Integration of Information Hiding and Compression for Biomedical Signals

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Abstract

This study proposes a method to reduce the carrying amount of Electrocardiogram (ECG) network transmission while preserving the original characteristics of ECG and protecting personal privacy. In watermarking part, we perform the quantization-based digital watermark encryption technology on the ECG signals to protect patient rights and information. In addition, the hidden information can be extracted without the original ECG. In compression part, we adopt the threshold-based compression technology to reduce the data amount of the ECG signal and preserve the original characteristics of ECG signals at the same time. The recovery of the compressed ECG signal adopts cubic spline. Experimental results verify the efficiency of the proposed method.

Keywords: Integrate, Watermarking, Compression, ECG, Quantization

1 Introduction

Electrocardiograms (ECG) reflect the process of the electrical activity of our heart, which can be taken as a reference for the study of cardiac pathology and cardiovascular system diagnostics. With ECG signals, we can analyze and identify various heart diseases, such as arrhythmias, myocardial damage etc. ECG has high requirements for accuracy. Thus, ECG is one of the very important types of bio-information to be protected. At the same time, it is necessary to apply watermarking on the ECG signals to protect patient rights and information. In other hand, it is important to reduce the carrying amount of ECG network transmission because of the rapid development of Internet.

There are many studies aiming at watermarking or compression individually. In watermarking, Huang et al. [1] proposed the usage of digital watermarking to ensure the safe transmission of ECG signals in a wireless network. Dey et al. [2] proposed a novel session based blind watermarking method with a secret key by embedding a binary watermark image into the ECG signal. In addition, the “P Q R S T”-peaks are marked and stored over the entire ECG signal and the time interval between two consecutive “R”-peaks, and intervals between other peaks, are measured to detect anomalies in the behavior of the heart. However, these two methods are non-blind. Ayman and Ibrahim proposed a wavelet-based steganography technique which combines encryption and scrambling technique to protect patient confidential data. The proposed method allows the ECG signal to hide its corresponding patient confidential data and other physiological information [3]. Three transform domains, DWT, DCT, and DFT are adopted to implement the quantization based watermarking technique [4]. The change in the amplitude of ECG signals before and after watermarking is very small in their transform-domain methods.

In the aspect of ECG compression, ECG signal compression is a key technology for ECG transmission. Zigel et al. [5] proposed an ECG compression algorithm, called analysis by synthesis ECG compressor (ASEC). Their ASEC algorithm is based on analysis by synthesis coding, and consists of a beat codebook, long and short-term predictors, and an adaptive residual quantizer. Their compression algorithm uses a defined distortion measure in order to efficiently encode every heartbeat, with minimum bit rate, while maintaining a predetermined distortion level. In addition, their compression algorithm was implemented and tested with both the percentage rms difference (PRD) measure and the recently introduced weighted diagnostic distortion (WDD) measure. By recognizing the strong similarity and correlation between successive beat patterns in biomedical waveform sequences, Chen et al. [6] proposed an efficient data compression scheme mainly based on pattern matching. The waveform codec consists mainly of four units: beat segmentation, beat normalization,

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two-stage pattern matching and template updating and residual beat coding. Three different residual beat coding methods, such as Huffman/run-length coding, Huffman/run-length coding in discrete cosine transform domain, and vector quantization, are employed. In method [7] proposed by Miaou et al., a wavelet-based vector quantization (VQ) approach was proposed to perform lossy compression of electrocardiogram (ECG) signals. In this paper, we investigate and fix its coding inefficiency problem in lossless compression and extend it to allow both lossy and lossless compression in a unified coding framework. In method [8] proposed by Mohammad et al., a novel ECG data compression method is presented which employs set partitioning in hierarchical trees algorithm (SPIHT), sub-band energy compression (SEC) method and two-dimensional electrocardiogram (2D-ECG). The 2D-ECG is a two-dimensioned array, which each row of this array indicates one or more period and amplitude normalized (PANed) ECG beats. Two algorithms suited for real-time biomedical signal compression are described in [9]. The two algorithms are amplitude threshold compression and SQ segment compression.

Internet development not only brings a lot of convenience but also relative risk. How to reduce the carrying amount of nature data and the hidden patient information in ECG network transmission at the same time is an important issue [10]. This study proposes a method to integrate ECG watermarking and ECG compression. The proposed method reduces the carrying amount of network transmission while preserving the original characteristics of ECG signals and protecting personal privacy. First of all, we perform the quantization-based digital watermark encryption technology on the ECG signals to embed patient rights and information. Next, we adopt the threshold-based compression technology to reduce the data amount of the embedded ECG signal. Finally, we evaluate the appropriate threshold ε and embedding strength Q to balance the tradeoff between CR and SNR. In addition, the hidden information can be extracted without the original ECG and the recovery of the compressed ECG signal adopts cubic spline.

The rest of this paper is organized as follows. Section 2 reviews some ECG fundamentals and relevant preliminaries. Section 3 presents the proposed integration method for ECG watermark and compression. Section 4 shows experimental results. Conclusions are finally drawn in Section 5.

2 Preliminaries

In this section, we will introduce some preliminaries.

2.1 ECG Principle

The abbreviation ECG [11-12] denotes the electrocardiogram wave, named by the Dutch physiologist W. Einthoven (the inventor of the ECG). He divided one cardiac cycle into P, Q, R, S, and T complex waves in Figure 1. Their meaning is discussed in the following.

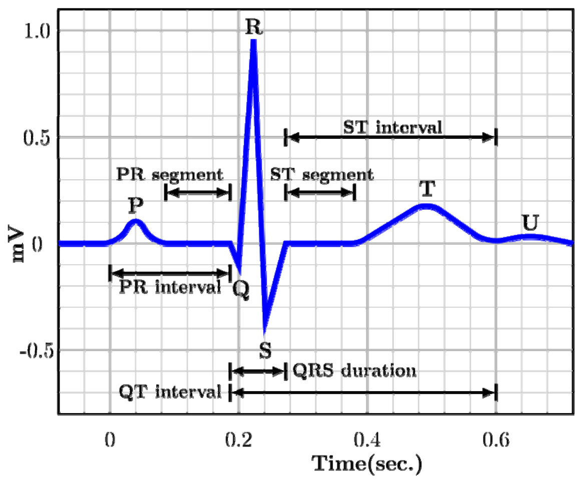

Figure 1. ECG signal

P wave: the excitation of the heart originates in the sinus node, and then reaches the atrium. The P wave is produced by the atrial depolarization. It is the first wave of each wave group and reflects the depolarization process of the left and right atrium. The first half of the P wave represents the right atrium, and the latter part of the P wave represents the left atrium.

QRS complex: a typical QRS complex includes three closely linked waves. The first downward wave is called the Q wave, followed by a high-tip vertical wave known as the R wave. The downward wave after the R wave is called the S wave. Because they are closely linked, and reflect the excitation of the ventricular electrical process, it is collectively referred to as the QRS complex. This wave group reflects the left and right ventricular depolarization process.

T wave: The T wave is located in the following ST segment. It is a relatively low and much longer wave. It is generated by ventricular repolarization.

2.2 Watermarking Description

Digital watermarking technology [12-14] refers to directly embedding some identification information (watermark) into the carrier (including multimedia, documents, software, etc.). It does not affect the usage of the original carrier and is hard to perceive by ordinary perception systems such as visual or auditory systems. The hidden information in the carrier can help us to confirm the content creators, buyers, and carrier's transmission of secret information to determine whether the carrier is altered or not during its transmitting process.

As shown in Figure 2, the research direction of digital watermarking can be roughly divided into two categories: visible watermarking and invisible watermarking. Invisible watermarking can be subdivided into type robustness (robust) or friability (fragile) according to the ability against malicious attacks.

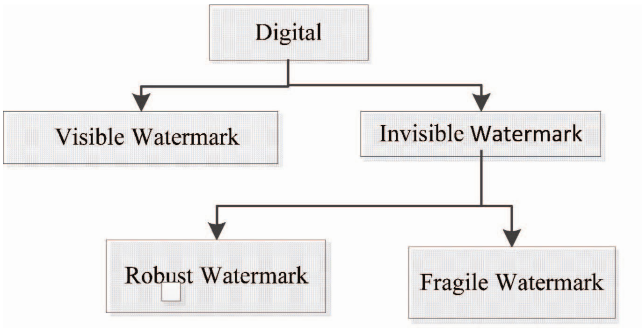

Figure 2. Watermarking classification chart

In general, transparency and robustness are two key performances of a watermarking scheme [14-15]. They are measured by signal-to-noise ratio (SNR) and bit error rate (BER) which are defined as follows formula [1-4]:

$$SNR = -10\log\frac{\sum_{i=1}^{N}\left(\tilde{s}_i - s_i\right)^2}{\sum_{i=1}^{N} s_i^{\,2}} \tag{1}$$

$$BER = \frac{Number\ of\ error\ bits}{Number\ of\ total\ bits}\times 100\% \tag{2}$$

In addition, we also apply relative root mean square error (rRMSE) and root mean square error (RMSE) to judge the transparency, which is defined as follows:

$$rRMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\tilde{s}_i - s_i}{s_i}\right)^2} \tag{3}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\tilde{s}_i - s_i\right)^2} \tag{4}$$

where $\{s_i\}$ represents the original ECG signal for ECG, $\{\tilde{s}_i\}$ represents the embedded (or modified) ECG signal.

2.3 Measurement for Quality of the Compression

In order to evaluate the quality of compression, compression ratio (CR) and percentage ratio difference (PRD) are utilized. Assume s is the original signal and $\breve{s}$ is the reconstruction from the compressed signal, then CR and PRD are defined as the formula [5-6].

$$CR = \frac{Data\ size\ before\ compression}{Data\ size\ after\ compression} \tag{5}$$

$$PRD = \sqrt{\frac{\sum_{i=1}^{N}\left(\breve{s}_i - s_i\right)^2}{\sum_{i=1}^{N} s_i^{\,2}}}\cdot 100 \tag{6}$$

where N is the number of testing samples in the signal s.

3 Proposed Method

In order to reduce the carrying amount of ECG and its patient data in Internet transmission, this section presents the proposed procedure integrating ECG signal information hiding and compression. Figure 3 and 4 show the flowchart of the proposed integration. The detail is introduced in the following.

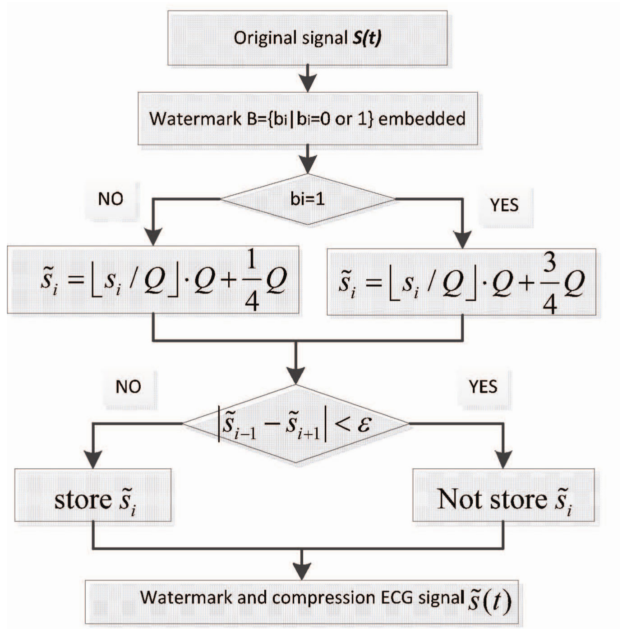

Figure 3. Watermark embedding and compression flow chart

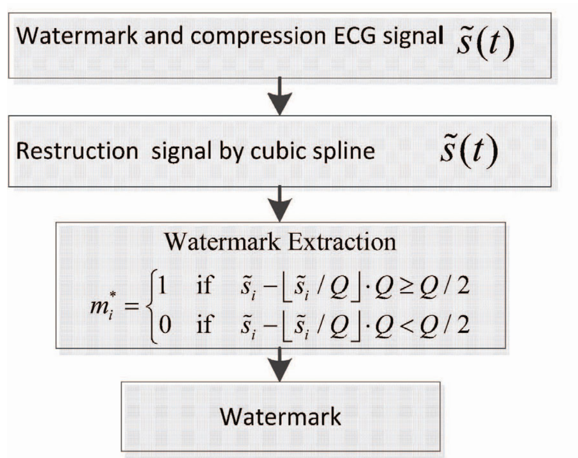

Figure 4. Watermark compression reduction, extracted watermark flowchart

3.1 Embedding Integrated with Compression

First of all, quantization-based embedding technique is applied to hide patients' information which is represent by binary bit. The quantization-based embedding technique is as the following formula (7):

$$\tilde{s}_i = \begin{cases} \lfloor s_i / Q \rfloor \cdot Q + \frac{3}{4}Q & if \quad m_i = 1 \\ \lfloor s_i / Q \rfloor \cdot Q + \frac{1}{4}Q & if \quad m_i = 0 \end{cases} \tag{7}$$

where $\{(t_i, s_i)\}_{i=0}^{N}$ represents the original ECG signal s_i with respect to time index t_i; $\{(t_i, s_i)\}_{i=0}^{N}$ represents the embedded ECG signal $\tilde{s}_i$ with respect to time index t_i; Q represents embedding strength and is adopted as a secret key; m_i represents watermark bit 1 or 0.

Next, the embedded ECG $\{\tilde{s}_i\}$ is compressed by threshold compression method which is defined as the formula (8):

$$\hat{t}_i = t_i ,\ 0 \le i \le N ;\ \hat{s}_0 = \tilde{s}_0 ,\ \hat{s}_N = \tilde{s}_N$$

$$\hat{s}_i = \begin{cases} \phi & if \left|\tilde{s}_{i-1} - \tilde{s}_{i+1}\right| < \varepsilon \\ \tilde{s} & otherwise \end{cases} ,\ i = \{1, 2, \cdots N-1\} \tag{8}$$

where ε represents the threshold.

3.2 Recovery and Extraction

For the compressed ECG signal $\{(t_i, s_i)\}_{i=0}^{N}$, cubic function represents the cloud gauge line with fragment continuous cubic function as the formula (9)

$$f_i(t) = a_i + b_i(t - t_i) + c_i(t - t_i)^2 + d_i(t - t_i)^3 \tag{9}$$

Found that the n cloud gauge line collection of functions $\{f_i(t) \mid i = 1, ..., N\}$ to describe the entire set of data, where $f_i(t)$ must be satisfy the following conditions.

$$f_i(t_i) = \hat{s}_i = f_{i-1}(t_i),\ f_i'(t_i) = f_{i-1}'(t_i),$$
$$f_i''(t_i) = f_{i-1}''(t_i),\ f_1''(t) = f_N''(t) = 0 .$$

Then, the embedded information is extracted as the formula (10):

$$m_i^* = \begin{cases} 1 & if \quad \hat{s}_i - \lfloor \hat{s}_i / Q \rfloor \cdot Q \ge Q/2 \\ 0 & if \quad \hat{s}_i - \lfloor \hat{s}_i / Q \rfloor \cdot Q < Q/2 \end{cases} \tag{10}$$

where $\{m_i^*\}$ represents the extracted information.

4 Experimental Results

At present, there are only three databases that are internationally recognized as the authorized ECG databases, namely, the MIT-BIH database of the Massachusetts Institute of Technology, the AHA database of the American Heart Association, and the European ST-T ECG database. In this study, we select the ECG data from the MIT-BIH Arrhythmia database [16]. This database includes 48 groups, within two-lead ECG recordings for half an hour, a total of up to 24 hours of information. This database contains 47 individuals' ECG information (datasets ID 201 and 202 are duplicated, so we select different signal segments for our test); subjects consist of 25 men aged from 32 to 89 and 22 women aged from 23 to 89. In this section, we execute the proposed method including information hiding encryption and compression on each ECG signal with length 4,096 sampled from 47 datasets in the MIT-BIH arrhythmia database. Each ECG signal is first adjusted to have zero mean to eliminate the DC offset. Evaluation of the proposed method is present in the following.

From the results in Table 1, two observations are discussed. First, for the same threshold value, strong embedding strength has better compression due to the fact that the variation of the overall audio is small when the embedding strength is strong. As a result, the SNR, rRMSE and RMSE are worse. Second, for different thresholds, we found that CR value is increased when the threshold value is greater than the embedding strength. Restate, compression is better when the threshold value is greater than the embedding strength. These two characteristics are verified in Table 2 and Table 3 respectively.

Furthermore, we evaluate the appropriate threshold ε and embedding strength Q to balance the tradeoff between CR and SNR. Figure 5 illustrates the equilibrium point between CR and SNR under fixed embedding strength Q=1. Figure 6 illustrates the equilibrium point between CR and SNR under fixed threshold ε=1.

5 Conclusions

In this paper, we study the integration method of the ECG signal information hiding and compression. The integration method not only protect the security of the ECG transmission but also reduce the amount of ECG transmission. Furthermore, we evaluate the appropriate threshold ε and embedding strength Q to balance the tradeoff between CR and SNR. The future work is to find the optimal ε and Q between the CR and SNR.

Table 1. ECG information hiding and compression test results

Data	Threshold	Q	CR	PDR	SNR	BER	rRMSE	RMSE
100	100	100	1.2824	1.3297	37.5249	0.9277	0.4937	60.9803
		500	1.8798	4.0031	27.9521	3.6621	0.5291	183.5937
		1000	2.9320	7.5325	22.4612	5.1514	0.6960	345.9822
		2048	4.5511	14.7435	16.6280	5.5664	0.9348	689.0186
		4096	7.5156	27.9128	11.0839	5.9570	1.0369	1.3805e+003
	500	100	3.3740	4.5119	26.9128	4.8096	1.5620	206.9169
		500	1.8798	4.0031	27.9521	3.6621	0.5291	183.5937
		1000	2.9320	7.5325	22.4612	5.1514	0.6960	345.9822
		2048	4.5511	14.7435	16.6280	5.5664	0.9348	689.0186
		4096	7.5156	27.9128	11.0839	5.9570	1.0369	1.3805e+003
	1000	100	10.9812	23.5140	12.5735	5.9570	7.8656	1.0784e+003
		500	7.0137	10.4851	19.5885	5.6152	1.4071	480.8776
		1000	2.9320	7.5325	22.4612	5.1514	0.6960	345.9822
		2048	4.5511	14.7435	16.6280	5.5664	0.9348	689.0186
		4096	7.5156	27.9128	11.0839	5.9570	1.0369	1.3805e+003
101	100	100	1.2518	1.1270	28.9612	0.7568	0.4117	47.0806
		500	1.9807	4.0070	27.7931	4.1260	0.5487	170.5452
		1000	3.1752	7.8114	22.1455	5.7861	0.6999	328.0321
		2048	5.1848	15.6673	16.1001	6.2012	0.8381	672.1536
		4096	8.5333	30.5124	10.3105	6.5186	1.0661	1.3756e+003
	500	100	3.8209	4.5273	26.8831	4.7119	1.5326	189.1233
		500	1.9807	4.0070	27.7931	4.1260	0.5487	170.5452
		1000	3.1752	7.8114	22.1455	5.7861	0.6999	328.0321
		2048	5.1848	15.6673	16.1001	6.2012	0.8381	672.1536
		4096	8.5333	30.5124	10.3105	6.5186	1.0661	1.3756e+003
	1000	100	12.5644	38.3754	8.3189	6.5674	11.1361	1.6031e+003
		500	8.2414	12.8264	17.8379	6.0791	1.3857	536.5359
		1000	3.1752	7.8114	22.1455	5.7861	0.6999	328.0321
		2048	5.1848	15.6673	16.1001	6.2012	0.8381	672.1536
		4096	8.5333	30.5124	10.3105	6.5186	1.0661	1.3756e+003
102	100	100	1.3889	1.2777	37.8712	1.0986	0.3735	70.3929
		500	2.0398	3.7400	28.5427	3.4668	0.5296	206.1828
		1000	3.2663	6.8321	23.3089	4.7119	0.6330	377.9388
		2048	5.6264	12.6983	17.9251	5.0049	0.7711	711.0507
		4096	10.1136	23.5035	12.5774	5.5176	0.9972	1.3591e+003
	500	100	3.7372	4.2549	27.4223	4.6387	1.0696	234.4087
		500	2.0398	3.7400	28.5427	3.4668	0.5296	206.1828
		1000	3.2663	6.8321	23.3089	4.7119	0.6330	377.9388
		2048	5.6264	12.6983	17.9251	5.0049	0.7711	711.0507
		4096	10.1136	23.5035	12.5774	5.5176	0.9972	1.3591e+003
	1000	100	15.8760	19.6754	14.1215	5.7373	5.4751	1.0840e+003
		500	8.0630	8.5770	21.333	5.4932	1.2893	472.8477
		1000	3.2663	6.8321	23.3089	4.7119	0.6330	377.9388
		2048	5.6264	12.6983	17.9251	5.0049	0.7711	711.0507
		4096	10.1136	23.5035	12.5774	5.5176	0.9972	1.3591e+003
103	100	100	1.3676	0.9204	40.7209	1.0254	0.3558	48.5834
		500	2.2934	3.3630	29.4656	4.3701	0.4141	177.6400
		1000	3.6868	6.3754	23.9098	5.5176	0.5336	337.8759
		2048	6.7927	12.8518	17.8207	6.1279	0.7803	686.8794
		4096	9.8462	23.7338	12.4927	6.3965	0.9554	1.3129e+003
	500	100	5.0135	6.3998	23.8767	5.2734	2.0738	337.8303
		500	2.2934	3.3630	29.4656	4.3701	0.4141	177.6400
		1000	3.6868	6.3754	23.9098	5.5176	0.5336	337.8759
		2048	6.7927	12.8518	17.8207	6.1279	0.7803	686.8794
		4096	9.8462	23.7338	12.4927	6.3965	0.9554	1.3129e+003
	1000	100	13.8847	43.4587	7.2385	6.3965	12.3850	2.2941e+003
		500	9.7062	16.2784	15.7678	5.8105	2.2083	859.8685
		1000	3.6868	6.3754	23.9098	5.5176	0.5336	337.8759
		2048	6.7927	12.8518	17.8207	6.1279	0.7803	686.8794
		4096	9.8462	23.7338	12.4927	6.3965	0.9554	1.3129e+003

Table 1. ECG information hiding and compression test results (continue)

Data	Threshold	Q	CR	PDR	SNR	BER	rRMSE	RMSE
104	100	100	1.4357	1.5636	36.1176	0.8301	0.2868	88.3859
		500	2.4294	3.6915	28.6561	3.4912	0.4774	208.7213
		1000	4.1839	6.4645	23.7893	4.8828	0.5592	366.5527
		2048	7.0499	12.4365	18.1060	5.2490	0.7744	712.3187
		4096	10.3696	23.3971	12.6168	5.5420	0.9197	1.3883e+003
	500	100	5.7528	3.8668	28.2485	4.7363	1.2352	218.6941
		500	2.4294	3.6915	28.6561	3.4912	0.4774	208.7213
		1000	4.1839	6.4645	23.7893	4.8828	0.5592	366.5527
		2048	7.0499	12.4365	18.1060	5.2490	0.7744	712.3187
		4096	10.3696	23.3971	12.6168	5.5420	0.9197	1.3883e+003
	1000	100	19.7874	47.5668	6.4539	5.6885	6.7055	2.6888e+003
		500	12.0032	14.1740	16.9702	5.5908	1.6149	801.4229
		1000	4.1839	6.4645	23.7893	4.8828	0.5592	366.5527
		2048	7.0499	12.4365	18.1060	5.2490	0.7744	712.3187
		4096	10.3696	23.3971	12.6168	5.5420	0.9197	1.3883e+003
105	100	100	1.3828	0.8311	41.6071	0.3418	0.2151	57.8068
		500	2.0635	2.7696	31.1516	2.6611	0.5141	192.7447
		1000	3.0705	5.1432	25.7754	3.8330	0.5916	358.1564
		2048	4.9290	9.8675	20.1159	4.2969	0.7854	690.8857
		4096	7.5294	18.2372	14.7808	4.8584	0.9328	1.3285e+003
	500	100	3.4682	2.8715	30.8378	3.1494	1.0476	199.7312
		500	2.0635	2.7696	31.1516	2.6611	0.5141	192.7447
		1000	3.0705	5.1432	25.7754	3.8330	0.5916	358.1564
		2048	4.9290	9.8675	20.1159	4.2969	0.7854	690.8857
		4096	7.5294	18.2372	14.7808	4.8584	0.9328	1.3285e+003
	1000	100	9.1429	17.2639	15.2572	4.4922	5.5332	1.2008e+003
		500	6.4810	7.2795	22.7580	4.4434	1.6574	506.5960
		1000	3.0705	5.1432	25.7754	3.8330	0.5916	358.1564
		2048	4.9290	9.8675	20.1159	4.2969	0.7854	690.8857
		4096	7.5294	18.2372	14.7808	4.8584	0.9328	1.3285e+003
106	100	100	1.3045	0.7215	42.8349	0.6104	0.1806	44.6872
		500	1.7941	2.5311	31.9338	3.6377	0.2941	156.7871
		1000	2.6324	5.1811	25.7116	5.5664	0.5132	321.5247
		2048	4.5461	10.5144	19.5643	7.2021	0.6998	658.0060
		4096	8.1109	20.4597	13.7820	7.7148	0.9237	1.3046e+003
	500	100	2.6684	2.8823	30.8051	4.7852	0.6075	178.5155
		500	1.7941	2.5311	31.9338	3.6377	0.2941	156.7871
		1000	2.6324	5.1811	25.7116	5.5664	0.5132	321.5247
		2048	4.5461	10.5144	19.5643	7.2021	0.6998	658.0060
		4096	8.1109	20.4597	13.7820	7.7148	0.9237	1.3046e+003
	1000	100	7.3669	15.1823	16.3732	7.2754	2.1630	940.3025
		500	4.7628	6.0079	24.4256	6.2500	0.6002	372.1514
		1000	2.6324	5.1811	25.7116	5.5664	0.5132	321.5247
		2048	4.5461	10.5144	19.5643	7.2021	0.6998	658.0060
		4096	8.1109	20.4597	13.7820	7.7148	0.9237	1.3046e+003
107	100	100	1.2978	0.2208	53.1216	0.3418	0.0640	31.4464
		500	1.7181	0.9809	40.1674	2.0752	0.2372	139.7287
		1000	2.3273	1.9785	34.0731	3.3203	0.2654	281.7709
		2048	3.7034	4.2914	27.3480	4.7607	0.3926	612.7127
		4096	6.3602	9.0222	20.8938	5.2002	0.6425	1.2949e+003
	500	100	2.3786	1.2534	38.0380	3.0029	0.6135	178.5460
		500	1.7181	0.9809	40.1674	2.0752	0.2372	139.7287
		1000	2.3273	1.9785	34.0731	3.3203	0.2654	281.7709
		2048	3.7034	4.2914	27.3480	4.7607	0.3926	612.7127
		4096	6.3602	9.0222	20.8938	5.2002	0.6425	1.2949e+003
	1000	100	4.5210	11.2999	18.9385	4.5410	4.6678	1.6096e+003
		500	3.3795	4.1278	27.6856	3.7109	0.4934	587.9960
		1000	2.3273	1.9785	34.0731	3.3203	0.2654	281.7709
		2048	3.7034	4.2914	27.3480	4.7607	0.3926	612.7127
		4096	6.3602	9.0222	20.8938	5.2002	0.6425	1.2949e+003

Table 2. Data No.101 in embedding strength Q=1 Different threshold ε, ECG watermark and compression test results

Data	Q	threshold	CR	PDR	SNR	BER	rRMSE	RMSE
101	1	0.1	1.2431	1.0948	39.2131	0.7080	0.4104	45.7355
		10	1.2431	1.0948	39.2131	0.7080	0.4104	45.7355
		100	1.2518	1.1270	38.9612	0.7568	0.4117	47.0806
		200	1.3871	1.6887	35.4492	1.6357	0.3973	70.5245
		300	1.5545	2.5729	31.7915	2.6611	0.4183	107.5203
		500	1.9807	4.0770	27.7931	4.1260	0.5487	170.5452
		1000	3.1752	7.8114	22.1455	5.7861	0.6999	328.0321
		2000	5.5187	15.4261	16.2349	6.1035	0.8476	658.4814

Table 3. Data No.101 in the threshold ε = 1, different embedding strength Q, ECG watermark and compression test results

Data	Threshold	Q	CR	PDR	SNR	BER	rRMSE	RMSE
101	1	100	1.2518	1.1270	38.9612	0.7568	0.4117	47.0806
		200	1.3871	1.6887	35.4492	1.6357	0.3973	70.5245
		300	1.5545	2.5729	31.7915	2.6611	0.4183	107.5203
		400	1.7670	3.2348	29.8031	3.3447	0.4380	135.0752
		500	1.9807	4.0770	27.7931	4.1260	0.5487	170.5452
		1000	3.1752	7.8114	22.1455	5.7861	0.6999	328.0321
		2048	5.1848	15.6673	16.1001	6.2012	0.8381	672.1536
		4096	8.5333	30.5124	10.3105	6.5186	1.0661	1.3756e+003

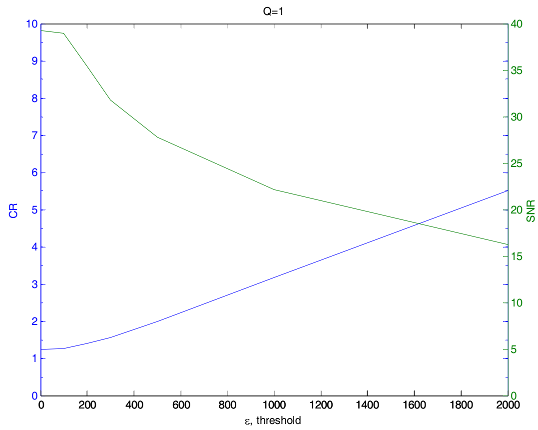

Figure 5. The equilibrium point between CR and SNR under fixed embedding strength Q=1

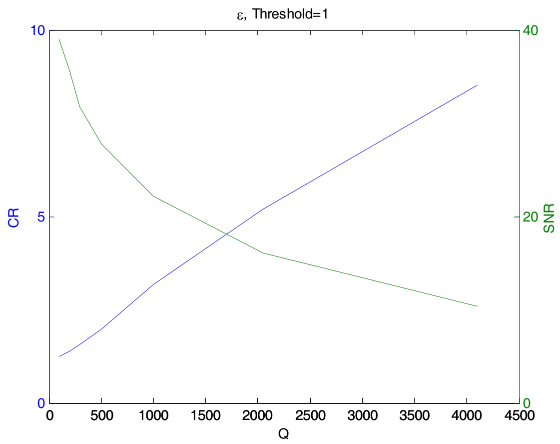

Figure 6. The equilibrium point between CR and SNR under fixed threshold ε=1

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