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Development of Pseudo Autonomous Wireless Sensor Monitoring System for Water Distribution Network

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***Abstract*—Water distribution networks require long term autonomous monitoring solutions, integrated, reliable and cost effective data transfer methods. This paper investigates the data delivery infrastructure of water distribution network sensor equipment used for network monitoring and billing of the subscribers. Water distribution network usually apply sensors to measure water flow, pressure and temperature. The main goal is to offer a wireless sensor system architecture comprising simplified and cost effective design for large scale deployments, maximizing autonomous running time and data transmission reliability. The proposed solution offers a periodic data acquisition system by removing the need of drive-by scenarios commonly used for water meter readouts collection. The idea of pseudo autonomous wireless sensor monitoring system is also discussed in the conclusion.**

Keywords—wireless sensor network; sensor nodes; water distribution network; resource constrained; embedded devices

I. INTRODUCTION

Water distribution network monitoring provides the opportunity for automatic billing data collection, unauthorized connections, infrastructure security (tampering), leak detection systems [1] and water quality monitoring. The majority of solutions for wireless water distribution network monitoring uses GSM/GPRS connectivity [2] however this increases the node costs and dramatically reduces the lifetime node to maximum of a few years [2] due to in battery discharge. Wireless sensor networks used for infrastructure monitoring in a spatially distributed environment have a common architecture [3]. Water distribution network monitoring needs a subset of features [4] that provide data acquisition via water meter specific interface, data transmission using a power efficient method, data reception at a wireless gateway that transfers the data of interest to the backend processing system using secure data transfer method.

The target of this research is to optimize energy consumption of all these components. The optimization will give a positive impact on minimization of cost, on prolongation of battery life time; it will simplify deployment of wireless sensor networks for monitoring existing and newly built water distribution networks.

II. CASE STUDY IN VENTSPILS

The municipality's owned water utility "Udeka" uses "Sensus" [5] residential water meters with 868MHz transmitters in a drive-by readout scenario. The readout is done once in a month and is not suitable for network monitoring and consumption forecasts for the consumer. In real life scenarios the drive-by scenario is problematic as the readout procedure might fail in and urbanized area range limitation due to signal attenuation, resulting the need for a repeated drive-by.

The proposed system provides fixed network metering infrastructure that utilizes a wireless embedded concentrator to receive and transfer meter data from transmitters located at each utility meter and selected water distribution pipe network segments to the utility data processing systems. The methods of sensor position selection for leak detection follow a model-based fault diagnosis approach, purposes are discussed in [6]. The sensor position estimate was calculated by temporal variations using EPANET solver engine [7] with sets of leak scenarios containing maximization of leak position accuracy. The trial network system has been implemented within "Smart Metering" project (Project No LLIV-312, year 2013) at a restricted segment of water distributed network in Ventspils city, Latvia [8]. The municipality's owned water utility "Udeka" staff provided support in order to integrate the trial network system with the existing IT systems of water utility.

The trial network system comprises of two types of transmitters for metering data: A pulse counter for a water meter with at least two inputs for cold and hot water and a pressure meter from pipeline manholes equipped with temperature sensors (see Fig.1).

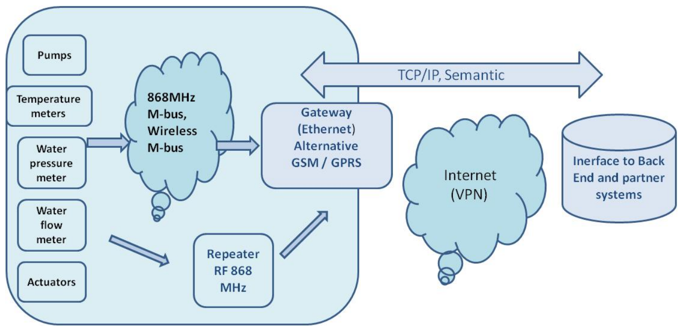

Fig.1. Trial area wireless sensor system architecture in Ventspils city

Temperature monitoring reduces the risk of the freezing of water pipe-line systems and thus prevents damages in pipe-lines and water supply cut-off.

Wireless concentrator is an interface to the wireless network at ISM band (868.50MHz) for collection of utility meter data, buffering and delivering. It uses service oriented architectures based on Hypertext transfer protocol functionalities. The main purpose is to provide an extendable base system that provides a cross-protocol resource access solution. In combination with virtual private network technologies [9] the security is enhanced and large scale deployments can be grouped by virtual networks in a per-site manner.

III. Battery Life Time Calculation

A lifetime calculation for the sensor device is proposed by the authors:

$$I_{avg} = I_{avg.m.} + I_{avg.t.} + I_{avg.losses} \quad (1)$$

$$I_{avg} = \frac{T_{awm}}{T_{mc}\times 1000} \times I_{mc} \times 1000 + \quad (2)$$
$$+ \frac{T_{awt}}{T_{tc}\times 1000} \times I_{tc} \times 1000 + I_{avg.losses}$$

$$T_{bat,h} = \frac{C_{new}}{I_{avg}} \times 1000 \times \frac{100-\left(1-\frac{C_{10y}}{C_{new}}\right)\times 100}{100} = \frac{1000\times C_{10y}}{I_{avg}} \quad (3)$$

Where: T_{awm} – Average working time of microcontroller (watchdog cycle) (ms);
$I_{avg.m.}$ – Average current of the microcontroller (mA);
$I_{avg.t.}$ – Average current of transmitter (mA);
$I_{avg.losses}$ – Average losses of circuit (mA) – experimental evaluation;
T_{mc} – Microcontroller working cycle (ms);
I_{mc} – Microcontroller current at working cycle (mA);
I_{tc} – Transmitter current at working cycle (mA);
T_{awt} - Average transmitting time of transmitter (ms);
T_{tc} – Transmitter working cycle (ms);
C_{new} – Capacity of fully charged battery (mAh);
C_{10y} – Estimated capacity of new battery after 10 years caused by self-discharge (mAh);
$T_{bat,h}$ - Estimated sensor node lifetime (h).

Furthermore one can see an example calculation. From the experimental hardware development the data rate of 4800bps and 23 bytes packet structure was used with transmissions of readout data every 15 minutes [2] from which the average transmitting time of the transmitter can be calculated:

$$T_{awt} = \frac{23\times 8}{4800} \times 1000 = 38.(3)ms \quad (4)$$

$$T_{tc} \approx 15\,min. \approx 900000ms \quad (5)$$

$$T_{awt} \approx 40ms \quad (6)$$

$$I_{avg.t.} \approx 80mA \quad (7)$$

$$T_{awm} \approx 20ms \quad (8)$$

$$T_{mc} \approx 16ms \quad (9)$$

$$I_{mc} \approx 3mA \quad (10)$$

$$I_{avg.losses} \approx 5\mu A \quad (11)$$

$$I_{avg} \approx \frac{20}{16\times 1000} \times 3 \times 1000 + \quad (12)$$
$$+ \frac{40}{900000} \times 80 \times 1000 + 5 \approx 12.25\mu A$$

$$T_{bat,h} \approx \frac{1000\times 2250}{12.25} \approx 183673h \approx 21\,years \quad (13)$$

The sensor estimation shows that the sensor design conforms to the industry requirements: the expected sensor node lifetime coincides to the typical water meter replacement intervals [10]. Low self-discharge rate Lithium-thionyl Chlorite batteries were selected for the trial network.

As we can see from the experimental results, the largest impact on the sensor node lifetime is the transmitting time (see Fig. 2) of the radio module. The size of the transmitted packet is the main optimization parameter. The microcontroller is the second largest energy consumer. However, minimization of the sleeping cycle is difficult as the meter interface and radio initialization has a fixed delay and further duty cycle reduction would bring minimal improvements.

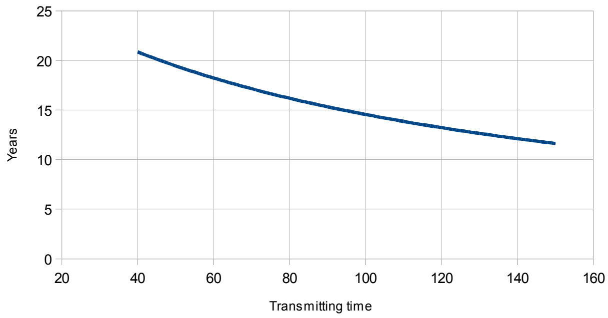

Fig.2. Sensor node lifetime depending on the transmitting time

IV. Packet Structure

Experimental evaluation of the transmitter radio using GFSK modulation and Manchester coding with a data rate of 4800bps showed minimal packet loss using preamble of 6 bytes and 2 synchronization bytes. The packet length has been kept minimal to include layer definitions and various sensor data parameters with future compatibility of multi-packet messages. The data block consists of 12 bytes (Fig. 3).

Bytes 10-13 are used for device identification where the first byte is the device type – the remaining three bytes are serial number coding with hardware revision information.

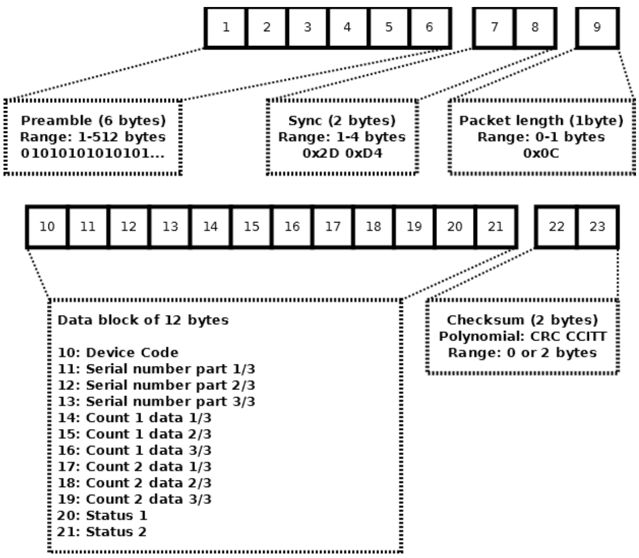

Fig. 3. Packet structure

An additional two status bytes (20 and 21) are used for sensor node monitoring and radio control parameters. The status byte 20th is divided into 3 bits for sensor node battery voltage (Table I) indication and the remaining 3 bits are repeater layer identifiers (these allow only 8 layers, but bit layout is adjusted depending on deployment scenario). The status byte 21st is subdivided into 3 bits and is used for packed type identification in case of multi message cascading where additional computational data is required for cumulative temperature readouts.

TABLE I.

3 BIT CODING OF LITHIUM-THIONYL CHLORIDE (LI-SOCL2) BATTERY VOLTAGE RANGE

Battery voltage, V	3 bit coding	Decimal value
>3.2	111	7
3.1...3.2	110	6
3.0...3.1	101	5
2.9...3.0	100	4
2.8...2.9	011	3
2.7...2.8	010	2
2.6...2.7	001	1
<2.6	000	0

The last 5 bits are reserved for future use (optionally one bit is used for domestic meter tampering status indication). The last 2 bytes are CRC CCITT polynomial with alternate CRC-16 (IBM), IEC-16, Biacheva variants supported at chip level.

V. PACKET FORWARDING

To overcome the limitations of the sensor range a repeater node is used. This node receives and forwards meter datagram solving the problem of gateway unavailability due to limited permanent power sources. The repeater is connected to a persistent power source and is equipped with a high-gain dipole antenna. A received datagram is modified to prevent retransmission loops using existing datagram structure by keeping compatibility with common gateway datagrams. This preserves backward compatibility for future packet format expansion.

The main issues to resolve during the project were:

1) Optimization of repeater positions to ensure maximization of the covered area by minimizing the repeaters and gateways number. 2) The forward index assignment using a fixed network metering infrastructure. 3) Transmission delay programming automation by parameter fitting of time delay (datagram transmission cycles) window, transmitter range, range covered transmitter density and microcontroller clock inaccuracy.

Collision avoidance and message forwarding can be accomplished by cognitive radio techniques and using wireless mesh, ad-hoc technologies with wireless technologies like IEEE 802.11, 802.16, 802.15. These technologies offer a wide variety of self-healing networks with algorithms for the shortest path and interference avoidance; all with the expense of greater power consumption. Different energy efficient MAC protocols have been compared [11]: UNPF, SIFT, TRAMA, T-MAC protocols. The proposed system is based on a reduced UNPF protocol concept that provides cost reduction in terms of hardware complexity for large scale deployments in water distribution networks.

The idea is to provide multilayered one way data forwarding infrastructure. Commonly in networking the problems arise when handling collisions and loops. As the communication is one-way, there is no hidden node etc. problems. For simplification, in terms of energy a computationally cheap solution is offered (Fig. 4):

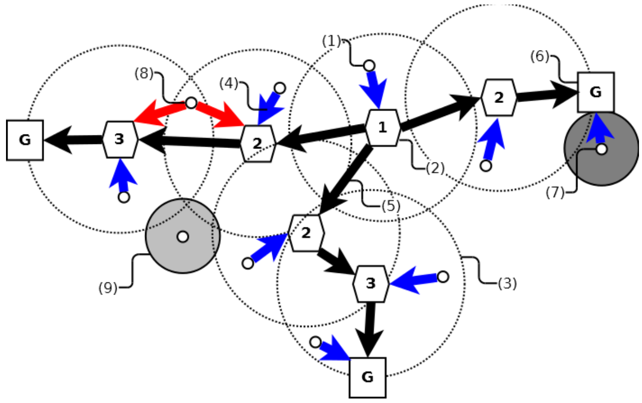

Fig.4. Packet transmission diagram [8]

1) If the sensor node (1) transmitter is in the range of the gateway (6) – data message (7) is received and decoded by the gateway (6) and delivered to the chosen processing backend system.

2) If the sensor node is out of range (9) of the gateway - additional repeaters (2) are installed. All repeaters are of the same type and functionality but provide a layer identifier to indicate the direction of message forwarding e. g. in Fig. 3. the repeater nodes (2) have identifiers 1, 2 and 3.

3) Repeater nodes are connected to permanent power supplies and supplied with higher gain antennas and higher transmit power by covering larger areas (3) than the area radio transmit range of a single node.

4) As a message is received by a repeater (4) and added to processing buffer. The repeater checks for the layer identifier byte and only retransmits the message, (5) if the received message layer identifier is not present or is less than the layer identifier of the repeater device itself – before the message is retransmitted the layer identifier is incremented. If the layer identifier is larger than that of the repeater node itself, the message is dropped.

5) The repeater layer identifier assignment is one of the crucial processes of planning. The suggested method of correct layer identifier assignment is for a region of sensors with fixed network behavior to be monitored. The region segmentation is done by the outer gateway coverage ranges to form an edge weighted complete graph by assuming minimum energy broadcasts [12]. Also to find a node (vertex) which distance of the farthest node is the smallest – this node is assumed to be the center of the graph and gets the minimum layer identifier. Algorithms like Floyd-Washall can be used [13] to find the center node:

Algorithm: 1) For each vertex pair find the length of the shortest path between them 2) Find vertex *i* such that the length of the shortest path to the farthest vertex is the smallest. The same algorithm can be used for the shortest path calculation from a center node to the gateway. Further assignments are performed using shortest path algorithms where each node traversal increases the layer identifier e. g. Fig. 5. From the center of the formed graph each next hop gets an incremented layer identifier – also a message multiplication effect example is shown in Fig. 5 left side message paths from the center node.

6) If the receiver of the sensor node message is a gateway it decodes the received message by ignoring the value of the layer identifier.

7) Depending on the deployment environment and geographical location battery backed hybrid solutions with alternate power generation methods like solar batteries have been developed during the experimental deployment.

8) In cases of sensor nodes that are between two or more different layer repeaters, a message multiplication can occur. However by taking into account network optimization for minimum energy the overhead message count should be minimal and should provide additional message transmission redundancy. If time slot allocation between sensor transmission cycles has been padded with empty slots that correspond to maximum retransmission delay from forwarding between layers (in case of possible message multiplication), no collisions should occur, as the longest multiplicated message delivery will be earlier than the next time slot allocated for a sensor node.

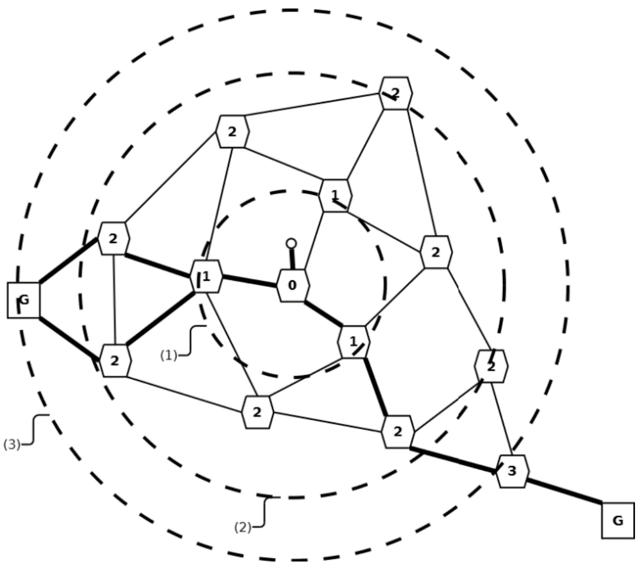

Fig. 5. Minimum energy broadcast graph with layer identifiers

9) As layer identifier maximum is limited to 3 bits in order to prevent long message propagation paths the sensor network should be split into sectors which approximation is formed by gateway positions.

VI. Collision Avoidance by Initialization

Network initialization procedure of the wireless network is a challenging task if minimum energy usage has to be achieved for long term operation. The proposed method for a sensor not capable of duplex communication is to perform an externally controlled initialization of the sensor nodes in the power-up procedure; where device codes and serial numbers are registered into a database. As the sensor nodes are prepared for deployment their start up and so the transmitting cycle is controlled (delayed) by the programming device (controller). The Fig. 5 shows the trial network [8] that was initialized using the mentioned method. The trial network consists of 15 flow meters (3) where one of them is the main network input flow monitor and the remaining ones are domestic subscriber meters for cold water. Also the network contains 10 pressure meters (2) where one is also located at the trial networks branches input. The trial network contains three gateways marked with red circles (see Fig 6). The trial network is located in a vegetation dense location that surprises the transmitted signal. There are also high buildings that cause multipath signal propagation. To ensure data delivery to the gateways from meters, where the received signal strength indicator is near the specified threshold, two repeater devices have been installed. After five months of successful operation, the data delivery and packet loss is sufficient to billing and monitoring needs (Table II).

TABLE II.

Packet transmission statistics for the trial network

Direct path form sensor to gateway	86%
Packets retransmitted from repeaters to gateway	8%
Lost packets	6%

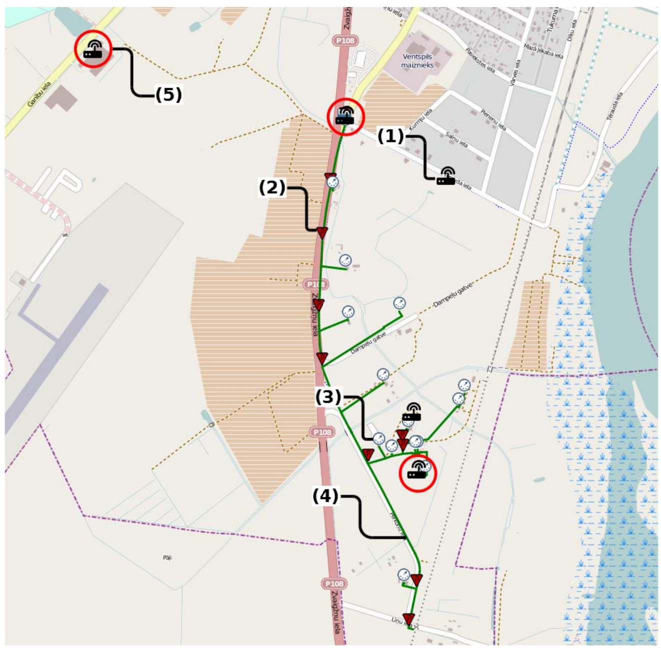

Fig. 6. Trial network [8] using layer principle for message forwarding

The sensor node activation is timed based on the calculated time windows of cyclical transmissions, transmission length and padding time to compensate for frequency instabilities that might drift the estimated timing parameters. The estimated approximate drift of 1.55 seconds daily [14] for off the shelf computing equipment is easily compensated with network time server synchronizations. Future sensor initialization for deployment is based on the time difference calculation of non-overlapping time windows, where the external controller delays the nodes initialization. The author offers an even time slot distribution depending on the initial number of sensor nodes as initialization time data base can be used to assign additional nodes in the unused time slots. This distribution evens the packet rate received at the gateways.

VII. Conclusions and Discussions

The optimization of the wireless transmitted packet for the needs for water distribution network monitoring significantly improves the sensor node battery lifetime.

During the initial deployment a controller with sensor database that initializes the sensors by delaying their startup (to prevent collisions) is an effective solution. Network scaling should be taken into account during the planning phases to estimate the needed padding windows and the possible node number depending on the nodes density.

Simplified packet repeater principle showed great results during trial network deployment and reduced the overall installation costs by minimizing the required gateway nodes count that need direct network connections.

The developed monitoring system for the Smart project does not provide a feedback system, however the proposed solution has capabilities of half-duplex and full duplex communication, therefore the proposed system is applicable also as wireless water distribution network control system. The basic solution is developed as direct control system, which without IT hardware extension, could be modified for control system with the feedback to regulators and actuators at a client site.

The integration of existing and proposed system may be drawn as sequence of microchips; actuators; sensors and processes between them, supported by equipment, tools and software for data acquisition as well analysis and alternatives development for decision making. Such system could be named as pseudo autonomous monitoring system, because water distribution network segments could be controlled autonomously.

Also the proposed case does not consider such solution; a pseudo autonomous system is tuned for minimal operational costs, including maximization of non-stoppable service uptime, by maximization of battery lifetime.

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