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 signal 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 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 \( \Delta T \) it takes for the signal to make a predefined change \( \Delta V \). The \( \Delta V \) 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 \( \Delta V \) (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 \( \Delta V \) required.

\[
T_{\text{res}} = \frac{\Delta V}{\left( \frac{\text{d}}{\text{dt}} (A \sin(2\pi f_{\text{max}} t)) \right)_{\text{max}}}, \tag{1}
\]

where \( T_{\text{res}} \) is the time resolution in seconds, \( \Delta V \) is the required voltage resolution, \( f_{\text{max}} \) 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 \( \Delta V \) variable is straightforward 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 \( (T_{\text{res}}) \) and the threshold voltage \( (\Delta V) \) controls the signal to noise ratio (SNR) of the signal acquisition system. Equation 2 shows the relationship of the SNR to \( \Delta V \) and \( T_{\text{res}} \).

\[
SNR_{\text{dB}} = 20 \log \left( \frac{V_{\text{in}}}{T_{\text{res}} \times \frac{\text{d}V_{\text{in}}}{\text{dt}} + (\Delta V)} \right) + 10 \log 3, \tag{2}
\]

where \( V_{\text{in}} \) 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 \( T_{\text{res}} \) and \( \Delta V \) are very important and must be chosen with care to ensure acceptable signal quality and also guarantee low power operation by avoiding oversampling \( (\Delta V) \) and overclocking \( (T_{\text{res}}) \).

As a general rule the threshold voltage \( \Delta V \) 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 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 \( \Delta V \) 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

![Signal acquisition system.](image)

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 en-
sures 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 ($\Delta V$) 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 acquisi-
tion system. The system is composed of the asynchronous
time encoder, which transforms our analog signal into time
information. The difference generator block is a sim-
ple subtract operator that calculates an absolute difference
between consecutive samples, thus ensuring that we will
not have many consecutive large time values and also en-
sures that we have zero values on constant gradient slopes
(QRS complexes) for maximum Golomb-Rice compres-
sion. The Encode block differs from that found in a clas-
sical Golomb-Rice encoder because it also performs bit
stuffing for the identification of segments of high time val-
ues that are not encoded. In the example shown in Table

<table>
<thead>
<tr>
<th>Encoded Time</th>
<th>Difference</th>
<th>Golomb-Rice Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>000000011</td>
<td>11</td>
<td>101</td>
</tr>
<tr>
<td>000000011</td>
<td>0</td>
<td>00</td>
</tr>
<tr>
<td>000000011</td>
<td>0</td>
<td>00</td>
</tr>
<tr>
<td>000000011</td>
<td>0</td>
<td>00</td>
</tr>
<tr>
<td>000000010</td>
<td>1</td>
<td>01</td>
</tr>
<tr>
<td>000000011</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>000000010</td>
<td>0</td>
<td>00</td>
</tr>
<tr>
<td>000000011</td>
<td>1</td>
<td>11</td>
</tr>
</tbody>
</table>

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 demar-
cation between the first bit and the subsequent bits. Table 1
shows a partial bit sequence of a QRS complex slope dur-
ing 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 ta-
ble. 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 rela-
tively 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 in-
corporating a Golomb-Rice encoder and carried out sim-
ulations on esophageal ECG signals (INSEL-EECG) col-
lected from our clinical trials as well as surface ECG sig-
als from the MIT-BIH arrhythmia database (MITBIH-
ECG) (records 100 to 124) [7]. We also developed a cus-
tom reconstruction and decoding algorithm for our irregu-
larly acquired time encoded data. The performance results
of the encoder where measured by comparing the original
classically sampled signals with the reconstructed out-
put of the encoder and the results are presented in Table
2. The MITBIH column shows the bit rate characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MITBIH-ECG</th>
<th>INSEL-EECG</th>
<th>TECG/TEECG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data (Bits/s)</td>
<td>3300</td>
<td>6000</td>
<td>1800-2200</td>
</tr>
<tr>
<td>G-RE (Bits/s)</td>
<td>NA</td>
<td>NA</td>
<td>600-980</td>
</tr>
<tr>
<td>PRD</td>
<td>NA</td>
<td>NA</td>
<td>4%</td>
</tr>
</tbody>
</table>

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 en-
coder of surface ECG signals and esophageal ECG sig-
als. The G-RE row shows the Golomb-Rice encoded out-
put 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 origi-
nal form. The percent-root-mean-square-difference (PRD)
degradation is due to time approximation of the signals and
application of the $\Delta V$' 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 pro-
posed solution offers signal activity dependent data ac-
quision 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 been 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


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