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SERVICES FOR SCIENCE AND EDUCATION

A New ECG Steganography Based on Enhanced Coefficient Adjustment Technique and Least Significant Bit Substitution

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ABSTRACT

A new data hiding technique was presented to conceal the privacy of patient's diagnosis and personal sensitive information in an electrocardiogram (ECG) signal. Instead of hiding one data bit in a host block at a time by traditional coefficient adjustment technique (CAT), we embed two data bits in the same size of the block via the proposed enhanced CAT (ECAT) method. The resultant payload provided by ECAT is nearly twice as large as that provided by the CAT scheme. In addition, if ECAT equipped with the least significant bit (LSB) substitution, then a large number of bits can be hidden in the ECG hosts while the resulting perceived quality is good. Simulations revealed that both the average payload and SNR and the proposed method are superior to those of the CAT-based schemes and existed ECG steganographic methods. The application of our method can be found in portable (or wearable) measurement devices.

Keywords: Data hiding, ECG steganography, CAT, ECAT, LSB.

INTRODUCTION

Due to steady growth of very high-speed backbone network service, the improving chip manufacturing technology and ubiquitous use of powerful applications in mobile devices, plus the maturity of artificial intelligence algorithms and 5G communication technology, people can easily roam from the Internet and share their resources conveniently. However, data can be eavesdropped or tampered with during transmission. Data hiding [1-3] provides a simple and economical ways to protect (or secure) sensitive or important information. Generally speaking, data hiding can be classified as steganography and digital watermarking [4-6]. A major goal of steganography is to achieve hiding storage as large as possible while the resultant perceived quality is good. Since a good perceived quality of marked media attracts no attention from the third parties. Typical applications of steganography can be found in covert channel communications between two parties and the hidden of private (or important) data in multimedia. As for a major purpose of digital watermarking is to purse robustness performance

while maintaining acceptable perceptual quality. Namely, the watermarking schemes intend to protect copyrights, hoping to avoid or prevent intentionally (or unintentionally) manipulating of watermarked multimedia. Recently, researchers pay attention to hide patient's diagnosis and personal data in biometric measure signals such as electrocardiogram (ECG) and Electroencephalography [7-13]. Since the objective of the proposed method is to conceal secret message in an ECG host and improve the performance of the variants of CAT-based ECG steganography [7,10, 12, 13], only related (lossy) methods are reviewed here.

Yang and Wang [7] used coefficient alignment and developed a high-quality and a high-capacity ECG steganography. Simulation revealed that the average SNR/ payload were 54.00 dB/ 7,500 bits and 42.47/ 14,783 for the high-quality and high-capacity versions, respectively. To improve previous work, Yang and Wang [10] suggested an absolute-value-decision policy to hide secrete bits in the ECG hosts. According to the decision policy, at most two data bits can be hidden in a host block via the adjustment of the coefficients in the block. In addition, to obtain a high-perceived quality, a 1-bit version of the method was presented to achieve the goal. An apparent merit of the method is to use no extra information during the bit embedding/extraction process. Simulations showed that the average SNR (in dB)/ payload (in bits) of the method was 47.54/ 19,614 and 57.80/ 9,982 for the 2-bit and 1-bit version of the method, respectively. Based on two-dimensional (2D) approach, Yang et al. [12] proposed an ECG steganography. Before conducting bit embedment, they converted input ECG data from one-dimensional (1D) arrangement into series of 2D block with the size of 3×3. According to the coefficient adjustment approach, six data bits can be hidden in a host block. Simulations indicated that the average SNR of the method is superior to that of existed techniques, whereas the payload of the method is competitive to that of the compared methods. An apparent disadvantage of the method was the waste of residual blocks (without being used for bit hidden) after the conversion of ECG from 1D to 2D.

Based on the integer wavelet transform (IWT), Yang and Wang [13] presented a data hiding to hide personal message in an ECG host via the offset of IWT coefficients. To embed data bits in the coefficients of a host block with the size of $1 \times n$, they used the coefficient adjusting rule, that is, $\left|\frac{\sum_{i=0}^{n-2} s_{ji}}{n-1} - s_{j(n-1)}\right| \leq \tau$, where τ is a control integer, n is the size of the host block, and s_{ji} is the ith coefficient of the jth block. Namely, a data bit 1 or 0 can be hidden in a host block of size 2 if $-\tau \leq (s_{j0} - s_{j1}) < 0 \ \ or \ 0 \leq (s_{j0} - s_{j1}) < \tau$ is satisfied. Subsequently, input the next bit 1 or 0 can be embedded in the block of size 3, if either $-\tau \leq \left(\frac{s_{j0}-s_{j1}}{2} - s_{j2}\right) < 0 \ \ or \ 0 \leq (\frac{s_{j0}-s_{j1}}{2} - s_{j2}) < \tau$ is satisfied. Theoretically, data bits (of length n – 1) can be concealed in a host block of size n. It is obvious that a large value of n provides a large hiding space, but degrades the perceived quality (with the lower SNR) by the method. The procedure of coefficient adjustment has to be conducted if rule-violation occurs during bit embedding. In addition, if a block (or sub-block) carries no data bit, it is referred to as a skipped block. No extra information is required for the recoding of the position of skipped blocks, because the skipped blocks can be easily detected at the receiver according to the above coefficient adjusting rule.

PROPOSED METHOD

To improve the hiding capacity of traditional CAT [13], an enhanced ECAT was presented here to achieve the goal. Instead of hiding two data bits in a host bundle with the size of 1×3, the proposed ECAT method embeds four bits in a host block with the same size. Theoretically, the coding efficiency (4 / 3) of the ECAT and is twice as large as that (2 / 3) of the CAT. Specifically, at most four data bits can be embedded in a bundle according to the following two decision rules, namely, R1 and R2. They are defined as follows:

$$R1: |x_i - x_{i+1}| < 2\tau \tag{1}$$

and

$$R2: \left|\frac{x_i - x_{i+1}}{2} - x_{i+2}\right| < 2\tau \tag{2}$$

where τ is a control parameter, x_i, x_{i+1}, and x_{i+2} are the three adjacent coefficients in a host bundle. Without loss of generality, let $\alpha, \beta, \gamma, and\ \delta$ be represented as the two bits "00," "01," "10," and "11," which come from input bit-stream. The proposed ECAT method consists of two phases. In phase I, $\alpha, \beta, \gamma, and\ \delta$ can be "virtually" hidden into a host bundle of size 2 if R1 is satisfied. In phase II, two data bits can be "carried" by the bundle of size 3 if R2 is satisfied. If none of the above rules is satisfies, then the bundle carries no data bit and is referred to as a skipped block. To further increasing hiding space, the ECAT equipped with the LSB substitution is presented here. That is, instead of skipping the bundle (or sub-bundle), we embed data bits in the skipped bundles by the LSB. Namely, in Phase I, we embed four data bits in the coefficients of x_i and x_{i+1} via the LSB as $2\tau \le |x_i - x_{i+1}|$ is true. However, to avoid the altering the values of the two coefficients (marked by Phase I), only two bits would be hidden into the coefficient x_{i+2} via the LSB (in Phase II) if the condition of $2\tau \le \left|\frac{(x_i + x_{i+1})}{2} - x_{i+2}\right|$ is satisfied. The main steps of bit embedding and bit extraction for the proposed ECAT with the LSB method is summarized in the following sections.

Bit Embedding

The main procedure of bit embedding is described in the following algorithm.

Algorithm 1: Embedding a secret message in an ECG host.

Input: Host ECG H, the size of a bundle n, control integer τ, and secret message W.

Output: Marked ECG $\widehat{H}$.

Method:

Step 1. Input a bundle, say $H_j = \{x_i\}_{i=0}^{n-1}$ from the jth bundle of H. If the end of input is encountered, then go to Step 14.

Step 2. Read in two data bits $\phi \in \{00, 01, 10, 11\}$ from W and compute the offset $\eta = x_i - x_{i+1}$.

[Phase I]

Step 3. If $2\tau \leq |\eta|$ then read in next two bits o $\in \{00, 01, 10, 11\}$ from W and embed ϕ and o in x_i and x_{i+1}, respectively, via the LSB technique. Proceed to Step 8.

Step 4. If the conditions of $\phi = \alpha$ and $0 \leq (x_i - x_{i+1}) < \tau$ are satisfied, then the bundle "carried" α and go to Step 8, otherwise, if $\phi = \alpha$, then repeat adjust both coefficients x_i and x_{i+1} either by increment or decrement, respectively, until $0 \leq (x_i - x_{i+1}) < \tau$ is true and proceed to Step 8.

Step 5. If the conditions of $\phi = \beta$ and $-\tau \leq (x_i - x_{i+1}) < 0$ are satisfied, then the bundle "carried" β and go to Step 8, otherwise, if $\phi = \beta$, then repeat adjust both coefficients x_i and x_{i+1} either by increment or decrement, respectively, until $-\tau \leq (x_i - x_{i+1}) < 0$ is true and proceed to Step 8.

Step 6. If the conditions of $\phi = \gamma$ and $\tau \leq (x_i - x_{i+1}) < 2\tau$ are satisfied, then the bundle "carried" γ and go to Step 8, otherwise, if $\phi = \gamma$, then repeat adjust both coefficients x_i and x_{i+1} either by increment or decrement, respectively, until $\tau \leq (x_i - x_{i+1}) < 2\tau$ is true and proceed to Step 8.

Step 7. If the conditions of $\phi = \delta$ and $-2\tau \leq (x_i - x_{i+1}) < \tau$ are satisfied, then the bundle "carried" δ and go to Step 8, otherwise, repeat adjust both coefficients x_i and x_{i+1} either by increment or decrement, respectively, until $-2\tau \leq (x_i - x_{i+1}) < -\tau$ is true.

[Phase II]

Step 8. Read in next two data bits $\nu \epsilon \{00,01,10,11\}$ from W and compute the offset $\kappa = \frac{(x_i - x_{i+1})}{2} - x_{i+2}$

Step 9. If $2\tau \leq |\kappa|$is true, then embed ν in x_{i+2} via the LSB technique. Return to Step 1.

Step 10. If the conditions of $\nu = \alpha$ and $0 \leq (\frac{(x_i - x_{i+1})}{2} - x_{i+2}) < \tau$ are satisfied, then the bundle "carried" α and go to Step 1, otherwise, if $\nu = \alpha$, then repeat adjust the coefficients (x_i, x_{i+1}) and x_{i+2} either by increment or decrement, respectively, until $0 \leq (\frac{(x_i - x_{i+1})}{2} - x_{i+2}) < \tau$ is true and proceed to Step 1.

Step 11. If the conditions of $\nu = \beta$ and $-\tau \leq (\frac{(x_i - x_{i+1})}{2} - x_{i+2}) < 0$ are satisfied, then the bundle "carried" α and go to Step 1, otherwise, if $\nu = \beta$, then repeat adjust the coefficients (x_i, x_{i+1}) and x_{i+2} either by increment or decrement, respectively, until $-\tau \leq (\frac{(x_i - x_{i+1})}{2} - x_{i+2}) < 0$ is true and proceed to Step 1.

Step 12. If the conditions of $\nu = \gamma$ and $\tau \leq (\frac{(x_i - x_{i+1})}{2} - x_{i+2}) < 2\tau$ are satisfied, then the bundle "carried" γ and go to Step 1, otherwise, if $\nu = \gamma$, then repeat adjust the coefficients (x_i, x_{i+1}) and x_{i+2} either by increment or decrement, respectively, until $\tau \leq (\frac{(x_i - x_{i+1})}{2} - x_{i+2}) < 2\tau$ is true and proceed to Step 1.

Step 13. If the conditions of $\nu = \delta$ and $-2\tau \leq (\frac{(x_i - x_{i+1})}{2} - x_{i+2}) < -\tau$ are satisfied, then the bundle "carried" δ and go to Step 1, otherwise, if $\nu = \delta$, then repeat adjust the coefficients (x_i, x_{i+1}) and x_{i+2} either by increment or decrement, respectively, until $-2\tau \leq (\frac{(x_i - x_{i+1})}{2} - x_{i+2}) < -\tau$ is true and proceed to Step 1.

Step 14. Stop.

Bit Extraction
The procedure of bit extraction is much simpler than that of bit embedding for the proposed ECAT with the LSB method. The major steps of bit extraction are summarized in the following algorithm.

Algorithm 2: Extracting hidden message from marked ECG.

Input: Marked ECG $\widehat{H}$and control integer τ.

Output: Extracted message W.

Method:
Step 1. Input a marked bundle $\{\hat{x}_i\}_{i=0}^{n-1}$ from $\widehat{H}$ and compute the offset $\eta = \hat{x}_i - \hat{x}_{i+1}$. If the end of input is encountered, then go to Step 6.

[Phase I]
Step 2. If $|\eta| < 2\tau$ is true, then two hidden bits can be extracted from the bundle, otherwise proceed to Step 3. That is, if $0 \leq (\hat{x}_i - \hat{x}_{i+1}) < \tau$, then "00" are recognized, else if $-\tau \leq (\hat{x}_i - \hat{x}_{i+1}) < 0$, then "01" is identified, else if $\tau \leq (\hat{x}_i - \hat{x}_{i+1}) < 2\tau$, then "10" are recognized, otherwise, "11" is identified.

Proceed to Step 4.

Step 3. Four hidden bits can be identified from the coefficients $\hat{x}_i$ and $\hat{x}_{i+1}$ via the LSB.

[Phase II]
Step 4. Compute the offset $\kappa = \frac{\hat{x}_i - \hat{x}_{i+1}}{2} - \hat{x}_{i+2}$ If the condition of $|\kappa| < 2\tau$ is satisfied, then two 2 hidden bits can be extracted from the bundle, otherwise proceed to Step 5. Namely, data bits "00," "01," "10," and "11," can be recognized if one of the following conditions:
$0 \leq (\frac{\hat{x}_i - \hat{x}_{i+1}}{2} - \hat{x}_{i+2}) < \tau, -\tau \leq (\frac{\hat{x}_i - \hat{x}_{i+1}}{2} - \hat{x}_{i+2}) < 0, \tau \leq (\frac{\hat{x}_i - \hat{x}_{i+1}}{2} - \hat{x}_{i+2}) < 2\tau$, and $-2\tau \leq (\frac{\hat{x}_i - \hat{x}_{i+1}}{2} - \hat{x}_{i+2}) < -\tau$ is satisfied, respectively. Return to Step 1.

Step 5. Two hidden bits can be identified from the coefficient $\hat{x}_{i+2}$ via the LSB. Proceed to Step 1.

Step 6. Assemble all of the extracted bits and form a watermark.

Step 7. Stop.

From the above Algorithms we can see that the control parameter τ plays an important role in the proposed ECAT method. In fact, the SNR performance of the algorithm is gradually decreased as τ increased. The reason is that the larger the value of τ, the larger the number of bundles encoded by the ECAT, which may result in significant distortion from the marked bundle. On the other hand, the payload size of the algorithm is increased as τ decreased. Due to the less value of τ, the larger the number of bundles encoded by LSB, which provides the larger hiding space.

EXPERIMENTAL RESULTS

A total of 23-set of ECG hosts were tested in our simulations. These test data were obtained from the MIT-BIH Arrhythmia Database [14]. Each ECG host was composed of 30,000 samples. Two commonly used objective measures such as signal-to-noise ratio (SNR) and percentage residual difference (PRD) are used to evaluate performance. Both are defined as follows:

$$\mathrm{SNR} = 10 \log_{10} \frac{\sum_i s_i^2}{\sum_i (s_i - \hat{s}_i)^2} \tag{3}$$

and

$$\mathrm{PRD} = \sqrt{\frac{\sum_i (s_i - \hat{s}_i)^2}{\sum_i s_i^2}} \times 100\% \tag{4}$$

where s_i, and $\hat{s}_i$stand for the coefficients in the original ECG, marked ECG, respectively. First, the payload/SNR/PRD performance of traditional CAT [13] is compared with that of our ECAT. Table 1 indicated that the average payload of our method is 1.8 times larger than that of traditional CAT [13] with the competitive SNR and PRD values. It can be summarized from Table 1 that the ECAT (using τ = 3) do provide larger hiding storage than traditional CAT (using τ= 20) does. Subsequently, trade-off between SNR and payload for the proposed ECAT with the LSB method using various τ (from 2 to 9) is depicted in Fig. 1.

At first glance, it seems that the performance cures in the figure against common sense. (Since the larger the payload size, the less the SNR value.) As mentioned in Section 2.2, the less τ employed by the proposed method, the less number of the host blocks encoded by ECAT, and the larger number of the blocks encoded by LSB. Namely, it resulted in less distortion introduced from the procedure of the coefficient adjustments, but increased hiding storage by the LSB substitution. From the figure we can see that ECG106 has the best performance in payload and SNR among the test ECGs, followed by ECG104, and ECG100 is the worst. In addition, relationship between PRD and payload of our method is depicted in Fig. 2. The figure confirmed the fact that the larger the SNR, the less the PRD, and vice versa. As we know, the larger the SNR, the smaller the PRD, and the better performance obtained by an ECG steganography.

Table 1. Performance comparison between traditional CAT and our ECAT.

ECG	Payload/SNR/PRD	
hosts	Traditional CAT† [13]	Our ECAT
100	19,135/ 54.68/ 0.184	36,822 / 52.03/ 0.250
101	19,142/ 53.17/ 0.220	35,362 / 51.80/ 0.257
102	19,452/ 53.07/ 0.222	36,160/ 51.71/ 0.260
103	18,975/ 53.33/ 0.190	35,396 / 51.81/ 0.257
104	18,931/ 51.55/ 0.264	33,024 / 52.03/ 0.250
105	18,591/ 52.21/ 0.245	33,174 / 51.86/ 0.255
106	19,125/ 52.17/ 0.246	33,692 / 51.60/ 0.263
108	19,786/ 51.37/ 0.270	34,198/ 51.62/ 0.262
109	18,107/ 51.70/ 0.260	31,788/ 51.83/ 0.256
Average	19,027/ 52.58/ 0.233	34,402/ 51.81/ 0.257

†When the method used the size of the host block is 3.

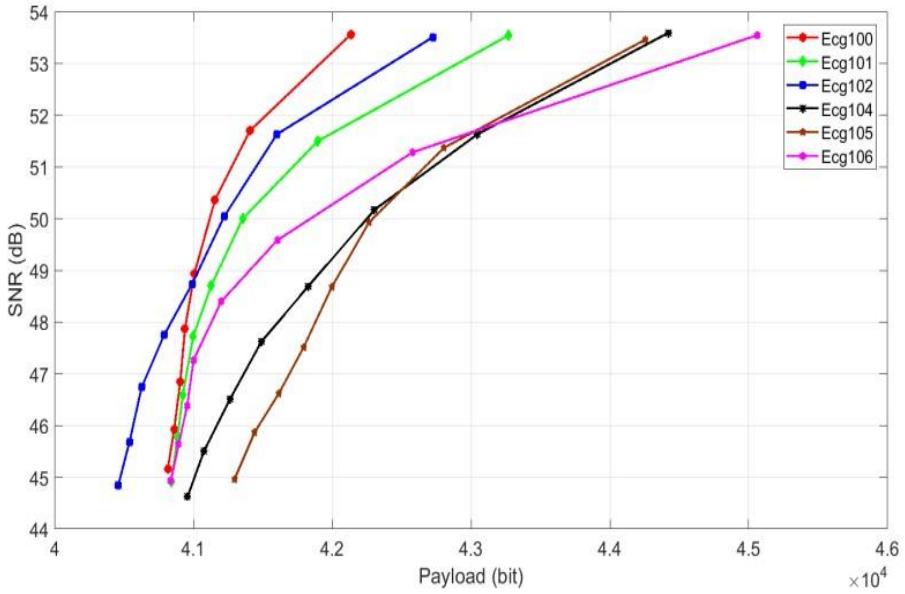


Fig. 1. Trade-off between SNR and payload of our method.

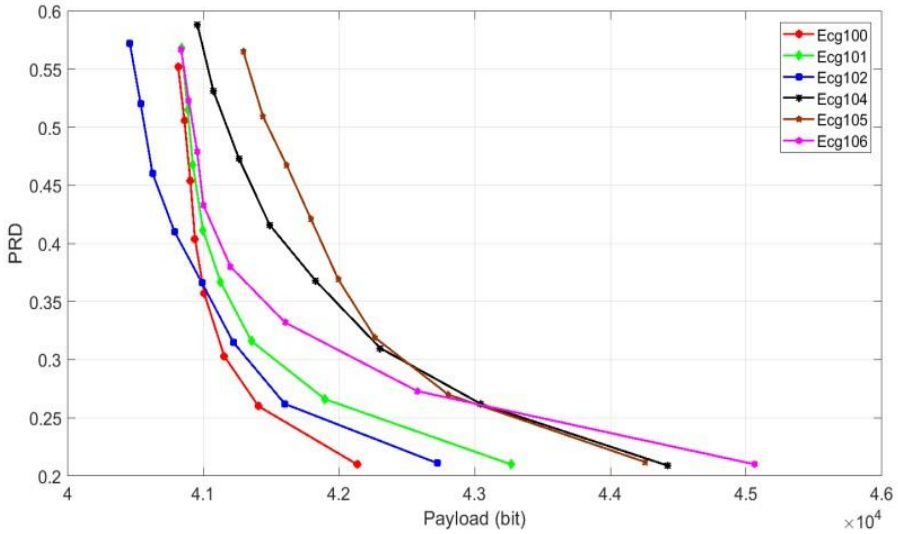
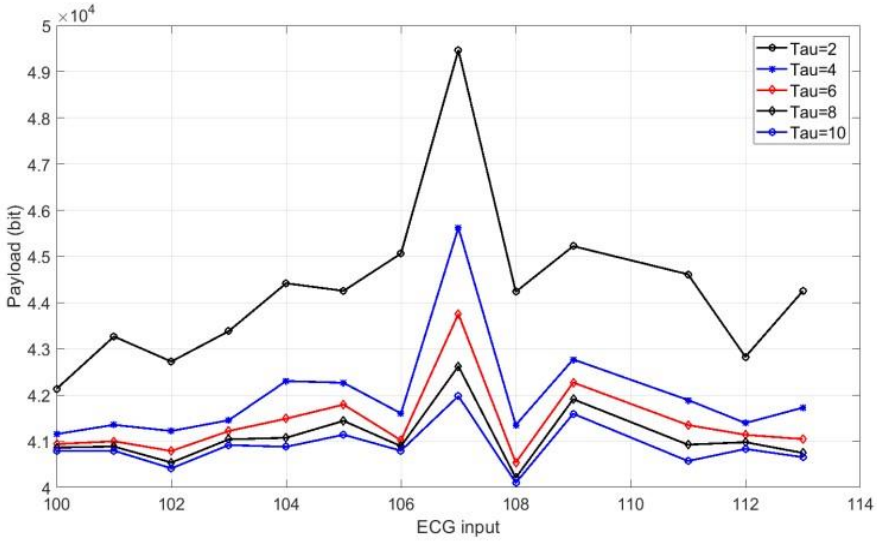
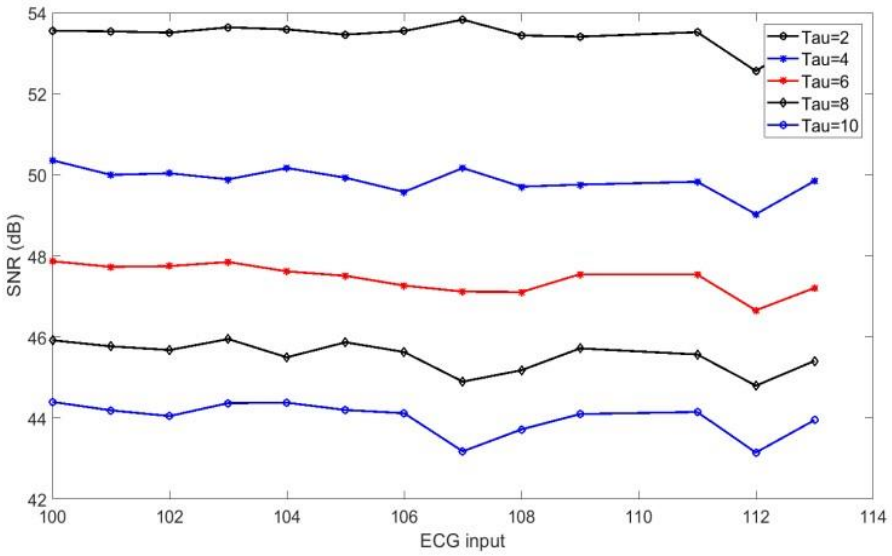


Fig. 2. Trade-off between PRD and payload of our method.

To further examine the hiding performance of the proposed method, the resulting payload and SNR of the test ECGs with five different τ are illustrated in Fig. 3. Figure 3(a) shows that the hiding capacity provided by ECG107 has the largest payload size, followed by ECG109, and ECG 108 provided the least payload as $\tau < 2$. Figure 3(b) indicates that ECG 107 provided the best SNR as $\tau < 4$ and the least SNR as $\tau > 2$. The distortions introduced by the proposed method using $\tau = 6$ (in the first 5-s interval) from the marked ECGs are illustrated in Fig. 4. The marked signal introduced by our method (red line) was approximately similar to the original one (blue line).

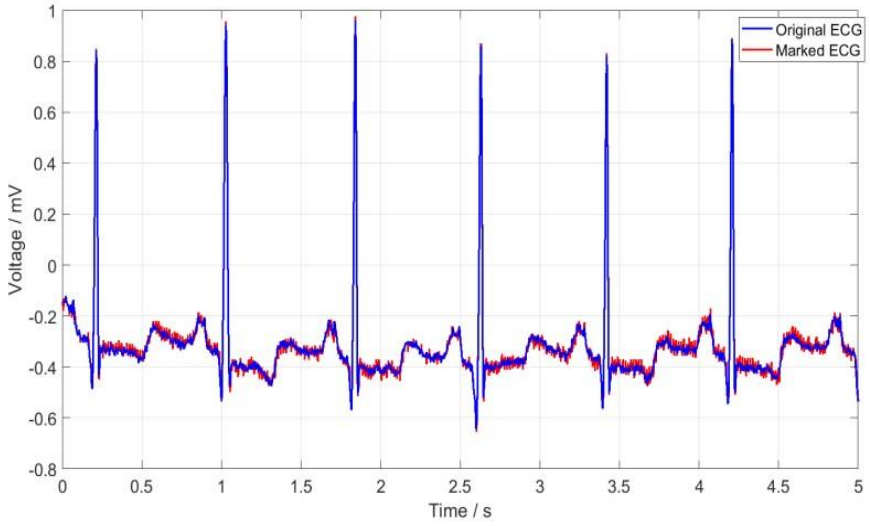


(a)

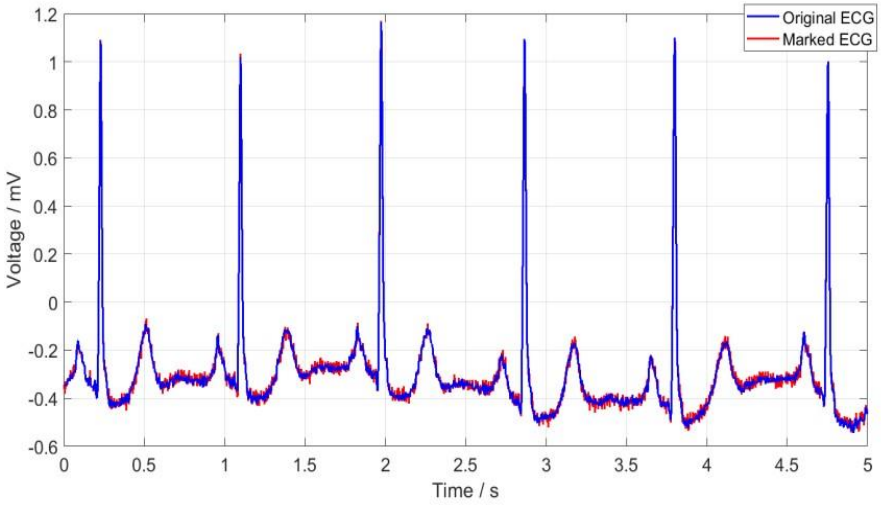


(b)

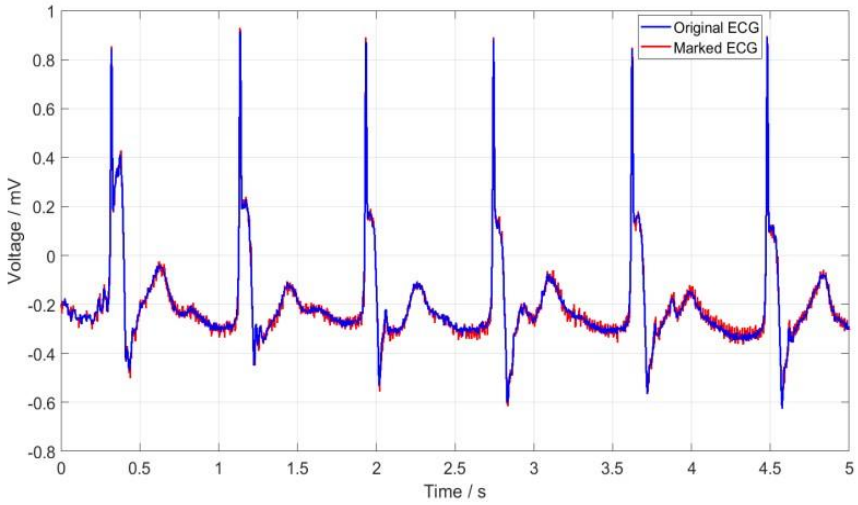
Fig. 3. Hiding performance of our method using five different τ. (a) payload and (b) SNR.



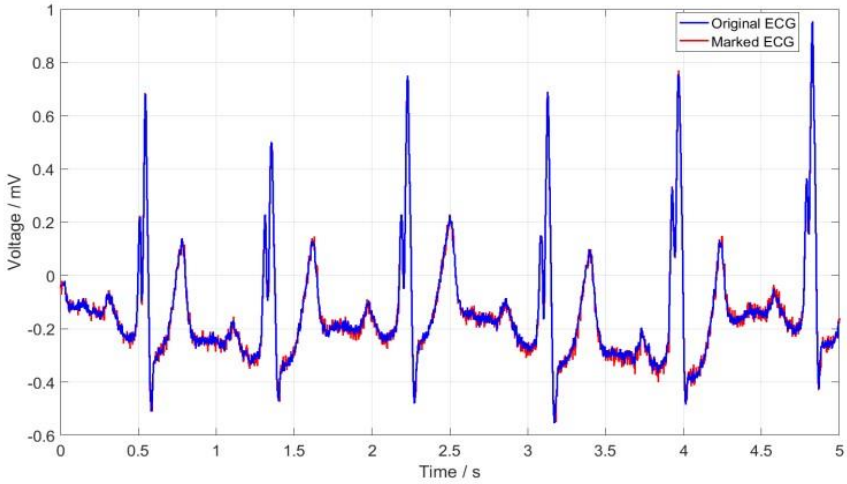
(a)


Original ECG
Marked ECG
Voltage / mV
Time / s

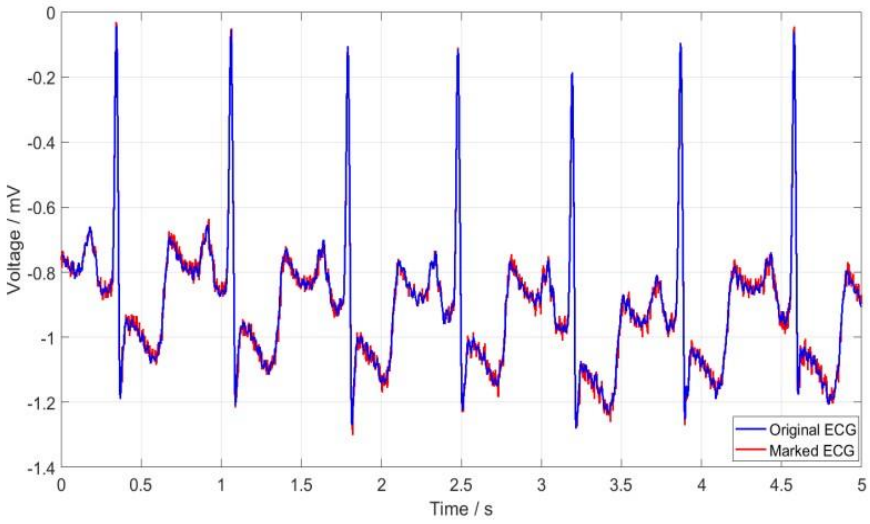
(b)


Original ECG
Marked ECG
Voltage / mV
Time / s

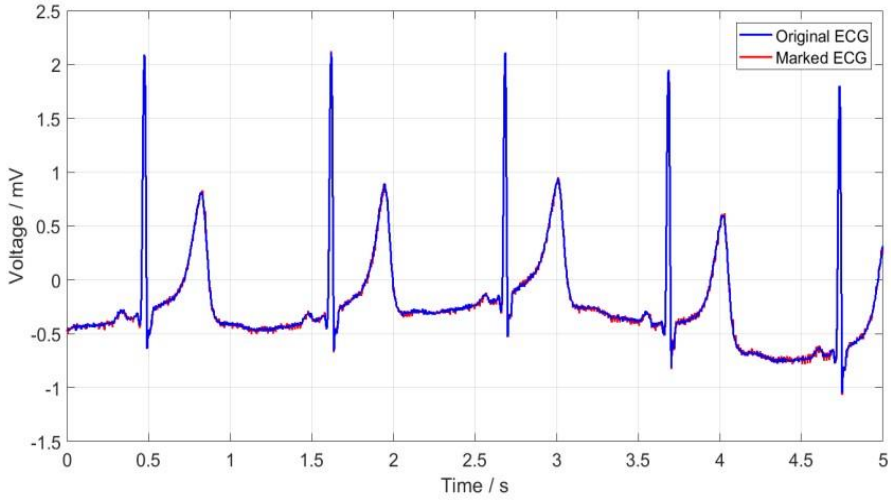
(c)


Original ECG
Marked ECG
Voltage / mV
Time / s

(d)



(e)



(f)

Fig. 4. Close observations of the marked ECGs introduced by our method using τ = 6. (a) ECG100, (b) ECG101, (c) ECG102, (d) ECG111, (e) ECG112, and (f) ECG113.

Performance comparison of existed techniques and our method in several test ECGs is given in Table 2. It is clear that the payload of our method is the largest among the compared methods. Namely, the payload provided by our method is two times larger than that provided by Yang and Wang [10], and is nearly two times bigger than that provided by Yang et al. [12]. In addition, the hiding storage of the proposed method is 1.84 times larger than that of the Yang and Wang [13]. In summary, the averages SNR of the proposed method is superior to that of other three CAT-based schemes. Furthermore, another objective measure which often used to evaluate the performance of data hiding is peak signalto-noise ratio (PSNR). The PSNR and payload performance comparison of various methods is listed in Table 3. Obviously, the average payload of our method is 6.13 times larger than that of the other two schemes [8, 11], while our PSNR is still better than theirs. The PSNR is defined as follows:

$$\mathrm{PSNR} = 10\log_{10}\frac{\mathrm{Max}(s_i)^2}{\frac{1}{K}\sum_i(s_i-\hat{s}_i)^2} \quad (5)$$

where $Max(s_i)$ and K stand for the maximum value of s_i and the number of input samples, respectively. From Tables 2 and 3 we can conclude that an efficient ECG steganography is achieved by the proposed method.

Table 2. SNR/payload performance comparison between various methods.

ECG data	SNR/Payload			
	Yang and Wang [10]	Yang et al.* [12]	Yang and Wang† [13]	Our method*
100	48.19/ 19,604	50.96/ 21,349	50.18/ 24,146	50.36/ 41,156
101	47.39/ 19,610	48.17/ 21,911	49.07/ 24,427	50.00/ 41,356
102	51.60/ 19,602	49.74/ 21,702	50.04/ 23,542	50.04/ 41,222
103	44.92/ 19,600	49.53/ 21,171	49.93/ 21,473	49.89/ 41,459
104	46.84/ 19,602	47.61/ 21,265	49.95/ 21,312	50.17/ 42,304
111	49.43/ 19,630	47.49/ 21,638	50.28/ 21,651	49.83/ 41,894
200	47.36/ 19,608	47.53/ 20,808	50.40/ 20,474	50.01/ 42,780
201	50.13/ 19,612	45.94/ 21,153	50.40/ 23,160	50.51/ 41,506
202	50.16/ 19,632	49.01/ 21,407	50.46/ 23,599	49.69/ 41,096
232	51.58/ 19,620	47.67/ 21,846	49.08/ 22,542	49.57/ 41,128
Average	48.76/ 19,612	48.37/ 21,425	49.95/ 22,633	50.01/ 41,590

*The size of a host block used by the method is 4*4

† The size of the host blocks employed by the method is larger than 3 * 3.

*Our method used the control parameter $\tau = 4$.

Table 3. PSNR/payload performance comparison of various methods.

Jero et al. [8]	Pandey et al. [11]	Our method
54.75/ 10,650	58.01/ 10,650	63.01/ 9,800
51.13/ 14,450	55.55/ 14,450	61.83/ 12,800
45.12/ 18,022	53.62/ 18,022	59.84/ 20,000
39.52/ 21,873	51.98/ 21,873	58.29/ 28,800
34.46/ 25,149	50.79/ 25,149	56.86/ 39,200
Average 45.00/ 18,029	Average 53.99/ 18,029	Average 59.97/ 110,600

CONCLUSION

In this article, we presented an efficient ECAT to promote the payload size of traditional CAT scheme. The payload of the former is apparently larger than that of the latter, while the resultant SNR (or perceived quality) of ECAT is competitive to that of CAT. In addition, a large number of data bits can be embedded in an ECG host as the proposed ECAT with the LSB method. Experimental results confirmed that both the average payload and SNR/PSNR of our method are superior to those of the variants of the CAT and existed schemes. In addition, the resultant perceived quality is good. Due to the algorithm is simple, the application of our method can be found in portable (or wearable) biometric measurements.

References

[1]. Eielinska, E., et al. Trends in steganography. Comm. of the ACM, 2014. 57(3): p. 86-95, doi: 10.1145/2566590.2566610.

[2]. Hussain, M. A., et al., Image steganography in spatial domain: A survey, Signal Processing: Image Communication, 2018. 65(7): p. 46-66, DOI: 10.1016/j.image.2018.03.012.

[3]. Hsiao, C.Y., et al., Simple and robust watermarking scheme based on square-root-modulus technique, Multimedia Tools and Applications, 2018. 77(5): p. 30419-30435, DOI: 10.1007/s11042-018-6121-3.

[4]. Liu, S., et al., Digital image watermarking method based on DCT and fractal encoding, IET Image Proc., 2017. 11(10): p. 815-821, DOI: 10.1049/iet-ipr.2016.0862.

[5]. Sahu, A.K. and Swain, G., Data hiding using adaptive LSB and PVD technique resisting PDH and RS analysis, Int. Journal of Electronic Security and Digital Forensics, 2019. 11(6): p. 458-476, DOI: 10.1504/IJESDF.2019.102567.

[6]. Kadhim, I.J., et al., Comprehensive survey of image steganography: Techniques, Evaluations, and trends in future research, Neurocomputing, 2019. 335(3): p. 299-326, DOI: 10.1016/j.neucom.2018.06.075.

[7]. Yang, C.Y. and Wang, W.F., Effective electrocardiogram steganography based on coefficient alignment, Journal of Medical Sys., 2016. 40(12), DOI: 10.1007/s10916-015-0426-9.

[8]. Jero, S.E., et al., Imperceptability-robustness tradeoff studies for ECG steganography using continuous ant colony optimization, Expert Systems with Applications, 2016. 49(1): p. 123-135, DOI: 10.1016/j.eswa.2015.12.010.

[9]. Shiu, H.J., et al., Preserving privacy of online digital physiological signals using blind and reversible steganography, Computer Methods and Programs in Biomedicine, 2017. 151(11): p. 159-170, DOI: 10.1016/j.cmpb.2017.08.015.

[10]. C.Y. Yang and W.F. Wang, “An improved high-capacity ECG steganography with smart offset coefficients,” The 14th Int. Conf. on Intelligent Information Hiding and Multimedia Signal Processing (IIH-MSP 2018), Nov. 26-28, Sendai, Japan, 2018.

[11]. Pandey, A., et al., A novel fused coupled chaotic map based confidential data embedding-then-encryption of electrocardiogram signal, Biocybernetics and Biomedical Engineering, 2019. 39(2): p. 282-300, DOI: 10.1016/j.bbe.2018.11.012.

[12]. Yang, C.Y., et al., Adaptive electrocardiogram steganography based on 2D approach with predetermined rules, Asian Journal of Computer and Information Systems, 2020. 8(1): p. 1-10, DOI: 10.24203/ajcis. v8i1.6059.

[13]. Yang, C.Y. and Wang, W.F., Progressive data hiding in integer wavelet transform of electrocardiogram by using simple decision rule and coefficient calibration, Revue d'Intelligence Artificielle, 2020. 34(2): p. 1120, DOI: 10.18280/ria.340102.

[14]. Moody, G.B. and Mark, R.G. The impact of the MIT-BIH arrhythmia database. IEEE Eng. in Medical and Biol., 2001. 20(3): p. 45-50, DOI: 10.1109/51.932724.