# COLLABORATIVE METHOD BASED ON THE ACOUSTICAL INTERACTION EFFECTS ON ACTIVE NOISE CONTROL SYSTEMS OVER DISTRIBUTED NETWORKS

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## ABSTRACT

This paper focus on the implementation of an active noise control system over a network of distributed nodes acoustically coupled. We have considered the distributed Multiple Error filtered-x Least Mean Square (DMEFxLMS) algorithm that allows collaboration between nodes following an incremental strategy. To reduce the computational network requirements, an alternative strategy which brings together only the acoustically coupled nodes has been used. However, a rule to define the subsets of nodes that are required to collaborate is needed. A collaborative condition based on the analysis in the frequency domain of the eigenvalues of the acoustic path matrix is proposed. Results demonstrate the ability of the introduced method to define the subsets of nodes that collaborate.

***Index Terms*—** active noise control, distributed networks, acoustic sensor networks, filtered-x least mean square

## 1. INTRODUCTION

Recently, wireless acoustic sensor networks (WASNs) offer many possibilities for developing new applications in the audio processing field [1] [2] due to a number of advantages such as low-power, low cost and small size of the sensors [3] [4]. For sound field control applications, such as active noise control (ANC), nodes capable of obtaining information from one or more microphones and capable of generating signals via one or more loudspeakers are necessary. Moreover, every node should have the ability to individually process signals and to interchange the necessary information with the other nodes using a suitable communication network.

ANC systems try to reduce a disturbance signal, called primary noise, at specific spatial points monitored by microphones, called error sensors [5] [6]. Generally speaking, the use of a large number of microphones strategically located produces larger zones of quiet. Similarly, multiple transducers are also commonly used to improve the system performance. Typically, those multichannel ANC systems use a single centralized controller that has access to all the signals involved in the system. Alternatively, distributed systems can offer a good solution to satisfy high computational requirements as well as capture, management and generation of multiple signals. While centralized systems work with all the signals involved, distributed systems employ independent processors which control a subset of loudspeakers from the signals picked up by a subset of microphones. Therefore, the support of a network that allows communication between controllers would be beneficial for the distributed ANC system to achieve results equivalent to those of the centralized method. Depending on the possibility of exchanging information, collaborative and non-collaborative distributed algorithms appear. The collaborative strategy could imply that each node estimates the coefficients of the rest of the nodes to achieve a global solution. When we consider the non-collaborative strategy, nodes do not interchange any local information. A distributed ANC system based on the Multiple Error filtered-x Least Mean Square (MEFxLMS) algorithm [7] using an incremental collaborative strategy in a ring network [8] and with sample-by-sample data acquisition was presented in [9]. In order to reduce the computational and communication requirements of the network, a distributed algorithm based on [9] where each node only collaborates with a subset of nodes acoustically coupled is proposed in [10]. To this aim, a criterion to determine which nodes should collaborate is required. As it is well known, the convergence characteristics of the MEFxLMS algorithm analyzed in the time domain are affected by the eigenvalue distribution of the autocorrelation matrix of the filtered reference signals [11] [12]. However, an analysis of the convergence properties of the algorithm in the frequency domain could allow to evaluate each frequency bin (FFT) separately, providing a better understanding of the physical problem [13]. Based on this, we propose a collaborative method based on the acoustically coupling among the nodes to identify when collaboration is needed in order to ensure distributed ANC system stability. The paper is organized as follows: In Section 2 we present the proposed collaborative method and the evaluation results

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for a two-node network in different scenarios. The experimental results to validate the proposed method for a six-node network are shown in Section 3. Finally, Section 4 outlines the main conclusions of the present work.

## 2. PROPOSED METHOD

### 2.1. Description of the algorithms

Let us consider an acoustic sensor network (ASN) of N nodes that supports an ANC system composed by N sensors and N actuators, as shown in Figure 1. For the sake of simplicity, we consider a single disturbance noise and single-channel acoustic nodes in a homogeneous network. This implies that all the nodes have the same computational and communication capabilities, execute the same algorithm and are composed of a single sensor and a single actuator. The signals recorded at the sensors at the discrete time instant $n$ are called error signals and denoted by $e_k(n)$ (where $k = 1, 2, \ \dots \ , N$). The actuators emit the filter output signals $y_j(n)$ (where $j = 1, 2, \ \dots \ , N$) and the estimated acoustic channel impulse response between actuator $j$ and sensor $k$ is denoted as $\mathbf{s}_{jk}$, which is defined as a FIR filter that models the real acoustic channel $\mathbf{h}_{jk}$. In feedforward systems, the reference signal, $x(n)$, is captured by a reference sensor used to detect the acoustic noise far away from the area of interest. When the noise is periodic, it can also be generated internally if its frequency is known. Since only one noise source exists, all the nodes will share the same reference signal $x(n)$. We want to cancel the acoustic noise signal at the sensor locations, $d_k(n)$, estimating an adaptive filter $\mathbf{w}_k(n)$ in every node. A possible solution is based on the well-known MEFxLMS algorithm that minimizes the sum of the power of the $N$ error signals. As stated in [9], the filter updating equation of the network can be calculated as

$$\mathbf{w}(n) = \mathbf{w}(n-1) \ - \mu \sum_{k=1}^{N} \mathbf{v}_k(n) e_k(n), \qquad (1)$$

where vector $\mathbf{w}(n) = [\mathbf{w}_1(n) \ \mathbf{w}_2(n) \cdots \ \mathbf{w}_N(n)]^T$ of size $[LN \times 1]$ concatenates the $N$ adaptive filters $\mathbf{w}_k(n)$ that contain the $L$ filter coefficients of the $k$th node. $\mu$ is the step-size parameter and $\mathbf{v}_k(n) = [\mathbf{v}_{1k}(n) \ \mathbf{v}_{2k}(n) \cdots \ \mathbf{v}_{Nk}(n)]^T$ is a vector of size $LN \times 1$ being $\mathbf{v}_{jk}(n)$ an $L$-length vector that contains the last $L$ samples of reference signal $x(n)$ filtered through $\mathbf{s}_{jk}$. Firstly, we consider a decentralized ANC system [11] [14] where the nodes perform a distributed and independent processing and they do not collaborate at all. If the nodes are located at such a distance which does not allow the acoustic interaction among them (uncoupled system), the non-collaborative strategy could be a sufficient solution to guarantee the stability of the system. Therefore, the filter updating equation at each node of the non-collaborative distributed MEFxLMS (NC-DMEFxLMS) algorithm described in [9] is given by

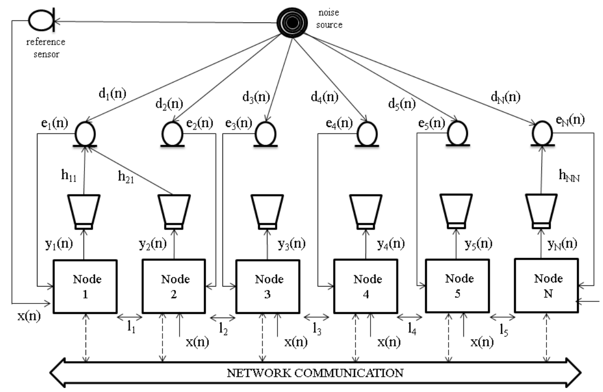


**Fig. 1**. ASN of N nodes for an ANC system.

$$\mathbf{w}_k(n) = \mathbf{w}_k(n-1) \ - \mu \mathbf{v}_{kk}(n) e_k(n). \qquad (2)$$

It can be seen in (2) that each node uses only local information to update its filter coefficients. The problem exists in those cases where the nodes get closer and the level of acoustic interaction increases (coupled systems) because the system turns unstable and does not converge. To solve this, the collaborative algorithms allow that each node updates the status of the global network using their local data and assuming some collaboration with its neighbors nodes to minimize the effects of the acoustic coupling. In the case of a ring network based on an incremental strategy [8], the coefficients of the adaptive filters are calculated by distributing the calculation among different nodes by transmitting information to an adjacent node in a consecutive order. If we define the global state of the network $\mathbf{w}(n)$ as the adaptive filter coefficients of each node of the network at the time instant $n$ and considering $\mathbf{w}^k(n)$ a local version of $\mathbf{w}(n)$ at the $k$th node, the updating rule of the state of the $k$th node of the distributed MEFxLMS (DMEFxLMS) algorithm [9] may be written as

$$\mathbf{w}^k(n) = \mathbf{w}^{k-1}(n) \ - \mu \mathbf{v}_k(n) \ e_k(n) \cdot \qquad (3)$$

Note that in (3) every node estimates all the adaptive filters of the $N$-node network at each instant and shares the filter coefficients with its neighbour node. Note that this information exchange is not required if the adjacent nodes are far enough and the level of interaction between them is not relevant to affect the ANC system performance. In order to reduce both computation and communication requirements, in [10] it is proposed to create subsets of nodes acoustically coupled, so that a node only exchanges information with the nodes of its subset. However, to the authors knowledge, a rule to properly define the subsets of nodes in order to ensure system stability and based on acoustical interaction among them is unknown.

### 2.2. Proposed collaborative method

In [11], it has been demostrated that the upper bound based on the stability of a two-node decentralized ASN working

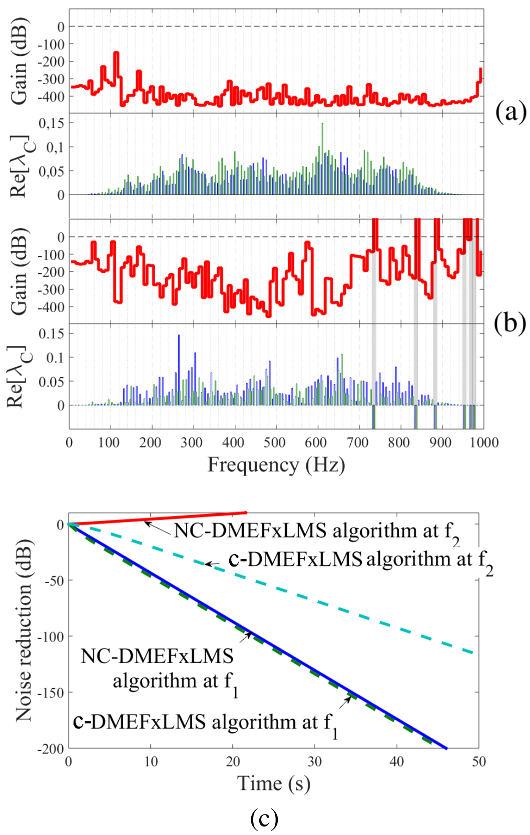


**Fig. 2**. Experimental results for a two-node network.

at a single frequency can be only obtained by examining the eigenvalues of the matrix $\tilde{\mathbf{H}}(w)^H\mathbf{H}(w)$ where

$$\tilde{\mathbf{H}}(w) = \begin{bmatrix} H_{jj} & 0 \\ 0 & H_{kk} \end{bmatrix}, \quad \mathbf{H}(w) = \begin{bmatrix} H_{jj} & H_{jk} \\ H_{kj} & H_{kk} \end{bmatrix}, \tag{4}$$

being $H_{jj}$ and $H_{kk}$ the coefficients of the Fourier Transform (FT) of the direct acoustic paths of the nodes ($\mathbf{h}_{jj}$,$\mathbf{h}_{kk}$) at the frequency $w$. Similarly, $H_{jk}$ and $H_{kj}$ are the coefficients of the FT of the cross acoustic paths between both nodes ($\mathbf{h}_{jk}$,$\mathbf{h}_{kj}$) at the frequency $w$. The superscript $H$ denotes the Hermitian transpose. The convergence condition must fulfill that Re[$\boldsymbol{\lambda}_{\mathbf{H}}(w)$] $> 0$, being $\boldsymbol{\lambda}_{\mathbf{H}}(w)$ the two eigenvalues of the matrix $\tilde{\mathbf{H}}(w)^H\mathbf{H}(w)$ at the frequency $w$ (for convenience, the frequency dependence will be suppressed in the notation below). As the matrixes defined in (4) can be calculated in a previous setup, the stability of the decentralized ASN can be determinated before its implementation.

Based on this, we extend the study of the acoustic paths matrixes to each frequency bin, $w$, defined as $w = 0, 1, 2, .., M/2$, where $M$ is the length of the acoustic paths. In addition, we proposed the following condition to decide when the nodes should collaborate: if the real parts of the $\boldsymbol{\lambda}_{\mathbf{H}}$ calculated at each $w$ are positive, the system will converge at that specific frequency. So, the nodes can work independently. But, if any of the real parts of the $\boldsymbol{\lambda}_{\mathbf{H}}$ calculated at each $w$ is negative, the condition is not fulfilled. In this case, the nodes should collaborate to ensure system stability.

### 2.3. Evaluation of the proposed method

We have considered two examples to illustrate how the proposed condition can be used to apply collaboration among the nodes and therefore, to create the subsets of nodes acoustically coupled. A network composed of two single-channel nodes that suports a distributed ANC system is used. Two different scenarios have been considered by varying the acoustical interaction among the nodes. Specifically, an uncoupled and coupled system. The main difference among them is their respective separation among the nodes: 340 cm (case A) and 60 cm (case B) of separation respectively, which will affect the level of acoustic coupling among them. Real acoustic channels have been measured in a listening room at a sampling rate $f_s$=2000 Hz. Some examples of the impulses responses of this listening room are available at [15]. These acoustic channels has been modeled as FIR filters of $M$=256 coefficients. Because of this, we obtain $M$ frequency bins where only $M/2$ are valid to the analysis in the frequency domain. Futhermore, through trial and error, it has been considered a step size parameter of $\mu$=5$\cdot$10$^{-4}$ as the highest value that ensures the stability of the algorithms at each case. Even if only 64 coefficients are necessary, we have oversized the adaptive filter length to $L$=130 coefficients in order to ensure accurate results.

For both cases, we perform a preliminary study of the acoustic paths at different frequency bins before the adaptive processing. As we consider 128 bins and $f_s$=2000 Hz, we have 128 frequencies between $[0, fs/2]$ Hz as the excitation signals of the system. In Figure 2.a, the real parts of the eigenvalues $\boldsymbol{\lambda}_{\mathbf{H}}$ (bottom) compared to the performance of the NC-DMEFxLMS algorithm (top) calculated at each excitation frequency are shown for the case A. In order to evaluate the performance of the non-collaborative algorithm at each excitation frequency, Figure 2.(a) top represents the steady-state Noise Reduction of the network at excitation frequency $f_k$, $NR_{f_k}(n)$, defined in dB as:

$$\lim_{n\to\infty} NR_{f_k}(n) = \lim_{n\to\infty} 10 \cdot log_{10}\left[\sum_{k=1}^{N} \frac{e_k^2(n)}{d_k^2(n)}\right], \tag{5}$$

where $d_k^2(n)$ is the signal power picked up at the $k$th microphone when the ANC system is inactive and $e_k^2(n)$ is the error signal power measured at the $k$th microphone when the ANC system works. Moreover, these signal powers have been estimated using an exponential windowing over the instantaneous signals. As Figure 2.(a) bottom shows, for case A, all the eigenvalues $\boldsymbol{\lambda}_{\mathbf{H}}$ satisfies the proposed condition. As expected, the NC-DMEFxLMS algorithm achieves the system convergence at each analyzed frequency, as we can see in Figure 2.(a) top. The same representation for the case B is shown in Figure 2.(b). In this case, we can see that the negative value

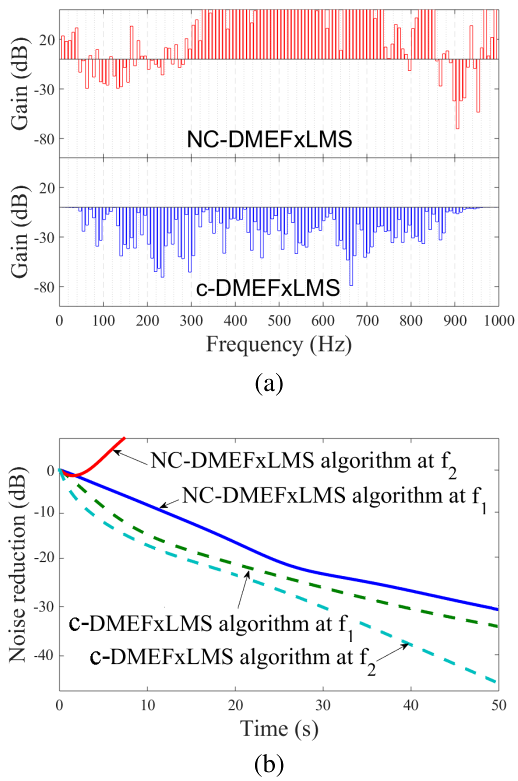


**Fig. 3**. Experimental results for a six-node network.

of the real part of $\boldsymbol{\lambda}_{\mathbf{H}}$ causes that the non-collaborative algorithm diverges making the system unstable at the frequencies in the shaded area. To validate the proposed method, we have evaluated the performance of both the NC-DMEFxLMS and the DMEFxLMS algorithm described in [9] [10], which we call customized DMEFxLMS (c-DMEFxLMS). It has been evaluated the case B at two specific frequencies which make the non-collaborative system stable ($f_1 = 250$ Hz) and unstable ($f_2 = 734.3$ Hz) respectively. Figure 2.c shows the time evolution of the $NR_{f_1}(n)$ and $NR_{f_2}(n)$ for both algorithms. Both algorithms obtain similar performance at $f_1$. But at $f_2$, the NC-DMEFxLMS algorithm diverges while the c-DMEFxLMS algorithm achieves the convergence of the system.

## 3. RESULTS FOR AN EXTENDED CASE

In this section, we present the simulations carried out to evaluate the proposed collaborative method comparing the performance of both the NC-DMEFxLMS and the c-DMEFxLMS algorithms over a ASN composed of six single-channel nodes (see Figure 1). For this case, $l_1$=20 cm, $l_2$=80 cm, $l_3$=80 cm, $l_4$=40 cm, and $l_5$=40 cm. The analysis of the system is carried out in the same terms as are indicated in the previous cases. For simplicity, the collaboration condition explained previously is evaluated by couple of nodes at each frequency bin. We calculate the eigenvalues $\boldsymbol{\lambda}_{\mathbf{H}}$ of the acoustic paths matrix defined in (4) between each couple of nodes (for $j$ and $k$ from 1 to 6 being $j \neq k$). If the condition is fulfilled, both nodes will not collaborate. But if the condition is not fulfilled, both nodes will be part of the same subset of collaboration. And so on for each couple of nodes of the network. The configuration parameter setup used in the two-node network has been considered. In a first stage, we have evaluated the performance of the NC-DMEFxLMS algorithm calculated for different excitation frequencies. Figure 3.(a) top represents the steady-state Noise reduction of the network defined in (5). We can see that the NC-DMEFxLMS algorithm does not fulfill the convergence condition for most of frequencies (74.2% of them, exactly). Therefore, collaboration among nodes seems necessary. The creation of the subsets of nodes based on the proposed collaborative condition is defined as follows: $Subset_1 = 1, 2, 3, 5$, $Subset_2 = 1, 2, 3$, $Subset_3 = 1, 2, 3, 4, 5$ , $Subset_4 = 3, 4, 5, 6$, $Subset_5 = 1, 3, 4, 5, 6$ and $Subset_6 = 5, 6$. In order to evaluate the performance of the c-DMEFxLMS algorithm at each excitation frequency applying the subsets of collaborative nodes, Figure 3.(a) bottom represents the $NR_{f_k}(n)$ of the network for $k = 1, 2, \ldots, M/2$. In this case, the system converges for all the frequencies improving the performance of the non-collaborative algorithm. To validate this results, we have evaluated the performance of both the NC-DMEFxLMS and the c-DMEFxLMS algorithm at two specific frequencies which make the non-collaborative system stable ($f_1 = 867.1$ Hz) and unstable ($f_2 = 507.8$ Hz) respectively. Figure 3.(b) shows the time evolution of the $NR_{f_1}(n)$ and the $NR_{f_2}(n)$ for both algorithms. As expected, at $f_1$ both algorithms achieves similar convergence levels. However, at $f_2$, the c-DMEFxLMS algorithm avoids the unstability of the NC-DMEFxLMS algorithm achieving the convergence of the system. Finally, note that all the results accomplished in this work depend on particular settings but their behavior can be easily extrapolated to other configurations.

## 4. CONCLUSIONS

In this paper, the influence of the level of acoustic interaction between nodes of an ASN has been studied. For this purpose, a simple but effective method to identify when it is necessary the collaboration between nodes has been introduced. A convergence analysis of the non-collaborative distributed ANC system over a two-nodes ASN at different excitation frequencies has been presented. A collaborative condition is derived based on the study of the eigenvalues of the acoustic paths matrix in the frequency domain. We have evaluated the proposed collaborative method comparing the performance of both the NC-DMEFxLMS and the c-DMEFxLMS algorithms over a ASN composed of six single-channel nodes at different excitation frequencies. Results demonstrate that the proposed method is valid to design subsets of nodes acoustically coupled according to the collaboration rule, reducing the computational and communication requirements of the network. However, some aspects like a review of the proposed condition for wideband signals must be considered in future works.

## 5. REFERENCES


[1] A. Bertrand and M. Moonen, "Robust distributed noise reduction in hearing aids with external acoustic sensor nodes," *EURASIP Journal on Advances in Signal Processing*, vol. 2009, no. 1, pp. 1–14, 2009.

[2] Y. Guo and M. Hazas, "Acoustic source localization of everyday sounds using wireless sensor networks," in *Proceedings of the 12th ACM international conference adjunct papers on Ubiquitous computing - Ubicomp*, 2010, pp. 411–412.

[3] A. Bertrand, "Applications and trends in wireless acoustic sensor networks: A signal processing perspective," in *2011 18th IEEE Symposium on Communications and Vehicular Technology in the Benelux (SCVT)*. IEEE, 2011, pp. 1–6.

[4] A. Flammini, P. Ferrari, D. Marioli, E. Sisinni, and A. Taroni, "Wired and wireless sensor networks for industrial applications," *Microelectronics Journal*, vol. 40, no. 9, pp. 1322–1336, 2009.

[5] S.J. Elliott, *Signal processing for active control*, Academic press, London, UK, 2001.

[6] S.J. Elliott and P.A. Nelson, "Active noise control," *IEEE Signal Process. Mag.*, vol. 10, no. 4, pp. 12–35, 1993.

[7] S.J. Elliott, I. Stothers, and P.A. Nelson, "A multiple error LMS algorithm and its application to the active control of sound and vibration," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 35, no. 10, pp. 1423–1434, 1987.

[8] C.G. Lopes and A.H. Sayed, "Incremental adaptive strategies over distributed networks," *IEEE Transactions on Signal Processing*, vol. 55, no. 8, pp. 4064–4077, 2007.

[9] M. Ferrer, M. de Diego, G. Piñero, and A. Gonzalez, "Active noise control over adaptive distributed networks," *Signal Processing*, vol. 107, pp. 82–95, 2015.

[10] J. Plata-Chaves, A. Bertrand, and M. Moonen, "Incremental multiple error filtered-x lms for node-specific active noise control over wireless acoustic sensor networks," in *IEEE Sensor Array and Multichannel Signal Processing Workshop*. IEEE, 2016, pp. 1–5.

[11] S.J. Elliott and C.C. Boucher, "Interaction between multiple feedforward active control systems," *IEEE Transactions on Speech and Audio Processing*, vol. 2, no. 4, pp. 521–530, 1994.

[12] B. Widrow and S.D. Stearns, *Adaptive signal processing*, Prentice Hall, Englewood Cliffs, NJ, US, 1985.

[13] G. Chen, M. Abe, and T. Sone, "Evaluation of the convergence characteristics of the filtered-x LMS algorithm in the frequency domain.," *Journal of the Acoustical Society of Japan*, vol. 16, no. 6, pp. 331–340, 1995.

[14] P. Grosdidier and M. Morari, "Interaction measures for systems under decentralized control," *Automatica*, vol. 22, no. 3, pp. 309–319, 1986.

[15] Audio and communications signal processing group (GTAC), *http://www.gtac.upv.es*.