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Wireless Sensor Networks Based Control System Development for Water Supply Infrastructure

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Abstract— **The early detection of leaks in water supply pipelines and water theft prevention is an economically important issue not only for Latvian water utilities. However, monitoring and control of underground infrastructure presents a severe challenge. In recent years, wireless sensor networks are applied for Automated Meters Reading (AMR) and Advanced Metering Infrastructure (AMI). In this paper, authors propose a particular wireless sensor networks solution for water distribution network monitoring system. The case study of solution successfully piloted at water distribution networks in Latvian city Ventspils is described.**

Keywords—wireless sensor networks, water distribution networks, information systems, SOA, sensors, gateways.

I. INTRODUCTION

The core of the Water Supply and Sanitation Technology Platform (WSSTP) vision is a sustainable, efficient, and integrated management of water resources by all water-consuming sectors (people, industry and agriculture) in harmony with the bearing capacity of nature [1].

Latvian water utilities suffer from leaks, ruptures in water supply pipelines and water theft. However, monitoring and control of such underground infrastructure presents a severe challenge. The survey provided in several Latvian municipalities revealed [2] losses in distribution networks at client's site about 20-50%, but sometimes even more. Nowadays the absolute majority of water flow meters are still monitored by visiting at the sites or by "walking-by / "drive-by". Clients still deliver metering data to water utilities by phone, e-mail, and post or bring "in hand". Therefore due to the lack of reliable data about the state of water distribution networks (WDN) it is difficult to localize incidents and to minimize loss caused by water leakages, illegal connections and customer fraud [2].

Emerging of new technologies opens great opportunities for smart metering, software, telecommunication infrastructure and internet services providers due to fast growing demand for Automated Meters Reading (AMR) and Advanced Metering Infrastructure (AMI) systems development and maintenance.

In recent years, the Service Oriented Architecture (SOA) is becoming important in the field of devices integration, because it creates new synergies between software systems and embedded devices [3]. SOA is able to support development of e-services for water supply client's community, however applying SOA to deeply constrained devices such as sensor nodes is still an open research problem, for example low memory of sensor nodes that restricts to use an excessive XML scheme [4], [5]. Another problematic issue derives from the scenarios, when replenishment of power resources might be impossible. Sensor node lifetime, therefore, shows a strong dependence on battery lifetime [6].

To resolve mentioned constrains the majority of research efforts have been directed towards using middleware software running on more capable devices or gateways [7]. To avoid resource-intensive operations being performed on the sensor nodes, middleware software deployed on gateway devices first communicates with the nodes in an ad-hoc manner and then translates their functionality as web services to external systems [3].

The performance of AMR is characterized at least by two measures: the first is operating lifetime of the system without replacing batteries, but the second is metering data reading and transmitting rate, which could be considered as reliability of sending data.

There are two key error control strategies in WSN for maintaining reliable communication over noisy channels. The first one is Forward Error Correction (FEC) [8], which relies on transmission of redundant data to allow the receiver node to reconstruct the original messages. The second strategy is Automatic Repeat Request (ARQ) [9], in which high-rate detection codes are normally used and a re-transmission is requested if the received data is found to be erroneous. The scheme combining ARQ with FEC is called Hybrid ARQ (H-ARQ) [9], which is an approach aiming to recover from lost or erroneous packets for near real-time communications.

Several data aggregation protocols have been proposed yet for WSNs. Real-time guarantees are usually provided through either real-time scheduling or real-time routing. SPEED [11] is a well-known protocol addressing soft real-time guarantee in WSNs in such a way that

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packet deadline is mapped to a velocity requirement. The node with a velocity higher than a specified requirement is more likely to be chosen as the upstream node. MMSPEED [11], which is an enhanced version of SPEED, aims to meet reliability and timeliness requirements together while utilizing multipath routing to handle reliability such that number of paths is in direct proportion with the required reliability.

R2TP [12] uses a reliable and real-time data dissemination, in which reliability is satisfied by sending several copies of one packet through multiple paths such that sum of the reliability of the considered paths is equal or higher than the requested reliability. The intermediate nodes drop the packet if the elapsed time of a given node is greater than the delivery time requirement.

Due to Latvian Smart metering deployment experience, there is no well-explored work to address these two quality of service (QoS) parameters, i.e., reliability and timeliness together in a chain-based WSN, in which only one (or a few) path(s) can be established between source and destination nodes.

However, both utilities and systems developers encounter notable risks following new technologies introduction due to underestimated cost of technical solutions, frustration in selecting technical solutions relevant for local needs, and the lack of competences in municipalities and in development companies.

During implementation of the project in Ventspils, the strict cost limits where settled by municipal water utility company, which cannot exceed 15 - 25 EUR per one sensor – transmitter [13]. Therefore, the challenge was to develop cheap, robust, but effective system.

In this paper, a particular wireless sensor networks solution for water distribution network monitoring system is proposed. The solution is piloted in Ventspils city (Latvia). Middleware software is deployed on gateway devices, which communicate with the nodes using ISM band frequency radios and then translate their functionality as web services using Ethernet. This trial wireless sensor network is successfully integrated with the existing SCADA that monitors neighbour WDN area and with a municipality owned wireless Wi-Fi network. The developed solution deploys SOA approach that enables integration with legacy municipal Wi-Fi network and development of e-services for users. This research results is ready to use novel technical solutions for water suppliers.

A novel approach offered in this work is the use of layer identifiers for forward transfer messages as a cost effective method for robust WSN, which monitors WDN. This novel solution can be easy integrated with the legacy monitoring systems and existing municipal Wi-Fi networks.

II. APPROACH FOR METERING DATA READING AND DELIVERY TO A BACK-END SYSTEM

Typical municipal automated meters reading system for water distribution networks usually take advantage of mobile network broadband communications (GSM/GPRS/UMTS etc.). Short range transmission systems, which use “drive-by” scenarios to acquire the needed sensors metering data for further analysis (mainly for billing), are popular among water utilities in Latvia. All these solutions incur fixed cost – payment to communication companies for service, or in the case of drive-by scenario – constant fuel expenses and labour cost.

An alternative way of communication is wired or wireless core infrastructure from the telecommunication service provider or MAN (Metropolitan Area Networks), WAN (Wide Area Networks) that suits the needs of data transport. Unfortunately such complex infrastructure is:

- Not available in small municipalities;
- There technical integration challenges;
- Is costly to provide as leased services based on existing infrastructure.

As the provided services often are time critical, for example billing, the service guarantees to be applied, otherwise inability to locate and repair faults in an acceptable time interval may cause serious problems. These systems usually are homogenous; the technological complexities are hidden from the client, which maintains services for end users – like in the case of GPRS.

To overcome the main pitfalls, the research team developed a range of hardware and technological solutions. The end result is a comprehensive base for further studies and engineering to advance these solutions for a wider market as a long-term alternative to the existing solutions with potential better cost-effective parameters and easier maintenance.

For easier and cheaper prototyping the radio frequency integrated circuit selection, HopeRF Electronics radio frequency (RF) modules, where chosen, because they contain a fair amount of usable modulation schemes – diversity of transmission modes in hardware level: transceivers or transmitters and receivers. The possibility for easy integration with Atmel series (ATmega48, ATmega88, ATmega168, ATmega328) microchips is an additional benefit to low cost, power efficiency and solid computation power to implement a pseudo multi-path prorogation algorithm.

A microcontroller communication with the radio module is done using the SPI (Serial Peripheral Interface Bus), which is a synchronous serial data link that operates in full duplex mode.

For the modulation scheme GFSK (Gaussian Frequency-Shift Keying) was chosen, as it have been adapted in common wireless technologies like Bluetooth, DECT etc. GFSK is based on FSK, but GFSK uses a Gaussian filter as well. Additional to GFSK modulation the Manchester encoding scheme is used in the communication process.

III. SELECTION AND A SCOPE OF A TRIAL NETWORK

Selection of a suitable region in order to create a trial water distribution network was an important task for success of the research. The selected location has to have the characteristics needed to cover maximum of all experimental trials for further analysis and development: easy accessible manholes, enough branches for data analysis and modelling, existing city infrastructure for receivers/transmitters installations, enabling of power supply, presence of high buildings for alternate signal reception points, etc.

Therefore, a water supply network segment in the outer region of the city was selected, because it was a closed segment with multiple branches and it suited the amount of available budget to be used for sensor installation. The main network water input is monitored by existing SCADA, which provides input pressure and flow measurements as a reference for overall network monitoring and data verification. All segments and branches of the trial network have been equipped with at least one water pressure meter. In addition, long distribution lines of the trial network are relevant for fluid dynamics simulation (wave propagation).

Technical problems to be resolved concerning metering data transmission from the water networks wells:

- Power supply for pressure meters;
- Existing flow and pressure reader adaption for 868MHz RF transmission instead of GPRS;
- Transmission signal strength – obstacles;
- Signal transmission from manholes;
- Data packet retransmission using Ethernet;
- Physical pressure and flow meters installation in the network wells and client premises;
- Software adaption for data processing and visualization (AquaMet).

The block diagram of Smart Metering system is shown at Fig. 1.

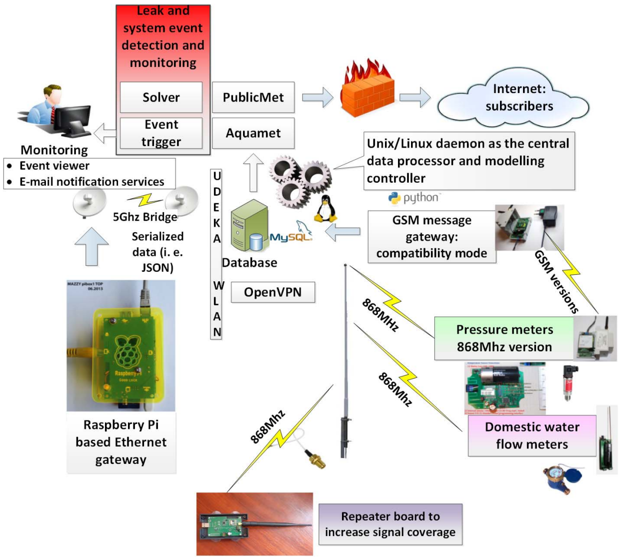

Figure 1. The block diagram of Smart Metering system

The system comprises main elements:

- Water flow and pressure meters;
- Sensors – data transmission devices 868 Mhz;
- Ethernet gateways that convert signals from sensors into TCP/IP;
- 5 Ghz Bridge for ensuring data traffic to municipality Wi-Fi network;
- GSM message gateways;
- System events and leaks monitoring and detection module;
- Central data base;

IV. FORWARD TRANSFER – REPEATER NODE PRINCIPLE

As the installation of internet enabling network access points (gateways) is difficult and expensive, the number of installations is kept to minimum. In the photo below the main 5GHz network bridge used to create the base network and provide network access for the Ethernet gateway, which collects the sensor data using 868MHz antennas, is depicted on Fig. 2.

Figure 2. 5GHz networks bridges used to create the base network

In order to overcome limitations of the sensors transmitting range and unavailability of the gateway nodes related to forward transfer, a repeater board was developed that ensures a feasible solution. The idea is to provide multi-layered one-way data forwarding infrastructure. However, the problems arise regarding handling collisions and loops. Due to communication is only one-way there are no hidden nodes or similar problems. For simplification in terms of energy, a computationally cheap solution is designed on Fig.3.

The algorithm working principle: all sensor node messages are transmitted blindly with no destination address information in a context of forward transfer – repeater node information. If a sensor node is in the range of the data sink (gateway), the data are received, decoded, and then message is encoded for further transmission to the processing backend. If the sensor node is out of range of a data sink an additional forward transfer – repeater nodes are installed, enabling the repeater nodes can receive the signals of the sensor nodes.

Forward transfer – repeater nodes have better antennas (in terms of sensitivity) and provide stronger transmission signals, as are connected to permanent power sources, so compared with the amount of sensor nodes only a limited amount repeater nodes is necessary. The problem of power sourcing still persists – utilization of renewable sources, in particular solar panel charging and night powering from battery where taken into account, but were recognized as not cost-effective in the project geographical location.

When the repeater node receives new sensor message blocks, it queues them for retransmission. Before retransmission, an additional identification byte is incremented from the previous value. The repeater node forwards only if the identifier is lower that its own layer identifier. After the addition of the layer identifier the message is broadcasted – the receiving nodes can be the data sink node or another repeater node. If the receiver is a data sink, it removes the layer byte and decodes the message. If the receiver is another repeater node, it checks for the layer byte and compares it with the layer identifier of itself. If the layer identifier is larger of equal, the message is dropped, but if the layer identifier is smaller the messages layer byte is overwritten by the identifier of the receiving repeater and is broadcasted (see Fig.3).

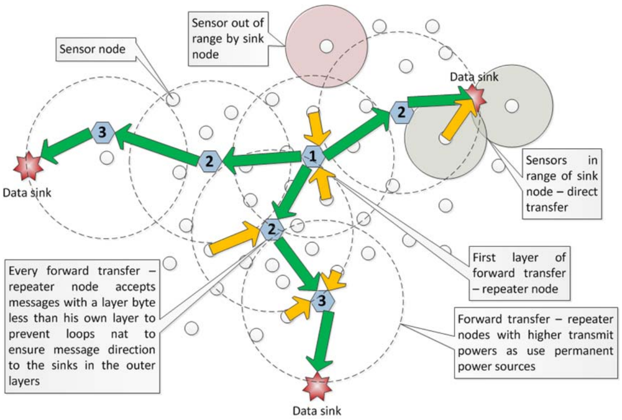

Figure 3. Signal forward transfer method

The layer identifiers have to be correctly assigned to create an “onion like” structure by checking the repeater layer visibility to the nearby layers N+1 and N-1 by using tester equipment. As the data sinks (Ethernet gateways) are capable to analyze messages with or without the layer byte, the forward transfer – repeater can be used as “normal” repeaters.

V. ETHERNET GATEWAY - CONCENTRATOR

A. *Pibox Ethernet Gateway Development Stages*

The functions of Ethernet gateway are as follows. Sensors data readings are sent to the gateway - concentrator, which collected data prepares for further transport to the processing systems. The recovered messages are checked and stored in the internal memory of the gateway. The receiver unit of the gateway is connected with a Raspberry Pi microcomputer (using a USB serial interface). Microcomputer software sends a special service commands to set up and capture sensor data reading from the concentrator's internal memory. Unlike water meter sensors, operation of gateways equipment requires an independent power source due to larger power consumption.

The initial prototyping platform of gateway - concentrator was based on open source networking equipment used for proof of a concept. The Ethernet gateway service used for data serialization and delivery to the backend servers was implemented using C and Python programming languages for easy porting to other future platforms.

The base equipment used, as reference was a Mazzy GPRS based gateway. The radio part was isolated and integrated into the new 868MHz design. All development was done by keeping the backward compatibility with the old design in cases of 868MHz signal transmission problems caused by sites with long distances or difficult accessibility – so GPRS solution can be still used without problems.

The first version of 868MHz sensor reception hardware was based on a testing device used by the installation personnel to diagnose sensors operations by displaying real time transmission data values on a LCD display. This device was expanded with a USB serial interface port that can be connected to an embedded Ethernet gateway controller or just to an ordinary PC using a standard USB interface. The USB device is recognized as a generic serial port. This interface provides the basic command interpretation for data request and parameter setup.

The second Ethernet gateway version was moved to a generic embedded platform. The popular Raspberry Pi ARM7 platform was selected, as it provides enough computing power and has a composite video output. So the device can be used also with a display for onsite diagnostics. The main system process monitoring of meter reading delivery to the backend servers was written in Python and supplemented with additional support services. The service ensures virtual private networking support for remote site setups, service automatic monitoring, failure notification and system level watchdog function, if some kind of errors occur, the CPU is automatically reset.

The main developments of the second gateway version:

- Aquamon multithreaded daemon to parse USB data and prepare for delivery to server;
- MONIT service notification and Aquamon service control (e-mail notification, problem detection, service recovery);
- VPN support (tinc, PPTP, OpenVPN);

- Watchdog: Broadcom BCM2708 watchdog support (gateway monitoring, overload, «data pipe lost» - reboot);
- Wear out prevention of SD card memory (RAMLOG).

The last Raspberry Pi based Ethernet gateway has 868MHz meter data reception RF daughter board. It is equipped with heartbeat indication, wireless network adapter and a safe-shutdown button. In addition, the composite output is used for easy diagnostics and monitoring.

In order to link Ethernet segments with system servers it was decided to create virtual private network. One of the open source virtual private network solution OpenVPN that apply Tinc was tested.

B. *Ethernet Gateway – Aquamon Services*

The service architecture is designed for autonomous service recovery and event logging for gateway monitoring from a central service centre. The main processing is done in the Aquamon service daemon.

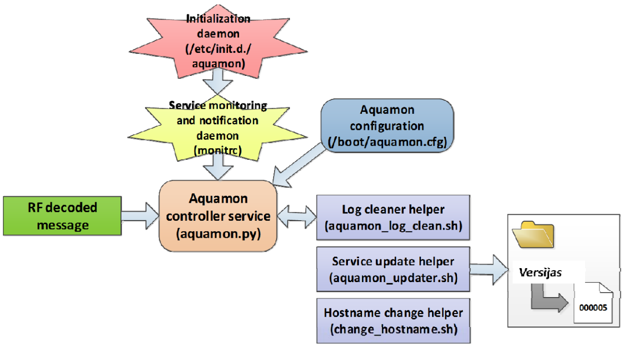

Figure 4. Aquamon services flowchart

Additional helper services provide supplementary functionality (see Fig. 4)

- Aquamon existence services checking and restarting on failure;
- Failure and internal event monitoring an logging;
- Update service to provide automatic service updates from the central management interface;
- Networking host configuration to enable multiple Ethernet gateways co-existence in the same network segment and networking functionality.

The monitoring system provides automatic reinstallation of all Ethernet gateway core software without accessing them manually.

VI. FINAL TRIAL NETWORK LAYOUT

The main backbone network infrastructure was built in a star topology by using relative cheap ubiquity wireless networking equipment. By combining Ethernet gateways with the repeater units an impressive meter transmissions coverage was achieved – only three Ethernet gateways and two repeater nodes.

On Fig. 5, the final network layout is depicted, where blue circles show Ethernet gateway range, but orange circles show repeater half-ranges.

The network comprises 14 water flow and 9 water pressure sensors. Additional flow sensors replacement was done in order to improve signal receiving: sensors transmission antennas height was increased. The total number of water pressure meters is nine.

The tests provided in order to access the quality of measurement receiving by central server showed that all data have been received within maximal delay of 2 hours. The worst case was observed for easier manageability, scaling and security.

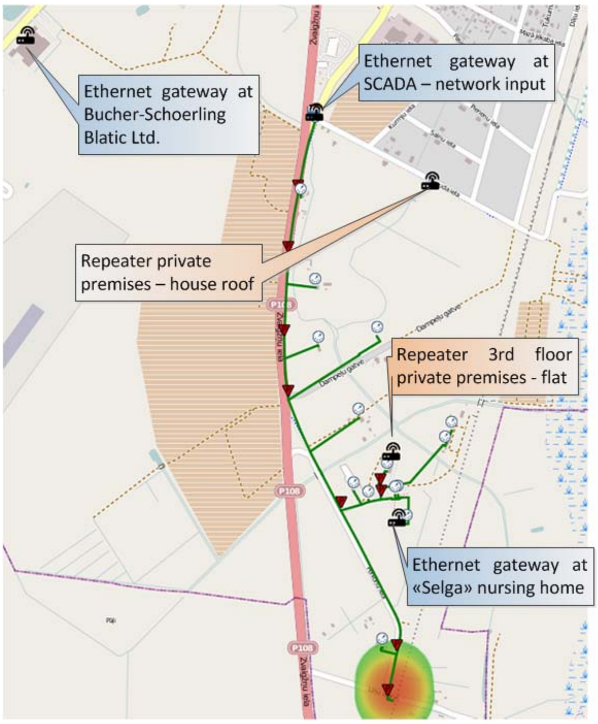

Figure 5. The final wireless network layout

VII. SMART METER INFORMATION SYSTEM ARCHITECTURE

Smart System software utilizes open source and Unix/Linux compatibility: ScicosLab, EPANET 2 and MySQL for network definition.

The developed system comprises water distribution network pressure and flow monitoring system and an interface for users, where the monthly water usage and consumption/time charts can be drawn and an estimate of the water usage cost can be computed.

The Smart Meter system consists of four base components:

- ***Meter reading reception gateway:*** This component receives HTTP encrypted POST generated by the Ethernet gateways, which accumulate and preprocess the sensor readings and performs a HTTP POST to the SmartMeter

WEB server (Apache) based on a DNS name. Apache web server redirects the requests to the specific gateway processing application – gateway daemon. The gateway script (PHP language) validates the POST data for corruption and authenticity. If data is accepted it is stored in the systems MySQL data base.

- ***Smart Meter monitoring, statistics and data visualization interface and backend.*** The SmartMeter system is built upon Ruby on Rails framework using MVC (Model, View, and Controller) architecture. The model consists of application data, business rules, logic, and functions.
- ***SmartMeter customer statistics for consumption and billing.*** This component runs on a separate server thread and is based on Ruby on Rails. It provides the web interface for the customers. The customers can see visualized water consumption as charts, tables for a selected period.
- ***SmartMeter leak detection module.*** The leak detection module consists of multiple separate applications that perform periodic recalculations based on systems sensor input data. There are separate components as SCADA system simulation service that provides a compatible interface for the existing flow and pressure meter's function logic - middleware.

The system enables a metering data export to user information system in a compatible format. The data about client's water consumption can be selected and retrieved according to predefined parameters. Therefore, water utility staff skips manual monthly measurements collection and manual recording into billing system.

VIII. CONCLUSIONS

Wireless sensor networks solution for water distribution network monitoring system, described in this article, was successfully piloted in Ventspils city. Middleware software was deployed on gateway devices, which communicate with the nodes using ISM band frequency radios and translate their functionality as web services using Ethernet. The wireless sensor network was successfully integrated with the existing SCADA, which monitors the input of the trial WDN.

The developed in the project solution deploys SOA approach that enables integration with the legacy Wi-Fi network and development of e-services for users. This research results is a ready to use novel technical solution for water suppliers.

A novel approach offered in this work is application of the layer identifiers for forward transfer messages. It is recognised as a cost effective method for robust WSN used for monitoring WDN. This solution can be easy integrated with the legacy monitoring systems and existing municipal Wi-Fi networks.

Limitation of battery power, feeding wireless sensor, still is a problem issue, which resolved mostly as a trade-off between the needs of timely data and transmitting cycle's frequency. Therefore, the further research is necessary in the topic of effective use of battery power taking into account strict system cost limitations.

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