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Fast communication

Maximum likelihood estimation of time delays in multipath acoustic channel

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ABSTRACT

This paper presents a solution to the problem of time delay estimation in multipath acoustic channel. Here the multipath acoustic channel output signal is modelled as a superposition of the delayed, attenuated, and filtered version of the stationary Gaussian stochastic input signal. A maximum likelihood (ML) estimator is developed for determining time delays in multipath acoustic channel in the presence of uncorrelated noise. Accuracy percentage (AP) performance measure has been introduced to characterize the performance of the estimators. The performance of the ML estimator is compared via computer simulation, using AP, with a generalized autocorrelation estimator (GAE) and AP_{CRLB} which is obtained by expressing the CRLB in terms of probability. Simulation results show that the performance of the ML estimator is superior to the GAE and approaches to AP_{CRLB}. The robustness of the algorithm has also been studied via computer simulation.

1. Introduction

During the last three decades, considerable attention has been given to the problem of time delay estimation in which the received signal contains multipath. Multipath is observed when the emitted source signal is received at the receiver through more than one path. Multipath phenomenon is common in radar, sonar and wireless communication systems and also finds application in seismic exploration, computerized tomography, and non-destructive testing, etc. [1–5]. In wireless communication systems these extra paths are useful but at the cost of additional complexity of the receiver [6]. However, in most of the applications these extra paths are not desirable e.g. in acoustic echo, which commonly appears in hands-free telephony and teleconferencing, etc. Acoustic echo results due to the coupling of the received voice and the mouthpiece of a mobile handset or the coupling of the speaker and microphone in hands-free applications. When this coupling of speaker and microphone takes place in an enclosure say room, such arrangement is called loudspeaker-enclosure-microphone (LEM) system. In LEM system model, loudspeaker emitted signal reaches the microphone not only directly but also via reflections from neighbouring objects [7–9]. Therefore, the signal received at the microphone is a superposition of the delayed, attenuated, and filtered versions of the emitted signal and the same can be modelled as multipath [10,11]. Thus the received signal contains a direct path plus extra paths resulting acoustic echo. Acoustic echo is typically more complex than the hybrid or network echo, and its impulse response is much longer. The acoustic echo-cancellation problem has been studied by many authors [12] for more than 30 years. Acoustic echo-cancellation can be achieved by using a single long length adaptive filter but due to its long length it has slow convergence and poor tracking behaviour. In [13,14] it has been suggested that convergence and tracking behaviour can be improved by using multiple-sub-filters in the place of a single long length filter provided that acoustic echo

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channel be modelled as a multipath channel. To realize multiple sub-filter based echo canceller knowledge of time delay associated with each path is required.

In this paper we derive a maximum likelihood (ML) estimator for estimation of time delay associated with each path in a multipath acoustic channel and compare its performance with a generalized autocorrelation estimator (GAE) [5] using accuracy percentage (AP) as a performance measure. Further, the performance of the algorithm is tested for different signal-noise scenarios and observation lengths. The robustness of this algorithm is evaluated by considering different time delay differences.

This paper is divided into five sections. In Section 2 multipath model is given and in Section 3 estimator analysis and performance measure are presented. In Section 4 simulation results are discussed and conclusions have been presented in Section 5.

2. Multipath model

The simplified multipath model for M extra paths apart from direct path is shown in Fig. 1. The observed signal $d(n)$ is a linear function of filter coefficients and attenuation but non-linear function of delay. The observed signal $d(n)$ (in mixed notation) can be expressed as [11]

$$d(n)=\sum_{i=0}^{M} g_i \times H_i(z)x(n-D_i)+\xi(n); \quad n=0,1,\ldots,N-1 \tag{1}$$

where $x(n)$ is the emitted source signal, $\xi(n)$ is the ambient noise with zero mean and variance σ_ξ^2, $H_i(z)$ denotes the low-pass filter of order L_i corresponding to the i th path and

$$H_i(z)=\sum_{n=0}^{L_i-1} h_i(n)z^{-n}$$

where g_i and $h_i(n)$ are the attenuation coefficient and impulse response respectively of the i th path. Further, by $H_i(z)x(n-D_i)$ we mean $h_i(n)*x(n-D_i)$ where '$*$' denotes convolution.

3. Estimator analysis and performance measure

We have assumed input $x(n)$ to be Gaussian and channel parameters to be unknown. So to obtain the joint estimate of the channel parameters attenuation

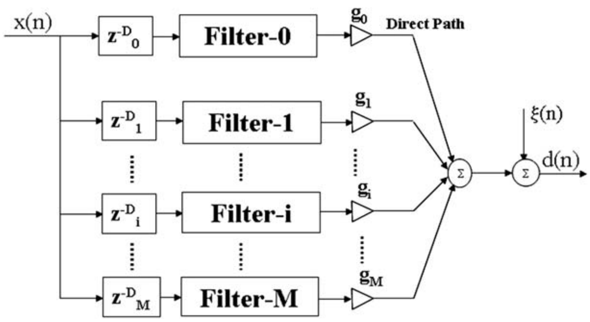

Fig. 1. Multipath model.

coefficients g_i and delays D_i, the likelihood function for these parameters can be written as

$$p_{d|\mathbf{G},\mathbf{D}}(\mathbf{d}|\mathbf{G},\mathbf{D})=\frac{1}{(2\pi\sigma_\xi^2)^{N/2}}\exp\left\{-\frac{1}{2\sigma_\xi^2}\sum_{n=0}^{N-1}\left[d(n)-\sum_{i=0}^{M} g_i \times H_i(z)x(n-D_i)\right]^2\right\}$$

Taking natural logarithm of both the sides we get

$$\ln(p_{d|\mathbf{G},\mathbf{D}}(\mathbf{d}|\mathbf{G},\mathbf{D}))=-\frac{N}{2}\ln(2\pi\sigma_\xi^2)-\frac{1}{2\sigma_\xi^2}\left\{\sum_{n=0}^{N-1}\left[d(n)-\sum_{i=0}^{M} g_i \times H_i(z)x(n-D_i)\right]^2\right\}$$

The ML estimate of parameters $\mathbf{g}$ and $\mathbf{D}$ is obtained by maximizing the log-likelihood function.

$$\max_{\mathbf{G},\mathbf{D}}[\ln(p_{d|\mathbf{G},\mathbf{D}}(\mathbf{d}|\mathbf{G},\mathbf{D}))]=\max_{\mathbf{G},\mathbf{D}}\left[-\frac{N}{2}\ln(2\pi\sigma_\xi^2)\right.$$
$$\left.-\frac{1}{2\sigma_\xi^2}\left\{\sum_{n=0}^{N-1}\left[d(n)-\sum_{i=0}^{M} g_i \times H_i(z)x(n-D_i)\right]^2\right\}\right]$$

This is equivalent to

$$\min_{\mathbf{G},\mathbf{D}}\left[\frac{N}{2}\ln(2\pi\sigma_\xi^2)+\frac{1}{2\sigma_\xi^2}\left\{\sum_{n=0}^{N-1}\left[d(n)-\sum_{i=0}^{M} g_i \times H_i(z)x(n-D_i)\right]^2\right\}\right]$$

Further simplifying we get

$$\min_{\mathbf{G},\mathbf{D}}\left[\frac{N}{2}\ln(2\pi\sigma_\xi^2)+\frac{1}{2\sigma_\xi^2}\sum_{n=0}^{N-1}\left\{d(n)^2+\left(\sum_{i=0}^{M} g_i \times H_i(z)x(n-D_i)\right)^2\right.\right.$$
$$\left.\left.-2\times d(n)\times\left(\sum_{i=0}^{M} g_i \times H_i(z)x(n-D_i)\right)\right\}\right]$$

Now removing the terms independent of parameters $\mathbf{g}$ and $\mathbf{D}$, the above can be further written as

$$\min_{\mathbf{G},\mathbf{D}}\left[\sum_{n=0}^{N-1}\left\{\left(\sum_{i=0}^{M} g_i \times H_i(z)x(n-D_i)\right)^2\right.\right.$$
$$\left.\left.-2\times d(n)\times\left(\sum_{i=0}^{M} g_i \times H_i(z)x(n-D_i)\right)\right\}\right] \tag{2}$$

For single path case i.e. $M=1$, the minima of the above expression can be easily obtained. For $M>1$, a closed form solution is difficult to obtain. Here, we assume that paths are non-overlapping for the sake of obtaining a closed form solution. Mathematically this implies that

$$\sum_{n=0}^{N-1}\left\{\sum_{i=0}^{M}\sum_{j=0}^{M} H_i(z)x(n-D_i)H_j(z)x(n-D_j)\right\}=0 \quad \text{for } i\neq j$$

Estimator designed using non-overlapping condition, when used in real life applications, may have deterioration in its performance. By applying the non-overlapping assumption, (2) gets decoupled for delay and attenuation parameters of the multipath channel and can be written as

$$\min_{\mathbf{G},\mathbf{D}}\left[\sum_{n=0}^{N-1}\left\{\sum_{i=0}^{M}(g_i \times H_i(z)x(n-D_i))^2-2\times d(n)\right.\right.$$
$$\left.\left.\times\left(\sum_{i=0}^{M} g_i \times H_i(z)x(n-D_i)\right)\right\}\right]$$

The energy of the emitted signal is given by $E_x=\sum_{n=0}^{N_1}[H_i(z)x(n-D_i)]^2$, where N_1 is the duration of the i th path. Therefore, we can simplify the above