Optimal Design of DPCM Scheme for ECG Signal Handling

BAHAR H. B. and KHIABANI Y.S.
Department of Electronics, Tabriz University,
Faculty of Electrical and Computer Engineering
I.R. IRAN

Abstract: - Differential pulse code modulation (DPCM) plays an important role in communication systems. In this paper, a theoretical work has been significantly carried out to design an optimal DPCM system. At DPCM structure, instead of direct coding of signal, difference between two signals, input to DPCM and output of predictor is encoded. The difference of two signals is so small in value that can be quantized by fewer bits. In this study, Levinson-Durbin algorithm is utilized to design the optimum predictor. Furthermore, classical and Lloyd methods are used to determine quantizer levels. The designed predictor should be coordinated with designed quantizer unit which is used to implement an optimum DPCM scheme. Finally, some simulations have been implemented to evaluate performance of different structures for DPCM system and to choose the best structure with least complexity and distortion. These simulations show the effectiveness of Designed scheme for ECG signal transmission.

***Key words**:* DPCM - Predictor - Quantizer - ECG Signal - MSE - Lloyd algorithm

1 Introduction

Electrocardiogram (ECG) is an objective sample of the electrical activity of heart, which is reflected in the form of electric potential changes on the surface of skin and can appear on the tape or oscilloscope monitor. Electrocardiogram is a complex signal and has been formed by a number of segments. Due to the amount of deviation of any segment out of its normal state, physicians can diagnose the effects which constraint normal activity of heart [1]. Thus it is necessary to have the signal of electrocardiogram for diagnosing heart diseases. Electrocardiogram is primarily analog signal, in this study; it would be digitized using the advantages of DPCM scheme. A broad spectrum of techniques for electrocardiogram (ECG) data compression has been proposed during the last three decades [2, 3, 4]. One of efficient methods for compression and transmission of ECG is DPCM method [2, 4]. However, the objective aim in representation of this work is to investigate how to use the advantages of DPCM system to transmit ECG signal and to utilize suitable methods for reducing the rate of error in transmitting ECG signal. In the structure of DPCM system, predictor and quantizer are fundamental units [5, 6, and 7], and their efficient design has a large effect on DPCM performance. This study provides this importance by employing the best structure for predictor and quantizer units that are coordinated with each other in DPCM system. Classical method and Lloyd algorithm have been employed for determining levels in quantizer unit, and Levinson-Durbin algorithm has been used for designing the optimum predictor [8]. DPCM uses a kind of differential encoding for reducing the number of transmission bits, which encodes the difference between signals and the predicted output values [6]. Therefore various parts of DPCM system have been designed in such a way that result of simulation would be in an optimum situation. In this work, programming in MATLAB environment has been used for all simulations. It should be mentioned that each complete period of ECG signal is formed approximately from 365 samples and the rate of sampling is 512 samples per second. In investigated periods, background noise effect into ECG signals has been observed. Among various IIR filters, for eliminating the background noise low-pass Butterworth filter, with 40 Hz cut-off frequency, has been selected since it provides a flat frequency response at pass-band region. In discussion of signal processing, the approach of designing filters and their functions on signal have been explained in detail in references [7, 8]. A typical period of noise free ECG signal ready to transmit through DPCM system has been shown in Fig.1.

2 Construction of DPCM System

Differential encoding techniques of DPCM are employed extensively in various fields such as sound, picture and speech processing. DPCM is a kind of closed-loop differential encoding that at its feed-back path there is a typical digital filter, called predictor. DPCM scheme uses a kind of differential encoding, instead of direct encoding, which encodes the difference between the signal itself and its predicted value. Fig.2 shows an overall structure of DPCM system where predictors are used at transmitter and receiver diagrams. A predictor is usually assembled at feed-back path and behaves as a linear prediction to estimate the magnitude of input sample at DPCM system.

At DPCM system, difference signal e_n, between input data sample x_n, and estimated data $\hat{x}_n$ is applied as input sample into quantizer unit, shown in Fig.2(a). Based on the error signal e_n , quantizer produces an equivalent integer binary number at its output y_n to transmit towards the receiver unit. The magnitude of error signal e_n, in comparison with x_n and $\hat{x}_n$ is very small thus the error signal e_n can be quantized with fewer number of binary bits and transmitter unit transmits fewer number of bits per data sample; and consequently, a considerable amount of raise at rate of data transmitting, can be achieved [5, 6]. But design of an optimal DPCM system for ECG signal handling with minimum reconstruction error needs to design optimal predictor and quantizer units that are coordinated together in DPCM structure to reach the best performance. The rest of the paper is focused on this problem and the best structure will be chosen based on the simulation results.

2.1 Design of Linear Predictor

Predicting output of a dynamic system, by observing previous values of output, has always been one of the important mathematical problems. Here, for sampled data signal, linear prediction algorithm has been used to design an optimum predictor [8, 9]. A typical, linear predictor is a low-pass discrete-time filter with finite impulse response (FIR). A designed linear predictor model produces estimated sample $\hat{x}_n$, as shown in Fig.2(a). In general, kth order linear predictor containing p coefficients, $p_1, p_2, ..., p_k$, and time delay, z^{-1} , between successive data samples are shown in Fig.3.

In general, predictor at feed-back path of DPCM system receives the sum of quantized error sample and its previous out-put data samples (see Fig.2). The output data sample of predictor is usually affected by quantized error sample. Therefore, additional error increasing would be expected at output data sample of predictor. The first step to reduce overall error at DPCM, is to design an optimum quantizer unit. This can be achieved with minimizing the quantization error for input error difference e_n . the quantization error will be discussed later in section 4.

Further reduction can be achieved by design of an optimum linear predictor; hence, mean square error (MSE) of prediction has to be minimized. MSE can be computed as follows:

$$E_p = E[(x(n) - \hat{x}(n))^2] = E[d(n)^2] \qquad (1)$$

And to minimize MSE, Wiener-Hopf equation can be obtained as follows

$$r = Ra \qquad (2)$$

$R_{p\times p}$ is correlation matrix, p is the order of the predictor, r is autocorrelation vector and $a = [a_1 \cdots a_p]$ is predictor coefficients vector which can be obtained by inverting Matrix R as follows :

$$a = R^{-1}r \qquad (3)$$

So design of optimal linear predictor includes following 3 steps:

1. Determine the order of the predictor, p
2. Estimate the correlation Matrix, $R_{p\times p}$ for input signal.
3. Solve equation (3)

according to equation (3) to obtain coefficients, a_k, it is inevitable to compute the inverse of the matrix R. R is a Toeplitz matrix, so we can efficiently use algorithms such as Levinson–Durbin to invert it. Levinson-Durbin algorithm computes recursively the prediction coefficients of order 1 to P and reduces error until the defined threshold value.

Steps of the algorithm are as fallows [5,6,8] :

1. $E_0 = r[0]$ ، $i = 0$
2. $i = i + 1$
3. $k_i = \frac{-1}{E_{i-1}}\left[\sum_{i=1}^{i-1} a_j^{i-1} r[i-j] + r[i]\right]$
4. $a_i^i = k_i$
5. For j = 1, 2,…, i-1
6. $a_j^i = a_j^{i-1} + k_i a_{i-j}^{i-1}$
6. end
7. $E_i = (1 - k_i^2)E_{i-1}$
8. if $i < p$ go to (2)
9. $[a_1 a_2 ... a_p] = [a_1^p a_2^p ... a_p^p]$

For defined ECG signal, MSE (Mean Square Error) should be as small as needed and the lowest possible order for the predictor must be chosen. The amount of MSE of prediction is computed for predictor orders p = 1 to p = 15, once for unfiltered ECG signal and once for ECG signal which has been passed through low-pass filter with 40Hz cut-off frequency, and obtained results are illustrated in Fig.4 and Fig.5, respectively. Fig.4 and Fig.5 shows that resulted MSE for unfiltered signal is approximately 6 times greater than resulted MSE for filtered signal. Thus filtering of signal, reduces the sharp signal variations resulted by noise, and leads to reduction of prediction error, and consequently reduction of predictor order. Finally, second order predictor is found to be optimum and lowest degree to process filtered ECG signal at DPCM system.

2.2 Investigation of Quantizer Unit

Quantizing process is carried out by converting continuous input signal to quantizer unit into numerous discrete quantities at output stage. In simulation of DPCM, two types of quantizers have been used. One kind of the quantizer is classical multi-level quantizer and the other is optimum quantizer based on L1oyd algorithm. In this study, one, two and three bit quantizers are used. In addition, canonical signed digit (SCD) encoding is also utilized [2]. To enable the quantization unit to perform correctly and to limit quantization error within acceptable boundary, in multi-level quantization, input of the quantizer must be located in a specific region by gain adjustment.

Increase in the number of quantizer bits and employing L1oyd method will improve quantizer performance. RMS criterion is used to analyze quantization error. Employing L1oyd algorithm can be effective in overall performance of DPCM system. In this algorithm initial quantization levels and spaces are determined and a successive process based on the PDF of input signal is performed on these quantizer parameters to reduce RMS error which finally concludes optimal levels and spaces with minimum RMS for quantizer unit. L1oyd algorithm in comparison with others provides some advantages, e.g. it doesn't need any gain adjustment to limit quantizer input in a specific boundary ,and its resulted RMS is less than others.

3 DPCM Design Techniques

In this section proposed method to design the optimal DPCM system is illustrated. Discussion on different approaches clarifies the characteristics of each concerned method and their influences on handling ECG signal by DPCM system. The following subsections explain the design techniques of DPCM system in detail.

3.1 DPCM with Classical Multilevel Quantizer

In this study, we have used one bit quantizer unit that based on the input sample, produces three-levels at output. Here, CSD encoding for each input sample is used to produce three levels, -1, 0, or +1 at the output of the quantizer.

The gain factor in Fig.2, is adjusted in such a way that error samples are limited within region of -1.5 and 1.5 , hence reconstructed signal would be in a desirable state. The reconstructed signal using 1 bit quantizer and 2 order predictor in Fig.6, is similar to the original signal in Fig.1, but it might not have enough precision. The RMS errors for DPCM system with 1 bit quantizer and 1, 2, 3 order predictors are given in Table 1. As shown in table 1 there is not enough decrease in RMS by increase at the order of predictor. To achieve an adequate precision CSD encoding for 2 bit quantizer with 7 levels, [-3 -2 -1 0 1 2 3] , is utilized.

Simulation results of DPCM with 2 bit quantizer for one, two and three order predictors are given in Table 1, that shows a considerable reduction in RMS error, compared with the results of 1 bit quantizer. By comparing original ECG signal in fig. 1 and reconstructed one in Fig. 7 it can be inducted that 2 bit quantizer with one order predictor results high distortion. Therefore, let us go back to Fig.5, in which MSE of prediction is plotted versus the orders of predictor. Fig.5 shows a sharp decrease in MSE error when the order of predictor rises from order one to two, and it shows a slight decrease when it rises to 3 or higher orders. In conclusion, optimum DPCM system could be designed by means of 2 order predictor and 2 bit quantizer. For verification, let us consider the results on original filtered ECG signal as illustrated in Fig.8 in which reconstructed signal is determined by ‘+’. The reconstructed ECG signal in Fig.8 is quite acceptable from research point of view, where there is not any distortion and lost information at output ECG signal.

Increasing the order of predictor will not have a significant effect on overall error. It could be inducted from RMS results of 2 bit quantizer in table 1. Results for 3 bit quantizer are also given in table 1, but these results don’t show a considerable improvement for 3 bit quantizer. Hence, the optimum and proper DPCM system with least complexity and cost point of view is one that consists of 2 bit quantizer with second order predictor.

3.2 DPCM Design Using L1oyd Method

Lloyd algorithm uses an iterative process to minimize the mean square quantization error in quantizer unit [10, 11]. L1oyds algorithm optimizes quantization parameters to reduce the overall system error. For given input samples of quantizer unit, both the levels and spaces of quantizer are optimally computed [9]. Simulation results of transmitting ECG signal using L1oyd method are shown in Fig.9. For 1, 2 and 3 bit quantizers, the RMS error variations are tabulated in Table 2. It shows that the best results are obtained by 3 bit quantizer. Then, 3 bit quantizer with 1 order predictor has been chosen to have the least complexity and RMS error.

In general, the resultant errors by L1oyd method, compared with errors in classical method given at Table 1, are very small and negligible. Hence, to handle ECG signal at DPCM scheme, L1oyd method is an optimum method to be applied at designing DPCM parameters.

4 Conclusion

In this work, advantages of DPCM systems are effectively used for transmitting and receiving of electrocardiogram (ECG). Three types of different approaches to realize an optimum DPCM system have been discussed in detail. Here, between classical methods which have been studied, the optimum DPCM system consists of 2 bit quantizer and 2-order predictor has the least complexity and the best performance. An alternative approach called L1oyd method has also been investigated. The resultant errors by L1oyd method, compared with RMS errors in classical method, are very small and negligible. Hence, to handle ECG signal at DPCM, L1oyd method with 3 bit quantizer and 1 order predictor, is the best structure for DPCM system.

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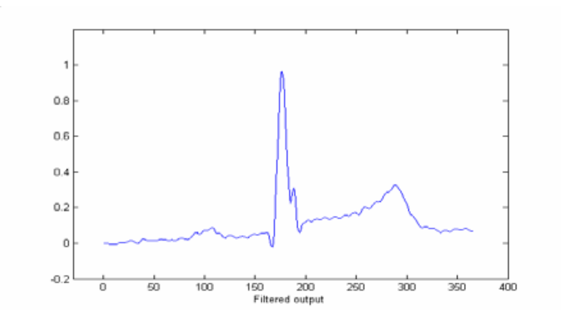

Fig.1: Original ECG signal, output of filter.

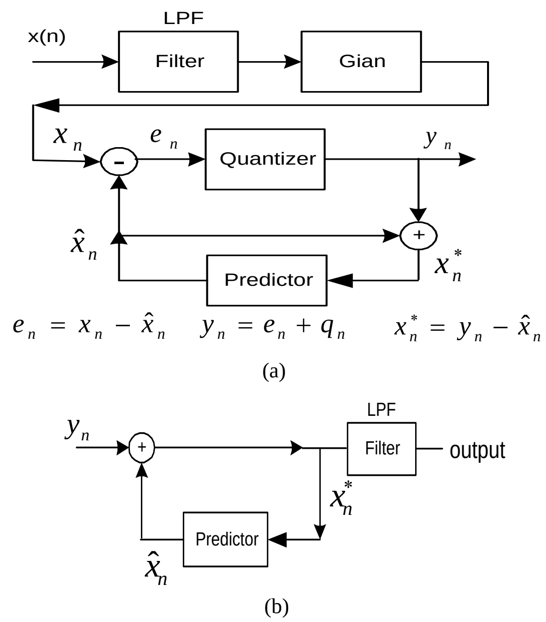

Fig.2: Complete DPCM structure, (a) Transmitter (b) Receiver.

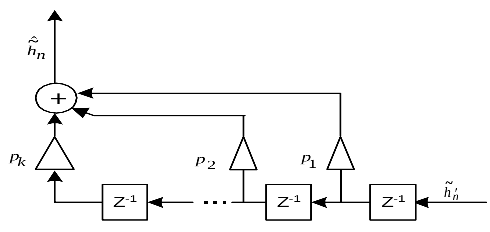

Fig.3: Typical kth order linear predictor.

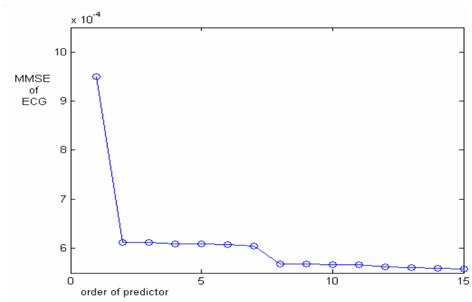

Fig.4: MSE versus prediction order for unfiltered ECG signal.

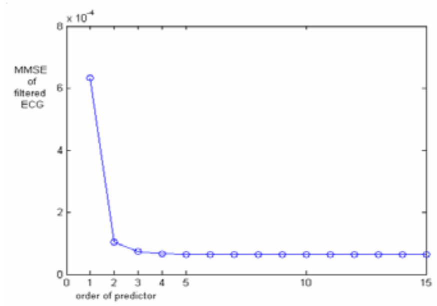

Fig.5: MSE versus predictor order for filtered ECG signal.

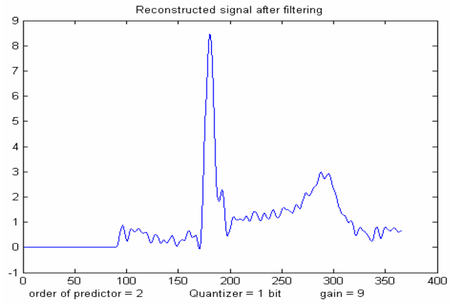

Fig.6: Reconstructed ECG signal using one bit quantizer and second order predictor.

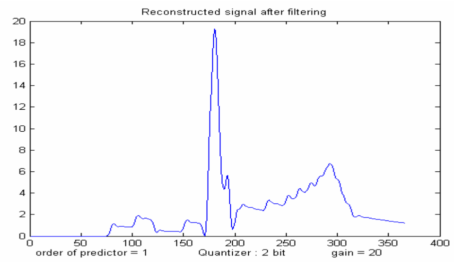

Fig.7: Reconstructed ECG signal using 2 bit quantizer and first order predictor.

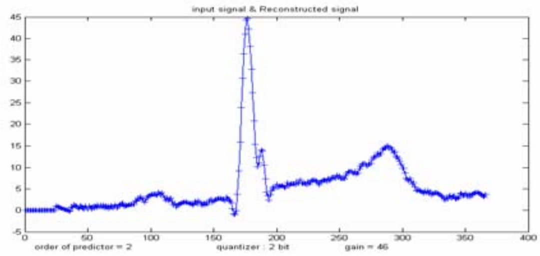

Fig.8: Comparison of reconstructed signal and input signal using 2 bit quantizer and second order predictor.

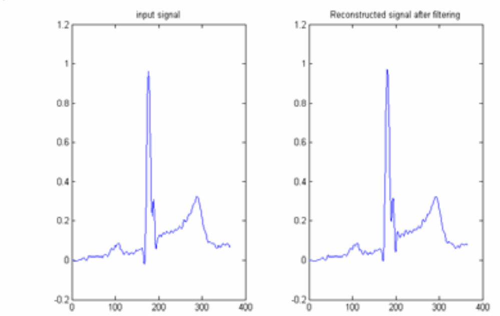

Fig.9: Comparison of original signal and reconstructed signal after filtering and using optimum L1oyd quantizer.

Table 1: Simulation results of DPCM system using normal quantizer

Quantizer unit	Gain (G)	Order of predictor	RMS error
one Bit quantizer	9	1	0.5532
	20	2	0.4680
	35	3	0.4550
two Bit quantizer	20	1	0.3315
	46	2	0.3051
	32	3	0.2832
three Bit quantizer	40	1	0.2916
	40	2	0.2792
	50	3	0.2810

Table 2: Simulation results of DPCM system using Lloyd quantizer

Quantizer unit	Order of predictor	RMS error
one Bit quantizer	1	0.11087
	2	0.1017
	3	0.1730
two Bit quantizer	1	0.0809
	2	0.0908
	3	0.2626
three Bit quantizer	1	0.0137
	2	0.0220
	3	0.0235