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Wireless Sensor Networks for Optimisation of District Heating

Anatolijs Zabasta[1], Viesturs Seļmanovs-Pless[2], Nadezda Kunicina[1] and Leonids Ribickis[1]

1. Faculty of Power and Electrical Engineering, Institute of Industrial Electronics and Electrical Engineering, Riga Technical University, Riga 1045, Latvia

2. Micro Dators Ltd., Riga 1045, Latvia

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Abstract: The upgrading of the DH (district heating) system through installing WSN (wireless sensor networks)—a technology by which to monitor and control quality operation of the DH system will lead to more effective use of thermal energy, enabling also the provision of quality customer services, as the data concerning the status of the existing networks is available in a timely manner, and in the stated amounts. Over the last decades, the use of WSN systems in enabling quality monitoring of heat production and supply process has been widely discussed among various researchers and industry experts, but has been little deployed in practice. These researchers and industry experts have analysed the advantages and constraints related to the use of the WSN in district heating. A pilot project conducted by Riga Heat (the main heating supplier in Riga, Latvia) has allowed to gain a real life experience as to the use of the WSN system in district in-house heating substations, and is deemed to be a major step towards future development of WSN technologies.

Key words: District heating, GPRS, heating substation, wireless sensor networks, XML.

1. Introduction

District heating is a technology that transfers energy in the form of hot water or steam from a central heat plant to customers, used mainly for the supply of collective central heating in high density residential areas. DH (district heating) is distributed over heating pipes that are designed for the transfer of heat energy from the source of its origin (cogeneration heat and power plants, boiler houses and other facilities) to buildings [1]. This DH supply model is deployed also in Latvia.

District heating satisfies the demand of the greatest part of customers, both residential and industrial clients [2] (Table 1):

According to the Lithuanian District Heating Association around 10 TWh of heat energy per year is generated in the district heating supply sector. The key consumers of the said energy are apartment dwellers who consume 73% of the total heat energy consumed in the country. The total length of heat transmission networks (double pipes) of various diameters, used currently by Lithuania, constitute around 2,500 km [3]. The Latvian DH consumption structure is similar to the Lithuanian structure: nearly three quarters of DH is consumed by residents [4].

The most fundamental problem related to heat energy transfer is known to be loss of heat occurring during the heat transfer process, which is mainly due to insufficient insulation of distribution pipes, and as there are leaks in heating substations, which occur due to use of defective pipes and equipment. For example, in Sweden the average heat loss on DH networks constitutes ~7% [5]. Such low heat loss has been attained in Sweden due to use of lower system temperatures and relatively high ΔT [6]. In comparison

Corresponding author: Anatolijs Zabasta, Ph.D., research field: computer control of electrical technology. E-mail: anatolijs.zabasta@eudata.lv.

Table 1 District heating customers % by country.

Countries	Denmark	Finland	Iceland
% of DH used to satisfy demand of customers	29%	49%	93.9%

Latvia	Lithuania	Poland	Russia	Sweden
28.7%	50%	47%	63%	55%

with Sweden, in Russia energy loss on the distribution network can reach as high as 70%, as the systems are very old and badly maintained [6]. More detailed statistics concerning heat loss can be found in Section 3 of this research [7].

Shutdown of block type substations and other heat supply system modernisation works have allowed to substantially reduce heat loss across the Lithuanian DH system (from 32% down to 15%) [3]. In-depth statistics reports are regularly released by EuroHeat & Power, a pan-European trade association of district heating operators and related companies and associations, advising of various ways of how to use DH to meet the growing demand of residents and other customers, as well as of heat loss quantities [2].

Once the hot water is transported to the customer, a maximum amount of energy per volume of water should be extracted and used for heating purposes, such as hot tap water and space heating. To achieve a maximum ΔT, energy transfer between the distribution medium to the point of consumption should be maximized, while the temperature of the returning distribution medium should be minimized. The ΔT is one of the most important factors in district energy systems, because a large ΔT contributes to reduced flow in distribution network, as more energy (q) can be transferred at constant mass flow (m), if the temperature difference (ΔT) is increased according to Eq. (1):

$$q = \int_0^t c_p \dot{m} \Delta T dt \qquad (1)$$

An increased system ΔT also contributes to reducing the energy used within the distribution pump, as less volume is needed to obtain the same amount of energy. The distribution losses from the return pipes will also be reduced as the temperature gradient to the surroundings is decreased. If the supply temperature is lowered, the distribution losses from the supply pipes will also be reduced.

In traditional radiator-systems, the radiator-system supply temperature is based on the local outdoor temperature—sees T_{out} in Fig. 1 for a typical example of how the radiator supply temperature is dependent on local outdoor temperature. To achieve the correct radiator system supply temperature with varying outdoor temperatures, the flow through the primary side of the heat exchanger is controlled with a valve mounted in series with the heat exchanger (Fig. 1).

Therefore, there is a feed forward path, which measures the outdoors temperature and regulates the flow of the primary circuit to achieve a specific temperature towards the radiators. The colder the outdoors temperature, the hotter the temperature to the radiators. The feedback mechanism controlling the indoors temperature is the thermostatic valves located in radiator circuit. The flow through the radiator circuit is achieved with a fix speed pump.

1.1 Obstacles of Traditional District Heating

Let us overview the main issues across district heating domain:

System balancing: One key factor in obtaining a high ΔT across a district heating substation is deemed to be the radiator circuit supply temperature. Usually, the radiator circuit supply temperature depends on the local outdoor temperature, which ensures a stable indoor temperature. The relationship between outdoor temperature and primary supply is often assumed to be linear (colder outdoor air leads to a warmer primary supply). Different factors, such as wind, solar radiation or peaks in hot water consumptions, can notably impact the relationship between outdoor and primary supply temperature [8].

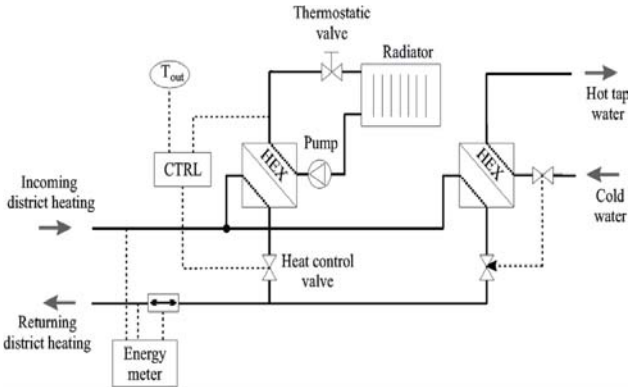

Fig. 1 Traditionally controlled district heating substation with outdoor temperature dependent radiator supply temperature control.

Another issue is related to adjustments in one part of the DH system that could cause unexpected deviations to other parts, evoking misbalance and even damage, therefore DH should not be considered as a set of independent autonomous systems.

The state of equipment control valves in the district heating substation often possess inappropriate dimensions, resulting in intermittent control, pressure shocks, and high return temperatures. A fouling valve that is stuck or does not move in accordance with the control signal may also be difficult to detect. Due to the high thermal time constant of a building, the indoor temperature is not directly affected. Therefore, an error in the control valve may be unnoticed for a considerable amount of time.

Small leaks in distribution pipes could remain unheeded for a long time, thus causing loss of hot water. It is not easy to identify places of leak, because the inspection is time-consuming, and is not always successful.

Client's fraud especially tampering of hot water meters causes loss of revenue and encourages such practice, when honest clients are forced to pay the bills that include stolen amount of hot water. Usually fraudulent behavior could be noticed only by inspection at client site [9].

Poor customer service the clients of heating companies: business and residents are eager to have the data concerning heat consumptions and the cost not only for the purpose of paying bills, but also for monitoring of their behavior in order to save expenses. Housing service providers need to have the data for rapid billing of such clients that leave their premises, or for analysis of possible leaks due to client's fraud [9, 10].

Dynamic load balancing is a method used to remove heat load peaks, and to divide power consumption between buildings. Dynamic load balancing is based on the presence of a large thermal time constant of each building. For instance, in a building with a high thermal time constant, the heating system can be turned off when the price of heat is high or during peak energy hours without causing any harm to clients. Such balancing is impossible without online automatic and independent action system to be used to decide which buildings will be shut down or provided a limited amount of thermal power [11].

2. The Purpose of the Research

The upgrading of the DH system through installing WSN (wireless sensor networks)—a technology by which to monitor and control quality operation of the DH system will lead to more effective use of thermal energy, enabling also the provision of quality customer services, as the data concerning the status of the existing networks is available in a timely manner and in the stated amounts. Over the last decades the use of WSN systems in enabling quality monitoring of heat production and supply process has been widely discussed among various researchers and industry experts, but has been little deployed in practice.

Therefore, this research aims to provide an overview of the technologies and methods by which to enable quality monitoring and control of DH systems, and to short-list the main problems and barriers to be overcome for broader application of WSN. This research is mainly based on the survey of various publications and pilot projects implemented in Latvia, Lithuania and Sweden.

3. Overview of Technologies and Main Problems

3.1 Advantages of Wireless Sensor Networks

Heat meter data can be collected using both network types—A traditional wire based or a wireless network. However, use of a wireless system allows to substantially simplify the installation of new sensors in the existing premises, as wireless architecture requires no wiring or drilling work, or any other such work, which eventually makes the whole process more cost effective and efficient.

Communication of information across a district heating substation contributes greatly to quality performance of the substation. For example, showing the difference of temperature between the supplied and returned temperature alerts that a building's substation is inefficient or has a malfunction, when the said difference is too small or too large [7]. Reduction of electrical energy consumption can be attained by reduced pumping through the distribution network and through increased efficiency if the actual ΔT data is available [11].

(1) Service quality: In order to prevent system failure all existing system components shall be periodically replaced with new components, having regard to their estimated shelf life, which is determined using fault statistics. However, statistics reveals only a trend, telling nothing about the specific equipment. With the wireless sensor network malfunctions in the substation are communicated to the provider of heat or home services, thereby detecting early faults or extending the in-use life of a component until it shows signs of aging. System faults and events are automatically recorded on a server and used for maintenance and analysis purposes. For client's convenience, in the case of unusual system behavior, alerts can be sent via e-mail or SMS.

(2) Geographical data: Each substation is able to provide the necessary information to the heat provider, such as the primary supplied and returned temperatures, as well as its through-flow. This information, assembled together from all the buildings in the district, allows a real time overlay to the map of the distribution area. One such map overlay can depict the distribution of heat over the network and energy losses in the ground over the portrayed area. This overlay also reveals the differences between buildings.

(3) Intersystem's cooperation: Communication to a central database operated by the heat provider encourages cooperation between the neighboring substations, and also between the heat plant and the customers to further reduce energy waste. Power consumption by residents and industrial clients has peak spread during the day, for instance, the demand for hot water increases between six and eight o'clock in the morning. Ref. [12] shows that buildings which have stored heat within their structure (i.e., thermal capacity) can reduce their space heating energy consumption in a coordinated fashion to minimise the peak heat demand without affecting indoor comfort. Such results can be attained without risking to affect the quality of services only on condition that the heat supplier possesses data concerning the status of the network.

The end result of such cooperation between the DH networks and ventilation systems in WSN accommodated buildings is an interdependent set of systems that cooperate among themselves by sharing information and support each other, therefore the peaks of load can be flattened out [5].

3.2 Constraints of Existing WSN Technologies

Over recent years, the SOA (service oriented architecture) technology has been deployed with good success by and large, distributing software systems with prime focus on business to business interaction. It is now becoming more and more important also in the field of device integration. Transferring the SOA "idea" to the device level is a promising approach to leverage ubiquitous intelligent devices and create new synergies between software systems and embedded devices [13]. SOA is able to support cooperative function between district heating system and other energy and comfort related system, e.g. ventilation, heat pumps, etc.. This approach will both enable energy savings and quality of service for indoor comfort. However, SOA application to deeply constrained devices such as sensor nodes is still an open research problem due to unresolved issues [14, 15], such as:

- Low data transmission speed from wireless sensor nodes to sinks;
- Limitations of processing capabilities of wireless sensor nodes;
- Low memory of sensor nodes that restrict the use of an excessive XML scheme;
- Limitation of battery power.

The above-mentioned constraints are mostly resolved using two approaches. The first approach is to use middleware in gateway devices for interaction with sensor networks. The second approach is to deploy interoperable SOAP (simple object access protocol) based web services on nodes without using gateway [16, 17].

The majority of research efforts have been directed towards using middleware software which runs on more capable devices or gateways [7]. This middleware is responsible for exposing the functionality of the whole sensor network as services using standard SOA technology. In this way, communication within the network still uses specialised, proprietary protocols; moreover, those service models are simplified although not standardised. 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. An example of such design was proposed by Aviles-Lopez and Garcıa-Macıas [13].

This approach has the benefit of leaving the resource-intensive tasks related to standard service implementation to the gateway, but it also has some drawbacks such as limitations of communication bandwidth, processing capabilities, and inability to support heterogeneity on the node level.

3.3 Results of the Riga Heat Pilot Project

Middleware in gateway devices has been best proven in practice when Riga Heat and Micro Dators conducted a joint pilot project, aiming to install wireless heat meter reading devices in 28 in-house district heating substations by which to transmit the collected heat meter readings to the system server several times per hour, enabling also "on demand" data transfer within a minute after the relevant request. For pilot project purposes, the two companies short-listed the most complex sites in Riga: the heating substations installed in the basements of various buildings located across the ancient part of Riga [18].

The main parameters to be measured and processed are:

Q = Current energy (MWh);
V = Current volume (m^3);
$T1$ = Current forward temperature (°C);
$T2$ = Current return temperature (°C);
$T1 - T2$ = Current temperature difference (°C);
P = Current power (MW);
F = Current flow rate (m^3/h).

All 28 substations were accommodated with Kamstrup Multical energy meters that enabled communication with external equipment using Multical protocol at logical level, and RS232 M-Bus connection at physical level. For pilot project purposes, RS232 interface connection was installed. Fig. 2 of this research shows the schematic of the technical solution for automatic collection of heat meter readings. The existing multical protocol was adjusted such that to enable transmission of two heat meter data collection requests, thereby attaining two data sequences which comprised all necessary data due for collection from the relevant heat meter. Table 2 of this reasearh shows a sample message so generated.

Fig. 2 A diagram featuring the technical solution for automatic collection of heat meter readings.

Periodical data transfer from heat meters to the system server was enabled using TCP/IP GPRS channel, whereas ad-hoc data was collected by way of GSM SMS, which is why the server was accommodated with a GSM modem. GSM system was used due to several reasons. First of all, there was no ready for use network with the required coverage in Riga but the GSM. Hence, substantial investments would have had to be made into the telecommunications infrastructure in order to conduct the pilot project. Moreover, the necessary radio tower installation works and the process of obtaining the relevant approvals for conducting such installations within the historic centre of the city would have taken a lot of time, adding also to the total project cost. Due to the existing time and budget restrictions it has been agreed to use the already existing ready for use network. GPRS has its advantages, as it enables collection of data from difficult to access heat meters, allowing also to use the existing mobile operator networks, to take benefit of the ongoing competition among the various network operators, and to faciliate necessary system upgrades and connect new customers without major investment. For instance, the monthly fee payable per SIM card has gone down to approximately 0.25-0.45 euro cents depending on the GSM operator and the actual number of connection points.

The automatic meter reading device TB1 manufactured by Micro Dators had an embedded Atmel microprocessor that acted as a "watchdog" and, upon detection of any operation failure, rebooted either the whole device or any of its sections. Telit Python GSM/GPRS modem in turn required the data from energy meters, recorded the said data, and then processed, stored and transferred further to the system server. The Multical energy meters were accommodated so that to store data in their memory, which allowed to read the data with the required frequency, and there was no need to store data at Python level.

The meter reading devices TB1 were accommodated with 220 V AC, as a result of which the devices could deploy full GSM modem capacity to enable connection to the server. The Multical energy meters in turn were operated by batteries with estimated battery shelf life from eight to ten years. The tests conducted within the framework of the pilot project revealed that frequent data collection requests, for example one request in every 60 seconds, would shorten the battery shelf life to approximately three to six months, hence this aspect needs to be taken into consideration at the time of planning automatic heat meter data collection across the district heating networks.

For pilot project purposes, OS Gentoo Linux system server and MySQL 5.0 database was used. The meter data was transferred over to the server in the following

Table 2 Sample message: seq 1:

0	1	2	3	4	5	6	7	8	9
0	0	43648	2886	2350	536	0	0	0	0
EQ	EV	Ht	T1	T2	T1－T2	Power1	Flow1	Peak pwr. act	Info
seq 2:									
10	11	12	13	14	15	16	17	18	19
4643705	0	3000	0	4200			34136	4720000	90422
Cust. No	TA2	TL2	TA3	TL3			ABCCC	DDEFFGG	Date

manner: the meter reading device TB1 periodically sends data collection requests to Multical, recording the data in its memory as small files with timestamps, which are then uploaded to the server and further arranged within the database according to the timestamp. Thus, almost all meter data reached the database, regardless of any GSM network interferences or TB1 device AC power outage. To ensure continuous operation of the TB1 devices during possible power outage lasting for more than 24 hours some of the TB1 devices were accommodated with batteries.

Data integration with third party IT systems (accounting, billing, real estate management and etc.) was enabled by way of web-based XML requests. Such approach allowed acquisition of the necessary meter readings for the stated period and in the required amounts, and within the respective range.

Main conclusions derived from the Riga Heat pilot project:

(1) The main problem related to district in-house heating substations installed in the basements of buildings was the lack of a reliable GSM signal. In order to guarantee the required signal parameters 10-20 meter long cables were used for antenna connection, which added to the existing cost;

(2) Communication with battery powered meters should not be more frequent than once per hour, as each data collection request activates the internal processor, which by default reduces the existing shelf life of the battery. Based on the project experience Micro Dators modified its meter reading devices, designing three new devices;

(3) A meter reading device which collects data straight from meters, and which deploys Atmel processor instead of Telit, as the Atmel is steadier in operation, while Telit is used only as a modem by which to process data to the server, and to receive commands from the server;

(4) A device that collects data from sensors-transmitters installed next to heat meters at client site. This device operates as a concentrator and, besides the Atmel processor and GSM modem content, deploys a 868 MHz radio receiver to receive messages from sensors. The concentrator is able to collect data from 30-120 neighboring sensors-transmitters, reducing considerably the cost per heating node, as the cost of a sensor-transmitter constitutes around 46% of the cost of a concentrator. This device was piloted in Rezekne town in the early part of 2012. A group of heating substations installed in the basements of apartment buildings were accommodated with 11 sensors-transmitters and two concentrators (a total of 12 such nodes). The cost of the devices used under this pilot project constituted only 59% of the cost of such solution, where nodes are accommodated with concentrators;

(5) A sensor-transmitter installed next to heat meters at client site. This device is accommodated with ATMEGA48/88 microprocessor, which receives impulses from meters, transforming them into mesages and transferring them over to the transmitter. The RFM22 transmitter transfers messages to the concentrator using 868 MHz frequency. The necessary power supply is enabled by way of a 3 V battery.

4. Conclusions

(1) This research has revealed the shortcomings of the existing DH monitoring system, such as lack of actual and historical data, and use of restrictive and static methods that do not allow to appropriately and efficiently tackle equipment failures, and to react to environmental changes and client behavior.

(2) The existing DH system is assumed to be a set of independent autonomous systems. However, the real life experience shows that adjustments in one part of the DH system could cause unexpected deviations to other parts, evoking misbalance and even damage.

(3) Use of WSN for the purpose of monitoring DH could notably improve the efficiency of the DH system by:

- maximising heat extraction from primary network circuits;

- alerting in the case of any heating substation equipment malfunction;
- improving the quality of services;
- providing necessary geographical information for system maintenance needs;
- minimising peaks of demand.

(4) The still pending DH issues as to how to apply SOA to deeply constrained devices, such as sensor nodes, need to be resolved in order to enable broader use of the WSN system.

(5) The pilot project conducted by Riga Heat has allowed to gain valuable experience as to the use of the WSN system in district in-house heating substations, and is regarded to be a major step towards further WSN technology development.

References

[1] M. Young, District Heating, The Technical Writer's Handbook [Online], Mill Valley, CA: University Science, 1989, http://en.wikipedia. org/wiki/District_heating.

[2] EuroHeat and Power, District heating and cooling, Country by country 2010 survey [Online], http://www.euroheat. org/Statistics-69.aspx.

[3] A. Janukonis, Lithuanian District Heating Association, Lithuanian heat sector: Today based on imported fossil fuel, tomorrow—on local bio fuel and wastes, http://www.worldenergy.org/documents/congresspapers/239.pdf.

[4] Latvia District Heating Associatio, Heat supply in Latvia, 2010, http://www.lsua.lv/en/index. php?option=com_content&task=view&id=4&Itemid=5.

[5] Swedish Energy Agency, Energy in Sweden 2007, http://www.energimyndigheten.se.

[6] J. Gustafsson, Wireless sensor network architectures as a foundation for efficient district heating, Dr. Thesis, Lulea University of Technology, Lulea, Sweden, 2011, pp. 1-224.

[7] P. Lauenburg, Improved supply of district heat to hydronic space heating systems, Ph.D. Thesis, Lund University, Lund, 2009, pp. 1-160.

[8] J. Gustafsson, J. Delsing, J. van Deventer, Improved district heating substation efficiency with a new control strategy, Applied Energy 87 (6) (2010) 1996-2004.

[9] Research on Justification of Development of the System for Monitoring and Control Water Resources, Latvia-Lithuania Cross-border cooperation program, project Innovative e-services for water supply management, LLIII-127 E-Water, 2011, unpublished.

[10] A. Zabasta, N. Kunicina, Y. Chaiko, L. Ribickis, Automatic meters reading for water distribution network in Talsi city, in: Proceedings of EUROCON 2011, Lisbon, Portugal, Apr. 27-29, 2011, pp. 1-6, http://ieeexplore.ieee.org/Xplore.

[11] F. Wernstedt, P. Davidsson, C. Johansson, Demand side management in district heating systems, in: Proceedings of the 6th International Joint Conference on Autonomous Agents and Multiagent Systems, New York, USA, 2007.

[12] F. Wernstedt, C. Johansson, J. Wollerstrand, Sankning of return temperatures through load managemengt, 2008.

[13] E. Aviles-Lopez, J.A. Garcıa-Macıas, TinySOA: A Service-Oriented Architecture for Wireless Sensor Networks, Service Oriented Computing and Applications, vol. SOCA 3, Springer-Verlag, London, 2009, pp. 99-108.

[14] J. Yick, B. Mukherjee, D. Ghosal, Wireless sensor networks: A survey, Computer Networks 52 (2008) 2292-2330.

[15] W. Su, I.F. Akyildiz, Y. Sankarasubramaniam, E. Cayirci, Wireless sensor networks: A survey, Computer Networks 38 (2002) 393-422.

[16] D. Barisic, M. Krogmann, G. Stromberg, P. Schramm, Making embedded software development more efficient with SOA, in: 21st International Conference on Advanced Information Networking and Applications Workshops (AINAW'07), Washington, USA, 2007, pp. 1-6.

[17] DPWS, Devices Profile for Web Services Version 1.1, OASIS Std. [Online], Feb. 2011, pp. 1-43, http://docs.oasis-open.org/ws-dd/dpws/1.1/os/wsdd-dpws-1.1-spec-os.pdf.

[18] Aquamet HeatMet manual, Riga Heat Project, 2009-10, Micro Dators ltd., IT House / ITH Group, unpublished.