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LEAK DETECTION AND LOCALIZATION IN WIRELESS SENSOR NETWORK 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 will 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 which 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

The occurrences of pipe bursts and water leakage become more frequent in water distribution system (WDS) as the age of most WDSs around the world are more than 50 years. Distribution systems carrying potable water to consumers consist of pipes, pumps, valves, storage tanks, reservoirs, meters, fittings, and other hydraulic appurtenances. Protecting and maintaining its infrastructure is crucial to ensure water quality, public safety and to prevent water loss. Moreover, locating the source of pipe burst is as important as identifying them in order to reduce the losses associated with pipeline leakage. These losses due to unexposed leaks include tangible costs such as water loss, energy required to generate lost water and intangible costs such as service disruption, customer 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 years, a number of researchers have been detecting and localizing the 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 the 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]. Time synchronized pressure signals are analyzed to extract signal features. To locate the burst, TDOA are estimated by looking at the extremum 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 are implemented and tested with controlled experiments. We have proposed a new method based on Joint Time Frequency Analysis (JTFA). In contrast, the work presented here is developed and tested on live WDS with real pipe burst scenario.

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 of error include network map inaccuracy, time synchronization error and arrival time estimation error. Therefore, to accurately estimate the time difference 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 in the water pipeline, sensor node further away from the location of the leak receives weaker transient pressure wave than nearer sensor. According to homogeneity, additive and time-frequency scaling properties of Fourier Transform, the magnitude and slope of pressure drop can determine the intensity of each of the frequencies [12]. Thus, the sensor closes 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, \[
\lambda_0 = 2L \quad (1)
\]
According to wavelength-frequency relationship in (2).
\[
\lambda_0 = \frac{v}{f_0} \quad (2)
\]
where \( v \) is wavespeed in the pipe. Therefore, the fundamental frequency of pipe of length \( L \) is (3).
\[
f_0 = \frac{v}{2L} \quad (3)
\]
And high frequency components are more vulnerable to attenuation. Therefore, 15-25 Hz frequency range is selected in the process for 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, we employ Short Time Fourier Transform (STFT) with Blackman window on normal pressure profile acquired from our sensor nodes.
\[
STFT[x(n)] = X(m, \omega) \quad (4)
\]
\[
X(m, \omega) = \sum_{n=-\infty}^{\infty} x[n] \omega[n - m] e^{-j\omega n} \quad (5)
\]
where \( x(n) \) is the signal to be transformed, \( j = \sqrt{-1} \) and \( \omega(n) \) is the Blackman window function in Equation (6). \( X \) is the 2-dimensional matrix with \( N \)-rows and \( M \)-columns.
\[
N = \begin{cases} 
\frac{\text{FFT Length}}{2} + 1, & \text{if } x(n) \text{ is real.} \\
\text{FFT Length}, & \text{if } x(n) \text{ is not real.}
\end{cases}
\]
\[
M = \text{floor} \left( \frac{\text{WindowSize} \text{ - WindowSize}}{\text{OverlapSize}} \right) + 1
\]
\[
\omega(n) = 0.42 + \frac{1}{2} \cos \left( \frac{2\pi n}{N} \right) + 0.08 \cos \left( \frac{4\pi n}{N} \right), \quad 0 \leq n \leq N-1
\quad (6)
\]
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.

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 (Equation 7) of the signal can be estimated by computing the squared magnitude of the STFT of the signal.
\[
\text{Spectrogram} \equiv |X(t, \omega)|^2 \quad (7)
\]

Then obtain an estimate \( \hat{\sigma} \) of the standard deviation \( \sigma \) of the background noise using (8).
\[
\hat{\sigma}_i = \sqrt{\frac{1}{N+1} \sum_{i=1}^{N+1} (x_j - \bar{x})^2} \quad (8)
\]
where \( \bar{x} = \frac{1}{n} \sum_{i=1}^{N+1} (x_j) \) and \( i \) is the frequency from 1-129 Hz. Then the threshold \( (T) \) is calculated using Equation (9).
\[
T_i = \frac{1}{N} \sum_{j=1}^{N} (\hat{\sigma} + \bar{x}) \quad (9)
\]
where \( N \) is the number of windowing that we use for stabilizing the predicted noise. Then, replace all frequencies with intensity less than the threshold values with the threshold values remove the station oriented noise of each of the sensor nodes. The threshold is set for each frequency band rather than the whole spectrum i.e. higher frequencies has 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 at frequency band 15-25 Hz at those nodes. Subtracting Time of Arrival (TOA) measurements from two nodes produce a relative TDOA.
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).

Fig. 3. Network layout for location of the leakage event. Sensor nodes M1, M2, M3, M4, M5 and M6 are the sensor nodes collecting the burst transients and are 1116 meters, 1145 meters, 140 meters, and 1605 meters from the leak respectively.

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 in our WaterWiSe@SG test-bed. The leak crack occurred on a live water pipeline during distribution. The pipe was 800 millimeters in diameter and 50 to 1800 meters away from our sensor nodes. M3, M4, M5, and M6 are the sensor nodes located within 2 kilometers of the source of the leakage. 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 may 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, it is possible that the arrival time of the shortest route may not be the smallest. In this case, there are two possible routes between sensor node M5 and M6, two theoretical TDOAs is calculated for route 1 and route 2.

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

Fig. 4. Measured pressure traces of real burst event scenario in 800mm steel pipe (Sept. 18, 2011). The sensor nodes M3, M4, M5 and M6 are 1116 meters, 1145 meters, 140 meters, and 1605 meters from the leak respectively.
Table 1. Theoretical TDOA and TDOA estimation using JTFA for real pipe burst event on Nicholl Highway

<table>
<thead>
<tr>
<th>Theoretical TDOA (route 1)</th>
<th>Theoretical TDOA (route 2)</th>
<th>TDOA using JTFA</th>
<th>TDOA using MW A</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDOA between M3 and M5</td>
<td>0.925</td>
<td>0.925</td>
<td>1.123</td>
</tr>
<tr>
<td>TDOA between M4 and M5</td>
<td>1.325</td>
<td>1.325</td>
<td>1.382</td>
</tr>
<tr>
<td>TDOA between M6 and M5</td>
<td>1.035</td>
<td>1.647</td>
<td>1.814</td>
</tr>
<tr>
<td>TDOA between M6 and M3</td>
<td>0.400</td>
<td>0.400</td>
<td>0.259</td>
</tr>
<tr>
<td>TDOA between M6 and M4</td>
<td>0.290</td>
<td>0.322</td>
<td>0.432</td>
</tr>
</tbody>
</table>

Fig. 5. Graphical representation for section of the distribution network where the leakage event occurred. The green dots represent the sensor nodes and the red dots are the junctions. The nodes are represented by the vertices and the pipes by the edges.

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 which is 32.85 meters from actual leak location.

\[
MSE = \frac{1}{N} \sum_{j=1}^{N} (y_j - x_j)^2
\]

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. These results demonstrate that the proposed technique for localizing leaks and bursts within a WDS.

4. PERFORMANCE EVALUATION

To assess the performance, proposed TDOA estimations for the three pipe breakage events on WaterWiSe@SG testbed is compared with that using multi-scale wavelet Analysis (MWA) [13]. The first pipe burst occurred on the pipe with 800 millimeters in diameter. Figure 3 shows the location map of the area around the pipe leakage. The transients were picked up by M3, M4, M5, and M6. As MWA only detects the burst from three sensor nodes (M3, M4 and M5), the TDOA is calculated for these nodes. Table 1 shows TDOA estimations of burst events at M3, M4 and M5. 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 Equation. (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 JTFA is 107.15 meters from sensor node M5 which is 32.85 meters from actual leak location and the sensor node M5, 140 meters from the burst, is estimated by MWA as the burst location.

The second event occurred on the pipe with 300 millimeters in diameter. 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 second which makes their distance around 10 km. This is because MWA eliminates the burst transient as a negative peak is trailing the transient. The MSE for JTFA and MWA are 0.1500 and 48.8493 respectively.

When these values are fed into 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.

According to Table 1, 2, this approach has a clear advantage over MWA for TDOA estimation. Although MWA has varying temporal and spectral resolution, its temporal reso-

Fig. 6. Network layout for leak on Keppel road. The sensor nodes M1, M2 and M3 are within 2.4 km² of the leakage.
Table 2. Performance evaluation of TDOA estimation using JTFA and MWA on real leak at Keppel road

<table>
<thead>
<tr>
<th></th>
<th>Theoretical TDOA</th>
<th>TDOA using JTFA</th>
<th>TDOA using MWA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDOA between M2 and M1</td>
<td>0.331</td>
<td>0.670</td>
<td>0.772</td>
</tr>
<tr>
<td>TDOA between M3 and M1</td>
<td>1.358</td>
<td>1.900</td>
<td>10.130</td>
</tr>
<tr>
<td>TDOA between M3 and M2</td>
<td>1.027</td>
<td>1.230</td>
<td>9.358</td>
</tr>
</tbody>
</table>

olution becomes coarse as the level goes higher. Due to this nature, wavelet based analysis is particularly useful to pick the high frequency component with better time resolution. In contrast, the temporal and spectral resolution of proposed method can be calculated from (11) and (12).

\[ \Delta t = \frac{1}{f_s} \] (11)

where \( \Delta t \) is temporal resolution and \( f_s \) is sampling frequency.

\[ \Delta f = \frac{f_s}{N} \] (12)

where \( N \) is the number of sample per window. Therefore, proposed method could provide up to 4 millisecond accuracy of detection capability. The trade-off for improved accuracy is an 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 multipath phenomenon.

REFERENCES