DTMF Signal Detection and Parameter Optimization Based on Goertzel Algorithm

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Abstract: ***In recent years, Dual-Tone Multi-Frequency (DTMF) signaling has become a cornerstone technology in a wide array of communication systems and interactive services, including telephone banking, vehicle navigation terminals, voicemail systems, and automated teller machines (ATMs). The integrity of these services is critically dependent on the reliable transmission and accurate demodulation of DTMF signals to retrieve the encoded digital commands. Consequently, the development of robust and efficient DTMF detection methodologies is of paramount importance. While the Fast Fourier Transform (FFT) is a common choice for spectral analysis, the Goertzel algorithm presents a superior alternative for DTMF detection due to its exceptional computational efficiency and high frequency resolution, particularly when only a small number of specific frequency components need to be identified. This algorithm is exceptionally well-suited for extracting the precise low and high-frequency group tones that constitute a DTMF symbol, thereby achieving the goal of accurate digit identification. This paper conducts a comprehensive study and implementation of the Goertzel algorithm for this specific application. A central focus of our investigation is the critical selection of key parameters that govern detection performance, most notably the number of sampling points (N), which directly impacts frequency resolution, computational load, and detection speed. We provide a rigorous, step-by-step elucidation of the complete DTMF detection process, from signal acquisition to decision logic. Furthermore, the paper presents a detailed analysis and discussion on strategies to optimize the algorithm's efficiency without compromising accuracy. The theoretical framework and performance claims are validated through extensive MATLAB simulations. These simulations demonstrate the algorithm's efficacy in correctly decoding DTMF digits under various conditions, confirming its practical utility as a highly efficient solution for embedded and real-time telecommunication systems.***

Keywords: DTMF Signaling, Goertzel Algorithm, Signal Detection, Spectral Analysis, MATLAB Simulation, Telecommunication Systems, Parameter Optimization.

1. INTRODUCTION

Bell Telephone Laboratories in the United States created dual tone multi frequency DTMF signals to provide signals for contemporary button based telephone dialing. To ensure their proper functioning, it is necessary to demodulate them correctly to obtain digital signals. This signal quickly replaced the traditional pulse dialing method and has been widely used in telecommunications systems. Chen, Yang, et al. (2025) proposed SyntheClean, an innovative approach to enhance large-scale multimodal models through adaptive data synthesis and cleaning, addressing data quality issues in AI training [1]. In the context of supply chain management, Wu, W., Bi, S., Zhan, Y., & Gu (2025) explored the impact of supply chain digitalization on energy efficiency in the gas and oil sectors, highlighting its potential contribution to achieving carbon neutrality targets [2]. For natural language processing tasks, Zhao, Shihao, et al. (2025) introduced KET-GPT, a modular framework designed for precision knowledge updates in pretrained language models, improving their adaptability and accuracy [4]. Meanwhile, Zhuo, Jiayang, et al. (2025) developed an intelligent-aware transformer with domain adaptation and contextual reasoning capabilities, enhancing question answering systems' performance [3]. Shih, Kowei, et al. (2025) proposed DST-GFN, a dual-stage transformer network with gated fusion, aimed at predicting pairwise user preferences in dialogue systems, which has implications for personalized recommendation systems [5]. In the field of computer vision, Li, Xuan, et al. (2025) introduced MLIF-Net, a multimodal fusion model combining vision transformers and large language models for AI image detection, demonstrating improved accuracy in visual recognition tasks [6]. In addition, Lin, Tingting (n.d.) discussed enterprise AI governance frameworks, emphasizing the importance of balancing innovation and risk in AI product management [7]. Chen, Rensi (2023) explored the application of data mining techniques in data analysis, providing insights into extracting valuable information from large datasets [8]. Chen, Yinda, et al. (2024) presented Bimcv-r, a landmark dataset for 3D CT text-image retrieval, facilitating research in medical image analysis [9]. Furthermore, Chen, Yinda, et al. (2023) proposed a generative text-guided 3D vision-language pretraining method for unified medical image segmentation, advancing the field of medical imaging [10]. Yu, Z., Sun, N., Wu, S., & Wang (2025) researched automatic text summarization using Transformer and Pointer-Generator Networks, offering a new approach to efficiently condense large volumes of text [11]. Sun, N., Yu, Z., Jiang, N., & Wang (2025) focused on constructing an Automated Machine Learning (AutoML) framework based on large language models, aiming to simplify the machine learning process [12]. Finally, Pal, P. et al. (2025) developed an AI-based credit risk assessment and intelligent matching mechanism in supply chain finance, providing a novel solution for financial risk management in supply chains [13].

This technology enables users to achieve high-speed dial-up internet access and calls through a simple circuit without changing existing telephone lines or lines. DTMF signals consist of eight frequency points, divided into high and low frequency groups, with each group containing four different frequencies. These different frequencies are independent of each other during communication. Each DTMF signal is composed of a combination of high-frequency and low-frequency signals. able 1 shows various frequency combinations corresponding to each number.

Table 1: Frequency correspondence of DTMF signals

Frequency (Hz)	**1209**	**1336**	**1447**	**1633**
697	1	2	3	A
770	4	5	6	B
852	7	8	9	C
941	*	0	#	D

The DTMF signal is composed of the superposition of two frequency signals in Table 1, and is also affected by channel noise and speech interference. Due to the influence of Doppler effect, the signal may still have frequency offset. The technical specifications of DTMF signal decoder are as follows:

(1) High and low frequency level difference: ≤4dB

(2) Level range: $-4 \sim -23\text{dBm}$

(3) Frequency offset: Passed validation within ±1.5%, failed validation above ±3.5%

(4) Second harmonic: more than 20dB lower than the fundamental frequency energy

So, decoding DTMF signals in the time domain is very difficult. Compared to other methods, a more effective decoding approach is to first use the Discrete Fourier Transform (DFT) to transform the DTMF signal into the frequency domain, and then perform energy calculations and identification on each frequency point within the frequency domain.

The drawback of directly calculating DFT is that it requires a large amount of computation. The FFT algorithm calculates the spectrum of all frequency points at once, but when decoding DTMF signals, only a few frequency points in Table 1 need to be calculated for spectrum. Therefore, both DFT and FFT are not suitable for decoding DTMF signals. From an engineering perspective, the Goertzel algorithm [3] is the most commonly used algorithm for decoding DTMF signals [4-5].

Although extensive research has been conducted on the Goertzel algorithm, there has not been much in-depth exploration into the parameter optimization issues involved in the detection process. This article aims to achieve the correct detection of DTMF signals based on the signal characteristics of DTMF and the recursive characteristics of Goertzel algorithm. The article also discusses in detail the relevant parameters involved in the detection, and provides the theoretical basis and demonstration results for selecting parameter N. Provide theoretical support for the appropriate selection of parameters in DTMF signal detection.

2. GOERTZEL ALGORITHM PRINCIPLE

The Goertzel algorithm was proposed by Gerald Goertzel in 1958 and belongs to the category of discrete Fourier transform. If *x[n]* is a sampling sequence of length N, *n[0,N,1]*, where n is a positive integer, then the DFT of *x[n]* is:

$$X[K] = \sum_{n=o}^{N-1} x[n] W_N^{kn}, k = 0,1,2,\cdots,N-1 \tag{1}$$

In the equation, $\mathrm{W_N} = \mathrm{e}^{-\mathrm{j}2\pi/\mathrm{N}}$, the calculation formula for Goertzel algorithm in equation (1) is:

$$y_k[m] = W_N^{-k} y_k[m-1] + x[m], m \in [0, N] \tag{2}$$

In the formula, m is an integer, x[N]=0: The Goertzel algorithm can be seen as a second-order IIR bandpass filter [6], and the transfer function of this filter can be expressed as:

$$H_k[z] = \frac{1}{1-W_N^{-k}z^{-1}} = \frac{1-W_N^{-k}z^{-1}}{1-2\cos(2\pi k/N)z^{-1}+z^{-2}} \tag{3}$$

Therefore, the structural diagram of implementing the filter is shown in Figure 1.

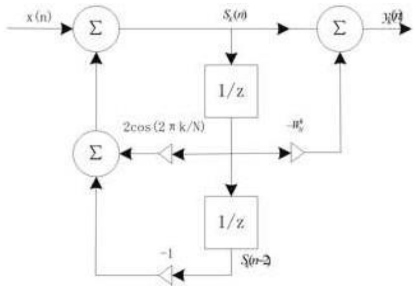

Figure 1: Algorithm Implementation Structure Block Diagram

The mathematical implementation of the filter derived from Figure 1 can be expressed as:

$$s_k[n] = x[n] + 2\cos(2\pi k/N)s_k[n-1] - s_k(n-2) \tag{4}$$

$$X[k] = y_k[N-1] = s_k[n-1] - W_N^k s_k(n-2) \tag{5}$$

In the formula,. For each sampled value, formula (4) is recursively calculated once (a total of N calculations). After the recursion is completed, formula (5) only needs to be calculated once. From this, it can be concluded that calculating the Fourier variable of a specific frequency requires a total of N+2 real multiplication operations and 2N+1 real addition operations [7]. In the process of DTMF signal detection, there is no need to care about the phase information of the signal, so formula (5) can be used to derive:

$$|X[k]^2| = s_k^2[N-1] - s_k^2[N-2] - 2\cos(2\pi k/N) \times s_k[N-1] \times s_k[N-2] \tag{6}$$

3. SPECIFIC IMPLEMENTATION AND PARAMETER SELECTION OF GOERTZEL ALGORITHM

According to the International Telecommunication Union standards, the shortest duration of a DTMF signal is 40ms, corresponding to a total of 320 samples at a sampling rate of 8KHz [8].

After the time-domain signal is discretized through digital sampling, the horizontal axis of the amplitude corresponding to a certain frequency can be represented by formula (7):

$$k_f = \frac{f_k \times N}{f_s}, 0 < k_f < \frac{N}{2} \tag{7}$$

In the formula, $\mathrm{f_s}$ represents the sampling frequency, N represents the number of samples, and the discrete time-domain signal is periodically extended. The signal will be discretized in the frequency domain, and the position of a frequency in the amplitude spectrum sequence can be represented by formula (8):

$$k = round\left(\frac{f_k \times N}{f_s}\right) = round(k_f), k = 0,1,2,3,\cdots,\frac{N}{2} \tag{8}$$

In the formula, round represents rounding floating point numbers to the nearest integer. In order to distinguish the 8 frequency components in DTMF signals, the k values of the 8 frequency components cannot be equal.

$$round\left(\frac{f_1 \times N}{f_s}\right) \neq round\left(\frac{f_2 \times N}{f_s}\right)$$

$$f_1, f_2 = 697,770,852,941,1209,1336,1477,1633, f_1 \neq f_2 \quad (9)$$

The range of N values that satisfy formula (9) is [73,74,81~86,91~97,99~320].

According to ITU standards, DTMF signals with frequency offset within ±1.5% should be considered valid signals, therefore the value of N should satisfy the following formula:

$$round\left(\frac{0.985 \times f_k \times N}{f_s}\right) \neq round\left(\frac{1.015 \times f_k \times N}{f_s}\right)$$

$$f_k = 697,770,852,941,1209,1336,1477,1633 \quad (10)$$

At this point, finding the value of N that minimizes y is the optimal value. The complete detection process of DTMF signals is shown in Figure 2.

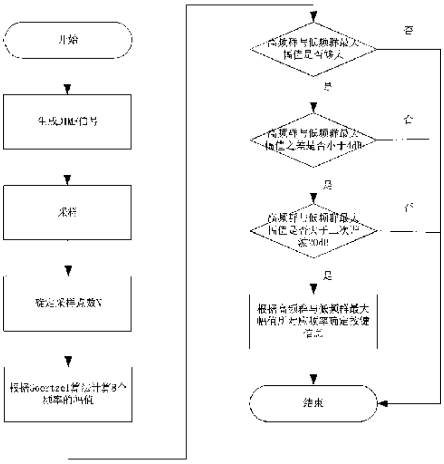

Figure 2: DTMF signal detection process

Some papers indicate that N=205 is the optimal value for DTMF signal detection [9-10]. Figure 3 shows a comparison of the detection results for key value "A" when N=113 and N=205.

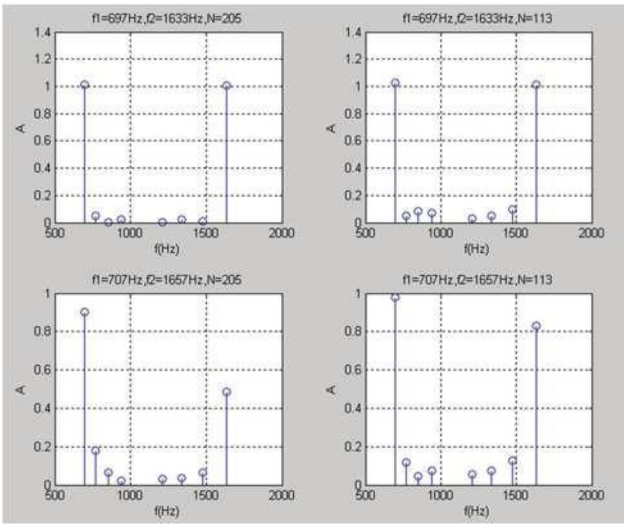

Figure 3: The detection results of key value "A" when N=205 and N=113

As shown in Figure 3, when the two frequency components of the key value "A" have a frequency offset of 0, both N=205 and N=113 can achieve good detection results. However, when the frequency offset of the two frequency components of the key value "A" is within the allowable range of the ITU standard by 1.5%, the result obtained by using N=205 is very poor. At this time, the amplitude difference between the low-frequency component and the high-frequency component is 5.4dB, which is a false detection according to the ITU detection standard. On the other hand, the amplitude difference between the low-frequency and high-frequency components obtained by using N=113 is 1.4dB, which is obviously a correct detection.

4. CONCLUSION

As an important technical signal for data communication systems and audio telephone systems. The fast and accurate detection of DTMF signals is crucial. This article provides a detailed analysis of the principle of using Goertzel algorithm for DTMF signal detection and the selection of its main parameters. Although there are currently many other DTMF signal detection algorithms, such as those based on support vector machines, there has not been much discussion on how to optimize the parameters in the detection process. This article specifically discusses the optimization of N values and provides detailed DTMF signal detection processes and simulation results.

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