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Hybrid Leak Localization Using Acoustic Sensors via Intercorrelation Method and MUSIC Algorithm

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Abstract

In this paper, we propose to combine the intercorrelation method and the Multiple Signal Classification algorithm (MUSIC) to locate a leak on a gas pipeline using acoustic sensors. We compare the Root Mean Square Error (RMSE) of the leak position estimate using hybrid localization based on a combination of MUSIC and intercorrelation method to the MUSIC algorithm and the intercorrelation method using two acoustic sensors and a pipeline of length 100m. At average Signal to Noise Ratio equal to 0 dB, the RMSE of the leak position estimate is equal to 0.88 m for the hybrid algorithm while it is 1.6 m for the MUSIC algorithm and 7.4 m for the intercorrelation method. The intercorrelation method, the hybrid, and the MUSIC algorithms are unbiased as the RMSE converges to zero at high SNR.

Disciplinary: Electrical and Computer Engineering & System.

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1 Introduction

Leak localization on gas pipelines is a very important process allowing to avoid accidents such as expositions and harmful pollution [1-4].

Any gas leak can result in a considerable gas loss. The identification and localization of leaks on gas pipelines allow for rapid pipeline repair [5-6]. Ultrasonic Testing (UT) is a method of determining the thickness of a gas pipeline and detecting any corrosion-related changes.

Acoustic sensors can also be used to detect and identify a gas tank leak. An acoustic signal is produced by the departing gas. The acoustic signal is received at sensors S1 and S2 with different propagation delays t1 and t2. An inter-correlation between the two sensed signals at S2 and S1, x2(t) and x1(t), has a maximum at t0=t2-t1. Let c the speed of the acoustic signal and d be the distance between the two sensors S1 and S2. We have d=(t1+t2)*c. We deduce t2=d/(2c)+t0/2. The distance between sensor S2 and the leak position is computed using d2=c *t2=d/2+t0c/2.

Magnetic sensors can be mounted inside the pipeline, and any leaks will produce a change in the magnetic field, which can be detected quickly. Magnetic sensors, on the other hand, can only detect the leak and not find it. The gas pipeline's pressures and flow rates (Kg/s) can be used to detect and pinpoint a leak. This strategy, however, necessitates a robust observation model [7-14].

A change in mass balance can also be used to detect a leak without any prior knowledge of its location. Magnetic induction sensors can also be used to detect subsurface pipeline leaks [17]. To detect any leak on gas pipelines, ground-penetrating radar (GPR) was proposed in [23-26]. Gas concentration sensors, for example, can be used to detect and locate a leak using the Maximum Likelihood algorithm (ML).

The main contributions of this paper are

- We propose the use of the MUSIC algorithm to locate a leak on a gas pipeline using acoustic sensors. The use of the MUSIC algorithm based on signals of acoustic sensors for leak localization has not been yet proposed in [1-26].
- We suggest combining the MUSIC algorithm and the intercorrelation method to minimize the Mean Square Error (MSE) of the leak location estimate.
- We compare the performance of the hybrid algorithm to MUSIC and the intercorrelation method. At average SNR equal to 0 dB, the RMSE of the leak position estimate is equal to 0.88 m for the hybrid algorithm while it is 1.6 m for the MUSIC algorithm and 7.4 m for the intercorrelation method. The hybrid and MUSIC algorithms as well as the intercorrelation method are unbiased as the RMSE converges to zero at high SNR.
- It is shown that the MSE of hybrid leak localization using two estimators is half of the harmonic mean of MSE of the two estimators. The MSE of the hybrid estimator is lower than the minimum of MSE of the MUSIC algorithm and the intercorrelation method.

2 Inter-correlation Method

As shown in Figure 1, acoustic sensors allow also detection and locate a leak in a gas tank. The escaping gas generates an acoustic signal. The acoustic signal is received at sensors S1 and S2 with different delays t1 and t2. An inter-correlation between the two sensed signal at S2 and S1, x2(t) and x1(t), has a maximum in t0=t2-t1. Let c the speed of the acoustic signal and d be the distance between the two sensors s1 and s2. We have d=(t1+t2)*c. Therefore, t2=d/(2c)+t0/2. The distance between sensor S2 and the leak position is computed using d2=c *t2=d/2+t0c/2. An intercorrelation between the sensed signals is shown in Figures 2 and 3 for SNR equal to 10 and 0 dB. In Figures 2 and 3, Ts is the sample period.

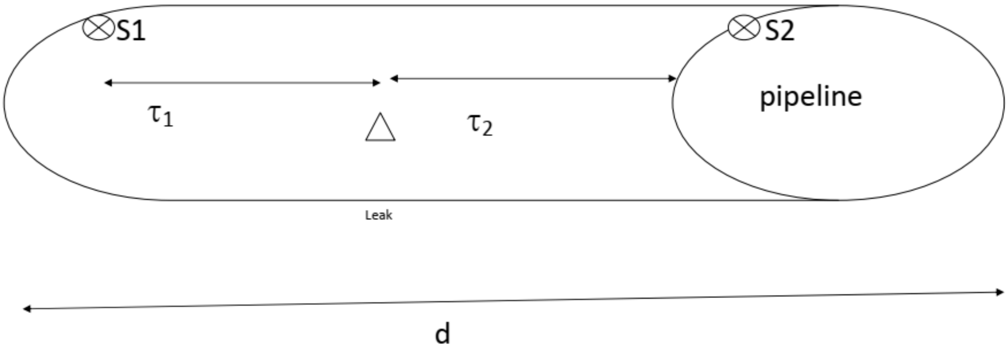

Figure 1: Leak localization using Acoustic sensors.

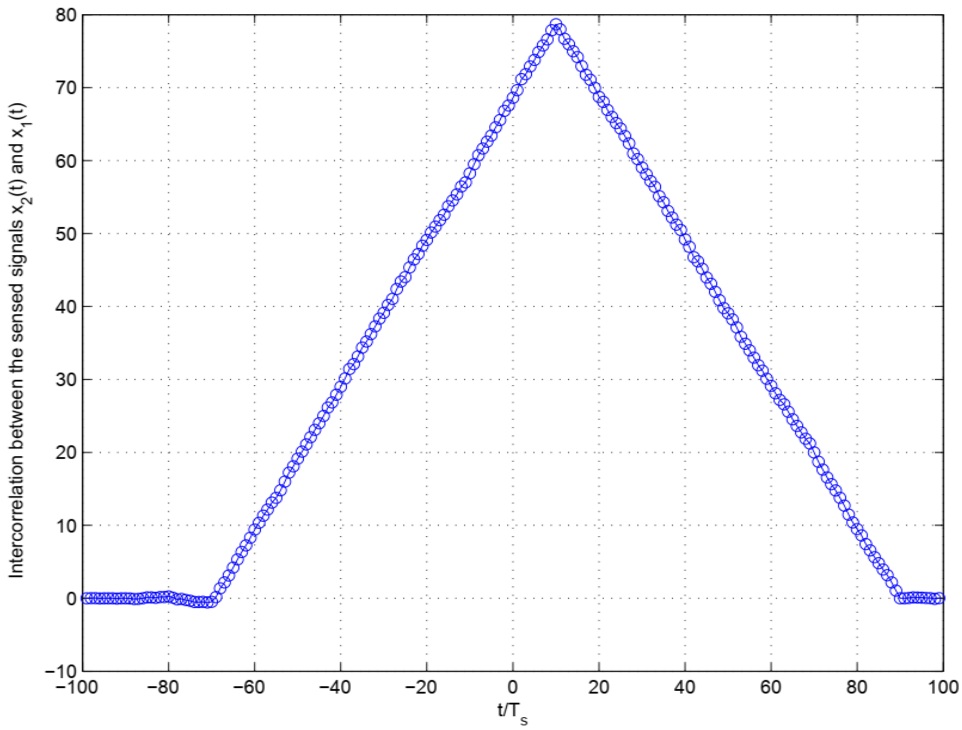

Figure 2: Intercorrelation between the sensed signals at sensors S2 and S1 at SNR=10dB.

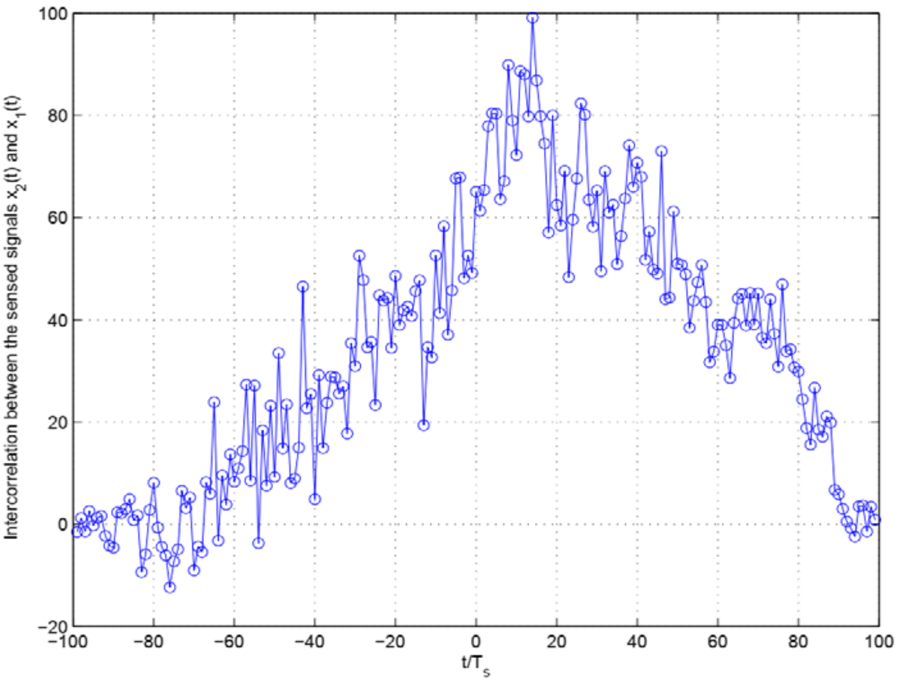

Figure 3: Intercorrelation between the sensed signals at sensors S2 and S1 at SNR=0dB.

3 Leak Localization Using Acoustic Sensors and MUSIC Algorithm

The received signal at time *t*, at *q*-th sensor over the m-th time slot can be written as

$$x_q^{(m)}(t) = s(t - \tau_q) + n_q^{(m)}(t) \quad (1),$$

where *s(t)* is the acoustic emitted by the leak, τq is the time delay between the leak and q-th acoustic sensor and $n_q^{(m)}(t)$ is an additive Gaussian noise with variance σ^2.

The samples of the received signal over the *m*-th time slot are written as

$$X_q^{(m)} = [x_q^{(m)}(T_0), x_q^{(m)}(T_0 - T_s), \dots, x_q^{(m)}(T_0 - (N-1)T_s)]^T + N_q^{(m)} \quad (2),$$

where T_0 is a sample time and T_s is the sample period, *N* is the number of samples and

$$N_q^{(m)} = \left[n_q^{(m)}(T_0), n_q^{(m)}(T_0 - T_s), \dots, n_q^{(m)}(T_0 - (N-1)T_s)\right]^T \quad (3).$$

The received signal can also be written as

$$X_q^{(m)} = S(\tau_q) + N_q^{(m)} \quad (4),$$

where

$$S(\tau) = [s(T_0 - \tau), s(T_0 - \tau - T_s), \dots, s(T_0 - (N-1)T_s - \tau)]^T \quad (5).$$

Using the signals of *L* time slots, an estimation of the time correlation matrix *Rq* at the q-th sensors can be computed as

$$R_q = \frac{\sum_{m=1}^{L} X_q^{(m)} (X_q^{(m)})^T}{L} \quad (6),$$

Matrix *Rq* can be decomposed as follows

$$R_q = V_s \Delta_s V_s^T + V_n \Delta_n V_n^T \quad (7),$$

where the columns of *Vs* are the eigenvectors that span the signal subspace while the column vectors of *Vn* span the noise subspace of dimension equal to one. Δs and Δn are diagonal matrices containing the eigenvalues of signal and noise subspaces.

An estimation of the time delay τq between the leak and q-th acoustic sensor can be obtained by maximizing the following metric

$$\hat{\tau}_q = argmax_\tau \frac{1}{S(\tau)^T V_n V_n^T S(\tau)} \quad (8),$$

A single sensor is sufficient to estimate the leak position. When two or many sensors are available, we can make an average of the obtained estimates.

4 Hybrid Localization of Leak

Let $\hat{x}_{0,1}$ be the leak position estimate using acoustic sensors and the intercorrelation method. Let $\hat{x}_{0,2}$ be the leak position estimate using acoustic sensors and the MUSIC algorithm. We suggest combining these two estimates of leak position to minimize the Mean Square Error (MSE). The hybrid estimator is written as

$$\hat{x}_{h,2} = \alpha\hat{x}_{0,1} + (1-\alpha)\hat{x}_{0,2} \quad (9),$$

where $0<\alpha<1$ is a weighting coefficient.

The MSE of the hybrid estimator is given by

$$MSE_2 = E\left[\left(x_0 - \hat{x}_{h,2}\right)^2\right] = \alpha^2\sigma_1^2 + (1-\alpha)^2\sigma_2^2 \quad (10),$$

where $E(.)$ is the expectation operator, x_0 is the leak position and σ_i^2 is the MSE of i-th estimator evaluated as

$$\sigma_i^2 = E\left[\left(x_0 - \hat{x}_{0,i}\right)^2\right] \quad (11).$$

To minimize the MSE2 of the hybrid estimator, we should have

$$\frac{\partial MSE_2}{\partial \alpha} = 0 \quad (12).$$

Using the last equation, we obtain

$$\alpha = \frac{\sigma_2^2}{\sigma_2^2+\sigma_1^2} \quad (13).$$

Using Equations (10) and (13), we obtain the expression of the minimum MSE by combining two estimators as

$$MSE_2 = \frac{\sigma_2^2\sigma_1^2}{\sigma_2^2+\sigma_1^2} = \frac{1}{\frac{1}{\sigma_1^2}+\frac{1}{\sigma_2^2}} < \min(\sigma_1^2, \sigma_2^2) \quad (14).$$

The MSE of hybrid leak localization using two estimators is half of the harmonic mean of MSE of the two estimators. The MSE of the hybrid estimator is lower than the minimum of MSE of the MUSIC algorithm and the intercorrelation method.

5 Numerical Results

We did 10000 Monte-Carlo simulations using two acoustic sensors for both the hybrid and MUSIC algorithms and the intercorrelation method using L=10 time slots. The length of the pipeline is d=100m$ with a random location of the leak. Figure 4 shows that the RMSE of leak position estimate the intercorrelation method of section 2 is about 7.4 m at average SNR equal to 0 dB. At high average SNR, the RMSE converges to zero confirming that the intercorrelation method is unbiased.

Figure 5 compares the RMSE of the leak position estimate using the MUSIC algorithm of section 3 and the intercorrelation method of section 2. The MUSIC algorithm offers better performance than the intercorrelation method since the RMS is about 1.6 m at SNR equal to 0 dB while the RMS is 7.4 m for the intercorrelation method. The MUSIC algorithm is also unbiased as the RMSE converges to zero at high SNR.

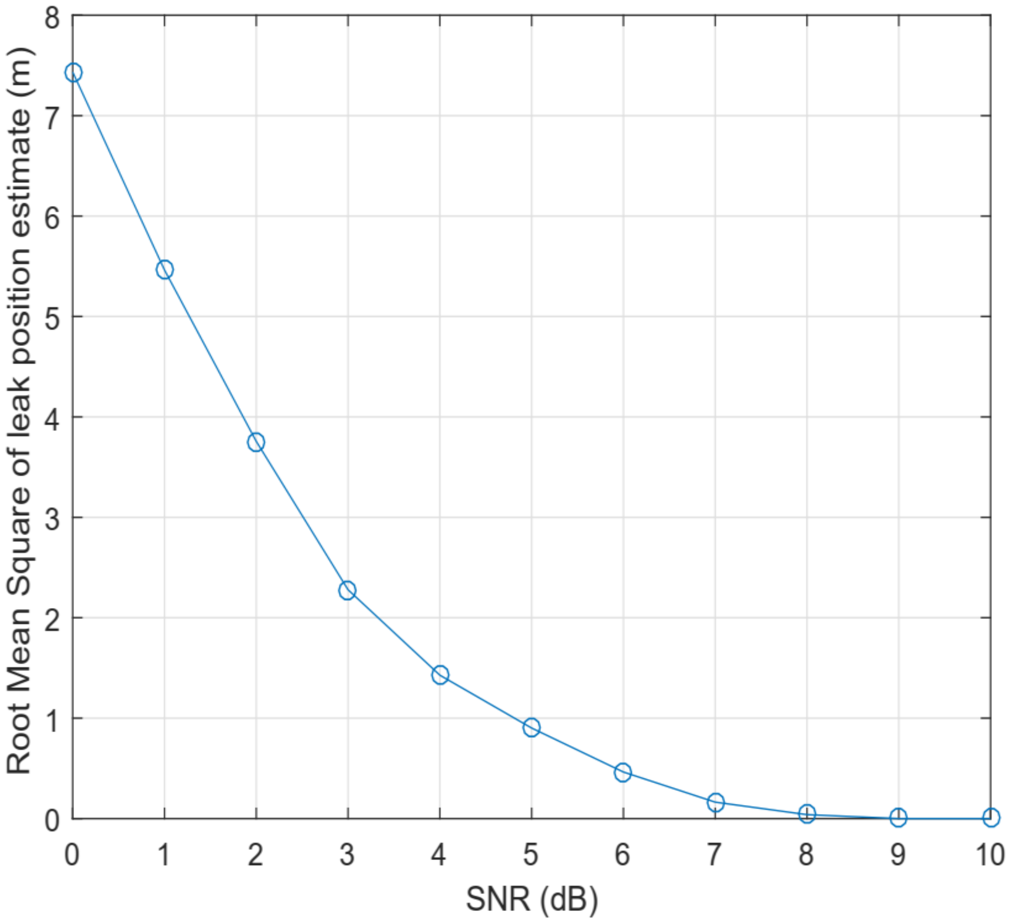

Figure 4: RMSE of leak position estimate using the inter-correlation method.

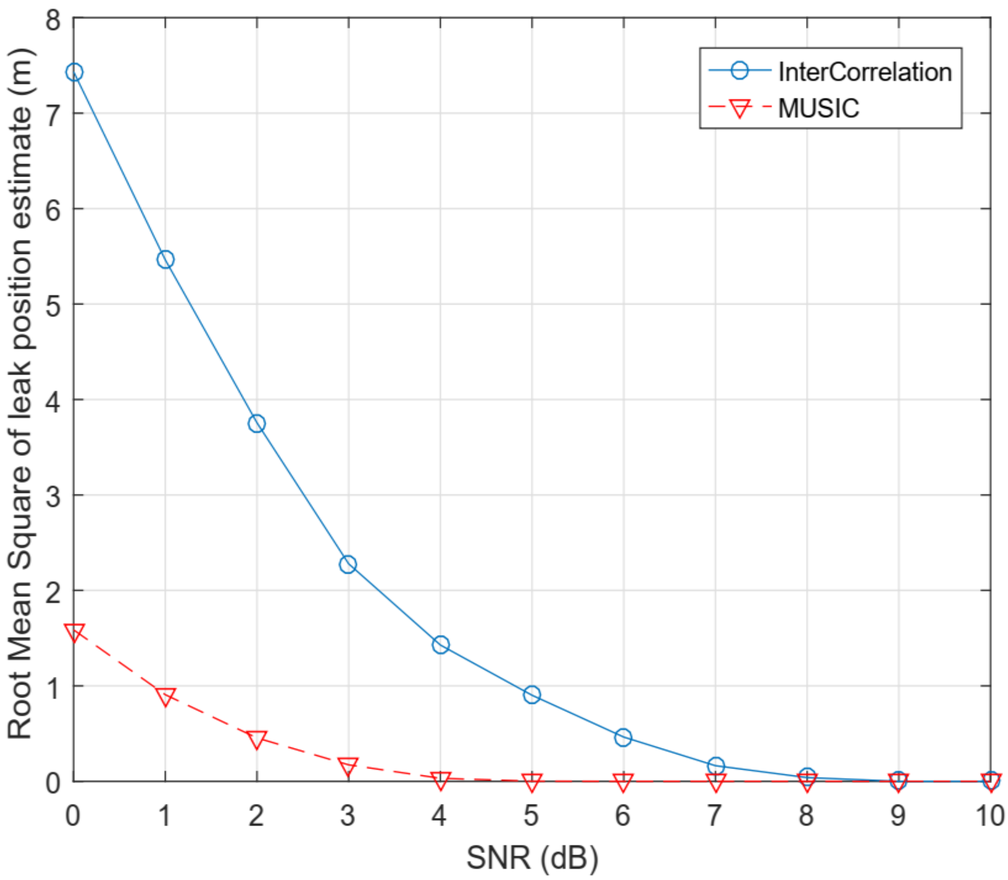

Figure 5: RMSE of leak position estimate using the inter-correlation method and MUSIC algorithm.

Figure 6 shows the MUSIC spectrum (8) with respect to the distance between the sensor and the leak d=τc. The MUSIC spectrum is maximum at the distance of 60m which is the real location of the leak. Therefore, the MUSIC allows precise estimation of the leak position.

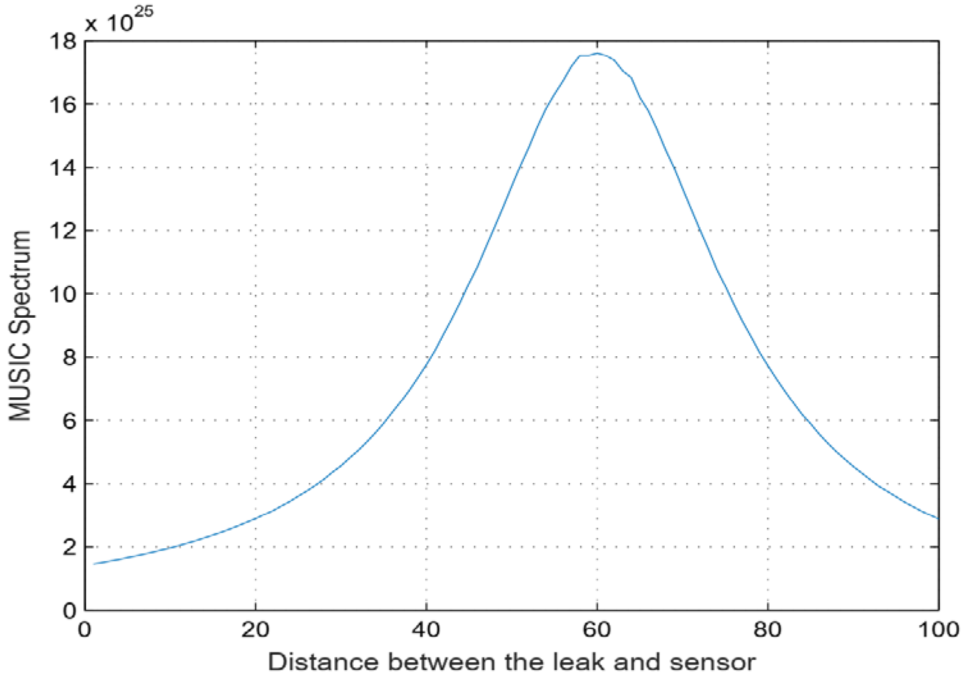

Figure 6: MUSIC algorithm for a leak at 60m from the sensor.

Figure 7 shows the RMSE using hybrid leak localization with the MUSIC algorithm and the intercorrelation method. The proposed hybrid localization technique offers a lower RMSE than the MUSIC algorithm and intercorrelation method. At SNR equal to 0 dB, the RMSE of hybrid localization is 0.88m while it is 1.6 m for the MUSIC algorithm and 7.4 m for the intercorrelation method.

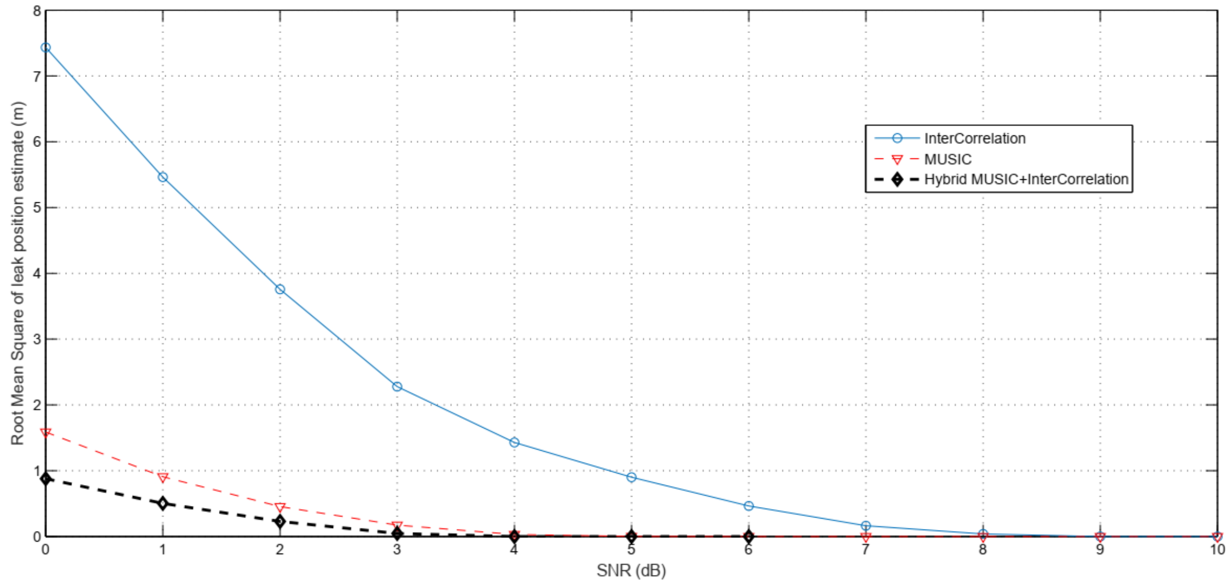

Figure 7: Hybrid localization using MUSIC algorithm and intercorrelation method.

6 Conclusion

In this paper, we combined the intercorrelation method and the MUSIC algorithm to locate a leak on a gas pipeline using acoustic sensors. We compared the RMSE of the leak position estimate using hybrid localization based on a combination of MUSIC and intercorrelation method to the MUSIC algorithm and the intercorrelation method using two acoustic sensors and a pipeline of length 100m. At average SNR equal to 0 dB, the RMSE of the leak position estimate is equal to 0.88 m for the hybrid algorithm while it is 1.6 m for the MUSIC algorithm and 7.4 m for the intercorrelation method. The intercorrelation method, the hybrid, and the MUSIC algorithms are unbiased as the RMSE converges to zero at high SNR. We have shown that the MSE of hybrid leak localization using two estimators is half of the harmonic mean of MSE of the two estimators. The MSE of the hybrid estimator is lower than the minimum of MSE of the MUSIC algorithm and the intercorrelation method.

As a perspective, we can work on leak localization on oil pipeline or using wireless sensors that harvests energy from radio frequency signals, wind, or solar energy.

7 Availability of Data and Material

Data can be made available by contacting the corresponding author.

8 Acknowledgement

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