Wireless Bluetooth noise-cancelling headphones exploring the design principles and different categories of products

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Abstract. Bluetooth headphones have almost overtaken the wired headphone in the past five to ten years. This is due to the improved stability and sound quality of the Bluetooth transmission technology and the decrease in delay during the transmission. The portability of Bluetooth headphones makes them popular with people who spend time away from home and desks. This paper aims to observe and compare the noise-cancellation technology in the commonly-seen Bluetooth headphones in the market. The paper illustrates the common noise cancellation methods in section 2. Section 3 describes four common noise-canceling headphones and their noise-cancelling mechanism. The future outlook is provided in section 4 to display the current limitation of Bluetooth headphones, which mainly demonstrates the active noise-cancellation technology.

Keywords: Bluetooth, headphones, noise-cancellation, technology

1. Introduction

Bluetooth headphone has become an integral part of modern society. It provides wireless convenience and allows people to enjoy music and talk comfortably in various scenarios. This chapter will introduce the historical background of Bluetooth headphones, its development process and its impact on people's life.

Bluetooth technology was first introduced in 1994 by the Swedish company Ericsson [1]. The technology was designed to transmit and communicate between connected devices via a wireless communication protocol. The initial goal was to replace device connections that used too many cables, such as data transfer between computers and cell phones. In 1998, the Bluetooth Alliance was formed with companies such as Ericsson, Nokia, and IBM [2]. This alliance promoted the rapid development and wide application of Bluetooth technology. The introduction of Bluetooth headphone can be traced back to 2000, when Ericsson released a product called "Headphones". This headphone uses Bluetooth technology to enable users to talk directly in their ears instead of holding a cell phone. It offers greater freedom and convenience than traditional wired headphones.

Bluetooth headphones also bring a lot of convenience to people's lives [3]. They remove the limitations of traditional wired headphones, allowing people to use them more freely when doing sports, working or traveling. In addition, Bluetooth headphones can connect to multiple devices, allowing users to switch freely between computers, cell phones, tablets, and many other devices. The popularity of Bluetooth headphones has also benefited from the development of the cell phone industry. With the popularity of smartphones, people's demand for music and calls has gradually increased. Bluetooth headphones fulfill the need for wireless audio, enabling users to enjoy quality music and calls anytime, anywhere.

With the advancement of technology and the improvement of Bluetooth technology, Bluetooth headphones soon made a major breakthrough. In 2004, with the introduction of Bluetooth 2.0 technology, the transmission distance and stability of Bluetooth headphones were significantly improved [4]. This breakthrough laid the foundation for the rapid popularization of Bluetooth headphones. Over time, the design and functionality of Bluetooth headphones have improved. Modern Bluetooth headphones feature smaller and lighter designs, making them more comfortable to wear. At the same time, new technologies such as noise-canceling, touch controls, and voice assistant support further enhance the user experience. The following chapter will focus on introducing and illustrating the principles of noise-canceling technology in Bluetooth headphones, as well as popular products from major manufacturers and the noise-canceling bean technology they use, and the development prospects of Bluetooth headphones.

2. Design Principles

2.1. Noise Cancellation Mechanisms

The noise cancellation mechanism aims to mitigate or eliminate ambient environmental noise, enhancing users' ability to perceive music, sounds, or communication. It typically employs two primary mechanisms: passive noise isolation (PNI) and active noise cancellation (ANC). Contemporary high-end noise cancelling headphones often integrate both active and passive noise cancellation mechanisms to achieve superior noise reduction. Users have the option to enable or disable the noise cancellation feature based on their requirements, thereby optimizing auditory experiences across diverse settings.

2.1.1. Passive Noise Isolation (PNI). PNI refers to the inherent capability of headphones, earbuds, and in-ear monitors to naturally block external ambient noise. These auditory devices create an acoustically isolated environment without relying on active technological countermeasures. The precise adaptation of earbuds to the anatomical contours of the ear impedes the intrusion of environmental sounds into the auditory canal. As a result, this tailored adaptation reduces the need for sound counterbalance, thereby facilitating lower acoustic thresholds. Simultaneously, passive noise isolation conserves energy, eliminating the need for additional battery power [5].

2.1.2. Active Noise Cancellation (ANC). ANC refers to the technology used by headphones to neutralize ambient environmental noise. ANC can be categorized into three main types: feedforward ANC, feedback ANC, and hybrid ANC. Feedforward ANC is relatively easier to implement and involves placing the microphone outside the headphones, away from the speaker. Feedback ANC, on the other hand, positions the microphone closer to the speaker, allowing it to capture noise information that closely resembles what the human ear hears, resulting in enhanced noise reduction performance. Hybrid ANC combines both feedforward and feedback approaches, synergistically boosting the overall noise cancellation capability.

The operational principle of ANC involves a sequence of steps. Initially, the integrated microphones within the headphones capture real-time ambient noise from the surrounding environment. Subsequently, a noise analysis is performed, with the captured noise being transmitted to an internal signal processor within the headphones for analysis.

The signal processor analyzes the features and spectrum of the noise to identify specific components that necessitate reduction or elimination. Following this, the signal processor generates an anti-phase signal, commonly referred to as "anti-noise." This anti-noise signal possesses a phase opposite to that of the noise signal, facilitating the cancellation of noise when they intersect within the headphones. The generated anti-noise signal is then combined with the audio signal currently playing. This process is shown as the figure 1. By incorporating the anti-noise signal into the audio signal, the headphones can counteract or diminish the noise present in the external environment [6].

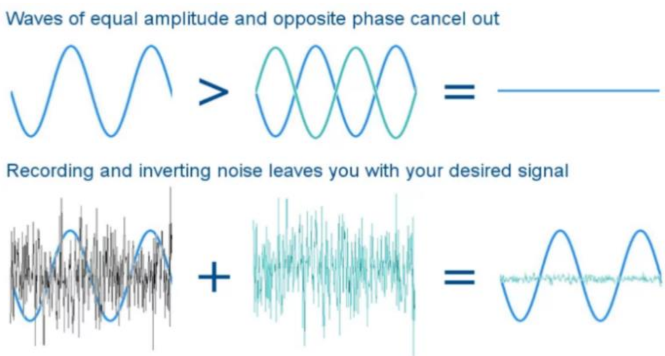

Figure 1. ANC working process [6]

As environmental noise can be constantly changing, the noise reduction system needs to continuously adjust the generated anti-phase noise in real-time. This typically requires the use of adaptive filtering algorithms, such as the Least Mean Squares (LMS) algorithm, The LMS algorithm adjusts filter coefficients based on the magnitude and direction of the error signal to minimize the error. Through continuous iterations, the filter coefficients gradually converge to a state where the generated anti-phase noise can effectively minimize the environmental noise present in the input signal.

The core of the LMS algorithm lies in adjusting the coefficients of the filter to minimize the mean square error of the error signal. The update for each filter coefficient can be represented as:

$$w(n+1) = w(n) + \mu * e(n) * x(n) \tag{1}$$

Where w(n+1) represents the weight vector at step n+1, w(n) represents the weight vector at step n, μ is the step size, x(n) is the input signal vector at step n, and e(n) is the error signal at step n.

$$e(n) = d(n) - y(n) \tag{2}$$

The desired output signal is denoted as d(n), and the actual output signal is denoted as y(n). The objective is to adjust the weight vector w(n) in a way that the actual output signal y(n) closely approximates the desired output signal d(n).

Exactly, the goal of the LMS algorithm is to minimize the Mean Squared Error (MSE), which is represented by the formula:

$$MSE = ||e(n)||^2 = e(n)^* \mathrm{e(n)} = \big(d(n) - y(n)\big)^* \big(d(n) - y(n)\big) \tag{3}$$

Here, $||e(n)||^2$ represents the squared magnitude of the error signal e(n) at step n.

Expanding the equation yields:

$$||e(n)||^2 = d(n)^* d(n) - 2\, d(n)^* y(n) + y(n)^* y(n) \tag{4}$$

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Here, $d(n)^* \, d(n)$ is a constant term unaffected by the weight vector w(n). Therefore, the objective is to minimize $-2\, d(n)^* \, y(n) + y(n)^* \, y(n)$, which is equivalent to minimizing $-2\, d(n)^* \, y(n)$. This is why there's a desire for y(n) to closely approach d(n), in order to minimize the error.

Substituting e(n) in, get:

$$w(n+1) = w(n) + \mu \, x(n)\big(d(n) - y(n)\big) \tag{5}$$

Multiplying both sides of the above equation by $x(n)^*$, get:

$$x(n)^* w(n+1) = x(n)^* \, w(n) + \mu \, x(n)^* x(n)\big(d(n) - y(n)\big) \tag{6}$$

Here, $x(n)^* \, w(n)$ represents the estimation of the current weight vector w(n) on the input signal x(n).

The goal is to minimize the MSE, which is to minimize $||e(n)||^2$. According to the above derivation, if make the weight vector w(n+1) gradually approach the weight vector w(n), then $x(n)^* w(n+1)$ will also gradually approach$x(n)^* \, w(n)$. As a result, the actual output signal y(n) will gradually approach the desired output signal d(n), ultimately reducing the error and achieving the objective of real-time reduction of environmental noise.

The ultimate audio output results from the amalgamation of the original audio signal and the anti-noise signal, thereby engendering an auditory effect characterized by diminished external noise perception.

2.2. Sound Generation Mechanisms

The process by which headphones sound generation mechanism is a precise and remarkable phenomenon, encompassing the transformation of electrical signals into audible audio [7]. This intricate process involves several intricate stages, spanning from the manipulation of electronic signals to the propagation of sound waves, ultimately culminating in the engagement of the auditory system [8].

2.2.1. Signal Input and Conversion. Initially, an audio source generates an electrical signal, commonly in the form of a digital audio signal. Subsequently, the digital-to-analog converter (DAC) comes into play, converting the digital signal into a continuous variation of analog voltage signals. Figure 2 shows this process.

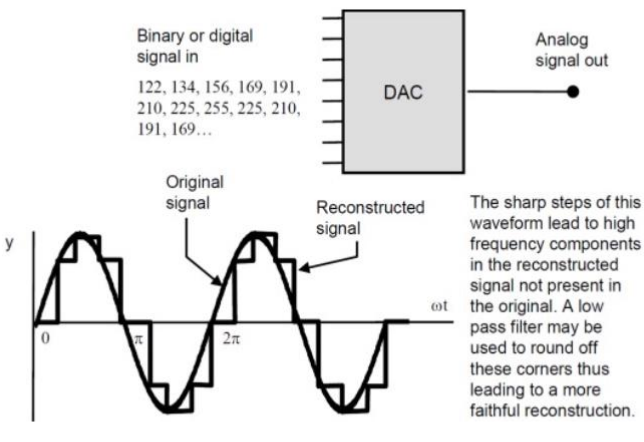

Figure 2. The process of DAC [9]

The DAC translates continuous signals into discrete numerical values through two sequential processes: quantization and sampling. In quantization, the DAC segments the continuous signal range into an array of discrete levels, subsequently mapping each discrete level to the nearest digital value. In the sampling process, the input signal is measured at specific time intervals, and these sampled points are employed for subsequent processing.

Following this, the quantized digital values are translated into the amplitude of analog signals. This conversion entails associating the digital values with the magnitude of analog signals in terms of voltage or current.

Since the output signal from the DAC is discrete, it may introduce high-frequency components. To alleviate these high-frequency components, a reconstruction filter is utilized to smoothen the output signal, resulting in the generation of a continuous analog waveform.

Ultimately, the analog signal is output, with its variations corresponding to the input digital data, specifically the alterations in the waveform of the sound.

2.2.2. Driver Unit and Sound Wave Generation. The driver unit of headphones is one of the core components, responsible for converting electrical signals into sound waves to generate audio. They consist of magnets, coils, and diaphragms. When an electric current passes through the coil, it moves back and forth within a magnetic field, causing the diaphragm to vibrate and produce sound waves. The size and type of driver unit can significantly impact the sound quality and performance of the headphones. The main types of driver units include Dynamic Drivers, Balanced Armature Drivers, Planar Magnetic Drivers, Electrostatic Drivers, Bone Conduction (Magnetostriction) Drivers and Hybrid Drivers [10].

2.3. Bluetooth Mechanisms

Bluetooth employs short-wavelength ultra-high frequency (UHF) radio waves, with a carrier frequency ranging from 2.400 GHz to 2.485 GHz. This frequency range is divided into 79 distinct channels, and the signals are organized into data packets that are transmitted across these channels. Each data packet is allocated a random channel 1600 times per second, a process known as frequency-hopping. Channel randomization is synchronized between paired devices to ensure the proper sequence for sending and receiving data packets. This mechanism also prevents communication between two unpaired devices.

In the transmission of digital audio, Bluetooth is utilized for the exchange of digital signals between devices. The operational principle of wireless headphones involves receiving digital audio signals composed of bits (fundamental units of computer language, represented as 0 and 1).

In Bluetooth connections, one of the primary modulation methods employed is Gaussian Frequency Shift Keying (GFSK) modulation. which represents digital data by introducing Frequency Shift Keying in the carrier signal. This FSK is based on the characteristics of the Gaussian (normal) function.

In GFSK modulation, the frequency of the modulating signal does not undergo an instantaneous change at the onset of each binary data symbol period. Consequently, the transition from bit 0 to bit 1, or vice versa, becomes more gradual. This implies that, relative to conventional FSK, there is a reduced magnitude of amplitude and phase variation in the modulated signal.

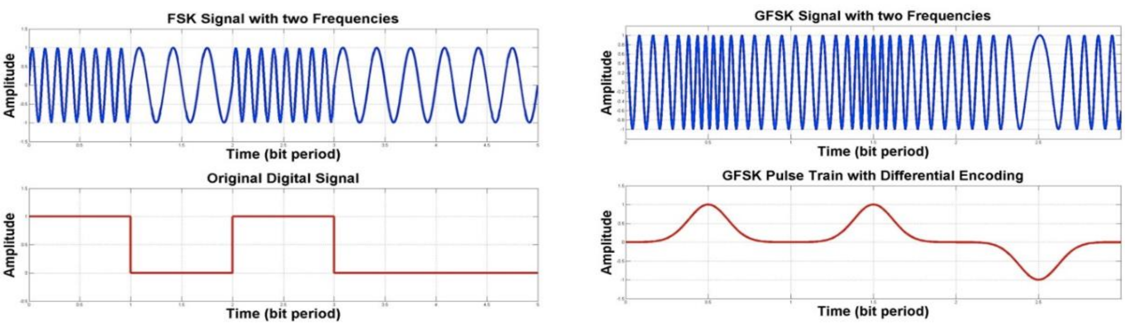

Figure 3. FSK modulated signal response and GFSK modulated signal response [11]

As depicted in Figure 3, it becomes more evident that the GFSK modulated signal exhibits comparatively diminished amplitude and phase variations. This characteristic aids in the precise determination of the carrier frequency of the received signal [11].

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3. Different Categories of Products

3.1. Description of several common noise reduction bean

In this part, this paper will list four specific headphones with its basic information and its pictures.

3.1.1. Sony WF-1000XM5. Sony Noise Cancelling Beans 5, equipped with the new generation HD Noise Cancelling Processor QN2e, the new generation high-performance integrated processor V2, and the new generation dual feedback microphone technology and 6-microphone system, presents noise cancelling performance and immersive sound quality that surpass traditional true wireless earphones. Sony also designs a new driver unit X, which reproduce ultra-wideband sound quality, showing deeper bass, delicate vocals, and realistic sound details. The advanced audio hardware technology combined with LDAC Bluetooth transmission technology provides rich, smooth, natural, and high-resolution sound effects, making users feel as if they are on the scene [12].

3.1.2. Bose QuietComfort® Earbuds. Bose Noise Cancelling Beans use active and passive noise cancelling technologies, mainly including: internal and external microphones; monitor the sound in the environment and the ear canal, and generate opposite signals in less than a millisecond to eliminate unwanted noise; CustomTune intelligent in-ear sound field tuning technology; provide personalized sound effects and world-class unparalleled noise cancelling technology according to the shape and size of each person's ears; Soft earbuds: fit the ear contours completely, forming a gentle seal, blocking the noise from the outside [13].

3.1.3. Airpods Pro. Airpods Pro also use active and passive noise cancelling technologies, mainly including: Outward-facing and inward-facing microphones: detect the external sound and the excess sound in the ear, and cancel them with equal anti-noise sound waves before you hear them. Adaptive equalizer: automatically adjusts the mid-low frequency music according to the seal degree of the earbuds and the ear canal, to provide consistent sound quality [14].

3.1.4. Soundcore Liberty Air 2 Pro. Soundcore Liberty Air 2 Pro's cancelling technologies includes: Hybrid microphone system: built-in two outward-facing and one inward-facing microphones, which can switch between traffic, indoor, outdoor or custom noise cancelling modes according to the environment. Transparency mode: can quickly switch the earbuds from noise cancelling mode to voice transparency mode, which enhances the surrounding voices without amplifying other sounds, for easy conversation. PureNote sound technology: uses a high-hardness 10-layer coating process to form the 11mm drivers in the earbuds, which can provide clear and accurate sound at all frequencies [15].

3.2. Description of Several Common Noise Cancelling Headphones

In this part, this paper will list four specific headphones with its basic information and its pictures.

3.2.1. Bose QuietComfort 35 II. The Bose QuietComfort 35 II integrates its exclusive Acoustic Noise Cancelling technology, founded on a proprietary blend of passive and active noise reduction mechanisms. Its innovative method involves an intricately calibrated combination of phase-inverted sound waves produced through multiple internal and external microphones. This pioneering approach achieves exceptional noise cancellation by effectively countering external noise sources across a broad spectrum of frequencies [16].

3.2.2. Sony WH-1000XM4. Sony WH-1000XM4 boasts the Adaptive Dual Noise Sensor technology, which leverages a duo of highly sensitive microphones to capture and analyze ambient sounds. By utilizing advanced algorithms, it dynamically adjusts noise cancellation parameters in real-time, optimizing its performance based on varying environmental factors. This distinctive technology results in a superior listening experience characterized by adaptability and precision [17].

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3.2.3. Sennheiser Momentum 3 Wireless. Sennheiser Momentum 3 Wireless introduces its exclusive Hybrid Anti-Wind Noise Cancellation, a sophisticated feature that distinguishes itself by mitigating the impact of wind noise on audio quality. This innovative approach involves combining traditional active noise cancellation with advanced wind noise prediction algorithms. By preemptively identifying and suppressing wind-related distortions, it ensures an uncompromised auditory experience, even in outdoor environments [18].

3.2.4. Apple AirPods Max. The Apple AirPods Max employs an avant-garde Computational Noise Cancellation technology, hinged upon the seamless interaction between custom-designed high-fidelity drivers and the proprietary Apple-designed audio-processing system. This cutting-edge fusion facilitates real-time adaptation to external acoustic conditions, resulting in unparalleled noise reduction and sonic immersion. Furthermore, its unique Dynamic Spatial Audio adds a new dimension by aligning sound with head movements, revolutionizing spatial perception within noise-canceling audio paradigms [19].

3.3. Comparison of Noise Reduction Performance of Several Common Noise Reduction Bean

The four earphone models exhibit distinctive noise-cancellation capabilities. Sony WF-1000XM5 and Bose QuietComfort® Earbuds manifest remarkable performance in noise reduction, attributable to their advanced active noise-cancellation technologies, effectively isolating external auditory disturbances and facilitating an immersive acoustic encounter. Nevertheless, Sony WF-1000XM5's comfort may be marginally impacted by its relatively larger dimensions, whereas Bose QuietComfort® Earbuds' physical design might render a perception of bulkiness.

Airpods Pro also demonstrates commendable noise-cancellation prowess, encompassing versatile active noise-cancellation and transparency modes to accommodate diverse auditory scenarios. However, its noise-cancellation efficacy may comparatively lag behind certain professional audio brands.

Soundcore Liberty Air 2 Pro, while economically attractive, potentially exhibits a relatively attenuated noise-cancellation capability. Despite featuring adjustable noise-cancellation functionalities, its noise-reduction effects might not parallel those of higher-tier counterparts.

In synthesis, Sony WF-1000XM5 and Bose QuietComfort® Earbuds ostensibly excel in noise-cancellation prowess, catering to those inclined toward superior sonic immersion and robust noise-abatement capabilities. Airpods Pro offers a comprehensive feature set within the Apple ecosystem, whereas Soundcore Liberty Air 2 Pro presents a cost-effective alternative. The selection process should be guided by individual predilections and requisites.

3.4. Comparison of Noise Reduction Performance of Noise Cancelling Headphones

These four headphone models exhibit distinct characteristics in terms of their noise-cancellation capabilities. The Bose QuietComfort 35 II is renowned for its exceptional active noise-cancellation technology, effectively attenuating environmental noise and providing a lucid auditory experience. However, it may exhibit slight deficiencies in the high-frequency range of sound, potentially rendering it less suitable for users with stringent high-fidelity requirements.

The Sony WH-1000XM4 employs a dual-sensor noise-cancellation technology, showcasing commendable performance in active noise cancellation and adaptive audio control. Nonetheless, it might entail a degree of low-frequency blurring, affecting the nuanced aspects of sound quality.

The Sennheiser Momentum 3 Wireless stands out with its distinctive transparency auditory feature and anti-wind noise reduction algorithm. While preserving situational awareness, it may not rival its competitors in terms of high-fidelity audio performance.

The Apple AirPods Max introduces computational audio technology, synergizing custom driver units with the Apple-designed H1 chip to achieve real-time adaptive noise cancellation. Nevertheless, its noise-cancellation efficacy might be relatively diminished in acoustically challenging environments, coupled with its higher price point.

Actually, these headphones' noise-cancellation prowess varies due to technological distinctions. The Bose QuietComfort 35 II and Sony WH-1000XM4 exhibit notable noise-cancellation performance, the

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Sennheiser Momentum 3 Wireless maintains environmental awareness, while the Apple AirPods Max amalgamates computational audio technology to offer a distinctive auditory experience. Users should judiciously assess these attributes based on individual needs and preferences when making a selection.

4. Future Directions and Potential Research Areas

Bluetooth headphone as a wireless audio device has made tremendous progress in just a few decades. However, with the continuous evolution of technology, the research direction and development potential of Bluetooth headphone is still huge. This paper will discuss the future research direction of Bluetooth headphone and look into its prospect.

4.1. Enhance the Sound Quality

One of the future research directions of Bluetooth headphone is to improve the sound quality. Although modern Bluetooth headphones have made significant progress in sound quality, there is still a gap compared with wired headphones [20]. Future research could focus on reducing sound quality loss and improving the stability and clarity of audio transmission. For example, higher audio coding standards and lower transmission latency could be explored to provide a better sound quality experience.

4.2. Add More Intelligent Features

The future development potential of Bluetooth headphone lies in the increase of intelligent functions. Modern Bluetooth headphones already have some intelligent features, such as touch control and voice assistant support. However, future research can go further and develop more intelligent features. For example, Bluetooth headphones can be combined with artificial intelligence to recognize the user's behavior and emotions and automatically adjust volume, playlists, etc. according to the user's needs. In addition, Bluetooth headphones can be connected with other smart devices (such as smart home) to realize more intelligent interactions.

4.3. Enhance the Human-computer Interaction Experience

The future research direction of Bluetooth headphone lies in better human-computer interaction experience. Modern Bluetooth headphones have been greatly improved in terms of human-computer interaction, such as through touch control and voice assistant operation. However, Bluetooth headphones still face some challenges, such as misuse and operational complexity. Future research can be dedicated to developing simpler and more intuitive human-computer interactions to provide a better user experience. For example, gesture recognition technology or brain-computer interface technology can be considered to achieve more natural and seamless human-computer interaction.

Overall, the future research direction and development potential of Bluetooth headphone is very broad. With the progress of science and technology, Believe that the future Bluetooth headphone will become a more intelligent and convenient audio equipment, bringing more fun and convenience to people's lives.

5. Conclusion

Bluetooth headphones play an important role in life, gradually replacing wired headphones in the market. Its convenience allows people who are away for a long time to be free from the constraints of cables, and this technology increases the maximum distance between the headphone and the device. Bluetooth headphones are also gradually becoming smaller and smaller and more portable. For instance, AirPods is approximately the size of a punch.

Today's Bluetooth headphones have developed more functions, such as noise reduction. Most noise-cancelling headphones use ANC technology. ANC works by using the principle of "destructive interference" to cancel external noise. A microphone built into the headphone or earpiece picks up noise signals from the surrounding environment and sends them to an internal processing unit. A processing unit analyses the frequency and amplitude of these noises and generates a sound wave that is the opposite of it, an “inverted” sound wave. When these anti-phase sound waves meet external noise, they create an interference effect that reduces or eliminates the original noise.

The limitations that the Bluetooth headphones currently on the market still need to deal with include improving the sound quality and signal transmission stability. Which can potentially add more artificial intelligence to realize more functions like gesture and emotion recognition. The human-computer interaction and connections to multi-devices are also the objectives.

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