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An Information Hiding Algorithm for Speech Perceptual Hashing Authentication System in G.729 Bitstream

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Abstract. *Aiming at the problem that how to hide and transmit perceptual hash value efficiently in mobile environment, based on matrix coding, an information hiding algorithm for speech perceptual hashing authentication system in G.729 bitstream was proposed in this paper. This algorithm employs matrix coding to embed perceptual hash values in the least significant bits of G.729 frames which are selected by the perceptual evaluation of the speech quality (PESQ) to carry secret data with less impact on the quality of decoded speech. Experimental results show that the proposed algorithm had good transparency (the average PESQ score was 3.76 and the loss of PESQ was less than 4%), higher embedding efficiency (the embedding efficiency was 2.56), and superb algorithm efficiency that satisfies the real-time performance requirement of the speech perceptual hashing authentication in G.729 bitstream.*

Keywords: Information hiding; Speech perceptual hashing; G.729 bitstream, Matrix coding; PESQ.

1. **Introduction.** As one of the most important means of communication in the internet, voice over IP (VoIP) is widely used with the rapid development. Besides the real-time properties [1], security of content is another important performance of VoIP. Currently, speech perceptual hashing authentication is regarded as an effective way of speech content authentication [2]. Consequently, realizing the hiding and transmission of perceptual hash values of authentication in low bit rate speech coding environment with good transparency, robustness and security has become an indispensable part in the research on speech perceptual hashing authentication [3], which is just important as perceptual hashing algorithm.

Perceptual hashing algorithm in compressed domain and low bit rate speech is a research hotspot in current speech perceptual hashing authentication studies. However, there are few research results in hash values hiding and transmission integrated with low bit rate speech codec. This is where this paper focuses on to perfect speech perceptual hashing authentication system in low bit rate speech coding environment. Realizing efficient hiding of hash values is an important step of speech perceptual hashing authentication in low bit rate speech coding environment. Information hiding algorithm is suitable for bitstream combines hiding with coding at low computational cost. Represented by a steganography algorithm for embedding data in the inactive frames of low bit rate audio streams is proposed in [4], hiding algorithm based on least significant bit (LSB) technology is regarded as the mainstream approach applied to low bit rate speech. The location of least significant bits is the first step in LSB. Researchers utilize speech quality evaluation criteria to locate least significant bits, such as PESQ in the internet low bit rate codec (iLBC) [5] and G.723.1 [6, 7], signal to noise ratio (SNR) in G.729 [8] and G.723.1 [9], and degree of distortion mentioned in [10]. From a comprehensive perspective, recommended by ITU-T [11], PESQ is more scientific and reasonable. Embedding is another important step after LSB location. However, considering the particularity of bit stream, there are few embedding algorithms or information hiding methods which are suitable for low bit rate speech coding environment. Representatives of few algorithms in this field are matrix encoding (ME) algorithm, which was first introduced in [12] and made popular in [13], and its improved algorithms named the dynamic matrix encoding (DME) was proposed in [14] and adjustable matrix encoding (AME) was proposed in [15] with the unsatisfying embedding rate $R= n/2n$-1 even inapplicable in perceptual hashing authentication whose secret data quantity is small. There is also an information hiding method based on dynamic codebook designed for iLBC [5]. Matrix coding [16] is another information hiding algorithm that is suitable for low bit rate speech and will be introduced in this paper in detail.

Aiming at perceptual hashing authentication for G.729 coded speech, based on a kind of steganography applied to low bit rate speech, an information hiding algorithm in low bit rate speech stream is proposed in this paper, embedding the scrambled perceptual hash values from the perceptual hashing in [17] in G.729 bitstream and realizing the hiding and transmission of perceptual hash values in low bit rate speech coding environment with good comprehensive properties.

The rest of this paper is organized as follows. Section 2 describes problem statement and preliminaries. Section 3 presents our proposed algorithm in detail. Performance evaluation and analysis of experimental results are given in Section 4. Finally, we conclude our paper in Section 5.

2. Problem Statement and Preliminaries.

2.1. Speech Perceptual Hashing Authentication in Low Bit Rate Speech Coding Environment. Speech perceptual hashing authentication in low bit rate speech coding environment consists of two parts: perceptual hashing and hash value hiding respectively integrated with low bit rate speech codec, which is represented by G.729. Detailed framework of authentication is shown in Fig. 1.

This paper mainly studies the hash value hiding integrated with G.729 low bit rate speech codec. More specifically, this paper studies hash embedding and extraction in G.729 bitstream. Considering the new requirements of computational efficiency of algorithms in speech perceptual hashing authentication in low bit rate speech coding environment raised by real-time voice communication, computational cost of information hiding algorithm is the key performance besides transparency and security. The perceptual hashing used in the experiments is the speech feature extraction method proposed in [17], which is designed specifically for G.729 codec and generates hash sequence from

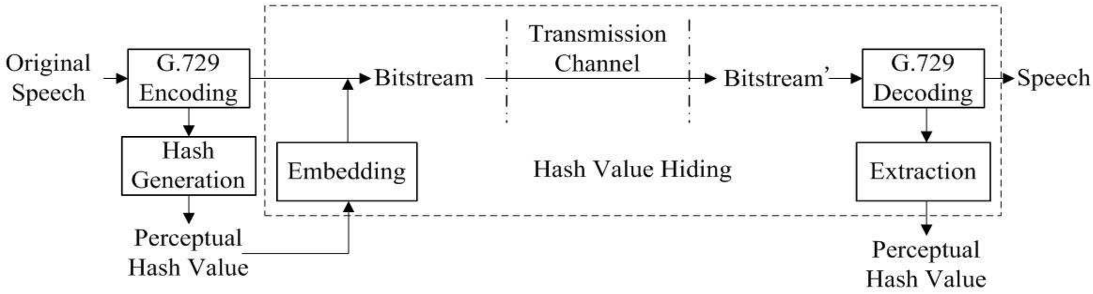


FIGURE 1. The framework of speech perceptual hashing authentication.

LSP coefficients and Pitch-delay in each frame. As the typical representative of integration with perceptual hashing and low bit rate speech codec, this method minimizes the computational cost and reduces the sizes of the features: totally 4 bits per frame.

2.2. **Matrix Coding.** Matrix coding [16] is one of the few information hiding algorithms which can be used in low bit rate speech. Based on bit exclusive-or operation, using an augmented identity matrix $W^{(L)}$ and some intermediate vectors, matrix coding embeds $2L$ bits secret data by changing, at most, L bits in the $(2L{+}1)$ bits cover data with high embedding efficiency and low computational cost satisfying the requirements of low bit rate speech codec. The detailed process of information hiding algorithm based on matrix coding for speech perceptual hashing authentication in low bit rate speech is described briefly in Section 3.

3. **Proposed Algorithm.** Considering that the length of perceptual hash values of perceptual hashing algorithm in [17], which is used in this paper for performance evaluation of information hiding algorithm, is 4 bit in each frame, the purpose of the information hiding algorithm proposed is to embed a 4-order binary vector in each frame which is compressed into 80 bits. According to the principle of matrix coding introduced in Section 2, in a frame consisted of 80 bits, the host of the secret information that to be embedded, a 4-order binary vector, is a 5-order binary cover vector.

3.1. **Embedding Process.** In the embedding process of frame, let $\boldsymbol{a}= (a_1,\ a_2,\ a_3,\ a_4,\ a_5)^T$ be the cover vector, that is the host which can be modified, $\boldsymbol{b}=(b_1,\ b_2,\ b_3,\ b_4)^T$ be the secret information, and both of them two are binary vectors.

The steps of embedding process are described as follows in detail:

Step 1.: Based on matrix coding [16], when the secret information is a 4 bit binary vector to each frame, the augmented identity matrix $W^{(L)}$ needs to be defined as follow:

$$W^{(2)} = (\boldsymbol{w}_1, \boldsymbol{w}_2, \boldsymbol{w}_3, \boldsymbol{w}_4, \boldsymbol{w}_5) = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{1}$$

where $\boldsymbol{w}_i$ is the column vector of the 4-order augmented identity matrix showed above.

The column vector values are 8, 4, 2, 1 and 15. The four-dimensional binary vector of any number between 1 and 15 can be calculated by no more than two column vectors of $W^{(L)}$ based on exclusive or operation.

Step 2.: Calculate the intermediate vector

$$\boldsymbol{c} = W\boldsymbol{a} = \boldsymbol{w}_1 a_1 \oplus \boldsymbol{w}_2 a_2 \oplus \boldsymbol{w}_3 a_3 \oplus \boldsymbol{w}_4 a_4 \oplus \boldsymbol{w}_5 a_5 \tag{2}$$

where $\boldsymbol{w}_i$ is i-th column vector of $W^{(2)}$, and the intermediate vector $\boldsymbol{c}$ is a 4-order binary vector.

Step 3.: Calculate the intermediate vector

$$\boldsymbol{d} = \boldsymbol{b} \oplus \boldsymbol{c} \tag{3}$$

If $|\boldsymbol{d}|$=0, namely $\boldsymbol{b}$=$\boldsymbol{c}$, there is no need to modify the cover vector $\boldsymbol{a}$, the host vector after being embedded $\boldsymbol{a}^{'}$=$\boldsymbol{a}$. If $|\boldsymbol{d}|\neq$0, namely $\boldsymbol{b}\neq\boldsymbol{c}$, there are no more than two column vectors in $W^{(2)}$, which satisfies:

$$\boldsymbol{d} = \boldsymbol{w}_{i1} \quad \text{or} \quad \boldsymbol{d} = \boldsymbol{w}_{i1} \oplus \boldsymbol{w}_{i2} \tag{4}$$

where $\boldsymbol{w}_{i1}$ and $\boldsymbol{w}_{i2}$ are one or two column vectors in $W^{(2)}$.

Step 4.: Negate bits in the cover vector $\boldsymbol{a}$ to obtain the host vector after being embedded of secret information $\boldsymbol{a}^{'}$:

$$\boldsymbol{a}^{'} = (\ldots, \sim a_{i1}, \ldots) \quad \text{or} \quad \boldsymbol{a}^{'} = (\ldots, \sim a_{i1}, \ldots, \sim a_{i2}, \ldots) \tag{5}$$

where a_{i1} and a_{i2} are the bits of $\boldsymbol{a}$ correspond to $\boldsymbol{w}_{i1}$ and $\boldsymbol{w}_{i2}$.

3.2. **Extraction Process.** In the extraction process which is relatively simple, let $\boldsymbol{a}^{'}$ be the host vector with secret information.

The steps of extraction process are described as follows in detail:

Step 1.: Create a 4-order augmented identity matrix $W^{(2)}$, the same as above in **Step 1** of embedding process.

Step 2.: Calculate the secret information:

$$\boldsymbol{b} = W\boldsymbol{a}^{'} \tag{6}$$

If $|\boldsymbol{d}|$=0, so $\boldsymbol{b}$=$\boldsymbol{c}$, $\boldsymbol{b}$=$W\boldsymbol{a}^{'}$= $W\boldsymbol{a}$ =$\boldsymbol{c}$=$\boldsymbol{b}$, if $|\boldsymbol{d}|\neq$0, so $\boldsymbol{b}\neq\boldsymbol{c}$,

$$\begin{aligned}\boldsymbol{b} &= W\boldsymbol{a}^{'} = W(a_1, \ldots, a_{i1} \oplus 1, \ldots, a_{i2} \oplus 1, \ldots, a_5) \\ &= [\boldsymbol{w}_1 a_1 \oplus \cdots \oplus \boldsymbol{w}_{i1} a_{i1} \oplus \cdots \oplus \boldsymbol{w}_{i2} a_{i2} \oplus \cdots \oplus \boldsymbol{w}_5 a_5] \oplus \boldsymbol{w}_{i1} \oplus \boldsymbol{w}_{i2} \\ &= \boldsymbol{c} \oplus \boldsymbol{d} \\ &= \boldsymbol{b}\end{aligned} \tag{7}$$

Moreover, the security of hash values hiding in the authentication is ensured by Logistic Map before embedding process and after extraction process.

4. **Experimental Results and Analysis.** In this part, embedding performance, transparency and efficiency of information hiding algorithm proposed in this paper are analyzed. Before transparency analysis, the least significant bits of G.729 frame are located. Evaluation criterion is introduced in each analysis part.

A total number of 800 English speech clips (16-bit signed, 8 kHz sampled and 4 s length) randomly selected from English Language Speech Database for Speaker Recognition (ELSDSR) speech database are used to evaluate the transparency of the proposed algorithm. The secret information in each frame is the perceptual hash sequence generated from perceptual hashing proposed in [17] of which length is 4. From what has been mentioned above in Section 2.2 and Section 3, the length of cover vector is 5.

Experiments are conducted on a PC with Intel(R) Core(TM) i5-4590 CPU 3.30 GHz and 4 GB main memory.

4.1. **Embedding Performance Analysis.** Common evaluation indexes, such as embedding rate (denoted by $W(r)$), average distortion (denoted by $S(r)$), bit-change rate (denoted by $D(r)$) and embedding efficiency (denoted by $E(r)$), where r is the length of secret information, are used in this part to analyze embedding performance of hiding algorithm proposed and calculated as follows with r=4.

$$W(r) = \frac{r}{l} = \frac{r}{r+1} = \frac{4}{5} \tag{8}$$

$$S(r) = 0 \times \frac{C_l^0}{2^r} + 1 \times \frac{C_l^1}{2^r} + 2 \times \frac{C_l^2}{2^r} = 1.5625 \tag{9}$$

$$D(r) = \frac{S(r)}{l} = 0.3125 \tag{10}$$

$$E(r) = \frac{W(r)}{D(r)} = 2.56 \tag{11}$$

where l is the length of cover vector. In this paper l=5.

Table 1 shows the comparisons in embedding performance between algorithm in this paper and other algorithms such as traditional LSB [18], matrix encoding (ME) [12], dynamic matrix encoding (DME) [14] (also used in [19]) and adjustable matrix encoding (AME) [15].

Table 1. Comparison of embedding performance

Algorithm	$W(4)$	$S(4)$	$D(4)$	$E(4)$
LSB [18]	1	0.5	0.5	2
ME [12]	0.2667	0.9375	0.0625	4.27
AME [15]*	0.2667	0.9375	0.0625	4.27
DME [14]	0.8008	-	0.3552	2.25
	0.7291	-	0.3005	2.43
This paper	0.8	1.5625	0.3125	2.56

*From what has been discussed in [15], the ME algorithm can only embed at most 5 bits of secret messages and the AME algorithm outperforms the ME algorithm on adaptability.

As shown in Table 1, the algorithm proposed in this paper has advantages in embedding rate and embedding efficiency. Although the ME algorithm and AME algorithm have great advantage in embedding efficiency, they need more cover bits in embedding process. Yet this is what should be avoided in information hiding with speech coding standard.

4.2. **The LSBs of G.729 Frame.** In order to locate the least significant bits of G.729 frame, a one by one bit flipping test of G.729 speech frames is conducted on a total number of 150 English speeches (16 bit signed, 8 kHz sampled and 4 s long) randomly selected from ELSDSR speech database by PESQ, whose range is −0.5 (worst) to 4.5 (best).

Each G.729 speech consist of several 80 bits frames representing 10ms speech clips of original speech separately. The bits allocation for G.729 speech frames [20] is shown in Table 2.

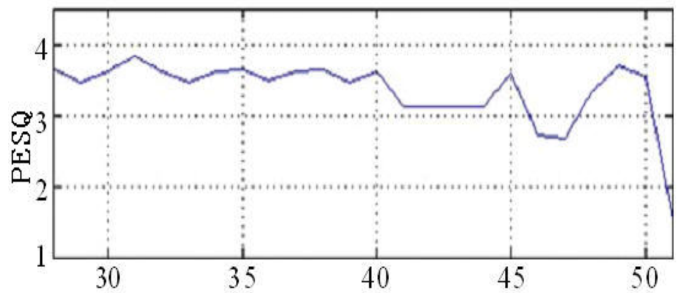
This test flips a bit of all speeches every time to judge if it can be recognized as the least significant bit.

According to the perceptual hashing algorithm [17] and description of information hiding algorithm proposed in Section 3, LSP coefficients denoted as $L0$, $L1$, $L2$, $L3$, and Pitch-delay denoted as $P1$ and $P2$ are used to structure perceptual hash values, whose total size is 4 bits per frame, so results of this test is 5 least significant bits of G.729

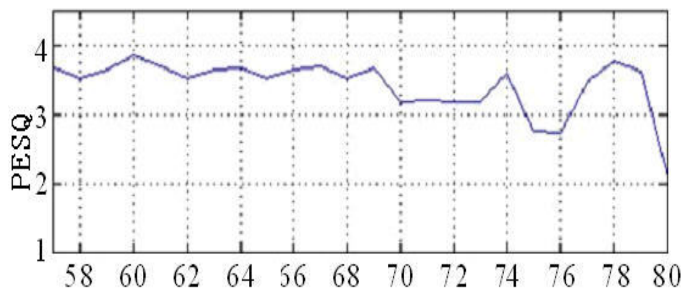
Table 2. Bits allocation for G.729 speech frames

Bit	Table	Bit	Table	Bit	Table	Bit	Table	Bit	Table
1	L0	17	L3-1	33	C1-7	49	GB1-2	65	C2-4
2	L1-6	18	L3-0	34	C1-6	50	GB1-1	66	C2-3
3	L1-5	19	P1-7	35	C1-5	51	GB1-0	67	C2-2
4	L1-4	20	P1-6	36	C1-4	52	P2-4	68	C2-1
5	L1-3	21	P1-5	37	C1-3	53	P2-3	69	C2-0
6	L1-2	22	P1-4	38	C1-2	54	P2-2	70	S2-3
7	L1-1	23	P1-3	39	C1-1	55	P2-1	71	S2-2
8	L1-0	24	P1-2	40	C1-0	56	P2-0	72	S2-1
9	L2-4	25	P1-1	41	S1-3	57	C2-12	73	S2-0
10	L2-3	26	P1-0	42	S1-2	58	C2-11	74	GA2-2
11	L2-2	27	P0	43	S1-1	59	C2-10	75	GA2-1
12	L2-1	28	C1-12	44	S1-0	60	C2-9	76	GA2-0
13	L2-0	29	C1-11	45	GA1-2	61	C2-8	77	GB2-3
14	L3-4	30	C1-10	46	GA1-1	62	C2-7	78	GB2-2
15	L3-3	31	C1-9	47	GA1-0	63	C2-6	79	GB2-1
16	L3-2	32	C1-8	48	GB1-3	64	C2-5	80	GB2-0

speech frame from 28 to 51 and 57 to 80. PESQ scores of these bits is shown in Fig. 2 and five bigger ones which can be used as least significant bits to be embedded are shown in Table 3.



(a) 28-51.



(b) 57-80.

Figure 2. PESQ scores of different bits in G.729 speech frame.

From what has been discussed above, C2-9, C1-9, GB2-2, GB1-2 and C2-8 are selected as the least significant bits.

4.3. **Transparency Analysis.** 800 speech clips including Chinese, English, man and woman, are used to evaluate the transparency of the algorithm proposed.

In this experiment, generate and embed secret information, namely the perceptual hash sequence of each frame based on perceptual hashing in [17] and hiding algorithm

Table 3. Least significant bits selected and PESQ scores

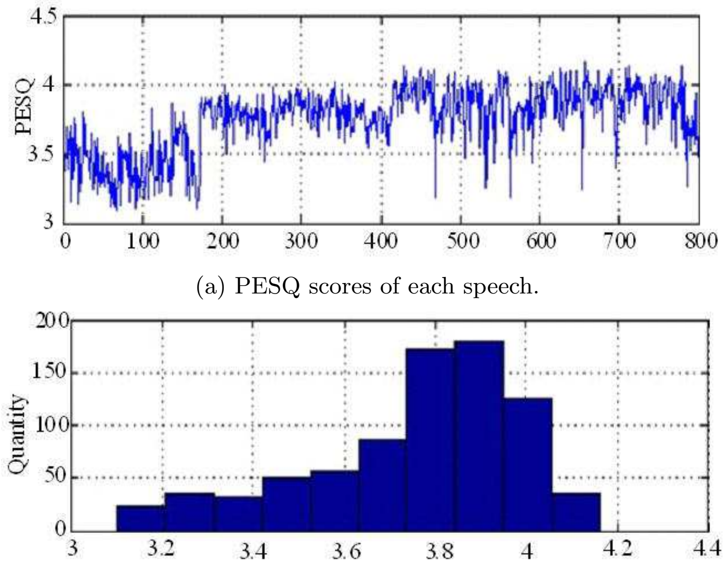
Bit	Table	PESQ
60	C2-9	3.8606
31	C1-9	3.8174
78	GB2-2	3.7729
49	GB1-2	3.7003
61	C2-8	3.6956

proposed in this paper. First speech sample can be obtained after G.729 decode. In addition, another speech sample can be obtained by conducting G.729 codec without hash generation and information embedding. These two speech samples are used in this transparency analysis based on PESQ. Average PESQ score is shown in Table 4.

Table 4. Average PESQ score of 800 speech clips

Speech clips	PESQ
800	3.76
400(English)	3.65
400(Chinese)	3.86

As shown in Table 4, the average PESQ score of 800 speech clips is 3.76. Considering the interval of PESQ, [−0.5, 4.5], the proposed information hiding algorithm is of good transparency. PESQ scores of each speeches and PESQ distribution are shown in Fig. 3.



(a) PESQ scores of each speech.

(b) PESQ distribution.

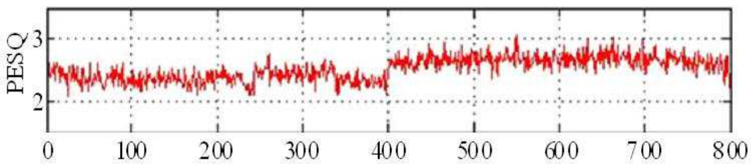
Figure 3. Results of transparency evaluation.

As shown in Fig. 3(b), PESQ scores of most speeches are more than 3.6, which proves the good transparency of algorithm proposed also.

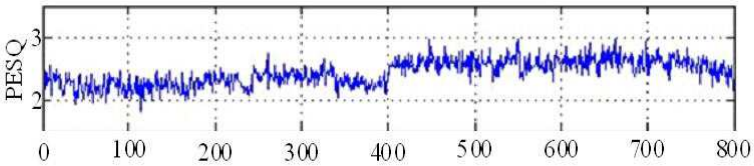
Loss of PESQ is another view of transparency analysis. Calculate the PESQ scores of the speeches after decoded without secret information and the original one, $PESQ_1$, and the scores of secret information embedded and the original, $PESQ_2$, shown in Fig. 4. Calculate the distance between these two, the loss of PESQ, shown in Table 5.

Table 5. Loss of PESQ

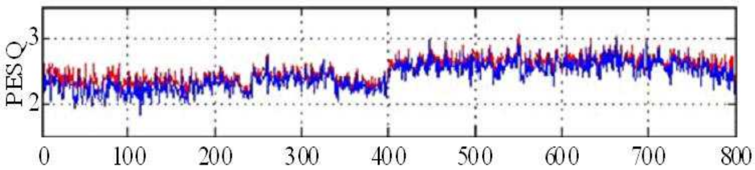
With/Without information embedded	PESQ
$PESQ_1$	2.53
$PESQ_2$	2.44
Loss of PESQ	3.56%



(a) PESQ scores between the speeches after decoded without secret information and the original ones, $PESQ_1$.



(b) PESQ scores between the speeches after decoded with secret information, $PESQ_2$.



(c) Comparison of these two, loss of PESQ.

Figure 4. Loss of PESQ evaluation results.

As shown in Fig. 4 and Table 5, the difference between $PESQ_1$ and $PESQ_2$ is not obvious, and the loss of PESQ of speech quality with secret information embedded is less than 4%, which shows a superb transparency.

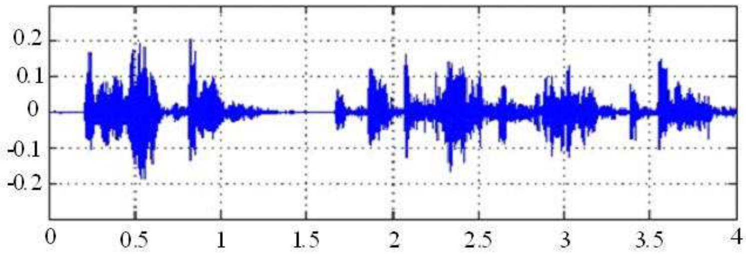
Take a speech clip named "MPRA-Sr32.wav" for instance, comparison of original speech and speech after G.729 decoded with information embedded is shown in Fig. 5.

As can be seen in Fig. 5, the difference between these two speeches is not obvious. Considering that different speech coding standard has different effect on speeches and there is only compution complexity difference between G.729 and G.729a, comparison of PESQ between this algorithm and algorithms in [1, 19], which all are designed for G.729 or G.729a bitstream, is shown in Table 6.

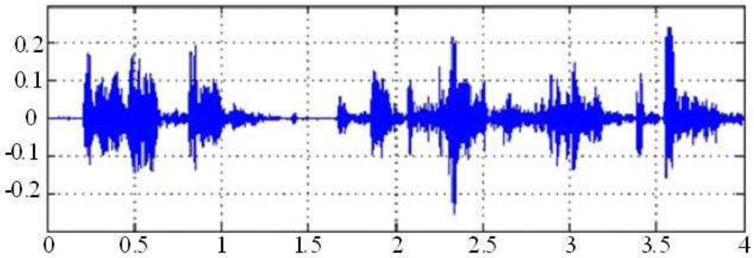
Table 6. Comparison of PESQ

Algorithm	PESQ
Method in [1]	3.11
Method in [19]	>3.4
This paper	3.76

As shown in Table 6, obviously the transparency of algorithm proposed is better than these two above.



(a) Original speech.



(b) Speech after G.729 decoded with information embedded.

Figure 5. Comparison of single speech in time domain

4.4. **Efficiency Analysis.** In order to evaluate the influence of the hiding algorithm proposed on the efficiency of G.729 codec, the computational cost, represented by time of embedding and extracting perceptual hashing value are recorded in Table 7.

Table 7. Time of Embedding and Extracting

Time of embedding	Time of extracting
6.92e−2 ms	3.46e−2 ms

Compared with time delay allowed in G.729 codec for a frame, 15 ms, and the time of embedding and extracting are negligible. Therefore, the hiding algorithm proposed satisfies the efficiency, that is, the real-time requirement of G.729 codec.

5. **Conclusions and Future Work.** An information hiding algorithm in G.729 bitstream is proposed in this paper for the purpose of realizing the hiding and transmission of perceptual hash values and perfecting perceptual hashing authentication system in low bit rate speech coding environment. This algorithm embeds secret information in least significant bits of G.729 bitstream located by PESQ, using bit exclusive or operation and an augmented identity matrix. Experiments show that the proposed method achieves good transparency, higher embedding efficiency, and low computational complexity, which satisfied the real-time requirement of perceptual hashing authentication.

In the future research, the robustness of authentication system in low bit rate speech coding environment and robust information hiding algorithm in G.729 bitstream will become the research focus.

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