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Waveform Codebook Design for Encrypted Bluetooth Speech Transmission (Postprint)

Authors: Hong Pengcheng, 黄一才, Bin Yu

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Abstract

To address the issue that encrypted Bluetooth voice signals lose their voice characteristics and cannot be transmitted through voice channels, we establish a Bluetooth voice encrypted data transmission model and propose a waveform codebook generation algorithm for Bluetooth voice encrypted transmission. This algorithm generates an initial modulation codebook via subcarrier modulation, obtains a demodulation codebook through data training, and seeks the optimal codebook by designing a particle-pair algorithm with a last-place elimination mechanism. Simulation analysis demonstrates that the proposed codebook generation algorithm offers the advantage of rapid convergence and can generate waveform codebooks with various bit transmission rates and low symbol error rates. Experimental results show that utilizing this waveform codebook for data transmission in Bluetooth achieves a low symbol error rate.

Full Text

Preamble

Waveform Codebook Design for Bluetooth Voice Encryption

Hong Pengcheng, Huang Yicai, Yu Bin

(Information Engineering University, Zhengzhou 450001, China)

Abstract: Aiming at the problem that Bluetooth voice signals cannot be transmitted through the voice channel after encryption, this paper establishes a Bluetooth voice encryption data transmission model and proposes a waveform codebook generation algorithm for Bluetooth voice encryption transmission. The algorithm uses subcarrier modulation to generate the initial modulation codebook, trains data to obtain the demodulation codebook, and designs a particle-pair algorithm with a last elimination mechanism to find the optimal codebook. Simulation analysis shows that the proposed algorithm has the advantages of fast convergence rate and can generate waveform codebooks with different bit transmission rates and low symbol error rate. Experiments show that using this waveform codebook to transmit data in Bluetooth has low symbol error rate.

Key words: Bluetooth; waveform codebook; waveform symbol; subcarrier modulation; particle-pair algorithm

0 Introduction

Bluetooth is a short-range wireless communication technology that has become standard in smartphones, computers, and other smart devices, enabling Bluetooth terminals to conveniently connect with different phone models for hands-free calling. To address security issues in mobile voice communications, implementing encrypted voice transmission in Bluetooth terminal devices represents a secure and reliable solution.

Both Bluetooth and mobile communication networks have two types of channels: data and voice. Data channels cannot meet real-time requirements for voice transmission, while voice channels employ speech codecs. Bluetooth voice uses Continuous Variable Slope Delta Modulation (CVSD), which quantizes each sample with only 1 bit. Mobile communication networks use lossy, memory-based compression codecs that additionally incorporate Voice Activity Detection (VAD). Neither codec can transmit encrypted voice signals that lack speech characteristics.

Current research by scholars domestically and internationally has focused extensively on transmitting arbitrary data over mobile communication network voice channels. The core idea is to convert data into speech-like signals for transmission, which can be categorized into three approaches: speech synthesis, frequency modulation, and waveform codebook.

Speech synthesis schemes map data to speech feature parameters to synthesize speech-like signals. References [4,5] map data to pitch frequency, line spectrum pairs, and frame energy, while reference [6] designs mapping relationships based on formant models. However, such schemes involve complex parameter extraction that is difficult to implement in real-time on embedded systems. Among frequency modulation schemes, the heuristic modulation algorithm proposed in reference [7] has low transmission rates, while references [8-10] employ Orthogonal Frequency Division Multiplexing (OFDM) technology to map data onto subcarriers within the speech frequency band to generate speech-like signals. However, when applied to Bluetooth terminal devices, the modulated waveforms become significantly distorted after multiple passes through codecs, resulting in high demodulation error rates.

Compared with the first two approaches, waveform codebook schemes offer the advantages of low computational complexity and small storage space. Waveform codebooks enable “data-symbol-data”transmission and are optimized from initial codebooks using genetic algorithms [11,12]. References [13,14] directly select human speech to screen optimal codebooks, but references [11-14] all design codebooks only for specific vocoders. Reference [15] establishes a probability model of the average Euclidean distance distribution of waveform symbols before and after channel transmission, generating waveform codebooks based on spatial models to achieve data transmission over vocoders. However, this method ignores the automatic amplitude adjustment characteristics of vocoders, causing Euclidean distance deviations that affect demodulation. Reference [16] uses pattern search algorithms to design codebooks that can transmit data across multiple different vocoders, but the scheme does not consider the impact of Bluetooth voice codecs and cannot be directly applied to Bluetooth terminals.

Compared with optimization algorithms such as genetic algorithms and pattern search, particle swarm optimization offers simple implementation, fast convergence, and is less affected by problem dimensionality [17]. Ji Zhen [17] designed a particle-pair algorithm with a population size of 2 based on particle swarm optimization, which has demonstrated good performance in applications such as image codebook updating and gene clustering, showing particular advantages in solving high-dimensional complex problems.

In summary, codebook design is critical for using codebooks to transmit Bluetooth encrypted voice signals. This paper proposes a waveform codebook generation algorithm for Bluetooth voice encryption transmission. The algorithm generates an initial modulation codebook through subcarrier modulation of speech-like signals, obtains a demodulation codebook by training data over the voice channel, and employs a particle-pair algorithm with a last elimination mechanism to find the optimal codebook.

Definition 5: Symbol Error Rate (SER) refers to the proportion of incorrectly demodulated waveform symbols to the total transmitted waveform symbols after transmission through the voice channel.

Definition 6: Optimal codebook refers to the waveform codebook that can achieve the lowest symbol error rate through optimization during data transmission.

Definition 7: Subcarrier refers to a fixed-frequency sine/cosine wave that is modulated to transmit signals.

1 Model Establishment

For convenience of description, the relevant symbols and their meanings are shown in Table 1 .

1.1 Related Definitions

Definition 1: Waveform symbol refers to a speech-like segment containing L sampling values, denoted as $\mathcal{S} = \{s_0, s_1, \dots, s_{L-1}\}$.

Definition 2: Modulation codebook refers to the set of waveform symbols $\mathcal{C}_A = \{S_0, S_1, \ldots, S_{N-1}\}$ that have a one-to-one correspondence with the dataset $\{0, 1, 2, \ldots, N-1\}$, used for speech-like modulation during voice transmission.

Definition 3: Demodulation codebook refers to the set $\mathcal{C}_B = \{\bar{S}_0^O, \bar{S}_1^O, \ldots, \bar{S}_{N-1}^O\}$ composed of the average values of all output waveform symbols at the receiver corresponding to each waveform symbol in modulation codebook $\mathcal{C}_A$ after transmission through the voice channel with a large amount of random data.

The waveform codebook includes both modulation codebook and demodulation codebook.

Definition 4: Bit transmission rate refers to the number of bits that can be transmitted per second using the waveform codebook over the voice channel, denoted as R.

Since the transmission object of the model is a binary bitstream, taking $N = 2^n$ (where n is an integer) facilitates establishing a mapping relationship between $\mathcal{C}_A$ and the bitstream.

1.2 Data Transmission Model

Based on the Bluetooth terminal voice data transmission process, the data transmission model is established as shown in Figure 1 [Figure 1: see original paper], comprising three stages: data transmission, data transport, and data reception.

During data transmission, the grouped binary bits are converted to data index i, then mapped to the corresponding waveform symbol S_i, i.e., $i \to S_i$. Finally, waveform symbols from different groups are concatenated in sequence to form continuous speech-like signals for transmission. Here, k represents the transmission sequence number of symbols, and i represents the symbol index in the codebook.

According to the data transmission model, the waveform of symbol S_i after transmission through the voice channel is S_i^O, whose value is primarily determined by S_i, but the previously transmitted waveform symbols $\{S_{i-1}, S_{i-2}, \ldots\}$ also cause varying degrees of distortion in S_i^O. Therefore, direct comparison and decision using $\mathcal{C}_A$ and S_i^O at the receiver cannot achieve optimal results.

To improve demodulation success rate, the demodulation codebook $\mathcal{C}_B$ is used for comparison with the received waveform to determine the transmitted waveform, achieving $S_i^O \to i$. The decision method calculates the cosine similarity between the received waveform symbol S_i^O and the symbol set $\mathcal{C}_B$ to achieve matching. The larger the cosine value, the higher the similarity between the two waveforms. The waveform corresponding to the maximum cosine value is demodulated as the transmitted waveform, and then the transmitted data is recovered, i.e., $i = \arg\max_{0 \le i \le N-1}[\cos(S_i^O, \bar{S}_i^O)]$.

Key metrics for evaluating a waveform codebook include bit transmission rate, computational complexity, storage requirements, and symbol error rate. The first three metrics are determined by codebook scale. This paper focuses on codebook generation and optimization with a scale of $N \times L$, i.e., obtaining waveform codebooks with low symbol error rate when the codebook scale is fixed. Additionally, the impact of codebook scale on symbol error rate is investigated.

2 Waveform Codebook Generation Algorithm

The algorithm generates an initial modulation codebook using subcarrier modulation to create speech-like waveforms, trains data to generate a demodulation codebook, and finds the optimal codebook through a particle-pair algorithm with a last elimination mechanism by designing particle encoding, an objective function, and a particle update mechanism.

2.1.1 Modulation Codebook Initialization

To ensure waveform symbols meet speech frequency band requirements ($f \in [300, 3400]$ Hz), subcarrier modulation is used to generate speech-like signals as waveform symbols. Within the $[f_{\min}, f_{\max}]$ frequency range, subcarrier frequency values are set at equal intervals of Δf, resulting in a total number of required subcarrier frequency values M:

$$M = \left\lfloor \frac{f_{\max} - f_{\min}}{\Delta f} \right\rfloor + 1$$

where each frequency value corresponds to one sine and one cosine subcarrier.

The initial generation process is as follows:

a) Randomly generate subcarrier amplitudes $G_i = \{z_{i,0}, z_{i,1}, \dots, z_{i,2M-1}\}$ for $0 \leq i \leq N-1$, where $z_{i,j}$ for even and odd j correspond to the amplitudes of sine and cosine subcarriers, respectively. The time-domain expression of the speech-like waveform obtained through subcarrier modulation is:

$$s_i(t) = \sum_{j=0}^{M-1} z_{i,2j} \sin(2\pi f_j t) + z_{i,2j+1} \cos(2\pi f_j t)$$

b) Sample $s_i(t)$ at the speech sampling rate f_s starting from time $t = 0$, and take the first L sampling values as S_i.

c) Perform power normalization: $S_i = S_i / \|S_i\|$, where $\|S_i\|$ represents the vector magnitude, to obtain the final waveform symbol.

Since subcarrier amplitudes are set within the $[-1, 1]$ interval, particle initialization only requires generating $2MN$ random numbers from the $[-1, 1]$ interval, and this initial particle corresponds to an initial modulation codebook.

Analysis of the waveform symbol initial generation process reveals: (a) subcarrier amplitudes G_i determine waveform symbol S_i; (b) randomly generated subcarrier amplitudes produce waveform symbols that satisfy speech frequency band requirements; (c) randomly generating N groups of subcarrier amplitudes yields N waveform symbols forming the initial modulation codebook $\mathcal{C}_A$; (d) the final sampling values of waveform symbol S are within $[-1, 1]$ and need to be converted to 16-bit width supported by Bluetooth during use.

To ensure consistent power across each waveform symbol, power normalization must be performed after obtaining the waveform symbols.

2.1.2 Demodulation Codebook Initialization

The demodulation codebook generation process is shown in Figure 2 [Figure 2: see original paper]. First, generate N_{tot} random numbers in $[0, N-1]$, map them to waveform symbols using $\mathcal{C}_A$ and combine them into continuous speech-like signals for transmission through H codec combinations. Then calculate the average of all output values after transmission through each combination as $\bar{S}_i^O$ to obtain the demodulation codebook $\mathcal{C}_B$.

The vocoders that data needs to pass through are represented as $\text{Vocoder}_1, \text{Vocoder}_2, \dots, \text{Vocoder}_H$. Therefore, the codec combinations experienced by the data are: CVSD+Vocoder_1, CVSD+Vocoder_2, ⋯, CVSD+Vocoder_H.

2.2 Codebook Optimization

As analyzed in Section 2.1, generating subcarrier amplitudes yields the corresponding modulation codebook and demodulation codebook, enabling calculation of the codebook' s SER, as shown in Figure 3 [Figure 3: see original paper]. Therefore, the problem is transformed into finding the subcarrier amplitudes that minimize SER.

2.2.1 Particle Encoding During optimization, each particle represents a modulation codebook, so all subcarrier amplitudes G_i of a modulation codebook must be encoded as a particle. Thus, N groups of subcarrier amplitudes $G_0, G_1, \dots, G_{N-1}$ can be arranged in sequence to obtain particle encoding, denoted as vector Z, as shown in Table 2 . Z is a $2MN$-dimensional vector.

Since subcarrier amplitudes are within $[-1, 1]$, particle initialization only requires generating $2MN$ random numbers from $[-1, 1]$.

2.2.2 Objective Function When evaluating particle quality, the corresponding demodulation codebook is first obtained. Then, N_{tot} random numbers are transmitted using the modulation codebook across H different codec combinations. The demodulation errors N_{err}^j in each combination are obtained through the demodulation codebook, and the average SER is calculated as the objective function:

$$D = \frac{1}{H}\sum_{j=1}^{H}\frac{N_{\text{err}}^{j}}{N_{\text{tot}}}$$

A smaller D value indicates better particle performance.

2.2.3 Particle Update Mechanism The optimization algorithm includes two independent particle pairs: $\{Z_1^{(k)}, Z_2^{(k)}\}$ and $\{Z_3^{(k)}, Z_4^{(k)}\}$, where k represents the iteration number. During each iteration, each particle pair updates as follows:

Update velocity:

$$V_i^{(k+1)} = \omega V_i^{(k)} + c_1 r_1 (p_i^{(k)} - Z_i^{(k)}) + c_2 r_2 (g^{(k)} - Z_i^{(k)})$$

Update position:

$$Z_i^{(k+1)} = Z_i^{(k)} + V_i^{(k+1)}$$

where r_1 and r_2 are random numbers in $[0, 1]$, c_1 and c_2 are learning factors, and ω is the weight factor. Particle position boundaries are set to $[-1, 1]$, and velocity boundaries to $[v_{\min}, v_{\max}]$.

To enhance particle search capability, the last elimination mechanism is applied to waveform symbols in the modulation codebook corresponding to poorer-performing particles. The specific implementation is: first, calculate the objective function values of the two particles and identify the particle with the larger value; then calculate the average SER of each waveform symbol in that particle' s codebook across H codec combinations, i.e., $f(i) = \frac{1}{H}\sum_{j=1}^{H} N_{\text{err}}^{j,i}$ for $0 \leq i \leq N-1$; finally, identify the waveform symbol S_q with the maximum $f(i)$ as the ineffective symbol and randomly generate a new subcarrier amplitude G_q to replace the corresponding position in the particle.

According to the above update mechanism, after iterating at most $N_{\max}$ times for particle pairs $\{Z_1^{(k)}, Z_2^{(k)}\}$ and $\{Z_3^{(k)}, Z_4^{(k)}\}$, the particles with lower objective function values are recombined into elite particle pairs $\{Z_5^{(k)}, Z_6^{(k)}\}$ and $\{Z_7^{(k)}, Z_8^{(k)}\}$. After continuing iteration for at most $N_{\max}/2$ times, the optimal particle Z_{best} is obtained, and its corresponding codebook serves as the optimal demodulation codebook.

2.2.4 Codebook Optimization Algorithm Flow The particle-pair algorithm with last elimination mechanism for codebook optimization is shown in Figure 4 [Figure 4: see original paper]. The specific process is as follows, where $p^{(k)}$ saves the optimal particle of the current iteration and $g^{(k)}$ saves the globally optimal particle since the iteration began.

a) Set threshold ε and maximum iteration number $N_{\max}$.

b) Set $k = 0$, initialize particle positions $Z_i^{(0)}$ and velocities $V_i^{(0)}$.

c) Particle $Z_i^{(k)}$ operations yield modulation codebook $\mathcal{C}_A^{(k)}$.

d) Map N_{tot} random numbers in $[0, N-1]$ to $\mathcal{C}_A^{(k)}$ for transmission through the voice channel, train to generate demodulation codebook $\mathcal{C}_B^{(k)}$.

e) Transmit N_{tot} random numbers using $\mathcal{C}_A^{(k)}$ and demodulate using $\mathcal{C}_B^{(k)}$ to obtain demodulation error rate $D_i^{(k)}$.

f) Calculate objective function values, set $p^{(k)}$ and $g^{(k)}$.

g) If $D_i^{(k)} < \varepsilon$, identify the symbol with highest SER in $\mathcal{C}_A^{(k)}$, randomly regenerate subcarrier amplitudes in particle $Z_i^{(k)}$; otherwise identify the symbol with highest SER in the particle with larger objective function value, randomly regenerate subcarrier amplitudes.

h) Set $k = k + 1$, update particle velocities and positions.

i) If $k < N_{\max}$, go to step c); otherwise proceed.

j) If $D^{(k)} - D^{(k-1)} > \varepsilon$, go to step b); otherwise set initial population as $\{Z_5^{(k)}, Z_6^{(k)}\}$ and $\{Z_7^{(k)}, Z_8^{(k)}\}$, go to step c).

k) Obtain better particle Z_{best}, end.

3 Experimental Analysis

The waveform codebook is first generated using the proposed algorithm in a simulation environment, where CVSD and vocoders are implemented according to standards set by the Bluetooth Special Interest Group and the European Telecommunications Standards Institute. Then, various metrics of the waveform codebook are analyzed. Finally, the application effect of the codebook in Bluetooth is verified through mobile phone calls.

3.1 Experimental Setup

Mobile communication networks use multiple vocoders including FR, EFR, HR, and AMR. The first three are used for 2G GSM communications, and the fourth for 3G/4G communications. The proposed algorithm selects CVSD combined with EFR, FR, AMR12.2, AMR10.2, and AMR7.95 vocoders to optimize codebooks of different scales. In the waveform codebook generation algorithm, $N_{\text{tot}} = 10^5$, $N_{\text{total}} = 5 \times 10^5$, $\varepsilon = 10^{-5}$, c_1 and c_2 are 0.3 and 0.5 respectively, particle position range is $[-1, 1]$, maximum particle velocity $v_{\max}$ is $[-0.1, 0.1]$, and weight ω is 0.1.

In the practical verification stage, two Xiaomi Mi 6 phones and two CSR8670 Bluetooth development platforms are used to test codebook transmission performance. The test environment is shown in Figure 5 [Figure 5: see original paper].

3.2 Results Analysis

Partial codebook metrics are shown in Table 3 . Computational complexity refers to the cosine calculation operations during received waveform demodulation, approximately $8000 \times N$ additions and multiplications per second. Storage requirement refers to the space occupied by $\mathcal{C}_A \times N \times L$ and $\mathcal{C}_B \times N \times L$, which is $2LN$.

Table 3 shows that the same codebook has different SER in different combinations. Codebooks perform better in CVSD+EFR and CVSD+AMR12.2 combinations, but worse in CVSD+FR combination.

Figure 6 [Figure 6: see original paper] shows the relationship between SER and waveform symbol length L when the number of waveform symbols N is constant. Longer waveform symbol length L results in lower SER, i.e., $SER \propto 1/L$.

Figure 7 [Figure 7: see original paper] shows the relationship between SER and waveform symbol number N when waveform symbol length L is constant. Smaller symbol number N results in lower SER, i.e., $SER \propto N$.

Figure 8 [Figure 8: see original paper] shows SER for different N and L combinations at the same R. It demonstrates that more waveform symbol sampling points L yield lower SER. However, as L increases, N grows exponentially, causing rapid increases in computational complexity and storage requirements. Simultaneously, finding N waveform symbols that are both distinctive and capable of passing through the voice channel becomes more difficult, and the SER reduction ratio becomes smaller. Therefore, when considering codebooks for a given bit transmission rate, trade-offs must be made among SER, storage, and computational complexity.

Figure 9 [Figure 9: see original paper] shows the relationship between SER and iteration number for CVSD+EFR combination when optimizing a 32×20 scale codebook. The initial particles are iterated 5,000 times, elite particles are iterated 2,000 times, with two particles searched per iteration, resulting in a total search count of 24,000.

Table 4 compares reference [16] with the proposed algorithm. Reference [16] uses pattern search algorithm optimization with actual search count being the product of 8,000 iteration times and 1,024 search directions per iteration, totaling 8,192,000 searches. While reference [16] has overall lower SER, it does not consider CVSD and has much higher computational complexity. The proposed algorithm demonstrates superior overall performance.

Table 5 shows the maximum bit transmission rates achievable using codebooks generated by the proposed algorithm in CVSD and different vocoder combinations, where SER within 5% is considered correctable through error correction codes.

Phones can set the voice call network but cannot specify the vocoder. Therefore, during practical testing, the waveform codebook is first burned into CSR8670, then 2G and 3G/4G networks are specified for voice calls. Each call transmits 1,000 waveform symbols cyclically. The receiver extracts the received data, implements synchronization in MATLAB, then demodulates and calculates SER. Ten experiments are conducted and averaged, with results shown in Table 6 .

Table 6 shows that practical experimental results are worse than simulation tests due to: (a) voice transmission being affected by more factors such as electromagnetic interference and signal attenuation; (b) mobile communication network voice calls switching between different vocoders (e.g., 2G may use EFR, FR, HR, while 3G/4G AMR vocoders adopt different coding rates based on channel conditions). However, the symbol error rate remains within acceptable range and can be effectively addressed through error correction codes.

4 Conclusion

Based on in-depth analysis of CVSD encoding and vocoder characteristics, this paper proposes a waveform codebook generation algorithm for Bluetooth voice encryption transmission. The algorithm uses subcarriers with fixed frequencies in the speech band to generate an initial modulation codebook, trains data over the voice channel to obtain a demodulation codebook, designs particle encoding, an objective function, and particle update mechanism, and employs a particle-pair algorithm with last elimination mechanism for optimization. Simulation analysis demonstrates that the algorithm converges quickly and can generate waveform codebooks with different bit transmission rates and low symbol error rates. Practical experiments verify that the codebook achieves low symbol error rate when transmitting data in Bluetooth devices. Future work needs to implement self-synchronization for Bluetooth voice encrypted data to achieve transparent transmission of encrypted voice data through the voice channel.

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