Research on Noise Optimization of CMOS Amplifier Used in ECG Signal

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Abstract. Electrocardiography has a wide range of applications in monitoring heart health and diagnosing diseases, among which how to efficiently and accurately reduce noise of electrocardiogram (ECG) signals is of great significance. This paper first writes the processing flow of ECG signals and the theoretical basis of low-noise CMOS amplifiers, then analyzes the difficulties of noise optimization of CMOS amplifiers in ECG scenarios, and then proposes feasible solutions for each difficulty. Considering these influencing factors comprehensively and using a variety of noise reduction methods in a reasonable combination will actively help the noise optimization of the ECG signal. Linking the CMOS amplifier with the noise reduction processing of the entire ECG circuit can reduce the interference of noise and improve the quality of the signal, so that the ECG signal can more accurately reflect the electrical activity of the heart. This is of great significance for the monitoring and research of heart health.

Keywords: ECG signals, amplifiers, noise optimization.

1. Introduction

The electrocardiogram is an important and commonly used tool for assessing heart function. Doctors can diagnose diseases, monitor heart health, and save lives by analyzing ECG signals. With the continuous development of technology, the application value of ECG signal is still expanding and deepening. The graphics recorded by the electrocardiogram reflecting the current and voltage changes of the subject's heart electrical activity must be true and accurate enough to ensure that it can help doctors make correct judgments [1]. Usually, the collected ECG signal contains a variety of noises, which affects the accuracy of the generated ECG waveform. Therefore, noise optimization is an important step in ECG signal processing, which can further improve the application potential of ECG signals.

First, this article writes the seven-step processing flow of the ECG signal. Secondly, taking the self-designed two-stage CMOS amplifier and its simulation results as an example, it introduces the theoretical basis of the low-noise CMOS amplifier from three aspects: circuit structure, working principle and characteristics. Then, in the context of ECG signal processing, the factors that affect the noise optimization of CMOS amplifiers are expounded and analyzed from three aspects, namely, device and technology factors, noise source factors, and the balance between noise optimization and other performance. And according to the proposed influencing factors, feasible measures are put forward for the noise optimization of ECG signals, including the selection of materials and technologies, the optimization of circuit structure and the adoption of cutting-edge algorithm models for noise sources. Finally, the summary and prospect of ECG signal noise reduction processing are made. ECG signal noise reduction processing can improve signal quality and accuracy, and it is more accurate and convenient to read signals and data processing in various scenarios such as disease monitoring and diagnosis, cardiac function evaluation, and daily cardiac monitoring.

2. ECG signal processing flow

The ECG signal has undergone signal acquisition, amplification, filtering and noise suppression, analog-to-digital conversion, data processing and analysis, as shown in the figure 1, and is finally visualized in the form of an electrocardiogram.

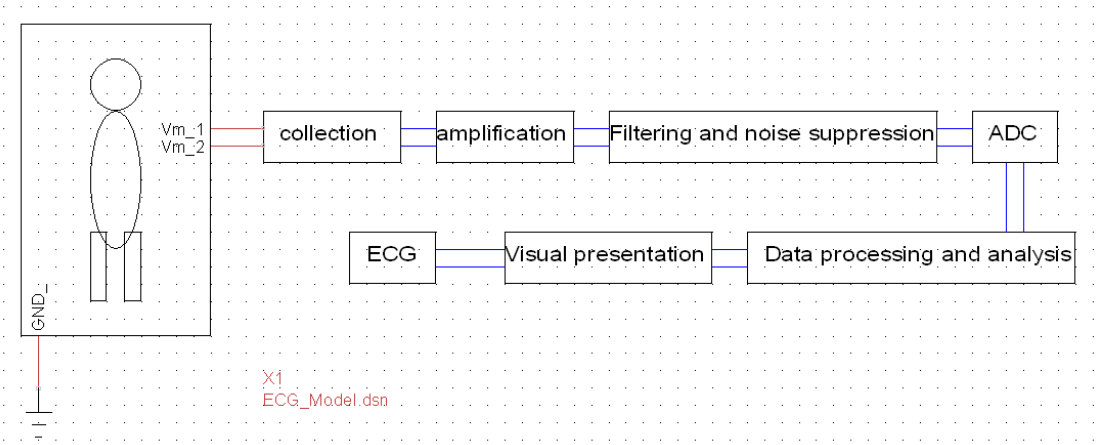


Figure 1. ECG signal processing flow (Photo/Picture credit: Original)

1. Collection of ECG signals: The regular contraction and relaxation of the heart promote blood circulation throughout the body, generating electrical excitations, which are transmitted from the tissues around the heart to the surface of the skin. The electrocardiogram records the heart's electrical activity by capturing the potential difference on the surface of the human body through wires placed at standard points on the body [2]. This is how ECG signals are generated. 2. Signal amplification: The collected ECG signal is usually a weak low-voltage signal, and the CMOS amplifier can be used to amplify the signal without distortion so that the output signal strength can be increased to help the signal be clearly observed and analyzed [3]. 3. Filtering and noise suppression: There will be various interference and noise in the ECG signal, such as power supply noise, muscle movement interference, etc. Filtering out interference and reducing noise is a very important part of ECG signal processing. 4. Analog-to-digital conversion: The obtained continuous analog signal needs to be input into an analog-to-digital converter (ADC) to convert it into a digital sample, and the digital signal is more convenient to process and store [4]. 5. Data processing and analysis: After digitization, various processing and analysis can be performed on the ECG signal. This may include heart rate calculations, QRS complex detection, arrhythmia detection, etc. 6. Visual presentation: Finally, the processed and analyzed ECG signal is presented in the form of graphics [5]. Usually, the obtained ECG waveform takes time as the horizontal axis and voltage as the vertical axis, which can clearly display the electrical activity of the heart, including P waves, QRS complexes, T waves, etc., as shown in the figure 2.

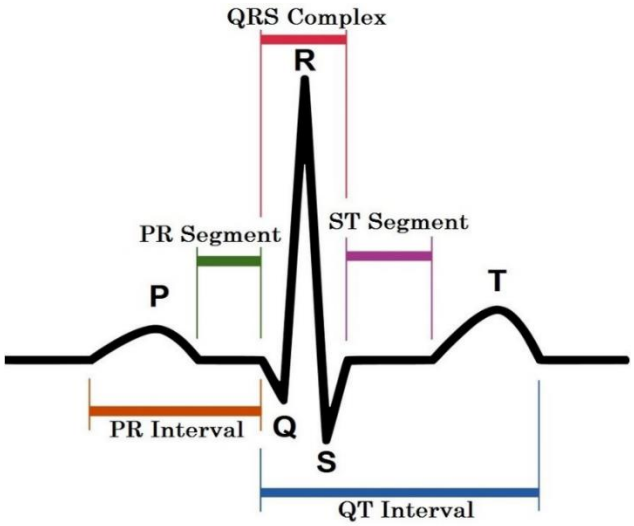


Figure 2. ECG waveform [5]

To sum up, this process is designed to extract and display the electrical activity signature of the heart to assist doctors in heart health assessment and diagnosis. Among them, for signal processing, the noise processing part of the CMOS amplifier is an extremely critical part.

3. Theoretical Basis of Low Noise CMOS Amplifier

3.1. Circuit structure

The circuit structure of the low-noise amplifier can take various forms. The figure 3 shows a common two-stage CMOS amplifier, which is widely used in various electronic systems and applications, including communications, audio, display, sensors, and interfaces.

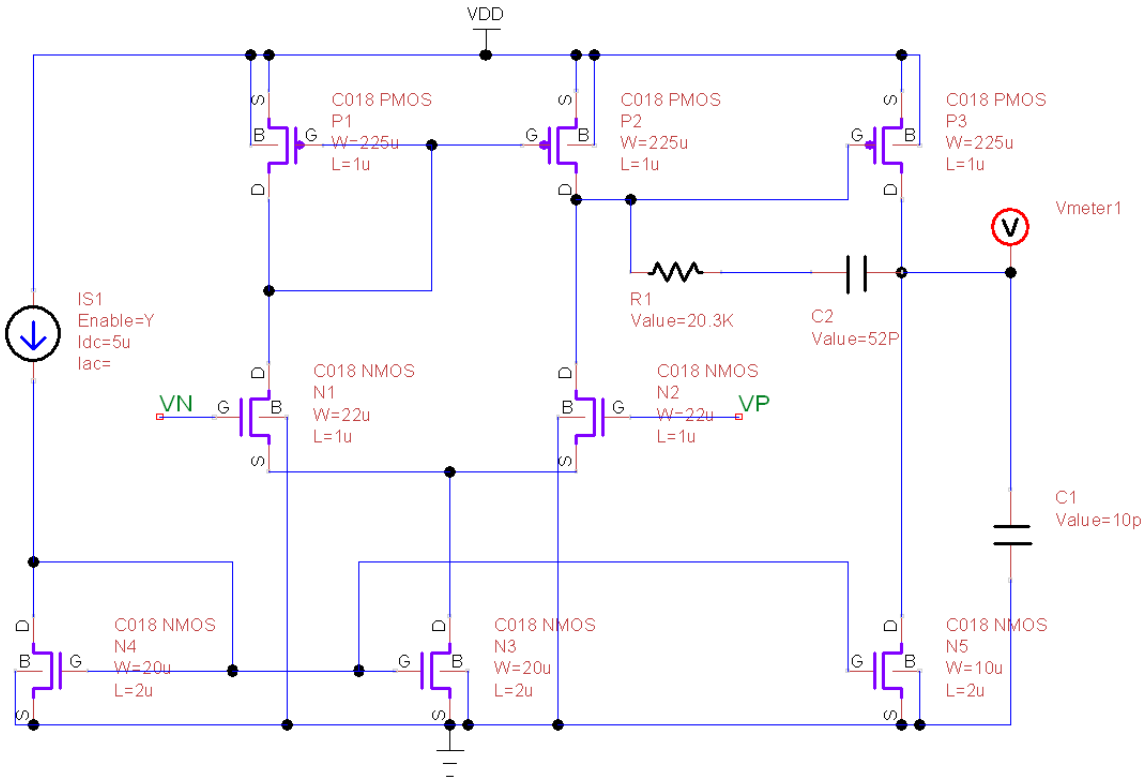


Figure 3. Two-stage CMOS amplifier circuit (Photo/Picture credit: Original)

3.2. Working principle

The CMOS two-stage amplifier consists of two cascaded CMOS transistors. The following is the working principle of the CMOS two-stage amplifier.

The first stage input stage: The first stage input stage is a differential amplifier consisting of a pair of NMOS and a pair of PMOS transistors. The drains of these two pairs of transistors are connected, and a constant current is provided by a current source through a current mirror. The input signal enters the differential amplifier from the input, where the common-mode portion is rejected and the differential-mode portion is amplified and passed to the second stage.

The second output stage: The second output stage is a common gate amplifier using PMOS transistors as the amplifier. The differential mode signal is passed from the first stage to the second stage, connected to the input terminal of the common gate amplifier, and provides a constant current through the current source. The common-gate amplifier amplifies the differential-mode signal a second time and produces an amplified differential-mode voltage at the output.

The circuit shown in the figure 3 also adds a zero resistor (R1) and a Miller capacitor (C2). The Miller capacitor can reduce the limitation of the bandwidth, make the circuit more stable and prevent the circuit from oscillating. The main function of the zero resistor in the circuit is to provide an instantaneous zero resistance path for the voltage in the circuit under the premise of ensuring the

continuity of the current, to overcome the resistance limitation in the circuit and improve the response speed of the circuit.

By cascading two amplification stages, a CMOS two-stage amplifier can achieve higher overall gain and better linear performance. The first-stage differential amplifier can provide voltage gain and the ability to reject common-mode signals, and the second-stage output stage can further amplify the signal and provide lower output impedance.

3.3. Characteristics of low noise amplifier:

Low-noise CMOS amplifiers are usually used to amplify analog signals, Due to the use of CMOS technology, through proper working principles and optimized circuit design, in addition to low noise, also have high gain, low power consumption, wide frequency response and temperature stability, etc., to meet the requirements for amplification Applications requiring weak signals and minimizing noise. As shown in the figure 4, the designed two-stage CMOS amplifier can achieve a gain of nearly 80 dB and a phase margin of more than 90.

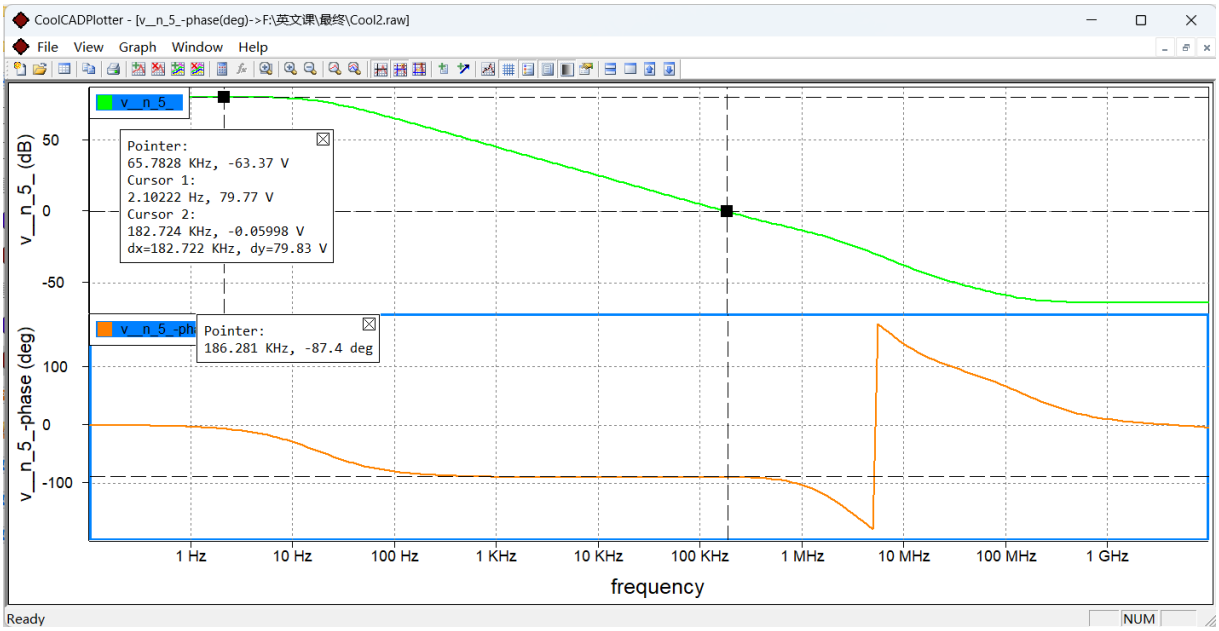


Figure 4. Circuit simulation model (Photo/Picture credit: Original)

4. Factors and Analysis Affecting CMOS Amplifier Noise Optimization in ECG Scenario

4.1. Constraints of devices and technologies

1. Silicon-based material characteristics: CMOS amplifiers use silicon materials as substrates, and silicon materials themselves have certain noises, and silicon-based CMOS is not suitable for working in high-temperature environments [6]. The temperature will cause random thermal movement of electrons, and these random thermal movements will cause random fluctuations in current and voltage, resulting in Thermal noise. Although ECG signal acquisition is mostly carried out at room temperature, it may also need to face various emergency situations. In addition, the application of other CMOS processes may need to adapt to various environments, such as the aerospace industry, which is limited by temperature and resistance value, thermal noise is unavoidable.

2. Characteristics of transistor devices: Transistors are mainly made of semiconductor materials, most of which are made of silicon materials. The transistor itself has noise, and its cut-off frequency, transconductance, threshold voltage changes and other aspects will affect the noise performance [7]. For example, 1/f noise exists not only in transistors, but also in energy-consuming devices such as resistors, and its generation is often related to impurities and imperfect lattice structures.

3. Accuracy and calibration: Low-noise CMOS amplifiers require high-precision design and manufacture. The CMOS process manufactures NMOS devices and PMOS devices on the same silicon substrate at the same time to make CMOS-integrated circuits. The circuit performance is good and the integration is very high. Manufacturing In each process of process, slight changes in design parameters may have a great impact on noise optimization, and the CMOS amplifier needs to be connected with other circuits to form a complete ECG monitoring instrument.

4.2. Complexity of Noise Sources

There will be a variety of noises in the process of ECG signal acquisition and transmission, including baseline drift, muscle motion noise, breathing motion noise, power interference, etc., people's mental state will affect the noise [8]. These noises not only have different spectral characteristics and amplitude ranges but also require specific analysis and specific devices or technologies for noise reduction in the face of each noise, making it difficult to accurately identify and remove these noises.

Secondly, the ECG signal is similar to the noise, and the spectrum range of the ECG signal is narrow, usually between 0.05 Hz and 100 Hz. Many noise sources in this frequency range have similar spectral characteristics to the ECG signal, making it difficult to distinguish noise from the signal. At the same time, the ECG signal itself also contains low-amplitude high-frequency noise components, which increases the overlap and confusion of the signal and noise. As shown in the figure 5, import the human body model and run Transient simulation to obtain a waveform with noise.

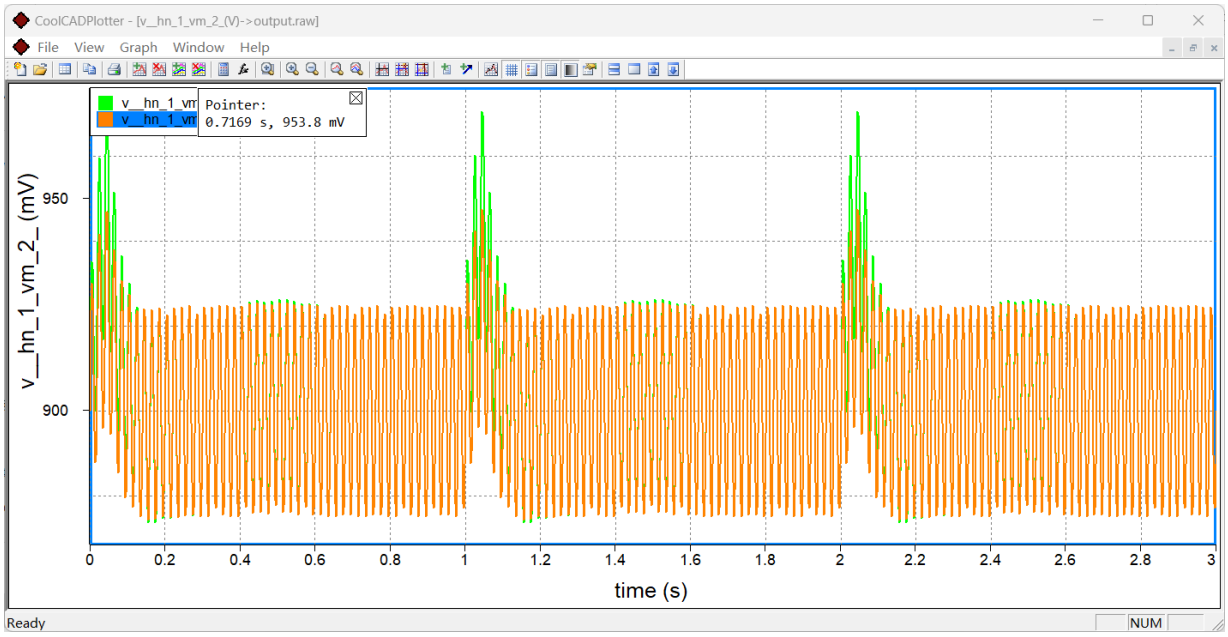


Figure 5. Waveform with noise (Photo/Picture credit: Original)

The noise performance of the amplifier is often evaluated by the noise figure NF, which can be expressed as the ratio of the input signal-to-noise ratio to the output signal-to-noise ratio [9]. ECG signals usually have a low signal-to-noise ratio, which may be more obvious in actual clinical environments. The lower signal-to-noise ratio makes it easier for the noise to cover up or confuse the details and characteristics of the ECG signal, increasing the difficulty of signal extraction and recovery.

In addition, the interference of other circuits is also the cause of noise. The CMOS amplifier is in the ECG circuit and may be interfered with by other circuits or power sources. These interferences may be suppressed by coupling and power supply noise reduction operations. There is a lack of comprehensive consideration when connecting circuits, which will affect the noise, gain, energy consumption, and other indicators [7].

4.3. Optimizing the balance between noise performance and other performance

For CMOS amplifiers used for ECG signals, if blindly focusing on noise reduction, other performance imbalances will result. Noise optimization needs to be balanced with other performances, and the relationship between each index should be properly handled [10]. This includes the following:

1. Signal fidelity: Ensuring the undistorted output of the signal is an important item in the research of CMOS amplifiers, especially for ECG signals, its distortion may lead to the loss of important information, affecting the judgment of doctors and the treatment of patients. Therefore, while reducing noise, it is necessary to maintain the authenticity and accuracy of the ECG signal as much as possible.

2. Low power consumption and high gain: The amplifier device needs to provide sufficient gain during the noise reduction process to amplify the ECG signal to an appropriate level. However, too high a gain may lead to increased power consumption of the amplifier, and additional noise will be introduced at the same time [11]. Therefore, to optimize the noise performance, it is necessary to reduce the power consumption as much as possible while providing sufficient gain, so as to keep the system complexity and energy consumption small.

3. Real-time: ECG signals usually need to be monitored and analyzed in real-time, so the noise reduction algorithm needs to be real-time and efficient. The noise reduction technology and devices also need to have sufficient computing power and processing speed while ensuring the effect of noise reduction.

4. Cost-effectiveness: ECG signal processing needs to pay attention to cost-effectiveness while reducing noise and anti-interference. In order to improve signal quality, some technologies and measures used may increase the cost and complexity of the system. At present, electrocardiogram monitors have been popularized, but too expensive or complex instruments are difficult to be widely used. Therefore, the optimization of ECG signal noise needs to balance cost-effectiveness.

5. Noise Optimization of CMOS Amplifier

5.1. Break through the constraints of devices and technologies

1. Advanced technology and materials: The use of advanced technology and materials, such as deep submicron technology, low-noise materials, etc., can significantly improve device performance and reduce noise. These processes and materials can provide better device characteristics, lower noise parameters and higher integration. Different materials can be compared and analyzed, and the one that is more beneficial to the optimization of ECG signal noise can be selected through calculation, experiment, and experience accumulation, and new advanced materials can be continuously developed at the same time.

2. Optimize device selection: Modern CMOS processes usually provide various types of transistors. For the selection of CMOS amplifier devices, you can choose transistor devices suitable for ECG signals. When selecting devices, you can pay attention to their noise parameters, such as cut-off frequency, sub- Threshold swing noise, etc. For example, choose a device with better flexibility and biocompatibility, and make a flexible and stretchable field effect transistor device [12].

3. Adaptive calibration and compensation: Through adaptive calibration and compensation technology, the uncertainty and changes of device parameters can be offset, thereby reducing the impact of noise on amplifier performance. Adaptive calibration techniques can be used to adjust bias current, calibrate gain, correct nonlinearity, etc., to improve the stability and performance of the amplifier. The research and application of new technologies will make the noise optimization of CMOS amplifiers go a step further. Among them are adaptive filtering methods, which automatically adjust the parameters of the filter according to the statistical properties of the signal. The adaptive filter can adapt to the variation of ECG signal and the variability of noise, so as to achieve better noise reduction effect.

5.2. Optimizing the circuit structure for noise sources

1. Use auxiliary circuits and feedback: auxiliary circuits and feedback techniques can be used to compensate for noise, interference, and imperfect device characteristics. For example, using a suitable bias circuit for ECG signals to select a suitable bias point can not only reduce noise but also help the gain of the circuit [13]. In addition, commonly used noise suppression circuits, negative feedback and other methods can reduce the impact of noise on the amplifier.

2. Parallel processing and digital signal processing: Using parallel processing and digital signal processing technology can improve the signal-to-noise ratio and weaken the influence of noise. These technologies can use methods such as filtering and noise reduction algorithms to suppress noise before the output of the amplifier, thereby improving signal quality. Perform a sophisticated analysis of different types of noise, analyze different solutions, and consider the combined use of these solutions.

3. Design and layout optimization: By optimizing the circuit design and layout of the amplifier and even the overall ECG, using good layout practices, reducing wire length, reducing cross-coupling, optimizing power supply and grounding networks, etc., the noise reduction performance of the amplifier can be improved to reduce noise propagation and coupling. For example, a new type of low-noise amplifier structure is designed by using two-stage capacitive cross-coupling cascading and balun as an inter-stage matching method. Selecting an appropriate MOS tube size, providing an appropriate bias voltage, and matching an appropriate circuit can achieve lower noise and higher gain, and have good linearity [10].

5.3. Algorithm optimization

The ECG signal has a sparse characteristic and a certain periodicity as a whole, and as the order of the difference operation increases, more and more values are close to zero, and the signal is sparser, so fewer useful details can be used Represents the original signal, which is beneficial for both noise optimization and signal representation [14]. A sparse matrix is shown in the figure 6.

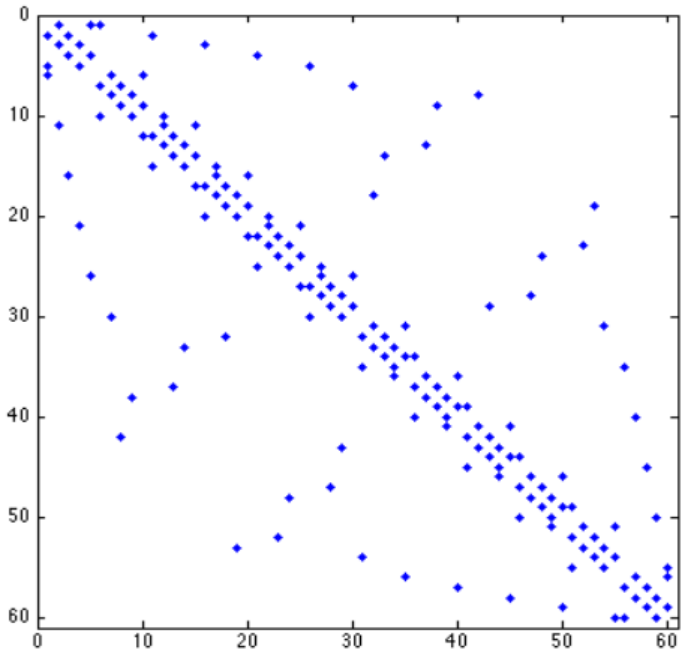


Figure 6. sparse matrix [14]

At present, the development of algorithms and theories based on sparse signal processing has been Becoming an active research area, algorithms based on sparse representations have also been applied in the processing of ECG signals. For example, for the baseline drift noise of the ECG signal, a denoising algorithm based on the combination of sparse characteristics and low-pass filtering is proposed by decomposing and modeling the ECG signal. ECG noise reduction technology, a new

fusion algorithm (RSSD-MN), and a full variation denoising algorithm based on sparse threshold function [15]. Based on the sparse characteristics of ECG signals, the algorithm model is established, and the calculation of various functions opens up new ideas for the noise optimization of ECG signals.

Also based on the wavelet analysis method for ECG signal processing and research, there are wavelet modulus maximum value denoising method and wavelet coefficient scale correlation denoising method [16]. For the analysis of ECG signals, various algorithms can be compared, and the appropriate algorithm can be selected. On the basis of the original algorithm, defects can be analyzed, functions can be improved, and a solution that is more suitable for solving practical problems can be obtained.

The application of deep learning in ECG signal noise reduction is also a direction worthy of research. Aiming at the deficiencies in traditional noise reduction methods, deep learning methods can be introduced in the processing of ECG signals, among which convolutional neural networks and confrontational neural networks are helpful for ECG processing analysis [3]. Convolutional neural network (CNN) is a deep learning model widely used in image processing and pattern recognition. CNN can be used to train ECG signal images to achieve the purpose of noise reduction. CNN can identify and filter out irrelevant noise by learning local features and hierarchical expressions [17]. A Generative Adversarial Network (GAN) is an adversarial model consisting of a generator and a discriminator. In ECG signal denoising, a generator is trained to generate clean ECG signals, and a discriminator is trained to distinguish generated clean signals from noisy signals. Through continuous confrontation training, a signal closer to the real ECG is finally generated. Data preprocessing and data augmentation are important links in deep learning methods, which can improve the noise reduction effect of the model. The application of deep learning in ECG signal denoising provides a powerful tool for accurate and automatic signal denoising and has broad application prospects in the fields of ECG analysis and diagnosis.

6. Conclusion

In the processing of ECG signals, low-noise CMOS amplifiers are widely used due to their excellent noise performance, adjustable gain, and low power consumption. The current difficulties in noise optimization in CMOS amplifiers and the entire ECG circuit need to be comprehensively considered, and then analyze the corresponding feasible solutions for different influencing factors. It is process0ed from the aspects of material and device selection, technology application, circuit structure design, algorithm optimization, etc., and the comprehensive application of these aspects needs to be considered.

Noise in the ECG signal may mask or alter important features associated with cardiac disease, potentially leading to misinterpretation, misjudgment, or omission of important information. The optimized noise reduction process helps to reduce these noises, highlight the useful information in the ECG signal, enable the interpreter to analyze and interpret the ECG waveform more accurately. This can efficiently understand the state of the heart and improve the accuracy of diagnosis, which is suitable for formulating It is of vital significance to improve the treatment plan and improve the quality of life of patients, and undertake the sacred mission of saving lives.

References

[1] Wei Xiaoqing. ECG signal processing algorithm and its implementation for wearable applications, 2019, 12.

[2] Li Duan. Research on Bioelectrical Signal Classification and Recognition Algorithms for Smart Healthcare. Beijing University of Posts and Telecommunications, 2018, 20 (3).

[3] Xu Bingxin. Research on ECG signal processing technology based on sparse features and deep learning, 2021, 6 (6).

[4] Wang Huaiming. Based on micro-Research on high-precision digital-to-analog conversion technology of difference measurement method, 2022, 29 (5).

[5] Li Wenkai, Cheng Miaoting, Qu Xingda, etc. Research on digital health information cognition based on visual presentation, 2023, 27 (5): 1 - 17.

[6] He Yulong. High-temperature CMOS integrated circuits based on 4H-SiC Key process design, 2021, 5.

[7] Chen Ye. Design and research of W-band high-gain low-noise amplifier, 2022, 6.

[8] Xu Hao, Li Xianhua, Yu Haohao, etc. Research on denoising of surface electromyographic signals based on combined wavelet transform, 2023, 15 (5): 24 - 27.

[9] Shang Kunpeng. Research and Design of Low Noise Amplifier Applied to 5G Communication RF Front-end Receive Path, 2022, 5.

[10] Zhang Zhitao. Design of a K-band low-noise amplifier based on CMOS technology, 2022, 12 (5).

[11] Zhao Xueyong. CMOS broadband limiting and reconfigurable low noise amplifier design and high-temperature application research, 2022, 6.

[12] Cui Haoran, Song Jian, Wang Yuelin, etc. Material selection and device of flexible stretchable field effect transistor device Preparation, 2021, 27 (4): 254 - 266.

[13] Yu Juchen. Limiting low-noise amplifier integration with out-of-band rejection characteristics Design, 2022, 9 (6).

[14] Wang Xiao. Research on key technologies of ECG signals intelligent processing, 2020, 12 (6).

[15] Shi Hao. ECG signal processing technology based on sparse representation and morphological component analysis Research, 2021, 6 (6).

[16] Ouyang Bo. Research on ECG signal processing technology based on wavelet analysis, 2014, 20 (4).

[17] Jin Zhongyi. Research on ECG signal processing technology based on sparse features and machine learning, 2020, 12 (6).