Encoding the Electrocardiogram Details in the Host Record's Bandgap for Authorization-Dependent ECG Quality

Piotr Augustyniak

AGH University of Science and Technology, Krakow, Poland

Abstract

In this paper we propose using the ECG bandgap storage area for coding high frequency details of the signal. Authorization-dependent access to these details allows privileged users for high precision analysis, while regular users with an access to standard resolution signal are still able to correctly calculate essential parameters.

The proposed algorithm performs limited ECG interpretation, analysis of bandgap properties and respective adjustment of supplementary details. Depending of selected coding bit depth, the algorithm slightly affects the ECG (PRD = 0.51% for 5 bps) or the supplementary details (PRD = 1.16% for 1 bps) The storage space is sufficient for accommodate oversampling details of 50 ms enhancing the signal in selected area (e.g. QRS-end for VLP).

1. Introduction

Recent progress in digital telecommunication services and their widespread application in medicine motivate the research of data protection techniques. Although the patients' privacy is in the main focus of numerous works, the intellectual property of software manufacturers or health care providers is rarely concerned by investigators. The use of different interpretation software packages to processing of an electrocardiogram encoded as time series of equally spaced voltage samples leads to different outcomes challenging the veracity of interpretation results.

This paper presents a novel encoding method dedicated to the electrocardiogram. The method consists in using of the bandgap (i.e. areas of ECG signal where cardiac component are not expected) as an extra storage space for high frequency details of the signal. Encoding these information allows privileged users for a high precision analysis, while regular users with an access to standard resolution signal are still able to correctly calculate essential parameters. The privileges assigned may depend on software manufacturer or health care provider and any available symmetric-key or asymmetric-key cryptographic algorithms may be used. These details fall out of the scope of this paper.

An interesting feature of the proposed method consists in encoding the supplementary information as watermarks, making it not only unavailable but also not detectable for regular users (steganography). The encoded information inherits statistical properties of noise present in an original ECG, therefore reliability of interpretation made by a regular user or software is maintained.

The digital content protection, referred to as 'watermarking' is commonly used in digital image or audio data and uses the specificity of its format (JPG, GIF, MP3 or WMA). In medical applications, such integration of public and private data is partly supported by the DICOM standard. In case of electrocardiogram, time series of voltage samples used as most common data containers are not suitable for a direct hiding of the existence of supplementary digital data without influencing the diagnostic results. However, certain progress has already be made thanks to the research of Bender (Patchwork) [1], van Schyndel (LSB) [2], and Chen (QIM) [3]. The early watermarking methods were summarized by Kong and Feng [4]. An implementation of low complexity high capacity ECG watermarking was recently published also in CinC proceedings [5] and [6].

The method presented in [6] was DWT-based technique dedicated for storage of patient-specific data in ECG signals and was based on the paper by Engin, Cidam, and Engin [7]. It used the concept of a bandgap resulting from the research on instantaneous bandwidth of cardiac components in the ECG related to the positions of P, QRS and T waves in the heart cycle [8]. The usage of constant sampling frequency of a value appropriate for the QRS complex (lasting for ca. 15% of beat's length) leads to oversampling of cardiac components in large remaining parts of the ECG record. This gap was previously explored for possible perceptual compression [9] and denoising of the ECG [10], but the results in [6] also prove its considerable storage capacity. This data carrier may be used for embedding of supplementary digital data into the ECG record without changing its diagnostability for a regular user. In this paper we propose to encode additional high-frequency components of the signal in order to increase the accuracy of its interpretation for privileged users.

2. Material and methods

2.1. Determining the bandgap capacity

The bandwidth of cardiac components varies with time following the temporal distribution of information in the signal [8]. Unlike in many stochastic signals, the bandwidth of cardiac components in the ECG is highly predictable due to sequential repetition of events in the heart cycle and to several physiological limitations of stimulus transmission in the heart conduction system. As most ECG recorders use constant sampling frequency adjusted to the component of highest bandwidth, a QRS complex, the bandgap extends between the actual bandwidth of cardiac components present in the record and the maximum frequency allowed by sampling theorem (also referred to as Nyquist frequency). Consequently, in a vast time of ECG (up to 85% in case of NSR), the bandgap (i.e. high scales of time-frequency representation) contains only medically meaningless extracardiac noise that could be replaced by a hidden message. The actual size of the bandgap depends on the duration of cardiac events (represented by ECG waves) and a covert replacement of noise by a message requires the codewords to be adapted to the statistics of noise.

Therefore, embedding the hidden message must be preceded by a thorough examination of the bandgap. First, we determine the size of the bandgap using procedures dedicated to beat detection and determination of selected fiducial points. Such procedures are part of standard medical interpretation of the ECG, thus various implementations can be found elsewhere [11, 12]. Next, we determine statistical properties of the 1^{-st} scale of time-frequency signal representation in each section from Q-end to P-ons, being the message carrier, in order to calculate the maximum bit depth of the message. To remain invisible, the message codewords and noise values must show indistinguishable statistics. This limits the bit depth usable for message coding to the value used by noise and consequently determines the storage capacity of the bandgap. Due to the use of low noise electronic circuits and converters, the value of noise level rarely exceeds 10 μV, thus assuming the bit resolution of 0.25 μV, the depth of storage space is 5 bits per sample.

2.2. Encoding the ECG details

The message hidden in the host record's bandgap consists of high frequency complementary details necessary for allowing an authorized user for a more accurate interpretation. Depending on the setup, these details are coefficients of two oversampling scales (indexed as 0^{-th} and -1^{-st}) in particular location of region of interest (ROI) relative to a fiducial point. These locations may correspond to QRS-onset, Ventricular Late Potentials area or other specified by the user. Due to the limited capacity of the bandgap as a carrier of the supplementary data, the statistics of these data are calculated, the data are sorted accordingly to decreased relevance, and finally the thresholding technique is applied to eliminate the least relevant data.

Supplementary data are stored uniquely in containers embedded in the 1^{-st} scale of host's ECG time-frequency representation. The 2^{-nd} scale embeds containers with data description. It enables the identification of the message and storage of three descriptors of the data container:

- the position of container beginning relative to the position of R-wave peak (6 bits),
- the length of container (9 bits), and
- bit depth used in message coding (3 bits).

These beat-specific data are preceded by a key pattern (up to 12 bits) corresponding to the respective key section. This identification tag is encoded using a simple LSB method [2] in time-frequency coefficients of the second scale and occupies 30 consecutive samples (i.e. 240 ms @ 500Hz). The key pattern starts in a specified R-to-Key (RK) distance from the peak of R wave (fig. 1).

The key is a fundamental element in embedding the hidden message into the host electrocardiogram. To increase the data protection, we use third protection scheme accordingly to Key Steganographic Schemes Classification [13]. Therefore the key consists of three sections with the following functions:

- specification of the wavelet family used,
- specification of the RK distance,
- key pattern.
-

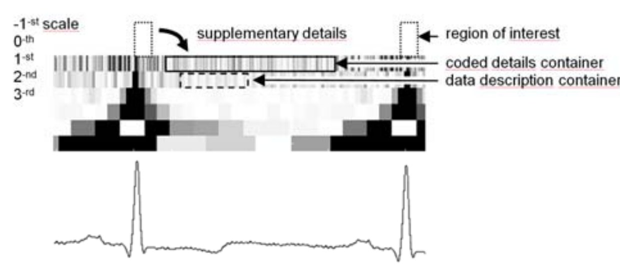

Figure 1. Scheme of data embedding in host's ECG bandwidth gap.

2.3. Encoding scheme

The ECG signal is acquired with a four-fold oversampling, therefore the scales are indexed as: {-1, 0, 1, 2, etc.}. The encoding algorithm starts with two steps typical for medical interpretation: heartbeat detection and delimitation of selected wave borders. Next, the Discrete Wavelet Transform (DWT) is performed and the content of scales the 1-st scale is analyzed between the Q-end and the P-onset of adjacent beats. The analysis provides three beat-specific parameters describing each bandgap container for the complementary details:

– the beginning with respect of precedent R peak,
– the maximum length, and
– the maximum coding bit depth.

Next step consists of analysis of the content of the -1-st and 0-th scales in specified ROI. The coefficients are decorrelated using a Discrete Cosine Transform [14] that sorts them in the order of decreasing energy. If the total volume of complementary details exceeds the capacity of data container, least significant components of the details are truncated causing minimal distortion of the details.

The complementary message is then coded using selected bit depth by replacement of lowest significant bits of the consecutive time-frequency coefficients in 1-st scale by the message content. Next, the data description layer is build and encoded in the 2-nd scale of host ECG. The position of first coefficient of the 1-st scale modified by the message is stored as container beginning. If the message is shorter than the maximum container length, the actual message length is stored instead.

Next the content of data description layer is coded along with the key pattern accordingly to the format described in section 2.2, and the inverse DWT transfers all but the -1-st and 0-th scales of the electrocardiogram back to the time domain (fig. 2, i.e. sampling frequency of stegano ECG is four times lower than original).

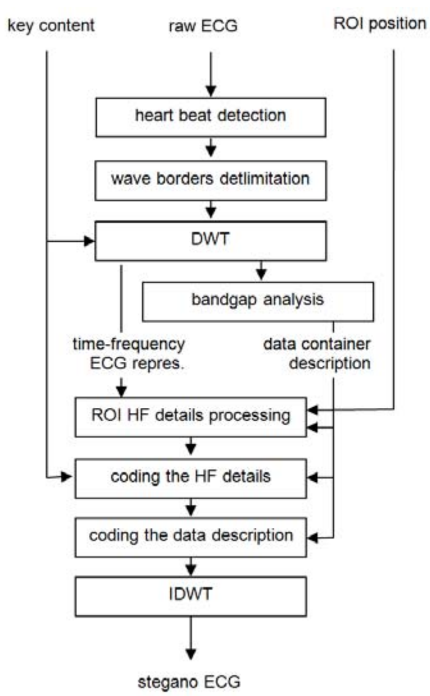

Figure 2. Block diagram of processing scheme for supplementary details encoding.

2.4. Authorization-dependent decoding

The decoding algorithm processes the input stegano ECG without oversampling. It starts with heartbeats detection and positioning of R-wave peaks. The R peaks are the only reference points for positioning of respective data containers, thus no further ECG-specific processing is necessary. The signal within the QRS is not affected by hidden details, thus the positions of R peaks are detected in original and stegano ECG with the same precision. Next, the DWT is performed, and the key pattern is identified in the LSB of the 2-nd scale coefficients.

In case when no matching string could be found, it is assumed that no message has been encoded in this heartbeat for this particular user. The non-authorized user is provided with stegano ECG, thus no further processing is necessary. Similarly, the regular user not expecting the hidden details, processes the stegano ECG signal as a regular ECG with a typical sampling frequency and doesn't distinguish the message from intrinsic noise.

Otherwise, data container parameters following the key pattern are detected and used for correct identification of data container position, length and coding bit depth. Next, the hidden complementary details are read, processed with Inverse Cosine Transform and positioned accordingly to the borders of ROI in the 0-th and -1-st scales. Beyond the ROI these scales are filled by zeros. In this case, the inverse DWT is performed including the 0-th and -1-st scales and finally the authorized user is provided with an oversampled ECG with appropriate details.

2.5. Testing conditions and signals

The proposed algorithm was tested accordingly to the industry standard with use of files from CSE Multilead Dataset 3 [15] (f_s = 500 Hz interpolated to 2 kHz) recommended by IEC60601-2-51 [16] for the repeatability of wavelength calculation in dependence of supplementary data density. The database contains 10 s Multilead records (leads were used as independent signals) and provides reference wave border points.

The details were artificially added 500 Hz triangular waves limited to the ROI with the amplitude of 6.25% of the QRS voltage. The size of ROI varies from 10 to 50 ms, what corresponds to details volume of 120 to 600 bits per heartbeat. Depending on applied coding bit depth (in the range of 1 to 5 bits/sample), the expected storage capacity at 72 bpm NSR is 180 to 900 bits per heartbeat.

We calculated the PRD values for pairs of signals:

– original database and stegano ECGs (E_{PRD}),
– original and decoded detail signals (D_{PRD}).

When the coding uses high bit depth, it fails to mimic the statistic properties of the noise and causes distortions in the electrocardiogram (E_{PRD}). On the other hand, using low bit depth limits the size of hidden data container (which additionally varies with the ECG content), thus the prioritized sequence of details has to be truncated accordingly causing detail signal distortions (D_{PRD}).

3. Results

Main results of testing are distortion values measured as D_{PRD} and E_{PRD} (tab. 1).

Table 1. Average complementary details (D_{PRD}) and ECG signal (E_{PRD}) distortion values for coding depth ranging from 1 to 5 bits per sample.

coding depth [bits]	D_{PRD} ROI duration [ms]			E_{PRD} [%]
	10	25	50	
1 (0.5 μV)	0	0.41	1.16	0.03
2 (1.0 μV)	0	0.14	0.59	0.06
3 (2.0 μV)	0	0.05	0.28	0.13
4 (4.0 μV)	0	0	0.07	0.27
5 (8.0 μV)	0	0	0	0.51

First column of table 1 presents coding depth and corresponding noise voltages. While E_{PRD} values only depends on the coding depth, the D_{PRD} is a result of truncating the prioritized chain of detail coefficients and additionally depends on the ROI duration.

4. Discussion

Since the average noise of CSE database signals falls slightly above 10 μV, and the signal resolution is 0.25 μV/LSB, coding depth of up to 5 bits/sample doesn't deteriorate the signal significantly (E_{PRD} = 0.51%). With use of higher coding depths, the supplementary data start changing the noise statistics and consequently (1) are more pronounced in statistical parameters and (2) systematically degrade the cardiac components.

Due to the adaptation of hidden data container to local ECG properties, precise prediction of its capacity is not possible. Therefore the adjustment of supplementary details representation has to be made for each heartbeat individually after the estimation of storage capacity of respective target data container. The results clearly show that except for a very short ROI of 10 ms, the coding depth is well controlling the compromise between possible distortion of ECG and supplementary details.

Acknowledgements

This work is supported by the AGH University of Science and Technology as a research project No. 11.11.120.612.

References

[1] Bender W, Gruhl D, Morimoto N, A.Lu. Techniques for data hiding. IBM Systems Journal 1996;35(3&4).
[2] van Schyndel RG, Tirkel AZ, Osborne CF. A digital watermark. In Proc. of the IEEE Int. Conf. on Image Processing (ICIP), volume 2. Austin, Texas, USA, 1994; 86–90.
[3] Chen B, Wornell G. Digital watermarking and information embedding using dither modulation. In 1998 IEEE Second Workshop on Multimedia Signal Processing 1998;273–278.
[4] Kong X, Feng R. Watermarking medical signals for telemedicine. IEEE Transactions on Information Technology in Biomedicine 2001;5:195–201.
[5] Ibaida A, Khalil I, van Schyndel RG. A low complexity high capacity ecg signal watermark for wearable sensor-net health monitoring system. Computing in Cardiology 2011;38:393−396.
[6] Augustyniak P. Analysis of ECG bandwidth gap as a possible carrier for supplementary digital data. Computing in Cardiology 2012;39:73–76
[7] Engin M, Cıdam O, Engin EZ. Wavelet transformation based watermarking technique for human electrocardiogram (ECG). Journal of Medical Systems 2005;29(6):589–594.
[8] Augustyniak P. How a human perceives the electrocardiogram - the pursuit of information distribution through scanpath analysis Computers in Cardiology 2003;30: 601-604
[9] Augustyniak P. Content-adaptive signal and data in pervasive cardiac monitoring. Computers in Cardiology 2005; 32: 825-828.
[10] Augustyniak P. Time-frequency modelling and discrimination of noise in the electrocardiogram - Physiological Measurement 2003;24: 753-767.
[11] zoghlami e, ayari ep, tielert r, wehn n. a new fitting approach for online electrocardiogram component waves delineation. Computers in Cardiology 2008;35:861−864.
[12] Johannesen L, Grove1 USL, Sørensen JS, Schmidt ML, Couderc J-P, Graff C. A wavelet-based algorithm for delineation and classification of wave patterns in continuous Holter ECG recordings. Computing in Cardiology 2010;37:979−982.
[13] http://en.wikipedia.org/wiki/Steganography
[14] Ahmed N, Natarajan T, Rao KR. Discrete cosine transform. IEEE Trans. on Computers, 1974, C–23, 90–93.
[15] Willems JL., Arnaud P, van Bemmel JH. et al. A reference database for multilead electrocardiographic computer measurement programs. Journal of the American College of Cardiology 1987; 6: 1313-1321.
[16] IEC 60601-2-51. Medical electrical equipment: Particular requirements for the safety, including essential performance, of ambulatory electrocardiographic systems. First edition 2003-02, International Electrotechnical Commission, Geneva, 2003

Address for correspondence:
Piotr Augustyniak
AGH University of Science and Technology,
30, Mickiewicz Ave. 30-059 Krakow, Poland
august@agh.edu.pl.