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StegTab: Steganography in Guitar Tablatures

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Abstract. *Steganography based on musical notation is a branch of music-based information hiding, which has good steganographic transparency. However, the existing steganographic methods would inevitably reduce the quality of music scores for concealing secret messages. Thus, in this paper, we present four practical strategies for hiding information in different part of guitar tablatures, which can maintain the good quality of music scores and achieve excellent steganographic transparency. Specifically, the first one conceals the secret message into common guitar chord variations; the second and third ones embed the secret message in the fingerings for both hands; the last one hides the secret message into numeric symbols of numbered musical notation. Furthermore, we design an embedding strategy to determine cover positions dynamically in original guitar tablatures to further strengthen the steganographic security. We evaluate our scheme through theoretical analysis and comprehensive experiments. The results demonstrate that our scheme can achieve excellent security (providing huge key space for embedding security and inducing little distortion for embedding transparency) and good embedding capacity (i.e., 10-16 bits/measure).*

Keywords: Information hiding, music-based steganography, tablature-based steganography, guitar tablature.

1. **Introduction.** Steganography is an information security technique which conceals the confidential message into seemingly ordinary carriers in imperceptible ways. In contrast with cryptographic techniques, steganographic security is achieved by concealing the existence of the communication. Thus, steganography can provide better security for secret messages to some extent. In recent years, modern steganography, which uses common multimedia [1, 2, 3, 4, 5, 6, 7, 8] as carriers, has attracted universal attention to the field of information hiding. Nowadays, with the rapid development of information technology, extensive researches on steganography have been carried out on almost all digital multimedia [9]. More recently, new steganographic techniques, which conceal messages into innocent carriers like text [10], music [11, 12, 13] and internet protocols [14], are

popularly considered as one of the priority directions for the development of secret communication. This paper will focus on music steganography, which is an emerging hotspot in the information hiding field.

Music is a subjective art for people to express their mood, emotion, and feeling [15]. The criterion for evaluating music will be determined by subjective feedback of human sensation, and people may have different feelings for a piece of music [15]. In other words, redundancy in music is the part of the human sensory experience that judges whether music is pleased or not. In addition, universality and epidemic are also characteristics of the music. Therefore, music can be considered as a type of ideal carrier for steganography. Differing from the studies on audio steganography that embed secret messages into audio signals, the music steganography technique discussed within this paper aims to conceal secret messages into musical content.

Music steganography has a long history which can date back to the 9^{th} century, when there were music cryptograms in western music theorists to assign notes to letter names [16]. Generally, music encryption techniques can be classified under two categories, namely, 'Syllables to Solmization Name' and 'Letters to Note Name' [17]. The first method proposed by Josquin des Prez [17] considers the similarities between letter pronunciations and musical notes, while the second one used in Bach's music in the 17th century [18] considers the similarities between letter graphemes and musical notes. It is noteworthy to mention that Bach's work is the first one called the music steganography formally [18].

In the recent years, with the rapid development of computer technology, music steganography has been endowed with new connotations. As can be seen from the existing literature, modern steganographic techniques based on music can be classified into three categories. The first one uses musical notes as the carriers to conceal secret messages, or hide secret messages by modulating music pitches. Messiaen developed a new cipher for his organ work, which involved in musical pitches and notes duration [19]. Hutchinson [20] proposed a method which conceals secret messages into musical notes in different octaves. Although the first category can provide protection for secret messages to some extent, the steganographic music might sound weird when people played it [21]. The second category employs the command field as the carriers and embeds secret messages into redundant part of command codes in MIDI files. Adli et al. [11] provided three methods which can hide data into the MIDI container. Yamamoto et al. [12] proposed a Standard MIDI File steganography based on the fluctuation of duration. Szczypiorski [13] presented a new steganographic scheme for club music in MIDI format to embed secret data in music beat. This category includes little distortion for embedding trenchancy while maintaining good embedding rate. The third one uses characteristics of different digital score formats to conceal secret messages into a digital music score. Funk et al. [22] proposed a watermarking technique for scanned music scores, which achieves relatively large embedding capacity.

This paper seeks to present a novel steganographic scheme for Portable Document Format (PDF) guitar tablature, which essentially belongs to the third category of music steganography. Specifically, we first present four practical strategies for embedding secret messages in digital guitar tablatures, further, we design an embedding scheme to determine cover positions dynamically in original guitar tablatures to further strengthen the steganographic security. It has been demonstrated by experimental results that our scheme can achieve excellent security and good embedding capacity.

The rest of this paper is organized as follows. Section 2 introduces four elements for embedding secret messages in the guitar tablature, and Section 3 provides the corresponding embedding strategies for these elements. The process of the dynamic embedding scheme is described in Section 4, followed by the analysis and evaluation of the scheme and its experimental results that are shown in Section 5. Finally, concluding remarks are given in Section 6.

2. Background and Preliminaries. Tablature is a popular form of musical notation for stringed fretted instruments, which, along with the staff (also called standard notation), are two of the most common musical notations used in guitar music. Generally, the staff is based on the visual representation of musical sounds, and the tablature is based on a visual representation of the strings and numeric indicators for fret. Compared with the staff, tablature has many useful advantages, such as direct visual representation, fingering position determination and simple typewriter-font representation [23]. Moreover, tablature has a short learn curve, so the beginner does not have to know anything about reading other music notation to read tablature. Because of its simplicity, tablature has become increasingly widespread in recent years.

A basic guitar tablature consists of six equidistant horizontal lines representing the six strings of the guitar. Symbols in the guitar tablature indicate the finger positions and fingering skills. In addition to the basic tablature, there are generally two elements appearing in the tablature, namely, guitar chord diagram and numbered musical notation. The guitar chord diagram, which consists of six vertical lines representing the guitar chord and a number of horizontal lines representing the guitar fret, is responsible for the melodic content played by the left hand. The numbered notation uses the numeric symbols to imply the pitches of notes, and provides a regular reference point for guitar players to pinpoint locations within a musical composition [24]. The use of these auxiliary elements allows guitar players to learn how to play songs according to the guitar tablature easily.

The purpose of the tablature is designed to represent the playing techniques as intuitively as possible, so the guitar tablature does not have a particular standard for writing compared to the standard notation, and different sheet-music publishers adopt different conventions [23, 25]. According to this property, guitar tablature can be considered as an ideal carrier for steganography. In our study, we consider four elements for the embedding of secret messages, namely, guitar chord variation, chord diagram symbol, tablature symbol and numeric symbol. The supplementary details will be described below.

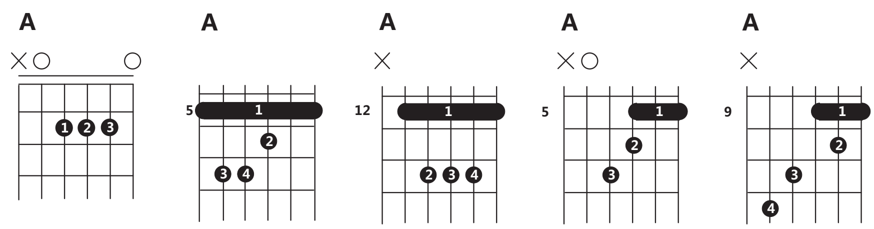


Figure 1. Position variations for A major chord [27]

2.1. Guitar Chord Variation. The guitar chord is a collection of three or more musical notes played simultaneously by guitar, which reflect the relationship between combinations of different pitches [26]. Each guitar chord has its own emotional character. Generally, a regular guitar chord in a standard guitar is comprised of no more than 6 notes. Unlike the piano, the guitar has the same notes on different strings, for example, C^4 can be played on five different guitar strings. Generally, guitarists often double notes within a guitar chord in order to increase the volume of sound [26]. Specifically, notes in the guitar chord can be doubled at identical pitches or in different octaves. In addition, as a result of this feature, a guitar chord can be played with the same notes in more than one place in guitar fretboard [26]. Fig.1 shows some variations for A Chord [27]. Guitarists can select different variations of chords in their music to provide similarities harmonic support for their music, so the change of the chord variation will not destroy the melodic and harmonic structure of music.

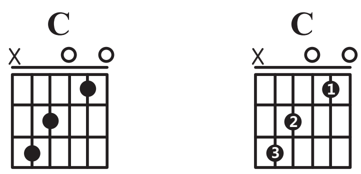


Figure 2. Chart for C major chord

2.2. **Chord Diagram Symbol.** The chord chart (also called chord diagram) is used to indicate the fingering of a particular guitar chord in the guitar fretboard. Generally, there are three commonly used diagram symbols in a chord chart, namely, black dot, o symbol and x symbol. Fig. 2 shows two normal types of charts for C Major Chord. The black dot on a vertical line and between the horizontal lines indicates the fingering of left hand, the o above the nut indicates a string that needs to be played openly, and the x above the nut indicates a string that is not used. In addition, the numbers inside the dots indicate the position of a particular finger on guitar fretboard. For a chord chart, there are visual redundancies that making the embedding of secret messages feasible. Specifically, the guitarist understands chords according to the position of the diagram symbol, so a slight change of the horizontal distance between diagram symbols will not affect the guitarist reading guitar chords.

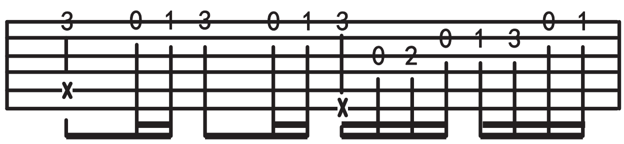


Figure 3. Rhythm fingering in the guitar tablature (Scores are a part of the music *"Cannon"*)

2.3. **Tablature Symbol.** Fig. 3 shows two basic tablature symbols in a part of the guitar tablature: the x symbol denotes the strings to be plucked by the right hand, and the numeric symbol corresponds to fret on the fretboard when the string is played. These two symbols are quite frequently used to indicate basic playing skills. Additionally, other tablature symbols such as arrows, brackets, or other letters are used to indicate advanced fingering techniques. For example, the letter h indicates a Hammer-On and the letter p indicates a Pull-Off. In the guitar tablature, the horizontal axis represents the elapsed time from an arbitrary starting time. Thus, the vertically aligned symbols indicate notes that should be played simultaneously, and the horizontally aligned symbols indicate notes on time series. Although the horizontal axis represents times, the duration of the note will be determined not by the horizontal width, but by the type of the corresponding note. This feature makes it possible for guitarists to understand guitar tablatures correctly even if the horizontal distance between adjacent symbols is deliberately modified.

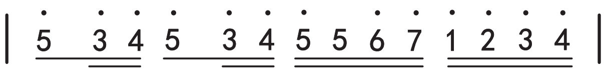


FIGURE 4. Numeric symbols in the numbered musical notation (Scores are about a part of the music "*Cannon*")

2.4. **Numeric Symbol.** The numbered musical notation is mainly composed of numeric symbols with dots and lines. Fig. 4 shows a part of the notation. In this notation, numbers 1 to 7 represent the scale degrees in a major scale, and dot above or below the musical note raises or lowers it to other octaves [28]. Horizontal lines below the note denote the duration of the note, specifically, the plain number represents a quarter note, each underline halves the note length, for example, one represents an eighth note, two represent a sixteenth note, and so on [28]. Like in the guitar tablature, the horizontal axis in the numbered notation also represents times. Thus, symbols in the numbered notation may have same visual characteristics as those in the guitar tablature.

3. **Proposed Embedding Strategies.** In this section, we design four practical strategies for hiding information in different part of guitar tablatures, which can maintain the good quality of music scores and achieve excellent steganographic transparency. Assume that in each strategy, the sender wants to embeds L_M bits of secret messages $M = \{m_i = 0 \text{ or } 1 \mid i = 1, 2, \ldots, L_M\}$ into the cover tablature; L_G is the number of measures in a tablature. In the remaining part of this section, we will describe the proposed four strategies in detail.

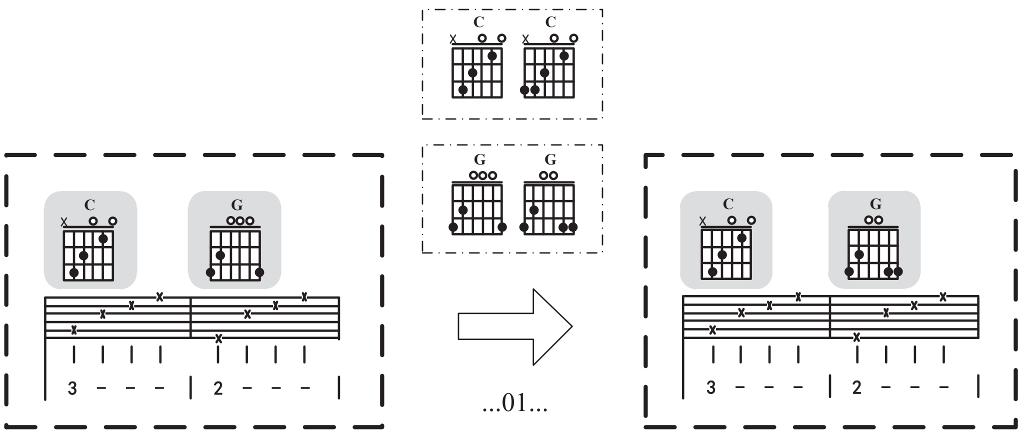


FIGURE 5. Embedding process of the strategy based on chord variation

3.1. **Chord Variation Based Embedding Strategy.** This strategy conceals secret data into guitar tablatures by modulating chord variations, which is illustrated in Fig.5. Let the chord variation sequence for the music be $Z = \{z_1, z_2 \ldots, z_{L_G}\}$, where z_i is the i-th chord variation of the i-th measure in the guitar tablature; Let the chord progression for the music be $A = \{\mathfrak{A}_i \mid i = 1, 2, \ldots, L_G\}$, where $\mathfrak{A}_i = \{a_{i,j} \mid j = 1, 2, \ldots, \alpha\}$, $a_{i,j}$ is the j-th variation of the i-th chord, and $\alpha \in \{2, 4, 8\}$ is the number of variations in $\mathfrak{A}_i$. Before embedding, M is divided into k_1 parts, namely, $M = \{\mathfrak{M}_1, \mathfrak{M}2, \ldots, \mathfrak{M}_{k_1}\}$, where $\mathfrak{M}_i = \{\mathfrak{m}_{i,1}, \mathfrak{m}_{i,2}, \ldots, \mathfrak{m}_{i,l_z}\}$, $i = 1, 2, \ldots, k_1$, $k_1 = \lceil L_M \ / \ l_z \rceil$, $l_z = \log 2(\alpha)$, $\mathfrak{m}_{i,j} = m_{((i-1)\times k_1)+j)}$, $j = 1, 2, \ldots, k_1$, $0 < k_1 < L_G$. For each chord variation z_i, the embedding process can be expressed as

$$z_i' = \begin{cases} a_{i,s}, & i \leq k_1 \\ z_i, & i > k_1 \end{cases}, \tag{1}$$

where z_i' is the steganographic chord variation of the i-th measure, s is the position index in $\mathfrak{A}_i$, which is calculated by the following expression:

$$s = \sum_{j=1}^{l_z} 2^{l_z - j} \times \mathfrak{m}_{k_1,j}. \tag{2}$$

Accordingly, at the receiving part, secret messages can be calculated as

$$\mathfrak{m}_{i,j} = (s - 2^{l_z} \times (1 - (\frac{1}{2})^{j-1})) \bmod 2, \quad i \leq k_1, \ z_i' = a_{i,s}. \tag{3}$$

The corresponding capacity E_Z for this strategy is

$$E_Z = L_G \times l_z = L_G \times \log 2(\alpha). \tag{4}$$

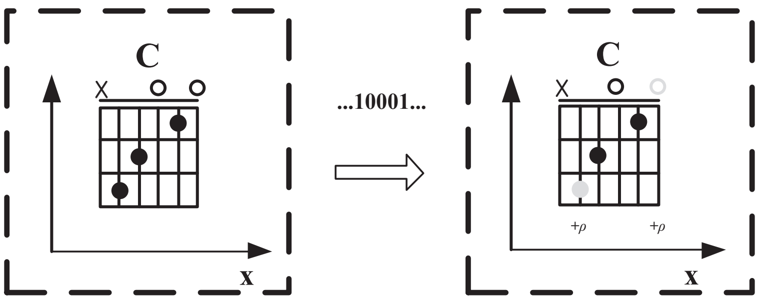


FIGURE 6. Embedding process of the strategy based on chord diagram

3.2. **Chord Diagram Based Embedding Strategy.** Differing from the first strategy, this strategy embeds secret messages into guitar chord diagrams. Specifically, the horizontal distance between the specific diagram symbols (e.g. black dot, o symbol and x symbol), will be modulated by the secret message. Fig.6 illustrates the embedding processes of this strategy. Let the carrier sequence be $D = \{\mathfrak{D}_i \mid i = 1, 2, \ldots, L_G\}$, where $\mathfrak{D}_i = \{d_{i,j} \mid j = 1, 2, \ldots, \beta\}$, $d_{i,j}$ is the abscissa of the j-th chord diagram symbol in the i-th chord chart, $\beta = 6$ is the number of available chord diagram symbols in a chord chart. Before the embedding process, M is divided into k_2 parts, namely, $M = \{\mathfrak{M}_1, \mathfrak{M}2, \ldots, \mathfrak{M}_{k_2}\}$, where $\mathfrak{M}_i = \{\mathfrak{m}_{i,1}, \mathfrak{m}_{i,2}, \ldots, \mathfrak{m}_{i,l_d}\}$, $i = 1, 2, \ldots, k_2$, $k_2 = \lceil L_M \ / \ l_d \rceil$,

$l_d = \beta - 1$, $\mathfrak{m}_{i,j} = m_{((i-1)\times k_2)+j)}$, $j = 1, 2, \ldots, k_2$, $0 < k_2 < L_G$. Assume that the steganographic carrier sequence is $D' = \{\mathfrak{D}'_i \mid i = 1, 2, \ldots, L_G\}$, and $\mathfrak{D}'_i = \{d'_{i,j} \mid j = 1, 2, \ldots, \beta\}$. The embedding process can be described as

$$d'_{i,j} = \begin{cases} d_{i,1} + p \times (j-1) + \mathfrak{m}_{i,j-1} \times \rho, & i \le k_2 \ , \ j \ne 1 \\ d_{i,j}, & i > k_2 \text{ or } j = 1 \end{cases}, \tag{5}$$

where p is the horizontal distance between the adjacent diagram symbols, and ρ represents the offset parameter, which is used to control the offset value for the diagram symbols.

The extracting process can be performed as

$$\mathfrak{m}_{i,j} = \frac{d'_{i,j+1} - d'_{i,1} - p \times j}{\rho}, \quad i \le k_2. \tag{6}$$

Further, the maximum capacity of this strategy E_D can be calculated as

$$E_D = L_G \times (\beta - 1). \tag{7}$$

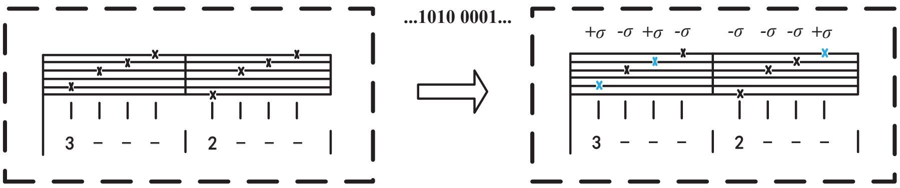


FIGURE 7. Embedding process of the strategy based on tablature

3.3. **Tablature Based Embedding Strategy.** In this part, we design a new embedding strategy to embed secret messages into tablature symbols, and perform the abscissa of x symbol in rhythm fingering as the carrier. Fig.7 shows the embedding processes of this strategy. In the experimental tablatures, each measure has the same number of x symbol except for the last measure. Let the carrier group be $T = \{\mathfrak{T}_i \mid i = 1, 2, \ldots, L_G - 1\}$, where $\mathfrak{T}_i = \{t_{i,j} \mid j = 1, 2, \ldots, \gamma\}$, $t_{i,j}$ is the abscissa of the j-th tablature symbol in the i-th measure, and γ is the number of x symbols in $\mathfrak{T}_i$. Prior to the embedding process, divide M into k_3 parts, namely, $M = \{\mathfrak{M}_1, \mathfrak{M}2, \ldots, \mathfrak{M}_{k_3}\}$, where $\mathfrak{M}_i = \{\mathfrak{m}_{i,1}, \mathfrak{m}_{i,2}, \ldots, \mathfrak{m}_{i,l_t}\}$, $i = 1, 2, \ldots, k_3$, $k_3 = \lceil L_M \ / \ l_t \rceil$, $l_t = \gamma$, $\mathfrak{m}_{i,j} = m_{((i-1)\times k_3)+j)}$, $j = 1, 2, \ldots, k_3$, $0 < k_3 < L_G - 1$. Assume that $T' = \{\mathfrak{T}'_i \mid i = 1, 2, \ldots, L_G - 1\}$ is steganographic object and $\mathfrak{T}'_i = \{t'_{i,j} \mid j = 1, 2, \ldots, \gamma\}$, $t'_{i,j}$ can be calculated as follows:

$$t'_{i,j} = \begin{cases} t_{i,1} + \sigma \times (1 + (-2) \times \mathfrak{m}_{i,j}), & i \le k_3 \\ t_{i,j}, & i > k_3 \end{cases}, \tag{8}$$

where σ denotes the offset for the tablature symbol.

The extracting process can be calculated as

$$\mathfrak{m}_{i,j} = \frac{1}{2} - \frac{t'_{i,j} - t_{i,j}}{2\sigma}, \quad i \le k_3. \tag{9}$$

This strategy can embed E_T bits into a guitar tablature, which is calculated as

$$E_T = (L_G - 1) \times \gamma. \tag{10}$$

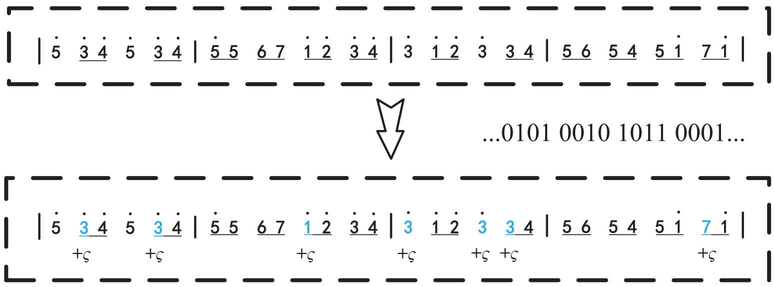


FIGURE 8. Embedding process of the strategy based on numbered notation

3.4. **Numbered Notation Based Embedding Strategy.** The last strategy conceals secret messages into specific numeric symbols in numbered musical notations. Fig. 8 shows the embedding process of this strategy. Let the carrier group be $S = \{\mathfrak{S}_i \mid i = 1, 2, \ldots, L_G\}$, where $\mathfrak{S}_i = \{s_{i,j} \mid j = 1, 2, \ldots, \delta\}$, $s_{i,j}$ is the abscissa of the first note in the j-th beat of the i-th measure, δ is the number of beats in a musical measure. Before the embedding phrase, M is divided into k_4 parts, namely, $M = \{\mathfrak{M}_1, \mathfrak{M}2, \ldots, \mathfrak{M}_{k_4}\}$, where $\mathfrak{M}_i = \{\mathfrak{m}_{i,1}, \mathfrak{m}_{i,2}, \ldots, \mathfrak{m}_{i,l_s}\}$, $i = 1, 2, \ldots, k_4$, $k_4 = \lceil L_M \ / \ l_s \rceil$, $l_s = \delta$, $\mathfrak{m}_{i,j} = m_{((i-1)\times k_4)+j)}$, $j = 1, 2, \ldots, k_4$, $0 < k_4 < L_G$. Assume that the steganographic object is $S' = \{\mathfrak{S}'_i \mid i = 1, 2, \ldots, L_G\}$, $\mathfrak{S}'_i = \{s'_{i,j} \mid j = 1, 2, \ldots, \delta\}$, the embedding process can be stated as

$$s'_{i,j} = \begin{cases} s_{i,j} + \varsigma \times \mathfrak{m}_{i,j}, & i \le k_4 \\ s_{i,j}, & i > k_4 \end{cases}, \tag{11}$$

where ς is the offset value for each numeric symbol.

Accordingly, the receiver can extract the secret part $\mathfrak{m}_{i,j}$ from the steganographic symbol $s'_{i,j}$ as

$$\mathfrak{m}_{i,j} = \frac{s'_{i,j} - s_{i,j}}{\varsigma}, \quad i \le k_4. \tag{12}$$

The capacity of this strategy E_S can be determined as

$$E_S = L_G \times \delta. \tag{13}$$

4. **A Dynamic Embedding Scheme.** As mentioned above, four embedding strategies, chord variation based embedding strategy, diagram symbol based embedding strategy, tablature based embedding strategy and numbered based embedding strategy, were introduced in Section 3. In this section, we design a dynamic steganographic scheme, based on the aforementioned embedding strategies. Fig. 9 shows the overview of our scheme. To facilitate the embedding process, we choose the first $L_G - 1$ measure in cover tablatures to hide secret messages.

Assume that the sender wants to send L_M bits of secret messages $M = \{m_i = 0 \text{ or } 1 \mid i = 1, 2, \ldots, L_M\}$ to receiver by concealing them into a guitar tablature Λ. Let the carrier group in a guitar tablature be $U = \{\mathfrak{U}_i \mid i = 1, 2, \ldots, L_G - 1\}$, where $\mathfrak{U}_i = \{z_i, \mathfrak{D}_i, \mathfrak{T}_i, \mathfrak{S}_i\}$, $L_{\mathfrak{U}_i} = |\mathfrak{U}_i| = 4$, $u_{i,j}$ is the j-th element of the i-th measure, and L_G is the number of measures in Λ. The embedding process can be conducted as follows:

Step 1: Let the capacity sequence be $V = \{v_i \mid i = 1, 2, \ldots, L_{\mathfrak{U}_i}\}$, where v_i indicates the embedding capacity of the above mentioned embedding strategies in a musical measure. Calculate v_i as

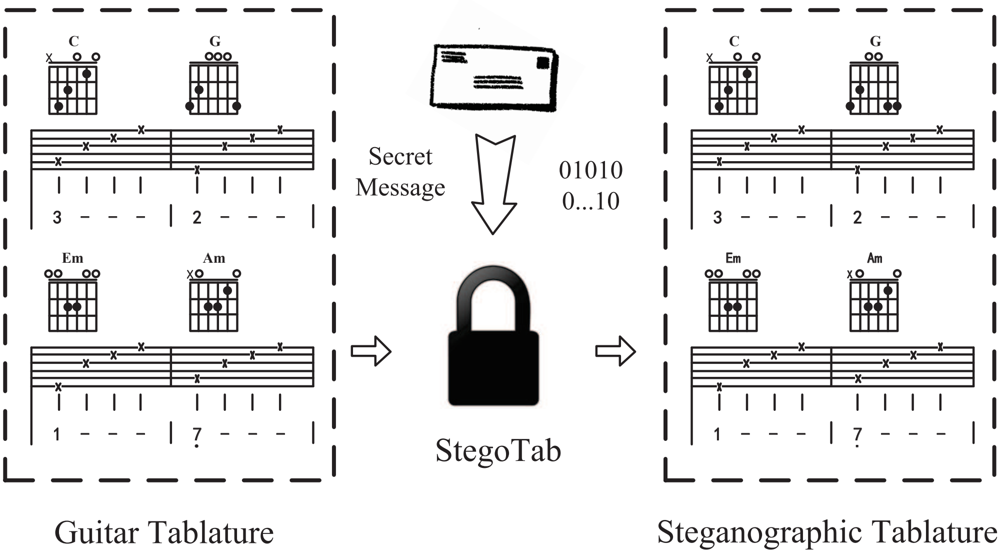


Figure 9. Overview of StegTab (Scores are a part of the music "*Cannon*")

$$v_i = \begin{cases} \dfrac{E_Z}{L_G}, & i = 1 \\ \dfrac{E_D}{L_G}, & i = 2 \\ \dfrac{E_T}{L_G - 1}, & i = 3 \\ \dfrac{E_S}{L_G}, & i = 4 \end{cases}. \tag{14}$$

where E_Z, E_D, E_T, and E_S respectively represent the maximum capacity for the corresponding embedding strategies.

Step 2: Divide M into r parts, denoted by $M = \{\mathcal{M}_i \mid i = 1, 2, \ldots, r\}$, where $\mathcal{M}_i = \{\mathfrak{M}_{i,j} \mid j = 1, 2, \ldots, L_{\mathfrak{U}}\}$, $\mathfrak{M}_{i,j} = \{\mathfrak{m}_{i,j,k} \mid k = 1, 2, \ldots, v_j\}$, $r = \lceil L_M \,/\, \sum_{i=1}^{L_{\mathfrak{U}_i}} v_i \rceil$. Note that r should be not more than $L_G - 1$ so that all the secret bits can be embedded. That is, the maximum capacity is $E_U = (L_G - 1) \times \sum_{i=1}^{L_{\mathfrak{U}_i}} v_i = ((L_G - 1)/L_G) \times (E_Z + E_D + E_S) + E_T$. Then, go to Step 3.

Step 3: Produce a binary sequence $W = \{\mathfrak{W}_i \mid i = 1, 2, \ldots, L_G - 1\}$ for the carrier group randomly using key_1,where $\mathfrak{W}_i = \{w_{i,j} \mid w_{i,j} = 0 \text{ or } 1, j = 1, 2, \ldots, L_{\mathfrak{U}_i}\}$, $1 \le i \le L_G - 1$, $\sum_{j=1}^{L_G - 1} w_{i,j} = r$. Assume the steganographic carrier is $U' = \{\mathfrak{U}'_i \mid i = 1, 2, \ldots, L_G - 1\}$, and $\mathfrak{U}'_i = \{u'_{i,j} \mid j = 1, 2, \ldots, L_{\mathfrak{U}_i}\}$, the steganographic object $u'_{i,j}$ can be determined by

$$u'_{i,j} = \begin{cases} (1 - w_{i,j}) \times \phi_{i,j} + w_{i,j} \times u_{i,j}, & i \le r \\ u_{i,j}, & i > r \end{cases}, \tag{15}$$

$$\phi_{i,j} = \begin{cases} \mathfrak{Z}_i \oplus \mathfrak{M}_{o,j}, & j = 1 \\ \mathfrak{D}_i \oplus \mathfrak{M}_{o,j}, & j = 2 \\ \mathfrak{T}_i \oplus \mathfrak{M}_{o,j}, & j = 3 \\ \mathfrak{S}_i \oplus \mathfrak{M}_{o,j}, & j = 4 \end{cases}, \tag{16}$$

$$o = \sum_{k=1}^{i} w_{k,j}. \tag{17}$$

where $\oplus$ is the embedding operation. For example, $z_i \oplus \mathfrak{M}_{i,j}$ means to embed the secret message part $\mathfrak{M}_{i,j}$ into its corresponding part z_i in the guitar tablature.

The extracting process is simple. The receiver first obtains V from the steganographic guitar tablature, and then generates the random binary sequence W with the shard key_1. For the vector W, the secret part of the secret message can be calculated by the following expression:

$$\mathfrak{M}_{o,j} = \begin{cases} \otimes z_i', & j=1,\ w_{o,j}=1 \\ \otimes \mathfrak{D}_i', & j=2,\ w_{o,j}=1 \\ \otimes \mathfrak{T}_i', & j=3,\ w_{o,j}=1 \\ \otimes \mathfrak{S}_i', & j=4,\ w_{o,j}=1 \end{cases}, \tag{18}$$

where $\otimes$ represent the extracting operation from the steganographic part to the secret message.

According to the dynamic steganographic strategy, this scheme can achieve excellent security. The key space for the secret messages in this scheme can be calculated by

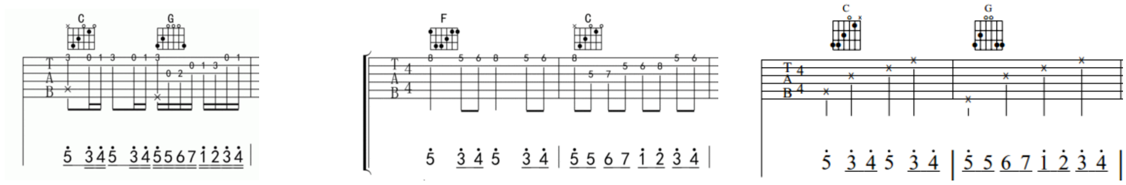
$$S_{key} = 2^{4\times(L_G-1)} \times 2^{L_M}. \tag{19}$$

For example, assume that a guitar tablature with 20 measures is used to embed secret messages at the rate of 10 bits per measure. According to Eq. (19), the key space would be $2^{4\times 19} \times 2^{190} = 2^{266}$, an astronomical number, which, thereby, cannot be broken in a limited time. Note that the key space would be much larger than 2^{266}, since there are often more measures in a practical guitar tablature and larger embedding capacities for each measure.

5. **Experimental Analysis.** In our experiments, the secret messages are randomly produced during the embedding procedure, and the experimental guitar tablatures are generated by the musical content which is collected from the Internet. Our scheme embeds secret messages in original guitar tablatures with $\alpha = 2$, and $\rho = \sigma = \varsigma = 0.1$. To evaluate the performance of our scheme, we show comprehensive results from different experiments.

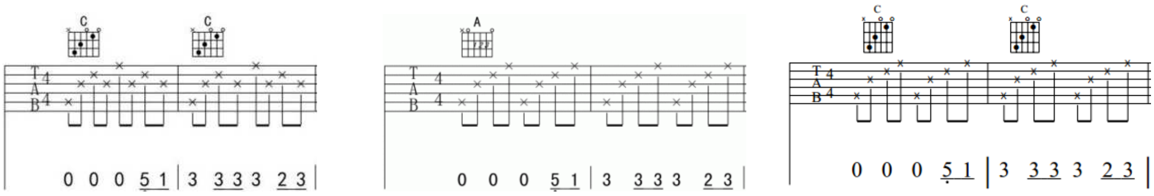
5.1. **Visual analysis of tablature.** Figs. 10, 11 and 12 show different types of guitar tablatures for 3 pieces of music. Tablatures (c) in these figures are steganographic tablatures generated by the steganographic operations, and the others are normal tablatures downloaded directly from the Internet [29]. It can be observed that there are not the particular rules about writing a guitar tablature for a piece of music, and the experimental tablatures are similar to those downloaded from the Internet. All these tablatures can be easily understood by a beginner. In addition, we can learn that the same melody can be played in different keys, and accordingly played over different chords. The results show that our method can achieve high imperceptibility.

5.2. **Auditory analysis of experimental music.** In order to evaluate the steganographic transparency of our scheme, we conduct an ABX test for experimental guitar tablatures. We create a test set of ten guitar tablatures and their corresponding ten pieces of MIDI music. In this test set, half of the tablatures are the original ones while the others are steganographic ones. We invite thirty people (include ten guitar lovers,



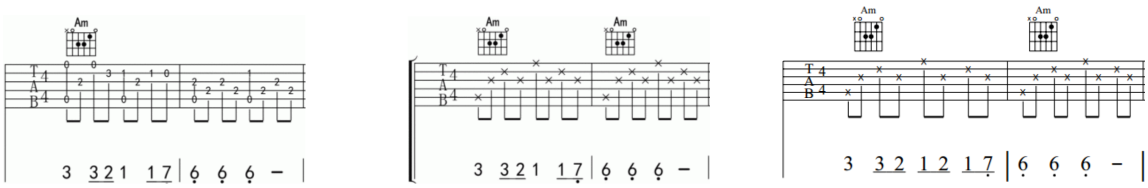
(a) (b) (c)

FIGURE 10. Tablatures for a part of the music *"Canon"*



(a) (b) (c)

FIGURE 11. Tablatures for a part of the music *"Red River Valley"*



(a) (b) (c)

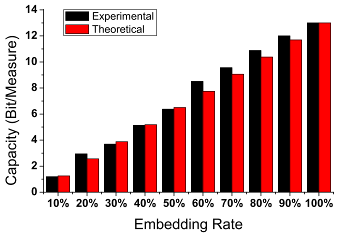
FIGURE 12. Tablatures for a part of the music *"Season Songs"*

ten professionals, and ten participators) to identify the category of experimental tablatures. Table I shows the result of the ABX test, from which, we can learn that in all the experimenters all the participators cannot distinguish the original and steganographic samples accurately. Although the guitar lovers know how to read guitar tablatures, they cannot accurately distinguish between the original and steganographic tablatures too. In summary, the experimental results demonstrate that our scheme can achieve relatively good steganographic transparency.

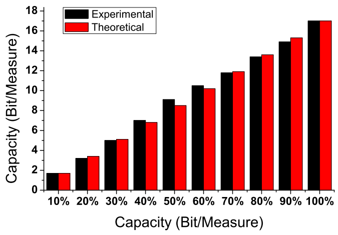
TABLE 1. Results of ABX tests

	Accuracy
Participators	49%
Professionals	49%
Cuitar Lovers	60%

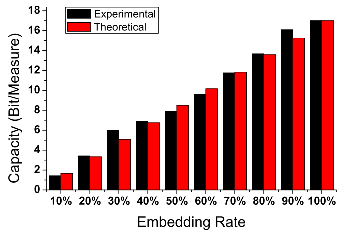
5.3. **Capacity Analysis.** Fig. 13 shows the hiding capacity of the experimental samples at the embedding rates from 10% to 100%, from which it is evident that, for each sample, the actual hiding capacity is nearly the same as the theoretical ones. Further, our scheme can embed nearly 13 bits in a musical measure. The maximum capacity of experimental guitar tablatures is 15.9 bits/measure and the minimum capacity is 10.4 bits/measure. Moreover, the capacity of our scheme can be further improved if we use smaller intervals to conceal secret messages in the adjacent tablature symbols.



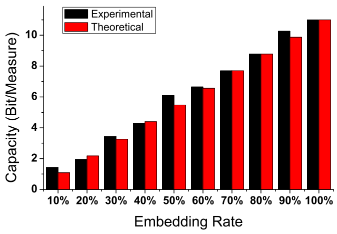
(a) Canon



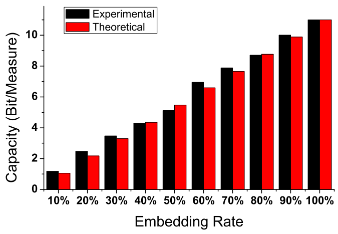
(b) Red River Valley



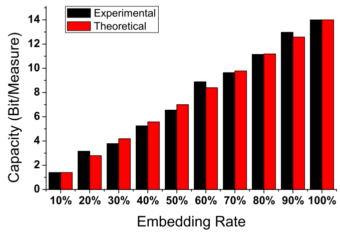
(c) Season Songs



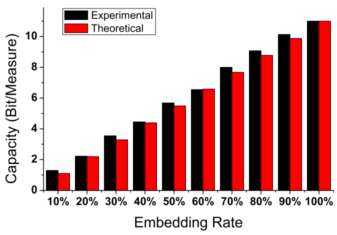
(d) Twinkle Twinkle Little Star



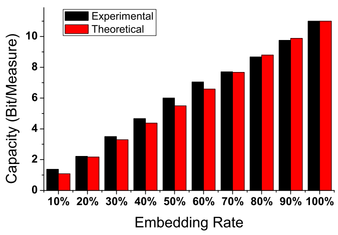
(e) Happy New Year



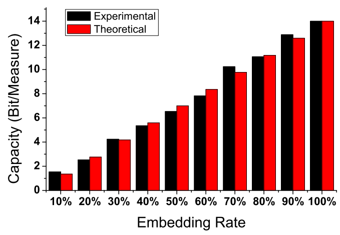
(f) Edelweiss



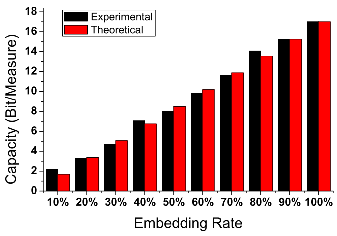
(g) Jingle Bells



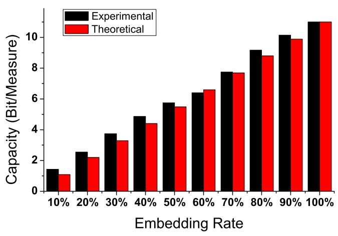
(h) We Wish You a Merry Christmas



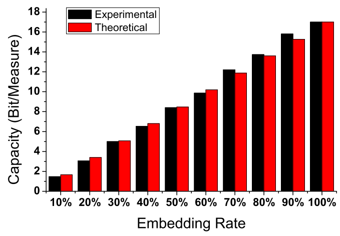
(i) Happy Birthday



(j) Two Tigers



(k) Donkey Donkey



(l) Old MacDonald Had a Farm

FIGURE 13. Hiding capacity of experimental samples with different embedding rates

6. **Conclusion.** Music steganography is the art and science of hiding secret messages in the music, which, in recent years, has attracted increasing attention. Up to now, many researches on music steganography have been carried out, and the steganographic objects have been extended from musical pitch to almost all music contents. However, there are only a few of efficient methods for embedding secret messages in music notation. To enrich existing research schemes, particularly in relation to music steganography, in this paper, we presented a dynamic tablature-based steganographic scheme, which achieves efficient embedding for digital guitar tablatures. Specifically, the proposed scheme embeds the secret messages by modulating chord variations and typesetting styles of symbols in the guitar tablature. Further, we design an efficient strategy to determine cover positions dynamically in original guitar tablature to strengthen the steganographic security. The theoretical analysis and experimental results demonstrate that the proposed scheme indeed achieves high security and good steganographic transparency.

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REFERENCES

[1] O. T. C. Chen and W. C. Wu, Highly robust, secure, and perceptual-quality echo hiding scheme, *IEEE Transactions on Audio, Speech, and Language Processing*, vol.16, no.3, pp.629–638, 2008.

[2] X. Ing, W. Huang, M. Zhang, and L. Zhao, A topography structure used in audio steganography, in *Proc. of the International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pp.2134–2138, 2016.

[3] R. J. Mstafa, K. M. Elleithy, A novel video steganography algorithm in DCT domain based on hamming and BCH codes, in *Proc. of 2016 IEEE 37th Sarnoff Symposium*, pp.208–213, 2016.

[4] S. A. Abbas, T. I. B. E. Arif, F. F. M. Ghaleb, and S.M. Khamis, Optimized video steganography using Cuckoo Search algorithm, in *Proc. of 2015 IEEE Seventh International Conference on Intelligent Computing and Information Systems (ICICIS)*, pp.572–577, 2015.

[5] F. Huang, X. Qu, H. J. Kim, and J. Huang, Reversible data hiding in JPEG images, *IEEE Transactions on Circuits and Systems for Video Technology*, vol.26, no.9, pp.1610–1621, 2016.

[6] Z. Qian, X. Zhang, Reversible data hiding in encrypted images with distributed source encoding, *IEEE Transactions on Circuits and Systems for Video Technology*, vol.26, no.4, pp.636–646, 2016.

[7] S. Weng, Y. Zhao, J. S. Pan, and R. Ni, Reversible watermarking based on invariability and adjustment on pixel pairs, *IEEE Signal Processing Letters*, vol.15, pp.721–724, 2008.

[8] S. Weng, J. S. Pan, and L. Li, Reversible data hiding based on an adaptive pixel-embedding strategy and two-layer embedding, *Information Sciences*, vol.369, pp.144–159, 2016.

[9] J. Qin, H. Tian, Y. Huang, J. Liu, Y. Chen, T. Wang, Y. Cai, and X. A. Wang, An efficient VoIP steganography based on random binary matrix, in *Proc. of 2015 10th International Conference on P2P, Parallel, Grid, Cloud and Internet Computing (3PGCIC)*, pp.462–465, 2015.

[10] S. Shi, Y. Qi, and Y. Huang, An approach to text steganography based on search in internet, in *Proc. of International Computer Symposium (ICS)*, pp.227-232, 2016.

[11] A. Anli and Z. Nakao, Three steganography algorithms for MIDI files, in *Proc. of 2005 International Conference on Machine Learning and Cybernetics*, vol.4, pp.2401–2404, 2005.

[12] K. Yamamoto and M. Iwakiri, A standard MIDI file steganography based on fluctuation of duration, in *Proc. of 2009 International Conference on Availability, Reliability and Security*,pp.774–779, 2009.

[13] K. Szczypiorski, StegIbiza: New method for information hiding in club music, in *Proc. of 2016 2nd International Conference on Frontiers of Signal Processing (ICFSP)*, pp.20–24, 2016.

[14] W. Mazurczyk, P. Szaga, and K. Szczypiorski, Using transcoding for hidden communication in IP telephony, *Multimed. Multimedia Tools and Applications*, vol.70, no.3, pp.2139–2165, 2014.

[15] C. L. Wu, C. H. Liu, and C. K. Ting, A novel genetic algorithm considering measures and phrases for generating melody, in *Proc. of 2014 IEEE Congress on Evolutionary Computation (CEC)*, pp.2101–2107, 2014.

[16] S. Sadie, *The New Grove Dictionary of Music and Musicians (6th Edition)*, vol.13, pp.348–349, 1980.

[17] Musical cryptogram. [Online]. Available: https://en.wikipedia.org/wiki/Musical_cryptogram.

[18] J.S. Bach and steganography. [Online]. Available: http://www.electrummagazine.com/2013/12/j-s-bach-and-steganography/.

[19] C. Halbreich, Ciphered creed, *Music and musicians*, vol.20, pp.18, 1972.

[20] L. Hutchinson, Live musical steganography, *Senior Theses*, 2014. [Online]. Available: https://scholarcommons.sc.edu/senior_theses/20.

[21] F. A. P. Petitcolas, R. J. Anderson, and M. G. Kuhn, Information hiding-a survey, in *Proc. of the IEEE*, vol.87, no.7, pp.1062–1078, 1999.

[22] W. Funk and M. Schmuker, High capacity information hiding in music scores, in *Proc. of the International Conference on Web Delivering of Music*, pp.12–19, 2001.
[23] Tablature. [Online]. Available: https://en.wikipedia.org/wiki/Tablature
[24] Bar. [Online]. Available: https://en.wikipedia.org/wiki/Bar_(music)
[25] How to read and write guitar tablature. [Online]. Available: http://www.guitartabs.cc/tabfaq.php
[26] Guitar chord. [Online]. Available: https://en.wikipedia.org/wiki/Guitar_chord
[27] A chord position variations. [Online]. Available: http://www.guitarchordsworld.com/a-variations/
[28] Numbered musical notation. [Online]. Available: https://en.wikipedia.org/wiki/Numbered_musical_notation
[29] Guitar tablatures. [Online]. Available: http://www.jitashe.org/search/tab