# A HYBRID APPROACH TO COMBINE WIRELESS AND EARCUP MICROPHONES FOR ANC HEADPHONES WITH ERROR SEPARATION MODULE

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**ABSTRACT**

Active noise control (ANC) technology is commonly used to cancel acoustic noise in daily life. The conventional ANC headphone, being one of the mature commercial products that implement this approach, utilizes microphones on its earcup to pick up the reference signal. However, in a multi-noise source situation, the reference signal mixed with uncorrelated interference usually results in poor noise reduction performance of the ANC system. Hence, we proposed a novel hybrid approach that employs wireless microphones to acquire high signal-to-noise-ratio reference signals from far-end noise sources, increasing coherence and thus improving noise reduction performance. Additionally, an error separation model is applied in the proposed structure to enhance the coherence between the error signal and each adaptive filter. As a result, the proposed hybrid approach to combine wireless and earcup microphones for ANC headphone significantly improves its noise reduction performance when dealing with multi-noise sources. Furthermore, numerical simulation and real-time experiments of the proposed structure have shown that it improves noise reduction performance by $4-6$ dB when compared to a conventional ANC headphone.

***Index Terms*—** Active noise control (ANC); wireless ANC; error separation module

## 1. INTRODUCTION

Urban noise pollution has caused a variety of health issues for humans in recent years. With advancement of the active noise control (ANC) technique, it has become an essential device to improve life quality [1–11]. The basic principle behind ANC is to generate an anti-noise with same amplitude but opposite phase as the undesired noise in order to suppress it. In daily life, an ANC headphone [12–16] effectively combines active low-frequency noise attenuation with passive high-frequency noise control to create a quiet zone around human's ears. Because of its ability to provide a wide range of noise cancellation, the feedforward ANC structure is commonly used in commercial ANC headphone products. To pick up the reference noise, the feedforward structure places one or more microphones on the earcup. The control filter processes the reference signals and generates the control signal that is sent to the secondary speaker in the earcup. The coefficients of the control filter are usually updated by an adaptive algorithm to minimize the error signal picked up by the error microphone inside the earcup.

In the real-world environment, there are always multiple noise sources that annoy the users during their daily activities. The reference microphones pick up the noise signals surrounding the earcup. These reference signals usually involve uncorrelated noises such as compressor noise, TV sound, fan noise in a living room, significantly reducing ANC's noise reduction performance. Several solutions to this problem have been proposed. Decorrelation was proposed as a method for multi-channel signal separation [17]. It reconstructed the input reference signals under the constraints that they were statistically uncorrelated. This method, however, required some additional reference signal information for the unknown ANC system. Another technique involved placing numerous reference microphones around the control point and calculating the time difference of arrival between the reference signals and the disturbance [18]. If the causality constraint was fulfilled based on the time difference of arrival, this reference was chosen as the algorithm's input. Hence, it ensured the causality of the ANC system. However, when multiple noises came from different directions, the noise reduction performance was degraded because it chose only one reference signal for control. According to the power spectrum density of the multiple reference signals, another method chose the highest-powered signal as the dominant reference signal using singular value decomposition [19]. However, it added to the computational load and was challenging to implement on the headphones.

In recent work, wireless microphones were used in multichannel ANC systems [20–22]. In these approaches, wireless microphones were placed around the potential noise sources to pick up and transmit the reference signals wirelessly to the control filters separately. Since the wireless microphone cannot pick up unknown noises, we propose a hybrid approach that collects reference signals using wireless and earcup microphones. Due to space constraints, a conventional ANC headphone typically has only one error microphone installed inside the earcup. As a result, the error signal is used to update the coefficients of multiple adaptive filters. Theoretical analysis revealed that the residual error components from other filters degraded the convergence performance of ANC [23]. Therefore, an adaptive filter cascaded with the noise control filter was introduced to separate signals at the error sensor. In the proposed hybrid approach, we extend the cascading adaptive algorithm to an error separation module (ESM) [24]. The ESM provides a separated error signal for each control filter that is implemented with an independent wireless reference signal, thus, improving the steady-state performance.

The paper is organised as follows. Section 2 proposes and analyzes the hybrid approach to combine wireless and earcup microphones for ANC headphones with error separation module. Sections 3 and 4 present results from simulations and real-time experiments, respectively. Section 5 concludes this paper.

## 2. PROPOSED METHOD

This section describes a new hybrid approach that uses wireless microphones and reference microphone on the earcup to pick up reference signals. The working principle of the hybrid approach is explained in Section 2.1, and the application of error separation module is discussed in Section 2.2.

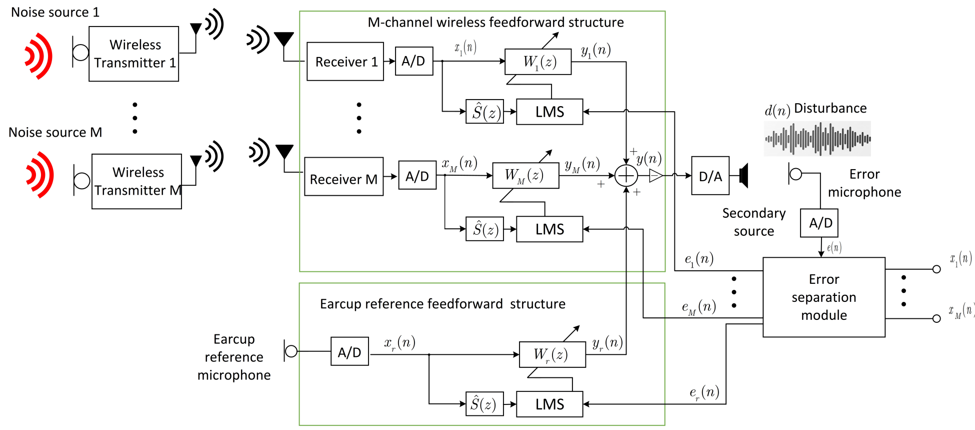


**Fig. 1**. Block diagram of hybrid approach to combine wireless and earcup microphones for ANC headphones with error separation module.

### 2.1. Hybrid combination of wireless and earcup microphone

In the proposed structure, as shown in Fig.1, the wireless microphones are placed near each potential noise source to collect the reference signal with a high signal-to-noise ratio. While a reference microphone is mounted on the earcup to collect the mixed noise that may contain the interference that cannot be captured by wireless microphone. Here, $x_m$ and $x_r$ denote the reference signals received by $m$th wireless microphone and earcup microphone, respectively. The control signal is given by

$$y(n) = \sum_{m=1}^{M} y_m(n) + y_r(n), \tag{1}$$

where $M$ denotes the number of potential noise sources, which are known in advance. $y_m$ denotes the output of the $m$th control filter $W_m(z)$, and $y_r$ represents the output of $W_r(z)$:

$$\begin{cases} y_m(n) = \mathbf{x}_m^{\mathrm{T}}(n)\mathbf{w}_m(n), \;\; m = 1, 2, \cdots, M \\ y_r(n) = \mathbf{x}_r^{\mathrm{T}}(n)\mathbf{w}_r(n). \end{cases} \tag{2}$$

after (2) $\mathbf{w}_m(n) = [w_{m1}(n), \cdots, w_{mL}(n)]^{\mathrm{T}}$ is the coefficient vectors of $m$th control filter $W_m(z)$ with length $L$ for wireless reference signal, and $\mathbf{w}_r(n) = [w_{r1}(n), \cdots, w_{rL}(n)]^{\mathrm{T}}$ represents the coefficient vectors of control filter $W_r(z)$ for the reference signal picked up by the microphone on the earcup. To minimize the instantaneous squared error, the filtered-x least mean square (FxLMS) algorithm [25, 26] with step size $\mu$ is used as

$$\begin{cases} \mathbf{w}_m(n+1) = \mathbf{w}_m(n) + \mu \mathbf{x}'_m(n) e_m(n) \\ \mathbf{w}_r(n+1) = \mathbf{w}_r(n) + \mu \mathbf{x}'_r(n) e_r(n). \end{cases} \tag{3}$$

The filtered reference signals are obtained from

$$\begin{cases} \mathbf{x}'_m(n) = \hat{s}(n) * \mathbf{x}_m(n) \\ \mathbf{x}'_r(n) = \hat{s}(n) * \mathbf{x}_r(n), \end{cases} \tag{4}$$

where $*$ represents linear convolution. $\hat{s}(n)$ is the estimated impulse response of secondary path. $e_m(n)$ and $e_r(n)$ denote the error signal used to update $W_m(z)$ and $W_r(z)$, which are separated from error signal $e(n)$ picked up by error microphone.

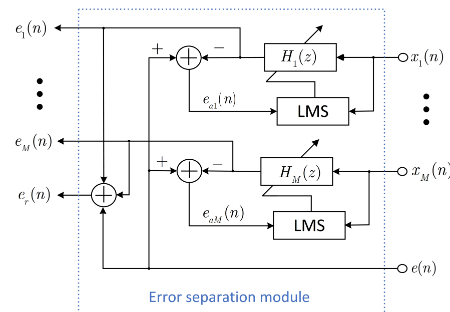


**Fig. 2**. Block diagram of error separation module (ESM).

### 2.2. Error separation module

The error separation module (ESM) is used to generate separated error signals for each wireless channel. With the split error signal, the steady-state performance of the adaptive filters for multiple wireless signals is improved significantly. The main idea behind ESM is to update the adaptive filters $W_m(z)$ and $W_r(z)$ with their associated error signals $e_m(n)$ and $e_r(n)$ rather than using a common $e(n)$, as shown in Fig.2. The $m$th separated error signal is generated by the filter $H_m(z)$ as

$$e_m(n) = \mathbf{x}_m^{\mathrm{T}}(n)\mathbf{h}_m(n), \;\; m = 1, 2, \cdots, M. \tag{5}$$

where $\mathbf{h}_m(n) = [h_{m1}(n), \cdots, h_{mL}(n)]^{\mathrm{T}}$ represents the coefficient vectors of $m$th adaptive filter. While the error signal used to update $W_r(z)$ is obtained from

$$e_r(n) = e(n) - \sum_{m=1}^{M} e_m(n). \tag{6}$$

The obtained wireless reference signal $\mathbf{x}_m(n)$ is fed into the filter $H_m(z)$, and the least-mean-square (LMS) is utilized to update the coefficients of $H_m(z)$ with step size $\mu_h$ as

$$\mathbf{h}_m(n+1) = \mathbf{h}_m(n) + \mu_h \mathbf{x}_m(n) e_{am}(n), \tag{7}$$

where $e_{am}(n)$ is the summation of the measured error signal $e(n)$ and the output of the filter $H_m(z)$. Here, we define the weight-error vector for $m$th control filter as

$$\boldsymbol{\varepsilon}_m(n) = \mathbf{w}_m(n) - \mathbf{w}_m^o, \tag{8}$$

where $\mathbf{w}_m^o$ denotes the $m$th optimal control filter. According to direct-averaging method described in Kushner [27], the averaged weight-error can be expressed as

$$\begin{aligned}&\bar{\boldsymbol{\varepsilon}}_m(n+1) = \\ &\quad [\mathbf{I} - \mu \mathbf{R_m}]\, \bar{\boldsymbol{\varepsilon}}_m(n) + \mu \mathbf{x}'_m \left[ d_m(n) - \mathbf{x}'_m(n)^{\mathrm{T}} \mathbf{w}_m^o \right],\end{aligned} \tag{9}$$

where $d_m(n)$ is the $m$th disturbance, and $\mathbf{I}$ denotes the identity matrix. $\mathbf{R_m}$ is obtained as

$$\mathbf{R_m} = \mathbf{E}\left[ \mathbf{x}'_m(n)^{\mathrm{T}} \mathbf{x}'_m(n) \right]. \tag{10}$$

The misalignment of adaptive weights in $m$th channel is defined as

$$\mathbf{v}_m(n) = \mathbf{Q}_m^{\mathrm{T}} \bar{\boldsymbol{\varepsilon}}_m(n). \tag{11}$$

and $\mathbf{Q}_m$ is the unitary matrix, whose columns are an orthogonal set of eigenvectors of $\mathbf{R}_m$. $\boldsymbol{\Lambda}_m$ is the diagonal matrix of eigenvalues:

$$\boldsymbol{\Lambda}_m = \mathbf{Q}_m^{\mathrm{T}} \mathbf{R}_m \mathbf{Q}_m. \tag{12}$$

Substituting (9) into (11) yields

$$\begin{aligned}\mathbf{v}_m(n+1) &= [\mathbf{I} - \mu \boldsymbol{\Lambda}_m]\, \mathbf{v}_m(n) \\ &\quad + \mu \mathbf{Q}_m^{\mathrm{T}} \mathbf{x}'_m \left[ d_m(n) - \mathbf{x}'_m(n)^{\mathrm{T}} \mathbf{w}_m^o \right].\end{aligned} \tag{13}$$

By taking expectation of (13) and bringing in the initial value $\bar{\mathbf{v}}_m(0)$, we can get

$$\bar{\mathbf{v}}_m(n) = [\mathbf{I} - \mu \boldsymbol{\Lambda}_m]^n\, \bar{\mathbf{v}}_m(0). \tag{14}$$

The square of the misalignment of $m$th weight of control filter is stated as

$$\kappa_1 = [\bar{\mathbf{v}}_m(n)]^2 = [\mathbf{I} - \mu \boldsymbol{\Lambda}_m]^{2n}\, \bar{\mathbf{v}}_m^2(0), \tag{15}$$

which is close to 0 if the step size is small enough at steady-state. In contrast, if the wireless ANC updates its control filter weights with the error signal $e(n)$, the squared misalignment is calculated as [28]

$$\kappa_2 \simeq \mu \sigma_v^2, \tag{16}$$

where $\sigma_v^2$ denotes the variance of residual error component of $M-1$ channels.

When comparing (15) and (16), it is clear that the weight misalignment of control filters is reduced when the error signal is separated, and thus, the overall noise reduction performance of wireless ANC is improved compared to ANC with mixed error signal. Simulation conducted in Section 3 also validates the improvement of steady-state performance for wireless ANC with ESM.

## 3. SIMULATION RESULT

The proposed method, as shown in Fig.1, is validated through simulation. The impulse responses of primary paths are measured in three different dimensions of a standard room in the simulation. The system sampling rate is set to 16000 Hz The distances between the noise sources and the earcup are 1.2m, 1.2m, and 5m, respectively. The secondary path is measured from the secondary speaker and error microphone inside the earcup. White Gaussian noise, broadband noise (300 − 500 Hz), and multi-tone noise (315 Hz, 415 Hz, 475 Hz) are three types of noises used in the simulation. The lengths of adaptive filters $W_m(z)$, $W_r(z)$, and $H_m(z)$ are all set to 350 taps. The step sizes are set at $1 \times 10^{-6}$, $1 \times 10^{-6}$ and $1 \times 10^{-3}$, respectively. The steady-state performance of multichannel wireless ANC with and without ESM is shown in Fig. 3. Both wireless ANCs perform well in a multiple noise source environment, while the proposed approach has 5dB noise reduction performance improvement in mean square error at the cost of increased computation complexity of ESM implementation. Because each ESM module requires the same number of computations as the conventional LMS algorithm, it is well suited for real-time applications.

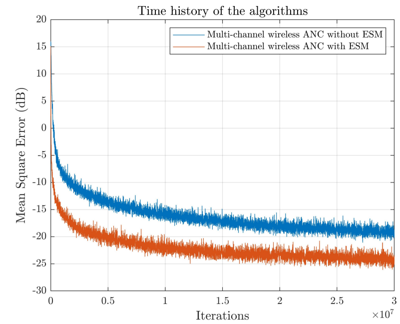


**Fig. 3**. Mean square error of multi-channel wireless ANC with/ without error separation module(ESM).

**Table 1**. Noise reduction levels of proposed method, multi-channel wireless ANC, ANC with wired microphone on earcup and commercial ANC headphone.

| ANC structure | Noise reduction |
|---|---|
| Proposed ANC | 29.6 dB |
| WANC [21] | 28.8 dB |
| Wired MIC ANC | 25.7 dB |
| Commercial headphone | 23.7 dB |

## 4. EXPERIMENT RESULTS

The proposed hybrid approach to combine wireless and earcup microphones is tested in real time to ensure effectiveness. As shown in Fig. 4, a dummy head (B&K HATS Type 4128C) is placed in a room with an ANC headphone attached. The earcup microphones and error microphones are implemented with binaural microphones (Sound Professionals Ultra-Low-Noise In-Ear Binaural microphones), while the wireless microphones (Academic EX-200) are placed close to the noise sources. The error microphones are located near the secondary speaker inside the earcup. National Instrument PXIe-8880 embedded controller is used to implement the ANC algorithm. The analog and digital conversions are completed with the ADC and DAC modules (National Instrument PXIe-6368). All experiment results are collected at the left ear by the monitoring microphone inside the dummy head for easy comprehension.

### 4.1. Multiple noise sources in the environment

In this experiment, two unrelated noise sources are used. Noise source #1 is a broadband noise with a frequency range of $300-800$ Hz, while noise source #2 has a frequency range of $500-1000$ Hz. To test noise reduction performance, a multi-channel wireless ANC [21], ANC with wired microphone on earcup, and a commercial ANC headphone, are used in the same environment for comparative evaluation. The control filters used in the ANC structures described above has a length of 1024 and a sampling rate of 16 kHz.

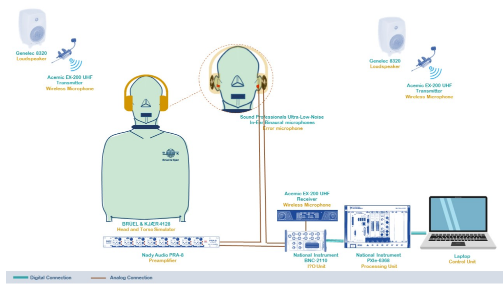

**Fig. 4**. The setup of the real time ANC experiments in a room.

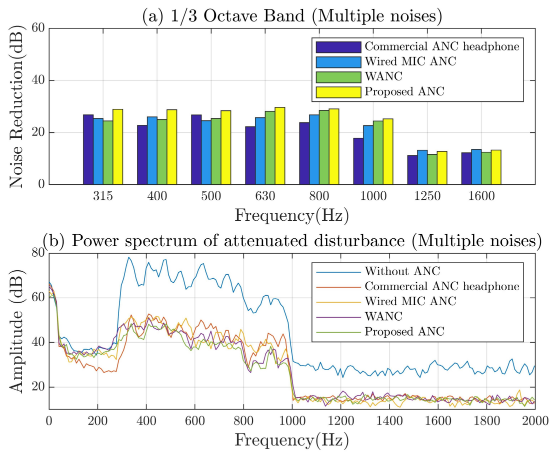


**Fig. 5**. Noise reduction performance of the proposed method, multi-channel wireless ANC, ANC with wired microphone on earcup and commercial ANC headphone in multi-noise environment: (a) $1/3$ octave band of noise reduction. (b) Power spectrum of disturbance $d(n)$ and residual error $e(n)$.

Figure 5 depicts the detailed $1/3$ octave band of noise reduction and power spectrum of disturbance $d(n)$ and residual error for the proposed method, multi-channel wireless ANC, ANC with wired microphone on earcup, and commercial ANC headphone. The figure shows that multi-channel wireless ANC and our proposed ANC achieve 28.8 dB and 29.6 dB noise reduction, respectively. The reason for this result is that all of the reference signals are picked up separately by the wireless microphones, without the interference of unknown noise. The noise reduction for the conventional feedforward ANC with earcup microphone and the commercial ANC headphone is 25.7 dB and 23.7 dB, respectively, as shown in Table.1.

### 4.2. Interference occurred in the environment

In this experiment, an uncorrelated noise occurs on the left side of the dummy head that is not picked up by the wireless microphones. Multiple noise sources still exist in the environment as the same as the first experiment. In two cases, the tone noise of 500 Hz and noise with frequency range of $600-700$ Hz are tested. Moreover, the wireless microphone has not acquired these interferences due to propagation attenuation. Table 2 shows that when the interference is a sine tone noise, the proposed hybrid approach achieves 24dB noise reduction. Because unexpected noise is picked up by the earcup microphone rather than the wireless microphones, multi-channel wireless ANC has the lowest performance (11.2 dB) among those ANC structures when compared to ANC with wired microphone on earcup (19.7 dB) and commercial ANC headphone (18.2 dB). The residual error power spectrum in Fig. 6 (a) also shows various noise reduction performances of four ANC structures. The interference in the second case is a noise with frequency range of $600-700$ Hz. The noise reduction is comparable to that of the first case. The proposed ANC structure reduces noise by 25.3 dB, which is 9 dB, 3.6 dB, and 5.8 dB more than multi-channel wireless ANC, ANC with wired microphone on earcup, and commercial ANC headphone, respectively. The degradation of noise reduction performance in conventional wireless ANC in these two cases is caused by the missing reference signal of wireless microphone.

**Table 2**. Noise reduction levels of proposed method, multi-channel wireless ANC, ANC with wired microphone on earcup and commercial ANC headphone when the interference occurring.

| **ANC structure** | **Acoustic interference** | |
|---|---|---|
| | 500 Hz | $600-700$ Hz |
| Proposed ANC | 24 dB | 25.3 dB |
| WANC | 11.2 dB | 16.3 dB |
| Wired MIC ANC | 19.7 dB | 21.7 dB |
| Commercial headphone | 18.2 dB | 19.5 dB |

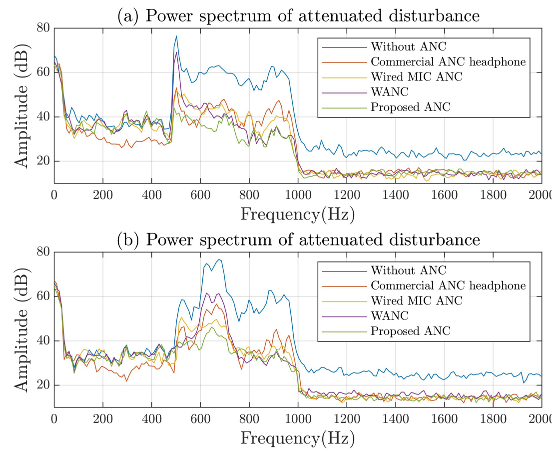


**Fig. 6**. Power spectrum of disturbance $d(n)$ and residual error $e(n)$ for proposed method, multi-channel wireless ANC, ANC with wired microphone on earcup and commercial ANC headphone: (a) The interference is 500 Hz sine-tone noise. (b) The interference is $600-700$ Hz noise.

## 5. CONCLUSION

This paper developed a novel hybrid approach for ANC structure that used wireless microphones and earcup microphones to acquire the reference signal with the high signal-to-noise ratio, resulting in improved noise reduction performance for the ANC headphone in a multi-source scenario. In addition, an error separation module was implemented to provide adaptive filters with individual error signals, which improved the noise reduction performance even more, as evidenced by numerical simulations. According to the real-time experiments, the proposed method outperformed ANC with a wired microphone on earcup and commercial ANC headphone noise reduction by $4-6$ dB. Moreover, the proposed method was effective for unidentified interference that occurred in the environment, reducing noise by 6 dB more than commercial ANC headphone.

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