최적화된 계층구조를 갖는 서브밴드 필터뱅크의 설계

박 규 식[†] · 박 재 현[††]

요 약

계층적 구조를 갖는 서브밴드 코덱은 그 구조의 간단성과 모듈적인 특성으로 인하여 데이타 압축/복원 시스템에 많이 쓰여왔다. 최근까지 연구되어 오고 있는 대부분의 계층적 서브밴드 코덱은 주로 양자화 영향을 고려하지 않은 상태에서 출력단에서 입력 신호를 복원하기 위한 완전복원(perfet Reconstruction)시스템에 제한되어 왔다. 그러나 실제적인 서브밴드 코덱 시스템에서는 분석 필터 뱅크를 통한 입력 신호가 양자화기를 거쳐 합성 필터 뱅크에 전송되므로, 양자화 오차가 발생하게 되어 완전복원은 불가능하게 된다. 따라서 이러한 양자화 오차를 최소화하여 출력단에서 가능한한 원 입력신호에 가깝게 재생할 수 있는 최적의 코덱 시스템을 필요로 하게 된다. 본 논문에서는 그동안 수학적 이론과 코덱 구조의 복합성 때문에 고려되지 않았던 양자화기에 의한 양자화 오차를 수학적으로 분석하여 최적화된 계층적 구조를 갖는 서브밴드 코덱의 설계를 제안한다. 본 논문에서의 최적화의 기준은 코덱에서 양자화기에 의해 발생하는 평균 제곱 오차를 최소화하는 계층적 분석/합성 필터 뱅크와 양자화기의 설계에 있다. 구체적인 최적화 설계 예제는 레벨-1, 레벨-2 계층적 구조를 갖는 코덱에 실제 적용되었으며, 설계된 코덱은 컴퓨터 모의 실험을 통하여 검증하였다.

The Design of Optimum Hierarchical Subband Filter Bank

Kyusik Park[†] · Jaehyun Park[††]

ABSTRACT

Hierarchical subband codec has been widely promoted in the field of data compression/decompression because of their simplicity and modular nature. Over the past years, the study has received great attention to the perfect reconstruction(PR) system which perfectly recovers the original input signal at the reconstructed output. However, in the actual subband codec system, the signals that passed through the analysis filter bank are quantized before transmission to the receiver side and reconstructed by the synthesis filter bank. Thus the PR system is impossible and the quantization effects must be carefully considered in the system design such that the system recovers the reconstructed output as close as possible to the the original input signal with minimum quantization error.

In this paper, we propose an optimum hierarchical subband codec structure in the presence of quantizer. The optimality criteria of the codec is given to the design of the hierarchical analysis/synthesis subband filter bank and the quantizer that minimize the output mean square error due to the quantizer in the codec. Specific optimum design examples are shown with level-1, level-2 hierarchical orthonormal structure. The optimal designs are verified by computer simulation.

† 정 회 원 : 상명대학교 정보통신학과
†† 정 회 원 : 삼성전자 마이크로 사업부 DSP
논문접수 : 1995년 12월 11일, 심사완료 : 1996년 3월 20일

1. Introduction

Digital data compression techniques such as transform coding and subband coding rely on the proper design of analysis/synthesis filter bank and the quantizer to reduce the number of bits allocated to each data sample. In the absence of coding errors such as quantization and channel noise, the topics related to the subband codec that achieves perfect reconstruction(PR) have been studied widely[1][2][3]. Especially, the hierarchical subband structure based on two-band split in frequency bands has received great attention for its simplicity and modular nature. Smith and Barnwell[4] have shown that a hierarchical subband codec, as in figure 1 is in perfect reconstruction such as $X(n)=y(n)$ within some delay if the progenitor two-band analysis-synthesis structure is PR with $\{H_0(z), H_1(z); G_0(z), G_1(z)\}$ satisfying perfect reconstruction condition.

Consequently, this structure can be iterated many times(levels) as we want with the assurance that PR is attained in the absence of all error sources.

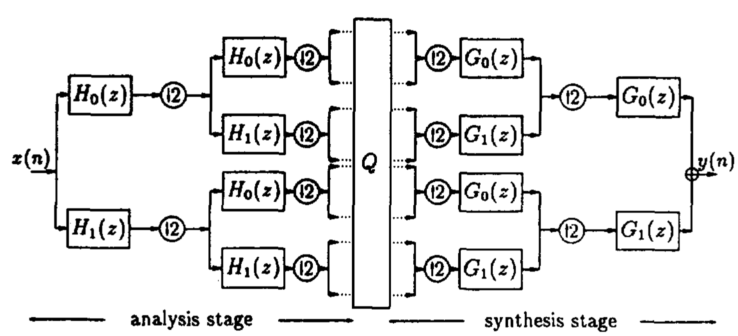
However, in the actual system, the signal is quantized before the transmission as in the figure 1. Thus the quantization effects should be carefully considered in the design.

In this paper, the encoding quantization effects in L-level hierarchical subband system has been considered. We will first transform the given hierarchical subband structure into a equivalent parallel structure by using the noble identity[1]. Then we expand the polyphase concept into the equivalent structure to extract the explicit formula for the mean square quantization error due to the quantizer. Then the minimization of this mean square error(MSE) provides the optimum designs; the analysis/synthesis filter bank and the quantizer. In other words, we select optimum filter banks and the quantizers that is strong to the quantization noise among all sets of possible PR filter banks. Specific design examples are shown with level-1, level-2 hierarchical orthonormal subband structure and they are verified by simulation.

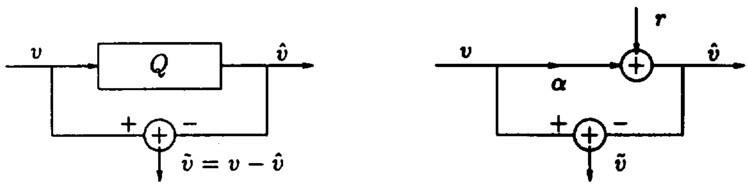
2. Preliminary

The Lloyd-Max quantizer[5] is a nonuniform quantizer which tailors the step-size of the quantizer to the pdf of the input signal. It uses small step sizes for more probable input values at the expense of larger step sizes for the less probable ones. Figure 2.(a) shows the block diagram representation of the pdf-optimized quantizer where v is the signal to be quantized, $\hat{v}$ is the quantized output, and the $\tilde{v}$ is the quantization error.

For the pdf-optimized quantizer, it can be shown that the quantization error is unbiased, and that the error is orthogonal to the quantized output



(Fig. 1) Multi-level hierarchical subband filter bank



(Fig. 2) (a) Pdf-optimized quantizer, (b) gain-plus-additive noise model.

$$E[\tilde{v}]=0, \qquad E[\tilde{v}\hat{v}]=0 \tag{1}$$

However the quantization error $\tilde{v}$ is correlated with the input v. Figure 2.(b) shows an equivalent gain-plus-additive noise model for the pdf-optimized quantizer[6]. By introducing the nonlinear gain α to the quantizer model, we force the fictitious random error rather than the actual quantization error $\tilde{v}$ to be uncorrelated with the input signal v such that $E=[rv]=0$ and

$$\alpha = 1-\sigma_{\tilde{v}}^2/\sigma_v^2, \qquad \sigma_r^2=\alpha(1-\alpha)\sigma_v^2=\alpha\sigma_{\tilde{v}}^2 \tag{2}$$

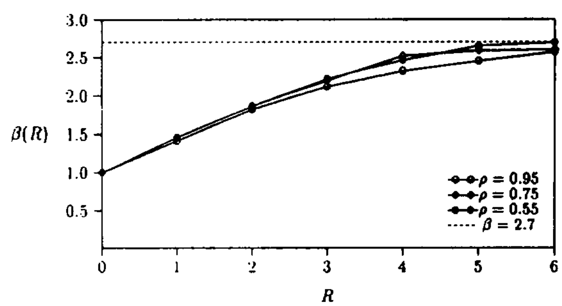
From the rate distortion theory[7], the quantization error variance $\sigma_{\tilde{v}}^2$ of the pdf-optimized quantizer is given by

$$\sigma_{\tilde{v}}^2=\beta(R)2^{-2r}\sigma_v^2, \tag{3}$$

where $\beta(R)$ depends on the pdf of the input signal v and R, the number of bits used in the quantizer. Earlier approaches treated $\beta(R)$ simply as a constant $\beta=2.7$[6]. But, in this paper, we actually determine the value of $\beta(R)$ with 20,000 samples of AR(1) gaussian input signal with different input correlation ρ and different number of bits assigned to the Llyod-Max quantizer. It is shown in figure 3.

Let us assume that the multi-level hierarchical subband structure, in figure 1, has L-stage. Then we can easily transform level-L hierarchical subband structure into $M=2^L$ band parallel structure in figure 4 by using the noble identity[1]. Therefore figure 1 and figure 4 are equivalent if

$$U_k(z)=H_{a_0}(z)H_{a_1}(z^2)H_{a_2}(z^4)\cdots H_{a_{L-1}}(z^M)$$
$$W_k(z)=G_{b_0}(z)G_{b_1}(z^2)G_{b_2}(z^4)\cdots G_{b_{L-1}}(z^M) \tag{4}$$



(Fig. 3) $\beta(R)$ vs. R for AR(1) gaussian input source

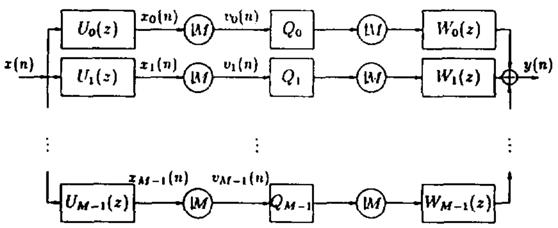
where k is decimal number representation of binary such that

$$(k)_{10}=(a_0a_1a_2\cdots a_{L-1})_2, \qquad k=0,1,2,\cdots,M-1$$

Now each pdf-optimized quantizer, in the parallel equivalent $M=2^L$ band parallel structure in figure 4, can be represented by figure 2(b). Then using the polyphase decomposition technique, we can express each analysis/synthesis filters $U_k(z)$, $W_k(z)$ in terms of M polyphase components[8]

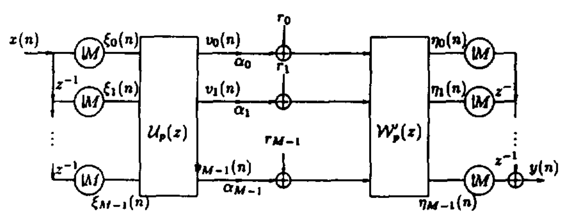
$$U_k(z)=\sum_{l=0}^{M-1}U_{k,l}(z^M), \quad W_k(z)=\sum_{l=0}^{M-1}z^{(M-l)-1}W_{k,(M-1-l)}(z^M)$$

Then we can represent the analysis filter bank in terms of the $M \times M$ polyphase matrix $\{U_p(z) = [U_{k,l}(z)];\ k, l = 0, 1, \cdots, M-1\}$ where $U_{k,l}$ is the lth polyphase components of the kth corresponding analysis filters of the equivalent structure. For the synthesis filter bank, we define a polyphase matrix $W_p'(z) \triangleq JW_p^T(z)$ in the same manner where J is the counter identity matrix[9].

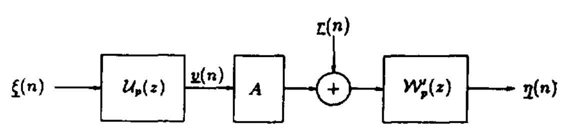


(Fig. 4) M-band parallel equivalent structure to figure 1

Then we replace the bank of filters by its polyphase equivalent and shift the samplers to the left and right of each polyphase matrix by using the noble identity. We then finally end up figure 5, the polyphase equivalent structure. Figure 6 is only a vector-matrix representation of figure 5 and it represents the time-invariant path from $\underline{\xi}(n)$ to $\underline{\eta}(n)$ between the downsampler and upsampler after the polyphase decomposition.



(Fig. 5) Polyphase decomposed structure of figure 4



(Fig. 6) Vector-matrix representation of figure 5

For this structure,

$$\underline{\xi}(n) = [\xi_0(n), \xi_1(n), \cdots, \xi_{M-1}(n)]^{T}$$

and $\underline{v}(n)$, $\underline{r}(n)$, $\underline{\eta}(n)$ are similarly defined. In our model, the signals

$$\underline{v}(n) = [v_0(n), v_1(n), \cdots, v_{M-1}(n)]^T,$$
$$\underline{r}(n) = [r_0(n), r_1(n), \cdots, r_{M-1}(n)]^T$$

are uncorrelated by construction, and A is a diagonal matrix,

$$A = diag[\alpha_0, \alpha_1, \cdots, \alpha_{M-1}]$$

where $v_i(n)$, $r_i(n)$, α_i is the subband signal, fictitious noise and the nonlinear gain for the ith channel. $U_p(z)$ and $W_p'(z)$ are polyphase matrices as defined earlier.

3. Quantization Effects in Hiearchical Orthonormal Structure

From figure 6, the quantized output is

$$\underline{\eta}(z) = W_p'(z) A U_p(z) \underline{\xi}(z) + W_p'(z) \underline{R}(z) \tag{5}$$

In the absence of the quantizer, the system output is

$$\underline{\eta}_o(z) = W_p'(z) U_p(z) \underline{\xi}(z) \tag{6}$$

Then we can define the quantization error at the system output as a difference between Eq.(5) and Eq.(6) such that

$$\begin{aligned}\underline{\eta}_q(z) &= \underline{\eta}(z) - \underline{\eta}_o(z)\\ &= W_p'(z)[A-I]U_p(z)\underline{\xi}(z) + W_p'(z)\underline{R}(z)\end{aligned} \tag{7}$$

where I is the $M \times M$ identity matrix.

To make notational simplification, we define $M \times M$ matrix B

$$B \triangleq A - I = diag[\alpha_0 - 1, \alpha_1 - 1, \cdots, \alpha_{M-1} - 1]$$

and vector $\underline{V}(z)=U_x(z)\,\underline{\xi}(z)$. Since $\underline{v}(n)$ and $\underline{r}(n)$ are uncorrelated from the quantization model, the output PSD and covariance matrices of $\underline{\eta}_q(z)$ can be derived

$$S_{\underline{\eta}_q\underline{\eta}_q}(0)=W_p{}'BS_{\underline{vv}}(z)B(W_p{}'(z))^T+W_p{}'(z^{-1})S_{\underline{rr}}(z)(W_p{}'(z))^T$$
$$R_{\underline{\eta}_q\underline{\eta}_q}(k)=W'_{p,-k}B*R_{\underline{vv}}(k)B(W^{l}_{p,k})^T+W'_{p,-k}R_{\underline{rr}}(k)*(W'_{p,-k})^T \tag{8}$$

where $S_{\underline{vv}}(z)$, $S_{\underline{rr}}(z)$ are PSD matrices of subband vector $\underline{v}(n)$ and random error vector $\underline{r}(n)$, respectively. Futhermore, at k = 0, Eq.(8) becomes

$$R_{\underline{\eta}_q\underline{\eta}_q}(0)=\sum_j\sum_k\{W^T_{p,j}BR_{\underline{vv}}(j-k)BW_{p,k}+W^T_{p,j}R_{\underline{rr}}(j-k)W_{p,k}\} \tag{9}$$

Then we can demonstrate $R_{\underline{\eta}_q\underline{\eta}_q}(0)$ is the covariance of the Mth block of output quantization error vector

$$\underline{\eta}^T_q(n)=[\eta_{q_0}(n),\ \eta_{q_1}(n),\ \cdots,\ \eta_{q_{M-1}}(n)]$$
$$=[y_q(Mn),\ y_q(Mn+1),\ \cdots,\ y_q(Mn+M-1)] \tag{10}$$

such that

$$R_{\underline{\eta}_q\underline{\eta}_q}[0]=$$
$$\begin{bmatrix} R_{y_qy_q}(Mn,\ Mn) & \cdots & R_{y_qy_q}(Mn,\ Mn+M-1) \\ R_{y_qy_q}(Mn+1,\ Mn) & \cdots & R_{y_qy_q}(Mn+1,\ Mn+M-1) \\ \vdots & \ddots & \vdots \\ R_{y_qy_q}(Mn+M-1,\ Mn) & \cdots & R_{y_qy_q}(Mn+M-1,\ Mn+M-1) \end{bmatrix}_{M\times M}$$

where $R_{y_qy_q}(Mn+k,\ Mn+j)=E[y_q(Mn+k)\,y_q(Mn+j)]$ for $k,\ j=0,\ 1,\ \cdots,\ M-1$ and $y_q(n)\triangleq y(n)-y_0(n)$. Here $y(n)$ is the quantized system output from figure 8 and $y_0(n)$ is output of the system without quantization.

We note that this is cyclostationary. Thus we take the MS quantization error as the average of the diagonal elements of $R_{\underline{\eta}_q\underline{\eta}_q}[0]$ such that

$$\sigma_{y_q}{}^2\triangleq E[y_q^2(n)]=\frac{1}{M}\ Trace[R_{\underline{\eta}_q\underline{\eta}_q}(0)] \tag{11}$$

If we now impose orthonomality conditions on the set of prototype analysis filters $\{H_0(z),\ H_1(z)\}$ of figure 1., then the impulse responses $h_0(n)$, $h_1(n)$ must satisfy[10]

$$\sum_k \mathrm{h_r(k)\,h_s(2n+k)}=\delta_{(r-s)}\delta(n)\ \text{ for } r,\ s=0,\ 1 \tag{12}$$

and also for the synthesis filters. This in turn implies that the set of analysis/synthesis filters $\{U_i(z),\ W_i(z)\}$, $i=0,\ 1,\ \cdots,\ M-1$ in the equivalent parallel structure in figure 4 are also orthonormal. In the time domain, this condition is given to

$$\sum_k \mathrm{u_r(k)\,u_s(4n+k)}=\delta_{(r-s)}\delta(n)\ \text{ for } r,\ s=0,\ 1,\ \cdots,\ M-1 \tag{13}$$

where $\{u_i(n),\ w_i(n);i=0,\ 1,\ 2,\ \cdots,\ M-1\}$ are

$$u_i(n)=h_{a_0}(n)*h_{a_1}(n/2)*\cdots*h_{a_{M-1}}(n/2^L)$$
$$w_i(n)=g_{b_0}(n)*g_{b_1}(n/2)*\cdots*g_{b_{M-1}}(n/2^L) \tag{14}$$

where $*$ represents the convolution operation and i is the decimal representation of the corresponding binary sequence as defined earlier.

If we now take the conditions in equation (13), (14) into (11), then with some manipulation we can show that the total mean square(MS) quantization error

$$\sigma_{y_q}{}^2=\frac{1}{M}\sum_{i=0}^{M-1}(\alpha_i-1)^2\sigma_{v_i}{}^2+\frac{1}{M}\sum_{i=0}^{M-1}\sigma_{r_i}{}^2 \tag{15}$$

In equation (15), $\sigma_{r_i}{}^2$ and $\sigma_{v_i}{}^2$ are the variances of fictitious random noise and the subband signal for ith channel respectively, and they are given as

$$\sigma_{r_i}{}^2=\alpha_i\,\sigma_{\tilde{v}}{}^2=\alpha_i\beta_i 2^{-2R_i}\sigma_{v_i}{}^2,$$

$$\sigma_{v_i}{}^2=\sum_k\sum_l \mathrm{u_i(k)\,u_i(l)\,R_{xx}(k-l)} \tag{16}$$

Thus far, we have formulated the output MSE in terms of the analysis filter coefficients $\{u_i(n),\ i=0,\ 1,\ 2,\ \cdots,\ M-1\}$ of the equivalent structure of figure 4., input autocorrelation function $R_{xx}(m)$, nonlinear quantizer gain α_i and the bits allocated to each quantizer R_i.

For those of the equations (14), (15), (16), our design problem is now to find optimum analysis/synthesis filter bank $u_i(n)$, $w_i(n)$ for $i=0, 1, 2, \cdots, M-1$, and optimum bits R_i allocated to quantizer Q_i that minimize the output MSE in equation (15).

4. Optimum Design Examples for Level-1, Level-2 Structure

In this section, we have developed specific optimum design examples for the Level-1, Level-2 hierarchical subband structure with prototype 2-channel 6 tap orthonormal filter $\{H_i(z); G_i(z), i=0, 1\}$.

We note that the given hierarchical structure is first transformed to the corresponding equivalent structure. Then our optimum design problem is to find the optimum PR analysis/synthesis filter bank $u_i(n)$, $w_i(n)$ and the bit allocation R_i assigned to quantizer that minimizes the output MSE Eq.(16) for a given total bit allocation. We assume that the quantizer takes only integer bits and the high frequency components of the subband signal gets at least 1 bit. Otherwise there is no way to recover high frequency component of input signal at the output.

Our optimization algorithm test for all the possible bit combinations for the given average bit rate R bits/sample, calculates the optimal filter coefficients, and MSE. Then we choose one with minimum MSE among them. This is implemented by using IMSL FORTRAN Library DNCONF.

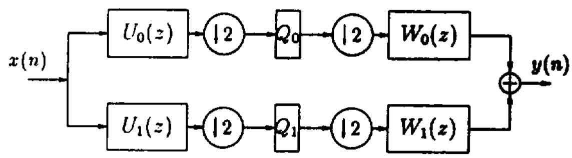
The analytical results were confirmed by simulation using 20,000 samples of AR(1) gaussian input. The AR(1) signal with correlation ρ was generated from

$$x(n)=\rho x(n-1)+\xi_g(n)$$

where $\eta_g(n)$ is zero mean, white gaussian sequence generated from IMSL subroutine GGNML.

4.1 level-1 Hierarchical subband structure

For level-1 structure, we have nothing but a two-band parallel structure as in figure-7.



(Fig. 7) Level-1, two-band parallel equivalent structure

For this case, we have only a two sets of analysis/synthesis filters

$$u_i(n)=h_i(n), \quad w_i(n)=g_i(n) \quad \text{for} \quad i=0, 1$$

and the resulting output MSE is

$$\sigma_{y_e}^2=\frac{1}{2}\sum_{i=0}^{1}(\alpha_i-1)^2\sigma_{v_i}^2+\frac{1}{2}\sum_{i=0}^{1}\sigma_{r_i}^2 \qquad (17)$$

Thus our optimization problem is to minimize Eq.(17) subject to $\sum_{0}^{1} R_i=2R$ where $\{R_i; i=0, 1\}$ is the bit allocation for the ith channel and R is the average bit rate in bits/sample for the 2-channel filter bank.

The analysis and simulation results for Level-1 hierarchical structure are shown in Table 1 for the input correlation $\rho=0.95$, 0.75. Table 1 lists the optimum integer bits allocated to each channel R_0, R_1, the theoretical calculations of the output MSE based on Eq.(17), MSE, and the simulation results, MSE_{sim}.

As seen from the tables, the optimal filter coefficients are quite insensitive to changes in average bit rate R although the output MSE is highly dependent on them. We note the difference between Table 1(a) and Table 1(b) in optimal bit allocation for the given average bit rate R. For the same average bit rate $R=2.5$, the optimum bits allocated to each channels are $R_0=4$, $R_1=1$ for input correlation $\rho=0.95$, while they are $R_0=3$, $R_1=2$ for $\rho=0.75$. The reason for the dif-

〈Table 1〉 Optimum designs for Level-1 hierarchical structure

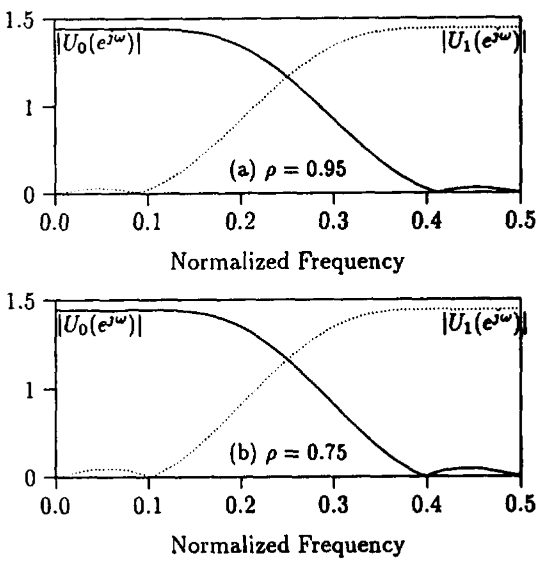
R	R_0	R_1	MSE	MSE_{sim}
1	1	1	0.35329	0.35128
1.5	2	1	0.11822	0.11831
2	3	1	0.03874	0.03913
2.5	4	1	0.01536	0.01536
3	5	1	0.00858	0.00874

(a) $\rho=0.95$

R	R_0	R_1	MSE	MSE_{sim}
1	1	1	0.36355	0.36134
1.5	2	1	0.14066	0.13881
2	3	1	0.06612	0.06606
2.5*	3	2	0.04219	0.04263
3*	4	4	0.02014	0.02046

(b) $\rho=0.75$

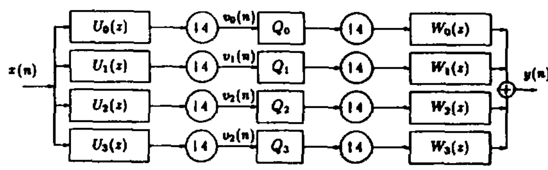
ferent bit allocation is that AR(1) input with $\rho=0.75$ has more energy at the higher frequencies than the one with $\rho=0.95$. The magnitude responses corresponding to Table 1 are shown in figure 8 for the given average bit rate $R=3$.



(Fig. 8) Magnitude response for Level-1 structure for $R=3$ bits/sample

4.2 Level-2 Hierarchical subband structure

For level-2 structure, we have a four-band parallel equivalent structure as in figure 9.



(Fig. 9) Level-2, four-band parallel equivalent structure

In this case, we have four sets of analysis/synthesis filters

$$U_0(z)=H_0(z)H_0(z^2) \qquad U_1(z)=H_0(z)H_1(z^2)$$
$$U_2(z)=H_1(z)H_0(z^2) \qquad U_3(z)=H_1(z)H_1(z^2) \qquad (18)$$

and similarly define for $W_i(z)$ for $i=0, 1, 2, 3$. We note that the length of analysis/synthesis filters $u_i(n)$, $w_i(n)$ is now 16-tap since the prototype filters are 6-tap. And the output MSE is

$$\sigma_{y_t}{}^2=\frac{1}{2}\sum_{i=0}^{3}(\alpha_i-1)^2\sigma_{v_i}{}^2+\frac{1}{4}\sum_{i=0}^{3}\sigma_{r_i}{}^2 \qquad (19)$$

Now our optimization problem is to minimize Eq.(19) subject to the average bit rate R in bits/sample for the 4-channel filter bank.

The optimal designs for the level-2 hierarchical orthonormal subband filter banks are shown in Table 2 for the case of $\rho=0.95$, 0.75. As seen from the table, the bits allocated to R_3 is greater than and equal to R_2, because in the parallel equivalent structure of figure 4., the analysis filter $U_2(z)$ actually plays a role of high pass filter while $U_3(z)$ as a bandpass filter.

We again note the difference between Table 2(a) and (b) in optimal bit allocations for the given average bit rate $R=2$. This can be explained in the same manner as in level-1 structure. The magnitude response of the designed filters for $U_i(z)$, $i=0, 1, 2, 3$ when the input correlation is $\rho=0.95$, 0.75 and $R=3$

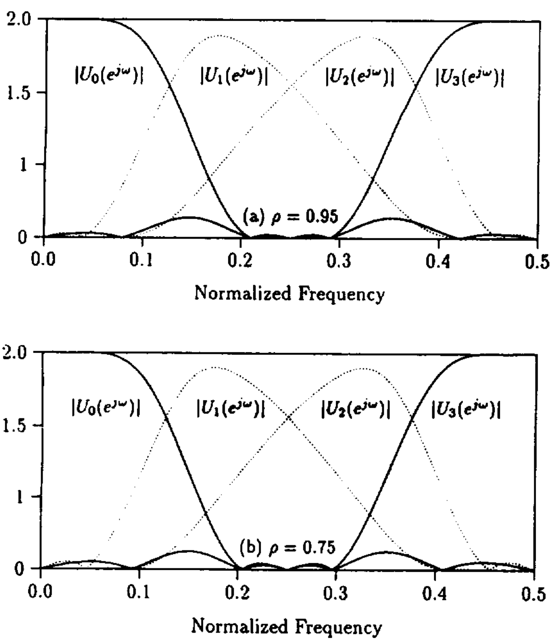
〈Table 2〉 Optimum designs for level-2 hierarchical structure

R	R_0	R_1	R_2	R_3	MSE	MSE_{sim}
1	1	1	1	1	0.35325	0.35124
1.5	3	1	1	1	0.04660	0.04573
2	5	1	1	1	0.01721	0.01683
2.5	4	1	1	1	0.00878	0.00881
3	5	2	1	2	0.00509	0.00512

(a) $\rho = 0.95$

R	R_0	R_1	R_2	R_3	MSE	MSE_{sim}
1	1	1	1	1	0.36156	0.36231
1.5	3	1	1	1	0.10756	0.11783
2*	4	2	1	1	0.05749	0.05651
2.5	5	2	1	2	0.03749	0.03812
3	6	3	1	2	0.02568	0.02552

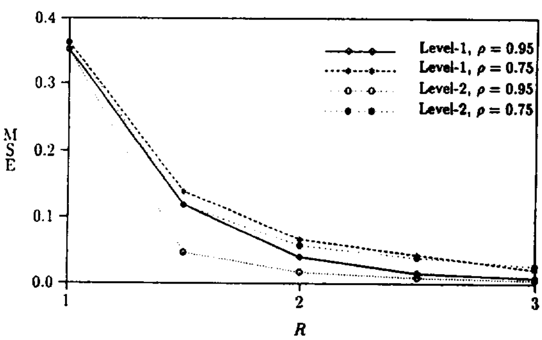
(b) $\rho = 0.75$



(Fig. 10) Magnitude response for Level-2 structure for R = 3 bits/sample

bit/sample are shown in figure 10, respectively. From the figures, we clearly see the effect of input correlation change in magnitude respônses. As the input correlation ρ decrease, the stop band ripples of each filter and spillover from one band to another are getting larger. Consequently, more aliasing is introduced between the channels which yields larger MSE at the output. Finally, figure 11 shows the MSE comparison between level-1 and level-2 hierarchical orthonormal subband structure. As seen from the figure, level-2 structure provides less mean square quantization error than that of level-1 structure.

This will be true as long as the level of structure is increased. However, as we see from the figure 8 and 10, the stopband ripple in the designed subband filters is getting larger as the level increased. Thus increasing the level of the structure is not always desirable.



(Fig. 11) Simulated MSE comparison between level-1 and level-2 structure

5. Conclusion

In this paper, we have established an explicit methodology to have mean square quantization error at the system output by formulas derived for the hierarchical subband codec. At first, we demonstrated that the given L-level hierarchical subband structure can be realized with equivalent parallel structure that have $M = 2^L$ channels. We then derived the output

MSE expression base on the parallel equivalent structure by using the gain-plus-additive noise model for the quantizer and the polyphase decomposition technique for the analysis/synthesis filter bank. The minimization of this MSE was then used as a optimality criteria for the design of filter banks, and the bits allocated to quantizer for the hierarchical subband structure.

Optimum design examples for the level-1 and level-2 hierarchical structure are developed with orthonormal filter bank. For the designed subband codec, it was clear to see the dependency of the magnitude response of the subband filter on the input signal correlation. As the input correlation decrease, the stopband ripples are getting larger and more MSE is presented. Also, the nature of optimum bit allocation base upon the energy distribution of the input signal was clearly observed from our simulation results. We note that the maximum allocation of the available bits to the first channel(where the most energy of the signal resides) was not the optimum solution for the level-2 hierarchical subband structure as it was in the simple level-1 structure. Finally, we observed that the mean square quantization error is decreased as the level of the hierarchical structure is increased. However, as the level of the structure is increased, the stopband ripple in the designed subband filter is relatively increased so that increasing the level does not always provide the optimum solution. For this reason, the proposed design method is well qualified up to level-4 (16 subbands in the equivalent parallel structure) hierarchical structure.

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박 규 식

1986년 (미)Polytechnic University 전자공학과(공학사)
1988년 (미)Polytechnic University 전자공학과(공학석사)
1994년 (미)Polytechnic University 전자공학과(공학박사)
1994년~1995년 삼성전자 반도체 마이크로 사업부 DSP, 선임연구원
1995년~1996년 한국해양대학교 전파공학과 전임강사
1996년~현재 상명대학교 정보통신학과 전임강사
관심분야: Digital Signal(Image) Processing, Multimedia Communication

박 재 현

1984년 서울대학교 전기공학과(공학사)
1986년 (미)Polytechnic University 전자공학과(공학석사)
1994년 (미)Polytechnic University 전자공학과(공학박사)
1994년~현재 삼성전자 반도체 마이크로 사업부
관심분야: Digital Image Processing, Communication System