ultraspherical window. As it can be observed that the clean and enhanced signals are comparable.

7. CONCLUSIONS

In this work, modified ultraspherical window function is developed and exploited for designing efficient QMF banks with the help of real coded genetic. When designed QMF banks are used for speech enhancement algorithm based on wavelets techniques, the obtained simulation results prove that the modified ultraspherical window gives good performance in terms of PESQ and SNR compared with such window functions.

REFERENCES

[1] Rajkumar, G., Jayabharathy, R., Narasimhan, K., Raju, N., Easwaran, M., Elamaran, V., Burbano-Fernandez, M. (2019). Spectral and SNR improvement analysis of normal and abnormal heart sound signals using different windows. Future Generation Computer Systems, 92: 438-443. https://doi.org/10.1016/j.future.2018.09.047

[2] Eleti, A.A., Zerek, A.R. (2013). FIR digital filter design by using windows method with MATLAB. In 14th International Conference on Sciences and Techniques of Automatic Control & Computer Engineering-STA'2013, pp. 282-287. https://doi.org/10.1109/STA.2013.6783144

[3] Takahashi, R., Suzuki, N., Tasaki, H. (2018). Window function for MIMO radar beamforming to mitigate multipath clutter. In 2018 International Conference on Radar (RADAR), pp. 1-6. https://doi.org/10.1109/RADAR.2018.8557234

[4] Molnar, G., Matijaščić, M. (2020). Window-to-polynomial transform and its application in antenna array design. In 2020 14th European Conference on Antennas and Propagation (EuCAP), pp. 1-5. https://doi.org/10.23919/EuCAP48036.2020.9135197

[5] Podder, P., Khan, T.Z., Khan, M.H., Rahman, M.M. (2014). Comparative performance analysis of hamming, Hanning and Blackman window. International Journal of Computer Applications, 96(18): 1-7.

[6] Kaiser, J.F. (1966). Digital filters. System Analysis by Digital Computer, 228-243.

[7] Peter, L. (1997). The Dolph–Chebyshev window: A simple optimal filter. American Meteorological Society, 125: 655-660.

[8] Avci, K., Nacaroglu, A. (2009). Cosh window family and its application to FIR filter design. AEU-International Journal of Electronics and Communications, 63(11): 907-916. https://doi.org/10.1016/j.aeue.2008.07.013

[9] Deczky, A.G. (2001). Unispherical windows. In ISCAS 2001. The 2001 IEEE International Symposium on Circuits and Systems (Cat. No. 01CH37196), 2: 85-88. https://doi.org/10.1109/ISCAS.2001.921012

[10] Saramaki, T. (1989). A class of window functions with nearly minimum sidelobe energy for designing FIR filters. In IEEE International Symposium on Circuits and Systems, pp. 359-362. https://doi.org/10.1109/ISCAS.1989.100365

[11] Kumar, A., Kuldeep, B. (2014). Design of cosine modulated pseudo QMF bank using modified Dolph-Chebyshev window. International Journal of Signal and Imaging Systems Engineering, 7(2): 126-133.

[12] Kumar, V., Bangar, S., Kumar, S.N., Jit, S. (2014). Design of effective window function for FIR filters. In 2014 International Conference on Advances in Engineering & Technology Research (ICAETR-2014), pp. 1-5. https://doi.org/10.1109/ICAETR.2014.7012964

[13] Kliewer, J., Brka, E. (2006). Near-perfect-reconstruction low-complexity two-band IIR/FIR QMF banks with FIR phase-compensation filters. Signal Processing, 86(1): 171-181. https://doi.org/10.1016/j.sigpro.2005.05.012

[14] Lee, J.H., Yang, Y.H. (2003). Design of two-channel linear-phase QMF banks based on real IIR all-pass filters. IEE Proceedings-Vision, Image and Signal Processing, 150(5): 331-338.

[15] Hu, Y., Loizou, P. (2007). Subjective comparison and evaluation of speech enhancement algorithms. Speech Communication, 49(7-8): 588-601. https://doi.org/10.1016/j.specom.2006.12.006

[16] Kuldeep, B., Kumar, A., Singh, G.K. (2015). Design of quadrature mirror filter bank using Lagrange multiplier method based on fractional derivative constraints. Engineering Science and Technology, an International Journal, 18(2): 235-243. https://doi.org/10.1016/j.jestch.2014.12.005

[17] Upendar, J., Gupta, C.P., Singh, G.K. (2010). Design of two-channel quadrature mirror filter bank using particle swarm optimization. Digital Signal Processing, 20(2): 304-313. https://doi.org/10.1016/j.dsp.2009.06.014

[18] Kumar, A., Singh, G.K., Anand, R.S. (2008). Near perfect reconstruction quadrature mirror filter. International Journal of Computer Science and Engineering, 2(3): 121-123.

[19] Bergen, S.W.A. (2005). Design of the ultraspherical window function and its applications. Thesis, B.Sc., University of Calgary.

[20] Deczky, A.G. (2001). Unispherical windows. In ISCAS 2001. The 2001 IEEE International Symposium on Circuits and Systems (Cat. No. 01CH37196), 2: 85-88. https://doi.org/10.1109/ISCAS.2001.921012

[21] Abramovich, F., Benjamini, Y. (1995). Thresholding of wavelet coefficients as multiple hypotheses testing procedure. In Wavelets and Statistics, 5-14. https://doi.org/10.1007/978-1-4612-2544-7_1

[22] Birgé, L., Massart, P. (1997). From model selection to adaptive estimation. In Festschrift for Lucien le Cam, 55-87. https://doi.org/10.1007/978-1-4612-1880-7_4

[23] Hu, Y., Loizou, P.C. (2004). Speech enhancement based on wavelet thresholding the multitaper spectrum. IEEE Transactions on Speech and Audio Processing, 12(1): 59-67. https://doi.org/10.1109/TSA.2003.819949

[24] Bhowmick, A., Chandra, M. (2017). Speech enhancement using voiced speech probability based wavelet decomposition. Computers & Electrical

Engineering, 62: 706-718. https://doi.org/10.1016/j.compeleceng.2017.01.013

[25] Agbinya, J.I. (1996). Discrete wavelet transform techniques in speech processing. In Proceedings of Digital Processing Applications (TENCON'96), 2: 514-519. https://doi.org/10.1109/TENCON.1996.608394

[26] Zhong, X., Dai, Y., Dai, Y., Jin, T. (2018). Study on processing of wavelet speech denoising in speech recognition system. International Journal of Speech Technology, 21(3): 563-569. https://doi.org/10.1007/s10772-018-9516-7

[27] Cengiz, Y., Arıöz, Y.D.U. (2016). An application for speech denoising using Discrete wavelet transform. In 2016 20th National Biomedical Engineering Meeting (BIYOMUT), pp. 1-4. https://doi.org/10.1109/BIYOMUT.2016.7849377