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Towards realisation of wireless sensor network-based water pipeline monitoring systems: a comprehensive review of techniques and platforms

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Abstract: Huge quantities of water are wasted on a daily basis worldwide because of leakages in water-transporting infrastructures causing water shortage, injuries, and so on. This problem is typically worsened by the lack of advanced monitoring systems. In this respect, wireless sensor networks (WSNs) have revolutionised water-monitoring systems providing reliable inspection, feasible communication and performing applications. This study presents a comprehensive survey on software and hardware solutions proposed in the literature for water pipeline infrastructure monitoring. In fact, several leak detection and localisation techniques like acoustic, ultrasound or pressure ones are studied and evaluated. Several research works tried to implement these techniques using different types of WSN platforms including microcontroller, digital signal processor, application-specific integrated circuit and field programmable gate array. These platforms are reviewed and discussed while highlighting their advantages and drawbacks. Finally, an integrated energy-aware system-on-chip solution using high-performance hardware is proposed to achieve optimal and reliable results.

1 Introduction

Influenced by the recent technological advancements, wireless sensor network (WSN) has emerged in our daily life and gained the interest of industrial and academic works. It consists of a large number of sensor nodes, which are densely deployed to collect and transmit data via wireless connections. Each sensor node is basically made up of a processing unit (microcontroller, memory, operating system, and so on), an acquisition unit [sensor(s), analogue-to-digital converter (ADC)], a transceiver(s) and a battery [1].

Nowadays, WSNs are being employed in a wide range of applications such as military, security, industry, medicine, environment, and so on [2]. Water pipeline monitoring (WPM) could be considered as one of the most crucial applications of WSN. In fact, water-transporting pipelines have been a concern during the past few years as any damage to pipes could affect the quantity and quality of water. Indeed, there are up to 60% of water waste in the world each year due to leaky pipelines [3]. This waste contributes as a main cause of water crisis as our planet is running out of fresh water and people are thirsty. Approximately 1 billion humans have no access to drinking water in the world [4]. With the ever increasing demand for water, even developed countries are nowadays worried about the future of water supplies. The havoc does not only concern the global water loss. It could threaten agricultural crops, infrastructure and even human life. As an example, in 2010, a catastrophic rupture of a huge pipe in Boston hit the region's water system. About 36 million litres per hour leaked from the pipe and the authorities declared a state of emergency [3]. Furthermore, wasted water affects the countries' economies. In fact, the World Bank estimates that the global costs of leaky pipes are ~$14 billion per year. Thus, these alarming statistics highlight the requirement of WPM systems [5].

Several WPM techniques have been used for this purpose [6]. They were based either on manual or wired inspections. Wired networks present several drawbacks including cost, installation, repair, and so on. Indeed, a mere wire damage could impinge the network performance or even more alter the whole network functioning. Furthermore, repairing or maintaining underground wire damage is a painful, time consuming and costly task. On the other half of the deal, WSN seems a reliable and novel method to overcome the challenge of terrestrial water monitoring as leaks in a water pipeline, water quality, pH and nitrate levels, and so on. In fact, researchers have emphasised on the potential and feasibility of WSNs for water monitoring [7]. Unlike the traditional methods, WSN are highly beneficial in terms of high performance, low cost and easy deployment.

Loads of works surveyed water transportation monitoring systems. As an illustration, we can cite Bedjaoui *et al.*, (2011) [8], Liu and Kleiner (2013) [9], Xu *et al.*, (2013) [10], and so on. These surveys are particularly focusing on software applications as leak detection algorithms, communication methods, placement and replacement algorithms, and so on.

Noticing the lack of interest allocated to WPM hardware design in the literature, the objective of this paper is to explore WSN platforms for water pipeline damages. It also targets a comprehensive review of leak detection and localisation techniques. Finally, novel design of wireless sensor node architecture is proposed for WPM.

To start with, Section 2 surveyed the techniques used for WPM detailing and evaluating the algorithms, techniques and sensors suggested in different research works. In Section 3, various WPM platforms based on WSNs are presented. These multiple platforms are discussed while emphasising their benefits and drawbacks. Section 4 presents the challenges and limitations of the mentioned works. It also describes the design of wireless sensor node architecture for pipeline infrastructure assessment. Finally, our conclusions are drawn and some recommendations are suggested in Section 5.

2 Techniques for WPM

Several factors could threaten the pipeline infrastructure, degrade the water quality in pipes and cause several damages including leaks, corrosion, obstruction, and so on. Some factors are related to the pipeline itself as material and size [6]. Some others are related to human intervention including human mistakes, illegal attacks and lack of protection [11]. In addition, natural dynamic alterations like climate, disasters and pressure changes could also be considered as important factors [6].

For preventive and corrective actions, many techniques have been proposed to monitor damages in the pipeline. In this paper, we would focus especially on leak detection and localisation methods. These methods have not really changed from wired systems to WSNs. They also depend on numerous parameters including pipeline characteristics, leak sensitivity, cost, localisation capabilities, maintenance requirements, and so on. As a matter of fact, pipeline inspection techniques are generally non-destructive-testing methods and rely on standards such as The American Society for Non-destructive Testing, American Petroleum Institute, International American Society for Testing and Materials, International Organisation for Standardisation (ISO), and so on [12]. The common principle of monitoring methods is to inspect the physical properties of the pipeline material and water flow characteristics to perceive abnormalities and damages. Some of these methods are described in this paper.

2.1 Visual inspection methods

The visual inspection method is the oldest technique to detect pipeline leaks using image or video sensors. Among the methods of this technique, we find the closed-circuit television (CCTV) inspection [13] and the laser scan [6]. In fact, CCTV system is composed of a remote-controlled pan and a camera mounted on a robot crawler travelling between two manholes inside the pipeline and controlled by certified operators. The visual inspection methods are not based on the same principle. For instance, different from the CCTV, laser scan method uses laser to inspect the outside or the inside of the pipe. It is based on many scanning techniques including triangulation, pulse-based and phase-based techniques. Another method uses laser coupled with detecting camera that captures the image of the laser light projected into the pipe. These images are analysed for leak detection [14].

In WSNs, the idea is to simply attach charge-coupled device (CCD) image sensors or complementary metal oxide semiconductor image sensors to the nodes. The captured images and/or videos are compressed and streamed to the base station for analysis. As an illustration, SPAMMS is a wireless WPM project using CCD sensors for leak detection and localisation [15].

Visual inspection techniques provide real time detection and other useful information for the inspectors. However, they are generally unable to detect small leaks, which are unapparent. Moreover, these techniques chiefly need high processing capabilities, large memories and human intervention.

2.2 Acoustic methods

Acoustic methods are non-destructive leak detection process using acoustic sensors as piezoelectric sensor, hydrophones, capacitive transducers, accelerometers, vibration sensor and laser interferometers deployed inside or outside the pipeline. In fact, the pipeline-escaped liquid flows turbulently and causes acoustic signals which are transient elastic waves that propagate along the pipe. These signals contribute to find anomalies in pipes [16]. The acoustic methods provide immediate and early information about the new cracks, corrosion and leaks in the infrastructure, allowing a complete and fast inspection [17]. Hence, they have been extensively applied in WSNs.

Ozevin and Harding [18], suggest a leak detection and localisation method in a pressurised pipeline using an acoustic emission. Qi and Que [19] used acoustic signals for underground WPM. Mostafapour and Davoudi [20] tested the feasibility of acoustic emission for pressure pipe.

One evident drawback of this technique is the acoustic signals quality. In fact, they are very weak and operate in noisy environments making the signal distinction very difficult. This requires reliable pre-amplifiers as well as filters to avoid noise [21]. These techniques are also not suitable for an underground pipeline due to the difficulties of deployment [22].

2.3 Ultrasound method

The ultrasound methods are based on the detection of ultrasound waves, which are mechanical vibrations. The propagation and reflection of these waves allow the measurement of the pipe wall thickness and leaks detection. Two types of waves have been used in the inspection: the longitudinal waves and the shear waves. This classification is related to the water atom vibration direction compared with the sound direction. Depending on the ultrasound technique, the ultrasonic sensors could be used inside as well as outside the pipe (see Fig. 1). The guided wave technique has been widely used in WSNs compared with other ultrasound techniques as discrete ultrasound, straight beam, immersion testing, phased array, and so on [23]. It is based on the ultrasound wave travelling in delimited pipes (i.e. long distance). This promotes its usage for an economical and easy inspection [24].

Schubert *et al.* [25], present the effectiveness of ultrasonic guided waves for high temperature pipes monitoring. El Kouche *et al.* [26], proposed modular WSN systems using the ultrasound method to monitor the thickness of the pipeline. Another work uses ultrasound guided waves for real time pipeline corrosion detection, where sensors are placed outside [27].

Although they allow easy and sensitive leak detection, the ultrasound methods should be applied together with other techniques to avoid false alarm and environment noise. For instance, Stoianov *et al.* [28], used ultrasonic sensors with piezoresistive sensors to give a decision about damages in the pipe. Nevertheless, they are sensitive to several parameters affecting the measurement accuracy such as temperature, air condition and pipe wall cleanliness. In addition, ultrasound techniques suffer from high power consumption.

2.4 Electromagnetic methods

The electromagnetic methods are generally used to measure variations in the electrical properties of a subsurface. Several methods have been applied to monitor pipeline leaks: magnetic flux leakage (MFL), ground-penetrating radar and ultra-wideband pulsed radar system [6].

2.5 Computational pipeline monitoring

Computational pipeline methods (CPMs) are based on algorithmic tools to monitor internal pipeline parameters (pressure, temperature, etc.). The collected data is analysed mathematically or statistically and the system operates by providing an alarm. The CPMs have many types including the mass balance (MB) and the real time transient modelling (RTTM) [10].

The MB method is based on the mass conservation and therefore the difference between an upstream and a down stream flow allows the detection of leakage. This method is simple, easy, cost effective and very sensitive. However, due to the changes in the flow pressure, it suffers from false detections. Moreover, it cannot normally localise the leak position [29].

The RTTM is based on the analysis of the hydraulic behaviour of the pipeline. It uses momentum calculations and numerous flow equations to detect and localise leaks. This method could model

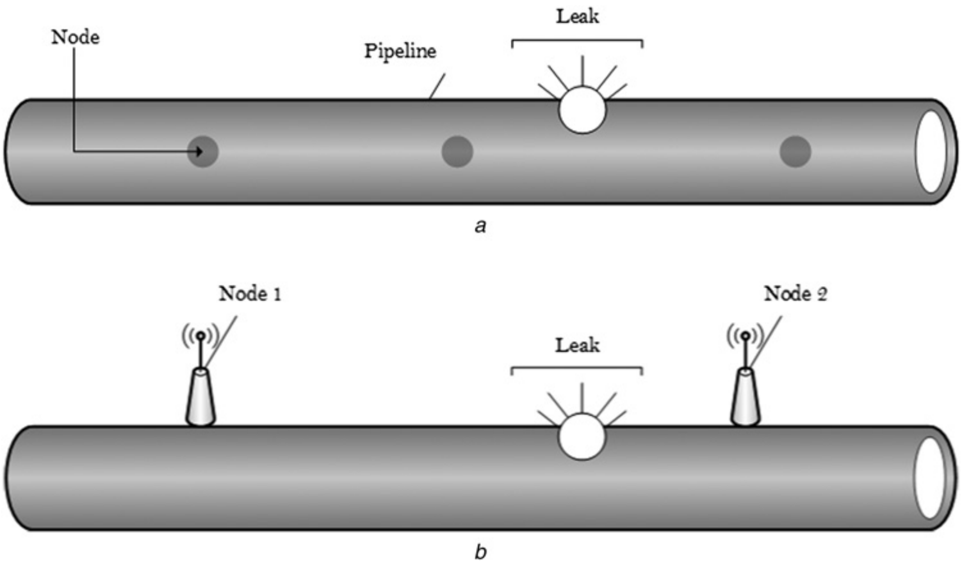

Fig. 1 *Sensor nodes for WPM*

a Sensor nodes placed inside the pipeline
b Sensor nodes placed outside the pipeline

the liquid parameters and the physical characteristics of the pipeline. However, it is complex and expensive compared with other methods [30].

It seems evident that each method has its weakness and strengths. Therefore, several WSN research projects combine methods to benefit from the advantages of each one. For instance, PipeNet project [28] uses acoustic and transient-based methods for leak detection and localisation (Fig. 2). MISE-PIPE [31] adopts soil property, transient and acoustic methods. Moreover, SmartPipe [32] utilised soil property and pressure methods for underground pipeline monitoring. These coupled methods improve the accuracy of the system. They are generally software implementations performed in commercial nodes.

To enhance the performance of leak detection methods, researchers have typically improved algorithms and/or combined techniques. However, not much attention has been given to the study and design of the hardware architecture of the sensor nodes. In fact, it is critical to select the best performing WSN node platforms since they should be carefully compared and analysed to make the best choice. Hence, in the following, we explain WSN projects and node platforms used for WPM.

3 WSN node platforms for pipeline monitoring

The research efforts in pipeline monitoring focused on ameliorating the techniques described above or on the placement and replacement of nodes. Some other works focused on communication between sensor nodes or sensor nodes and gateways or base stations especially for underground pipelines. Therefore, in the literature, the WSN research projects are generally focusing on software implementation. Insignificant effort has been devoted to the nodes' architecture. This could ameliorate significantly the performance of the monitoring system by enhancing the performance of the hardware components. To begin with, the word platform, in computer science, refers typically to different usages in both software and hardware. In this paper, a platform refers to either the board type in which the hardware components are implemented, or the processor type in the case of digital signal processors (DSPs) and microcontrollers. Besides, the word architecture was adopted in different WSN researches for the same meaning. Microcontrollers are most commonly used in WPM applications as commercial motes usually integrate it. However, few other works use alternative architectures such as DSPs, application-specific integrated circuit (ASIC) and field programmable gate array (FPGA) for WPM.

3.1 Sensor nodes based on microcontroller

A microcontroller is an integrated circuit that contains a single microprocessor, memory and other input/output peripherals. Attracted by its low cost, low power consumption and the availability of the development environment, WSN projects [15, 28, 31–34] have intensively used this platform. In fact, the advancement in microcontroller technology provided users with an easy option to achieve their software implementations. It performs multiple tasks of sensor data processing and allows making decisions about the existence of a leak and its localisation. WSN nodes based on microcontrollers are mainly made up of a radio transceiver, an antenna, a processor, a memory unit, sensors and a battery (Fig. 3.).

For instance, PipeNet [28] is one of the well-known projects for WPM. It allows the detection and localisation of leaks and other complex problems in the pipelines infrastructure. In this respect, the authors implement signal processing algorithms (wavelet transform, cross-correlation function), pattern recognition algorithms and other algorithms which need high processing capabilities. The sensor node is based on Intel mote. It is a

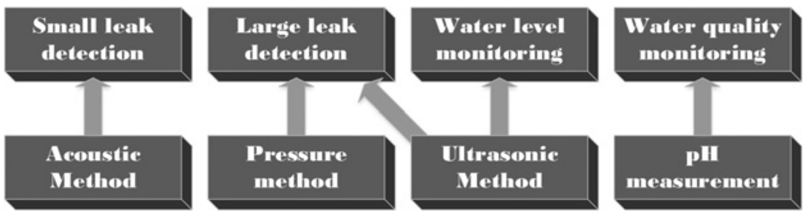

Fig. 2 *PipeNet's monitoring methods*

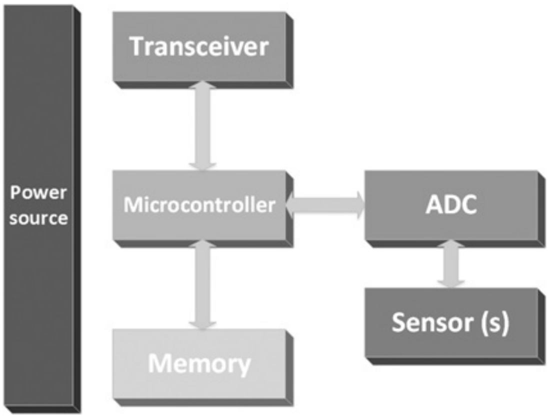

Fig. 3 *WSN node based on microcontroller*

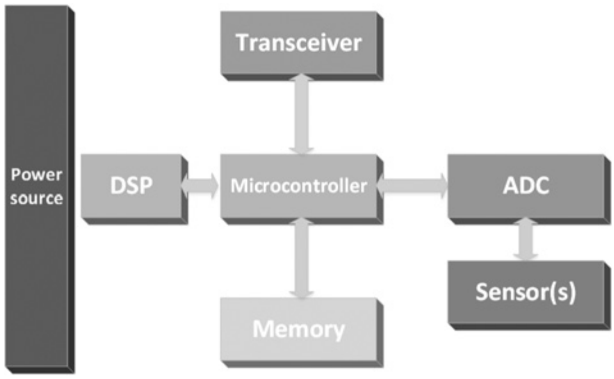

Fig. 4 *WSN node based on DSP*

commercial mote from Intel composed of an ARM7 core, a 512 KB Flash, a 64 KB RAM and a Bluetooth communication.

SPAMMS [15] is also an autonomous and cost effective system that permits corrective monitoring, localisation and maintenance of the pipeline by combining static sensors, mobile sensors and robot technology. It uses different kinds of inspection methods using CCD sensors, chemical sensors, pressure sensors and sonar sensors. These methods require high processing capabilities as they need signal processing algorithms, image processing, and so on. The prototype consists of MiCA1 mobile sensor mote, an EM4001 ISO radio-frequency identification system and a robot agent. Mica1 consists of an ATMega103 microcontroller, a 128 KB flash memory, a 512 EEPROM and a 4 KB RAM. It consumes 27 mW in active mode.

PipeProbe [33] is a mobile WSN system with hydro molecule form. It consists of EcoMote and a MS5541C pressure sensor from Intersema. EcoMote is a wireless sensor node composed of the nRF24E1 [2, 4 GHz radio-frequency (RF) transceiver with an embedded DW8051 microcontroller], an antenna, sensors, a 32 KB external EEPROM, a battery and a flex-printed circuit board expansion port.

TriopusNet [34] is a mobile autonomous wireless sensor WPM network. It consists of a Kmote, a motor, a spherical case and other sensors (intersema MS5541C water pressure sensor, gyro-scope sensor) used for node localisation. The Kmote is a wireless sensor mote, which consists of MSP430 microcontroller and CC2420 radio transceiver. The deployment and the maintenance of the WSNs are automated to overcome the battery short lifetime constraint of the node. This work focuses on the automatic replacement of the failed nodes and uses a replacement algorithm. The collection tree protocol is used for data collection.

A recent work (2014) named SmartPipe [32] proposes a non-invasive WSN for underground pipeline monitoring using force sensitive resistors. The sensor node consists of a PIC16LF1827 microcontroller, an eRA400TRS 433 MHz transceiver, two temperature sensors and one force sensitive resistor (FSR)-based pressure sensor.

Although microcontrollers are widely used, these platforms suffer from limited processing capabilities (processors frequency generally between 4 and 50 MHz) and small memory size (RAM size between 1 and 8 KB). Table 1 details the limited resources of the microcontrollers used for WPM.

The microcontrollers have been attractive in WSN mainly for their low cost and low power consumption. However, running complex algorithms in limited-resource devices could deplete rapidly the battery of the node. Hence, alternatives that overcome the microcontroller's limitations exist. Among these alternatives, we can cite DSP, which has been used for WPM.

3.2 Sensor nodes based on DSP

General purpose processors are not always suitable for specific applications as filtering, Fourier analyses, audio processing and other signal processing algorithms. The DSP is a microprocessor designed and optimised to perform real time digital signal processing applications. It permits acceleration, real time processing, high speed streaming data and optimisation of this kind of algorithms thanks to its specific architecture comparing with microcontrollers. Despite its advantages, only few implementations based on DSP in the WSN for the WPM. The DSP is generally used as a coprocessor in WSNs to accelerate processing tasks as shown in Fig. 4.

Gaizi and Zongzuo [35] proposed an implementation of a leak detection and localisation algorithm based on fast Fourier transform correlation on DSP for underground pipeline monitoring using sound sensor. Another correlation function was revealed in [36] where the authors have used a DSP to perform real time processing of a leak detection and localisation methods based on acoustic signals. In [37], the authors design a leak detection and localisation system based on a DSP for underground water pipeline. This system is based on a sound analysis mechanism.

Despite the evolution of DSPs, they could not usually meet the high processing capabilities, high performance and low-power consumption requirements of a sensor node. Hence, very few research works have considered applying advanced technologies and platforms such as FPGAs and ASIC for WPM.

3.3 Sensor nodes based on FPGA/ASIC

To the best of our knowledge, ASIC/FPGA technologies have not been extensively used for the development of a sensor node for water-monitoring applications. There exists very few papers where ASIC was directly/indirectly used. The sensor node proposed in [28] consists of a modified OEM piezoresistive silicon sensor that

Table 1 WSN motes used in WPM systems

Project	Mote	MCU	Frequency, MHz	RAM, KB	Flash, KB	EEPROM	Transceiver	Power, mW
SPAMMS	MICA (2002)	Atmega 103	4	4	128	512 KB	TR1000	27
MISEPIPE	MICA2 (2003)	Atmega 128	8	4	128	512 KB	CC1000	89
PipeNet	Imote (2003)	ARM7TDMI	12–48	–	64	512 KB	Zeevo BT	120
Smartpipe	(2014)	Pic16LF1827	32	8	7	256 KB	eRA400TRS	2.2 μW
Pipeprobe	Eco mote (2006)	nRF24E1	16	4	512	32	Nordic nRF24E1	55
TriopusNet	Kmote (2007)	MSP430F1611	8	10	48	1 M	CC2420	21.1 mA

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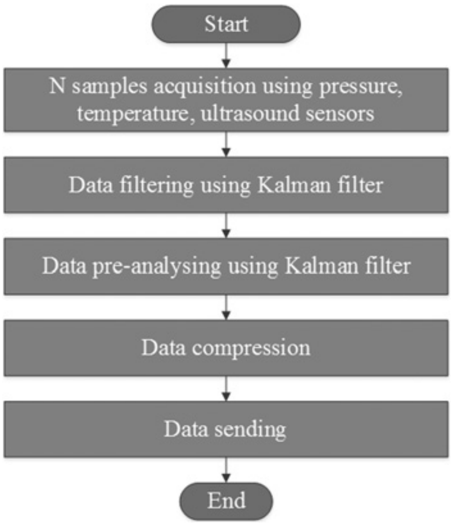

Fig. 5 *Leak detection algorithm in a leaf node*

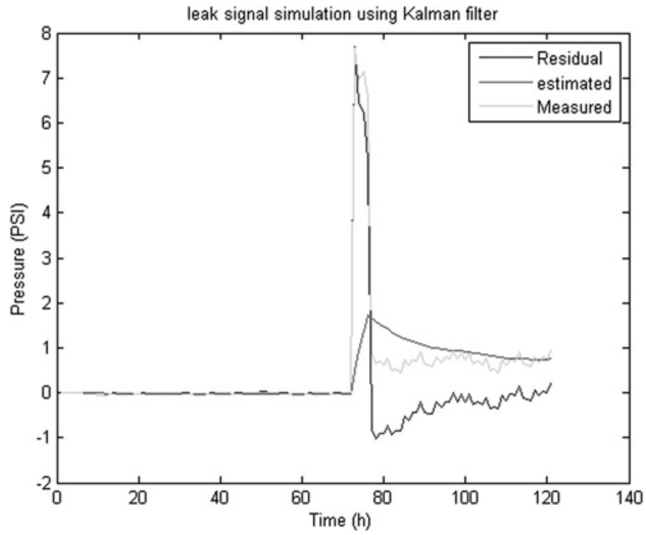

Fig. 7 *Leak simulation using Kalman filter*

includes an ASIC compensation-based technology to achieve accuracy better than ±0.2%.

FPGA has emerged as a platform of choice for faster achievement of compute-intensive applications. It provides hardware speed, software flexibility and price/performance ratio much more favourable than ASICs [38]. It also allows the system to be reconfigured even after the deployment in the field which is suitable for WSN nodes [39]. FPGAs have been used for the development of sensor systems for different applications as discussed in [40].

In [36], an FPGA-based data acquisition system was used as coprocessor jointly with a DSP for leak detection and positioning using acoustic signals. The system consists of acoustic sensors, DSP, liquid-crystal-display, wireless module, an ADC and an FPGA. Jun-jun. [41], suggested an MFL method for pipeline inspection implemented on Altera FPGA (cyclone series).

Saving energy is of prime importance for battery-operated WSN nodes deployed for monitoring applications. With the recent advancement and availability of ultra-low power FPGAs, it is now possible to develop ultra-low energy WSN nodes.

The design of ASIC/FPGA-based sensor node for the WPM applications would result in an energy efficient and flexible solution. However, these solutions do not provide full integration and autonomy to wireless sensor nodes. A single-chip fully integrated autonomous system-on-chip (SoC)-based wireless sensor node which could provide low-power and low-cost solution is required.

4 Towards SoC-based solution

As discussed in the previous sections, WPM applications face several challenges [42]. On one hand and despite the diversity of current monitoring techniques, none of them could offer reliable inspection. They suffer from non-real time processing, extrinsic analyses and a high rate of false alarms. Therefore, thinking about ameliorating these techniques is necessary. For this purpose, a Kalman filter has been implemented for leak detection and localisation. Kalman filter is an optimal recursive data processing algorithm originally proposed by Kalman in 1960 [43]. It is widely used in WSNs thanks to its low complexity, low memory requirements and its ability to cope with missing data. It is used in our application not only to detect and locate leaks but also to filter noise and to reduce communication cost between nodes (Fig. 5).

A pipeline system has been modelled using EPANET which is an open source software that models water-distribution systems and allows extended period simulation of the designed piping network [44]. The system is composed of a collection of 305 m pipes, a pump, a reservoir and a tank (Fig. 6).

The leak is simulated by a valve and an emitter. An emitter is a device assimilated to orifices that discharges to the atmosphere. The pressure and the flow rate equation through the emitter can be given as

$$q = c \times (p)^{\gamma}$$

where q is the flow rate, p is the pressure, c is the discharge coefficient and γ is the pressure exponent. Emitter is used for irrigation networks. It can also be used to simulate leakage in a pipe.

Our simulation is done during 5 days and the leak is induced in the third day by opening the valve. The nodes from 2 to 9 are junctions and the nodes from 10 to 27 are virtual nodes (sensor nodes) with zero demand used to measure pressure at those points. The pressure data of the leaky pipe are then analysed using Matlab (Fig. 7). More details will be given in our future work.

On the other hand, as described in Section 3, very little interest was given to the sensor node architecture. The low cost and the

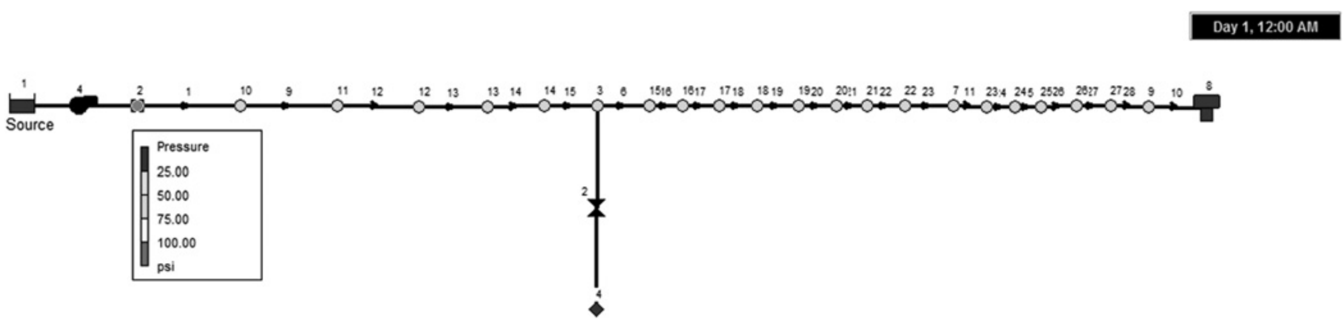

Fig. 6 *Pipeline model*

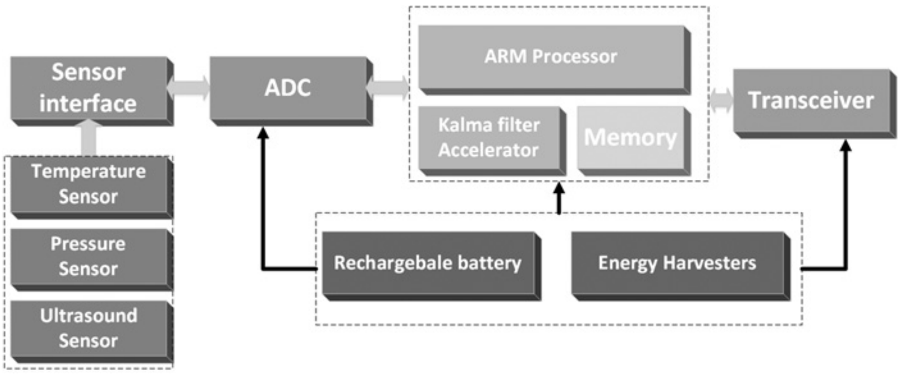

Fig. 8 *EARN-PIPE architecture*

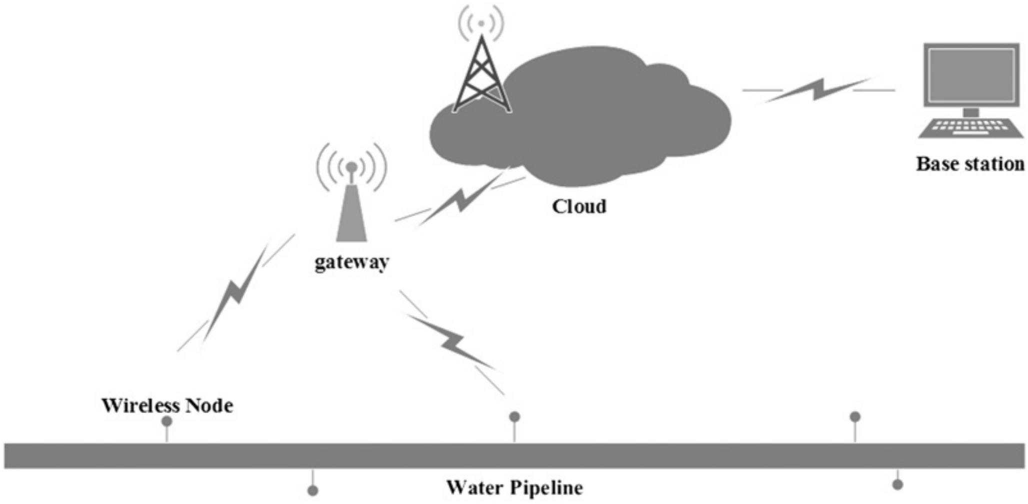

Fig. 9 *Proposed WSN system*

easiness of commercial motes based on microcontroller makes it the first candidate for water applications. However, advanced technologies might overcome such deficiencies as small memory size and low processing capabilities of the microcontrollers.

Inspired by hardware and software exploration of WPM solution, we suggested a complete solution of energy-aware reconfigurable sensor node for water pipeline monitoring (EARN-PIPE). This proposal combines high-performance platform and reliable inspection coupled methods using co-design tools and the algorithm architecture adequacy. Nowadays, the trend in WSNs is based on the conception and the implementation of an SoC solution, which involves all or some functional units (processing, communication, acquisition and power supply) in the same single chip. For example in [45], authors present the modelling, simulation and estimation of power consumption of nodes made up of SoC for WSN applications using SystemC/TLM. The SoC contains an microprocessor without interlocked pipeline stages (MIPS)-based processor, a memory, a bus, a timer, a transceiver and a battery. The model is intended to allow power estimation in a WSN simulation. Although, WiseNET was the first wireless sensor node based on SoC, it required external components such as power source, RF antenna, passive devices and sensors [46].

Unfortunately, this has not been explored in WPM applications yet. So, to overcome the drawbacks associated with the presented solutions, we propose a wireless sensor node SoC as shown in Fig. 8 which consists of a sensor interface, ADC, processor(s), memory along with some hardware accelerator (using ultra-low power FPGA), a radio transceiver, a power supply and management unit. For instance, a variety of temperature, pressure and ultrasound sensors will be attached to the node for efficient monitoring of a water pipeline. The sensor node is energy constrained and mostly relies on battery or alternative energy sources to provide continuous power in difficult areas. Since battery energy is limited, an energy harvesting module will be developed. Since the processors used in SoC contributes to major power consumption even while carrying out simple operations, it is therefore required to assign the compute-intensive task to a hardware accelerator.

In reality, we propose to develop smart sensor network system for long distance WPM applications. A complete solution as shown in Fig. 9 is envisaged to be built. The solution is based on multi-hop clustering architecture and tree topology. The sensor nodes are first forwarded from nodes to cluster heads, and then to the gateway by a multi-hop procedure.

5 Conclusions and future perspectives

Water is a basic need for life on earth. It is far beyond the reach of some people because of its scarcity while, in several places all over the world, it is increasingly wasted due to leaky pipes providing drinking water. They become vital for human's life and well-being. Consequently, pipelines need to be inspected. A large number of techniques have been surveyed for the pipeline integrity inspection such as pressure methods, visual inspection methods, ultrasound methods, and so on. These methods could be used apart or combined for greater precision using WSNs. In fact, the WSN arises as a promoter to overcome drawbacks of traditional inspection ways based on wired or manual inspection. The architecture of the wireless sensor node has evolved from the standard RF-frontend plus microcontroller to DSP, ASIC and FPGA. Each of these platforms has its own strengths and weaknesses. For a high-performance monitoring application, an SoC was proposed for non-invasive pipeline monitoring. Integrating low cost and high-performance components on a single chip may leads to a significant performance improvement. Indeed, future advancement in WSNs technology requires further studies and advanced research to overcome the limitations posed by current architectures/techniques, mainly, real time execution and energy efficiency. In this context, we intend to develop an EARN for WPM applications. A fully-integrated autonomous SoC including hardware accelerators, dedicated intellectual properties and high level of integration will be designed using computer-aided design tools, and optimised algorithms. The designed system will subsequently be prototyped and evaluated using reconfigurable and low power consumption platforms.

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