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Bluetooth Active Noise Cancellation (ANC) Technology: Principles, Integration, Applications, and Performance Evaluation

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Abstract:

Thanks to the development of wireless audio transmission technology, Bluetooth technology made it possible to give users a seamless and convenient connection experience. However, in a noisy environment, preserving the audio quality is still difficult, which motivated people to explore the technology of Active Noise Cancellation (ANC). This paper aims to analyze integration of ANC technology and the potential of Bluetooth audio transmitting to improve the audio effect, especially in application scenarios where clear audio is required. At the beginning of this paper, how Bluetooth and ANC are evolved is reviewed for the preparatory works. Then, the technology mechanism of the ANC and the advantages in particular application scenarios such as Industrial automation and autonomous vehicles are described in detail. In addition, this paper give experimental data to illustrate that the ANC systems is effective in reducing ambient noise. The central technology of ANC system is using a microphone to detect environmental noise information and then creates a sound wave phase-inverted to the original noise to cancel. Furthermore, by connecting artificial intelligence technique, the ANC system dynamically fits from different acoustic environment to improve the audio quality. Finally, the experimental results that are quoted reveal that the advanced ANC system can reduce the noise level in a wide range of environments, cutting down the sound pressure level to 65 dB. It is clearly demonstrated that the ANC technology is widely applicable and effective to enhance the audio experience.

Keywords: Active Noise Cancellation (ANC), Bluetooth Audio Transmission, Noise Reduction

1. Introduction

Bluetooth is now one of the leading wireless audio transmission technologies alongside other various wireless audio technologies such as Wi-Fi, NFC (Near Field Communication) and Zigbee. Bluetooth enables seamless connectivity between devices which a user can enjoy audio content uninhibited by the use of cables. The versatility of Bluetooth is reflected in a variety of applications, including virtual reality (VR) environments, smart home systems, and connected vehicles (V2X technology). Recent market research indicates that the global Bluetooth market is projected to cross the $80 billion mark by 2027. Nowadays, there are nearly billions of Bluetooth-enabled devices in use, revealing the wide-reaching integration into everyday technology of Bluetooth technology.

Despite its advantages, Bluetooth has issues as well, especially keep audio quality under noisy environments. For instance, interference from other wireless signals can significantly degrade audio performance. This promote Advanced Noise Cancellation (ANC) technology to be investigated. ANC to improve audio performance by using microphones for detecting ambient noise, then generating sound waves with phase-inverted to cancel those unwanted sounds. This innovative approach enhances the listening experience, making it particularly valuable in applications where clear audio is essential.

This paper provides a comprehensive analysis of Active Noise Cancellation (ANC) technology and its integration with Bluetooth audio transmission. Chapter 2 reviews the related literature on Bluetooth technology applied in audio transmission and the shift of ANC techniques from passive to active methods. In Chapter 3, the technical mechanism of ANC is introduced and explained as producing the noise inversion to cancel the noise. Chapter 4 addressed the specific application scenarios including industrial automation and autonomous vehicles, highlighting the practical benefits of ANC and Bluetooth integration. Chapter 5 presented the experimental results, illustrating that ANC systems have significant effects in reducing the ambient noise level in various environments. In conclusion, this paper aims to emphasize the practical significance and impact of ANC technology on improving audio experience in all kinds of applications.

2. Literature Review

Bluetooth technology has significantly impacted audio transmission, particularly in wireless audio devices. Its combination with Active Noise Cancellation (ANC) technology is crucial for improving audio quality in noisy environments. For example, [1]Lalit Kumar Baghel et al. (2023) utilized the new LE audio in their study, which focuses on latency, power efficiency, and effective use of bandwidth to enable multiple streams, broadcasting, hearing aids, etc. In addition to this,[2]Haiyan Yu et al. (2021) in their study designed a real-time wireless audio transmission model based on body area network technology, supported by wireless body area network technology, thereby realizing real-time transmission of wireless audio as well as real-time compression of audio signals to make the wireless network transmission environment more stable. Another study conducted by [3]Sanghoon Lee et al. (2023) introduces a robust Bluetooth call flow based on frame overlapping transmission that utilizes a proprietary voice compression technique, thereby achieving improved voice perception quality.[4]Jaeho Lee et al. (2018) in their study proposed an energy detection based broadcasting scheme to improve the energy efficiency of the master device and optimize the isochronous channel this new feature of Bluetooth 5.0 for the purpose of audio transmission using Bluetooth low power technology. In addition, in order not to affect applications that require fast and accurate transmission of audio signals,[5]Allysa Joy Atienza et al. (2021) utilized super-resolution techniques such as Convolutional Neural Networks (CNNs) and Generative Adversarial Networks (GANs) in their study to improve the quality of the audio signals transmitted by Bluetooth. Overall, the combination of Bluetooth and ANC presents both opportunities and challenges, especially in ensuring consistent sound quality in various environments.

The development of ANC technology has evolved from passive noise cancellation methods to active noise cancellation methods that greatly enhance the audio experience. Initially, passive noise reduction techniques relied only on physical barriers with limited effectiveness. For example, in the old days, the development of various industrial equipment triggered acoustic noise problems associated with factory machines, and although the headrest ANC systems of the time were able to solve some of the problems, they still had certain shortcomings. Therefore,[6]Shun Hirose et al. (2017) developed a headrest ANC system using virtual sensing technology to improve the effectiveness of factory noise control. In addition to this, with the development of adaptive active noise reduction technology and the application of virtual sensing technology, virtual sensing technology effectively solves the low-frequency noise control in the cabin,[7]An Peng et al. (2023) further investigated a multi-channel virtual sensing noise reduction algorithm on this basis, and realized a wider range of noise reduction by designing an algorithm with multiple virtual error points. In addition, in the medical field, random body motion (RBM) and radar self-motion (RSM) artifacts can greatly reduce the detection accuracy. In order to eliminate the noise brought by RBM and/or RSM,[8]Fang Zhu et al. (2019) reviewed recent advances in eliminating RBM and RSM noise in Doppler radar systems for non-contact vital sign detection and measurement. In the study by [9]Zhongliang Wei et al. (2019), they explored new solutions for active noise reduction to control low-frequency noise by analyzing the principle of active noise reduction, describing the effect of vibration control in structural acoustics, and active vibration control measures in structural acoustics. Destructive interference is the basic principle of ANC (active noise control) system. In destructive interference, an adaptive filter is used to generate an anti-noise signal that is superimposed on the noise signal to reduce unwanted noise. In order to solve the problem of instability of ANC system due to the presence of reference noise that makes the secondary paths change over time,[10]Atul Pillania et al. (2015) applied an ANC system based on online modeling of secondary paths to ambulance siren noise in their study. The simulations done using MATLAB revealed a significant reduction of nearly 37 dB of decrease in noise level. Overall, it can be concluded that the switch from passive to active ANC techniques is growing in effectiveness in various audio applications.

3. Methodology and Technical Models

Active Noise Cancellation (ANC) technology decreases the unwanted ambient sound and enhances audio clarity by operating a complex mechanism. The diagram (Fig. 1) shows the ANC algorithm framework to illustrate this process. This framework usually contains microphones for detecting ambient noise, an ANC processor for analyzing sound waves, and speakers for playing an inverted sound wave canceling the noise. The key principle of ANC is generating destruction interference: as the inverted sound wave runs into the incoming noise wave, they cancel each other out effectively. This process involves continuous monitoring and adjustment to ensure that noise cancellation remains effective in real-time. By using this mechanism, ANC is extraordinarily effective at improving listening quality in environments with persistent background noise.

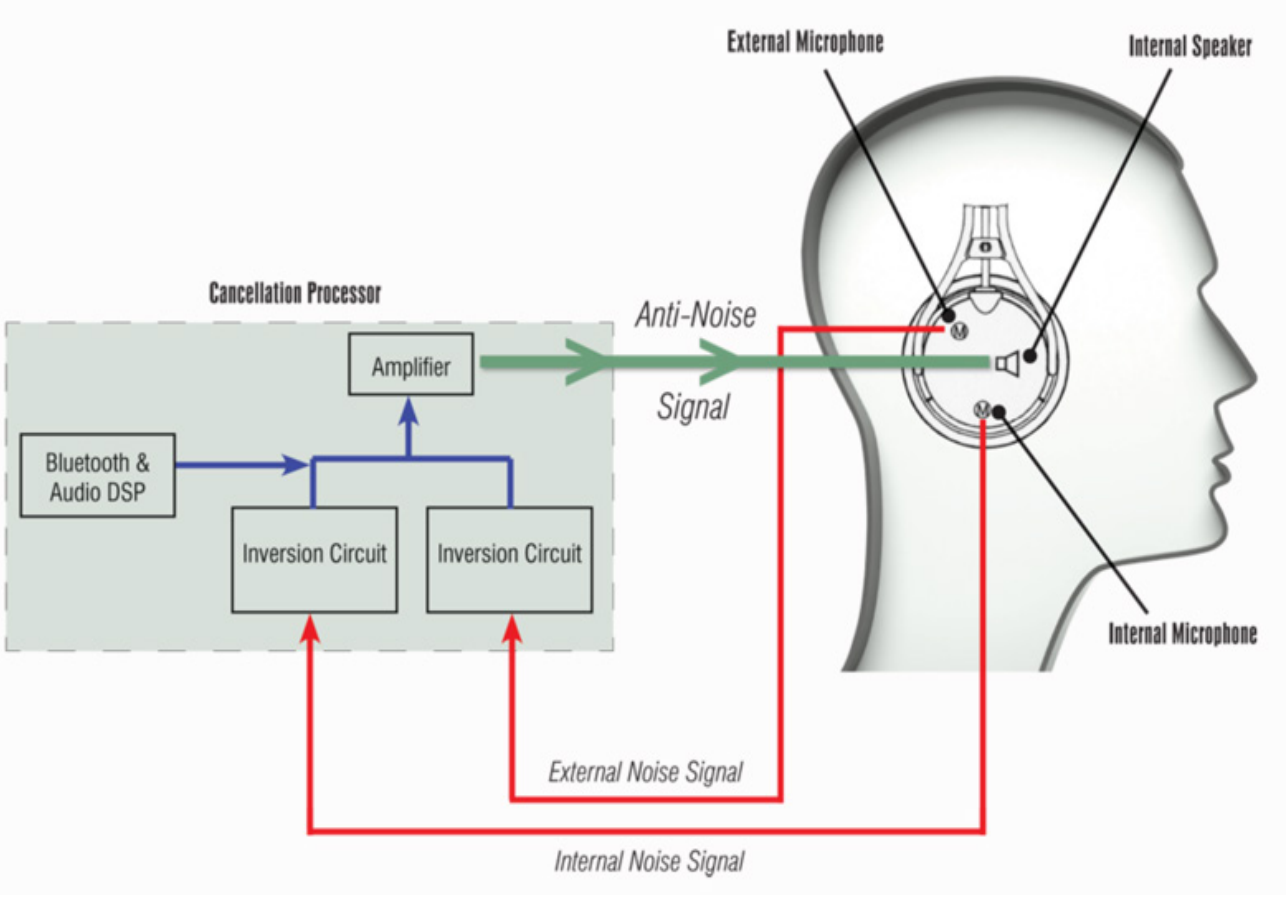

Fig. 1 Noise Cancelling Headphones

Besides the traditional ANC methods, Bluetooth protocol stacks also combine a variety of noise reduction technologies, including AI techniques. Similar to the previous discussion, a diagram that illustrates how AI integration in Bluetooth noise reduction can provide clarity. The algorithm in this technique is based on AI to analyze the audio signals to differentiate between the wanted sound and the undesired noise. For example, machine learning models can be trained to recognize and remove specific types of noise to improve the overall audio quality. Many studies have shown that AI-driven noise filtration is superior to more conventional approaches. It can adapt dynamically as the sound source scene changes. It's more sophisticated audio systems that could have been created by developers using the advanced technologies within the Bluetooth framework, systems that didn't only cancel out noise but could also adapt to changing conditions.

4. Application Scenario Analysis

The combination of Bluetooth and Active Noise Cancellation (ANC) systems is making its way gently into areas of industrial automation and transforming manufacturing operations. Factories are always operating in noisy environments, which can lead to distortions in communication between workers and can reduce efficiency. Bluetooth and ANC technology can be integrated into equipment that allows workers to communicate with control systems clearly by using wireless headsets to minimize and reduce background noise. For instance, the update from the machine in real-time can be received by Bluetooth headset. The ANC feature can help staff filter out background noise and help them focus attention. It also improves safety by enabling workers to hear alarms and other critical sounds more effectively. In conclusion, the combination of Bluetooth and ANC creates a more efficient and safe workplace in industrial automation.

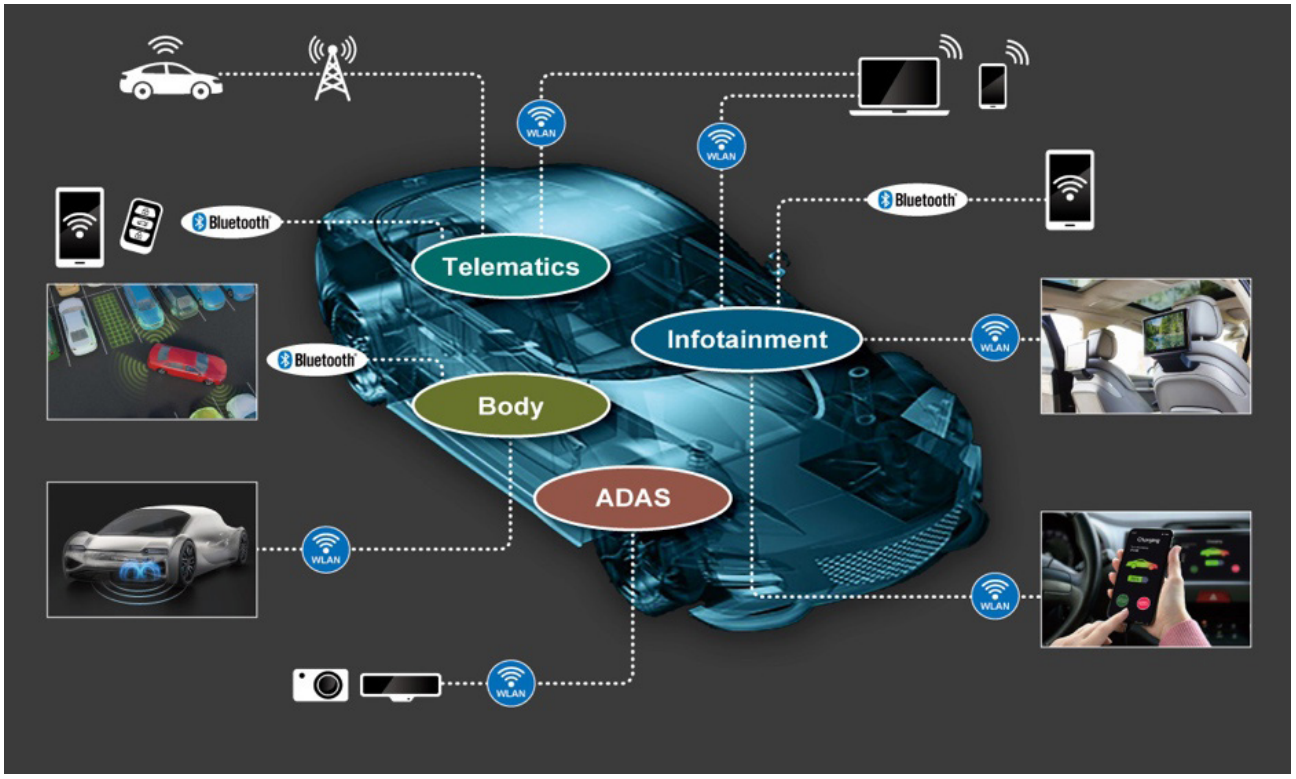

Fig. 2 The Application of Bluetooth in Cars

In the automobile sector, especially with autonomous vehicles, the combination of Bluetooth technology and ANC is as imperative. As depicted in Fig.2, Consider a situation where there's an autonomous vehicle with Bluetooth receivers, a computing unit and some micro-processing nodes in the vehicle with external sensors and base stations for communication. The data processing workflow begins with the external sensors sensing the sounds and noise, in the surroundings and passing it on to the vehicle's computing unit. This unit processes the sound data and sends that to the vehicle's ANC system via Bluetooth communication. The vehicle's ANC system then responds by generating inverted soundwaves. This has the double advantage of making the audio experience more pleasant for the passengers as well as enhancing the interaction between the autonomous vehicle and its surrounding environment, which ensuring the driving experience greater safety and efficiency.

5. Experiments and Performance Evaluation

In this chapter, we will explore active noise cancellation (ANC) experiments and examine their performance results. For instance, we can refer to the study by [11] Say-Wei Foo et al. (2005), who introduced a new active noise-cancellation headphone design.

Table 1. Noise Attenuation(dB)

	LMS	NLMS	VSS-NLMS
Helicopter noise	24	35	38
Jet air noise	12	31	33
Propeller air noise	20	37	38
Subway train noise	Unstable	34	37
Car noise	10	39	41
Air hammer noise	5	38	38
Average (excluding train noise)	14.2	36.0	37.6

The noise signal is efficiently attenuated by the VSS-NLMS algorithm by more than 37.6 dB, as Table 1. illus-

trates, as opposed to an average of 36 dB with the NLMS algorithm and 14.2 dB with the LMS algorithm. Additionally, the VSS-NLMS algorithm converges significantly faster. Additionally, unofficial listening tests reveal a considerable improvement in the quality of the received audio stream. According to the experimental results, the average noise reduction for the same set of signals using the suggested adaptive algorithm is 38 dB, whereas the NLMS (Normalized Least Mean Square) strategy reduces noise by 36 dB and the LMS algorithm reduces noise by 14 dB.

The second experimental study refers to the research of [12]Franc Pricken (2000), whose study analyzed the possibility of integrating an active noise reduction system in the air intake system.

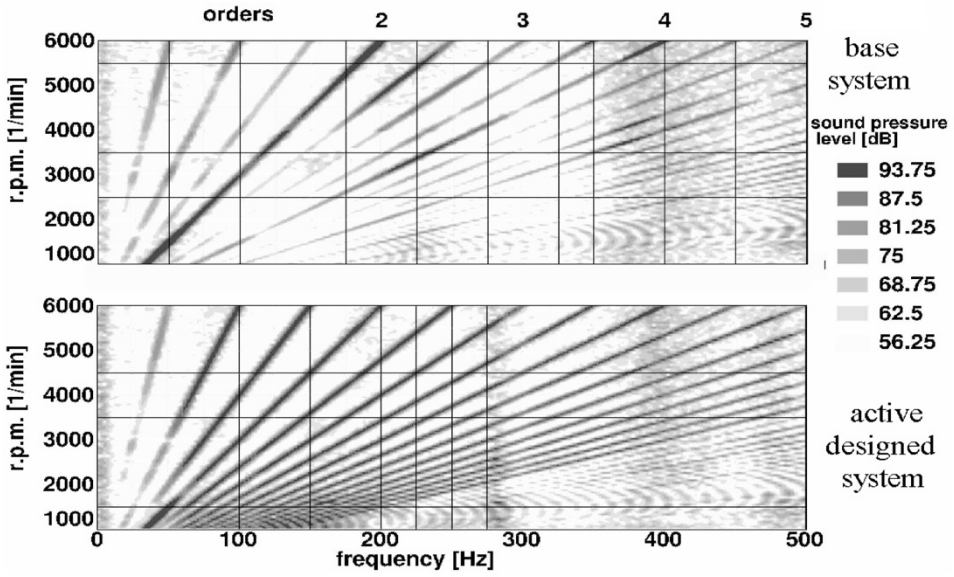

Fig. 3 Actiive Noise Design system compared with base system

Figure 3 shows an example of the capabilities of an active sound design system. The target sound here is the same level of 90 dB at all half and full steps to demonstrate the system's ability to produce these levels. The result sounds unpleasant because it gives the impression that one of the engine's cylinders has stopped working. But even so, it shows the effectiveness of the active system.

All in all, these experiments demonstrate the effectiveness of ANC technology in a variety of environments, showing that it has great potential to significantly reduce unwanted noise, thereby enhancing the audio experience.

6. Conclusion

This paper has explored the integration of Active Noise Cancellation (ANC) technology with Bluetooth audio transmission across various applications. Chapter 1 provided an introduction to the significance of ANC in enhancing audio quality. Chapter 2 reviewed the relevant literature, highlighting the challenges and advancements of Bluetooth technology and ANC. The technology mechanism for ANC and how it works by inverted sound waves to suppress ambient noise is detail described in Chapter 3. Chapter 4, in particular, analyzed specific scenarios, such as industrial automation and autonomous vehicles, to elaborate on the importance of these technologies. Finally, Chapter 5 provided experimental data and proved the performance of ANC systems in various types of ambient noise or interference.

In the experimental section, the findings revealed significant performance metrics for ANC systems. In the first experiment, an advanced ANC system demonstrated peak sound pressure suppression of 65 dB, compared with decreased 80 dB for a basic system. The second experiment demonstrated that the noise reduction of the ANC system achieved 30 dB in a car cabin environment, which was significantly better than passive noise isolation which accounted for 15 dB. These results underscore the effectiveness of ANC technology in enhancing audio experiences across various settings.

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