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Adaptive Predictive Coding speech coding techniques applied to electrocardiogram signals

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Abstract — **This paper describes a lossy ECG signal coder with an adaptive predictive coding scheme initially proposed for speech coders. The predictors include linear predictive coding that takes advantage of the correlation between consecutive samples and long-term predictor that takes advantage of the signal quasi-periodicity. The prediction residue, with less dynamic range and therefore able to be encoded with less bits than the original, is transmitted sample by sample. The prediction coefficients and the amplitude of the residue are transmitted once for each heartbeat, with a negligible number of bits compared to the total bit rate. The long-term predictor is shown to obtain reliable performance when the heart rate does not change rapidly. Linear predictive coding, on the contrary, is more reliable and presents better prediction gain. The best developed coder uses double prediction and with 45% compression ratio allows a prediction gain of 24.8 dB.**

Keywords: ECG, Speech, Adaptive Predictive Coding, Linear Prediction Coding, Long-Term Prediction, Signal to noise ratio.

I. Introduction

Signal coding is intended to decrease the signal representation binary rate. The main applications are to transmit or store signals using a low bit rate, which leads to the use of cheaper and lower power modems and less storage memory.

In addition to the traditional Electrocardiogram (ECG) medical applications, ECG signal applications [1-2] are increasingly emerging on devices such as smartwatches, sport watches or chest straps, not only to measure heart rate but also to check for fatigue, to predict heart failure, or authenticate the user. In an increasing number of applications, the ECG signal must be transmitted and stored to smartphones or to the cloud. ECG signals are also stored in hospital information systems (HIS), in the patient history. In all these cases, there is a need for transmission and storage, for which decreasing bit rate is an important contribution.

There are two main methods of signal coding: lossless and lossy methods [3]. Lossless methods obtain an exact reconstruction of the signal, but the compression ratio is low. Lossy methods can achieve bigger compression ratio but do not represent the exact original signal.

The main goal of lossy methods is to achieve high compression ratio without compromising the quality. For ECG signals, this corresponds to maintain the diagnostic capability of the original signal.

Speech signal coding has a history [4-10] of decades and is a very mature field. Depending on the applications and the tradeoff between compression ratio and quality requirements, it is possible to find standard coders with bit rates between 800 bit/s [8] and 64 kbit/s [9,10].

Adaptive Predictive Coding (APC) [11] is a low complex and high-quality speech coder that is a good compromise between quality and bit rate. The APC coder predicts the speech signal taking advantage of the almost periodic structure in voiced regions and the high correlation between adjacent samples. Only the prediction residue is transmitted sample by sample, reducing the bit rate.

Given that the ECG and speech signals have in common an almost periodic structure, the long-term predictor used in speech that takes advantage of this characteristic can be applied to ECG signals [12]. At the same time, a small variation in some parts of the ECG signal also reveals a correlation between consecutive samples, capable to predict one sample from the immediately previous (Linear Predictive Coding [13-14]), making it necessary to find out the best prediction order and the prediction capacity. The APC coder can be, therefore, an alternative solution to more traditional ECG coding methods [15-16].

This paper presents the development of an ECG signal lossy coder using the APC speech coder scheme. Section II characterizes the ECG signal. Section III presents the APC coder. Section IV presents the proposed method, including the database, the measures to assess the coders performance and the development method. Section V presents the results and discussion, including the optimization of each parameter and the all quantized coders for each type of predictor. Section VI finishes the paper with the conclusions and directions for future work.

II. ECG signal

ECG signals represent the electrical activity of the heart and are recorded by electrodes connected to the body. The signal has a quasi-periodic structure, being each period one heartbeat. The same quasi-periodic structure can be found in voiced regions (produced with vocal folds vibration) of speech

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signals. In each heartbeat it is possible to find 5 well-defined fiducial points, represented by the letters P, Q, R, S, T, as in Fig. 1. Analysis of the waveform between these points and the relative latency time and wave signal allows to evaluate the transients of the electrical stimulus from the auricles to the ventricles, analyse the cardiac rhythm (regular or arrhythmias), evaluate possible hypertrophy of the cardiac cavities and to evaluate signs of deficient irrigation of the heart, for example, in coronary heart disease or ischemic.

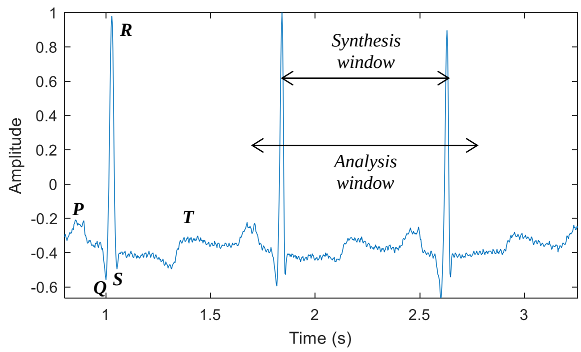

Fig. 1. ECG signal

Despite the assumption of quasi-periodic structure, ECG signals can have variability between consecutive periods, depending on the subject activity, which will change heart rate, as can be seen in Fig. 2, either with changes in amplitude, period and shape. Also, in case of heart diseases such as arrhythmias, the quasi-periodic structure is also called into question.

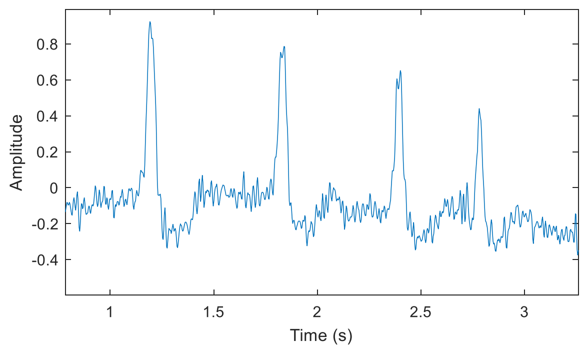

Fig. 2. Non-periodic ECG signal.

III. APC CODER

The adaptive predictive coding method [11], presented in Fig. 3, quantizes in Pulse Code Modulation (PCM) the prediction residue $r[n]$, defined as the difference between the input original signal $s[n]$ and a prediction $s_p[n]$ estimated from the last quantized samples $s_q[n]$. In the receiver, the quantized prediction residue $r_q[n]$ is added to the prediction to calculate the actual quantized sample. The better the predictor works, the lower the dynamic range of the prediction residue and the better the final quality of the quantized signal.

Taking advantage of the quasi-stationarity of the signals, the prediction coefficients must be estimated frame by frame and transmitted to the receiver. Typically, speech frames are 5 to 30 ms long.

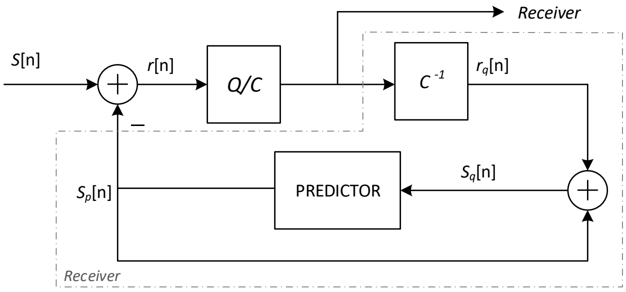

Fig. 3. APC transmitter. The receiver is embedded in the transmitter.

A. LPC prediction

Linear predictive coding (LPC) [13] takes advantage of the correlation between consecutive samples to predict one sample from a linear combination of past samples, as in equation (1), that translates the equation of a Finite Impulse Response (FIR) filter.

$$s_p[n] = -\sum_{k=1}^{p} a_k s_q[n-k]. \qquad (1)$$

The prediction coefficients, a_k, are estimated in order to minimize the prediction residue and have information about the spectral envelope.

B. Long-term prediction

For quasi-periodical signals, as the ECG and speech signals in voiced regions, one entire heartbeat period can be predicted by replication of the previous period. This predictor is known as long-term (LT) predictor as one sample is predicted with a delay of one heartbeat period T_P, equation (2), and not consecutive samples as in LPC prediction.

$$s_p[n] = a_p s_q[n - T_P], \qquad (2)$$

where a_p is the LT prediction coefficient.

To estimate the LT period, T_P, maximum autocorrelation or similar methods [17] are normally used in speech analysis. *QRS* detection [18] can also be used to estimate periodicity. Setting always the same initial point in the period is also desirable. Align the *R* peaks can be done with an adaptive threshold comparison and absolute maximum detection.

To accommodate period change, the LT period, T_P, must be interpolated/decimated sample by sample in order to time warp the previous period to have the same length as the period to predict. As can be seen in Fig. 4, where 12 consecutive heartbeat periods are interpolated to have the same duration, this procedure aligns the *PQRST* points to improve the prediction.

The LT prediction coefficient, a_p is estimated in order to minimize the prediction error and corresponds to the normalized correlation with delay T_P, between the periods to predict and the interpolated/decimated previous period,

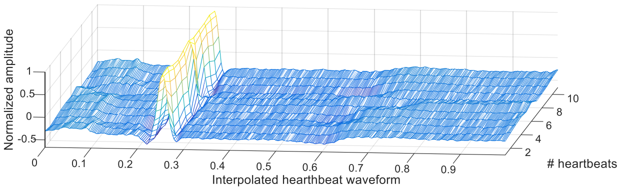

Fig. 4. Interpolated heartbeats.

$$a_p = \frac{R[n-T_P]}{E}, \quad (3)$$

on what $R[n - T_P]$ is the autocorrelation with delay T_P and E is the energy of the interpolated/decimated previous period.

C. Double prediction

The LPC residue has the same periodicity as the original signal. Therefore, the LT predictor can be applied to this residue, resulting in a double predictor, minimizing even more the dynamic range of the double prediction residue and increasing the quality. Fig. 5 shows the complete block diagram of the APC encoder with double prediction.

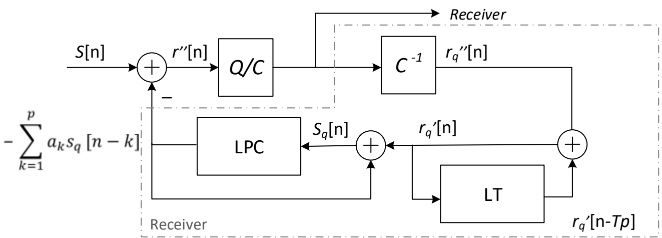

Fig. 5. APC with double prediction (LPC+LT).

IV. Proposed Method

This Section presents the proposed method, including the database, the measures to assess the coders performance and the development method.

A. Database

The Massachusetts Institute of Technology (MIT) and the Boston's Beth Israel Hospital (now the Beth Israel Deaconess Medical Center) developed an ECG database, the MIT-BIH Arrhythmia Database [19], that contains 48 half-hour excerpts of two-channel ambulatory ECG recordings, obtained from 47 subjects studied by the BIH Arrhythmia Laboratory. This database is available since 1980 and is one of the reference databases in the field. The signals are sampled at 360 Hz and stored in PCM with 11 bits per sample.

From this database, a set of 19 signals are chosen, of which 10 seconds are extracted to develop and test the ECG coder. All the signals are normalized in amplitude. Only integer periods from the second heartbeat period are considered to the quality measure, as the first period cannot be predicted with LT predictors. These correspond to an average of 8.2 seconds and 10.2 heartbeat periods per signal, in a total of 155.5 seconds and 193 heartbeat periods. The average heart rate is 74 heartbeats per minute.

B. Quality assessment

To assess the quality of the coder, the signal to noise ratio, (*SNR*) given by the ratio of a reference or original signal power P to the noise power N, in decibels as in equation (4), is used,

$$SNR_{dB} = 10log_{10}\left(\frac{P}{N}\right). \quad (4)$$

In coders assessment, the noise takes origin in samples and parameters quantization, and the *SNR* is denominated as quantization *SNR*.

In this study, the quantization noise is the difference between the 11-bit PCM signal, taken as the reference, and the output of the coder. The quantization *SNR* average between the 19 signals of the database is estimated for each coder and is assumed to be the quantization *SNR* of that coder.

For the APC coder, the increase in the signal to noise ratio in relation to the PCM direct coding or reference coder, denominated the prediction gain, is,

$$G_{pdB} = 10log_{10}\left(\frac{V^2}{V_1^2}\right), \quad (5)$$

where V is the maximum quantization value in PCM (reference coder) and V_1 is the maximum quantization value in APC. The better the predictor, the lower the maximum quantization value and the greater the prediction gain.

C. Development method

Taking advantage of the quasi-stationarity of the signals, LPC can be transmitted frame by frame. The length of the synthesis window (frame length) is chosen to be a heartbeat period between R peaks (Fig. 1), resulting in a variable bit rate coder. The analysis window to estimate the LPC coefficients is extended in one third.

The quantization of the prediction residue consumes most of the quantization bits, since this signal is transmitted sample by sample and not by heartbeat period, practically defining the final bit rate. The number of bits to quantize the prediction residue is fixed and a PCM coder (equivalent to an APC coder without prediction) is assessed and taken as a coder reference.

With the same bits per sample to quantize the prediction residue of the reference coder, but without any further quantization, each predictor (LT, LPC and LT+LPC double predictor) is evaluated and adjusted based on the prediction gain, defined as the *SNR* difference in relation to the reference coder.

After adjusting the predictors, each quantizer is trained to minimize the quantization error and the number of bits to quantize the predictor parameters (prediction residue amplitude, LT coefficient and LPC coefficients) are tune individually, based in the *SNR* loss.

To train each quantizer [20], 10 ECG signals are used, with no quantization of any parameter beyond the prediction error. The quantizers are trained from the corresponding non quantized values distributions. The remaining 9 signals are used to test if the trained quantizer is generalizing.

V. Results and Discussion

This section follows the development method from section IV, starting by to define the reference coder, with which all results will be compared, and all the parameters optimized. Then the best LPC order is found, followed by the individual optimization of the quantizers. This section ends with the presentation and discussion of the complete coder.

A. Reference coder

A PCM coder with 6 bits per sample was taken as a reference, corresponding to 2160 bit/s, a 45% reduction in relation to the 11-bit original PCM coder. To define a reference in terms of quality, the 19 signals from the database were re-quantized in PCM, corresponding to the removal of the two predictors. The average quantization *SNR* obtained in the 19 ECG signals of the database is 30.9 dB. For each additional quantization bit, a gain of 6.02 dB is obtained, but the bit rate also increases in 360 bit/s.

B. Heartbeat period estimation and quantization

The alignment of the *R* peaks is achieved with an adaptive threshold comparison of 0.3 and absolute maximum detection. The heartbeat period, T_P, is estimated from the time between consecutive *R* peaks.

A minimum heart rate of 30 beats per minute and a maximum of 232 beats per minute are assumed. At a sample rate of 360 Hz, this corresponds to 720 to 93 samples per heartbeat. The range of values is 720-93 = 627, requiring 10 code bits for each heartbeat, assuming that the heartbeat period is a multiple of the sampling period and does not suffer from additional quantization error.

The maximum bit rate added due to this parameter is 39 bit/s for a heart rate of 232 heartbeats per minute.

On average, for the 19 signals, the heart rate is 74 heartbeats per minute, corresponding to 1.24 bit/s for each coding bit per heartbeat period. Using 10 bits to code each heartbeat, 12.4 bit/s are added.

The LT prediction coefficient, a_p, and LPC prediction coefficients, a_k, are estimated per heartbeat. The maximum quantization value, V_1, which depends on the prediction gain, G_p, is also estimated per heartbeat and transmitted to the receiver. This value cannot be constant, as a value that is too low implies a slope overload and a value that is too high implies a decrease in the prediction gain.

C. LPC order

Typically, order 10 is used in speech coders, a good tradeoff between spectral envelope definition and bit rate, as these coefficients must be transmitted to the receiver. One question to be answered when using ECG signals is which order of prediction to use, assuming this tradeoff.

Table I presents the prediction gain compared to the reference coder (30.9 dB), for different orders of the LPC predictor, without quantization of the coefficients. The covariance method [13] to estimate the LPC coefficients is chosen since it can achieve better results than the more traditional autocorrelation method.

The order 3 of the LPC is chosen since the prediction gain increases considerably up to that order. From that order, the increase in the order of the LPC only slightly increases the *SNR* but increases the complexity and the bit rate.

Table I
Prediction gain with different LPC orders

LPC order	*SNR* [dB]	*Gp* [dB]
1	42.6	11.7
2	50.1	19.2
3	53.2	22.3
4	53.7	22.8
5	53.7	22.8
10	54.0	**23.1**

D. Prediction residue quantization

As the prediction coefficients are transmitted per heartbeat period, prediction residue quantization bits correspond to most of the transmitted bits. Table II presents the *SNR* for the different predictors (LT, 3rd order LPC and LT+LPC), where no parameters are quantized beyond the prediction residue.

For LT single prediction, as presented in Fig. 6, the prediction coefficient distribution is located around 1, indicating that consecutive periods have high similarity. Using a constant coefficient $a_p = 1$, the *SNR* even increases 0.4 dB, so this value is adopted as it does not need to be transmitted to the receiver.

Table II
SNR for 6-bit Quantizers

	PCM	LT	LT a_p=1	LPC	LT+LPC	LT+LPC a_p=0.6
SNR [dB]	30.9	43.2	43.6	53.2	55.8	**55.8**

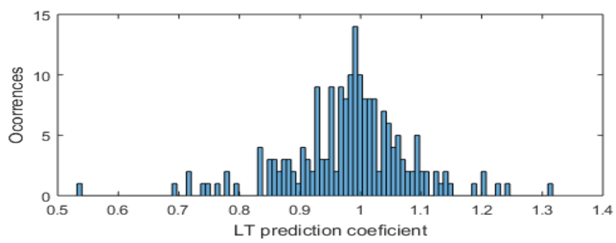

Fig. 6. Prediction values distribution for LT single prediction.

For the double prediction, as presented in Fig. 7, the prediction coefficient distribution is not located around a value. Using a constant value of 0.6, as presented in Table II, the *SNR* is the same, so this value is adopted as it does not need to be transmitted to the receiver. The best *SNR* with only the quantization of the prediction residue is achieved with LT+LPC double prediction, obtains 55.8 dB, a prediction gain of 25 dB than the reference coder.

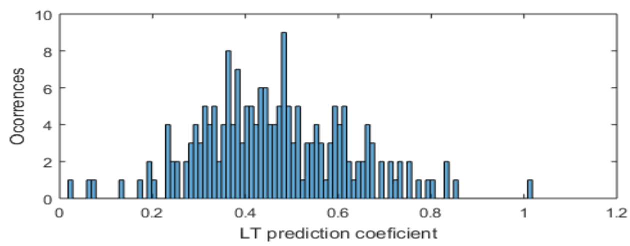

Fig. 7. LT prediction coefficient distribution for double prediction.

E. Prediction residue amplitude quantization

The maximum quantization value, V_1, is an important parameter to be set. Too high implies a decrease in the *SNR*, and too low implies slope overload. To solve this problem, the maximum quantization value is estimated and transmitted per heartbeat period.

Fig. 8, 9 and 10 presents the maximum quantization value distributions for LT single prediction, LT+LPC double prediction and LPC prediction, respectively. As it can be seen, values from LT single prediction are higher than for LPC prediction and the lowest are from LT+LPC double prediction, in line with the increase in the *SNR*.

Table III presents the quantization loss when using different number of bits to code the prediction residue amplitude, compared to results from Table II.

TABLE III
SNR QUANTIZATION LOSS FOR *V*1 QUANTIZATION

# of bits	5	6	7
LT SNR loss [dB]	0.4	**0.1**	0.1
LPC SNR loss [dB]	1.6	0.3	**0.1**
LT+LPC SNR loss [dB]	1.1	0.5	**0.1**

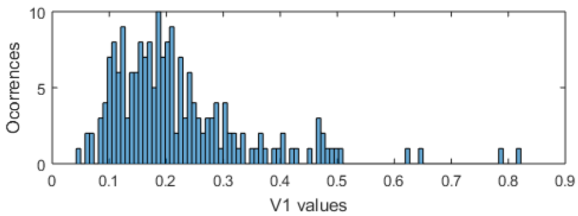

Fig. 8. V1 distribution for LT single prediction.

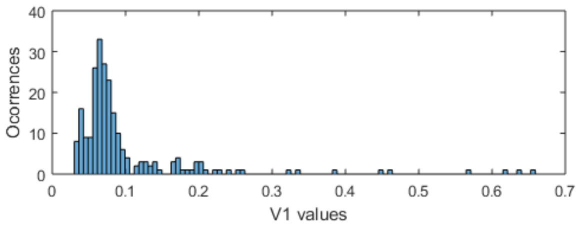

Fig. 9. V1 distribution for LPC prediction.

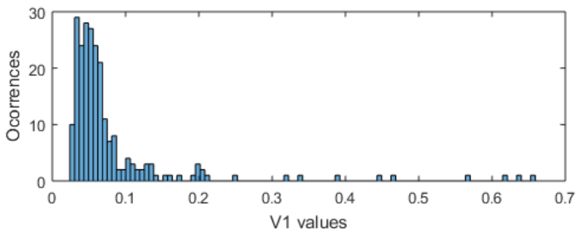

Fig. 10. V1 distribution for LT+LPC double prediction.

To code the prediction residue amplitude, considering the tradeoff between quality and bit rate, 7 bits are chosen, as it corresponds to only 0.1 dB of *SNR* loss. This corresponds to 8.7 bit/s at an average heart rate of 74 heartbeats per minute.

F. LPC coefficients quantization

The direct transmission of the LPC coefficients is not recommended as the quantization error can change significantly the spectral envelope or turn the filter instable. To solve this problem, the use of a Line Spectrum Pair (LSP) transformation [21], widely used in speech coders [4][6-7][22], guarantees the stability and minimizes the sensitivity of the filter.

After the LSP transformation, the LSP parameters must be quantized. LSP values are in ascending order and between 0 and 0.5 (0.5 corresponds to $\pi/2$ radians or half of the sample frequency). The stability of the filter is guaranteed by imposing that the LSP coefficients maintain the ascending order after quantization.

Since the LSP parameters are not uniformly distributed, as presented in Fig. 11, 12 and 13 for order 3, respectively for the first, second and third coefficients, the quantizers for each coefficient must be trained to minimize the quantization error.

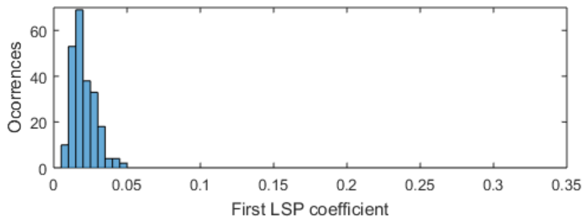

Fig. 11. First LSP coefficient distribution

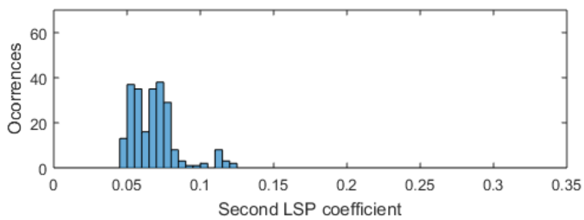

Fig. 12. Second LSP coefficient distribution

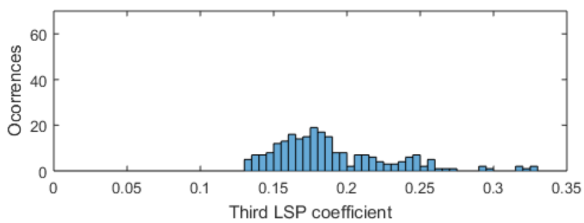

Fig. 13. Third LSP coefficient distribution

Table IV shows the *SNR* loss using 3 bits per coefficient. The degradation in the entire database is 0.1 dB for LPC prediction and LT+LPC double prediction. These values are used in the final coder corresponding to 11.1 bit/s.

TABLE IV
SNR QUANTIZATION LOSS FOR LSP QUANTIZATION

	Training set	Test set	Entire database
LPC SNR loss [dB]	0.06	0.15	0.11
LT+LPC SNR loss [dB]	0.13	0.02	0.08

G. Full quantized coders

Table V presents the bit rate distribution for each quantized parameter. It is considered an average heart rate of 74 heartbeats per second.

TABLE V
FINAL BITS ASSIGNMENT

Parameter	[bit]	*bit rate* [bit/s]
Prediction residue	6	2160
Heartbeat period	10	12.4
Prediction residue amplitude	7	8.7
LPC/LSP (3+3+3)	9	11.1
Total		2192

Table VI presents the quantized *SNR*, the prediction gain, the bit rate and the compression ratio for the full quantized coders, in the 19 ECG signals from the database.

TABLE VI
FINAL RESULTS

	SNR [dB]	*Prediction* Gain [dB]	*mean bit rate* [bit/s]	*Compression ratio* [%]
PCM	30.9	----	**2160**	45.5
LT	43.5	12.6	2181	44.9
LPC	53.0	22.1	2192	**44.6**
LT+LPC	**55.7**	**24.8**	2192	**44.6**

Comparing the results from Table VI and Table II, the *SNR* quantization loss due to quantization is 0.1, 0.2 and 0.1 dB, respectively to the LT, LPC and LT+LPC quantizer.

The LT+LPC double predictor presents a prediction gain of only 2.7 dB compared to the LPC predictor. This is because the first predictor, the LPC, decorrelates is residue and, when there is physical activity of the subject, the heart rate is constantly altered and the assumption of the periodicity of the signal is no longer valid. The latter reason also applies for the LT single predictor, where the prediction gain is also lower, 12.6 dB, compared to the LPC predictor, with 22.1 dB prediction gain.

As already pointed out, the main origin of the bit rate is the coding of the prediction residue, transmitted sample by sample. The other parameters, transmitted by heartbeat period, correspond to only 32 bit/s out of 2192 bit/s total bit rate. The difference between the compression ratio with the different predictors is less than 1%, with a compression ratio of about 45%.

VI. CONCLUSIONS

This paper describes an ECG signal lossy coder with an adaptive predictive coding scheme initially proposed for speech coders.

It was concluded that the LT predictor is the worst predictor with a gain of only 12.6 dB, due to variations in heart rate that occur during physical activity. After the LPC predictor, the LT predictor even has a lower gain of only 2.7 dB.

The variation in the cardiac rhythm and the 5 distinct parts of the heartbeat explains the low third order of the LPC predictor for the ECG signal, comparing with the order 10 for speech signals.

The quantization loss is less than 0.2% for all the predictors, a value negligible in the final *SNR*.

As expected, the best predictor is the LT+LPC double predictor with a prediction gain of 24.8 dB, a total of 55.7 dB and a compression ratio of 44.6%. Since for each bit per sample in PCM a gain of 6.02 dB is obtained, 4 bits are needed to have the same quality just re-quantizing in PCM, but this procedure corresponds to 66% increase in the bitrate and a compression ratio of only 9%.

The ECG signal can be divided into two zones. One corresponds to the signal points belonging to the QRS complex. The other corresponds to the points between peak S of a complex and next peak Q. As a future work, it is suggested to implement the division of the LPC in these two zones, as it can significantly improve the quality of the coding.

One of the reasons that the LT predictor does not produce a high-quality gain is because the cardiac cycle period does not coincide with a multiple of the sampling period. It is suggested to solve this problem through fractional pitch techniques already used in speech signal coding.

In addition, further testing will be performed with ECG acquired using less intrusive settings, as off-the-person approaches, where ECG is acquired while the user is interacting only with the hands with an ECG sensing device.

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