NONLINEAR ECHO CANCELLATION USING A CORRELATION LMS ADAPTATION SCHEME

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ABSTRACT

In this paper, a robust nonlinear echo cancellation is proposed, where a third-order adaptive Volterra filtering is employed along with a correlation LMS adaptation scheme. In particular, the adaptive Volterra filtering technique is employed to compensate for the nonlinear distortion in the echo path (e.g., DAC of the hybrid network). Finally, the robustness in the echo cancellation of the proposed approach is demonstrated using computer simulations, where high attenuation of echo signals is achieved even in the double-talk situation.

1. INTRODUCTION

In the telephone network, the echo signals may result in the degradation of the network performance. The main factors leading to such echo signals include the impedance mismatch in the two-to-four wire hybrid network[1,2]. For example, when a two-to-four wire hybrid network is considered as in Fig. 1, then the undesired leakage of the signal (e.g., $x'_1(t)$) can be generated in the network output when the compensating impedance z_c differs more or less than z_l . In particular, adaptive filtering has been a general technique to cancel such echo signals in the telephone network. Furthermore, the digital to analog converter (DAC) and the analog to digital converter (ADC) may be the sources of the nonlinear distortion in the hybrid network[3,4]. Accordingly, such nonlinear echo signals may result in the degradation of the adaptive echo cancellation. To solve such problem, an adaptive Volterra filtering was introduced to compensate for the nonlinear distortion in the telephone network[2-4]. However, particularly in the presence of the double-talk situation, the near-end signal can cause any fluctuation of tap coefficients, and they may diverge greatly. To overcome the double-talk problem, numerous research results have been reported[10-14]. When the double-talk is detected, one solution to inhibit the divergence of the tap coefficients can be obtained by setting the step-size of the adopted adaptive algorithm to zero. Also, in subband echo cancellation, M convolutions and adaptations with subsampled signals are performed in parallel [11], instead of filtering the fullband signal and adapting on filter at the high sampling rate. Another approach uses a novel adaptation scheme, where the step size varies[12] by comparing the power of the input signal with that of the error signal. Also, the correlation LMS algorithm was introduced [9] to achieve echo cancellation in the linear telephone network, which is based on the fact that the far-end signal is uncorrelated with the near-end signal.

In this paper, a robust nonlinear echo cancellation technique, obtained by extending the echo cancellation in the linear telephone network to that in the nonlinear telephone network as in [2,3,4], is to achieve nonlinear echo cancellation in the hybrid telephone network and proposed to solve the double-talk problem. For that purpose, a third-order adaptive Volterra filtering is employed along with a correlation LMS adaptation scheme to compensate for the nonlinear distortion in the echo path (e.g., DAC of the hybrid network).

In the next section, Volterra series modeling and nonlinear echo cancellation are considered, and in Section 3, the Volterra filtering along with a correlation LMS adaptation scheme is discussed. Finally, some computer simulation results are provided in Section 4 to demonstrate the validity of the proposed nonlinear echo cancellation technique.

2. VOLTERRA SERIES MODELING AND THE NONLINEAR ECHO CANCELLATION

The Volterra series is an extended form of Taylor series with memory. Since the output is linear with respect to system kernels, the linear filter theory can be applied to the nonlinear system analysis[5-8]. In particular, the DAC of the hybrid telephone network can be modeled as the following third-order Volterra system[3]:

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$$y[n] = \sum_{i=0}^{N-1} h_1[i]x[n-i] + \sum_{i=0}^{N-1}\sum_{j=1}^{N-1} h_2[i,j]x[n-i]x[n-j] + \sum_{i=0}^{N-1}\sum_{j=i}^{N-1}\sum_{k=j}^{N-1} h_3[i,j,k]x[n-i]x[n-j]x[n-k] \quad (2.1)$$

where $h_1[i]$, $h_2[i,j]$, and $h_3[i,j,k]$ are first-, second-, and third-order Volterra kernels, respectively, and N denotes the system memory size. Also, nonlinear kernels (i.e., $h_2[i,j]$, and $h_3[i,j,k]$) are assumed to be symmetric. Then, (2.1) can be expressed in the following vector form:

$$y[n] = \mathbf{h}_v^T[n]\mathbf{x}_v[n] \quad (2.2)$$

where the Volterra kernel vector $\mathbf{h}_v[n]$ consists of linear, quadratic, and cubic kernels, and Volterra input vector $\mathbf{x}_v[n]$ consists of linear, quadratic, and cubic inputs: i.e.,

$$\mathbf{x}_v[n] = [\ x[n],\cdots,x[n-N+1],x^2[n],x[n]x[n-1],\cdots,x[n]x[n-N+1], x^2[n-1],\ \cdots,x[n-1]x[n-N+1],x[n-2]x[n-2],\cdots, x^2[n-N+1],x^3[n],\cdots,\ x^2[n]\cdot x[n-N+1],\cdots,x^3[n-N+1]\ ]^T \quad (2.3)$$

$$\mathbf{h}_v[n] = [\ h_1[0],\cdots,h_1[N-1],h_2[0,0],h_2[0,1],\cdots,h_2[0,N-1],h_2[1,1],\cdots, h_2[1,N-1],h_2[2,2],\cdots,h_2[N-1,N-1],h_3[0,0,0],\cdots,h_3[0,0,N-1], \cdots,h_3[N-1,N-1,N-1]\ ]^T \quad (2.4)$$

The conventional structure of nonlinear echo cancellation [2-4] is shown in Fig. 2. Specifically, the echo replica $\hat{y}[n]$ is the output of the third-order Volterra filter, and the error signal $e[n]$ is defined as the difference between the echo signal $y[n]$ and the echo replica $\hat{y}[n]$

$$e[n] = y[n] - \hat{y}[n] \quad (2.5)$$

The Volterra filter coefficients can be updated in an adaptive way by using the normalized LMS algorithm:

$$\mathbf{h}_v[n+1] = \mathbf{h}_v[n] + \mu\, e[n]\frac{\mathbf{x}_v[n]}{\|\mathbf{x}_v[n]\|^2} \quad (2.6)$$

3. ADAPTIVE VOLTERRA FILTERING WITH A CORRELATION LMS ADAPTATION SCHEME

In the double-talk situation, a near-end signal $s[n]$ is the error signal $e[n]$ as in Fig. 2 and Fig. 3. Thus, the large error signal may yield the fault adaptation of filter coefficients (i.e., they can diverge greatly). To overcome this problem, the correlation LMS algorithm can be employed for efficient nonlinear echo cancellation in the double-talk situation. In the previous work, the correlation LMS algorithm showed the robustness in the linear echo cancellation in a hands-free telephone system[9], even under the double-talk condition. The correlation LMS algorithm utilizes the fact that a far-end signal is not correlated with a near-end signal. Accordingly, the residual error for the tap adaptation is relatively small, when compared to that of the conventional normalized LMS algorithm. More specifically, in the correlation LMS approach, the auto-correlation input vector is used as a canceller input, rather than the input vector itself. Also, the desired value is defined as the cross-correlation between input and echo signal. That is, the input auto-correlation vector $\mathbf{\Phi}_{xx}[n]$ and the cross-correlation $\varphi_{dx}[n]$ between the desired value and the input signal are defined as follows.

$$\mathbf{\Phi}_{xx}[n] = \mathbf{x}_v[n]x[n] \quad (3.1)$$

$$\varphi_{dx}[n] = \sum_{i=0}^{n} d[i]x[i] \quad (3.2)$$

Note that $\mathbf{\Phi}_{xx}[n]$ is an auto-correlation vector of the Volterra input, and $\varphi_{dx}[n]$ is the cross-correlation between the desired value $d[n]$ and the system input $x[n]$. Moreover, the desired signal $d[n]$ consists of the echo signal $y[n]$ and the near-end signal $s[n]$.

$$d[n] = y[n] + s[n] \quad (3.3)$$

Since the far-end signal $x[n]$ is uncorrelated with the near-end signal $s[n]$, the cross-correlation can reduce to:

$$\varphi_{dx}[n] = \varphi_{sx}[n] + \sum_{i=0}^{n} y[i]x[i] \cong \sum_{i=0}^{n} y[i]x[i] \quad (3.4)$$

The echo signal $y[n]$ is the output of the echo path r_i when excited by the input $x[n]$. In addition, when $\varphi_{xx}[n,i]$ is the *i-th* element of $\mathbf{\Phi}_{xx}[n]$, the cross-correlation $\varphi_{dx}[n]$ can be expressed as

$$\varphi_{dx}[n] \cong \sum_i r_i \varphi_{xx}[n,i] \quad (3.5)$$

The estimate of the desired cross-correlation signal $\varphi_{dx}[n,i]$ can be expressed as

$$\hat{\varphi}_{dx}[n] = \sum_i h_v[n,i]\varphi_{xx}[n,i] \quad (3.6)$$

where $h_v[n,i]$ is the *i-th* element of $\mathbf{h}_v[n]$.

Just as in the adaptive filter theory, the nonlinear echo path can be estimated by adjusting the Volterra filter coefficients (or $\mathbf{h}_v[n]$). Also, the error signal $e[n]$ for the tap adaptation is calculated as

$$e[n] = \varphi_{dx}[n] - \hat{\varphi}_{dx}[n] \quad (3.7)$$

The objective of this procedure is to find an optimal kernel vector $\mathbf{h}_v[n]$ at time n, minimizing the mean-square error:

$$\xi[n] = E\{|e[n]|^2\} = E\{|\varphi_{dx}[n] - \hat{\varphi}_{dx}[n]|^2\} \quad (3.8)$$

Using the steepest descent algorithm, the gradient of the MSE can be described by

$$\nabla_i = -2E\{e[n]\varphi_{xx}[n,i]\} \quad (3.9)$$

In the LMS algorithm, the correction term, applied to $\mathbf{h}_v[n]$, is proportional to $\mathbf{\Phi}_{xx}[n]$. When each element of the input vector is large, the gradient noise amplification may be observed in the LMS algorithm. By normalizing the LMS step size as in (3.9) by using the norm of the input vector,

$$h_i[n+1] = h_i[n] + 2\mu_0 e[n]\varphi_{xx}[n,i]/(1+\|\mathbf{\Phi}_{xx}[n]\|^2) \quad (3.10)$$

the noise amplification problem can be reduced.

Finally, to estimate in an adaptive way the auto-correlation and cross-correlation, the following formula can be used:

$$\varphi_{xx}[n,i] = (1-\alpha)\varphi_{xx}[n-1,i] + \alpha x[n]x_v[n,i] \quad (3.11)$$

$$\varphi_{dx}[n] = (1-\beta)\varphi_{dx}[n-1] + \beta d[n]x[n] \quad (3.12)$$

where $x_v[n,i]$ is the *i-th* element of $\mathbf{x}_v[n]$.

4. SIMULATIONS

To demonstrate the performance of the proposed algorithm, the DAC of the hybrid network is considered, where the DAC is implemented in MOS technology and its transfer function can be modeled as the following third-order polynomial system:

$$f(x) = 1.01333x - 0.01333x^3 \quad (4.1)$$

Also, the simple echo path impulse response is given by

$$g_i = e^{-0.8i} \quad (4.2)$$

The quantitative performance measure for the proposed approach, the following Echo Return Loss Enhancement (ERLE) is adopted:

$$ERLE = 10\log_{10}\frac{E\{y^2[n]\}}{E\{\varepsilon^2[n]\}} \quad (4.3)$$

where $y[n]$ and $\varepsilon[n]$ are the echo signal and the undistorted error signal, respectively. Note that the undistorted error signal $\varepsilon[n]$ can be written as

$$\varepsilon[n] = e[n] - s[n] \quad (4.4)$$

In this simulation, (i) the simple echo impulse response is changed at 0.13 sec, (ii) then the double-talk situation is enforced at the same time, and (iii) the system finally returned to the single-talk situation at 0.5 sec. Three simulation results (i.e., obtained by applying the correlation LMS, NLMS, and projection correlation[14] methods) are shown in Fig. 4. That is, the result, depicted using the straight line, denotes the ERLE value obtained when the proposed approach is applied, and the dashed line result denotes the ERLE value obtained when the normalized LMS is applied. Finally, the dotted line result, denotes the ERLE value obtained when the projection-correlation algorithm is utilized. Among them, the proposed nonlinear echo cancellation approach with a correlation LMS adaptation scheme provides more robustness in the situation where the echo path is changed or the double-talk is produced as in Fig. 4.

5. CONCLUSION

In this paper, a robust nonlinear echo cancellation is proposed, where (i) a third-order adaptive Volterra filtering is employed along with a correlation LMS adaptation scheme, and (ii) the input auto-correlation is used as a canceller input, and the canceller output is compared with the cross-correlation between input and desired signals. In particular, the adaptive Volterra filtering technique is employed to compensate for the nonlinear distortion in the echo path (e.g., DAC of the hybrid network). Finally, the simulation results show that the proposed nonlinear echo cancellation approach is more robust even in the double-talk situation.

6. REFERENCES

[1] M. Sondhi, and D. Berkley, "Silencing echoes on the telephone network," *Proceedings of the IEEE*, vol. 68, no. 8, pp. 948-963, Aug. 1980.

[2] F. Kuch, and W. Kellermann, "Nonlinear line echo cancellation using a simplified second order Volterra filter," *Proc. ICASSP'2002,* vol. 2, pp. 1117-1120, 2002.

[3] O. Agazzi et al. "Nonlinear echo cancellation of data signals," *IEEE Trans. Comm.*, vol. 30, pp. 2421-2433, Nov. 1982

[4] J. Chen, and J. Vandevalle, "Study of adaptive nonlinear echo canceller with Volterra expansion," *Proc. ICASSP'89*, pp. 1376-1379, Glasgow, 1989.

[5] M. Schetzen, *The Volterra and Wiener Theories of Nonlinear System*, John Widly and Sons, Inc., New York, 1980

[6] V. J. Mathews, and Giovanni L. Sicuranza, *Polynomial Signal Processing*, John Wiley & Sons, Inc., 2000

[7] V. J. Mathews, "Adaptive polynomial filters," *IEEE Signal Proc. Mag.,* vol. 8, no. 3, pp. 10-26, Jul. 1991.

[8] D.W. Grffith and G.R. Arce, "Partially decoupled Volterra filters: Formulation and LMS adaptation," *IEEE Trans. Signal Processing,* vol. 45, no. 6, pp. 2664-2673, Jun. 1997.

[9] M.R. Asharif, T. Hayashi, and K. Yamashita, "Correlation LMS algorithm and Its application to double-talk echo cancelling," *Electronics Letters*, vol. 35, no. 3, pp. 194-195, Feb. 1999.

[10] Heitkamper, "An adaptive control for acoustic echo cancellers,' *IEEE Sig. Process. Lett.*, vol. 4, pp. 170-172, Jun 1997.

[11] E. Hansler, and Gerhard Uwe Schmidt, "Hands-free telephones – Joint control of echo cancellation and postfiltering," *Signal Processing,* vol. 80, pp. 2295-2305, 2000.

[12] J. Liu, "A novel adaptation scheme in the NLMS algorithm for echo cancellation," *IEEE Sig. Proc. Lett.*, vol. 8, pp. 20-22, Jan. 2001.

[13] M. Nekuii and M. Atarodi, "Composite PNLMS and NLMS adaptation: A new method for network echo cancellation," *14th Int. Conf. on Digital Signal Processing,* vol. 2, pp. 757-760, 2002.

[14] T. Creasy, and T. Aboulnar, "A projection-correlation algorithm for acoustic echo cancellation in the presence of double talk," *Proc. ICASSP'00,* vol. 1, pp. 436-439, 2000.

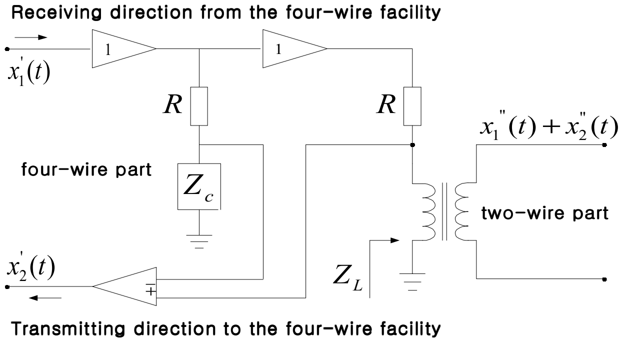

Fig. 1. Realization of a two-to-four wire hybrid network

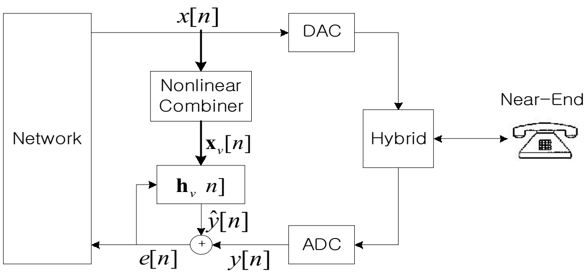

Fig. 2. The conventional nonlinear line echo canceller.

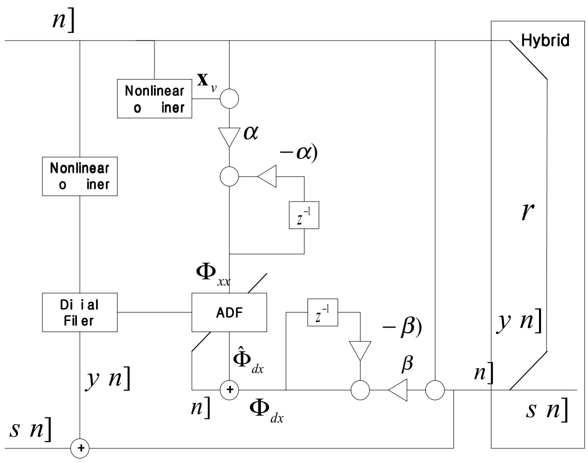

Fig. 3. The proposed nonlinear echo cancellation system.

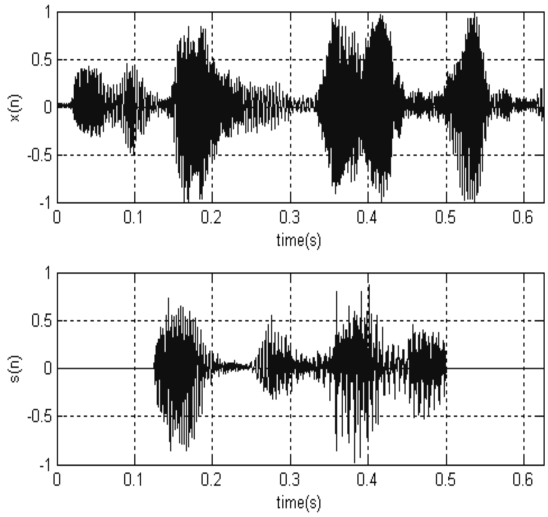

Fig. 4. A near-end signal $x[n]$ and a far-end signal $s[n]$.

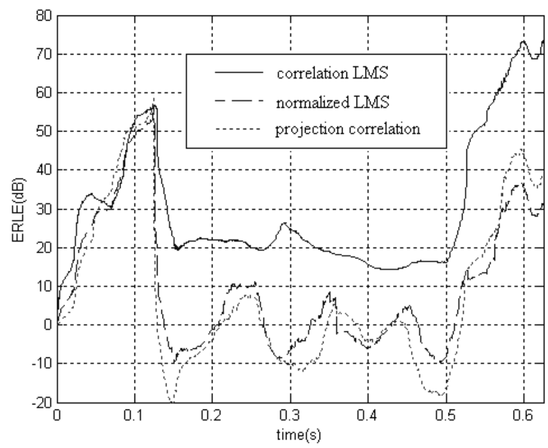

Fig. 5. ERLE curves in the nonlinear echo cancellation