Asynchronous ECG Time Sampling: Saving Bits with Golomb-Rice Encoding

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Abstract

We present a technique for online compression of ECG signals using the Golomb-Rice encoding algorithm. This is facilitated by a novel time encoding asynchronous analog-to-digital converter targeted for low-power, implantable, long-term bio-medical sensing applications. In contrast to capturing the actual signal (voltage) values the asynchronous time encoder captures and encodes the time information at which predefined changes occur in the signal thereby minimizing the sensor's energy use and the number of bits we store to represent the information by not capturing unnecessary samples. The time encoder transforms the ECG signal data to pure time information that has a geometric distribution such that the Golomb-Rice encoding algorithm can be used to further compress the data. An overall online compression rate of about 6 times is achievable without the usual computations associated with most compression methods.

1. Introduction

Continuous long-term bio-electrical signal acquisition devices have high energy and memory requirements, to capture and store data for a long period. To reduce both, memory and energy requirements, and in turn the device volume, we present as a solution an asynchronous time-encoder with a built-in differential Golomb-Rice encoder. The asynchronous time encoder captures and encodes the times when preset signal changes occur, as opposed to either constant Nyquist-rate or asynchronous and adaptive signal amplitude sampling [1, 2]. The asynchronous sampling scheme reduces the energy-times-memory product by signal-activity dependent sampling. To ensure maximum energy efficiency there is need to only capture the minimum number of samples necessary to reconstruct our data. This requires taking into consideration the nature of our signals when designing Analog to Digital Converters (ADCs) for these applications. The solution presented herein is designed for implantable esophageal ECG sig-

nal recording, however the same technique can be applied to surface ECG signals [3, 4]. A surface ECG signal of the cardiac cycle consists of a P wave (arterial signal), a QRS complex (ventricular signal), a T wave, and a U wave, which is not always visible on surface ECG signals. The highest rates of signal changes occur during the QRS complex for surface ECG signals and during the arterial and ventricular complex for esophageal ECG signals [4]. The Figure 1 shows the sections in a typical surface ECG signal with the most visible features (U wave left out). Figure
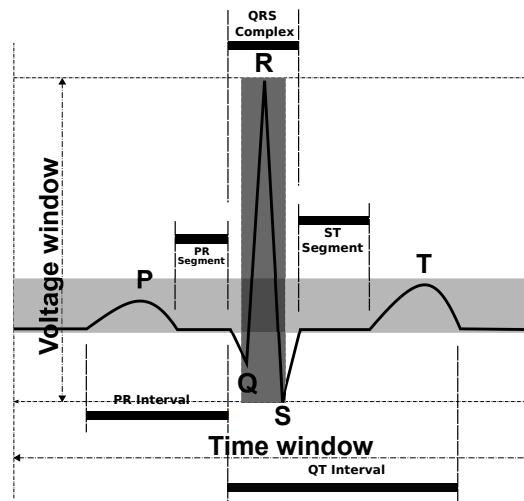

Figure 1. Typical surface ECG signal heart beat.

1 shows that most of the signal activity is during the QRS complex (highlighted in dark gray) the P and T wave sections occupy a small portion of the voltage window (highlighted in light gray); however the QRS complex occurs over a much shorter time period than the P and T waves. This means that most of our signal dependent time encoding (sampling) will occur during the short duration of the QRS complex. Since the data is composed of time information these time values will be small numbers. This phenomenon means that the Golomb-Rice encoder can then be used to compress the time information. The combination

of the asynchronous time encoder and the Golomb-Rice encoder takes advantage of the fact that more than 75% of our data is composed of small time values that can then be compressed by Golomb-Rice encoding [5].

2.   Asynchronous time encoding

The main role of the time encoder in the technique being presented is to asynchronously transform our signal into time information. The principle of operation of the time encoder is to capture the changes in time ΔT it takes for the signal to make a predefined change ΔV. The ΔV is a flexible design parameter that controls the level of detail with which we acquire our signal. The amount of data to be stored depends on ΔV (threshold voltage) , the timer resolution and the Golomb-Rice encoding codes used. The timer resolution should be optimally set to ensure that no signal thresholds are crossed while the counter has a count of zero, and also that the resolution is not unnecessarily too high. The timer resolution is therefore a function of the derivative of the highest frequency component required to be present in the signal of interest and the predefined signal change ΔV required.

$$T_{\mathrm{res}} = \frac{\Delta V}{(\frac{d}{dt}(A.\sin(2\pi f_{\mathrm{max}}t)))_{\mathrm{max}}}, \qquad (1)$$

where T_{res} is the time resolution in seconds, ΔV is the required voltage resolution, f_{max} is the maximum frequency component in the signal and A is the signal's amplitude. As a working guide Equation 1 gives the relationship of the system parameters to the timer setting. The setting of the ΔV variable is straight forward from a qualitative point of view as it depends on the features that are required to be captured by the time encoder. Combined together the time resolution (T_{res}) and the threshold voltage (ΔV) controls the signal to noise ratio (SNR) of the signal acquisition system. Equation 2 shows the relationship of the SNR to ΔV and ΔT.

$$SNR_{\mathrm{dB}} = 20\log\left(\frac{V_{\mathrm{in}}}{(T_{\mathrm{res}} \times \frac{dV_{\mathrm{in}}}{dt}) + (\Delta V)}\right) + 10\log 3, \qquad (2)$$

where V_{in} is the input signal. From the equation 2 it is clear that the higher the input bandwidth the higher the timer resolution required to maintain a certain level of SNR. The system variables T_{res} and ΔV are very important and must be chosen with care to ensure acceptable signal quality and also guarantee low power operation by avoiding oversampling (ΔV) and overclocking (T_{res}).

As a general rule the threshold voltage ΔV variable must be above the noise floor of the signal to ensure that we do not waste energy and memory by storing samples generated by the noise in the signal. The noise floor depends

on the signal input amplifier stage's performance (not part of the time encoder). The first phase of data compression
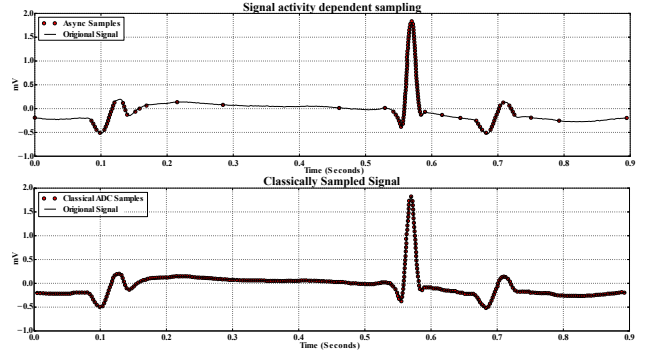

Figure 2.   Asynchronous sampling versus Synchronous sampling.

is achieved by signal dependent sampling of the time encoder, which by the nature of its operation compresses the signal in the low signal activity portions of the signal. Figure 2 shows an esophageal ECG signal heart beat sampled by the time encoder and by a classical Nyquist ADC with the dots being the sampling points. From Figure 2 it can be seen that the time encoder generates no samples during portions of low signal activity. The time encoder however generates bursts of closely spaced samples (on the time axis) during the P and T waves and QRS complex.

The time converter converts the input signal into three types of data values which are increasing signal threshold crossing (voltage changes of ΔV in the signal) time values, decreasing signal threshold crossing time values, and a timer overflow indicator, in the case where there is no signal activity. In the case of increasing and decreasing threshold crossing events, the timer value when these events occur is captured and encoded appropriately. In the case that the timer overflows before a signal increase or decrease event occurs, only a flag of the overflow event is recorded for time keeping purposes.

3.   Golomb-Rice encoding

Golomb coding is a loss-less data compression method using a family of data compression codes invented by Solomon W. Golomb [5]. Rice codes are a class of Golomb codes in which the adjustable parameter is a power of two. This makes Rice codes simpler to implement in hardware, since multiplication and division by two can be implemented in binary arithmetic (shift operations) [6]. Data sequences following a geometric distribution in which small values are more likely than large ones will be optimally encoded by Golomb-Rice encoding [5]. Thus Golomb-Rice coding is highly suitable for time data where the occurrence of small time values is significantly more likely

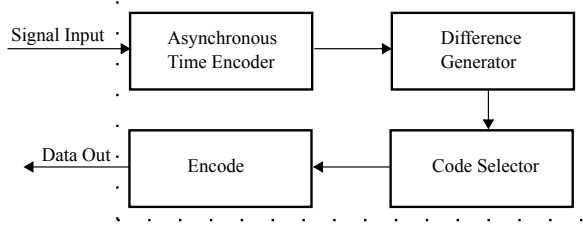than large time values. The asynchronous time encoder

Figure 3. Signal acquisition system.

enforces the Golomb-Rice encoding requirements on the data sequences. This is done by transforming our input signal into time information. The input signal's nature ensures that more than 75% of the data is made up of small time change numbers generated during the rapid signal change portions (PQRS sections) of the esophageal and surface ECG signals. This is due to the fact the encoder captures timer values when the signal makes a predefined change (ΔV) and restarts the timer guaranteeing that small timer values are significantly more likely than large values during portions when rapid signal changes occur, which is where most of the data is also generated.

Figure 3 shows the general layout of the data acquisition system. The system is composed of the asynchronous time encoder, which transforms our analog signal into time information. The difference generator block is a simple subtract operator that calculates an absolute difference between consecutive samples, thus ensuring that we will not have many consecutive large time values and also ensures that we have zero values on constant gradient slopes (QRS complexes) for maximum Golomb-Rice compression. The Encode block differs from that found in a classical Golomb-Rice encoder because it also performs bit stuffing for the identification of segments of high time values that are not encoded. In the example shown in Table

Encoded Time	Difference	Golomb-Rice Output
0000000011	11	101
0000000011	0	00
0000000011	0	00
0000000011	0	00
0000000010	1	01
0000000011	1	11
0000000010	1	01
0000000010	0	00
0000000011	1	11

Table 1. Partial QRS complex slope data sequence.

1, the Golomb-Rice encoder operates by changing all bits after the first bit into coded ones and uses a zero for demarcation between the first bit and the subsequent bits. Table 1 shows a partial bit sequence of a QRS complex slope during a heart beat. The asynchronous operation of the time

encoder ensures that more than 75% of the data generated during the heart beat can be compressed as shown in the table. Golomb-Rice encoding is inefficient for large values of time thus our encoder block is able to decide whether to encode an incoming difference or not. To avoid degrading the compression ratio during low signal activity intervals which are characterized by very few samples with relatively large time values between them, the encoding block does not encode them but inserts identifier sequences in the bit sequence. Since they are a few samples over long time intervals means that they are already compressed by the time encoder and should bypass the encoding block.

4. Results

We have developed a model of our time encoder incorporating a Golomb-Rice encoder and carried out simulations on esophageal ECG signals (INSEL-EECG) collected from our clinical trials as well as surface ECG signals from the MIT-BIH arrhythmia database (MITBIH-ECG) (records 100 to 124) [7]. We also developed a custom reconstruction and decoding algorithm for our irregularly acquired time encoded data. The performance results of the encoder where measured by comparing the original classically sampled signals with the reconstructed output of the encoder and the results are presented in Table 2. The MITBIH column shows the bit rate characteristics

Parameter	MITBIH-ECG	INSEL-EECG	TECG/TEECG
Data (Bits/s)	3300	6000	1800-2200
G-RE (Bits/s)	NA	NA	600-980
PRD	NA	NA	4%

Table 2. Performance comparison table.

of the MIT-BIH database signals used. The INSEL-EECG column shows the bit rate characteristics of the esophageal ECG signals in our INSEL-EECG database signals. The TECG/TEECG column shows the results of the time encoder of surface ECG signals and esophageal ECG signals. The G-RE row shows the Golomb-Rice encoded output bit count, this row is marked NA for the classically sampled data from the two signal databases used since the bit sequences does not yield any compression in its original form. The percent-root-mean-square-difference (PRD) degradation is due to time approximation of the signals and application of the ΔV threshold by the asynchronous time encoder as it transformed classically sampled signals into time information during the simulation and not from the Golomb-Rice encoding which is loss-less [8]. The proposed solution offers signal activity dependent data acquisition and non-computationally intensive loss-less time data compression. These combined attributes minimize the system's energy and memory requirements.

5. Conclusion

The combination of the asynchronous time encoding analog-to-digital converter and the Golomb-Rice encoder achieves an overall compression of about 6 times on esophageal and surface ECG signals compared to the classical Nyquist ADC architectures and needs no intensive computations for this compressed data acquisition. Our novel approach has also be evaluated with signals acquired during episodes of different arrhythmias without performance degradation. We eliminate the inefficiency of the Golomb-Rice encoding technique for relatively large time values by incorporating a difference operation, which was also suggested in [6]; this further reduces the time values since the signal's nature ensures that time values encoded with large and small numbers occur in different sections of the signal. We also considered the large time values to be already compressed by the asynchronous time converter and thus they bypassed the Golomb-Rice encoder. However, the performance of this solution is degraded in the situation where a signal has excessive baseline wander which is common in esophageal ECG signals. The degradation occurs at the time encoding stage due to the capturing of samples triggered by the baseline wander. We are going on with research to find a solution to deal with this degradation.

References

[1] Sayiner HS, Viswanathan T. A level-crossing sampling scheme for A/D conversion. IEEE Transactions on Circuits and Systems II 1996;43:335–339.

[2] Tsividis YP. Event-Driven Data Acquisition and Digital Signal Processing - A Tutorial. IEEE Trans on Circuits and Systems 2010;57-II(8):577–581.

[3] Niederhauser T, Marisa T, Haeberlin A, Goette J, Vogel R. High Resolution Esophageal Long-Term ECG Recorder. Biomedizinische TechnikBiomedical Engineering September 2011;vol. 56.

[4] Haeberlin A, Niederhauser T, Marisa T, Goette J, Jacomet M, Tanner H, Fuhrer J, Vogel R. First validation of esophageal long-term electrocardiography as an alternative technique for long-term heart rhythm monitoring, 2011.

[5] Golomb SW. Run-length encodings. IEEE Transactions on Information Theory September 1966;12:399–401.

[6] Rice RF, Plaunt JR. Adaptive variable-length coding for efficient compression of spacecraft television data. IEEE Trans Commun December 1971;COM-19:889–897.

[7] Goldberger AL, Amaral LAN, Glass L, Hausdorff JM, Ivanov PC, Mark RG, Mietus JE, Moody GB, Peng CK, Stanley HE. PhysioBank, PhysioToolkit, and PhysioNet: Components of a new research resource for complex physiologic signals. Circulation 2000 (June 13);101(23):e215–e220. Circulation Electronic Pages: http://circ.ahajournals.org/cgi/content/full/101/23/e215 PMID:1085218; doi: 10.1161/01.CIR.101.23.e215.

[8] Armstrong JS, Collopy F. Error measures for generalizing about forecasting methods: Empirical comparisons. International Journal of Forecasting 1992;8(1):69–80.

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