Extended summary

Ultra low power wireless system development for water pipe real-time monitoring and leakage localization

Curriculum: Architecture, Constructions and Structures

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Abstract. Water loss is a major challenge in all advanced societies, with economic costs arising from the waste of the precious resource. The work here presented in this thesis describes the development of an innovative system for detecting and locating leaks in water pipes, able to combine diagnostic accuracy and advanced features such as automatic and continuous monitoring in real time. This is allowed thanks to a wireless sensor network designed ad hoc, in which all devices implement power saving features in order to be able to stay in operation for years without maintenance. Further the wireless system ensures a stable mesh network for the data collection from the sensors, and communication toward remote server for additional computing. The devices designed for the acquisition, sample**s** signals produced by the leakages in the pipeline by using MEMS acceleration sensors. The detection of the loss occurs by using a probability index developed starting from the equivalent levels of noise calculated on time intervals of consecutive measurements. The localization of the position of the loss occurs through the application of the method of cross-correlation, which is shown with an analysis of the base function (BCC) and the generalized (GCC) along with PHAT estimator.

Keywords. Wireless Sensor Network, leakage detection

1 Introduction and Objectives

Water loss is a major challenge in all advanced societies, with economic costs arising from the waste of the precious resource. The work here presented in this thesis describes the development of an innovative system for detecting and locating leaks in water pipes, able to combine diagnostic accuracy and advanced features such as automatic and continuous monitoring in real time. This is allowed thanks to a wireless sensor network designed ad hoc, in which all devices implement power saving features in order to be able to stay in operation for years without maintenance. Further the wireless system ensures a stable mesh network for the data collection from the sensors, and communication toward remote server for additional computing. The devices designed for the acquisition, samples signals produced by the leakages in the pipeline by using MEMS acceleration sensors. The detection of the loss occurs by using a probability index developed starting from the equivalent levels of noise calculated on time intervals of consecutive measurements. The localization of the position of the loss occurs through the application of the method of cross-correlation, which is shown with an analysis of the base function (BCC) and the generalized (GCC) along with PHAT estimator.

2 Leakage localization

2.1 Basic cross-correlation method (BCC)

To locate a leakage along a pipeline, acoustic signal must be sampled corresponding to two different places, using accelerometers or idrophones, deployed on the sides of a point of interest, as explained in [31]

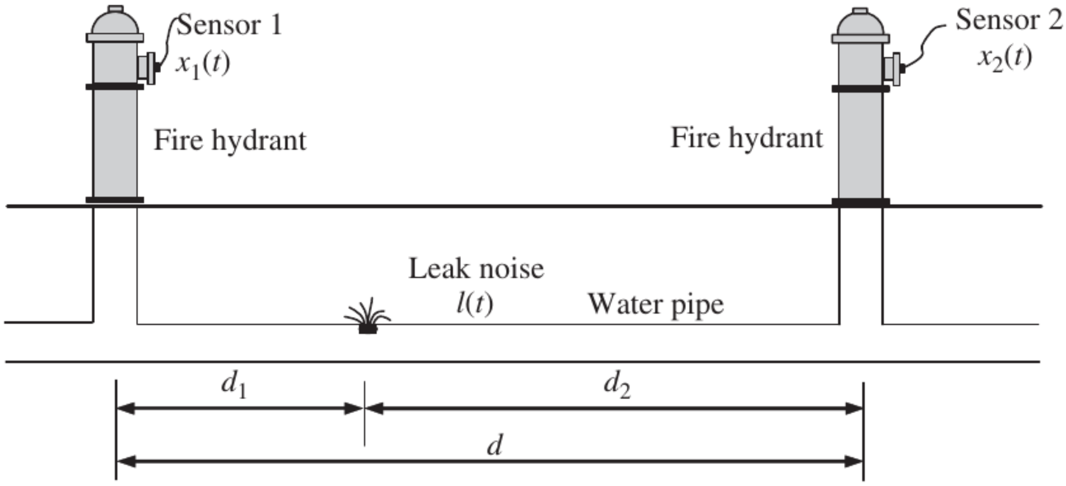


Figure 1: Leak detection schema

If a leakage exists, a marked peak will be noticed on the cross-correlation between signals $x_1(t)$ e $x_2(t)$. Such a peak provides the time delay τ_{peak} corresponding to the different time arrival of the vibrations to sensors. The leakage distance form a measure point d_1, can be calculated using the relationship standing between time delay τ_{peak}, distance between sensors d and waves propagation speed inside the pipeline,

$$d_1 = \frac{d - c\tau_{\text{peak}}}{2}.$$

If $x_1(t)$ e $x_2(t)$ are two stationary, causal and zero mean signals, cross-correlation function is defined as

$$R_{x_1x_2}(\tau) = E[x_1(t)x_2(t+\tau)],$$

where t id the delay and $E[\,]$ is the mean value operator. The t value that maximizes the equation above provides an estimation of the time delay τ_{peak}. A procedure to calculate the basic cross-correlation function (BCC) is shown in the fig[]: the BBC estimator can be obtained by the inverse Fourier Transform $X_1(f)X_2(f)$ properly normalized, where $X_1(f)$ and $X_2(f)$ respectively are the Fourier Transform of $x_1(t)$ and $x_2(t)$ and * stands for the complex conjugate operator.

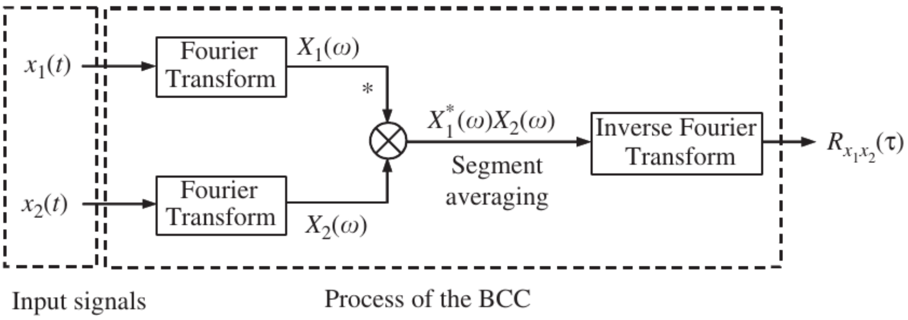


Figure 2: BCC schema

Cross-correlation function $R_{x_1x_2}(t)$ is related to the power spectral density $S_{x_1x_2}(\omega)$, by the inverse Fourier Transform

$$R_{x_1x_2}(\tau) = F^{-1}\{S_{x_1x_2}(\omega)\} = \frac{1}{2\pi}\int_{-\infty}^{+\infty} S_{x_1x_2}(\omega)\mathrm{e}^{\mathrm{i}\omega\tau}\,\mathrm{d}\omega,$$

where F^{-1} indicates the inverse transform operation. It means that only an estimation of CSD can be obtained, since it's derived from a time limited serie of $x_1(t)$ and $x_2(t)$. However, to simplify issues, the ideal CSD will be consider to introduce time delay estimators

2.2 General cross-correlation method (GCC)

In order to amplify cross-correlation peak related to the time delay, input signal can be prefiltered. In the time domain signals are filtered before to apply the delay, multiplication and integration, while in the frequency domain a weighting function or a window is applied to the CSD before to perform the inverse Fourier transformation. Thus the global cross correlation function (GCC) $R^g{}_{x_1x_2}(\omega)$ between signal sensor $x_1(t)$ and $x_2(t)$ is given by the following equation

$$R^g_{x_1x_2}(\tau) = F^{-1}\{\Psi_g(\omega)S_{x_1x_2}(\omega)\} = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \Psi_g(\omega)S_{x_1x_2}(\omega)\mathrm{e}^{\mathrm{i}\omega\tau}\,\mathrm{d}\omega,$$

where $\Psi_{2n}(\omega)$ is the frequency weighting function. When $\Psi_{2n}(\omega) = 1$, GCC function reduces to a BCC.

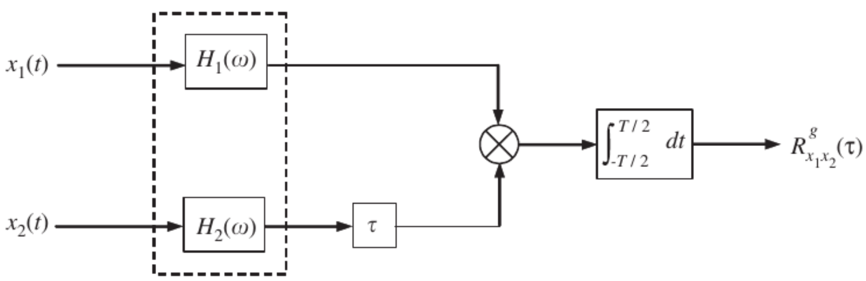
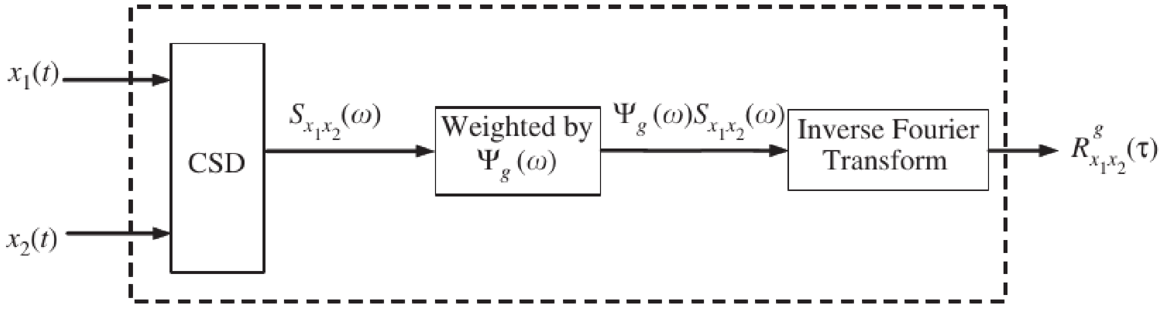


Figura 2.8 schema a blocchi della GCC



$$\Psi_g(\omega) = \overset{*}{H}_1(\omega)H_2(\omega)$$

Figure 3: GCC schema

2.3 PHAT estimator

Substituting frequency weighting function PHAT $\Psi_P(\omega) = 1/|S_{x_1x_2}(\omega)|$, and using CSD $S_{x_1x_2}(\omega)$, it results in

$$R^P_{x_1x_2}(\tau) = F^{-1}\{\Psi_P(\omega)S_{x_1x_2}(\omega)\} = \delta(\tau + T_0).$$

It can be noticed that, doing a pre-filtering upon the CSD sampled, PHAT estimator effectively removes propagation distortions and frequency modification introduced by the sensor itself, improving global spectrum estimation of signals. For non dispersive waves propagation, it results in a delta function perfectly located at T_0.

3 System architecture

To perform sound sampling alongside pipelines, an ultra low power wireless sensor network has been developed, starting from working prototypes, improving them and designing new ones.

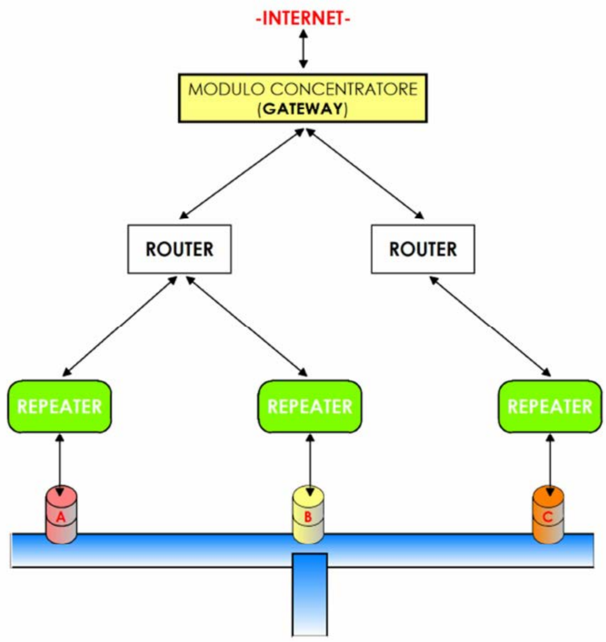


Figura 4: System architecture for data acquisition and process

The network is made up of following device categories:

- Gateway
- Router
- Repeater
- NoiseLogger

The gateway is the device that collects all the data coming from the network and then forwards them toward remote server. It is provided of a Zigbee tranceiver working in the 2.4GHz frequency band to communicate with routers: it is the only device that needs power supply from the power grid. Routers provide network functionalities, building up and maintaining routes for sensor data forwarding. It is achieved by using a Zigbee based protocol, modified adding exclusive low power features. Such a network implements the mesh topology, where each node can be moved and asynchronously polled according to the needing. No static routes are forced, but they are continuously calculated taking into account devices positions and self-distance from the gateway. Routers use a second transceiver for the communication with sensors, working in the 868MHz ISM frequency band with the FSK modulation. Repeaters are devices able to extend routers and sensors radio scope. Noiseloggers are devices designed for vibration sampling by the means of mems accelerometers. Simply putting them in contact with pipeline they can collect sound data and send them to routers with the 868MHz ISM transceiver.
Only two AAA 1,5V batteries are used as power supply for router and sensor devices. The radio scope among devices is up to 100mt, and they can keep working for years without any maintenance thanks to the ultra low power features introduced.
To control and analyze data acquisition from noiseloggers, a software tool has been developed in order to send commands and receive responses through network devices.

3.1 Noiselogger device

The noiselogger device has been developed thanks to SmartSpaceSolutions s.r.l. laboratories. All components has been chosen in order to obtain the better performances and the proper integration with the wireless network, keeping low production costs. The schema of the device is reported in fig[5].

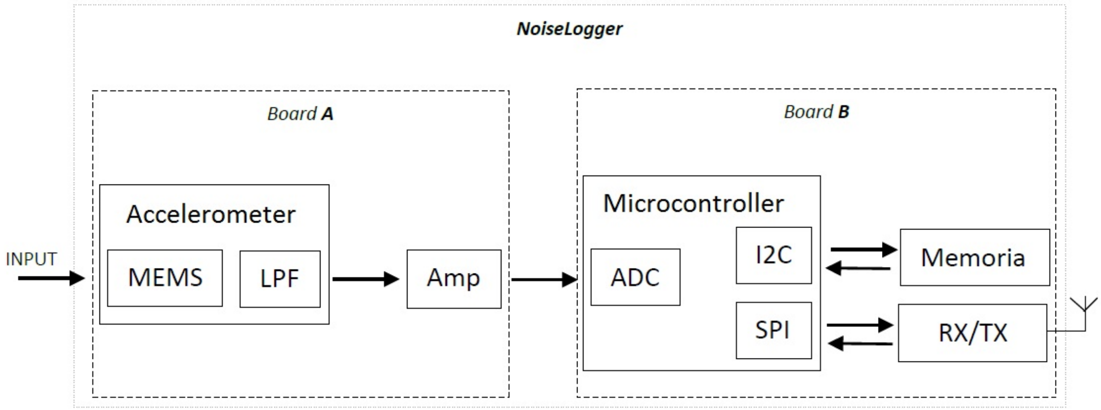


Figure 5: Noiselogger schema

Once deployed, the noiselogger will perform periodic vibration sampling through the MEMS accelerometer. The analogic signal is then passed through the low pass filter with a 3dB cut frequency at 500kHz, then it gets properly amplified by a factor of 10 and afterwards sent to the analog to digital converter (ADC) of the microcontroller. The latter will sample the signal at 1kHz frequency, then will store groups of 16 samples per time inside

Figura 3.2-1 schema a blocchi di un noiselogger the external SPI memory. Those samples can be used locally, to evaluate equivalent noise level and leakage detection, or remotely, to compute the leakage localization.

3.1.1 Accelerometer sensor

The KXR94-2050 accelerometer sensor has been chosen to perform vibration measures. It is produced by Kionix, and it shows good performances in sensitivity, signal band pass, noise density and power consumpion.

Figure 6: KXR94-2050 accelerometer

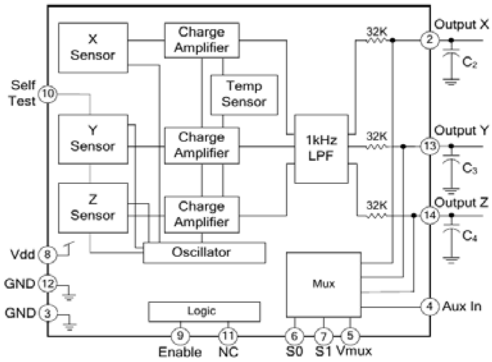


Figure 7: KXR94-2050 blocks

The sensor is a silicon micro machine (MEMS) with a three axial accelerometer, made up of a transducer element and an ASIC inside the same package. The acceleration detection is based on the principle of the measures of the differential capacitance generated by the induced movement. Three analogic output related to X, Y and Z axes are provided upon respectively pins.

3.1.2 The 868MHz tranceiver

The transceiver used to transmit data across the wireless network is the RFM22B, produced by HopeRF Company. It is an embedded transceiver operating at 868MHz ISM frequency band, its maximum transmission power is 20dBm and its voltage supply must be between 1.8V and 3.6V with a limited current consumption. It operates as a time division duplexing transceiver when alternatively receives and transmits data using a single low frequency conversion mixer for FSK/GFSK/OOK modulations. The signal received is amplified through a programmable gain amplifier (PGA) and then converted by means of a fast $\Sigma\Delta$ ADC; afterwards it is computed by the DSP processor for filtering operations, demodulation and packet management. The packet can be stored in a 64 bytes buffer and sent to an external microcontroller with the SPI peripheral.

4 Tests and Results

In order to evaluate system performances tests have been made in a controlled environment, by using a steel pipe with a thickness of 3mm and a diameter of 27mm and three taps in different positions alongside the pipe itself. To simulate leakages the taps has been opened and closed alternatively while water was flowing inside the pipe. Two noiselogger were located at both sides of the pipe, as reported into the following schema. The low power wireless network has been deployed inside the noiseloggers radio scope, in order to support data collection ad verify system performances.

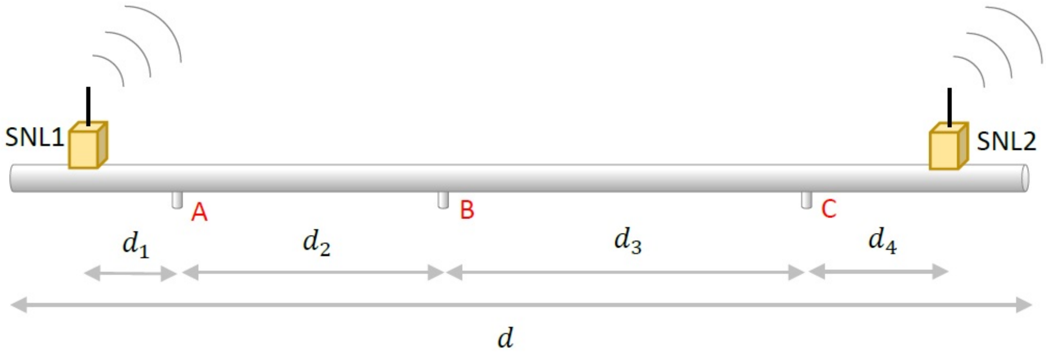


Figure 8: Test environment schema

Points of interest [m]	
d	48
d_1	5,2
d_2	12
d_3	18,3
d_4	11

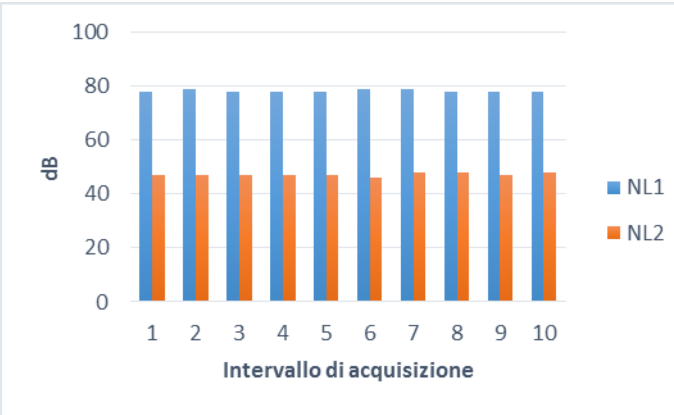
Test Scenario

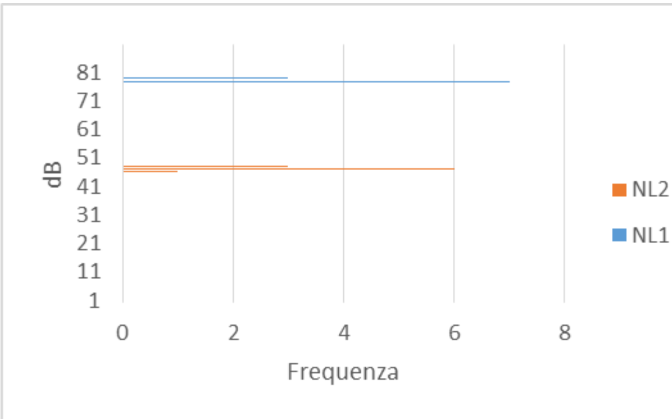
Pipe features
length: 48m
diameter: 27mm
thickness: 3mm

4.1 Equivalent noise level measurement

Measurement values are shown below. They are related to specific sampling train intervals, each one during for 2 seconds and separated from the following by 1 second, and performed with a simulated leakage at "A" position along the pipe.

PRESENCE OF LEAKAGE	POSITION A



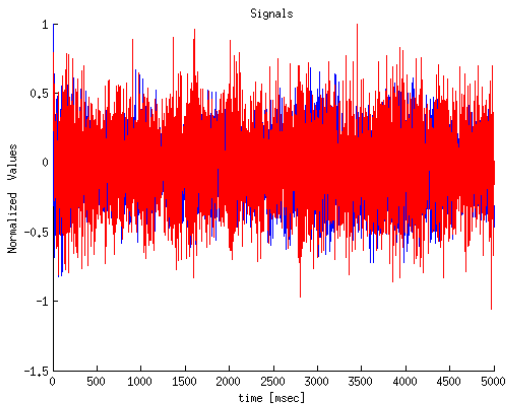


LEAKAGE PROBABILITY: NL1: 100% - NL2: 86%

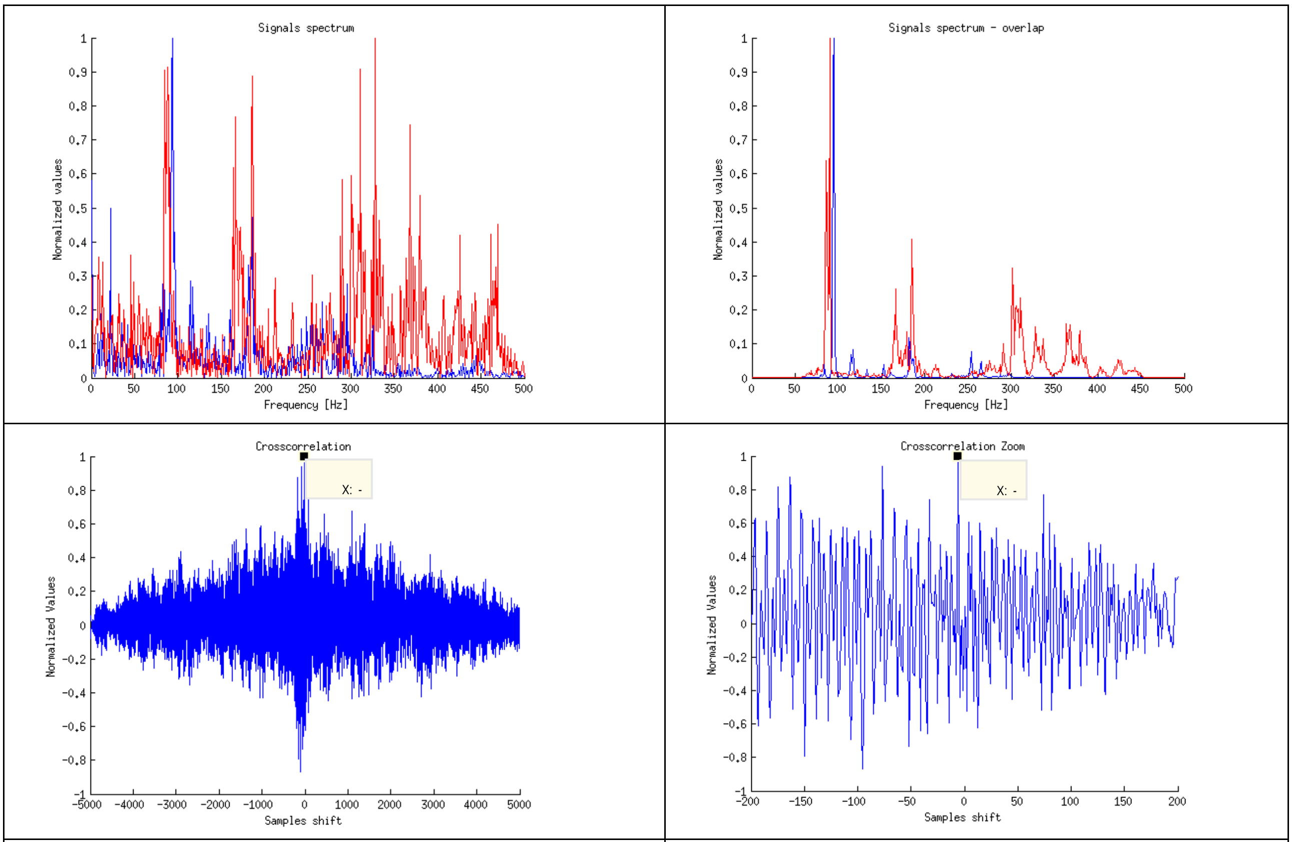
4.2 Leakage localization

Measurement values are shown below. They are related to specific sampling interval during for 5 seconds and performed with a simulated leakage at "A" position along the pipe.

PRESENCE OF LEAKAGE	POSITION A



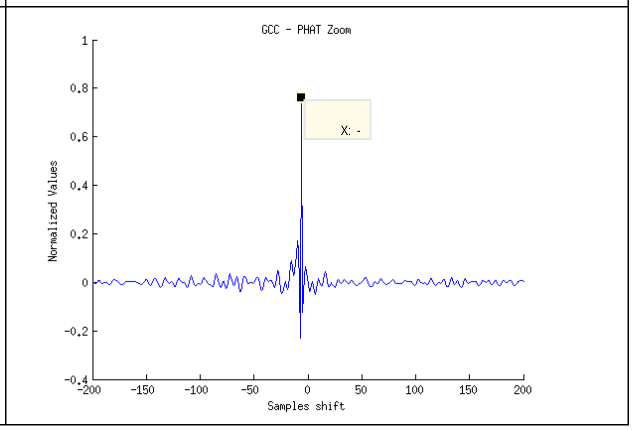
$$d_{SNL1}(x) = d_1$$
$$d_{SNL2}(x) = d_2 + d_3 + d_4$$



[m]

$$\text{CROSSCORR}\begin{cases} d_{SNL1}(x) = 5{,}45 \\ d_{SNL2}(x) = 41{,}05 \end{cases}$$

$$\text{PHAT}\begin{cases} d_{SNL1}(x) = 4{,}77 \\ d_{SNL2}(x) = 41{,}73 \end{cases}$$



5 Conclusions

In this PhD thesis an ultra low power system for leakage detection and localization inside water pipes has been developed.
In the work described has been developed a wireless system, low energy consumption, for detecting and locating water losses. The implementation of this system has shown the potential of an innovative method for real-time monitoring, filling a void left by all other functional technologies.
After treating the localization method using the function of cross-correlation between the signals of interest, suitable signal analysis techniques has been analyzed to obtain the best possible estimate of the information, starting from its sampling. Analyzing a model for the propagation of the direct and reflected waves inside a pipe filled with liquid in the presence of discontinuities, the PHAT estimator has been taken into account to obtain a sharp peak within the cross-correlation function. Noiselogger device has been developed for detecting vibrations through MEMS accelerometer, equipped with a wireless transceiver for ISM band 869MHz able to forward the data to the remote host. For that purpose network devices has been developed, such as routers and gateways, which, by means of a modified tranceiver Zigbee, are capable of building up and maintaining an ultra low power asynchronous mesh network, and send data to a remote server. The system was therefore installed inside a test site, where it was possible to generate controlled leaks along a water filled pipe. Noiseloggers were able to correctly discriminate the presence or absence of a leak by calculating the probability leak value based on equivalent noise level. Subsequently, leaks position were detected by means of synchronous acquisitions and cross-correlation method. In particular basic cross-correlation method (BCC) and general cross-correlation method (GCC) adopting the PHAT estimator have been used. Both have given excellent results, although with the BCC a markedly oscillating function has been obtained: the GCC with PHAT has eliminated the best disorders caused by reflections, standing waves, and frequency shift due to the signal acquisition devices (noiselogger) . The system was able to limit to 0.5m the maximum estimation error of the leakage position. To obtain best results, sampling process has to be done at a higher frequency (> 1 kHz) and detailed physical models for the pipes on which acquisitions take place should be taken into account.

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