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THE CONCEPT OF AN IMPROVED ACOUSTIC WIRELESS SENSOR NODE FOR LEAK DETECTION AND LOCATION IN A WATER DISTRIBUTION NETWORK

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Abstract

The paper presents the concept of a node of an acoustic-based system for leak detection and location. The system monitors hydraulic parameters and condition of a water distribution network (WDN) using a wireless sensor network (WSN). The WSN's nodes communicate with each other using acoustic waves propagating through water in the pipeline. Alternatively, a WSN uses a combination of acoustic-based and radiowave-based communication. The preliminary research positively verified communication capabilities of the WSN in laboratory conditions. The paper discusses the improvements of an idea presented in [12, 14] and its possible application to leak detection and location. The paper continues the long-term research on diagnostics of water distribution networks conducted by the Institute of Fundamentals of Machinery Design.

Keywords: wireless sensor network, acoustic communication, monitoring system, leak detection, water distribution network

KONCEPCJA ULEPSZONEGO AKUSTYCZNEGO BEZPRZEWODOWEGO WĘZŁA SENSORYCZNEGO DO DETEKCJI I LOKALIZACJI WYCIEKÓW W SIECI WODOCIĄGOWEJ

Streszczenie

Niniejsza praca przedstawia koncepcję węzła akustycznego systemu detekcji i lokalizacji wycieków. System monitoruje parametry hydrauliczne i stan sieci wodociągowej wykorzystując bezprzewodową sieć sensoryczną. Węzły sieci komunikują się ze sobą za pomocą fal akustycznych rozchodzących się wewnątrz wypełnionego wodą rurociągu. Rozwiązaniem alternatywnym jest wykorzystanie zarówno fal akustycznych, jak i radiowych. Wstępne badania pozytywnie zweryfikowały możliwości komunikacyjne sieci w warunkach laboratoryjnych. Praca omawia szereg ulepszeń pomysłu przedstawionego w [12, 14] oraz potencjalne zastosowanie do detekcji i lokalizacji wycieków. Praca kontynuuje wieloletnie badania nad diagnozowaniem sieci wodociągowych prowadzone przez Instytut Podstaw Konstrukcji Maszyn.

Słowa kluczowe: bezprzewodowa sieć sensoryczna, komunikacja akustyczna, system monitorujący, detekcja wycieków, sieć wodociągowa

1. INTRODUCTION

Water loss is one of the major problems of the human civilization. It is mostly apparent in developing countries where the losses could reach 50% of total water consumption. Even in well-developed societies a 3-7% loss due to leaks could be observed [1, 2, 3].

The leaks are a result of mechanical damage of the pipeline caused e.g. by: (1) assembling errors, (2) natural processes of wear, (3) corrosion of inner and outer surfaces of pipes, (4) mechanical damage of pipes caused by excessive loads, (5) seasonal temperature changes, (6) movements of subsoil, and (7) material defects of pipes [1, 4]. Leakages result mostly in economical loss. However they are also responsible for water pollution and contamination due to reduced pressure inside the pipeline [1, 4]. Therefore it is crucial to constantly observe the condition of the pipeline and to detect and locate the leaks.

A water distribution network (WDN) is a technical megasystem of great importance to the industry and households alike [5]. In the age of Industry 4.0 gathering diagnostic data of different technical objects becomes a standard. And effective monitoring of a WDN is a demanding task due to its sheer size and complexity. A concept of an acoustic wireless sensor network (WSN) is a response to the Horizon 2020 project *Inducement prize: Zero Power Water Infrastructure Monitoring*[1].

A multitude of different methods of detection and location could be found in the literature. Some of them include: (1) flow variability analysis, especially during nights, (2) step testing, (3) correlation analysis of leakage noise, (4) transient and frequency analysis of pressure waves and (5)

[1] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/powerwaterprize-01-2017

direct inspection with a ground penetrating radar [1, 2, 3, 6, 7]. New and innovative methods of measurement are constantly being developed. Some of them include mobile devices for inline inspection and leak detection via gas injection [8].

The research [3] states that the night flow variability analysis is the most effective of the implemented methods of leakage detection. However methods employing measurement of momentary values of process variables such as flow or pressure are also employed [5, 6].

To process big data gathered from the megasystem cloud computing methods could be utilized. WSNs are well-known and widely used monitoring and data computing solutions across the world nowadays.

SmartFlow [9] is one of the WSNs recently deployed in polish WDNs. Future Processing, the authoring company of said WSN, implemented the network in cooperation with Microsoft and MPWiK (local water and sewage company). The aim was to fight the problem of ever-increasing water price due to undiscovered water loses in the city of Wroclaw. The company boasts that the implementation resulted in savings of about 500 millions of litres (about 9% of water used by the city) just in 2016. *SmartFlow* has also reduced the detection time of leakages to 3 days from about 180 days without the WSN [9].

WaterWiSe@SG [7] is another example of a WSN-based system. It is an experimental network able to continuously monitor hydraulic parameters in Singapore's WDN. The system was deployed in June 2010 as a collaboration between the Singapore Public Utilities Board, MIT, the Singapore-MIT Alliance for Research and Technology, and the Intelligent Systems Centre at Nanyang Technological University. *WaterWiSe@SG* consists of 8 wireless nodes, where each node has a set of sensors, 3G and GPS antennae, batteries, and a power source. The node is powered either by a solar panel or directly by wire from a nearby lamp post and consumes around 4.5 W to 6 W. The device supports 3 types of sensors: a flowmeter, a pressure sensor, and a hydrophone. The last two are sampled with rates up to 48 kHz. The high-rate measurements allow the detection of burst or leak events while the derived low-rate data show the trends of hydraulic parameters. Acoustic waves as one of the sources of information about a possible leakage have been also mentioned in [10, 11].

Most of the "traditional" WSN nodes communicate electromagnetically, e.g. using wi-fi. The solution is perfectly viable as long as the signal between the nodes propagates freely and there is enough space to place the required infrastructure (external antennae) near the node. The problem arises if the neighbouring nodes are placed inside the remote sections of the pipeline. Sometimes it is difficult to access such pipelines to mount the node's sensors and placing the antenna is virtually impossible [12].

The communication problem has been addressed in patents [10, 11, 13] and a patent application [14], among others. The patent application [14] describes a concept of WSN nodes that transmit data via acoustic waves using the liquid medium in the pipeline as a wave carrier. The invented device sends data through water in a pipeline as a modulated acoustic wave. An acoustic receiver, e.g. a piezoelectric element, receives an acoustic signal. The signal is then converted to an electrical form. Next it is amplified and demodulated to be processed by a central processing unit (CPU). The CPU fuses the received data with the sensors' measurements and sends it to a modulator and further to an amplifier. The electric signal is converted again to mechanical form (e.g. via inverse piezoelectric effect) and transmitted to the medium as acoustic waves.

The further research described in [12] confirmed that an acoustic transmission through the liquid medium in a pipeline is a viable solution in laboratory conditions. The tests were conducted for different types of receivers and transmitters including piezoelectric elements, low- and high-frequency miniature audio speakers and a hydrophone. The commercial use of the proposed technology in an industry-standard pipeline has yet to be confirmed.

BaltRobotics company however reports that an acoustic channel has been already proved to be viable to transmit real-time video (30 frames per second). It was used to control Remotely Operated Vehicles (ROVs) underwater [15]. The researchers achieved transfer speed of 115.2 kbod, full-duplex mode, on distance of 200 m with carrier frequencies of 500 kHz and 1000 kHz. The company expects to expand the distance to 350 m [15]. According to [16] sending telemetry data including data from hydrophones, sonars or other sensors requires transmission speeds of just tens of kilobits per second with bit error ranging from 10^{-4} to 10^{-3}.

2. THEORETICAL BASIS OF HYDROACOUSTIC SYSTEMS

Acoustic waves are longitudinal waves propagating by means of local compression and movement of particles. The compression is expressed as acoustic pressure, while acoustic velocity describes the movement. Acoustic intensity is a product of acoustic velocity and acoustic pressure and describes density of energy carried by a wave [17]. In a specific case of ultrasonic waves propagating in water, acoustic intensity could also be expressed as (1) [18].

$$I = pv = 0.5\rho v(A\omega)^2 \qquad (1)$$

where:

I – acoustic intensity [W/m^2]
p – acoustic pressure [Pa]
v – acoustic velocity [m/s]
ρ – water density [kg/m^3]
A – amplitude [m]
ω – angular frequency, $\omega = 2\pi f$

f – frequency [Hz]

Velocity of an acoustic wave propagating in water ranges from 1450 m/s to 1545 m/s for bodies of water [19]. Velocity changes, however, with temperature, salinity and hydrostatic pressure [19]. Salinity is constant for a WDN, therefore velocity depends on changes of temperature (daily and seasonal) and hydrostatic pressure (e.g. due to variable water consumption).

Changes of the flow caused by usage of water intakes, variability of pipeline's cross-sections and possible leaks [19] are the main sources of noise in a pipeline. The noise however is valuable for diagnostics as it carries data concerning the condition of the pipeline [7].

Variability of the flow is also associated with Doppler's phenomenon. The phenomenon's intensity grows proportional to a ratio of the relative transmitter-receiver velocity to the wave's propagation speed. Lower propagation speed of acoustics makes it much more severe than for electromagnetic (EM) waves [16].

Reflection and refraction are another phenomena important especially for communication in closed environments such as a pipeline. Both result in multipath propagation. The receiver registers not only the primary wave, but also its delayed and distorted copies [19].

In water damping of acoustic waves is lower than of EM waves. Acoustic damping increases with salinity and wave's frequency [19].

In general a communication system consists of: (1) a source of information, (2) a transmitter, (3) a communication channel, (4) a receiver and (5) a recipient of information [17]. A structure of the system is shown in Fig. 1.

3. THE CONCEPT OF AN ACOUSTIC WSN

The described idea is a specialization of a general concept presented in [12, 14, 20]. It expands the node's capabilities by leak detection and location similar to WSNs described e.g. in [6, 7, 9]. Fig. 2 presents said acoustic WSN node as a part of a measurement unit. The unit consists of three distinct modules: (1) a measurement and diagnostics module, (2) a leak detection and location module and (3) an auxiliary data sources. The first one is responsible for data processing and communication while the others are sets of specialized sensors.

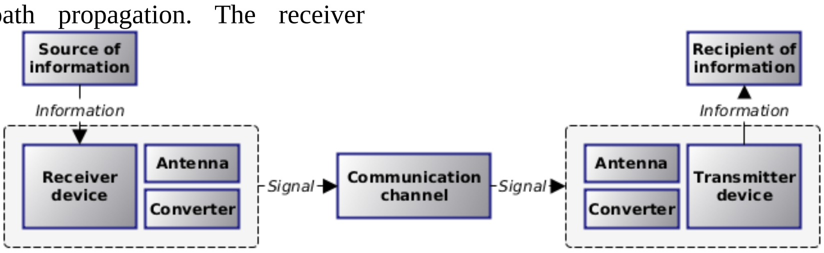

Fig. 1. A general structure of communication system based on [17]

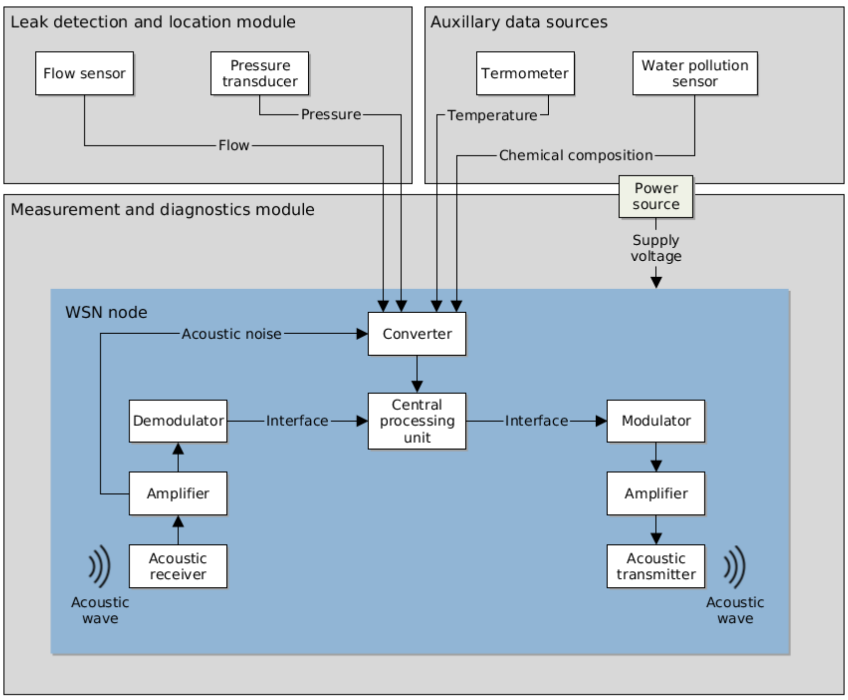

Fig. 2. A measurement unit with the improved acoustic WSN node

The measurement and diagnostics module encloses the WSN node, a power source and a set of different sensors. On the current stage of development it is assumed that a node is provided with sufficient power, be it from internal batteries or from external sources. The power supply problem and its possible solutions will be covered in the consequent research.

The node consists of a receiver module, a transmitter module and a processing module. Main elements of the receiver module are at least one acoustic receiver, a demodulator and a converter. The processing module consists of a CPU and a converter. The transmitter module includes at least a modulator, an amplifier and an acoustic transmitter.

The node sends data through water in a pipeline as a modulated acoustic wave. The acoustic receiver (e.g. a piezoelectric element) receives an acoustic signal. Then the signal is converted to an electrical form. Next it is amplified and demodulated into a coded message processed then by the CPU.

The receiver also registers acoustic noise that is further converted and used as a source of measurement data. The CPU fuses the received data with the sensors measurements and sends it to the modulator and further to the amplifier. Acoustic recievers are used both as communication devices and as data sources thus reducing the complexicity of devices.

If the node's power consumption is not the major concern, an actual processing of data could also take place inside the node itself reducing the size of data packets. The power consumption versus data size issue will be investigated in the further research.

Tranferring data through medium itself implies possible connection problems if an obstruction is found between the nodes. However, it could be used to an advantage as effective indicator of pipeline malfunction (e.g. a leak or a blockage). It could be especially effective in mesh-shaped pipelines where signal from farther nodes could be still transferred by an alternate route.

Nodes are organized in networks as described in detail in [13, 14]. Data from the nodes are sent consequently from the most remote ones up to the WSN's central management unit (CMU). The CMU then collects and processes the data. In [14] three distinct topologies have been specified.

Fig. 3 illustrates a WSN in which data are transmitted as acoustic waves only. This solution reduces additional infrastructure to the minimum in exchange of poor transmission speed and a risk of creating communication bottlenecks.

Fig. 4 and 5 show an evolution of that concept. Neighboring nodes are organized as clusters. Data inside the cluster are sent as acoustic waves between the nodes starting from the most remote nodes up to the central node of the cluster. Data from clusters are further transmitted to the CMU, but this time through a radio transmitter as EM waves.

Data are transmitted either directly to the CMU as in Fig. 4 or on hierarchical basis as in Fig. 5. It is a compromise between reduction of additional infrastructure and speed of data transmission. The placement of nodes could be further optimized e.g. according to the theory of optimal design of experiments and multi-objective evolutionary algorithms described in [4, 21].

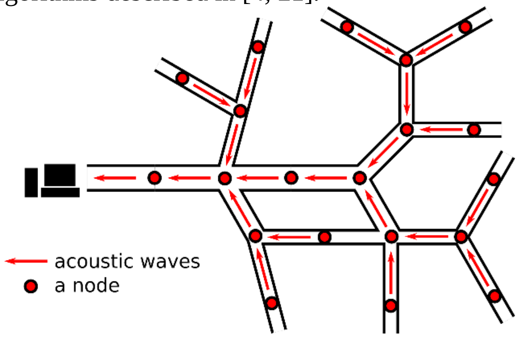

Fig. 3. Topology of an acoustic-only WSN based on [14]

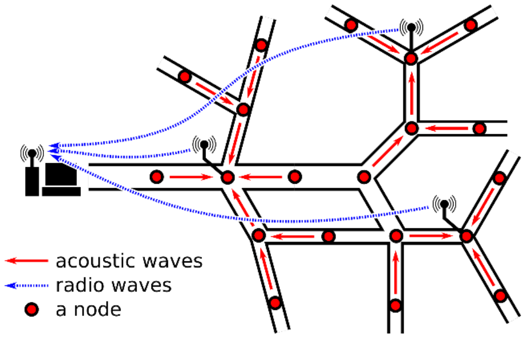

Fig. 4. Topology of an acoustic WSN with direct EM connectivity of clusters based on [14]

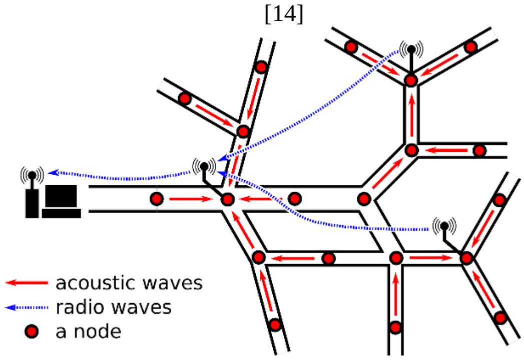

Fig. 5. Topology of an acoustic WSN with hierarchical EM connectivity of clusters based on [14]

4. LEAK DETECTION AND LOCATION

The work presented in the paper relates mostly to communication and hardware aspects of leak detection and location. A system such as SysDetLok [2] could be used as a software part.

SysDetLok is a modular diagnostic system, which uses a PostgreSQL blackboard and a model-based approach (Fig. 6). A hydraulic model of a WDN simulates virtual leaks. Virtual flow values are computed in respect to the placement of real

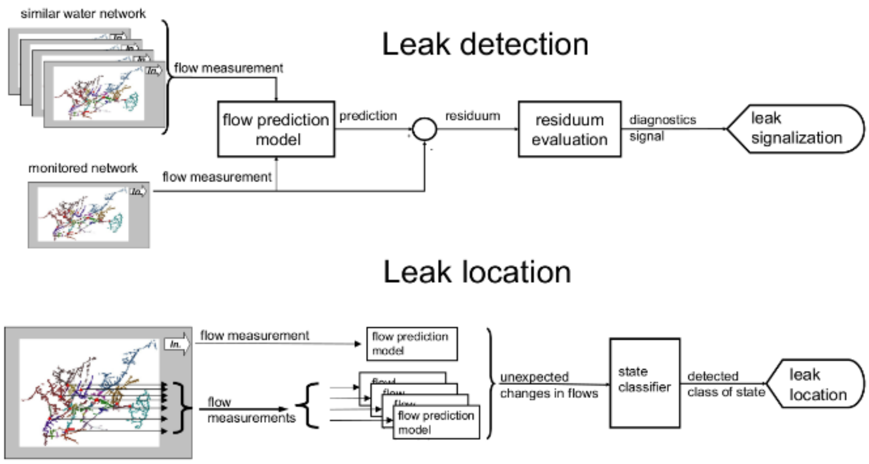

Fig. 6. Model-based leak detection and location [22]

nodes in the pipeline. The so called vector of state holds a number of flow measurements (momentary values) which describe the current state of the WDN. The model's output is then compared with the real measurements and a resulting residuum is used to deduce the presence of a leakage. The leak is then located by comparing outputs of similar models that simulate different leakages and choosing the best-fitting model [1, 6, 22].

Based on research [7], capabilities of the node presented in the paper could be exploited by simultaneously measuring additional parameters. The measurements of momentary values of flow (as in [1, 2, 6]), pressure and acoustic noise (as in [7]) could be fused to provide more accurate result.

5. VERIFICATION STUDY

The preliminary tests of communication method were conducted mostly in a configurable laboratory stand made of press-fitted polypropylene piping elements.

The prototype of a node is depicted on Fig. 7. Two chemically welded acoustic transceivers (1) are mounted on device's ends. Centering rings (2) and casing (3) are made of 3D-printed ABS. Transciever modules are connected using embedded threaded brass fittings (4 and 5) secured with PTFE tape. All data processing was made on external equipment.

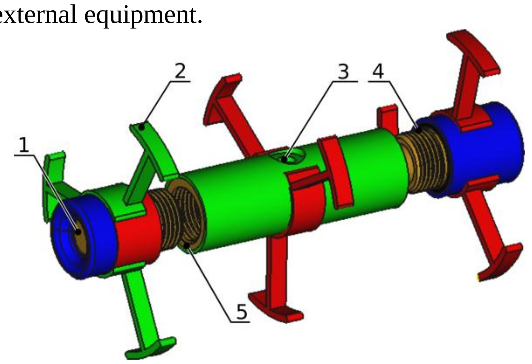

Fig. 7. A view of the prototype model assembly [20]

Data frames used during the verification study were encoded mostly using digital modulation to ensure greater robustness to noise. Fig. 8. illustrates a general configuration of the apparatus used during the research. A data frame (Fig. 9) is created offline on a PC. Then a function generator creates a carrier wave, which is modulated according to the data frame. The signal is transmitted into a pipeline as acoustic waves. A receiver registers the signal, which is then amplified, filtered and registered by the digital oscilloscope. The data is then processed offline on a PC [12, 20].

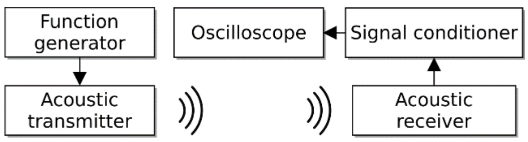

Fig. 8. A general configuration of the apparatus [20]

Fig. 10. illustrates the result of communication using an external hydrophone and a waterproof piezoelectric transmitter with nominal frequency of 40 kHz. An ASK-modulated signal of frequency of 48 kHz and amplitude of 20 V_{pp} was used. The signal was correctly received, demodulated and decoded over a distance of about 3 m. The results for other configurations of elements and a detailed design of a node are described in detail in [12, 20].

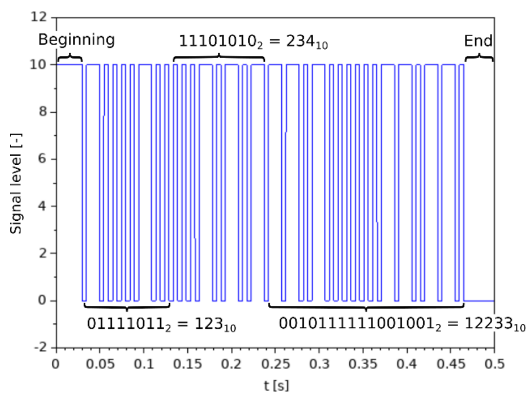

Fig. 9. An example of a data frame [20]

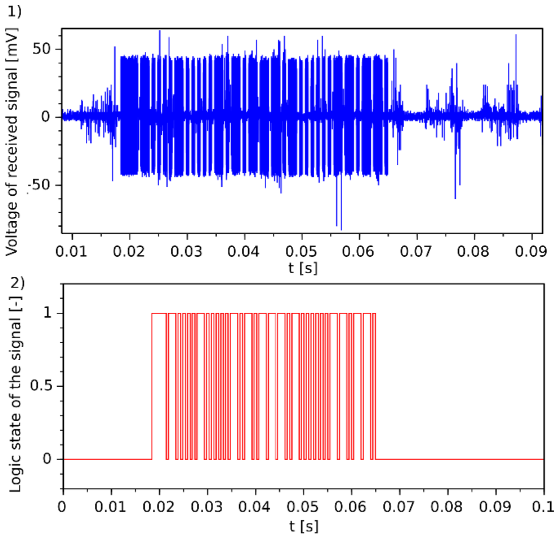

Fig. 10. The received signal before (1) and after demodulation [20]

5. CONCLUSIONS

Antenna-independent acoustic-based WSN is a possible solution to accessibility issues in leak detection and location systems for WDNs. However, signal quality now strictly depends on the parameters of medium itself. It means that the proposed method is more vulnerable to e.g. leak-induced signal loses caused by distortions of flow or pressure. The method was proven to be viable solution in laboratory conditions, but its potential use in industry is yet to be determined.

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