Ultra-pervasive district monitoring for water leak detection

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Purpose One of the main concerns regarding integrated water resources management is related to the development of scalable monitoring and control systems for pro-active maintenance of water distribution networks. It is necessary for the availability of ultra-pervasive sensor-actuator networks to be deployed at the district level. The same technology is useful for several other applications involving sensors accrued from city to building scale. This paper deals with the design, development, and initial experiments of a first prototype of ultra-pervasive monitoring network for automated leakage detection in water distributions system (WDS). These pose technology challenges mainly generated by the need to transmit from underground. **Method** The availability of a new generation of ultra-pervasive communication and monitoring systems is a prerequisite for providing fine-grained, real-time monitoring data at district level, so that control policies can be applied in real-time. The sensing layer developed in the system object of this paper is intended for a dense deployment even underground. It is based on short-range battery-operated wireless networks, forming a mesh made up of end devices (sensors/actuators), routers/repeaters and coordinators/gateways. The coordinators/gateways –besides coordinating the network routing– transfer sensors packets to a host application enabling interconnection to fixed and mobile networks made available by the Telco operator. Because of this set-up the network can cover a large territory at low cost. It supports leakage detection algorithms, estimates leakage occurrence probability and pinpoints them. **Results & Discussion** First laboratory trials and preliminary onsite experiments show the feasibility of the approach and the potential for ultrapervasive communication through the network. Results indicate this system to be cheap and easily deployable alongside WDS.

***Keywords**: information technology, ultra-pervasive sensing, district monitoring, maintenance*

INTRODUCTION

ICT-supported integrated water resources management for water supply systems has great potentials of ensuring higher water quality and longer network life-time, fewer water leakages and lower consumption levels. To that purpose, intelligent decision support tools must be fed by large scale and ultra-pervasive sensor-actuator platforms, hooked up with widespread telecom side communication networks.

Optimal water resources management is one of the utmost and greatest 21st century challenges worldwide, because water resources are presently under stress[1]. In fact, droughts have become more severe over the past 30 years and they are aggravated by concurrent demand from several domains such as agriculture, industry, domestic users and, additionally, inefficient water use.

Several countries, including those located in Southern Europe, register low levels of pipelines maintenance, which are still based on budgetary restrictions rather than on authentic technical and economic considerations[2]. This approach leads to a very low rehabilitation rate and does not allow for the assessment and management of risks. Finally, according to available studies, in some Southern European areas, leakage in water distribution networks still accounts for up to 50% (approximately 25% on average) of water entering the network[3]. Moreover, spatially accurate leakage data are unavailable.

Nowadays new integrated water management systems, organized through modular and flexible architectures and adaptable to various situations, are under development. Among them, automated leakage detection of buried water supply systems is one of the most important services and asks for the availability of a large scale monitoring, communication and control networks, which should be used for data gathering and to feed the decision support models running on top, performing automated diagnoses. This poses the new great challenge of territorial integration of large scale embedded (multipurpose) wireless sensor/actuator networks as interfaced to intelligent decision support models.

With respect to real-time water management services, to date remarkable EU projects such as “Autoleak” (http://www.autoleak.eu/default.html) and “Warmer” (http://www.projectwarmer.eu/) are each oriented towards a specific focus: the former aims at the integration of existing advanced technologies for leakages pinpointing and the latter at creating a system for continuous monitoring of surface water quality. In the field of pipelines diagnosis, besides traditional "craft" approaches such as acoustic rods and ground phones[4], nowadays leaks detection is carried out through specific systems, which must be kept deployed on site until enough data are collected, and their data subsequently elaborated for the final leaks localization[5,6]. They require human resources for deployment, data collection and analysis. As it is a manual approach, it causes leaks to be pinpointed with a certain time lag and no intervention prioritization is had. In this framework, the field of water services is already waiting for an ultra-pervasive network. WaterWise project[7] demonstrated the application and control of a low cost wireless sensor network for on-line monitoring of water distribution systems enabling remote sensing and prediction of pipe burst events but with limited spatial resolution. The usage of near zero power wireless sensor networks (WSNs) can increase the spatial and temporal resolution of operational data and thus address the challenge of near real-time monitoring[8]. The WaterSense Project (http://www.projectwatersense.nl/?lid=en) is involved in the development of an integral decision support system for water quantity and quality management for a large area but with a relatively low spatial resolution, too.

Hence long-life and low-cost (hence allowing high spatial density) self-powering or battery operated sensors' development is a relatively unexplored field. Their availability would allow the implementation of automated procedures based on already existing knowledge on leakage diagnosis: noise sensors pervasively deployed across water distribution networks would be able to immediately warn when new water spills are under formation or are likely to be present; the advanced data processing algorithms for cross correlation and pre-filtering[4] would be able to pinpoint the failures positions. In this paper we present the first part of the system, conceived as an ultra-pervasive monitoring and communication network, designed so as to be interfaced and expanded through existing telecom infrastructures (e.g. phone cables) in order to cover very wide territories with the minimum usage of added infrastructure.

The proposed ultra-pervasive network is made up of cheap, noninvasive, easy deployable sensors, whereas communication features shall be flexible, versatile and thus usable for a number of applications in order to reduce installation costs. Services shall be remotely operated and monitored in order to improve efficiency and keep real-time control of the whole system.

THE PERVASIVE MONITORING SYSTEM

Automated leakage detection for the implementation of advanced maintenance policies is one of the many services made feasible by the availability of an ultra-pervasive monitoring and communication platform. Other functionalities have potentials to be included in a comprehensive management systems for water supply networks, such as:

Fig.1. Pervasive communication in a Smart town

- real-time control of correct operation and optimization of the systems, such as adaptive pressure, flow rates, and monitoring of chemical and physical indicators;
- intelligent modulation of operations aimed at the optimization of energy consumptions;
- bi-directional communication based on intelligent support systems, in order to align both the demand and supply sides, which should decrease peak demands and shortage time periods, as a consequence;
- quality of service improvement (e.g. real-time metering and adaptive pricing, advising customers through cost-benefit assessment).

Finally, the availability of such ultra-pervasive communication platforms, would extend its benefits onto companion fields of the smart town concept (Fig. 1), such as intelligent management of waste, parking, touristic routes, lighting, security, facility management[9] etc..

In this paper not only a prototype of monitoring system has been developed, but it has also been customized to automated water leakage detection.

The design of the communication logic's architecture was tailored towards a flexible structure, and making it easy to deploy (Fig. 2). A software interface will have bi-directional communication with the machine to machine (M2M) platform which is thought to potentially implement also the "Future Internet" concepts (distributed agents, workflow and orchestration and web services interface).

The ultra-pervasive network is composed by two layers that shall interface and interoperate:

1) short range battery operated wireless networks for connecting the high spatial resolution sensors and devices together and to the Short Range/Long Range Gateway;

2) long range network based on the Telco networks. It can be both Wire-line (xDSL and Fiber, phone cables, PLC through electric network) and Wireless (2G/3G/4G, WiFi).

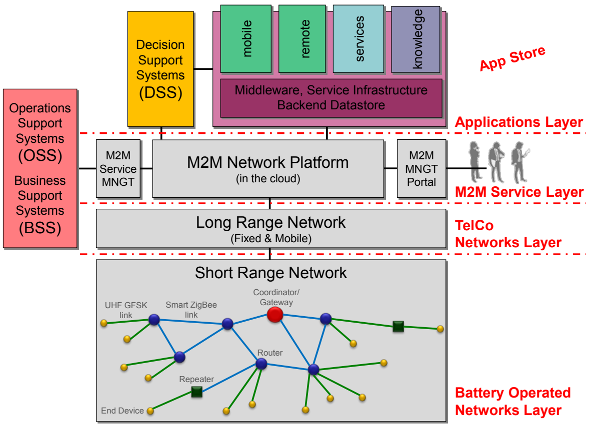

Fig.2. Architecture of the Pervasive network

It depends on the availability of existing infrastructures by the local Telco operators: sometimes a redundancy of choices is available and some other times they are constrained by the effective availability. Hence also the gateway will be manufactured differently according to the real on site situation.
Short range high spatial resolution network shall be an ubiquitous battery powered low cost wireless sensor network capable of enabling two-way wireless communication for real time monitoring in water distribution infrastructure management: the ability to put a sensor anywhere, without wiring, allows easy network deployments and maintenance. The network devices are called: Coordinator/Gateway, Routers/Repeaters and End-devices (Sensors/Actuators). Technically, Coordinator/Gateway is a device that coordinates routing, aggregates sensor packets and transfer them to a host application enabling the interconnection to fixed and mobile networks. Routers/Repeaters are ultra-low power wireless transceivers that forward data to and from associated sensors or actuators and use an on-board radio to send the packets to neighboring routers. These pass the packets on to other routers and, in a series of "hops", deliver the data to their destination. An end-device is made up of two main parts: a communication device and a measurement probe (i.e. accelerometer).
To be noticed that the proposed architecture allows information to be spread easily and using existing infrastructure, which is in fact economically efficient.

THE NEW CONCEPT OF AUTOMATED LEAKAGE DETECTION

At the bottom battery-powered noise loggers (equipped with accelerometers) are deployed along water pipelines: they perform a pre-elaboration of signals through a micro-processor and then forward the required messages to the closest routers through an 868 MHz transceiver. Routers are other battery-powered nodes, used to cover communication at the urban and extra-urban levels and scattered over wide territories. As depicted in Fig. 3, communication between noise loggers and routers passes through some repeaters, which are located close to noise loggers, whose distance depends on how deep they are buried.

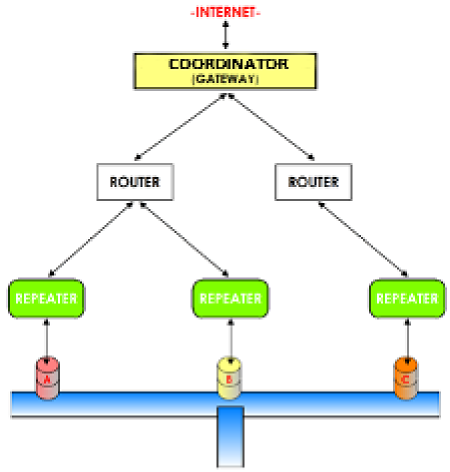

Fig.3. Three tier communication system

The routers transfer their messages to the coordinator, which manages the network and interfaces to the widespread communication network, acting in fact as a gateway.
Two preconditions must hold in order for the previously depicted automated leakage detection system to be feasible:

- the system should automatically recognize and alert in (near) real-time when leakages are occurring;
- all the network's devices, but the coordinator/gateway, must be battery operated, hence have very low consumption levels in order to guarantee long life of service (with minimum maintenance costs).

As far as the first item, noise loggers equipped with accelerometers will be deployed on pipelines to record and pre-process vibration levels, subsequently they will transmit an alert only if a leak is suspected and its localization is required. The pipelines will be accessed through existing inspection pits (generally located a few hundred meters apart) and the sensors will be connected to the ultra-pervasive communication network. Once acceleration measures are performed, embedded micro-processors will pre-elaborate the information collected, in order to transmit only compact data for post-processing that would allow for the server to work-out the leakage probability and localization.

As short range high spatial resolution network shall be a ubiquitous battery-powered and low cost wireless sensor network capable of enabling two-way wireless communication, easy network deployment and autonomy are compelling requirements.
In this direction, a fully battery powered wireless network capable of guaranteeing extremely low

power consumption (as far as 0,05 mW) was developed through customization of the system manufactured by the company Smart Space Solutions srl. It maintains the same performance levels of standard wireless devices, such as conventional Zigbee, but operates in asynchronous mode, that is with no latency and with no timeslot restriction to communication and data throughput[10].
At the long range level, existing mobile and fixed network (with several options, such as using existing telephone cables -e.g. twisted pairs- to power sensors) will be exploited, and will be part of further research steps. Instead this paper is focused on the development and testing of the short range communication module.

Leakage probability estimation

As soon as a water leakage takes place, in that same point vibrations and then a continuous noise are caused. They propagate along the pipeline, until are faded out by dumping, which in metal pipes requires very long distances. That is why the first step in leakage detection is generally recording noise levels at pre-determined positions of the pipeline, which is carried out preferably during the night, as other interferences are reduced to the minimum (i.e. low traffic, few human activities etc..). Equivalent noise levels (w.r.t certain reference noise level) are recorded based on acceleration data over a few minute wise time period, and then ranked according to their intensity, until distribution graphs (equivalent noise level vs. number of recorded levels) of the kind in Fig. 4 are worked out. Assuming that noise produced by leakages is always present and that noises are additive, the minimum noise level in the resulting distribution is due to the leak if it is present. When this minimum level is rather high (usually higher than 10 dB depending on the reference sound level), then a leakage is very likely (Fig. 4.a). Disturbances in the measurements are added to the leakage noise and thus affect only the spread of the distribution (Fig. 4.b): when they are sharp and the minimum level is rather high (usually higher than 10 dB depending on the reference sound level) then a leakage is very likely (case *a* in figure); the spreader is the distribution the less likely is the presence of leakages (case *b* in figure).

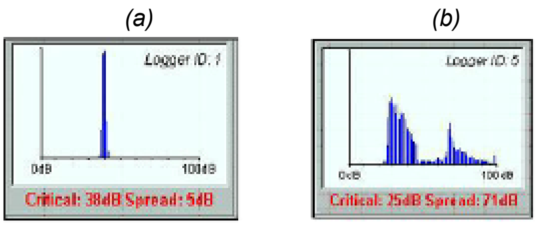

Fig.4. Sharp noise level indicating a leak (a) and spread diagram (b) when leak probability is low

The "leak value" ($LV_{\%}$) is defined as the probability of a leakage taking place and is expressed as a percentage). Leak Value is computed as function of the 5% inferior quintile ($q_{5\%}$), because it represents how high noise levels are, and of the diagram's spread (defined as $q_{95\%}$-$q_{5\%}$), because it represents how interfered the noise is. The general relationship is given as in the equation below and generally worked out from empirical samples performed in the laboratory, as reported in the following paragraph:

$$LV_{\%} = c_1 + c_2 \cdot q_{5\%} + c_3 \cdot (q_{95\%} - q_{5\%}) \qquad (1)$$

Leakage localization

If the probability of leakage occurrence is high, cross-correlation between two signals recorded by two noise-loggers placed on opposite directions from the area where the leak is generated, is used to pinpoint it[4]. The basic concept is to measure how similar the signals are. Computation can be performed through the following relationship:

$$C_{s1s2}(\tau) = \int_{-\infty}^{+\infty} s_1(t+\tau) \cdot s_2^*(t)\,dt \qquad (2)$$

where *τ(tau)* is the translation amount of the second function over the first. When the integral is computed, if the signals are similar there is a value of tau which maximizes the integral (Fig. 5a).

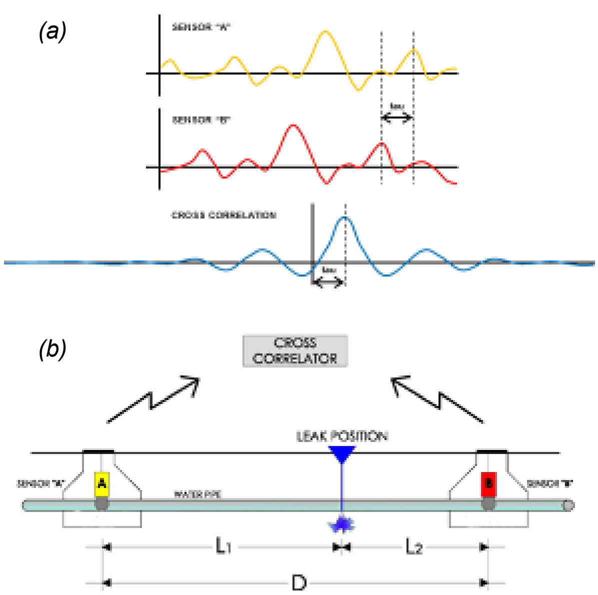

Fig.5. The cross-correlation principle (a) and corresponding system deployment (b). The second signal is translated towards the first until the integral is maximized; if the two signal are uncorrelated there is no sharp correlation peak

On the contrary, if the integral gives back a diagram containing no sharp peaks, it means the two noise loggers have received different signals, hence they have not been generated by the same source and a leakage is likely not present, or the generated vibration has been completely damped out. For that reason noise loggers are usually deployed at the corners of pipeline networks, so that each branch can be isolated and tested for leakage (i.e. confirmation of presence and estimation of distance). The system's logic in this case works as in Fig. 5.b. Once cross-correlation is performed, given *D* as the distance between noise loggers, *v* the noise speed along the pipe (known from material, pipe thickness etc..), the estimated leak distance off the first noise logger is:

$$L_1 = \frac{D + v \cdot \tau}{2} \tag{3}$$

DEVELOPMENT OF THE MONITORING SYSTEM'S PROTOTYPE

The smart noise logger in Fig. 6 was thought to be permanently deployed on steel pipelines, taken in place through a magnet at the bottom of the external cylinder. Its components were chosen also to make it: cheap, low power, light, small sized, capable of pre-processing, having a high transmission range (from underground). Its main components are:

- one piezoelectric accelerometer type "BU-23173-000" by Knowles Electronics™ (USA), which has good and flat sensitivity until 10^3 Hz with sufficiently low noise (Table 1);
- one PIC micro-processor;
- one printed circuit board with complementary electronic devices;
- two replaceable AA batteries;
- one external radio antenna;
- one magnet;
- one external cylindrical hard cover made by high density PE80 polyethylene, which has a 0.032m diameter, is 0.003m thick, 0.165m long (0.28 with the TX/RX antenna).

The used ultra low-power accelerometer provides a voltage signal proportional to measured acceleration.

(a) *(b)*

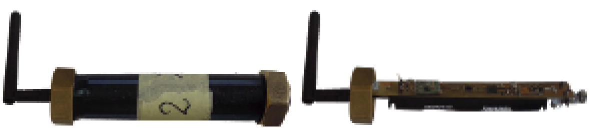

Fig.6. external view (a) and interior (b) of the prototypical noise loggers used for the experimental phase

DC SUPPLY	BATTERY CURRENT DRAIN	"A" WEIGHTED NOISE (RE 1.0V)	OUTPUT IMPEDANCE OHMS (AT 1 kHz)		
			MIN.	NOM.	MAX.
1.5 V	50 μA MAX.	-103 dB MAX.	4900	5200	5500

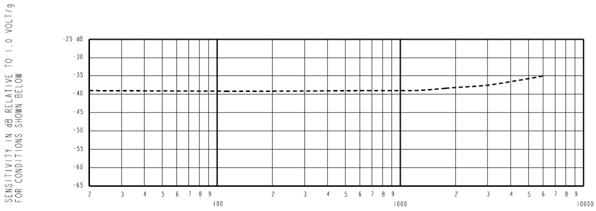

Table 1. Datasheet excerpts of the BU23173 accelerometer embedded in the noise loggers

This signal is converted to a digital value by the microprocessor after having passed a suitable anti-alias filter: the result is a digital 16 bit signal with 1024Hz of data rate.

In order to compute an equivalent noise level, a sequence of N digital values is acquired and converted to acceleration values a_i. Given a reference acceleration a_0, the microcontroller implements the following equation:

$$L_{eq}[dB] = 10\log_{10}\left(\sum_{i=1}^{N} a_i^{\,2} \Big/ N a_0^{\,2}\right)$$

but only the compact information of the resulting level is retained in its internal memory.

As previously shown, correlation is defined as a continuous time integral but it must be computed here from discrete time signals. In this case it is useful to compute it in the frequency domain by using the Discrete Fourier Transform (DFT) operator: frequency domain correlation can be efficiently computed by simply multiplying the DFT of the first signal by the conjugate of the DFT of the second signal. This gives an information about the frequency spectrum of correlating signals and allows to detect eventual disturbances. By anti-transforming this spectrum one can get the correlation in time domain. The main caution to be adopted is to apply windowing of the discrete time signal in order to reduce the spectral leakage due to the truncation of the considered time domain sequence. Here a Blackman-Harris window is used and transformation is done via Fast Fourier Transform (FFT) algorithm.

A software interface based on Microsoft™ VisualC# language has been developed and used for testing purposes (Fig. 7). It offers the following features:

- noise loggers programming for noise levels recording, when acquisition times and durations are transferred from the local PC or remotely;
- downloading of the pre-processed data regarding noise levels acquisition (leak values);
- synchronization of the noise loggers and programming of the acquisition time and extension;

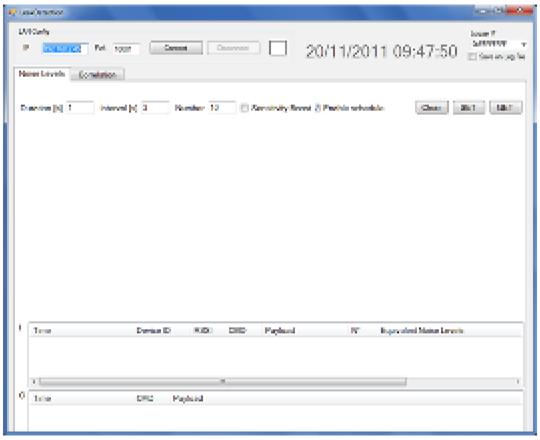

Fig.7. The main software interface

- estimation of the sound speed in the pipelines starting from their physical characteristics;
- downloading of the noise signals recorded by the sensors.

Cross correlations are offline performed through another graphical user interface (Fig. 9.b) that uses the built-in functions provided by MatLab™.

Preliminary testing

Several preliminary laboratory trials have been carried out in order to:

1. calibrate the noise levels to compute the probability of leakages;
2. localize leakages along a steel pipe (usually used for irrigation inside a laboratory greenhouse): the leakage was simulated by opening an intermediate tip.

The step no. 1 in the list was performed collecting vibration data from a mock-up installation and "leak value" levels from a commercial system working in parallel with the prototype under development. The setup was obtained like in Fig. 8: a steel pipe was supported by two resilient bases and caused to vibrate through a small fan; vibration levels at the points depicted in Fig. 8 were measured first using a commercial noise logger (which records leak values) and then using the prototypical noise logger whose accelerometers measured vibration's sound intensity. Then a best fitting algorithm between the LV estimated by the commercial systems and the sound intensity and spread measured by the system under development were applied according to eq. (1), which gave back the following coefficients estimations: c_1=-12.58; c_2=4.32; c_3=-0.12. Correlation gave back an R-squared equals to 0.9743, which is acceptable.

The trail in step no. 2 was performed on an above-ground pipe, which is used by the laboratory personnel for irrigation and water distribution to the various users of the laboratory (Fig. 9.a). First noise levels estimated by the noise loggers when water is not flowing were verified to be very low (under 10 dB restituting an LV almost null). Then a leakage situation was simulated through opening one of the derivations from the pipe located approximately in the middle and noise levels were noticed to rise. In addition, the software in Fig. 7 was run to insert inputs regarding pipeline features (Fig. 9.b), synchronize the loggers, record 16 s long signals at each end of the pipe and estimate the leakage position, like in Fig. 9.c.

The error between the real position of the fake leakage and the estimated one resulted to be lower than 1 m, which is acceptable by those in charge of making a survey, excavating and replacing the portion of broken pipe.

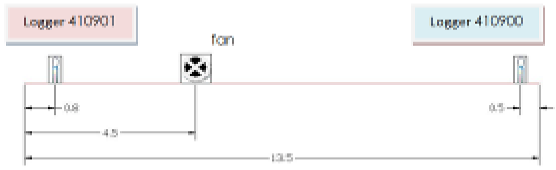

Fig.8. setup used to calibrate the noise logger's accelerometer during laboratory trials

(a) *(b)* *(c)*

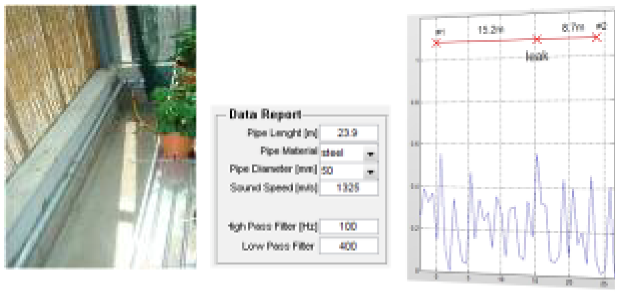

Fig.9. Laboratory trials for leakage simulation: a portion of the irrigation pipe (a), input data about the pipe (b) and leakage detection by the software (c)

ON-FIELD TRIALS

Finally, given the high criticality of the communication system, an on-field test was performed to assess the capabilities of the system to send signal from underground. The main purpose was estimating the maximum distance allowed between buried noise loggers and repeaters, and then verify that noise levels are correctly transferred (which means the packets have not been corrupted by too low communication power). The site was offered by the "Azienda Multiservizi" of Ancona, and it was performed at a residential district in the small town of Agugliano (AN). Two noise loggers were installed in two inspections pits like in Fig. 10.a, separated by a distance of 106 m. Then each repeater was moved away from each noise logger until the maximum communication distance was reached, which resulted to be equal to 60m (Fig. 10.b). Finally the above described software was used to acquire and analyze noise levels at that time, which gave back the results in Fig. 10.c, meaning that:

- when the distance between noise loggers (0.8 m underground in concrete pits) and repeaters is equal to 60m noise levels are not corrupted and the communication works well;
- during the on-site tests, performed at about 4 pm, there was no leakage and relatively water low volume flow, which acceptable, because the residential area was built few years ago (hence the pipelines are quite new) and no people were at home, being a working day.

(a)

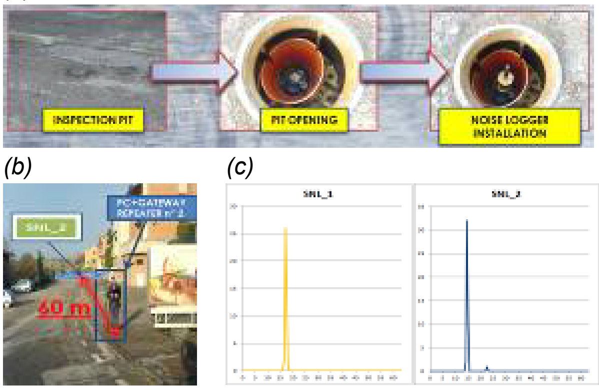

Fig.10. Installation of the noise loggers on a real pipeline (a), maximum distance between loggers and repeaters (b) and noise levels diagrams processed by the two loggers (c)

CONCLUSIONS

Integrated water resources management at the district level asks for the availability of a widespread communication networks and intelligent algorithms to offer several services. In this paper we have done a first step towards water supply systems leak automated detection, which provided the following good results: the implemented algorithm for leak probability assessment and leakage positioning worked well during laboratory trials; the communication system performed well even when installed on a real site. Future research step will be devoted to the simulation of a permanent installation of the system, in order to check its capability to locate leakages in real pipelines and also to communicate remotely and to transfer long packets (noise signals several seconds long for correlation) from noise loggers to repeaters.

ACKNOWLEDGMENTS

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