RIGA TECHNICAL UNIVERSITY

Faculty of Power and Electrical Engineering Institute of Industrial Electronics and Electrical Engineering

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PhD student of the doctoral program “Computer control of electrical technology”

DEVELOPMENT OF COMPUTER CONTROL METHODS AND APPROACHES FOR CRITICAL INFRASTRUCTURE INTERDEPENDENCIES ANALYSIS

Summary of Thesis

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Riga 2014

UDK 621.3(043.2)
Za 010 d

Zabašta A. Development of computerised control methods and approaches for critical infrastructure interdependencies analysis.-R.: RTU Press, 2014. - 26 pages.

Printed according to the decision of RTU doctorate board — RTU P-14 on 15th May 2014 protocol Nr. 77.

This work has been supported by the European Social Fund within the project "Support for the implementation of doctoral studies at Riga Technical University".

ISBN 978-9934-10-581-4

DOCTORATE WORK
PRESENTED TO OBTAIN THE DOCTOR'S DEGREE IN ENGINEERING SCIENCES

Doctoral thesis for the doctor's degree in the engineering sciences was publicly presented on the meeting of RTU P-14 Doctorate board 15.07.2014 in Riga Technical University, Kaļķu str. 1–119.

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CONFIRMATION

Hereby I confirm that I have worked out the present doctoral thesis, which is submitted for consideration to the Riga's Technical University for the degree of Doctor of engineering sciences. Doctoral thesis has not been submitted in any other university for obtaining the Doctor‘s degree.

Anatolijs Zabašta: …………………………….

Date: ………………………

The doctoral thesis is written in Latvian language, contains: introduction, 5 chapters, conclusions, 91 references, 5 attachments, 57 figures, total 155 pages.

TABLE OF CONTENT

Actuality of theme

Critical infrastructure's (electricity, heat, water, and information and communication technology networks) security, stability and reliability are closely related to the interaction phenomenon. If interacts a number of large-scale critical infrastructures, the direct links between its elements create feedback that can lead to mutual influences.

Due to the increasing amount of data transferred, increase a dependence on telecommunications and internet services, so data integrity and security is becoming a very important aspect for the utility services providers and energy suppliers. In such circumstances, the need is increasing for methods and tools that enable infrastructure managers to evaluate and predict their critical infrastructure operations as the failures, emergency or service degradation occur in other related infrastructures.

The study aims

The goal of the thesis is to develop a model, methods and metrics that enable quantitative evaluation of electric power and telecommunications infrastructure critical impact on the water supply of critical infrastructure, where the level of service or service interruption of electricity supply and telecommunications infrastructure threatens water supply infrastructure operation and verify the correctness of the approach developed by the real infrastructure example.

Research objectives

1. Research the critical infrastructures interdependences' assessment methods and provide a method for assessing the power and telecommunications infrastructure critical impact on the water supply critical infrastructure in urban areas.
2. Offer metrics that enable quantitative evaluation of electric power, telecommunications and water supply, critical infrastructure mutual influence.
3. Develop a simulation model for assessing power and telecommunications infrastructure critical impact on the water supply of critical infrastructure in urban areas where the level of service or service interruption of electricity supply and telecommunications critical infrastructure threatens water supply critical infrastructure operations.
4. Using a simulation model and developed metrics, to provide a quantitative evaluation of electrical and telecommunication critical infrastructure nodes on the water supply infrastructure nodes in one Latvian town.
5. Explore technical solutions, technologies, and ways to control the water supply network node status using wireless sensor networks.

Scientific novelty

1. The thesis research critical infrastructure implications, assessment methods and offers specific metrics that allow a quantitative estimate of electricity, telecommunications and water supply critical infrastructures interdependencies.
2. The thesis presents a simulation model based on modern theory and technology with the aim of exploring the interdependencies of critical infrastructures.
3. Using a simulation model, is experimentally tested a method that allows to explore the water supply network nodes the average down time dependence on the battery life time and the battery replacement time cross- correlations, within the parameters set, when outages in power infrastructure arise and taking into account also the impact of telecommunication nodes.
4. The paper examines and develops the technical solutions that allows controlling the state of the water supply network nodes using wireless sensor networks.

This study is the first one in Latvia and in the Baltic countries, which develops and experimentally tests the model that simulates three critical infrastructure mutual influence and quantitatively measures its interdependences.

Research methods

Analysis of the problem, the solution hypothesis, analysis and synthesis, holistic - reductionist approach and modelling, infrastructures interaction modelling with UML tools, computer modelling and simulation of interaction with MatLab® Simulink® StateFlow tools, a multi-criteria optimization method, mathematical statistics method, experimental design and processing software program EDAOpt.

The results are presented and discussed in nine international conferences (see Annex 1).

Practical application

The method described in this study will help critical infrastructure managers operating in a common area to assess the impact of infrastructures interdependencies and plan risk reduction measures. For example, if the power operator is aware of their impact on the telecommunication, transport or water supply critical infrastructures, it can identify restoration priorities for action in emergencies. Alternatively, water supplier, recognizing electrical supply failure risks may decide to reserve the power of water supply network nodes.

List of author publications 2010 – 2014

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Structure of the thesis

The thesis is divided into five chapters.

The first chapter analyses the different approaches described in the literature that are used to simulate the critical infrastructure interdependencies.

The second chapter explores the critical infrastructure modelling and simulation studies carried out to review.

In the third chapter the author examines the critical infrastructure's interaction and quantitative characteristics, undertakes metrics analysis and classification.

In the fourth chapter metrics approbation is done by examining three infrastructures (electricity, telecommunications and water supply network) interdependencies effect by using the simulation model.

In the fifth chapter, the author analyses the problems encountered by technicians and researchers who puts into practice the computer control techniques for the critical infrastructures, using wireless sensor networks, and describes the technical solutions developed in reviewed projects.

1. Methods and approaches for analysing of critical infrastructures interdependencies

This work uses by Rinaldi [5] proposed classification, by which interdependencies are classified as: *physical*, *cybernetic*, *geospatial* and *temporal*. The focus is only on the phenomena associated with critical infrastructure service quality and/or functional degradation.

In order to determine the interdependency index, the abstract concept of "*inoperability*" is used. Inoperability means the infrastructure or its components failure to comply with its intended function.

Based on the definition of interdependence, it can be concluded that the growth inoperability in one infrastructure contributes to the increase inoperability in the other infrastructure, which is expressed by (1.1) [2]

$$\frac{A \Leftarrow B}{\mu_{A,i}^{T}, \mu_{B,j}^{T}} \rightarrow \Delta x_A(t) = \phi(t, x_A^0, x_B^0, \Delta x_B^0) \ , \tag{1.1}$$

where t $\in$[t_0,t_0+T], but x_A^0 shows infrastructure *A* inoperability level, measured by metric $\mu_{A,I}$ before impact from infrastructure *B*; x_B^0 shows infrastructure *B* inoperability level, measured by metric $\mu_{B,I}$ before inoperability appears. Δx_A represents the level of inoperability of the infrastructure *A* in conjunction with inoperability level grows increase in *B*. *T* a period in which the inoperability effect was observed.

According to this definition, it is easy to define *dependency index*: dependency index is the ratio between the inoperability increases in dependent infrastructure to inoperability increase in influencing infrastructure. Then the index (1.2) is measured as the degree of dependence between the two infrastructures that respond to inoperability causing in one of the infrastructures:

$$\delta_{A,B}^{T} = (\int_{t_0}^{t_0+T} \Delta x_A(\tau) d\tau) / (\int_{t_0}^{t_0+T} \Delta x_B(\tau) d\tau) . \tag{1.2}$$

Note that the *dependency index* depends on a large set of parameters (1.3):

$$\delta_{A,B} = \delta_{A,B}(x_A^0, x_B^0, \Delta x_B^0, \Delta x_A, \eta_{A,i}, \eta_{B,j}, t_0, T) . \tag{1.3}$$

Inoperability level changes in infrastructure *A* can be expressed with respect to the dependence on infrastructure components *q*. Infrastructure A depends on the components *q*, respectively, with the rise in the level of inoperability in components *q*, then increase the level of inoperability of infrastructure *A* in general:

$$\Delta x_A(t) = \phi(x_A^0, x_q^0, \Delta \mathring{x}_q) \text{, where } t \in [t_0, t_0+T]. \tag{1.4}$$

Here *q* may belong to both A infrastructure and other infrastructure *B*. It can be concluded that the *dependence index* is characterized by a level of dependency of infrastructure *A* for all *n* components of the infrastructure *B*. Therefore, dependency index will be defined as follows:

$$\left\langle \delta_{A,B(q)}^{T} \right\rangle_W = \frac{1}{n} \sum_{i=1}^{n} w_i [\int_{t_0}^{t_0+T} \Delta x_A(\tau, q_i) d\tau] / [\int_{t_0}^{t_0+T} \Delta x_B(\tau, q_i) d\tau] =$$
$$= \frac{1}{n} \sum_{i=1}^{n} w_i [\int_{t_0}^{t_0+T} \phi_A(\tau, x_A^0, x_B^0, \Delta \mathring{x}_{qi}) d\tau] / [\int_{t_0}^{t_0+T} \phi_B(\tau, x_A^0, x_B^0, \Delta \mathring{x}_{qi}) d\tau] , \tag{1.5}$$

where w_i is each component *q* weight $w_i \in [0,1]$.

The relative length $R_{i,j} = T_j / T_i$ is defined as the ratio of idle time T_j of infrastructure *J* and downtime T_i infrastructure *I*, which becomes the cause of the failure downtime of *J* infrastructure.

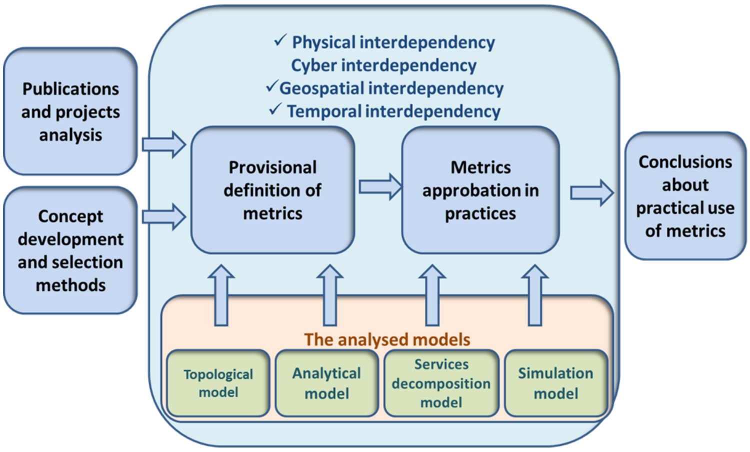


Fig. 1.1. The method used in the research

The thesis explores the *physical*, *cybernetic*, *geospatial and temporal dependences*, when the priority is put forward, as the data availability and granularity. The study proposed method uses a *holistic*, *topological*, *holistic - reductionistic*, *analytical and simulation* approaches.

CI named dependency in the following chapters of the study are analysed using four models: *topological*, *analytical*, *service decomposition and simulation* model, and each model offers appropriate metrics for CI interaction qualitative and quantitative analysis (see Fig. 1.1.).

2. Analysis of critical infrastructure interdependency models

Based on data *availability and granularity* approach, the author of the study analysed the modelling methods in terms of infrastructure interdependency types and reached conclusions about the use of models (see Fig. 2.12. Figure).

Topological model is successfully used to study the physical and cyber interdependences; however, it is poorly suited for geospatial interdependency research and is not applied to the temporal dependence. Seen from the point of view of scalability, the *topological model* is suitable for different sizes of networks, taking into account the model development and analysis costs.

The analytical model is clearly used to simulate the physical, cyber and temporal interdependence. Meanwhile, geospatial interdependence was not comprehensively modelled. Based on the model development and set up costs, the *analytical model* is very close to the simulation model. Although the analytical model requires less computing resources, developments of feedback links and the transformation function requires more human resources.

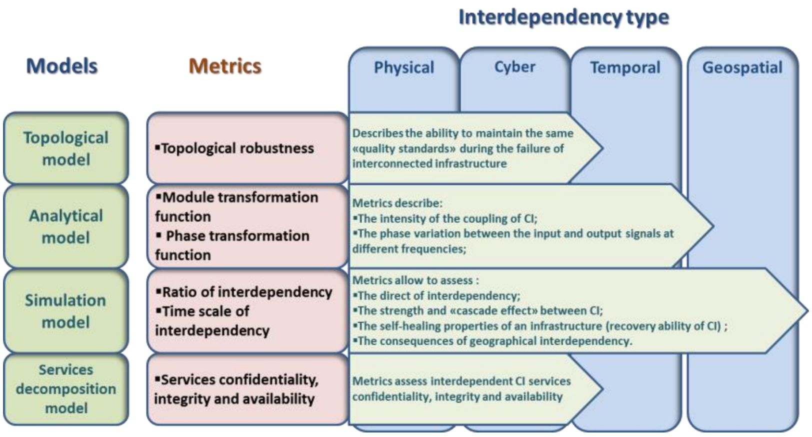


Fig. 2.12. The models used for CI interdependency studies

This chapter reveals that the *Service Decomposition* model is successfully used to study the interdependence between water distribution networks, which demonstrates its dependence on electricity supplier services, and telecommunications service provider, using risk-based methodology.

The *simulation model* makes it possible to simulate all types of interdependence (see Fig. 2.12). The *simulation model* is the most suitable for the modelling and simulation physical, cyber and temporal consistencies, which leads to the water supply network failures and faults that occur due to failures in electricity and telecommunications networks. So simulation model is used to analyse the interaction of the three CIs in particular example in Chapter 4.

3. Metrics analysis of critical infrastructure

To assess the interaction between infrastructures nodes, the author use *Ratio of Physical Dependency (RPD), Ratio of Cyber Dependency (RCD) and Ratio Geospatial Dependency (RGD)* [1].

Ratio of physical dependency water infrastructure:

$$RPD_{WN} = \frac{N(WN\,|\,PN)}{N(PN)}, \tag{3.1}$$

where $N(NP)$ is a power supply node malfunction ratio and $N(NW|NP)$ is a water supply network nodes malfunction proportion due to the energy supply failures.

Ratio of physical dependency telecommunication infrastructure:

$$RPD_{TN} = \frac{N(TN\,|\,PN)}{N(PN)}, \tag{3.2}$$

N(NP) is evaluated as the number of the energy infrastructure or its components degraded the quality of the services due to external events in the time interval *T*.

Ratio of Cyber Dependency**:**

$$RCD_{NP} = \frac{N(NP\,|\,NT)}{N(NT)}, \tag{3.3}$$

where *N(NP)* is a power supply node malfunction ratio and *N(NP|NT)* is a power supply node malfunction proportion due to interruption of telecommunication services.

Ratio of Geospatial Dependency:

$$RGD_{NWTP} = \frac{N(NW\,|\,NP)}{N(NP)} + \frac{N(NT\,|\,NP)}{N(NP)} + \frac{N(NP\,|\,NT)}{N(NT)}, \tag{3.4}$$

where *N(NW|NP), N(NT|NP)* and *N(NP|NT)* water, telecommunications and electricity infrastructure dependency ratio due to geospatial factors.

Looking at ratios (3.1)-(3.4), can be accepted, as it can be lower, higher or equivalent to “1”. If $N(NW|NP)/\, N(NP) \geq 1$, it means that the water supply network nodes have a strong dependence on the electricity supply network nodes.

Temporal scale of interdependencies:

The concept of *Temporal scale of interdependencies* can be used in a scenario in which the electricity, telecommunications and water supply network interaction, in order to measure *Temporal scale of physical interdependencies (TFI)* and *Temporal scale of cyber interdependencies (CFI).*

Water supply nodes *Temporal scale of physical interdependencies:*

$$TFI_{NW} = \frac{T(NW)}{T(NP)} \tag{3.5}$$

Telecommunication network nodes *Temporal scale of physical interdependencies:*

$$TFI_{NT} = \frac{T(NT)}{T(NP)}, \tag{3.6}$$

Power supply network nodes *Temporal scale of cyber interdependencies:*

$$TCI_{NP} = \frac{T(NP)}{T(NT)}, \tag{3.7}$$

In addition to the metrics defined in Chapter 2, the metrics are defined:

- ***Network topological robustness = <1 - P2 >.***
- Researching the ***analytical approaches*** based models the metrics are defined:
  - ***Module transformation function*** $|G(j\omega)|$, which provides metrics by which one can measure the link between infrastructures, which interaction is modelled.
  - ***Phase transformation function*** $\angle G(j\omega)$, which analyses the phase difference between the input and output signals in different frequency bands.
- Researching the ***service decomposition*** principle-based models the metrics are defined:
  - ***Confidentiality***: the absence of unauthorized disclosure of information concerning the data used for critical infrastructure;

- ***Integrity***: the absence of unauthorized changes in the systems for critical services;
- ***Availability***: readiness to provide critical services at the appropriate level of service.

The results are summarized in the Table 3.1:

Table 3.1

Metrics for assessing the interaction of critical infrastructures

Nr.	Metrics	Interdependency type			
		Physical	Cyber	Geospatial	Temporal
1	Ratio of physical dependency	Yes	Yes	Yes	No
2	Ratio of cyber dependency	Yes	Yes	Yes	No
3	Ratio of geospatial dependency	Yes	Yes	Yes	No
4	Temporal scale of physical interdependency and Temporal scale of cyber interdependency	No	No	No	Yes
5	Network topological robustness	Yes	Yes	No	No
6	Module transformation function and Phase transformation function	Yes	Yes	No	Yes
7	Services confidentiality, integrity and availability	Yes	Yes	No	No

4. Electricity, telecommunications and water supply network node interdependence model development and simulation

The proposed simulation scenario simulates water distribution network (WDN) nodes interaction with electricity and telecommunications network nodes.

An assumption is made:

- A model allows to explore the water supply network nodes the average down time dependence on the battery life time and the battery replacement time cross-correlations, when outages in power infrastructure arise and taking into account also the impact of telecommunication nodes.
- It is possible to examine the interaction with a polynomial, and minimize the water supply network nodes the average down time within bound parameters.

$$R_{i,j,k} = f(t, m_j^1, m_j^2, \dots m_j^p, m_k^1; m_k^2 \dots m_k^p; m_i^1, m_i^2 \dots m_i^r) \to \min,$$

where

$$m_j^l \in M_j; m_k^n \in M_k; m_i^r \in M_i$$

$R_{i;j}$ - function $f(.)$ time t. A specific set of metrics: M_j (power supply network), M_k (telecommunication network) and M_i, (water supply network), used to measure infrastructures *j*, *k and i* performance level.

Water distribution network nodes parameters selection

Backup battery life time lifetime (BLT): based on a preliminary analysis, the selected water supply network nodes running time of the backup power supply is assumed 0.1–6 hours.

Backup battery replacement time (BRT) is assumed 4–48 hours.

Power supply network nodes parameters selection

Parameters of power supply node were selected by analysing the SAFI, SAIDI and CAID data of Talsi and Ventspils distribution network regions and total data about Latvia of 2011. Model parameters are calculated using the above data (see Table 4.3).

Table 4.3

Model parameters: mean time to repair and mean time to failure

Parameters (hours)	Talsi	Ventspils	Latvija
Average mean time to repair (MTTR average)	2.00	1.98	2.81
Maximum mean time to repair (MTTR max.)	6.05	7.02	Not available
Average mean time to failure (MTTF average)	43817	66235	1564
Minimum mean time to failure (MTTF min.)	13519	20278	Not available

- As a result, the model uses the following parameters:
- *Mean time to failure*: 1564 : 5 = 313 hours. (200–500 h.)
- *The simulation time* is limited 4000 hours that enables 9-12 cycles.
- *Mean time to repair*: 2.81 hours (±2б = 0.28 – 5.34 h.)

Telecommunications (GSM) network nodes parameters selection and justification

Mean time to failure (MTTF): the model simulation results are used.

Backup battery life time lifetime (BLT) - according to the regulations TELE 2 base station backup power supply length is designed for 2 hours. The assumption was made that the minimum and maximum duration to be used in the model: 0.1–5 hours.

Mean time to repair – TELE 2 for backup power sources uses portable generators. A pessimistic assumption is done that the replacement of a battery or connection of a portable generator can last from 3 to 32 hours.

Model description

This study used MatLab® Simulink® StateFlow modelling and simulation tool as a popular engineering and scientific modelling tool. Figure 4.3 depicts the system model, which includes a power supply node, a telecommunications network node and three WDN nodes.

In addition, 4.4. Figure shows a simulation model of the part representing the water node operation.

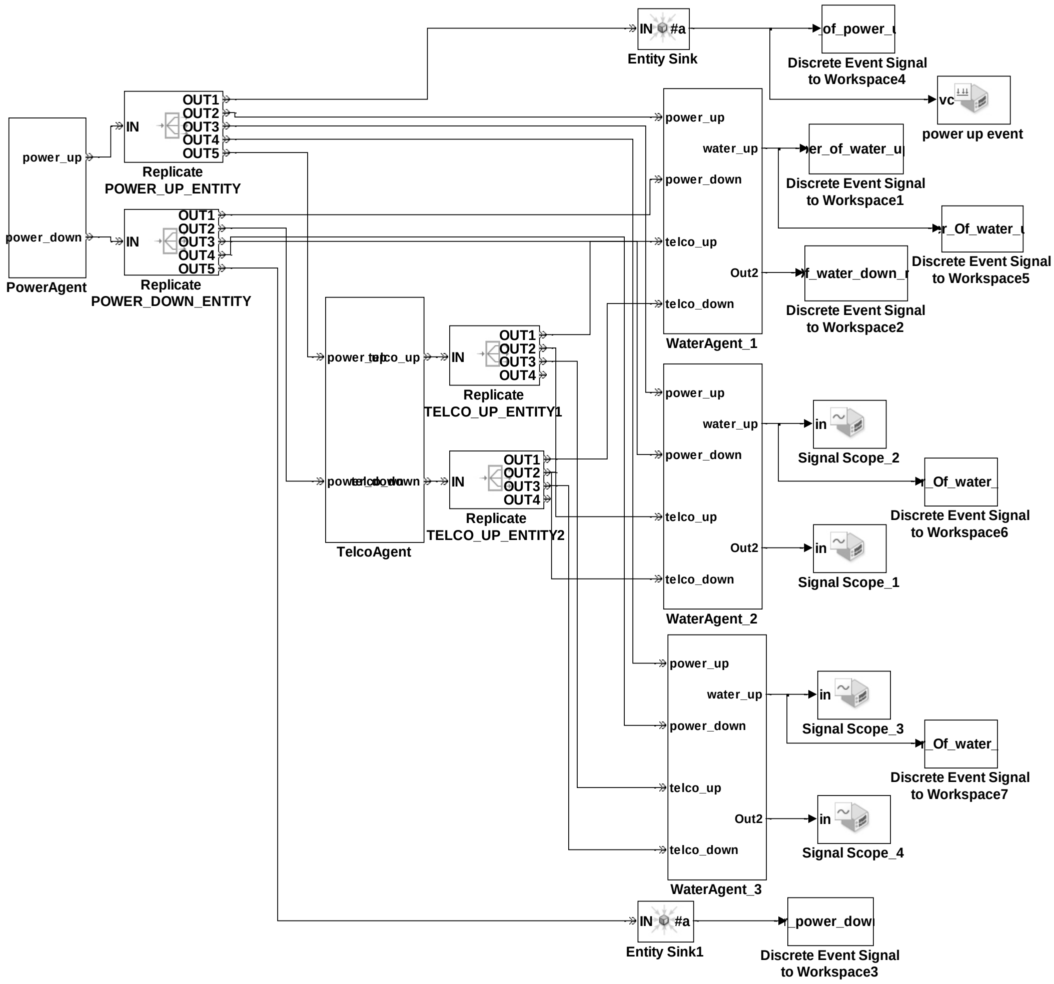


Fig. 4.3. The system model, which includes power supply, telecommunications and water supply network nodes

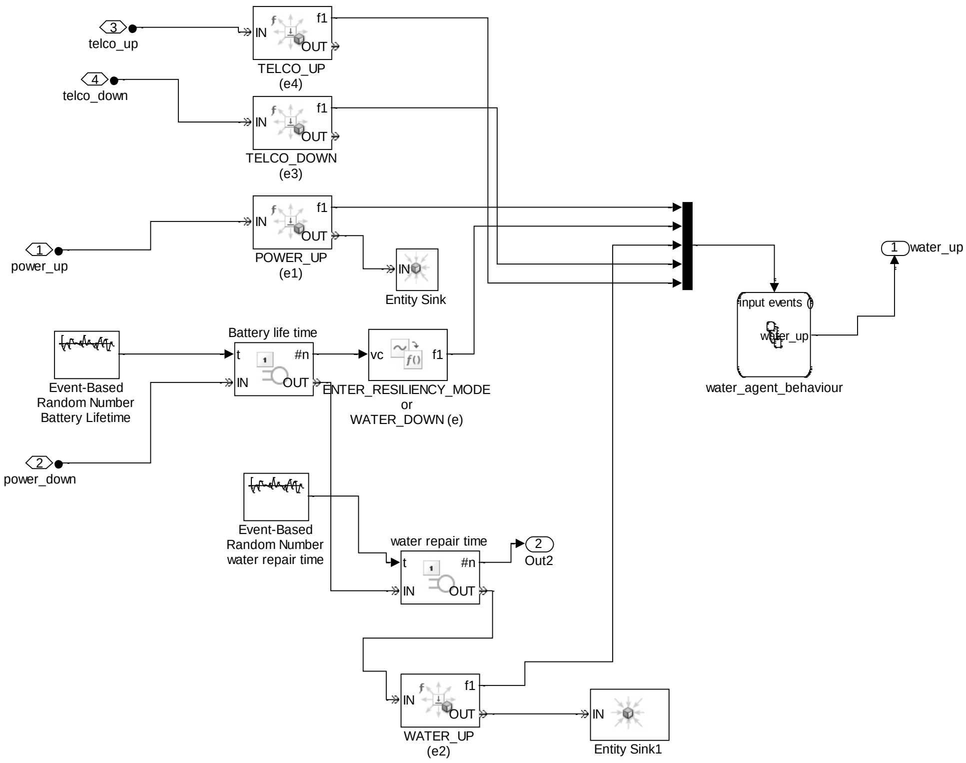


Fig. 4.4. A part of the model representing water node operation

Water inputs to node (see Fig. 4.4) are provided with exits from the power supply model: average downtime ("power_down") and mean time between failures ("power_up"). Inputs from the telecommunications network node model comes in the form of downtime ("telco_down") and as a restoring the signals ("telco_up"). The first random numbers generator generates BLT, and the second random number generator generates BRT parameters.

"State flow chart" (SFC) at Fig. 4.5a switches between water node states "water up", "water node in resilience mode" (receives power from the backup source) and "water down", when the node is not working in normal mode due to power supply or telecommunications infrastructure failures. Fig. 4.5b shows the interaction between inputs, functions and ports of the SFC water node.

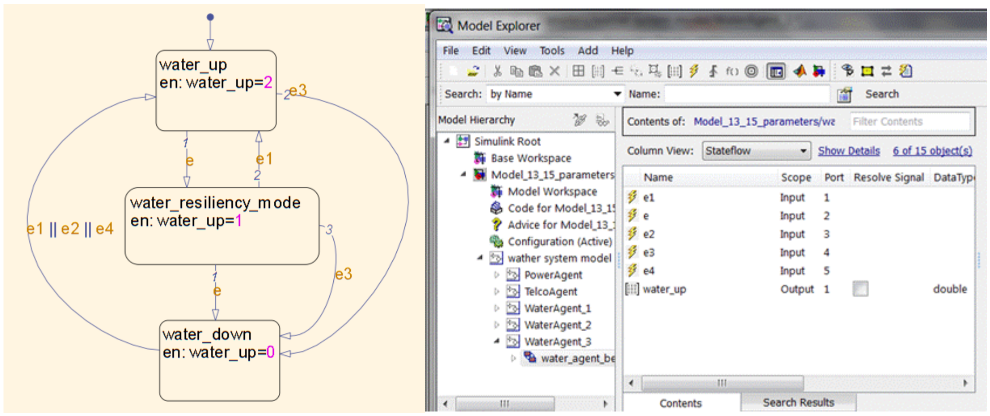


Fig. 4.5. a) Water node „State Flow Chart"; b) Model Explorer, which shows the interaction between inputs, functions and ports of water node SFC

Figure 4.6 depicts the number of power nodes downtime, while figures 4.7 and 4.8 show the water supply network node state, where "2" means the normal operating mode, "1" - node provides its functions using a backup power source, and a "0" - node is not functioning due to lack of power, or due to the fact that telecommunications network node is not available.

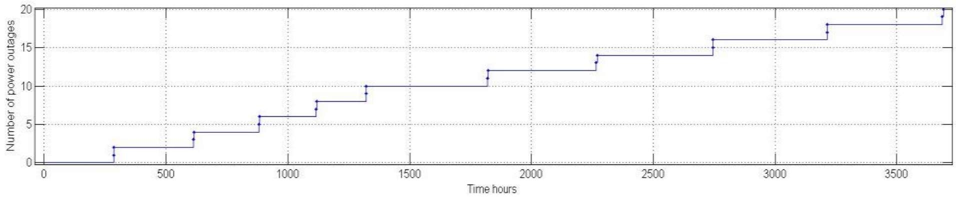


Fig. 4.6. Power supply node downtime during the simulation

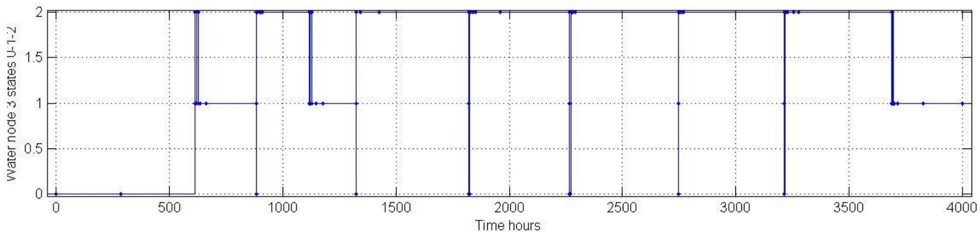


Fig. 4.7. Water supply network node (W1) downtime during simulation: 0-1-2

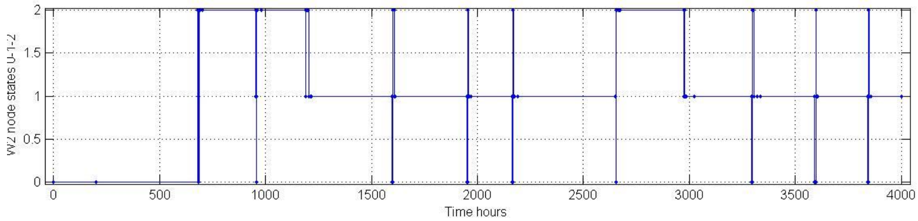


Fig. 4.8. Water supply network node (W2) downtime during simulation: 0-1-2

The model simulation results are summarized in the Table 4.4. Detailed simulation results are in the Attachment 3.

Simulation results show the close relationship between the power supply nodes failures and downtimes in water distribution networks, because:

Ratio of physical dependency $RPD_{NW} = \dfrac{N(NW \mid NP)}{N(NP)}$ = 116/150 = 0.77

WDN average downtime 2:36 hours and power supply nodes average downtime is 2.69 hours, so the time scale of physical dependency ratio:

Temporal scale of physical interdependencies: $TPI_{NW} = \dfrac{T(NW)}{T(NP)}$ = 0.88.

If one uses average water nodes downtime, given the number of power network nodes downtime, 1.80 hours, then:

$$TPI_{NW} = \frac{T(NW)}{T(NP)} = 0.67.$$

Table 4.4

The model simulation results summary

Simulation results								
Simulation numbers	1	2	3	4	5	6	7	8
Water distribution network backup battery lifetime (h)	0.1	3	6	1.5	4.5	5.5	2.75	1
Water distribution network backup battery replacement time (h)	48	24	4	36	12	46	43	38
Water distribution network average downtime (h)	2.27	2.34	1.49	1.81	2.12	2.65	2.14	1.75
Power supply network average downtime (h)	2.34	2.34	2.34	2.55	2.55	2.55	2.49	2.49
Temporal scale of physical interdependencies of water nodes	0.97	1.00	0.64	0.71	0.83	1.04	0.86	0.70
Water distribution network average downtime, given the number of power network downtimes (h)	2.27	1.56	0.99	1.92	1.65	1.77	1.71	1.81
Temporal scale of physical interdependencies of water nodes, given the number of power network downtimes (h)	0.97	0.67	0.42	0.75	0.65	0.69	0.69	0.73

Simulation results								
Simulation numbers	9	10	11	12	13	14	15	Average
Water distribution network backup battery lifetime (h)	4	2.5	1.75	5	0.5	3.5	2	
Water distribution network backup battery replacement time (h)	32	28	22	19	15	10	6	
Water distribution network average downtime (h)	2.88	3.16	1.74	3.62	2.42	2.60	2.46	**2.36**
Power supply network average downtime (h)	2.49	3.16	3.30	3.30	2.80	2.80	2.80	**2.69**
Temporal scale of physical interdependencies of water nodes	1.16	1.00	0.53	1.10	0.86	0.93	0.88	**0.88**
Water distribution network average downtime, given the number of power network downtimes (h)	1.73	2.01	1.74	1.98	2.42	1.82	1.57	**1.80**
Temporal scale of physical interdependencies of water nodes, given the number of power network downtimes (h)	0.69	0.64	0.53	0.60	0.86	0.65	0.56	**0.67**

The experimental results demonstrate not only the lack of an escalation effect, but also the WDN significant reduction of downtime, because the temporal scale of physical dependency ratio, taking into account the power supply node downtime number, is 0.67

The polynomial approximation of the experimental results

Simulation data have been processed by EDAOpt experimental results processing tool developed by researchers of RTU.

The analysis of the WDN nodes average downtime ratio dependence on backup battery lifetime (BLT) and backup battery replacement time (BRT) cross-correlation parameters specified parameters is made. Fig. 4.10 depicts in two-and three-dimensional images that demonstrate the correlation between the water WDN nodes BLT, BRT and WDN nodes downtime.

EDAOpt computed the polynomial coefficients of the quadratic approximation with one attempt exclusion.

$$R = 2.3532 – 0.3894*X_1+ 0.00812*X_2+ 0.0289*X_1*X_1+ 0.0035*X_1*X_2$$

In its turn, the quadratic approximation with the exclusion of two attempts gave the following polynomial:

$$R = 2.2919 – 0.4901*X_1+ 0.0201*X_2+ 0.0448*X_1*X_1+ 0.0037*X_1*X_2$$

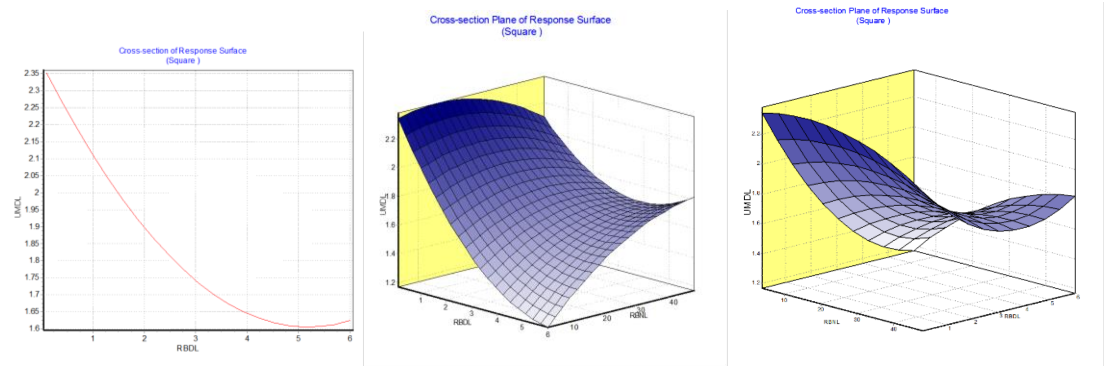


Fig. 4.10. Quadratic approximation with one attempt exclusion

The following local approximation is carried out with the aim of identifying possible local minims. Looking at Fig. 4.11, one can see at least two local minimums within modelling parameters set.

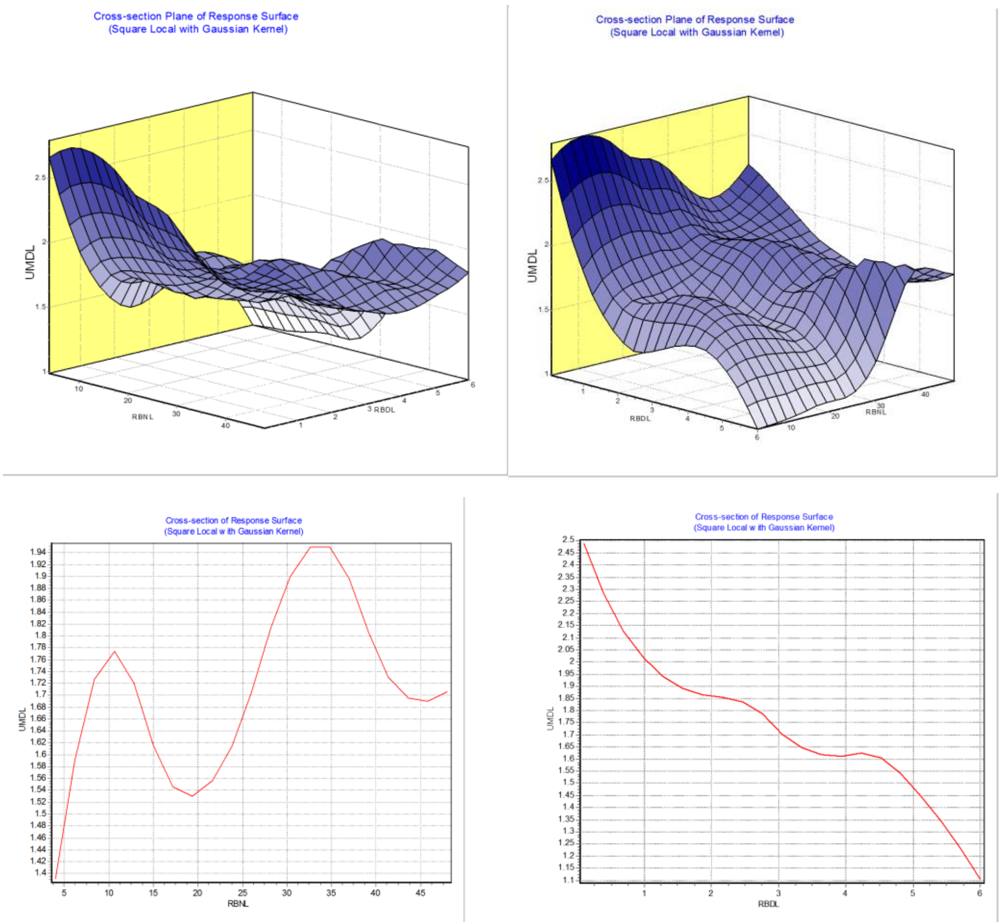


Fig. 4.11. Local quadratic approximation with one attempt exclusion

5. Critical infrastructure computer control methods using wireless sensor networks

This section describes two technical solutions developed in projects involving the dissertation author.

Description of computer control system for water distribution network in Talsi (from 2009 to 2011)

Talsi computer control system for water distribution network technical solutions [4] can be viewed Figure 5.1.

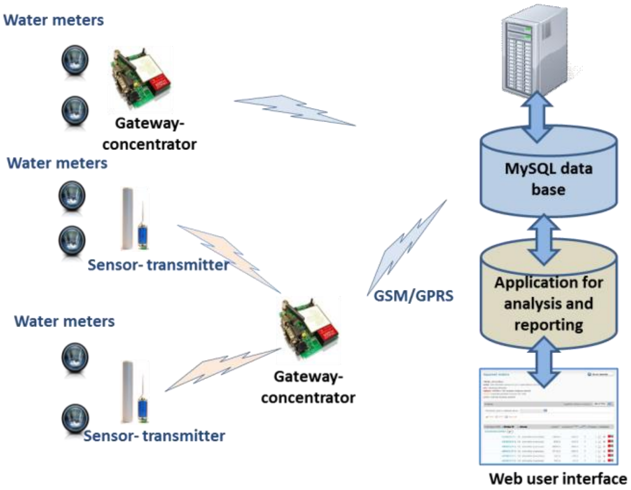


Fig. 5.1. The block diagram of the technical solution (Zabašta [6])

The control system uses the following solutions:

- Water flow and water pressure meters with pulse outputs provide data to the sensors - transmitters. They are equipped with hercon relay, which converts magnetic signals to electrical impulses;
- Data transmitting from the sensors to gateways - concentrators using the "Short Range Devices" (SRD) unlicensed band 868 MHz telemetry;
- GSM network (GPRS) is used for data transmission between the gateway - concentrators and the server;
- MySQL database is used for the measurement data storage and processing;
- System user’s access to the database is implemented through a Web interface.

This solution ensures the following benefits:

- Central server can be deployed on any Latvian or foreign data centre, which is connected to the Internet;
- Selection of any available GSM network operator or multiple operators at the same time;
- Using the existing mobile operator networks and telecommunications network investment in infrastructure are kept at minimum;
- Advantage of competition between network operators, choosing the best prices and services;
- Deployment of new customers without large capital investments;

Gateway - concentrator, shown at Fig. 5.2 periodically receives the measurement data sent from the water flow and water pressure meters and transmits them to the server.

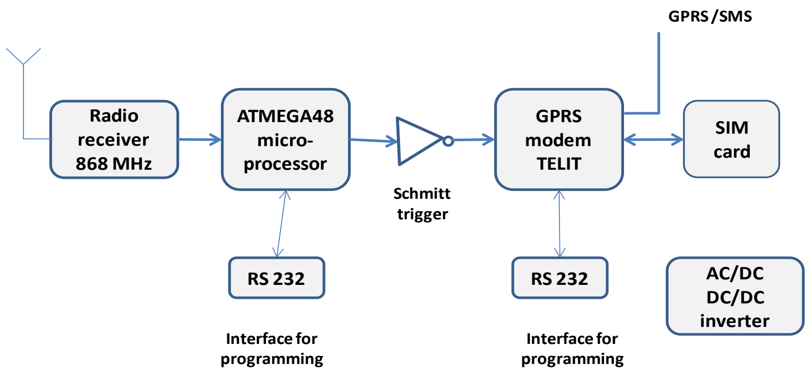


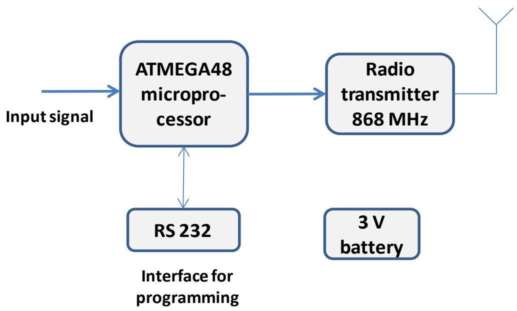
Fig. 5.2. Gateway - concentrator block diagram (Talsi)

The main elements of a gateway - concentrator:

- Microcontroller (Atmel), which controls the receivers and all of the concentrator. It is also provides a storage place for the data obtained from the sensors.
- The receiver uses a Short Range Devices (SRD) telemetry unlicensed band 868–870 MHz;
- TELIT GM862 GSM modem (or later versions) for data transmission implements the GPRS modem functions. The modem has an internal processor and memory to perform the programming at Python.

Sensor - Transmitter's main function is to receive pulses from the meters, transform those messages and transmit with set frequency to the devoted concentrator. Sensor - transmitter block diagram (see Fig. 5.3) consists of the following modules:

- ATMEGA48/88 microprocessor receives impulses from the flow and pressure meters, transforms into the message ("telegram") and forward them to the transmitter. The microprocessor is connected to the meter by a wired circuit. It captures a reading relay status changes (pulses) and record them in the memory.
- The microprocessor uses the "C"-language programs. Wireless M-Bus protocol adjusted for local needs is used to create a radio link.
- RFM22 transmitter transmits telegrams to the concentrator, using the 868 MHz frequency.
- Power supply module is equipped with 3 V battery, the duration of which is estimated at around 6-10 years.



5.3. att. Sensor - transmitter block diagram [6]

Fig. 5.4 illustrates the sensor - transmitter ICR upper plate (RR42) circuitry.

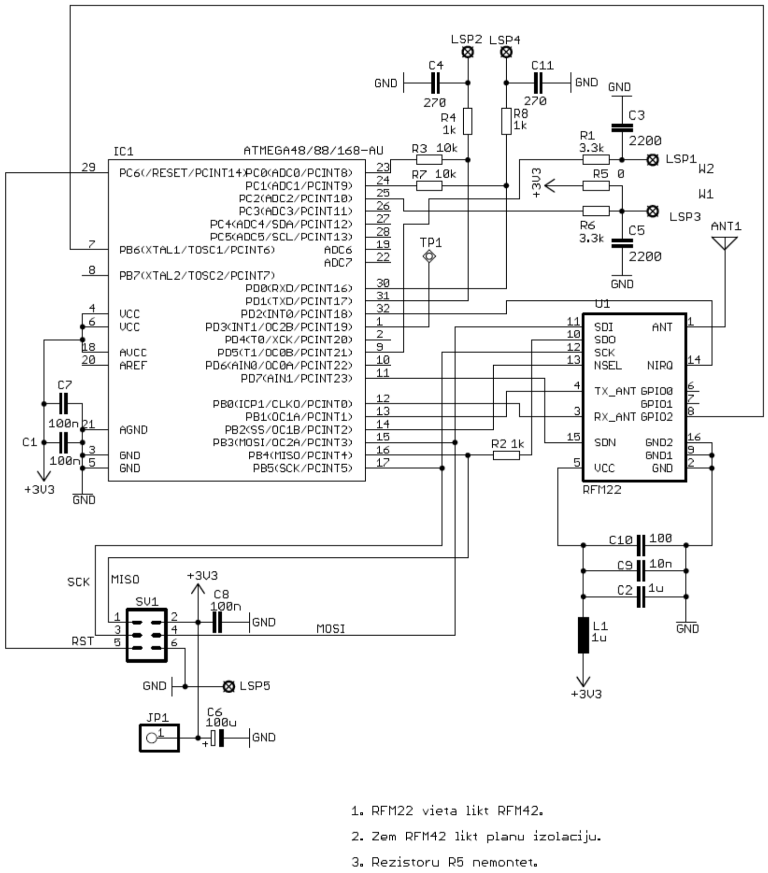


Fig. 5.4. Sensor - transmitter ICR the upper plate (RR42) circuitry

Figure 5.5 depicts the sensor - transmitter ICR with 3 V battery that is located between the upper and lower plate.

Fig. 5.5. Sensor - transmitter outward

Wireless sensor network technology research and experimentation in Ventspils (2012–2013. Participants: Research Centre of Ventspils University, Kaunas University of Technology, Latvian Internet Association and water utility Ventspils Udeka).

Water distribution network closed segment with several branches was selected for experiments. The network input is controlled by the SCADA, which provides input pressure and flow measurements.

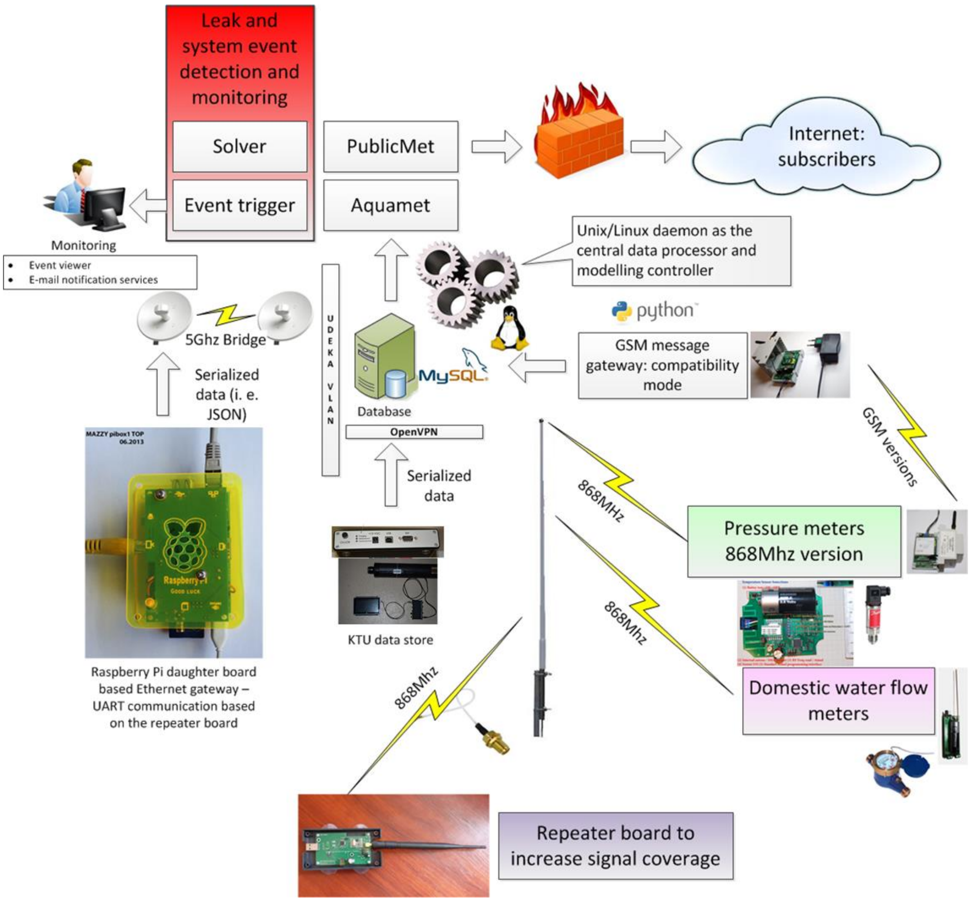


Fig. 5.8. “Smart Metering” block diagram of the system (Zabašta at al. [7])

"Smart Metering" system, created during the project, consists of the following components (see Fig. 5.8):

- Water flow and pressure meters;
- Sensors - data transmission apparatus, the ISM 868 MHz band;
- Ethernet gateway that converts signals from the sensors to TCP/IP;
- 5 GHz Bridge to ensure the flow of data on the municipal Wi-Fi network;
- GSM data transfer gateway;
- System events and leakages monitoring and detection system;
- A central data base ;
- The technical solution for data storage of measurements carried out on the heating mains by Kaunas University researchers;

Sensors - transceivers

For ease of prototyping and cost-effective use of radio frequency integrated circuits "HopeRF Electronics' radio frequency (RFM (22B/23B) modules are selected. Such microchips could be easy integrated with Atmel series (ATMEGA48, ATmega88, ATMEGA168, ATMega328). Microcontroller communication with the radio module is done through SPI (Serial Peripheral Interface Bus). Modulation scheme GFSK (Gaussian Frequency Shift Keying-) was chosen because it is adapted to the most commonly used wireless technologies such as Bluetooth, DECT, etc. Additional GFSK modulation "Manchester" coding scheme [3] is used in the communication process.

Figure 5.9 shows the sensor - transceiver outward. Marked contacts are used for hardware testing and programming.

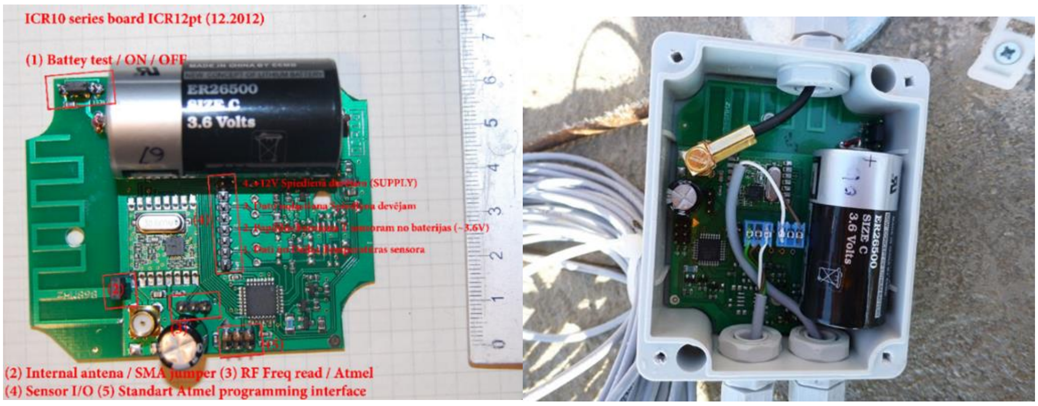


Fig. 5.9. Sensor – transceiver outward

One of the wireless network problems arising from conflict of message collisions and routing control. Since the message' transmission is in one direction, it happens without hidden nodes and other problems. The developed solution (see Fig. 5.11) envisages additional identification byte addition to the message before retransmission to being able to identify, which level of repeater relays the message.

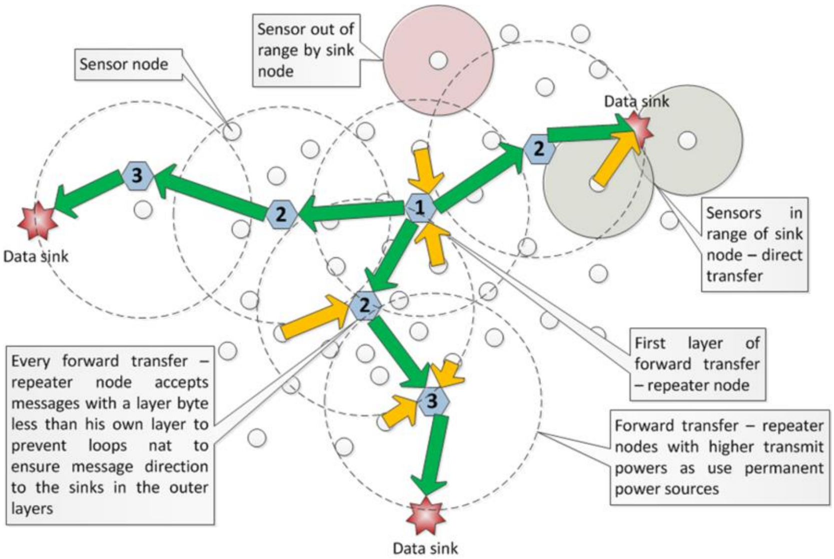


Fig. 5.11. The description of the method for message retransmission (Zabašta at al. [7])

Ethernet gateway - concentrator

Ethernet gateway the first version consists of a capture device, which is connected to the "Raspberry Pi" microcomputer (via USB serial interface). Microcomputer software sends commands to obtain the measurement data from the sensor internal memory. The received data is serialized and sent to the central database. For the sensor signals receiving, as the first version, 868MHz testing device that is used to diagnose the sensor operation, showing in real time on the LCD display data values, was adjusted.

Fig. 5.17 depicts an example of a hardware captured readings, are displayed as simple text strings: the measurement date of record, the month, time, serial number, two meter readings, battery measurements (STAT) and the received signal strength (RS - this is the RSSI signal strength).

Date	Time	SerialNr	Count1	Count2	STAT	rs	fr
00.00	00:00:00	00000000	000000	000000	0000	FA	00
23.01	18:23:39	141B7C9F	000000	000000	031D	6E	00
23.01	12:56:29	141B7C45	000000	000000	0307	65	00
26.01	14:48:10	141B76CC	000CF1	000000	0317	5B	00
24.01	12:12:33	0C00006C	00FFFF	000000	0032	6E	00
24.01	12:06:29	0C000068	00FFFF	000232	0034	79	00
26.01	15:15:47	141B7D21	000001	000000	031B	5D	00
26.01	15:16:59	141B78F6	0058B5	000000	031E	86	00

Fig. 5.17. An example of a hardware captured readings

In the example below, one can see the measurement data after processing and encryption sent by the Ethernet gateway system to a central database for further processing purposes.

```
Setting DateTime: w30012330
Date and Time
30012330
Hash: 48aeac7f70751d80b09a6ac23eb5375b DateTimeRec: 1359581312 Device type: 10 Device serial: 1B7C45 Value 1: 958 Value 2: 0 Battery: 796 RSSI: 120
http://exec.bitdev.lv/post.php?hash=48aeac7f70751d80b09a6ac23eb5375b&battery=796&timestamp=1359581312&value2=0&value1=958&rssi=120&serial=1B7C45&type=10
```

The second Ethernet gateway version (see Fig. 18.5) is developed according the general embedded platform principles ("generic embedded platform"). Raspberry Pi ARM7 platform is chosen, because it provides necessary computing power, and it has got a composite video output. The device may also be used with the display to perform diagnosis by staff at an object. The main system process, measurement data reading and delivery to the system server were written in Python language and supplemented with additional support services.

Fig. 5.18. One of the first versions of the gateway
(installed at a nursing home "Selga" roof)

The key improvements of the second version of the gateway:

- "Multi-Threaded Aquamon Daemon" software processes the USB data and prepare for delivery to the server;
- MONIT service announcements and Aquamon services control (e-mail communication, problem determination, service recovery);
- VPN support (Tinc, PPTP, OpenVPN);
- Watchdog: Broadcom BCM2708 'watchdog' support (gateway monitoring, overloads occasional restart;
- SD memory card and log file monitoring (RAMLOG).

The last on Raspberry Pi Ethernet gateway based version is equipped with an 868 MHz RF capturing "daughter" board, "heartbeat" indication, the wireless network adapter and secured with the power button. Composite output is used for easy diagnostics and control (see Fig. 5.19).

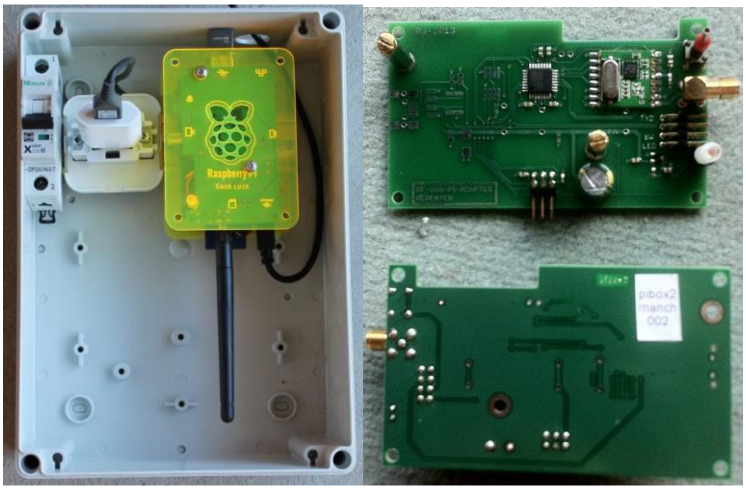


Fig. 5.19. Pibox Ethernet gateway outward

At Fig. 5.22, one can see the final layout of the trial network, where the blue circles represent Ethernet gateway coverage area, while yellow circles show the repeaters receiving - transmitting areas. The total number of water-flow sensor is 14, but the water pressure meters total number is nine.

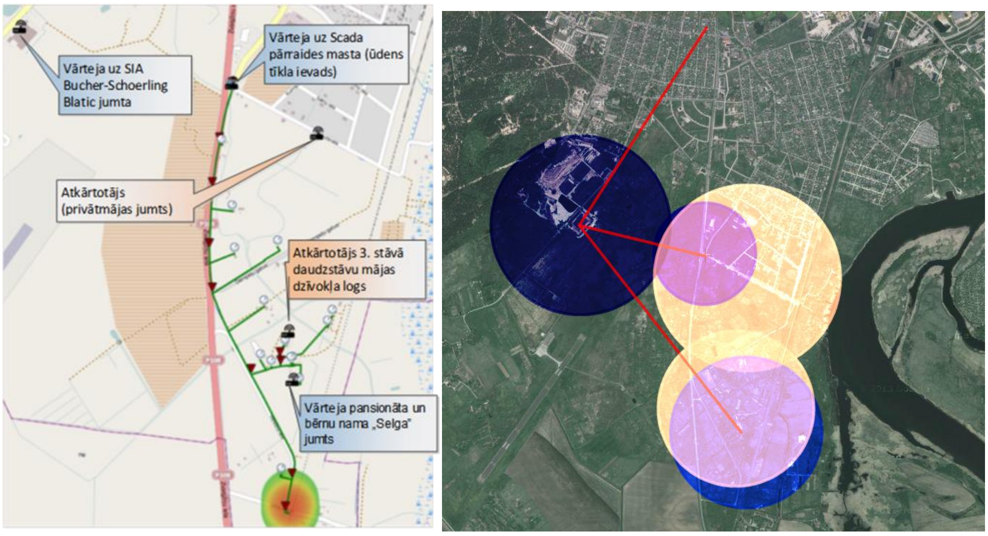


Fig. 5.22. The trial network final composition

Quality tests performed to evaluate the performance of the sensor network, in order to evaluate a ration of messages reached the central system, revealed that all data were received with a maximum delay time of 2 hours.

Conclusions

- Based on data availability and granularity, modelling techniques infrastructures interdependency types are analysed. It has been shown that the service decomposition model can be applied successfully using data availability and access granularity.
- Explored the service decomposition model of CI modelling dependencies in four stages in real scenario, a small Latvian town area, where the UML tools PIM model was established and has been validated for the assessment of risk-based metrics. Unlike existed models, this scenario allows to explore the city water distribution network (Talsi Water), services dependency on the electricity supplier (Latvenergo), and telecommunication provider (GSM Operator) services.
- Critical infrastructure interaction qualitative and quantitative metrics are analysed and classified, and it is proved that:
  - metrics can be categorized and summarized as a matrix in relation of mutual dependence, such as *Physical independency ratio, Cyber independency ratio, Relative length of physical dependence, Network topological robustness,* etc.;
  - in practical application metrics should use the thresholds, as may be permitted that the parameters of metrics may be justified only within certain limits.
- Using *MatLaB*® *Simulink*® *Stateflow* simulation model is designed and experimentally tested a method, which, unlike the existed methods allows to explore the water supply network nodes the average down time dependence on the battery life time and the battery replacement time cross- correlations, within the parameters set, when outages in power infrastructure arise and taking into account also the impact of telecommunication nodes. It has been proven that:
  - Water nodes down time shows by a quadratic polynomial described the dependence of the backup battery life time lifetime (BLT) and backup battery replacement time (BRT) cross - correlation in parameters set;
  - although approximations graphs shows that in the explored parameter range polynomial function approaches to a minimum when BLT tends to peak, however, local minimums of the function are revealed, which are associated with a telecommunications network nodes resilience to external power supply interruptions;
  - explored that backup power sources for water supply network nodes is an effective solution, taking into account the reasonable costs, however, it is not sufficient to ensure consistent and reliable data collection, because the physical dependency ratio is 0.77, but the time scale of physical dependency ratio is 0.67 ;
  - solutions that ensure consistent and reliable data collection from the water supply network objects can be:
    - backup power source lifetime increasing;
    - additional (redundant) network node installation that in this way increase the sensor network robustness.
- By exploring technical solutions and technologies that control water supply network node status using wireless sensor networks has been developed and tested:
  - wireless sensor network gateway prototype, which in addition to GSM-GPRS communication channel to the central system offers Ethernet output to 5.8 GHz wireless networks ;
  - water supply network pressure measurement data transmission system that, unlike the existed models includes urethane casing to protect the antenna, which is mounted at well cover, and 868 MNz sensor – transmitter;
  - wireless sensor network that is being built, use the star topology , combining 868 MHz RF sensors, Ethernet gateways (5.8 GHz), RF repeaters and SCADA hardware, which is integrated into the existing municipal Wi - Fi network that covers the territory of the city;

- "Smart Meter" system consists of four basic components: Meter data receiving component; Monitoring, statistics and data visualization interface; Clients consumption statistics for accounting and billing and Leak detection component;
- water leakage detection economical method, which, unlike the existed methods allows the use four- leakage detectors to locate potential leak location.

❖ Further research direction is related to development the computer control of wireless network elements for water supply network:
  - Modular communications gateway interface modules (GSM/GPRS - mobile broadband connections, CAN, Ethernet, 802.11b / g)
  - The impact of low temperature and high humidity on the wireless network elements, including the sensor-transmitters installed in wells.

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