LEAK DETECTION AND LOCALIZATION IN WATER DISTRIBUTION SYSTEM USING TIME FREQUENCY ANALYSIS

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ABSTRACT

Water loss through burst events or leaks is a significant problem affecting water utilities worldwide and is exacerbated by deterioration of the underground infrastructure. This paper shall report on our method to localize the source of a pipe burst by estimating the arrival time of the pressure transients at sensor nodes. Our proposed method uses Short Time Fourier Transform that has shown to overcome the limitation of Fourier Transform temporal deficiency. The paper will in addition report on the results obtained from a real leakage data obtained on the WaterWiSe@SG test-bed, which shows the superiority of our method compared to multi-level wavelet transform.

Index Terms— event localization, transient detection, time frequency analysis, Short Time Fourier Transform

1. INTRODUCTION

Pipe bursts and water losses through leakage in the underground distribution network represents a major and growing problem associated with aging infrastructure in many cities worldwide. Distribution systems carrying potable water to consumers consist of pipes, pumps, valves, storage tanks, reservoirs, meters, fittings, and other hydraulic appurtenances. Protecting and maintaining this infrastructure is crucial to ensure water quality, public safety and to prevent water loss. Real time detection and localization of burst events in an underground pipe can enable utilities to isolate the problem and mitigate damage (flooding, sinkhole creation etc.). The losses through undetected leaks include tangible costs such as water loss, energy required to generate lost water and intangible costs such as service disruption, customers' dissatisfaction and public safety. According to [1], the survey on 20 utilities in the United States, more than \$250 billion is required over the next 30 years to replace pipes and infrastructure.

Over the past few year, a number of researchers have been working on the detection and localization of leaks. Hunaidi, et al. [2, 3, 4, 5] introduced a method to locate the leak within the suspected area using vibration and acoustic sensors with a specially controlled experiment. PipeNet [6] developed a prototype system that make use of acoustic leak detection method to identify small leaks and estimate Time Difference of Arrival (TDOA) at different measurement points by taking the cross-correlation of acoustic signals. Srirangarajan, et al. [7] proposed wavelet transform for leak detection and localization using WaterWiSe@SG test-bed [8]. Pressure signals acquired from time-synchronized sensors are analyzed extract features. To locate the burst, TDOA are estimated by looking at the extrema of the detail coefficients at different wavelet levels.

A number of methods have been proposed to localize the leaks/bursts. However, most of these methods have only been implemented and tested in laboratory or well controlled field test sites. We propose a new method based on Joint Time Frequency Analysis (JTFA) that has been developed and validated within a fully operational water distribution system including detection of actual burst events.

2. TIME DIFFERENCE OF ARRIVAL ESTIMATION USING JOINT TIME FREQUENCY ANALYSIS

Different methods have been proposed for leak localization. For transient based leak localization approaches, the sources

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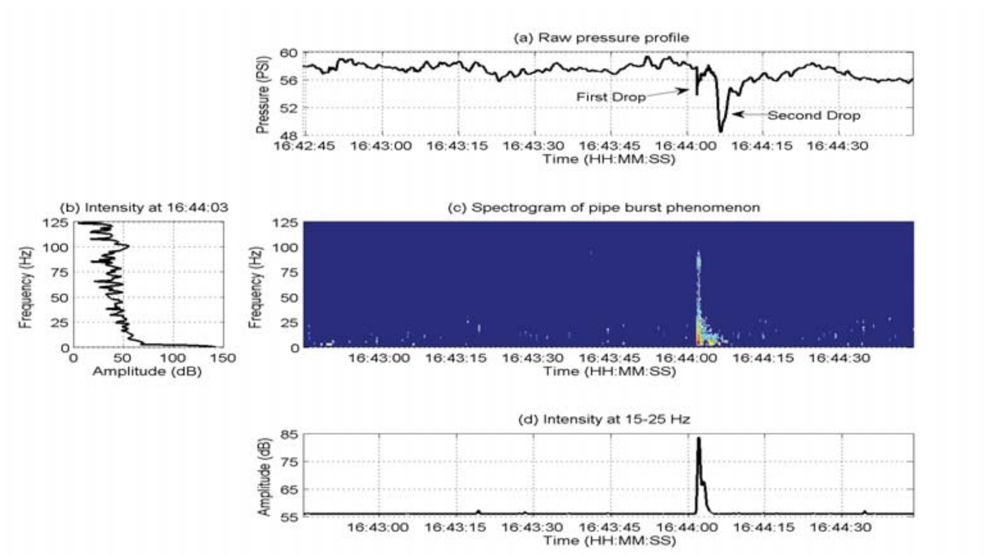


Fig. 1. Joint time frequency analysis of pipe failure on WaterWiSe@SG. The raw pressure profile is represented in (a). The intensity distribution is depicted in (b) and time-frequency distribution in (c). The spectral intensity is localized around the average time t = 16:44:03. The intensity distribution across temporal scale is shown in (d).

of error include network map inaccuracy, time synchronization error and arrival time estimation error. Therefore, to accurately estimate the time different of arrival is very crucial.

To localize, the presence of the leak is first identified by analyzing the transient signals using spectrogram [9, 10]– one of the time frequency analysis techniques. The detail procedure can be found in [11]. Due to the attenuation within the water pipeline, sensor nodes further away from the location of the leak receive weaker transient pressure wave than those closer to the source. According to homogeneity, additive and time-frequency scaling properties of Fourier Transform, the magnitude and slope of the drop in pressure can determine the intensity of each of the frequencies [12]. Thus, the sensor closer to the leak will receive the higher intensity in the frequency spectrum. However, the lowest frequencies (0-15 Hz) are composed of natural frequency of the pipe and sensor dependent noise depending on the material and length of the pipe. For a pipe of length L with both ends open, the wavelength of the fundamental frequency f_0 is $2L$. Hence,

$$\lambda_0 = 2L. \tag{1}$$

According to wavelength-frequency relationship in (2).

$$\lambda_0 = \frac{v}{f_0}. \tag{2}$$

where v is wavespeed in the pipe. Therefore, the fundamental frequency of pipe of length L is (3).

$$f_0 = \frac{v}{2L}. \tag{3}$$

And high frequency components are more vulnerable to attenuation. Therefore, 15-25 Hz frequency range is selected for

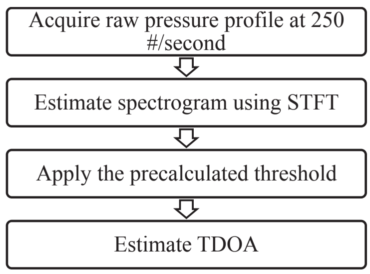


Fig. 2. Process of TDOA estimation using Time Frequency Analysis.

determining the presence of leak. Joint time frequency analysis of transient signal is shown in Figure 1. The procedure for estimating TDOA is depicted in Figure 2.

To obtain a more probable threshold to filter the background noise, the following procedure is carried out.

1. We employ Short Time Fourier Transform (STFT) with Blackman window on normal pressure profile acquired from the sensor nodes.

$$STFT[x(n)] = X(m, \omega). \tag{4}$$

$$X(m, \omega) = \sum_{n=-\infty}^{\infty} x[n]\omega[n-m]e^{-j\omega n}. \tag{5}$$

where x(n) is the signal to be transformed, j = $\sqrt{-1}$ and ω (n) is the Blackman window function in (6). X is the 2-dimensional matrix with N-rows and M-columns.

$$\mathrm{N} = \begin{cases} \frac{\text{FFT Length}}{2} + 1, & \text{if x(n) is real.} \\ \text{FFT Length}, & \text{if x(n) is not real.} \end{cases}$$

$$\mathrm{M} = \ \text{floor}\left(\frac{\text{Data Size - Window Size}}{\text{Window Size - Overlap Size}}\right) + 1.$$

$$\omega(n) = 0.42 + \tfrac{1}{2}cos\left(\tfrac{2\pi n}{N}\right) + 0.08cos\left(\tfrac{4\pi n}{N}\right), 0 \le n \le N-1. \tag{6}$$

where N represents the window length, in samples, of the symmetrical Blackman window $\omega(n)$. To compensate for the loss at the edges of the window, individual chunks may overlap in time.

2. According to Parseval′s relationship of the Fourier Transform, the area under the energy spectral density curve is equal to the squared magnitude of the energy. Therefore, the spectrogram (7) of the signal can be estimated by computing the squared magnitude of the STFT of the signal.

$$Spectrogram\ x[t] \equiv |X(\tau, \omega)|^2. \tag{7}$$

3. An estimate $\widehat{\sigma}$ of the standard deviation σ of the background noise is pre-calculated from the historical data using (8).

$$\widehat{\sigma}_i = \sqrt{\frac{1}{N+1}\sum_{j=1}^{N+1}(x_j - \bar{x})^2}. \tag{8}$$

where $\bar{x} = \frac{1}{n}\sum_{j=1}^{N+1}(x_j)$ and i is the frequency from 1-129 Hz.

4. The threshold (T) is calculated using (9).

$$T = \frac{1}{N}\sum_{i=1}^{N}(\widehat{\sigma}_i + \bar{x}). \tag{9}$$

where N is the number of windowing that we use for stabilizing the predicted noise.

5. Replace all frequencies with intensity less than the threshold values with the threshold values in order to remove the station-oriented noise for each of the sensor nodes.

The threshold is set for each frequency band rather than the whole spectrum i.e. higher frequencies have smaller intensity than the lower frequencies, so that their threshold values are smaller than that of the lower frequencies. Then, we estimate TDOA from the difference in the arrival times of the signal from the burst at multiple sensor nodes. This is accomplished by estimating the arrival times corresponding to the peak intensity within the 15-25 Hz frequency band at those nodes. Subtracting Time of Arrival (TOA) measurements from two nodes produce a relative TDOA.

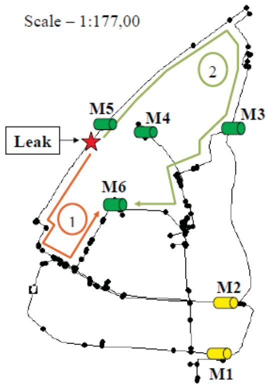


Fig. 3. Network layout for location of the leakage event. M1, M2, M3, M4, M5 and M6 are the sensor nodes.

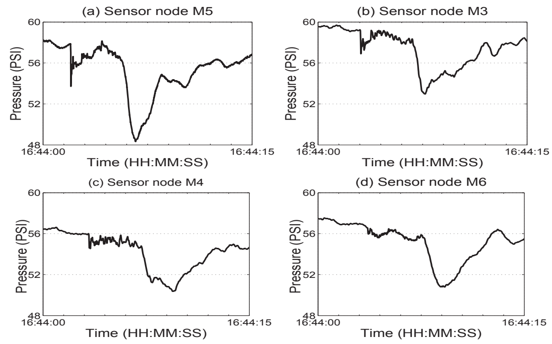


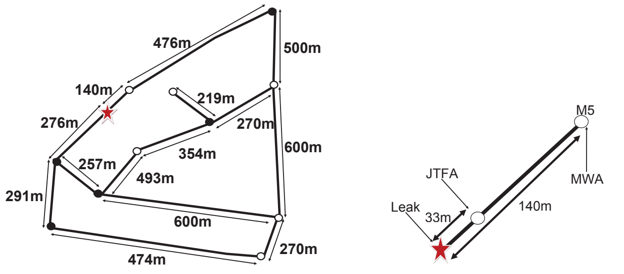
Fig. 4. Measured pressure traces of real burst event scenario in 800 mm steel pipe.

3. CASE STUDY

The proposed methodology is verified with a real leak on WaterWiSE@SG test bed in a live WDS. Figure 3 shows the location map of the area where the real pipeline leakage occurred. The leak occurred due to a crack within an 800 mm diameter steel pipe. The sensor nodes M3 - M6 (Figure 3) are located 50 - 1800 m away from the source. The measured pressure traces of leaks are shown in Figure 4. The sensors detected two subsequent pressure drops. The initial drop is rapid and the subsequent one is less rapid but more significant. This signature reflects the actual pipe break (first pressure drop) and a reflection from the closed valve (second drop). To estimate the TDOA from the source of the pipeline leakage to the measurement sensor nodes, the magnitude of frequency at 15-25 Hz are calculated and Time of Arrival (TOA) at each sensor node is derived. Theoretically, there can be more than one route between the two sensor nodes which have the same arrival time. Wavespeed can vary considerably for different pipe materials and roughness, hence, it is possible that the shortest pipe does not correspond to the first arrival from the source. In this case, there are two possible routes between sensor node M5 and M6, two theoretical TDOAs are calculated for route 1 and route 2.

Table 1. Theoretical TDOA and TDOA estimation using JTFA for real pipe burst event NH1

	Theoretical (route 1)	Theoretical (route 2)	JTFA	MWA
Internode TDOA M3-M5	0.925	0.925	1.123	1.092
Internode TDOA M4-M5	1.325	1.325	1.382	1.305
Internode TDOA M6-M5	1.035	1.647	1.814	-
Internode TDOA M4-M3	0.400	0.400	0.259	0.213
Internode TDOA M6-M3	0.110	0.722	0.691	-
Internode TDOA M6-M4	-0.290	0.322	0.432	-



(a) (b)

Fig. 5. (a) Graphical representation for section of the distribution network where the leakage event occurred. The $'\circ'$ represent the sensor nodes and $'\bullet'$ are the junctions. The nodes are represented by the vertices and the pipes by the edges. (b)Burst locations estimated by JFTA and MWA.

Table 1 shows TDOA estimations of the burst events at the four measurement points. As we have the knowledge of network topology of bursts location, the distances between adjoining nodes and the estimation of wavespeed, the theoretical TDOAs between M3, M4, M5 and M6 are calculated.

Then the TDOAs are fed into graph based localization algorithm [13, 14] to estimate the location of the burst. The graphical representation of the map is shown in Figure 5.

The location of the burst is calculated using TDOA, wavespeed and section of the network. The Dijkstra's shortest path algorithm is used and the estimated burst location is 107.15 meters from sensor node M5 that is 32.85 meters from actual leak location.

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(y_j - x_j)^2. \tag{10}$$

where y is a vector of estimated TDOAs and x is a vector of theoretical TDOAs.

The mean squared error (MSE) is estimated to evaluate the performance of proposed TDOA method using (10). The MSE for JTFA-based TDOA with respect to theoretical TDOAs of route 1 and route 2 are 0.2548 and 0.0172 respectively. The localization error is 32.85 meters. With this level of accuracy in localization, field crews can better pinpoint/locate the leak source.

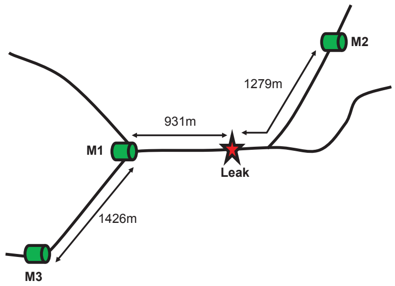


Fig. 6. Network layout for KR1 leak event.

4. PERFORMANCE EVALUATION

To assess the performance, proposed TDOA estimations for two pipe breakage events NH1, and KR1 are compared with results using multi-scale wavelet Analysis (MWA) [13]. For the NH1 burst event (Figure 3), the MWA only detected anomalous pressure transients at nodes M3, M4 and M4, from which TDOA values were reported in Table 1. With the knowledge of network topology of bursts location, the distances between adjoining nodes and the estimation of wavespeed, the expected TDOAs between M3, M4 and M5 are calculated.

To compare the performance, the MSE for both methods are calculated using (10). The MSE for JTFA of the transient taking route 1 and 2 are 0.2548 and 0.0172 respectively. The MSE for JTFA and MWA for sensor nodes M3, M4 and M5 are 0.0208 and 0.0211 respectively.

These values are then fed into localization algorithm, the estimated burst location using JFTA is 107.15 meters from sensor node M5 which is 32.85 meters from actual leak location. Using MWA, the burst is estimated at the sensor node M5, 140 meters from the burst location.

The second event KR1 occurred on a 300 mm pipe. Figure 6 shows the location map of the leakage area. The leak transients were picked up by the sensor nodes M1, M2, and M3 which are 931 meters, 1279 meters, and 2357 meters from the leak respectively. Table 2 shows TDOA estimations of burst events at M1, M2 and M3. The theoretical TDOAs between M1,M2 and M3 are calculated. TDOA estimations from M3 with two other nodes using MWA are around 10 seconds which makes their distance around 10 km. This is because MWA misses the burst transient and picks the following transient. The MSE for JTFA and MWA are 0.1500 and 48.8493 respectively.

When these values are fed into the localization algorithm, the most probable burst location is estimated 860.24 meters from node M1 towards node M2 which is 70.76 meters from the actual leak location. One of the factors associating with localization inaccuracy is that the sensors are sparsely located around the area.

Table 2. Performance evaluation of TDOA estimation using JTFA and MWA on real leak KR1

	Theoretical	JTFA	MWA
Internode TDOA M2-M1	0.331	0.670	0.772
Internode TDOA M3-M1	1.358	1.900	10.130
Internode TDOA M3-M2	1.027	1.230	9.358

According to Table 1, 2, our approach using JFTA has a clear advantage over MWA for TDOA estimation. Although MWA has varying temporal and spectral resolution, temporal resolution becomes coarse as the level goes higher. Due to this characteristics, wavelet based analysis is particularly useful to pick the high frequency component with better time resolution. However, the frequency content of leak signal is below 50 Hz [3]. In contrast, the temporal and spectral resolution of the proposed JFTA method can be calculated from (11) and (12).

$$\triangle t = \frac{1}{f_s}. \tag{11}$$

where $\triangle t$ is temporal resolution and f_s is sampling frequency.

$$\triangle f = \frac{f_s}{N}. \tag{12}$$

where N is the number of sample per window. Therefore, proposed method could provide up to 4 milliseconds accuracy of detection capability. The trade-off for improved accuracy is increased computational time and memory required to calculate the TDOA. The localization accuracy of proposed leak localization algorithm is within 100 meters.

5. CONCLUSION

This paper proposes a method to estimate location of the leaks or bursts in WDS. This technique drastically reduces the TDOA estimation errors as it could provide up to 4 milliseconds accuracy. Currently in our test we have obtained accuracy within 100 meters of the actual leak. The calculation of the localization is based on flow speed and the accuracy of the sensor timer(sampling rate) and the estimation of the TOA.

The feasibility of the proposed method has been verified and tested on live WDS with real leaks. In addition, to improve the TDOA estimation and localization performance, the proposed method would require more accurate network model and implement more sophisticated algorithm to solve the multi-path phenomenon.

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