**RIGA TECHNICAL UNIVERSITY**
The Faculty of Computer Science and Information Technology
Institute of Applied Computer Systems

**Aleksejs JURENOKS**
PhD student of doctoral study program "Computer Systems"

# DEVELOPMENT AND ESTIMATION OF WIRELESS SENSOR NETWORK LIFE EXPECTANCY ASSESSING MODEL AND METHODS

**Summary of doctoral thesis**

Scientific Supervisor
Dr.Habil.sc.ing., Professor
Leonīds Novickis

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OFFICIAL REVIEWERS:

Professor, Dr.habil.sc.comp. Valērijs Zagurskis
Riga Technical University, Riga, Latvia

Arnis Cīrulis
Asoc. Professor, Dr.sc.ing.
Vidzemes Augstskola, Latvia

Asoc. Professor, Dr.sc.ing. Krzysztof Amborski
Warsaw University of Technology, Poland

APPROVAL

I approve that I have developed this thesis submitted for examination to Riga Technical University for doctor of engineering degree. This thesis has not been submitted to any other university for degree.

Aleksejs Jurenoks ……………………………. (signature)

Data: ………………………

The thesis is written in Latvian, contains an introduction, 4 chapters, conclusions, a list of references, 59 drawings and illustrations, 10 tables, all together 156 pages. The list of references contains 130 references.

# ABBREVIATIONS

| | |
|---|---|
| ACL | Receiving authorization |
| WST | Wireless sensor network |
| CCA | Clear Channel Assignment |
| FFD | Full Function Device |
| GMRE | Greedy Maximum Residual Energy |
| KPFI | Climate change financial instrument |
| MRE | Maximum Residual Energy |
| MREML | Maximum Residual Energy Maximal Lifetime |
| RFD | Reduced Function Device |
| $E_0$ | Initial battery power |
| $E_{np}$ | Square wave amplitude |
| $C_k$ | User defined lower limit ratio $Q_k$ |
| $G$ | Wave gain |
| $h_1,\ h_2$ | Radio communications antenna position height |
| $I_i$ | Data flow intensity |
| $L$ | Packet number of bits |
| $O$ | Service area size in bits |
| $P$ | Transponder power factor |
| $P_a$ | The average capacity of the router receiving information from sensors |
| $P_{tx}$ | The average power consumed in transmission mode [W] |
| $P_s$ | The average power consumed in sleeping mode [W] |
| $P_{rx}$ | Router power consumed in receiving mode |
| $r$ | radiocommunication distance |
| $r_a$ | information from sensors receivng time |
| s | Number Coordinators Network |
| T | System running time interval |
| $t_s$ | Time, as the system is in sleep mode |
| $t_i$ | The time need information to be received from one terminal |
| $t_{tx}$ | The time that is required for sending information network |
| $V_n$ | A set of network nodes |
| λ | Wavelength. |

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# INTRODUCTION

The number of different devices for use with computer networks which provide mutual interaction of information is increasing daily. Recently the number of systems that do not require human intervention in the system process (Machine-to-Machine communication) has increased.

According to the concept of the Internet of things, by 2019 there will be more than a few trillion telecommunications devices connected in the World Wide Web [COL 2015], the majority of which will form the "things" systems, in accordance with the recommendation of the International Telecommunications Union Y.2069 [TER 2015].For the telecommunications devices to be able to interact with each other or to operate by following the user instructions, various sensor nodes, which are able to not only read information about the environment, but also communicate with one another via network protocols, have been integrated into them.

Lately, low power computing systems have been regaining a lot of popularity. Today's technology allows anyone to reduce the size of the existing computing systems by creating an inexpensive, low power autonomous system that makes it possible to use both physical and wireless networks in order to transmit information. This type of technology gained most of its popularity by receiving information from sensors as well as in the area of control systems. Networks that use low power computing systems and also transmit data via a wireless connection are known as wireless sensor networks whose main task is to obtain information from the sensors and transmitting it within the network.

The origins of wireless sensor networks are mentioned in 1999, when in the first publication [КОМ 2012] the possibility of using low power systems for obtaining information from the environment was mentioned. With the development of technology, it was applied progressively not only in the area of monitoring the environmental parameters, but also in medicine [STA 2005, ВАБ 2010, КУР 2011], security and safety systems [RAM 2012] as well as tracking tasks [THE 2015]. There are a number of non-standard solutions, in which sometimes a wireless sensor network is used unconventionally, in other words, for multimedia data transmission [BAR 2004], for processing inertial sensor data in tracking systems [ВАБ 2010], for detecting object movements as well as for monitoring.

Lately, the number of applications offering the use of mobile devices for receiving complex information has been increasing. Among the most advanced mobile wireless sensor network applications the following can be emphasized – underwater monitoring systems [GOY 2009], the control system for object location in a certain space [THE 2015, IEE 2015] and the more recently developed personal barometric systems.

Nowadays the topical research of a wireless sensor network is based on the new network transmission protocol improvement [MIE 2012, TAR 2014], the routing of transmission [КОМ 2012] and the formation of the network structure [КУР 2011] which makes it possible to increase the overall life expectancy of a wireless sensor network.

## The topicality of the subject matter

Recently the number of studies relating to problems in expanding the life expectancy of a wireless sensor network has increased. The modern research can be divided into two categories:

- Research related to the modeling and optimization of data flow [YOU 2004, SIN 2010, MIS 2009]. It is necessary to emphasize that the data flow of WSN is dependent on the usage of the network and the network performance scenario. There are systems in which the frequency and quantity of the transmitted information is strictly determined and there is no possibility to perform optimization of the network which results in uneven energy consumption in the network nodes and the network cannot operate at the moment when there is a lack of electricity in some network nodes, even if the largest part of the network continues to operate.

- Research related to the improvement of the technical characteristics of a wireless sensor network for increasing the life expectancy of a network. The main drawback of a wireless sensor network is the low power battery which significantly limits the life expectancy of a network. Currently there are a number of methods that allow solving this problem [THA 2008, RAG 2002, ZHO 2005]. These include the choice of the individual capacity of a battery, the density of locating the node, the adjustment of the transmitter power, the usage of energy efficient data transmission protocol, the positioning of the network nodes as well as other methods that are related to additional costs of implementing a network.

Relatively recently a new method for balancing energy through the mobility of the network coordinator node was offered [VLA 2009], which provides the opportunity of dynamic network reconfiguration or, in other words, the change of network topology. The absence of the wireless sensor network life expectancy assessment model is considered to be a significant drawback in this research.

One of the essential wireless sensor network research results that are related to modeling methods for increasing the life expectancy of a wireless sensor network have been proposed by the University of Berkeley and is a real-time simulation platform which is implemented by the MEMSIC [FIR 2015] company. The platforms TelosB, MicaZ, Imote2 are used in the modelling process. All the solutions on display support the TinyOs operating system that is widely used in sensor networks. Looking at the proposed platform, it was concluded that it allows anyone to view the results with higher productivity, but the properties for energy efficiency are difficult to view in it. All three solutions given in the dissertation follow the standard IEEE 802.15.4; moreover, the TelosB and MicaZ platforms use the technical solutions that have been developed at the University of Berkeley and are not certified for use in the EU. The temperature, light and humidity sensors have been integrated in TelosB products; also, the MicaZ products are meant to connect any external sensor by any manufacturer.

Currently, the issues related to the protocol optimization of WSN data transmission and the interaction of individual network elements within a network are actively studied in Riga Technical University. Various scientific works deal with issues that are related to interactions of wireless sensor network components [JON 1999] and routing protocol optimization [MIE 2012] which provide the grouping of the wireless sensor network node, the transmission protocol optimization and adaptation to the current environment as well as to ensure the reduction of energy consumption in the network.

## The aim of the dissertation

To develop and explore the wireless sensor network life expectancy assessment model and the methods that will increase the overall life expectancy of a wireless sensor network and will balance the amount of energy in the network nodes.

## The objectives

The following objectives have been defined in the dissertation:

- To analyse the existing methods for increasing the life expectancy of a wireless network.
- To determine the factors in network nodes which are affecting the overall life expectancy of a system.
- To develop a model for assessing the life expectancy of a sensor network.

- To develop methods for wireless sensor network performance management which help balancing the amount of energy in the network nodes and increasing the overall life expectancy of WSN.
- To perform the experimental approbation of the developed model in real wireless sensor network systems.
- To conduct a research of the developed methods using the simulation modelling tool.

## The subject and object of the research

The research subject of the dissertation is the wireless sensor network without alternative options for using energy. The research object of the dissertation is the structure of wireless network node elements and communication algorithms. In addition to the research object, the technical characteristics related to the quality of the transmission signal, network configuration parameters and the consumed energy of the existing optimization methods have been discussed.

## Hypotheses

Whilst developing the new model for assessing and the method for increasing the life expectancy of a wireless sensor network the following hypotheses were established:

- The use of a dynamic coordinator balances the remaining amount of power in the nodes and increases the overall life expectancy of a wireless sensor network.
- The methods for balancing the remaining energy must be applied together with the routing algorithms that allow dynamic adjustment of the power of each network node transmitter.
- The methods for increasing the life expectancy of a network can be appropriately used in networks with a large amount of nodes where the sleeping time of the nodes is $t_{idle} \rightarrow min$.

## Scientific novelty

The dissertation brings forth the following scientific acquisitions:

- A model for assessing the life expectancy of a wireless sensor network has been designed and it allows determining the time of withdrawal of the network including the ability to restore a network.
- A method for managing the dynamic coordinator node that allows balancing the energy consumption in the network has been designed.
- A method for controlling wireless sensor module data flow has been designed, which structures the network topology while using a routing algorithm and it balances the amount of consumed energy in the network.
- A method for managing the virtual coordinator node in order to change the network topology has been offered and it uses a heuristic algorithm MREML for increasing the life expectancy of a network.

## The practical significance

The practical value of the research consists of the experimental approbation of reconfigurable assessment methods and model of the life expectancy of a wireless sensor network.

The dissertation bears the following practical significance:

- An experimental prototype of a wireless sensor network sensor node has been developed which can operate in terminal and router mode through dynamic reconfiguration.

- During two international projects certain experiments were carried out introducing the method for increasing the life expectancy of a wireless sensor network as well as co-financing of KPFI was received for the approbation of the prototype in the private sector.
- An experimental software prototype was developed for increasing the life expectancy of wireless sensor network methods for simulation modelling. Based on the results obtained during the simulation modelling, the restrictions and conditions of WSN life expectancy method application were defined.

The practical results of the dissertation can be used by the companies developing automated wireless sensor management systems if they want to increase the life expectancy of the proposed autonomous solutions simultaneously not increasing the total expenses.

The model for assessing and the method for increasing the life expectancy developed as part of the dissertation were validated in practice:

- Within the project of climate change financial instrument called "The use of renewable energy sources in the household sector" for implementing the method of increasing the life expectancy of a wireless sensor network with a single coordinator (in cooperation with "MODERATOR" Ltd.).
- The implementation of a sensor unit with integrated dynamic configuration in the market of Latvia (in cooperation with Chelsea Trade Ltd.).
- The 6th EU Framework Programme project UNITE (Unified Teaching Environment for the School): the approbation of the model for establishing the life expectancy of a wireless sensor network for learners' work-load sensor autonomous life expectancy evaluation.
- Within the project eLogmar: the approbation of the model for calculating the life expectancy of a wireless sensor network defining the identification sensor autonomous operating time.
- Within "Saulkrastu komunālserviss" Ltd.: the use of a model for calculating the life expectancy of a wireless sensor network in order to evaluate the life expectancy of an autonomous sensor

## Approbation of the results

The results of the dissertation were reported at international conferences:

1. IST4Balt Training Day, 2005. 9. december, Tallin, Estonia.
2. IST4Balt International Workshop, Riga, 2005. 6.–7. April.
3. International Conference IVETA (Innovative Vocational Education and Training in the Transport Area), Riga, 2005. 24.–25. February.
4. International eLogmar Conference "Web Based and Mobile Solutions with Logistics and Maritime Applications", Riga, 2006. 26. September.
5. International Conference "Distance Learning in Applied Informatics" Nitra, Slovakia, 2008, 13.–14. May.
6. 10$^{th}$ International Conference on Perspectives in Business Informatics Research BIR 2011. International Workshop INTEL-EDU Riga, 2011. 6.–8. October.
7. 3. Combined World Latvian scientist's congress "Zinātne, sabiedrība un nacionālā identitāte." Section "Computer Science and Information Technology", Riga, 2011. 24.-27. October.
8. International BONITA project workshops, (Finland, 2012. 12. march).
9. International BONITA project workshops, (Riga, 2012. 12. march).
10. 7.IP International project eINTERASIA partner's seminar, Bremen, Germany, 2013. g. 24.-25. June.

11. 56th International Scientific Conference of Riga Technical University, Riga, 2014. 14.–17. October.
12. 7.IP International project eINTERASIA partner's seminar, Vilnius, Lithuania, 2015. g. 12.-13. march.
13. 10th International Scientific Practical Conference "Environment. Technology. Resources", Rezekne, Latvia, 2015. 18.–20. June.
14. 29th European Simulation and Modelling Conference (ESM 2015), Leicester, United Kingdom, 2015. 26.–28. October.
15. 13th International Conference on DATA NETWORKS, COMMUNICATIONS, COMPUTERS (DNCOCO '15), Budapest, Hungary, 2015, 12.-14. december.
16. IEEE 3rd Workshop on Advances in Information, Electronic and Electrical Engineering, Riga, Latvia, 2015. 13.-14. November.

The results achieved in the dissertation are presented in the following publications:

1. A.Jurenoks, Mobile Positioning. In Proceeding: EC Project IST4Balt News Journal vol.2. (Proceedings of the IST4Balt Workshop) 2005, pp. 57 – 60. ISSN: 1816-8701
2. T.Rikure, A.Jurenoks, E.Latiševa. Wireless network technologies: security and e-learning applications. In: Scientific Proceedings of Riga Technical University, Computer Science Applied Computer System, Vol. 5, Riga 2005, ISSN: 1407-7493, pp.140-148. **CITED IN: EBSCO, VINITI.**
3. A.Jurenoks. Mobile Solutions in Transport Logistics. In: Proceedings of IST4Balt International workshop "IST 6th Framework Programme – Great opportunity for cooperation & collaboration", 6-7 April, 2005, Riga, Latvia, pp. 88 - 90, ISBN: 9984-32-178-9
4. T.Rikure, A.Jurenoks. Wireless Network Technologies in Transport Area: Security and eLearning Applications. In: Proceedings of the International Conference IVETTA (Innovative Vocational Education and Training in the Transport Area) 2005, 24-25 February, 2005, Riga, Latvia, ISBN: 9984-9820-0-9, pp. 249-255.
5. A.Jurenoks, Evolution of Wireless applications. In: Annual Proceedings of Vidzeme University College "ICTE in Regional Development", Valmiera, Latvia, 2006, pp. 124 - 126., ISBN: 9984-633-03-9.
6. A. Jurenoks. Wireless communication technologies in multimedia systems. In: Scientific Proceedings of the Project eLOGMAR-M, 2006, ISBN: 9984-30-119-2, pp. 151-155.
7. A. Jurenoks, T. Rikure, L. Novickis, V. Šitikovs. e-Learning Environment Implementation in Riga 3rd Secondary School. In: Proceeding of International Project's IST4BALT "IST4Balt News Journal", vol. 3, 2007, ISSN 1816-8701, pp. 29 – 30.
8. A. Jurenoks, J. Lavendels, V. Šitikovs. Usage of e-Learning System UNITE in Informatics Course of Secondary School. (European Project's Case Study). In: Proceedings of International Conference "Distance Learning in Applied Informatics", Slovakia, Nitra, May 2008, ISBN: 978-80-8094-317-2, pp. 209-215.
9. L. Novickis, A. Mitasiunas, T. Rikure, A. Jurenoks. Promotion of e-Learning Solution via Information Technology Transfer Concept and Baltic Regional Competence Network. In: Proceeding of the International Conference "Virtual and Augmented Reality in Education" (VARE 2011), Vidzemes Augstskola, March 2011. pp. 71 - 80. **CITED IN: EBSCO.**

10. A. Mitasiunas, T. Rikure, L. Novickis, A. Jurenoks. Further development of Information Technology Transfer Concept for Adaptation and Exploitation of European Research Results in the Baltic Sea Region Countries. In: Scientific Journal of Riga Technical University. Computer Science. Vol. 45, Issue 1, pp. 9-16. ISSN 1407-7493, February 2012 **CITED IN: IEEE, ACM, LNCS, DE Gruyter, EBSCO, VINITI.**
11. A. Jurenoks, L. Novickis. Wireless Sensor Networks LifeTime Assessment Model Development. In: Proceedings of 10th International Scientific and Practical Conference "Environment. Technology. Resources", Rezekne, Latvia, 2015. June, ISSN 1691-5402, pp. 121 – 126. **Will be indexed: SCOPUS.**
12. A. Jurenoks, L. Novickis. Wireless Sensor Network Live Circle Simulation Tools to Balance Energy Consumption in the Network Nodes. In: Proceedings of 29th European Simulation and Modelling Conference (ESM 2015), Leicester, United Kingdom, 2015. 26.–28. October. ISBN 978-9077381-908 (IEEE Xplore), pp. 245 – 249. **Cited by: IEEE Xplore**. **Will be indexed: SCOPUS.**
13. A. Jurenoks, L. Novickis. Modification of routing protocols of the wireless sensor network for increasing the network life expectancy. In: Proceedings of 13th International Conference on DATA NETWORKS, COMMUNICATIONS, COMPUTERS (DNCOCO '15), Budapest, Hungary, 2015, 12-14. November, pp. 110-118, ISBN 978-1-61804-355-9. **Will be indexed: SCOPUS.**
14. A. Jurenoks. Method for node lifetime assessment in wireless sensor network with dynamic coordinator. In: Proceedings of Information, Electronic and Electrical Engineering (AIEEE), 2015 IEEE 3rd Workshop on Advances in Information, Electronic and Electrical Engineering. 13 – 14. Nov. 2015, Riga, Latvia. **CITED IN: DOI: 10.1109/AIEEE.2015.7367302.**
15. A. Jurenoks, L. Novickis. Method for Balancing Energy through the Mobility of Node Agent in Mobile Sensor Network. Scientific Journal of Riga Technical University, Information Technology and Management Science, 2015, Vol.18, RTU, Riga, pp. 17-23. **CITED IN: EBSCO, Google Scholar, Ulrich's International Periodicals Directory, VINITI.**
16. A. Jurenoks, M. Boronowsky. Dynamic Coordinator Mobility Management Methodology for Balancing Energy Consumption in the Wireless Sensor Network. In: Procedia Computer Science Volume 77, ICTE in regional Development 2015 Valmiera, Latvia, pp. 176–183, **CITED IN: DOI: 10.1016/j.procs.2015.12.380. Will be indexed: SCOPUS.**

## Structure of the research

The dissertation consists of introduction, 4 chapters, conclusions, bibliography, 59 images and 10 tables. The main text comprises 156 pages. The bibliography contains 130 sources. The structure of the dissertation is as follows:

***The introduction*** justifies the significance of the topicality of the research; the area of the subject has been explored, the main objectives and aims of the dissertation have been formulated, the scientific novelty of the research and the practical acquisition of the achieved results have been described as well as the process of approbation has been expounded.

***The first chapter*** "Problems of Measuring the Life Expectancy of Wireless Sensor Networks, the Current Situation Analysis. System Architecture" covers the general types and properties of configuring a wireless network that are to be used in the network model-building process. The existing standards and uses of the wireless sensor network are addressed as well. The factors that affect the wireless network activity and data transmission quality have been defined.

The chapter provides a general view on the life expectancy of a wireless sensor network with an autonomous power supply without the option of renewing energy and the potential ways of increasing the life expectancy of a network are analysed as well.

The group of methods for balancing the energy in network nodes has been analysed in detail and in it the perspective method of dynamic reconfiguration of the network is distributed.

***The second chapter*** "The Model Development for Assessing the Life Expectancy of a Wireless Sensor Network" addresses the developed sensor network model which allows assessing the life expectancy of a network through viewable network topology design and the technical characteristics of the node. Also, the main method for calculating the model parameters has been described in detail. The life expectancy of individual network nodes is estimated using the technical values of a wireless sensor network node.

The chapter describes the conditions of the distribution of network nodes and the basic coefficients that affect the overall life expectancy of a wireless sensor network have been determined.

The methods for calculating the life cycle of the main nodes in a wireless sensor network have been analysed and a model for assessing the life expectancy of a wireless sensor network has been offered taking into account the operating range of the network elements as well as the load of the transmittable information. The example of the calculation of energy consumed in an individual node is practically implemented using the proposed model for assessing the life expectancy.

***The third chapter*** "Developing the Reconfiguration Method of a Wireless Sensor Network" describes the developed methods that allow solving the projection task of data flow whilst balancing the node energy in the network. The factors influencing the network reconfiguration capabilities have been defined. Two options dependent on the network topology have been viewed:

- The network elements possess a strictly defined functional nature which is described by constant energy consumption for each possible node configuration.
- The network configuration may change mid-operation; thus, the energy consumption of individual network elements is different in each phase.

One scenario offers a more effective path searching method using the condition of the increase in life expectancy which is based on task solving through programming.

***The fourth chapter*** "Wireless Sensor Network Life Expectancy Model And Method Simulation-Based Experemental Research" is devoted to the experimental approbation of the developed methods and the model. It contains three physical experiments and related tasks.

The chapter reviews the existing environment of the simulation modelling; also, it shows the necessity to create a specialized and the developed topology oriented set of software in order to assess the WSN life expectancy.

Whilst using the developed software the following has been carried out:

- the comparison of the effectiveness of the proposed methods and algorithms in relation to the existing methods;
- the possibility of increasing life expectancy has been explored depending on the operating parameters of the WSN node.

# 1. PROBLEMS OF MEASURING THE LIFE EXPECTANCY OF WIRELESS SENSOR NETWORKS, THE CURRENT SITUATION ANALYSIS. SYSTEM ARCHITECTURE

The analysis of the available resources showed that wireless sensor networks is the perspective of technology that is widely used for collecting information from the external environment for ensuring the autonomous management in different areas.

## The review of wireless sensor network research

Using the information provided in certain scientific papers [BI 2007, VLA 2009] it can be argued that regarding to the most recent wireless sensor network research the current research directions have been determined:

- The organization of information flow in the network that is connected to the increase of the life expectancy of a wireless sensor network.
- The adaptation of power sources in order to use alternative energy in wireless sensor networks [WAN 2005, [NXP 2015].
- Research related to the increase of life expectancy of wireless sensor networks using unmodified wireless sensor networks [THA 2008, RAG 2002].

Currently, there are universities in Latvia where the performance problems of wireless sensor networks are actively discussed with the prospect of increasing the overall life expectancy of a wireless sensor network while maintaining the quality of information collection:

- Riga Technical University addresses the issues related to the optimization of WSN data transmission protocol and the interaction of individual network elements within the network. The scientific research explores issues related to wireless sensor network component interactions [JON 1999] and the optimization of routing protocol [MIE 2012] which allows for wireless sensor network node grouping, the transmission protocol optimization and adaptation to the specific environment as well as the reduction of energy consumption in the network.
- Sharif E. Guseynov, the professor of the Mathematics and Information Technology Institute of Liepaja University, has been discussing the issues related to the mathematical modeling of the received the results in wireless sensor networks with the aim to reduce the amount of information transmitted in the network [GUS 2015].

### The concept of a wireless sensor network

A sensor network is a well-known wireless network with the possibility of reconfiguring the network nodes which consist of small dimension intellectual sensor devices [KRI 2005, ВИШ 2005]. Each device is equipped with a central low power computing processor, radio transponder, power supply and with the necessary sensors in order to make any external environment measurements (e.g. temperature, brightness of light, vibration, pressure, sound level, etc.).

The sensor networks are a part of the “situation based” network category (ad hoc) [ИВА 2008] consisting of equally distributed nodes where each node can exchange data (converse) with other adjacent nodes. The largest technical feature of the sensor network is the ability to accurately divide the network elements according to the operational tasks through the criteria assigned to a node.

Nowadays, a wireless sensor network is one of the most promising directions of development of communication networks.

WSN is composed of many separate nodes that allow:

- reading the condition of the environment such as temperature, humidity and atmospheric contents;
- selecting the object properties, such as speed or size;
- storing and analgising the information received from sensors;
- transmitting information through modern communication channels and transmission types.
- The wireless sensor network has three significant differences from traditional computer networks:
- The network consists of a large number of objects which can be dynamically updated during the operation.
- Network nodes use dynamic configuration.
- Limited technical possibilities of individual nodes.
- The network uses dynamic network topology.
- Low power consumption in the nodes.

The chapter describes the technical specification IEEE 802.11.x of a wireless sensor network which refers to the factors that determine the quality and speed of the transmitted information. The transmitter states that determine the overall life expectancy of a node have been identified.

Wireless sensor network data flow models and their properties that are used nowadays have been discussed in the chapter. The characteristics of using an ON-OFF network model as well as the effect of the OFF interval on the overall life expectancy of a network have been viewed in detail.

As a result, it has been proven:

- a minimal time interval $T_{min}^{ON}$ exists in a network operating cycle in which the node must be in working mode for executing all iterations.
- if the network node is in the sleep mode with an operating transponder node, the system continues consuming energy whilst transmitting technical information.

**The concept of sensor network life cycle**

The primary indicator of WSN, which provides practical network application, is the overall life expectancy of a network and the tasks that are related to modelling the life expectancy as well as the practical application. Using a reconfigurable network is one of the most promising methods for increasing the life expectancy and it allows reducing the excess energy that is unused within the nodes.

The concept of a sensor network provides that any network node uses an independent power supply. Any network element performs certain tasks in the common network which according to the network scenario are pre-programmed.

If a component stops working, it ascertains:

- the set of tasks performed by the network element is not critical which might mean that the quality (QoS) of network services (data collection) is reduced [CHE 2006].
- the node performs the key part of the system – the refusal and inability to replace it with other dynamic elements of the network can mean the rejection of the entire sensor network.

In accordance with the fact that all sensor network elements are autonomous, there will be a moment when inevitably the network will no longer be able to fulfil its purpose and it will cease to exist. The time between the start and halt of a network is defined as the sensor network life cycle [ЖДА 2009].

Looking at life cycle of the sensor network, it is important to pay attention to the network energy efficiency. The energy efficiency of a network is dependent on the characteristics of the applied standards, the algorithm used and the network protocol. Whilst developing the project of a network one of the most important factors is increasing energy efficiency and the operating cycle of the network depends on it.

Nowadays, there are no universal definitions of energy efficiency – everything depends on certain application areas. Sometimes the capability and options of renewing network energy resources are considered to be energy efficient. For example, [ЕФР 2007] defines the energy efficiency ratio:

$$Э = \frac{W_l}{W_l + W_{nl}}, \quad (1.1.)$$

where $W_l$ – appropriately used energy and $W_{nl}$ – unsuitably used energy or energy used based on unforeseen actions.

Often when actions are related to WSN the term network energy efficiency is equated to the operating cycle of the autonomous network and it is believed that a longer operating time of the autonomous network ensures a higher energy efficiency of the network. This may not be true for a network where, for example, does not exist any transmission of the useful data, but the energy is only used in sub-processes ($W_{nl}$) and the autonomous operating time is bigger than for a network that transmits useful information. Using the energy efficiency formula, if the parameter of useful energy is $W_l = 0$ then the efficiency ratio will be equal to 0.

## The possibilities of using energy balancing methods groups

Modern technologies allow creating processors with very low power consumption; as a result, the operation of the processor does not significantly influence the life cycle of the system. Mainly electricity is consumed through data transmission using both physical and wireless networks.

To level the energy consumed in all network nodes a variety of energy balancing methods are used. Let us analyse some basic energy balancing techniques and approaches.

The structure of a heterogeneous network requires the use of various techniques in order to improve energy efficiency.

- The adjustment of battery capacity based on the location of the element in the network [HAL 2011].
- Differentiated density of network node depending on the intended density of transmission in a particular area [HAM 2009].
- Mainly routing protocols are used on the software level and they are based on the remaining power units in the nodes [CHE 2012], the use of virtual coordinates [БАС 2009], the alternation of long-range and short-range transmission [ZHU 2008], the positioning of nodes [КУР 2011] as well as the use of sets [SUN 2002].

The use of mobility of network components is considered as a prospective balancing method. In various researches [VOS 2009, WU 2005] authors have showed that the use of mobility is good for increasing the autonomous actions of a sensor network. Therefore, this approach will be discussed in further detail in the following parts of the dissertation.

## The methods used during modeling of the wireless sensor life cycle

Towards the end of the chapter the methods used for modelling the operating cycle of a wireless sensor network have been discussed. The comparison of modelling methods has been given and afterwards it can be concluded that in the case of modelling the WSN operating cycle a hybrid version of modelling should be used which includes a number of methods to achieve the objectives.

Using the comparison of the modeling methods that have been used mentioned in the respective literature [GUS 2015, MUN 2009], table 1.1 shows this comparison whilst modelling the life expectancy of a wireless sensor network.

Table 1.1.

Comparison of methods used during the modelling process

| Method / Model | Precision | Amount of necessary resources | Possibility of adaption |
|---|---|---|---|
| Probability theory | not supported | supported | not supported |
| Queuing theory | not supported | not supported | supported |
| Petri nets | not supported | not supported | not supported |
| Graph theory | supported | not supported | supported |
| Automata theory | supported | not supported | not supported |

This leads to the conclusion that none methods used for network modelling do not conform the modelling of the life expectancy of a network. It is necessary to use a hybrid version which includes several methods in order to achieve the objectives.

# 2. THE MODEL DEVELOPMENT FOR ASSESSING THE LIFE EXPECTANCY OF A WIRELESS SENSOR NETWORK

## The interaction of the evaluation of WSN life expectancy methods and models

In order to assess the life expectancy of a wireless sensor network, a model has been developed as a part of the dissertation which allows determining the maximum amount of iterations in the network using individual assessment of life expectancy of the nodes during the time of structure function as well as using the factors affecting the quality of the transmitted information.

The method of using the model consists of the following stages:

1. Using the technical characteristics of the wireless sensor network 802.11.4 protocol described in the first chapter of the dissertation, the node operating modes that influence overall durability of the node have been defined.
2. The technical parameters of an operating node have been industrially defined as well as the factors which are determined by the specification of the used protocol, the environment and physical characteristics. Based on the statements of other authors regarding the classification of the external factors influencing the wireless sensor network [IEE 2015, LAJ 2009, OPE 2015], the dissertation explores four technical factors that determine the amount of power used by each node:

- Defining the IEEE 802.15.4 channel availability coefficient.
- Defining the IEEE 802.15.4 standard feature coefficient.
- Defining the coefficient of technical information transfer time.
- Detecting the operating range.

3. In determining the amount of consumed energy in the node, the operating state of the node within the network iteration process has been defined. In case the amount of consumed energy is zero, whilst the node is in sending mode, it is assumed that the node performs the role of a terminal or in other cases it performs the role of routing.
4. For each position of the node a method for determining the amount of consumed energy is offered in each process of the network iteration.
5. Using the methods for detecting the life expectancy of a network described in the works of other authors [CHE 2004, COL 2007, YE 2004, COL 2007], certain

indicators that determine the state of activity of a wireless sensor network have been defined:

- indicator based on the operating node,
- indicator based on the coverage area,
- indicator based on the delay of transmitting information,
- network topology change time indicator.

6. Finally, a model for assessing the life expectancy of a wireless sensor network has been described and it allows defining the maximum amount of iterations in the network which uses fixed topology.

## The influencing factors of the energy consumption in the sensor network nodes

It is understandable that wireless sensor network nodes can be seen as active for as long as they are capable of reading the information from the sensors correctly as well as transferring it to the coordinator node within a network. Whilst developing the network it is necessary to timely assess the approximate duration of each network element until the element will require battery replacement.

The overall network energy consumption depends on several factors:

- The technical parameters of the node (battery capacity as well as the capacity of the processor, the transmitter, the sensors and the other elements).
- Data collection frequency which may depend on the situation and the environment in which the network operates.
- Physical and channel level protocols that determine the control of access mechanism in the environment [LAJ 2009, PU  2010, ZHA 2009, LUO 2014].
- Network topology that defines amount of the transmitted information flow within each node (including the flow of technical information).
- The use of routing protocols that complement the network with additional service data flow [POL 2004, SHA 2003].

Any sensor network has three node types – the terminals, the routers and the coordinator or data collector. Data collectors do not affect the overall life expectancy of a system because they are provided with a permanent power supply or are equipped with a much more powerful autonomous power supply.

Let us view the terminal and the router life-cycle calculation method. It is based on some assumptions:

- The operating algorithm of the network nodes is strictly determined. In case the system is affected by external factors, there is a clear mathematical reasoning for any changes in the methods.
- There are no battery renewal options. If there is such a possibility, it can be used by increasing the size of the initial amount of energy [SCH 2003]. As a result, knowing the initial amount $E_0$ of battery energy as well as the total power $\Delta P$ used by the node, the life expectancy of the system is defined as $t = \frac{E_0}{\Delta P}$.

## The terminal life expectancy assessment method

The terminal node of the sensor network is intended to reading information from the sensors for the further transmission of data in the network.

The main difference in the node from the router is the impossibility of information transmission. This means that the terminal node does not use power and time for reception of information.

Using an event-based or list-based model, node use cyclical activities scheme (pic.2.1.).

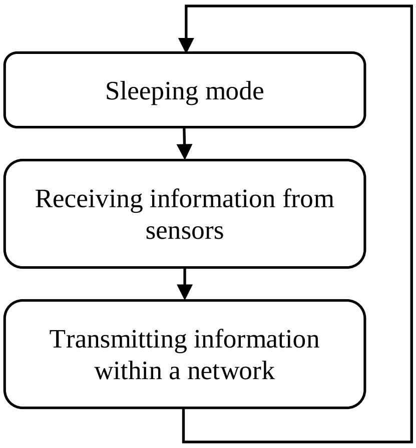



Fig. 2.1. The operating algorithm of the terminal node

The consumed terminal energy in one operating cycle of the system can be defined by the following formula:

$$P_{term} = P_{tx} * t_{tx} + P_s * t_s + P_a * t_a, \tag{2.1}$$

where $P_{tx}$– the average conumed energy in the transmission mode (W);
$t_{tx}$ – time that is required for the information transmission in the network (s);
$P_s$ – average power consumed in a sleeping mode (W);
$t_s$ – time in which the system is in the sleeping mode (s);
$P_a$– consumed power on processing of data (reading the information from sensors) (W);
$t_a$ – time that is intended for processing the information (s).

It is assumed that $t_{tx} + t_a > t_s$, which means that the system has sufficient time to be in the sleeping mode. The value of parameters is determined by the technical data of processor and properties of software algorithm (Fig. 2.2.)

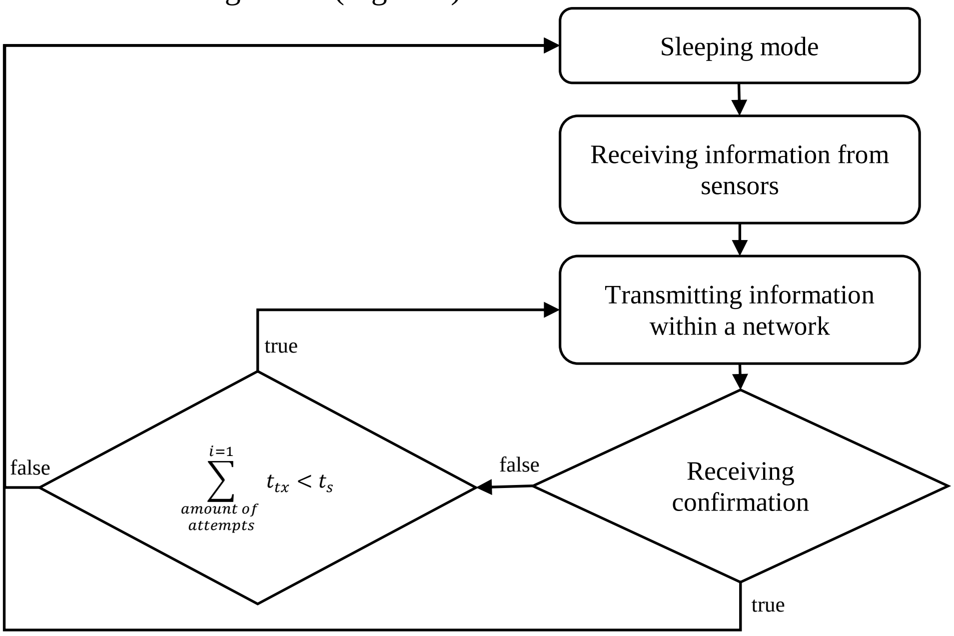



Fig. 2.2. The terminal operating algorithm with error validation

## The router life expectancy assessment method

It is known that in sensor networks oriented on events, which are using asynchronous data access environment, a router is the weakest point regarding the duration of life circle of the system.

It is based on the fact that a node spends very little time or at all does not spend time in the sleeping mode, but consumes power on reception of information from the network and the transmission of information into network.

The total power consumption of the router very much depends on the selected routing protocol that in the end determines the table of service data flow for safety.

A router has four operating conditions:

$t_s$ - sleeping mode of the system;

$t_s$ - The information reception from a network;

$t_{tx}$ - Information sharing in a network;

$t_a$ - Reading the information from the sensors.

Since the performance of the network is highly determined, it can be considered that the router $\Delta t_{rx} + \Delta t_{tx} \leq t_s$. While transmitting the information, an error may appear in the network; consequently, it will take more time to send and receive data; as a result, it is necessary to introduce an additional parameter $p_e$ - percentage denoting error probability.

The amount of time the system spends on the reception of all the information is equal to:

$$r_{rx}(T) = \sum_{i=1}^{n} t_i{}^T * I_i, \tag{2.2}$$

where $t_i$- the time necessary for the reception of information from one terminal (s);

$I_i$ - i-the intensity of data flow.

The amount of time that the system will spend on sending the information in the network is equal to:

$$r_{tx}(T) = \sum_{i=1}^{n+1} t_i{}^T * I_i, \tag{2.3}$$

There is a situation when the system is not able to transfer all the necessary information that has been received by the node $r_{rx} > r_{tx}$. Before the information is received the system checks whether there will be sufficient time for transferring the information.

When planning the router load, the total life cycle of the router $\Delta r$ must be taken into account.

$$\Delta r < p_e(r_{rx} + r_{tx)} + r_a, \tag{2.4}$$

where $r_a$-the time consumed by the system to receive information from the sensors (s).

Let us look at the situation $r_{rx} + r_{tx} + r_a \leq r_s$, when the router is able to fulfill its task and transfer the information to the network. In this case, the router's power consumption will be equal to:

$$P_m = P_a * r_a + P_{tx} * r_{tx} + P_{rx} * r_{rx} + (r_s - r_{tx} - r_{rs}) * P_s, \tag{2.5}$$

where $P_{tx}$– the average power of router in the transmission mode, $P_{rx}$ - the average power of router in the receiving mode, $P_a$ - the average power of router receiving information from sensors, $P_s$ - the power of router in the sleeping mode.

## The component of the calculation model of the influencing factors of the consumed power in the network nodes

The determination of the coefficient of availability of channels according to IEEE 802.15.4

The IEEE 802.15.4 standard uses a widely applied accessibility scheme distributed by CSMA/CA [LAJ 2009]. Based on the description of the operation of the scheme, each time the system needs to transmit data, it performs the following action steps: a random time interval is selected, the capacity of a channel is checked (Clear Channel Assignment - CCA). Within the standard [IEE 2015] the timeout is defined by the formula:

$$t_{wait}(T) = R * aUnitBackOffPeriod, \tag{2.6}$$

where $R$ is a random number in the range [0..2BE-1] which is generated every time at the start of action. $aUnitBackOffPeriod$ is a constant value which is equal to 20 character long strokes?

If a channel is available, the system transmits information; otherwise it waits for a new time. In the worst case scenario if the value of variable $R$ is equal to 7 the standby time $t_{wait}$ will be equal to 2.24 ms. The hearing time $t_{CCA}$ of the channel is constant for testing the capacity and, using the selected IEEE 802.15.4 standard, it is equal to 8 character strokes or 128 ms.

The determination of the coefficient of characteristics according to the standard IEEE 802.15.4

The maximum size of the load efficiency pertaining to frame is dependent on the length of service field. The standard describes the maximum length of the physical level of the frame$aMaxPHYPacketSize = 127 bytes$. If to take into account the minimum size of addressing technical frame comprises 4 bytes, the maximum coefficient of efficiency load will be equal to 112 bytes.

IEEE 802.15.4 standard operates at 2.4 GHz frequency with a permissible transfer rate of channel $f$ = 250 kbit/s. The result time required for transmission of information in the network can be calculated using the following formula:

$$t_{DATA}(T) = \frac{L+O}{f}, \tag{2.7}$$

where $L$ – the number of bits per packet, $O$ - the size of the service field in bits.

Technical information transfer for determining the time coefficient

The level of information confirmation frames consists of 11 bytes (88 bits) [IEE 2015]. Using the formula, it can be calculated how much time is required for confirming the information

$$t_{ACL}(T) = \frac{88}{250} = 0.352, \tag{2.8}$$

Before sending the confirmation of data transmission in the network, the IEEE 802.15.4 standard defines the technical delay time = 192 ms which is necessary for the transition of the devices from the receiving to the sending mode [IEE 2015]. For a device to have sufficient time for processing the information received, the standard defines the minimum delay time after the approval of each frame: the frame length up to 18 bytes including is 288 ms and the frame length over 18 bytes is 640 ms.

Each frame is sent with the device gradually locating in in four possible stages of operation – waiting (WAIT), channel hearing (CCA), frame transmission (DATA) and receiving authorization (ACL).

The most important factor for a sensor network is the distribution of the operation modes. Using the IEEE 802.15.4 protocol division of information sending operational stages it can be concluded that:

- through channel hearing (CCA) and receiving an approval (ACL), the energy consumption of the system corresponds to the receiving mode;
- the waiting time of the protocol provides system detection in active mode.

As a result, the average capacity of the node during the whole information transmission cycle is equal to:

$$P_f = \frac{P_a * t_{wait} + P_{rx} * t_{CCA} + P_{tx} * t_{DATA} + P_{rx} * t_{ACK}}{t_f}, \quad (2.9)$$

where $t_f = t_{wait} + t_{CCA} + t_{data} + t_{ACK}$.

**Defining the operating range**

It is known that the system consumes certain power for the transmission of data to the maximum distance [12]. Using the formula for determination of radio signal amplitude provided by Boris Vvedensky, it is possible to determine the admissible maximum distance to which the information can be transmitted.

$$E_{np} = \frac{4\pi\sqrt{P*G}}{\lambda * r^2} * h_1 * h_2, \quad (2.10)$$

where

$E_{np}$ - wave amplitude in the receiving point;

$P$ - power coefficient of retranslator;

$G$ - coefficient of wave amplifier;

$\lambda$ - wavelength;

$r$ - distance of radio communications;

$h_1, h_2$ - height to which radio antenna was lifted.

It is assumed that all network nodes in our system use antennas of the same type and do not use additional intensifiers; thus, the simplified formula can be used:

$$E_{np} = \frac{4\pi\sqrt{P}}{\lambda * r^2}. \quad (2.11)$$

Changing the distances of network node, it is important not to lose the quality of signal. It is assumed that in case of increasing the distance the $E_{np}$ value will remain unchanged. In the result the $P_k$ coefficient of consumed power pertaining to router is equal to:

$$P_k = \frac{{E_{np}}^2 * \lambda^2 * r^4}{(4\pi)^2}. \quad (2.12)$$

When planning the operation scheme of sensor network there is a possibility to equalize the consumed power of network element by adapting the power of transmitter and operating range to certain network segment. This approach will allow to equalize the total duration of life circle pertaining to nodes by decreasing the left out quantity of energy in the nodes.

As a result, the consumed power of router while transmitting the information in the network is equal to:

$$P_{tx} = \begin{cases} P_{tx}, & ja\ K_r <= 1 \\ P_{tx} * \frac{{E_{np}}^2 * \lambda^2 * {K_r}^4}{(4\pi)^2}, & ja\ K_r > 1 \end{cases} \quad (2.13)$$

where $K_r$ - the coefficient of working range against standard working range.

## The component of the model for determining the influencing factors of the network life expectancy

Network life expectancy depends on how long its elements operate. Given the fact that the networks often contain redundancy of words, different demands of quality of the results obtained from the network exist as well as various indicators of the life expectancy of a network.

### The Index Based on the Working Node

The total time of network operation can be marked as $T_k^n$ time, in which at least k of the n units are in operation [CHE 2004, COL 2007, KAN 2011, VLA 2009]. However, there is one drawback of this marking- the types of network nodes are not defined. Mostly in the networks there are primary nodes - which provide data retransmission and significantly impact the overall network performance. If one of the "bearing" nodes stops working, it automatically means that the network ceases to exist. That is why in many works [HIL 2005, RAK 2009], analysing the life circle of system, variable m, which means the number of critical important elements in the network, which must be active at all times, is defined. For example, they could be the nodes of network cluster management [SUN 2002]. For the other nodes, metrics is used $T_k^{n-m}$. In the researches it is often used a case when $k = n$. In this case the network is considered as able-bodied as long as all the network nodes are active or:

$$T_k^n(T) = \min_{i \in V_n(T)} t_i(T), \quad (2.14)$$

where: $V_n$ – the quantity of network nodes, $T_i$ - the life circle of each network node.

### The Indicator Based on the Area Coverage

This indicator is related to the use of network sensor- the quantity of information that is necessary to get from the concrete network segment. There are two approaches on the determination of the indicators based in the coverage. On the basis of the first approach the network is considered as able-bodied as long as α percent of the overall network coverage is covered by at least one sensor (α - coverage) [YE 2004]. The second approach is based on provision of redundancy and requires that in each network segment should be at least k – number of active sensors (k - coverage) [KWO 2009].

The biggest disadvantage pertaining to the detection of indicators based coverage is the complex process of algorithmic presentation.

### Index Based on the Delay of Information Transmission

According to the research, this index is mostly used when working with information gathering sensor network systems. The full definition of the index is provided in the paper [COL 2007]. Let us improve this index in order to cover previously mentioned index groups.

Suppose that the environment, which is carried out by the sensor network monitoring system, at each time interval occurs in certain activities which need to be identified. The events can be considered as external events, such as alerts, temperature changes of the system and other technical information, as well as described determinate event of the internal network, such as a regular transmission of information.

Let us introduce the parameters of quality pertaining to working network for each zone at specified time interval t. Suppose that $N_k(t)$ – in the range k there is the total amount of events in the time interval t and $I_k(t)$ - the total amount of the events from the $N_k(t)$ number that are delivered to a data collector at the determined period of time. The total time t is defined for the whole range k. The parameters $\Delta t_k$ are defined on the basis of the necessary network intensity in the determined network segment. In the result zone at k time in the t interval the indicator of network working quality will be equal to:

$$Q_k(t) = \begin{cases} \frac{I_k(t)}{N_k(t)}, & ja\ N_k(t) \neq 0 \\ 1, & ja\ N_k(t) = 0 \end{cases}. \tag{2.15}$$

For acting network there is a threshold $c_k$ that exists in order to indicate the lowest ratio value $Q_k$ below which the network can not be regarded as working age. Thus, for the possible duration of the network can be considered:

$$\forall t < \tau_1, \forall k \in [1,2,..m], Q_k(t) \geq C_k, \tag{2.16}$$

where $C_k$ – user defined lowest $Q_k$ value.

**The indicator of the moment of network topology change**

Within a working network there is a time when the system is unable to carry out its tasks based on external factors or the lack of energy in various network elements and then there is a need for a network topology change.

Let us define the number N of points in time when the system crosses the border $c_k$. Suppose that $t_{max}$ is the maximum allowable time (s) in which the system may be situated below the $c_k$ range through performing the necessary actions for changing the network topology. As a result, the system in question remains active as long as the following condition is fulfilled:

$$t_{n+1} - t_n < t_{max}. \tag{2.17}$$

By controlling the overall network management, it is impossible to determine the remaining amount of power in the nodes in real time because it requires additional operations to transfer information. The only way to control the viability of the node is delaying the control whilst transmitting the data. If the system reconfiguration time is $T$ greater than $t_{max}$ , then it is possible to identify the individual deviation of the system nodes

## The algorithm of the model for assessing the life expectancy of a wireless sensor

Let us look at the assessment task of the life expectancy of a wireless sensor network. The sensor network $N = (V_n, U_n, P)$ will be used. The task at hand is to assess the life expectancy of the network N, taking into account the starting amount of energy in all nodes P.

The life expectancy of a network depends on the selected network topology determined by the location of the network coordinator. Suppose that the coordinator in the given network is mobile and the trajectory (route) of the coordinator is known in the network - $S$. As a result, the modified sensor network model will be used by introducing the parameter $N = (V_a, U_n, S, P)$ for the coordinator trajectory.

Suppose, the network uses the same amount of energy in each of the nodes; further the following formula will be assumed as the amount of starting energy in the node $E_i$=P.

The primary task is to calculate what will the remaining amount of energy in the network nodes be when the coordinator will gather information from the network *l* nodes:

$$E_{r_i}(l) = E_i - (\sum_{j=1}^{l} P_m), \quad (2.18)$$

where $E_{r_i}(l)$ is the remaining amount of energy taking into account the amount of node i.

The assessment of the WSN life expectancy depends on the performance scheme of a network, the type of movement of the coordinator and the location time of the coordinator in each position. The network will cease to function when at least in one of the nodes the remaining amount of energy is $E_r \leq 0$.

Let us consider the algorithm (fig. 2.3.) that allows setting the maximum number of iterations in the network until at least one of the nodes stops functioning.

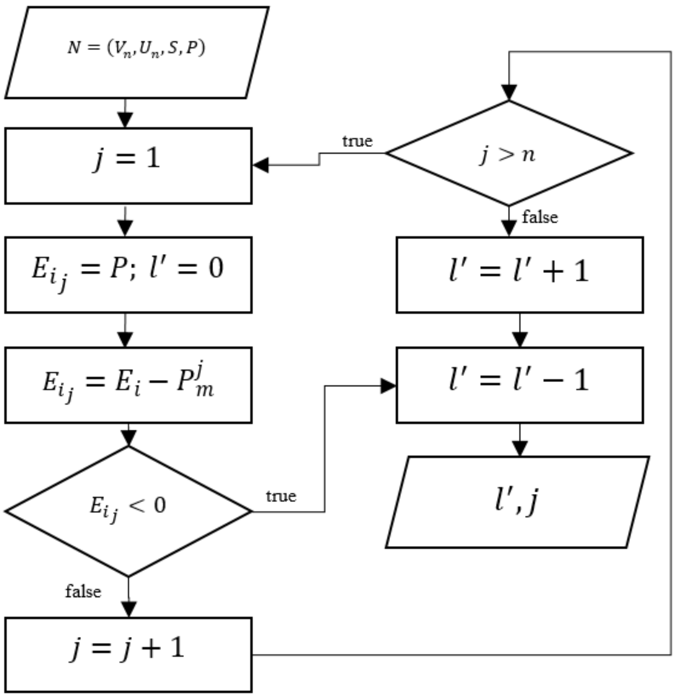



Fig. 2.3. The algorithm for defining the maximum number of iteration in the network

As a result, the algorithm refers to the maximum number of iterations that a network can execute provided that the data is collected every time when the coordinator node activates in the network or if it changes the position in the network.

Let us consider the case when it is impossible to predict the possibility and time of the coordinator movement and how long the coordinator will be located in each position. If there is a possibility to change the time in which the coordinator would stay in any position, it is necessary to choose any position k which would allow the network to operate effectively without changing the network topology as long as possible within time $\Delta t$:

$$\exists k \in \max_{j\in[1..m]} (\min_{i\in[1..n]} \frac{E_{r_i}}{p_j^i}) \quad (2.19)$$

As a result, the life expectancy of the network will be determined on the condition that the coordinator is in position k and the network is able to function as long as all the elements are active $T_n^n = \min_{i\in V_n} T_i$, using the algorithm shown in the image 2.4.

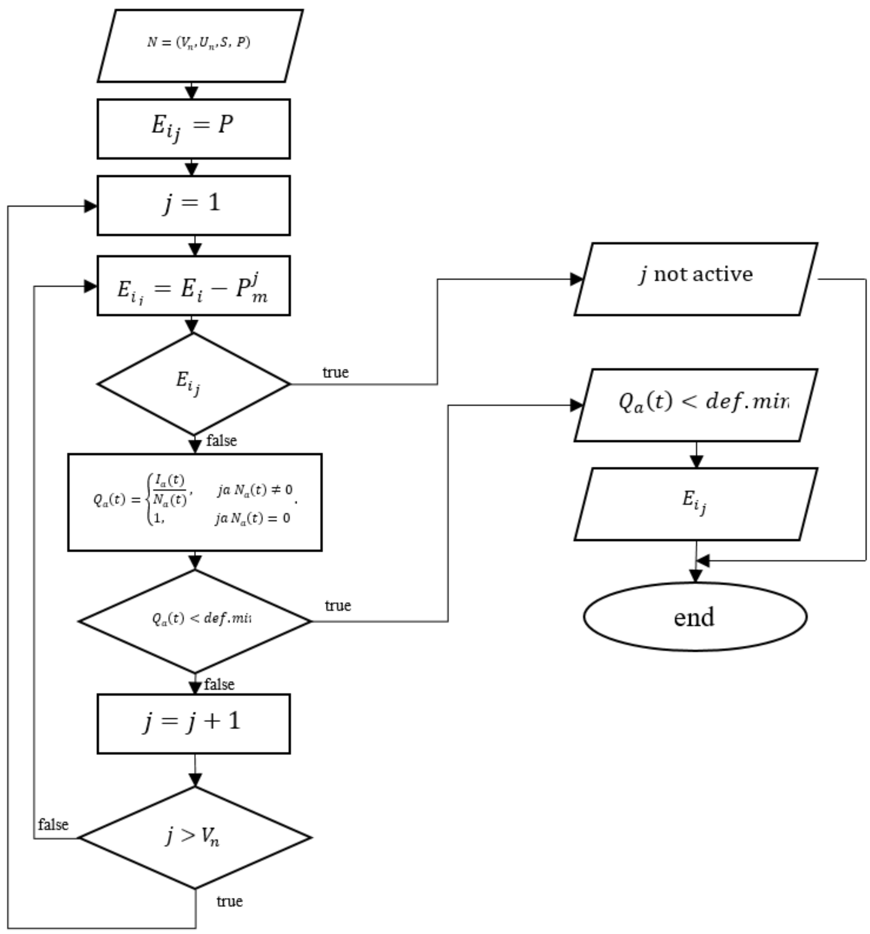



Fig. 2.4. The algorithm for evaluating the network life expectancy without the network topology change

While the network is functioning there is a time when it is necessary to perform the change in network topology. The topology change can be promoted by the change of the coordinator location within the network as well as the network node management module which is described in the 3rd chapter of the dissertation.

As a result, the life expectancy of the network with the mobile coordinator will be determined using the algorithm shown in Fig. 2.5.

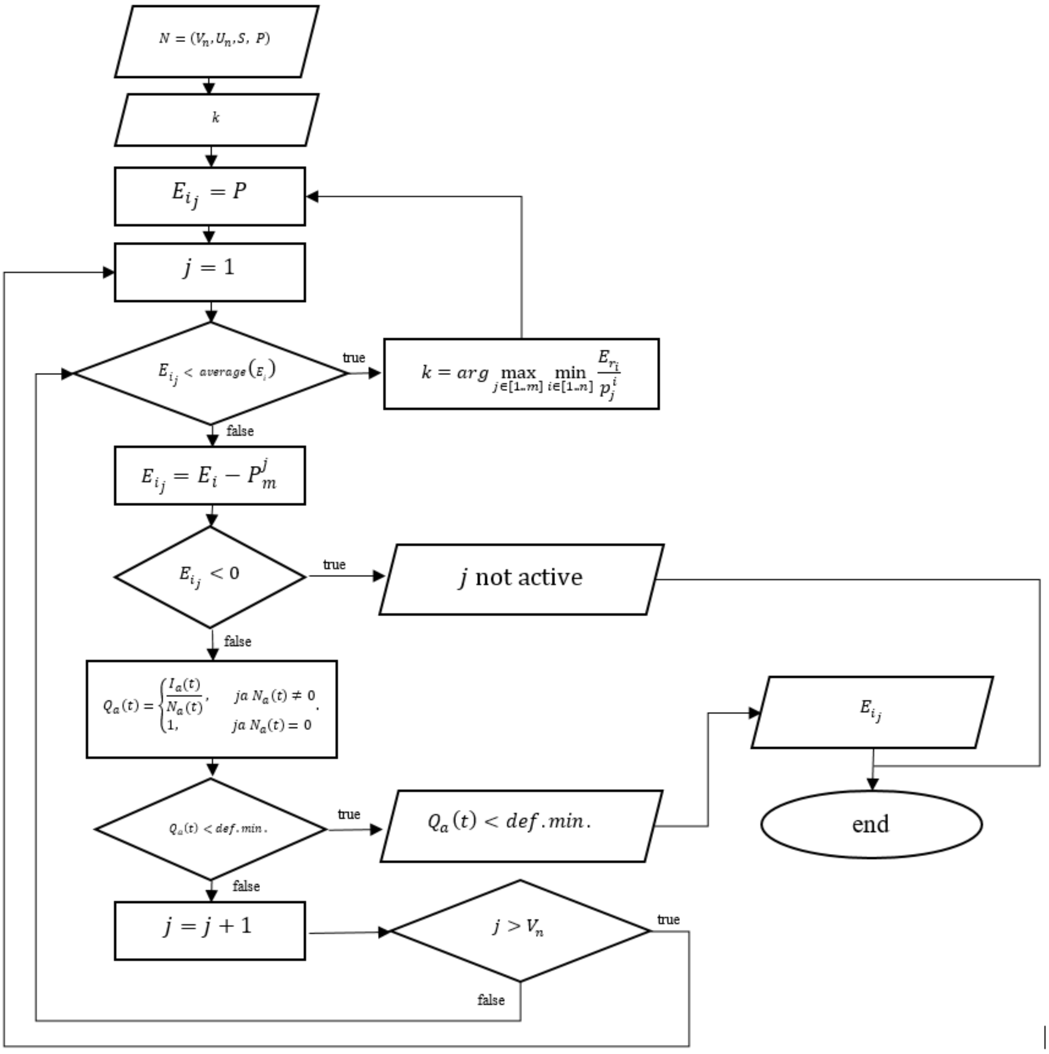



Fig. 2.5. The algorithm for evaluating the network life expectancy through the network topology change

When the algorithm for assessing the life expectancy is executed, at the beginning the coordinator is located in position k. The amount of initial energy in all the nodes is defined in the WSN model $E_{i_j} = P$. The network operates using the generated topology as long as the remaining amount of energy in each node is not less than the average amount $E_{i_j} < average(E_i)$ of energy in the network. If necessary, the network performs the topology change locating the coordinator in a position at which the network is able to function as long as possible without changing the topology.

# 3. DEVELOPING THE RECONFIGURATION METHOD OF A WIRELESS SENSOR NETWORK

## The methods for reconfiguring the wireless sensor network and the interaction of algorithms

The primary task of the network reconfiguration method is to increase the time interval of the network topology change. In the particular case it will be determined by the conditions which will promote the creation of new network reorganization at the beginning of each operating cycle.

The interaction process of the network topology change methods and the diagram consists of:

1. Network coordinator node management method. In a functioning system there are some restrictions that do not allow preparing all the information required for assessing the life expectancy of a network. At the beginning of the method the behaviour of the coordinator node in the network is determined using the following conditions:
   - whether it is possible to find out how the network coordinator will behave,
   - whether the location of the network coordinator remains constant.
2. In the phase of detecting the network configuration the system determines the location of the coordinator. The system uses a dynamic coordinator if the following conditions are fulfilled:
   - The location of the coordinator changes – $V^a_{(x,y)} \notin \{V^1_{(x,y)} .. V^n_{(x,y)}\}$.
   - There is a large difference of the amount of remaining energy in network elements – $p_{min} > \max_i P_i - \min_j P_j$ where i and j = 1,2,…,n.
3. In the case if the coordinator is a dynamic algorithm of the network management operating module which will examine the need to modify the network configuration of the current iteration time and, if necessary, using the model for assessing life expectancy that has been developed in the second chapter of the dissertation, it will contribute to changing the network topology.
4. In case the coordinator is static or it is not possible to identify the location of the coordinator in the network, in order to increase the life expectancy of a network a virtual coordinator node has been introduced which is managed through the heuristic method proposed in the dissertation.

## The management method of the dynamic coordinator node

During the working of the system the local area network module has been introduced which controls the conditions that promote the sensor network reconfiguration in the nodes:

1. The location of the coordinator changes – $V^a_{(x,y)} \notin \{V^1_{(x,y)} .. V^n_{(x,y)}\}$.
2. A large difference of the remaining power in the network elements has been discovered – $p_{min} > \max_i P_i - \min_j P_j$, where *i,j = 1,2,…,n.*

The software module has two main tasks in the system:

- To ensure the collection and storage of the remaining amount of power in the nodes according to the specified step $t^n_c$.
- To determine the period $t^n_c$ when it is necessary to carry out the reorganisation of the routing path.

The management part of the node module is multifunctional unlike the network sensor elements. Some module tasks can be executed simultaneously. Each executable cycle or condition is carried out as an independent operation. An action scheduler is cyclically operating in the node control module which regardless of the situation performs set tasks in the network.

This approach allows managing the operations of the control module as well as managing every executable process.

In the particular model each of the network coordinator nodes has a local node management module that provides the interaction between the node and the network.

The initialization phase of the node management module is defined by the overall network node communication model $Mi$ in accordance with the formula 3.1.

$$Mi = \{Sa, Se, Sp, L, Sra\}, \tag{3.1}$$

where Sa is the number of nodes $Sa = \{a_1, a_2, .. a_n\}$ participating in the communication process; Se is the number of sectors in the communication environment in which certain operations are conducted; Sp is the number of congested sectors in the network where the nodes consume the largest amount of energy; L is the length of the path from the place of the coordinator to the node in the network and Sra is the number of routing nodes in the path that the node control module will use in order to transmit information to the management node.

When the node module is operating cyclically, the dependence on the node operational status has been determined in the intensity of the information between the nodes $Mi$.

The figure 3.1 shows that as a result of the use of the current algorithm it is possible to reduce the overall life expectancy of WSN because a situation in which the coordinator remains unchanged in the network $V_{(x,y)}^{a} = V_{(x,y)}^{a+1}$ or is located in the position $V_{(x,y)}^{a}$ where there is only one possible network configuration $k \to \max(R_{iN})$, the energy will be wasted on creating configuration; thus, the original topology will be created.

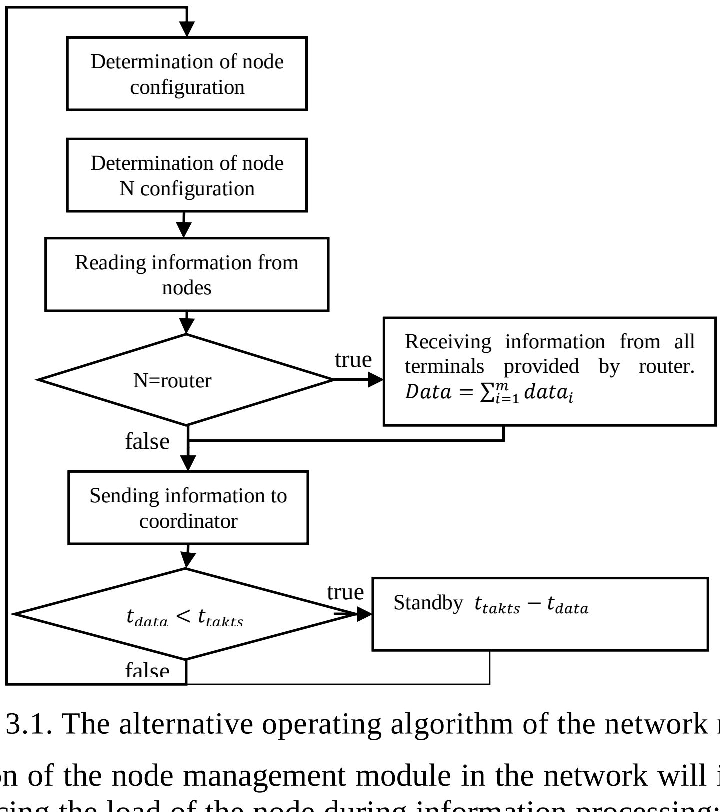



Fig. 3.1. The alternative operating algorithm of the network nodes

The introduction of the node management module in the network will improve network performance by reducing the load of the node during information processing; similarly, it will allow responding to the current changes in real time because the module operates independently of the state of node and the amount of energy.

## Data flow control method

An efficiently operating system is unable to obtain all the necessary information in order to determine the life expectancy of a wireless sensor network. Some network model base values, such as the capacity of the transponder may vary depending on the time which takes the system to remain active as well as the external environment which the system works in. Let us look at some examples where it is not possible to precisely define the required parameters for the network life expectancy assessment:

- There are technical difficulties that reduce the quality of the transmitted information in some network segments. This may be due to another network in the same region with similar or adjacent frequency. In this case the need for a repeated transition of information is increased resulting in a significant increase in energy consumption in the sensitive area.
- The influence of the external climatic factors on the autonomous power supply can result in an increase the power consumption in the standby mode.

For example, wireless sensor networks can be represented with the help of a directed graph. Based on the structure of the graph, each route (v,u) can be used for transmitting information from node v node u. Each of the v nodes has a defined amount of adjacent objects $N(v) \subset V$ that may communicate with the v node. Whilst generating a route, the broadband data retransmission is used in the network [KUM 2005], the information is transmitted from the $N(v)$ node to the entire network simultaneously.

The following data flow handling algorithm in the network is described in this doctoral dissertation. After receiving the transmitted information from node S, which is designed to receive node D, node V uses the following sequence of actions:

1. The potential transponder set $R(v,d) \subset N_v$ is selected and sorted by priority from the set $N(v)$.
2. The potential transponder set of nodes belongs to the set $R(v,d) \in N_v$ and determines the operating strategy of node v.
3. Information on the functionality of the node is recorded in the service of the transmission packet and distributed to the network management agent.

To determine the retransmission priority, it is important to take into account the remaining amount of energy in each individual node. The node control module selects a transponder with the greatest amount of remaining energy $E_0$ in the node. The route building algorithm completely concludes its operations once it has reached the recipient node d.

The doctoral dissertation states that each network element can operate in two modes (terminal or router). In order to split the task into the early stage of network reconfiguration of each node has to remain in listening mode. During the listening mode the remaining amount of energy $E_0^n$ in the node is assessed.

The route of the wireless sensor network from the terminal S to the coordinator D – $S(s,d)$ takes the dendriform structure which is built using the recursive approach from terminal to the coordinator. The first stage is defined by the possible network router set $R(s,d) \in N(s)$. This will allow describing the path $S(s,d)$ as the sorted sub-route list:

$$S(s,d) = [S(v_1,d), \dots, S(v_n,d)], v_j \in R(s,d) \quad (3.2)$$

The next step is to set up the local action strategy $R(v_j,d)$ for each router. As a result, each list of sub-routes can be improved:

$$S(v_j,d) = \left[S(v_{j,1},d), \dots, S(v_j,m,d)\right], v_{j,i} \in R(v_j,d). \quad (3.3)$$

The path from the terminal to the coordinator can be displayed as the dendriform list placed on the second level:

$$S(s,d) = \left[\left[S\left(v_{1,1},d\right),\ldots,S\left(v_{1,m1},d\right)\right],\ldots,\left[S\left(v_{n,1},d\right),\ldots,S\left(v_{n,m_n},d\right)\right]\right]. \quad (3.4)$$

When creating a route, the level is extended up until the router list contains only one coordinator D node. In this case, the segment of the sensor network is equipped with the only remaining coordinator node. Henceforth, it is to be assumed that the recipient node D (the coordinator) is fixed and will not be used in any formulas.

Let us introduce a way to combine paths. Suppose that $S(v)$ is the path from node V to the coordinator in the router list $R(v) = (v_1, v_2, \ldots, v_n)$ where the node U does not exist. Also, supposedly, S(u) is a path consisting of R(v) nodes that have been excluded from the list.

Let us define the path which uses the combined list of $S(v) \in S(u)$ where U nodes are used with low levels of a factor, like this: $R(v) = (v_1, v_2, \ldots, v_n, u)$.

In an operating system the management module of a node has two functions:

- to provide the collection and storage of the remaining amount of energy in the nodes in the particular step $t_c^n$.
- to determine the period $t_c^n$ when it is necessary to carry out the re-organization of the routing path.

The node control module part is multifunctional unlike the network sensor elements. Some module tasks can be done simultaneously. Each executable cycle or condition is fulfilled as an independent operation. An action scheduler is cyclically operating in the node control module which executes the set tasks within the network regardless of any situation. This approach allows coordinating the actions of the control module as well as managing every executable process.

In the proposed model each network coordinator node has a local node management module that provides the interaction between the network and the node.

## The use of the dynamic coordinator within a network

When working with actual systems there are some restrictions that do not allow preparing all the necessary information in order to model the life expectancy of a system:

- it is impossible to find out the precise actions of the network coordinator, whether it will stagnate and whether it will use the expected movement trajectory or location.
- The power $p_k^i$ consumed in the nodes can change over time.

In an operating system there might be a situation when it is impossible to establish a communication route between the sensor node and the coordinator. As a result, the energy consumption is increased which provides inefficient means of communication between the terminal nodes and the coordinator. To increase the life expectancy of the network the virtual coordinator node should be introduced; it moves within the network cyclically using a familiar motion trajectory.

Additional labels should be introduced for the description of the algorithm of a virtual coordinator:

$S(k)$- a set of graph $G_s$vertices which includes the adjacent vertices of the *k* and *k* vertices:

$$S(k) = \{k\} \cup \{j: (k,j) \in E_s\}. \quad (3.5)$$

$S(k)$ – the amount of nodes that are physically connected to the virtual coordinator node k and is located in its vicinity:

$$D(k) = i \in V_n : (u, i) \in E_n(k), where\ u \in V_n - coordinator\ node. \quad (3.6)$$

In every step n when the coordinator is located in one of the positions $p_n$ it chooses a new position from the list $S(p_n)$ in order to take the next step $p_{n+1}$ based on the remaining amount of energy in the nodes. If the network management module facilitates the change of network topology based on the conditions described in the article, the coordinator changes its location. While located in a new position, the virtual coordinator processes the information within the node spending the time $t_s$ in it which is defined by the user. The key step of an algorithm is the choice of the next position $p_{n+1}$. Mainly, it is executed by using one of the heuristics methods.

Different sources offer a variety of heuristics methods [BAS 2007, BLO 2002, MAU 2011]. One of the simplest methods is considered to be the random position selection from the list of possible positions: $p_{n+1} = random(S(p_n)$. In a paper by one author [BLO 2002] it was offered to provide the movement of the coordinator along a visible network perimeter. This approach is based on the fact that most operating network elements within the network center have a lower amount of remaining power in the nodes.

The proposed method (placing the coordinator node on the network perimeter) allows loading the nodes where the remaining amount of energy is higher.

In a paper by one author [MAU 2011] it was offered to provide the movement of the coordinator along a visible network perimeter. This approach is based on the fact that most operating network elements within the network center have a lower amount of remaining power in the nodes.

The proposed method (placing the coordinator node on the network perimeter) allows loading the nodes where the remaining amount of energy is higher.

In his works Basagni proposes the usage of MRE (Maximum Residual Energy) [BAS 2007] coordinator motion algorithm. The coordinator node determines the remaining energy in the adjacent nodes through the GMRE algorithm and selects a single node with the largest remaining amount of energy in it. In this case the planning of the coordinator movements is linked to searching maximum remaining amount of energy in the nodes.

There are several types of function $E_k$ which allow determining the location of the coordinator k:

1. $E_k(t) = \frac{1}{|D(k)|} \sum_{j \in D(k)} E_{rj}(t);$

2. $E_k(t) = min_{j \in D(k)} E_{rj}(t);$

3. $E_k(t) = max_{j \in D(k)} E_{rj}(t).$

Regardless of how the function $E_k$ is defined, the remaining amount of energy only partially characterizes the total state of the network and cannot be used as the sole condition. For example, a node with the smallest amount of remaining energy $E_0$ and the lowest consumption of power is able to function longer than a node with the highest $E_0$ and the highest energy consumption. The use of the MRE method only places the coordinator node in a position with the highest $E_0$ value and in case if the network management module does not facilitate a new topology change then this method will not increase the overall network life expectancy.

The doctoral dissertation offers an alternative method: in every operational step choose such a location $p_n$ of a virtual coordinator which allows the network to function as long as possible on the condition that the network topology will not be changed. Using an analogue, the name of the power method MREML (Maximum Residual Energy Maximal Life expectancy) is to be defined:

$$E_k(t) = \arg(max_{k \in S(p_n)} min_{n \in D(k)} \frac{E_0^n(t)}{p_k^n(t)}), \quad (3.7)$$

where: $p_k^n$ is the total power consumed in an operating cycle of the node k.

The total power consumption of the network node can be calculated or changed dynamically based on external factors. If the time which the coordinator spends in each of the node k positions equals $t_k$, if the remaining amount of energy in the nodes is known before the coordinator is placed in a certain position $E_0^n(t)$ and if the amount of energy is known when the coordinator will leave the position $E_0^n(t+t_k)$, then the power consumption of each node can be expressed by using a formula:

$$p_k^n = \frac{E_0^n(t) - E_0^n(t+t_k)}{t_k}. \quad (3.8)$$

MRE in contrast to the MREML method uses the network node local information about the remaining amount of energy that regularly requires additional power when analysing the remaining amount of the adjacent nodes. The proposed method in the article requires using a network node control module and the static coordinator node for storing information. This approach allows receiving a global overview of the entire network configuration if there is a change in the network topology; additionally, it allows the virtual coordinator node to take the best position for collecting the information from the nodes.

# 4. WIRELESS SENSOR NETWORK LIFE EXPECTANCY MODEL AND METHOD SIMULATION-BASED EXPEREMENTAL RESEARCH

## The experimental approbation of the methods for increasing the life expectancy of wireless sensor networks through the physical network

Regarding the experimental approbation of methods for increasing the life expectancy of wireless sensor networks, there have been three physical experiments carried out in the dissertation:

1. Approbation of the methods for calculating the life expectancy through a network with a static coordinator node.
2. An experiment for defining the technical parameters of the network nodes using the WSN life expectancy assessment model.
3. The use of methods for increasing the life expectancy of the wireless sensor network in a network with a dynamic coordinator node.

### The approbation of life expectancy calculation methods through a network with a static coordinator node as well as the description of the experiment scenario

With the co-financing of Climate change financial instrument for the project “the use of renewable energy in the household sector” in cooperation with “Moderator” Ltd. a heating system was set up in a detached house which uses alternative and renewable resources for producing energy.

The project was implemented after the residential buildings was put into service when all the interior work was completed which did not allow the use of sensors with permanent power supply and a connection to a physical computer network. The autonomous heating and hot water preparation system that was installed during the project works using several temperature, water flow and pressure sensors for managing the central boiler and the control of the pump groups. The automation of the sensors is implemented with the aim of reducing energy consumption (thermal energy and electricity) during its operation.

**The aim of the experiment**

1. To check the wireless sensor network life expectancy assessment method offered in the dissertation using the created sensor network of water / air temperature, water flow and water pressure.
2. To verify the efficiency of the widely applied method used for increasing the battery capacity
3. To assess the increase in life expectancy by changing the network topology.

**The object of the experiment**

The object – a wireless sensor network provided by the company Syxthsense consisting of 54 terminal nodes Syxthsense TX-VTRX TX, 17 routers Syxthsense SST-RXTX-P306 as well as 1 coordinator node ModBusMaster RX JaCe. The coefficient of the operating range for all nodes = 1; the node transponder uses the On/Off operating mode and the radio receiver operates with a permanent capacity. Each node operates using 2x1.5V (AA) type batteries. The network topology is defined manually and is constant for the entire duration of the network. The network routers can connect to the coordinator node or any other router node in the network.

**Duration of the experiment**

The experiment was carried out in three stages:

- The first stage – September 2012 to May 2013. During this period the WSN node configuration installed by the manufacturers was used as well as during installation an automatically generated network topology for assessing the duration of the WSN.
- The second stage – September 2013 to May 2014. During this period the installed by the manufacturers was used and the battery capacity of router nodes was increased; the network operated using the network topology generated during the first stage.
- The second stage – September 2014 to May 2015. During this period the WSN node configuration installed by the manufacturers was used with the proposed industrial power supply. WSN network topology was changed manually at the beginning of each month using the MREML method proposed in the dissertation.

**The input data of the experiment**

The experiment was done through using one system in the time frame of three years. The technical characteristics of WSN were not changed during the experiments; the system was functioning using the operating structure defined during the first year. As a result, it can be assumed that the node energy consumption for each working position and time when the system is in any state can be regarded as a constant value.

The experiment was carried out in one place which is characterized by a constant, preset temperature indoors and the same number of people who use the water; the system was activated on the 1st of September and the time of termination was the 20th of May. The only external factor that can affect the WSN which does the heating and water preparation system is the air temperature outside the room.

For the experiment to be regarded as valid, on the basis of table 4.1., let us define the particular time interval of three years when the average deviations of the air temperature of Latvia are insignificant in the time frame of a month [LAT 2015]. This determines that the most effective result-integrating time frame is the first three months of every year.

Table 4.1.

The average temperature in Latvia

| | 2015 | 2014 | 2013 | 2012 |
|---|---|---|---|---|
| January | −0,7 °C | −6,1 °C | −6,2 °C | −3,4 °C |
| February | −0,2 °C | +0,4 °C | −2,2 °C | −8,8 °C |
| March | +3,4 °C | +3,4 °C | −5,5 °C | +0,9 °C |
| April | +5,9 °C | +7,2 °C | +4,0 °C | +5,9 °C |
| May | +11,9 °C | +12,0 °C | +14,4 °C | +11,7 °C |
| June | | +13,8 °C | +17,6 °C | +13,9 °C |
| July | | +19,7 °C | +17,8 °C | +18,2 °C |
| August | | +17,3 °C | +17,1 °C | +15,9 °C |
| September | | +12,7 °C | +11,9 °C | +13,0 °C |
| October | | +6,5 °C | +8,1 °C | +6,9 °C |
| November | | +2,3 °C | +4,7 °C | +4,0 °C |
| December | | −0,9 °C | +2,2 °C | −4,8 °C |

**Determining the standard value of the WSN life expectancy**

The network operation time $t_{st}$ of the first year will be assumed as the standard. Let us assume that the wireless sensor network can be considered active as long as all the nodes are active.

An efficiency ratio $\delta_w$ of the operating network should be introduced and it points to the increase in the life expectancy of a network in percentage:

$$\delta_w = \left(\frac{t}{t_{st}} - 1\right) * 100\%, \tag{4.1}$$

where $t$ is the network life expectancy in the particular stage.

The efficiency coefficient $\delta_c$ introduces the system implementation and expenses of the usage:

$$\delta_c = \left(\frac{C_{st}/t_{st}}{C/t} - 1\right) * 100\%, \tag{4.2}$$

where $C$ refers to the system expenses during the stage and $C_{st}$ refers to the standard model system expenses.

The error detection rate $\delta_m$ refers to the assessment methods indicating the accuracy of the methods for calculating the life expectancy in percentage in relation to the actually operating system.

$$\delta_m = \left(\frac{t'}{t_{st}} - 1\right) * 100\%, \tag{4.3}$$

where $t'$ refers to the network life which is calculated using the method described in the 2nd chapter of the dissertation. The results of the experiment are summarized in table 4.2.

Table 4.2.

The summary of experiment results on the constant coordinator

| $t_{st}$ | 624 | | | | | | |
|---|---|---|---|---|---|---|---|
| $E_0$ | Battery paid | battery-building method | Manual network topology change through Dijkstra algorithm | t' | $\delta_w$ | $\delta_c$ | $\delta_m$ |
| 18 KJ | 2 x 0,79 EUR | | 696 | 642 | 11,54% | 11,54% | 3% |
| 27 KJ | 3 x 0,79 EUR | 864 | 912 | 912 | 38,46% | -7,69% | 6% |
| 36 KJ | 4 x 0,79 EUR | 984 | 1072 | 1082 | 57,69% | -21,15% | 10% |

**The summary of experiment results**

1. Increasing the capacity of the batteries gave a large expansion to the life expectancy $\delta_w$, but it turned out to be economically inefficient – $\delta_c$. It can be concluded that by means of increasing the capacity of the batteries – the greater the increase in life expectancy, using the method for increasing the battery capacity, the higher the expenses of the system.
2. Using the network topology change in all cases, the actual increase in network life expectancy with the same battery expenses can be seen. Therefore, it can be concluded that the WSN reconfiguration method works but should be used to increase the operational efficiency using the autonomous method proposed in the dissertation.
3. The dissertation shows that using the industrial parameters of a wireless sensor network, the assessment method of the WSN life expectancy works accurately. It can be assumed that the error rate $\delta_m$ of 3% is insignificant. In cases when the technical parameters of the system were partly replaced, the calculating error rate $\delta_m$ increased significantly.

This can be explained by useless or unaccounted energy hubs which have changed without any adaptation from an industrial node configuration.

**The experiment for defining the technical parameters of the network nodes using the model for detecting the life expectancy of WSN**

During the second experiment ready to use wireless sensor network solutions were used and the system prototype of water supply tracking and centralized disconnection was developed and it is installed in the private sector in Saulkrasti the in collaboration with "Saulkrastu komunālserviss" Ltd. The system in which the experiment was made has one coordinator, 8 routers and 236 network node elements which function as the terminal with the DDA and Ankor modules by reading the information on the water flow rate and temperature and, if necessary, it controls a valve of the NC type.

The router nodes are continuously connected to a power source, but they are simultaneously equipped with a backup 12V battery for reading the information during the winter with the reduced time frequency. The aim of the experiment is to verify the possibility to increase the action in an autonomous network in case of power shortage using the network reconfiguration method. The reconfiguration of network elements was ensured by using the developed software security which allows the network topology change.

**The technical characteristics of the prototype used during the experiment**

As part of the practical work, a wireless sensor node was developed by using adaptive configuration of network topology formation.

Table 4.3. shows the technical specification of the module:

Table 4.3.

The technical characteristics of the ATmega328 microcontroller

| Parameter | Value |
|---|---|
| External Memory | 32 kbytes |
| Internal memory | 2 kbytes |
| Number of convectors | 28 |
| The maximum operating frequency | 20MHz |
| CPU | 8-bit AVR |

Table 4.3. continue

| | |
|---|---|
| The number of stored measurements | <390 |
| Radio receiver | 2400MHz to 2483,5 MHz with programmable step 1MHz. |
| The transmittable (TX) speed | 250kbps |
| Operating range | <250 meters |
| The power used in the receiving mode | 19.7 mA |
| Consumed power TX, -10 dBm | 11 mA |
| Consumed power TX, -5 dBm | 14 mA |
| Consumed power TX, 0 dBm | 17.4 mA |
| The power used in the standby mode | 20 µA |
| The power used in the sleeping mode | 1 µA |

**The aim of the second experiment**

1. To verify the usage of WSN life expectancy assessment model in order to determine the technical parameters of a network node.
2. To assess the interaction of different modes of operation affecting the WSN life expectancy.

**The object**

The research object was the wireless sensor network of the company DIYPower and HYDROLINK consisting of 236 terminal DIYPowe FS4001A G1 nodes, 8 HYDROLINK RFMTXE routers and 1 coordinator node MBUS Master Unit HYDROlink. The coefficient of operating range for all nodes = 1 the module of the radio receiver works with a permanent capacity. Each node is running on a permanent power supply and backup 12V type batteries. Network topology is defined manually and is a constant for the entire duration of the network. The network routers may connect to the coordinator node or any other router node in the network.

**Duration of the experiment**

The experiment was carried out for two years and is divided into two stages:

- The first stage – June 2010 to June 2011. The system design, installation and the adaptation of technical parameters using the WSN network life expectancy assessment model offered in the dissertation.
- The second stage – June 2011 to June 16, 2013. Introduction of the network topology and its development.

**The input data of the experiment**

The experiment was done through using one system over the course of three years. The technical characteristics of WSN were not changed during the experiments; the system runs on the algorithm and operating structure that was defined during the second year of the experiment. As a result, it can be assumed that the node capacity of each operational state and the time at which the system is located in each state, is a constant value.

The experiment was carried out in one place and all the terminal nodes had a defined identical initial configuration as well as the network topology. In order to avoid the influence of external factors on the network nodes and to protect the nodes from physical damage, the nodes were placed into specifically designed containers with limited access (Figure 4.1). It can be assumed that all the technical characteristics of the node as well as the operating frequency has been a constant value over the course of three years.

Fig. 4.1. Water supply control unit

**Determining the standard value of the WSN life expectancy**

In the second experiment the WSN network can be seen as working for as long as at least one of the terminal nodes is active. Time $t_{st}$ is considered as a standard value which indicates how much the terminal node can operate while transmitting information and maintaining the NC valve in an open position; in the event of power outage the industrially defined operating frequency and network topology can be used.

Let us introduce the coefficient $\delta_w$ referencing the efficiency of the operating network which points to the network life expectancy as a percentage:

$$\delta_w = \left(\frac{t}{t_{st}} - 1\right) * 100\%, \tag{4.4}$$

where $t$ is the network life expectancy in this stage.

Let us introduce the coefficient $\delta_{t_w}$ in percentage referencing the total operating time of the system and the dependency of the WSN life expectancy which will indicate the dependence of the duration of the system life expectancy in relation to the overall one operating cycle $t_c$.

$$\delta_{t_w} = \left(\frac{t'_c}{t'}\right) * 100\%, \tag{4.5}$$

where $t'_c$ is the total time of one cycle in a modeled system; $t'$ is the overall life expectancy of the modeled system.

The results of the experiment are summarized in figure 4.2.

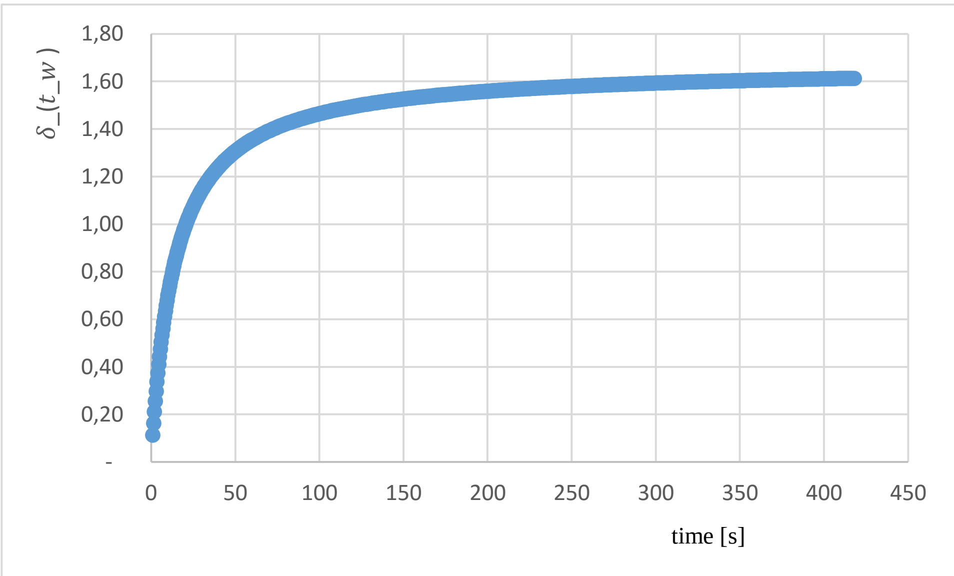



Fig. 4.2. The dependence of the life expectancy of WSN on the total one operating cycle

**The summary of the experiment results**

1. As it can be seen in figure 4.2. there is a determined maximal border $sup(t'_c)$ over which it is useless to increase the $t'_c$ value.
2. Using the information obtained in the experiment, it can be concluded that the overall life expectancy of the system is significantly affected by the tasks in the node that are completed when the node is in the sleep mode. In case the unit is equipped with Ankor modules for controlling external objects, the energy that is consumed when the system is in standby mode will increase; therefore, the total system life expectancy reduces and the methods proposed in the dissertation do not significantly increase the life expectancy of WSN.
3. Using the network topology changes the actual increase in life expectancy of a network with equal technical configuration of a node can be seen in every case. In this case the increase in life expectancy of the WSN ranges from 1.5% to 6% depending on the node operating cycle that has been chosen. As mentioned above, a small increase in WSN life expectancy is due to the fact that the system in question uses a large amount of power while being in sleep mode.

**The usage of the methods for increasing the life expectancy of a wireless sensor network within a network with a dynamic coordinator node**

During the third experiment the wireless sensor network developed by the project UNITE was used for monitoring the work-load of learners in schools. This WSN differs from others with the fact that the network elements, while exchanging information in the network, use the generated data flow path-building algorithm because it is impossible to provide the location of each network element in it; hence, it is possible to use wireless sensor network reconfiguration methods whilst viewing the formation of the network topology from the point of view of energy consumption. The system, in which the experiment was carried out, has 2 coordinator nodes and 120 nodes that could fulfil both the terminal and coordinating functions depending on the situation. In cooperation with the Riga State Gymnasium No.3 the sensor module was used during the experiments which operated in accordance with the developed WSN node prototype.

**Aim of the third experiment**

The goal of the experiment is to test the possibility to increase the autonomous operations of the network using the wireless sensor network reconfiguration methods offered in the dissertation.

**The object**

The research object is the wireless sensor network prototype created during the project UNITE which used the modules of management designed with the help of the ASUS P527 Windows Mobile equipment. Each network node is running on the ASUS P527 autonomous power supply with the Li-Ion 1300mAh battery whose original unmodified operating time is 6 hours whilst continuously using the 3G network. The network topology is defined manually and is constant for the entire duration of the network.

**Duration of the experiment**

The experiment was carried out for two years and divided into two stages:

- The first stage – June 2006 to March 2007. System design, prototype development and prototype approbation in Riga State Gymnasium No.3.
- The second stage – September 2007 to December 2007. The approbation of the prototype during the learning process by involving 72 learners – 31 students from Latvia and 41 students from the UK. During the second stage the method of use

of the dynamic coordinator was approbated in order to increase the life expectancy of the WSN.

### Input data of the experiment

The experiment was carried out using one system over the course of two years. The technical characteristics of WSN were not changed during the experiments; the system was operating by means of the operating structure and algorithm defined at the beginning of the experiment. It can be assumed that the power used by the nodes in each operational state as well as the time in which the system is positioned in each state, is a constant value.

The experiment was carried out in one place and all the terminal nodes had a defined identical initial configuration as well as the network topology. During the experiment the most important parameter affecting the energy consumption of each node, was the system operating range R; therefore, it is assumed that all nodes are functioning whilst using the technically defined power of the transmitter to the max for transferring information to the maximum distance which determined that the range value can be regarded as a constant.

### The determination of the standard value of WSN life expectancy

During the third experiment the WSN network can be seen as functioning for as long as at least 60% of all network nodes are active. It is based on the design specifications – the lesson can be considered as done, if at least 60% of students have participated in it. For the standard value let us assume the first year standard obtained in the experiment during gaining the maximum life expectancy $t_{st}$ of the system which indicates how long the terminal node can operate whilst transmitting information and using one type of topology in the entire life cycle.

Let us introduce the network operating efficiency coefficient $\delta_w$ that points to increase of the network life expectancy as a percentage:

$$\delta_w = \left(\frac{t}{t_{st}} - 1\right) * 100\%, \qquad (4.6)$$

where $t$ is the network life expectancy in this particular stage. The table 4.4. shows the results obtained during experiments.

Table 4.4.

The WSN life expectancy dependence on the network operating methods

| Node number | System life expectancy with a fixed topology and a single coordinator | “RANDOM” method use | Modelled MREML method |
|---|---|---|---|
| 10 | 4 | 2,78 | 3,3584 |
| 20 | 4,5 | 4,2111 | 4,01175 |
| 30 | 4,8 | 4,7784 | 4,74144 |
| 40 | 5 | 5,4225 | 5,35 |
| 50 | 5,2 | 6,03096 | 6,03824 |
| 60 | 5,5 | 6,9432 | 7,05925 |
| 72 | 5,7 | 7,88025 | 8,06664 |

### The summary of the experiment results

1. As can be seen in figure 4.4., by using small-scale networks where the number of nodes is m<40 the risk is that the method used will result in a reduction in life expectancy; because of the position of the coordinator inefficient network topology will be created.

2. By using the information obtained in the experiment, it can be concluded that the results of network methods are dependent on the amount of network nodes and the technical specifications of the nodes. There is a minimum number of nodes in every situation that is viewed which determines the need for the described application methods.

### The summary of results obtained during the physical experiments

During the experiment, the results confirmed:

- When using the network topology changes the network shows the increase of the life expectancy in relation to the technical parameters defined in the node; however, there are cases when the network uses the only available routing path and then if the network topology changes, there will be consumption of excess energy.
- The life expectancy of the WSN depends on the processes that are activated in the node while it is in the sleeping mode. The nodes which used Ancor modules, the method for increasing life expectancy of a wireless sensor network showed a negative result because of the increased amount of energy consumed by the node.
- In the nodes with dynamic configuration the maximal border $\sup(t'_c)$ was determined over which it is useless to increase the total duration of one cycle.
- The minimum number of network nodes has been defined when the methods for increasing the life expectancy of a wireless sensor network are ineffective.

During the experiment, the results obtained theoretically depend on the technical characteristics of the model.

They refer to two disadvantages:

- The experiment proved that the technical characteristics of the node specified by the manufacturer are approximate and they are not possible to use for referencing the model data.
- Because of the lack of time it is impossible to carry out a complete experiment over a longer period of time; thus, the physical data collected during the experiment describes the situation during the particular interval which cannot be used for full wireless sensor network life cycle analysis.

During the experiment, the results showed the need to use simulation modelling to receive precise approbation of the methods over a longer period of time by viewing the full life cycle of the wireless sensor network.

### The simulation modelling of methods for increasing the life expectancy of a wireless sensor network

The need for increasing the life expectancy of a wireless sensor network with possibility of simulation modelling is based on several factors:

- The inability to perform the physical experiment using existing technologies.
- It is necessary to carry out the experiment within a larger interval of time to create a large disbalance of the amount of the remaining energy $E_0^n$ in the network. This will enable the system to make the necessary changes to the network topology for balancing energy by using the methods described in the 3rd chapter.

**The experimental approbation of the methods for increasing life expectancy of a wireless sensor network using modeling tools**

In order to perform the experimental approbation of methods for increasing the life expectancy of a wireless sensor network the dissertation offers the following actions:

- In the wireless sensor network simulation software, the network topology is set up and the constant values of the network have been divided.
- Experimentally determined standard value of the life expectancy of a wireless sensor network.
- The placement impact of the network components on the overall operation of the network has been experimentally tested.
- Experimentally testing the impact of using the transmitter capacity on the overall life expectancy.
- Experimentally testing the impact of individual operating modes in the nodes on the overall life expectancy of the network.
- Experimentally comparing the effectiveness of methods for increasing the life expectancy of a wireless sensor network

**The system input data used during the process of simulation modeling**

While performing the simulation modelling such statements will be taken into account:

- Network activity area is $L \times L$ where $L$=100m;
- Network node coordinates $x, y$ is determined by a random number generator in the range of 0 to $L$;
- The packet size of the information transmitted in the network is equal to 100 bytes;
- Generated data flow $\lambda = 0{,}2\ frames/second$;
- The location of the coordinator is determined by simulation scenario.

**The structure of the network topology of the wireless sensor modeling process**

Network node management module facilitates network topology change (Chapter 3). All nodes located directly in $R$ or closer to the coordinator use the direct connection with the coordinator node.

For other nodes the router is selected by using the following criteria:

1. Number of routers on the way to the coordinator.
2. Router load (Number of the connected nodes).
3. The distance factor.
4. The remaining amount of energy in transponder nodes.

The technical parameters of the system (amount of power used in different modes) are taken from the project ASDK Technology that use the transponder module widely used in the market [MEM 2015].

All the constant value data used in the modeling process are shown in the table 4.5.

Table 4.5.

The constant values used in the modeling process.

| Technical parameter (symbol) | Value |
|---|---|
| Network size in meters $L$ | 100 |
| Number of nodes in the network $n$ | 100 |
| The initial energy $E_0$ in the node | 20 |
| The density of frame transmission in each of the network nodes $\lambda$ | 0,2 |
| The size $L_{freim}$ of the transmitted frames | 100 |

**Determining the standard value of the network life expectancy using a modeling tool**

Each network operating cycle is unique. Depending on the established situation in the network, new network topology is formed. While modelling the overall life expectancy of the WSN, the states of the network can be divided into categories m when the network is in one position and uses the fixed topology.

Within each network there is one most efficient location for the coordinator when after the formation of the operating network topology the autonomous operating time of network has increased:

$$k_{st} = arg \max_{k\in[1..m]} \min_{i\in[1..n]} \frac{E_i}{p_k^i}. \tag{4.7}$$

The operating time of a network with the fixed network topology can be described using the formula:

$$t_{st} = \max_{k\in[1..m]} \min_{i\in[1..n]} \frac{E_i}{p_k^i}. \tag{4.8}$$

Simulating the operation of the network coordinator with the fixed location and the permanent network topology, it is possible to see that the imbalance of the remaining energy appears in the nodes. Figure 4.3 shows the established network topology with the generated network nodes for determining the location of the coordinator more effectively. Figure 4.4. shows the remaining amount of energy in a modulated situation. Nodes located near the coordinator have significantly higher energy consumption than the nodes located in the furthest points.

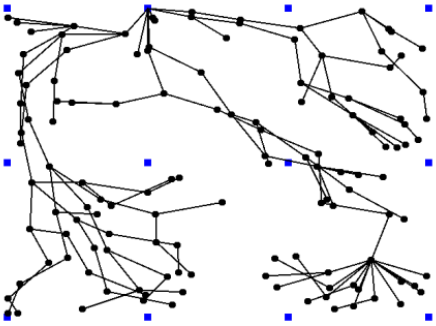


Fig. 4.3. The network topology established in the process of modeling

While modelling a situation with the fixed network topology it can be concluded that if one network node stops working, the total remaining amount of energy in the network will be ~ 73%.

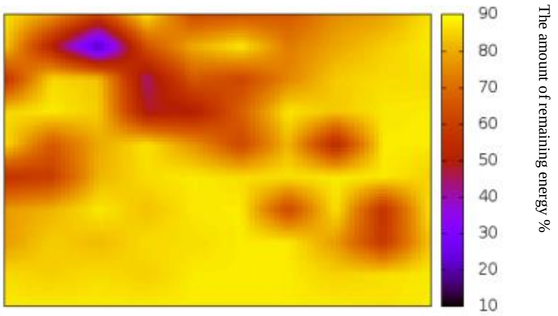



Fig. 4.4. The amount of remaining energy in the modeling process

By subsequent network modelling the case of the network topology will be considered as the starting point and any further comparison of results will be made in relation to it. This is justified by the fact that the life expectancy of the network is technically impossible to define as it depends on many factors [Chapter 2]. For example, when increasing the battery capacity in one of the network nodes the remaining amount of energy $E_0$ will be increased on the network as well.

Let us use the coefficient of operating network efficiency which refers to the increase of the life expectancy of a network expressed in percentage:

$$\delta_t = \left(\frac{t}{t_{st}} - 1\right) * 100\%, \tag{4.9}$$

where $t_{st}$ is network life expectancy with constant network topology; $t$ is network life expectancy with an active control module for topology change.

**The impact of wireless sensor network component placement on the life expectancy of a network**

As previously mentioned, the network life expectancy depends on several factors. Let us view how the network is affected by the location of the nodes in the network. Suppose that the number of network is $n$=100 and the transponder range is 50m. During modelling a big difference in the results obtained can be seen and in some situations the fluctuations account for up to 36%.

Despite the fact that the change of network topology allows the network to increase the life expectancy of up to 20%, there are situations where the change of the network structure gives the opposite effect by reducing the life expectancy accordingly. This is based on the fact that while generating the data flow route in the network, the load of transponder nodes changes every time. Looking at the network route structure it is possible to see that closer to the coordinator node there are some links that transmit the largest amount of information (in the figure 4.3.).

Let us experimentally view how the load of the channels changes in the more active nodes. During the experiment let us reduce the amount of network nodes: $n=50$ it will activate more nodes and view the real results. Suppose the initial amount of energy is $E_0=20$; the system performs 10 iterations. In order to determine the actual load of the network segments, the network topology will have to be changed manually by restoring the initial value of the amount of energy $E_0=20$.

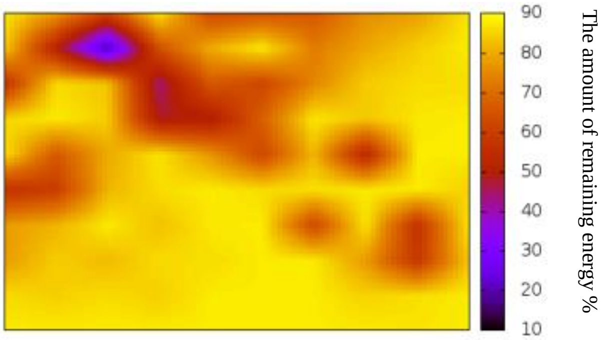



Fig. 4.5. Energy distribution in the nodes after 10 iterations

Figure 4.5. shows that when changing the network topology there are locations where the energy consumption remains at the highest level in the nodes. Fluctuations in energy consumption are only in the range of 8%. This proves that the effectiveness of the method developed for increasing life expectancy of the WSN depends on the coordinator location.

Let us check how the coordinator relocation affects the load of network nodes. During the experiment the number of network nodes was $n=50$ and the initial amount of energy $E_0=20$ and the system performs 10 iterations. To be able to see the actual load of network segments the network topology will have to be changed manually by changing the location of the coordinator.

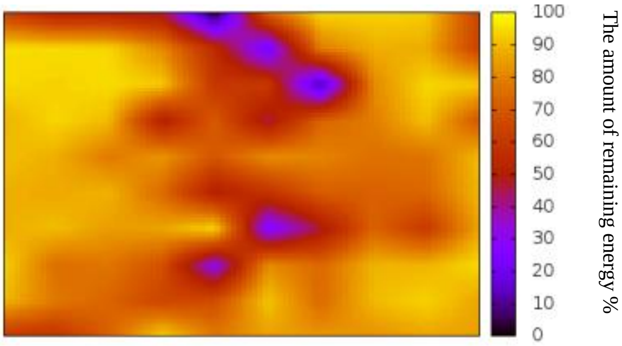



Fig. 4.6. The amount of the remaining energy with the variable coordinator node

In figure 4.6. it is possible to see that by changing the location of the coordinator, the energy consumption of the network nodes is in partial disbalance. During the modelling time it can be seen that when the coordinator changes its location, the segments, in which a major data transmission is done, also change their location. By changing the location of the coordinator the increase in the network life expectancy is 27% in relation to the fixed network topology.

The location modelling of the network nodes enables to determine the methods used for increasing the WSN life expectancy and determine their efficiency as well as to define the initial technical parameters that help to accommodate the network framework.

**The influence of the operating range of WSN node transponder on the life expectancy of a network**

Let us view the three network scenarios generated by the network node location. During the modeling time the impact of the transmission distance coefficient on the operating network coefficient $\delta_t$ can be seen. By increasing the distance in locations where the value of the coefficient increases in relation to the previous value. Simulation modelling results are shown in Figure 4.7.

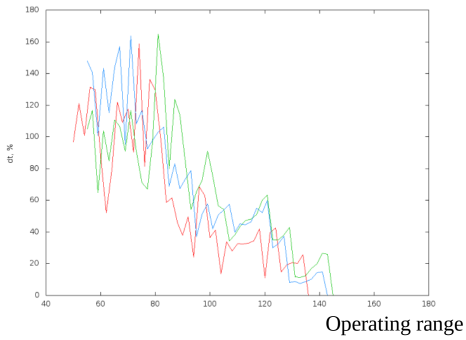



Fig. 4.7. The effect of the transmitted distance coefficient on $\boldsymbol{\delta_t}$

According to the modelling results there are three major characteristics:

- In an operating network each network node exists in an operating range where the energy consumption is more efficient;
- There are situations where it is more effective to increase a range of transmitting information to a further distance discarding the routing functions;
- The methods for energy balancing should be used in combination with routing protocols which allow modifying the power of transmitter.

By using a large operating range with the coefficient *R* a situation may be present when the network will operate through a star topology; the sensor nodes will be connected to the coordinator node without routing protocols. In this situation the only way of increasing the life expectancy of the network is increasing battery power or the use of alternative energy in the nodes.

**The impact of the separate operation modes in the network nodes on the overall life expectancy of WSN**

The 2nd chapter of the dissertation describes in detail wireless sensor network nodes used in the capacity calculation methods. Mathematically, it was proven that the total energy consumed in a single node operating cycle $\Delta t$ depends on the time that each network node spends in the sleeping mode. Let us look at the ratio $\frac{P_{rx}}{P_{idle}}$ of the power used in the nodes when modelling the operation of a network consisting of 200 nodes.

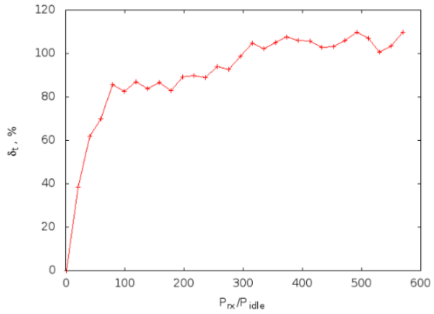



Fig.4.8. The ratio of power $\frac{P_{rx}}{P_{idle}}$ used in nodes

Modeling results (figure 4.8.) indicate a vital dependence that determines the boundaries of application of the methods. In the case of operational efficiency $\delta_t$ and power ratio equal to 1, the application of methods will not affect the overall life expectancy of a system. This is justified by the fact that there is no large difference in consumed energy in the network because the power consumed is not dependent on the data flow transmitted by the node. With the increase of this ratio, the value of the function is growing rapidly. If the trend of increase slows down, it will show that the system needs a certain minimum amount of energy to be able to perform tasks. Based on the modelling data it can be concluded that the energy balancing method is appropriate to use when the amount of power used in the nodes in standby mode is $P_{idle}$ at least 10 times lower than with an active transmitter $P_{rx}$.

**The proposed determination of effectiveness of methods for increasing the life expectancy of wireless sensor networks within networks of various sizes**

The table 4.6. shows the dependence of the coefficient $\delta_t$ on the modelled network size. From the data obtained in the experiment it can be concluded that by using the proposed method of increasing life expectancy, the increase of the coefficient $\delta_t$ depends on network size. This is based on the fact that by increasing the amount of network nodes the difference between the energy consumed in the nodes increases. Using a network reconfiguration method, it is possible to increase the overall life expectancy of the network with the largest amount of energy difference between the nodes.

Table 4.6.

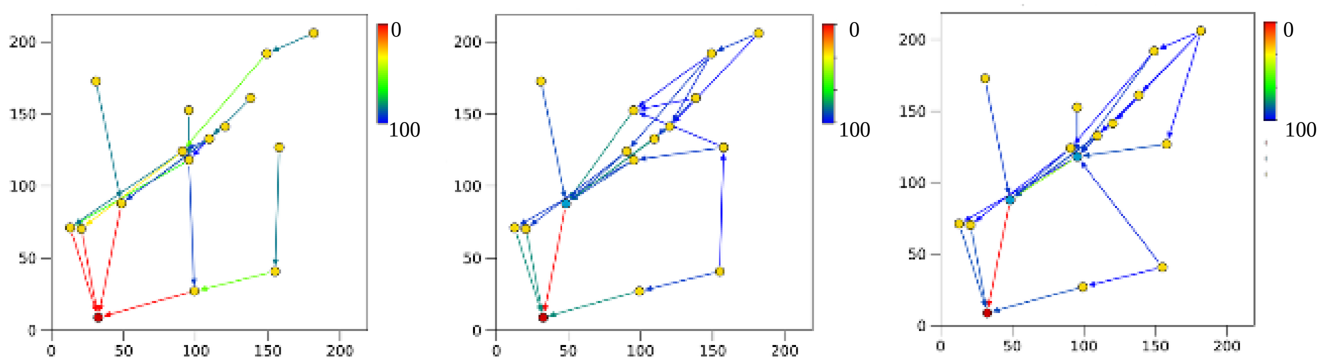
The dependence of coefficient $\boldsymbol{\delta_t}$ on the modeled network size using a variety of heuristic methods

| Amount of nodes | MRE | RANDOM | MREML |
|---|---|---|---|
| 10 | 20.1408 | -30.5998 | -16.0439 |
| 30 | 43.5082 | -5.4268 | -11.4561 |
| 50 | 62.6674 | -0.4599 | 1.4793 |
| 70 | 88.7197 | 15.4599 | 23.4793 |
| 90 | 112.335 | 31.9885 | 40.2624 |
| 110 | 115.114 | 46.2421 | 54.7148 |
| 130 | 122.283 | 42.2984 | 62.8865 |

Using small-scale networks where the number of nodes is $m<50$ there is a risk that the applied network methods for increasing life expectancy will lead to a reduction in life expectancy; the coordinator location will be created due to inefficient network topology.

### Modeling of network performance routing protocol simulation

Figure 4.9 shows figure the remaining amount of energy of a network in three ways: static operation with constant coordinator location (Fig. 4.9. a), casual activity, when the network topology is formed using the Dijkstra's algorithm without accounting the energy (Fig. 4.9. b) and the proposed method algorithm of the dissertation (Fig. 4.9. c) is modelled with a network node quantity of $m=150$.




a b c

Fig. 4.9. The distribution of the remaining energy in network nodes.

Using a static coordinator location, there are locations in the network where the nodes barely use their energy and the network stops working; the remaining amount of energy in the nodes comprises 90% of the initial amount of energy. While using the new network route generating possibility in each transmission cycle (RANDOM) it will be understandable that there is a balance in energy consumption. With the proposed methods of increasing the life expectancy of the network by using the moving coordinator it is possible to see that the amount of energy consumed is in disbalance except the locations that are physically located in distant points throughout the network and during the operating time of a network have only sensor functions.

### The compilation of results obtained during simulation modelling

Using the simulation modelling tool, the dissertation gave the following results:

- With the dynamic coordinator node, the life expectancy was 27% in relation to the standard model value of the fixed network topology.

- Using the high-range coefficient R, the situation may arise when the network will operate through a star topology and as a result the network will lower the total life expectancy.
- There are minimal boundaries in standby mode $P_{idle}$ that define the efficiency of network balancing methods. Using a simulation modelling tool there is a determined condition for balancing methods: $P_{idle} < P_{rx} \cdot 10$.
- Using small-scale networks where the number of nodes is $m$<50, the offered methods for increasing life expectancy of a network reduce the overall network life expectancy wasting energy for the network topology change.

## THE FULL RESEARCH RESULTS, CONCLUSIONS AND FURTHER STUDY

The aim of the dissertation was to develop and explore the wireless sensor network life expectancy assessment model and the methods that will increase the overall life expectancy of a wireless sensor network and will balance the amount of energy in the network nodes.

To achieve the aim, the following objectives were completed:

- Analysing the existing methods for increasing the life expectancy of a wireless network.
- Ascertaining specific factors of network nodes that affect the overall life expectancy of a system.
- Developing a model for assessing the life expectancy of a sensor network.
- Designing the methods in wireless sensor network for increasing energy balancing in network nodes.
- Carrying out and developing the methods for increasing the life expectancy of a model and the network and their experimental approbation in real wireless sensor network systems.
- Conducting a study of the methods for increasing the network life expectancy using the simulation modelling tool.

During the analysis of literature through a variety of wireless sensor network types and topology, it was concluded:

- Wireless sensor networks have the prospect of a technology that is used in both public and private sector. The large range of scientific work, which is related to WSN research, as well as the issues, described in the dissertation points to the topicality.
- In recent years, the overview of scientific reports and the analysis indicate that the primary object of the study of wireless sensor networks remains the increase in life expectancy of a system. Recently, several definitions for life expectancy of WSN and the definitions of increase have been differentiated [КУР 2011]. The method for assessing the life expectancy of a network that has been offered in the dissertation determines the essential network characteristics which affect the life expectancy of the network: the operating range of a node, the options of reconfiguration of the node and energy balancing.

The model for assessing the life expectancy of a network and the method for increasing it has been designed as a part of the dissertation. The proposed assessment model and the methods for increasing life expectancy were experimentally validated to verify the hypotheses.

The results of the experiments showed:

- The developed wireless sensor network life expectancy assessment model allows identifying the life expectancy of each network element using WSN node primary actions. It allows assessing the overall network life expectancy taking into account the network reconfiguration options. The most important difference between the model proposed and the previously developed ones is the wide application and adaptation of the researched network features: network topology, wireless standards, and the technical characteristics of the module as well as the operating frequency and topology change.

- In cases where the network parameters are changed in time, it is proposed to use the dynamic coordinator node management method by activating the autonomous network node management module. Based on analysis, the control method of the virtual coordinator has been used in the dissertation by proposing heuristic algorithm MREML, which, compared to the already existing algorithms, significantly increases the overall life expectancy of WSN.
- During simulation modelling, using developed modeling tool described in the dissertation made it possible to assess the efficiency of the viewed methods and algorithms as well as set the network configuration requirements that need to be followed while modelling the WSN. The proposed tool allows modelling an autonomous operation of the network for as long as possible and it forms the necessary technical requirements for the simulated network.
- A control method for data flow of the wireless sensor module has been developed which by using the algorithm described in the dissertation form the network topology by balancing the amount of energy in the network. The dissertation proposes two significant advantages for the presented algorithm: the opportunity to integrate the terminal node which has limited technical resources and the amount of energy as well as path-creating is the primary parameter considered for the remaining amount of energy in the network.
- Using the results obtained in the dissertation and subject to the requirements of the proposed network topology creation, there is a possibility to achieve an increase in life expectancy of WSN up to an average of 23% and the maximum increase of the simulation modelling was 32%.

The following hypotheses have been proven in the dissertation:

*Hypothesis*: The use of a dynamic coordinator balances the remaining amount of power in the nodes and increases the overall life expectancy of a wireless sensor network.

*Proof*: The results of the experiments showed that the use of static location of the coordinator in the network, there are locations where nodes barely use their energy and the network stops working, but the remaining amount of energy in the nodes accounts for 90% of the initial amount of energy. Using dynamic management method for the coordinator, the energy consumption in the network is in disbalance.

*Hypothesis:* The methods for balancing the remaining energy must be applied together with the routing algorithms that allow dynamic adjustment of the power of each network node transmitter.

*Proof*: The results of the experiments showed that when using the data flow control method of the network node for increasing the network life expectancy, it can be seen that the amount of energy consumed in the disbalance, except for the locations that are physically located further, and during the operating time of the network complete only the sensor functions.

*Hypothesis:* The methods for increasing the life expectancy of a network can be appropriately used in networks with a large amount of nodes where the sleeping time of the nodes is $t_{idle} \rightarrow min$.

*Proof*: Using small-scale networks where the number of nodes are $m$<50 the methods used for increasing the life expectancy of a network offered in the dissertation reduce the overall network life expectancy uselessly wasting the energy in order to change the network topology.

There is a minimal waiting boundary in the standby mode $P_{idle}$ that defines the methods for balancing the network efficiency. Using a simulation tool provides the conditions for methods used in balancing: $P_{idle} < P_{rx} \cdot 10$.

**Doctoral Thesis achieved scientific results**

- A model for assessing the life expectancy of a wireless sensor network has been designed and it allows determining the time of withdrawal of the network including the ability to restore a network.
- A method for managing the dynamic coordinator node that allows balancing the energy consumption in the network has been designed.
- A method for controlling wireless sensor module data flow has been designed, which structures the network topology while using a routing algorithm and it balances the amount of consumed energy in the network.
- A method for managing the virtual coordinator node in order to change the network topology has been offered and it uses a heuristic algorithm MREML for increasing the life expectancy of a network.

**Doctoral Thesis achieved practical results**

- An experimental prototype of a wireless sensor network sensor node has been developed which can operate in terminal and router mode through dynamic reconfiguration.
- During two international projects certain experiments were carried out introducing the method for increasing the life expectancy of a wireless sensor network as well as co-financing of KPFI was received for the approbation of the prototype in the private sector.
- An experimental software prototype was developed for increasing the life expectancy of wireless sensor network methods for simulation modelling. Based on the results obtained during the simulation modelling, the restrictions and conditions of WSN life expectancy method application were defined.

Thesis practical realization:

- The dissertation deals with the problem solutions that are used in the EU 6th Framework Programme project Unite which was implemented in cooperation with the Riga State Gymnasium No.3 from 01.02.2006. to 01.07.2008. During the project a monitoring tool aimed at the learners' work-load was developed.
- The planning method for transmitting information network was approbated within the framework of the 6th EU project eLogmar-M. During the project the path-building concept of mobile cargo monitoring was set up whilst using sensor nodes.
- Wireless sensor networks have been used within the Baltic Sea Region INTERREG program project BONITA for recording the flow of people and for providing the information to the exhibition hall. During this project an autonomous reconfigurable WSN node was created which was later used as a separate multifunctional prototype of WSN sensor elements.
- In collaboration with the climate change financial instrument in 2012 an autonomous and efficient "smart house" wireless sensor network for maintenance and management was developed and is used and it is integrated into 3 detached houses in Latvia. The technical solution that was developed extended the interval of the home sensor module service from the industrially defined 2 years to 5 years.

The results have been used in two RTU subjects:

- “Adaptive data processing systems (DIP320)” in the learning process,
- “Applied Computer Systems Software (DIP392)” in the learning process.

The further development directions of the dissertation:

- The practical integration of the method for increasing the life expectancy of a wireless sensor network at the system level of wireless nodes. The integration of the methods for increasing the life expectancy will facilitate the basic node operation scheme description as well as relieve the main processor of the node.
- The practical integration of a wireless sensor network simulation tool for the network topology planning software that will allow using the methods proposed in the dissertation to analyse the projected life expectancy of the network.

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