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A COOPERATIVE INTERACTION OF COMPONENTS IN WIRELESS SENSOR NETWORKS

Summary of the doctoral thesis

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A DISSERTATION SUBMITTED TO RIGA TECHNICAL UNIVERSITY IN FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE DOCTOR OF SCIENCE IN ENGINEERING

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CONFIRMATION

I confirm that the work contained in the Dissertation submitted by me to Riga Technical University for the Doctor's Degree in Engineering is my own original work and has not previously been submitted by me for a degree at this or any other University.

Romans Taranovs ....(Signature)

Date: ....

Thesis consists of an introduction, six chapters, conclusion, three appendices, list of references resulting in 219 pages, 48 figures, 14 tables and 133 used reference.

CONTENTS

GENERAL DESCRIPTION

Theme topicality

Computers and computing devices are becoming smaller, cheaper, but at the same time also their performance increases that allows building in the computing power into modern devices. During last ten years Wireless Sensor Networks (WSN) [2] appears as a new technology that combines sensing, embedded processing and wireless networking in small embedded devices. However some WSN components are not based on completely new ideas, nevertheless technological improvements, especially micro-electromechanical systems (MEMS) allowed their integration [11] in small embedded computers.

As the earliest study of WSN is considered to be the article published in the 1999th about the project [1], which is related to the development of low-energy consumption devices which would allow building large WSN. From a classic view WSN are built in order to perform tasks related primarily to the monitoring of physical object's parameters. But in modern researches there are found cases of WSN usage, which allow to apply these technologies in medicine [27, 3, 12], for tracking tasks [25], for military use [18] etc. In such cases WSN is often structured - that is to say, it is formed of clusters, which may be installed beforehand or formed into a decentralized manner. In the promotion thesis are studied cases of WSN application that are related to the formation of effective communication of WSN cluster and collective interaction of sensor network's components. Communication efficiency is ensured by collision-free communication which is necessary for collision-sensitive application such as medical usage with the self-coordination and self-organization capabilities of the nodes. The aim of the thesis is to identify obstacles for the implementation of such communication and to propose solutions in order to overcome them.

Nowadays, extensive researches in the wireless sensor networks are carried out. This is demonstrated by a number of organized global conferences, a few of them may be mentioned: ACM Sensys 2013 [24], IEEE INFOCOM [14], UbiComp [29]. During last years WSN researches have mainly affected systems or wireless sensor network applications.

From the recent studies it can be concluded that the most common class of WSN applications, are health care applications, monitoring applications, military applications, tracking applications, as well as the use of class as environmental body area network – BAN. For some classes, such as the military, health and body network environment, as well as some other classes of applications it is important to guarantee correct transmission of the sensor node runoff. The runoff is the end user who is to receive the data. In other words, for data communication among wireless sensor network elements data must not be lost. For example, let's consider the task of health class when in a ward there are several patients. Each patient has sensors attached for nonstop monitoring of his/her condition. Meanwhile there are nodes that receive data about condition of ward environment: about air temperature, air quality, acoustics etc. Then it is clear that a number of wireless sensor nodes or WSN element may reach several dozens. Their intensive communication can cause collision of data packets, which leads to the loss of received data packets because of the communication protocols. [31]. Another example can be mentioned taken from monitoring task class. An example of such system was observed [17] where mobile platforms were meant for the monitoring or tracking of a room. Also here it is necessary to have effective communication, because there will be several devices at the same time in the radio range. Depending on the task set, they simultaneously to the surveillance create and/or renew map of the room/object. Then it is clear that while communication mobile nodes will intensively share their data with each other and with the runoff. Of course in this case also collisions of data packets can appear resulting in their loss. Another use case is application of WSN together with WSN [20] or other type of multimedia data transmission, for instance, video conferencing [28], where the task of WSN together with data transmission is also determination of node position[21]. There it may be seen that every time sensor nodes initialize communication with each other they have to try to make intensive data flow, i.e., it again may cause loss of data packets. Of course loss of data packets occurs because of the collision of MAC protocol frames. MAC protocol is responsible for the access of network elements to the environment. In case WSN uses MAC protocol, which is based on competition, it has negative feature - when the load increases number of collisions increases, too .[16] that usually appears in the phase of initialization. In the case of WSN sensor nodes often have initialization phase because sensor node does not maintain communication connection during whole operating time, it, for example, can fall asleep because of energy-saving and when it wakes initialization has to be started from the very beginning.

Moreover, very often there is already existing infrastructure and its replacement is not profitable or is prohibited. For example local network in the hospital can be created using Ethernet and Wi-Fi technologies, but in general it works with TCP/IP protocol stack management. Thus implementation of a new data collection technology in already existing infrastructure requires its continuation of working with already existing communication protocols, mainly by increasing quality and quantity of service with enlargement of the system and not by its reconstruction. It is one of the nowadays studied issues in the wireless sensor networks.

As it was already mentioned in the beginning for the solution of proposed task classes and tasks set for them it is proposed to use hierarchical systems. In general, these systems are able to collect data from WSN and transfer them to the runoff, as well as to perform data processing, e.g. data filtering, merging, as well as to ensure data transfer to external network, such as TCP-IP networks with the help of special modules. These modules are called gateways –GW. In the WSN systems gateways are often to be found in clusters organized by WSN. In recent years, division of network into clusters has become one of the most popular approaches to the organization of the network into connected hierarchy [34]. Using network division into clusters, nodes are organized in groups, which are called clusters. For each cluster is selected cluster coordinator, described as the cluster head - CH, and number of depending nodes. Comparing wireless sensor network architecture without division into clusters several advantages may be mentioned:

- *Distributed determined data collection and communication:* It is proposed to use clustering for determination of information flow, when thanks to the specific MAC protocol and cluster installation preferable information flow may be achieved. Furthermore the node does not need to maintain tables with neighbor's data or destination data. As a result, inter cluster communication implementation requires fewer resources because among clusters data will be transferred only by CH, other nodes will not know about the existence of other clusters. CH existence provides cluster management, namely, the control commands are sent only to it and not separately for each sensor node.

- *The sensor node grouping:* Clustering allows to combine sensor nodes according the task or part of it for achieving better communication.

- *Reduction of energy consumption:* This is a combination of the previous two paragraphs. Routing of data packets from the sensor node to run-off is to be made through CH, caring only for a few jumps routing. Such jump is defined by creating a cluster, namely, number of jumps is in advance defined value, and the packet routing in the opposite direction (from the runoff to the sensor unit) is going through a cluster CH. This allows considerable reducing of energy consumption of the separate sensor during packet routing. The combination of sensor node cluster will reduce the number of collisions due to the ability to provide effective communication within the cluster than if the unit is not allocated to the cluster. Clusters are distributed so as to minimize impact on each other. Also CH can organize communications within the cluster so that sensor nodes switch to extended sleep mode.

- *Data aggregation:* The deletion of that data head that repeats or is not needed to be further transferred in cluster, deletion from the network, which also leads to the power energy saving and improving of necessary data transfer time.
- *Cluster self-organization :* It is the ability of sensor nodes to improve cluster structure if any of them have gone out of order.
- *Easy to understand and use:* Clustering is more visible for users, because it enables them to divide logically WSN in groups or to carry out division automatically according to the given task.

Aim of the promotion thesis and formulation of an objective

The main objective of the thesis is to propose solutions and design technique for wireless sensor networks with two-level hierarchical structure, which are divided into clusters. In the first level is to be provided collective interaction of sensor node components of the wireless sensor network. As well at the second system level to ensure collective interaction between gateways. So to offer a system approach to building or class of tasks, this has the following characteristics:

- Collision-free access to the environment and initialization in frames of WSN.
- Determined speed of data collection or determined information flows in WSN.
- Possibility to distribute additional communication resources to sensor nodes, as well to ensure energy saving operation.
- Self-organized installation of clusters by sensor nodes and function of self-recovery.
- Possibility of integration into existing infrastructure of TCP/IP using GW.
- Gateways assist in WSN self-recovering, in initialization of participants, as well as in data routing among other clusters.

For the solution of the task class put forward in the promotion thesis the following objectives are set:

1. To create overview of protocols and cluster division algorithm. To evaluate existing two-level systems, to use results for the design of proposed two-level system.
2. To create detailed system model in SysML from two diagrams – usage and block defined diagram.
3. To design the first system layer, i.e. WSN layer according to the requirements of the system and to create collision-free MAC protocol with determined environment access feature. To propose autonomous clustering algorithm for self-organization of sensor nodes.
4. According to the system limitations set to design the second or gateway layer. To propose transport protocol for data transferring to the main computer and providing of cluster management.
5. To propose the design methodology of the first and the second layer.
6. To propose analytical system model for such cases, where it is necessary to evaluate chosen hardware and to consider system throughput.

Research subject and object

Research subject is architecture of the two-level clustered wireless sensor network including WSN clustering with collision-free data transfer. Research object is stack of corresponding communication protocols and algorithms that ensures creation of research object. Furthermore research object is extended with questions relating to the autonomous reconfiguration, recovery and installation of divided network. In the notion of examined system are included study of algorithms and solutions for inter-cluster communication or data routing among clusters and main computer.

Scientific innovation of the thesis

In the developed thesis there are the following innovations:

1. Is provided a new collision-free communication ensuring wireless sensor network MAC layer protocol. It is based on TDMA principle with determined access to the environment.

Also is developed clustering algorithm that allows ensuring autonomous cluster forming in the WSN layer, providing collision-free communication maintenance.

2. Functions in the system of the second hierarchical system layer's element gateway are summarized and displayed. Here are proposed sensor nodes data processing algorithms and data transport protocol.

3. Is proposed statistical model for determination of data transfer speed in hierarchical system. Is shown system computing example that allows evaluation of not only chosen hardware, but also system's expected data transfer speed.

Practical value and approbation

The practical value of the thesis is development of hierarchical wireless sensor networking system. The system is designed for easy inclusion in existing TCP / IP network infrastructure and provides efficient data collection on the research objects. As the practical value the following benefits also are worth mentioning:

1. Provided approach for description of such systems with the help of SysML on the basis of proposed system.

2. When designing each system level design methodologies are offered, they are proposed in the design and creation of MAC protocol, and in the creation of gateways and clustering algorithm.

3. Are shown schemes for reception of specific time constants protocol and selection of system's hardware support.

4. Is developed a prototype of WSN infrastructure, which meets the requirements of the architecture of the proposed two-level system.

Approbation of the results was carried out by participating in several scientific conferences and is presented in 11 publications in scientific proceedings. As well in several projects - Latvian National Research Program ”Scientific Foundations of Information Technology” in project ”Development and research of original signal processing method for creation of a competitive IT technology” and grants of Latvian Council of Science:

- Latvian Council of Science research grant Nr.09.1564 - ”Simulation and computational intelligence methods for logistics and e-business optimization” (years 2009 – 2012).

- Latvian Council of Science research grant Nr.09.1541 - "Development and energy consumption optimization of embedded and RFID systems based on innovative DSP technologies" (years 2010 - 2012).

Proposed system's two-levels has been introduced in international project STRATOS, where sensor nodes (placed on tractors and trailers) mutual communication has been constructed with usage of collision-free MAC protocol. Communication trough Internet has been based on gateway construction principal. Moreover the work results have been used and approbated in other bachelor and master graduation papers. For instance in [30] paper various WSN modelling programs have been studied. Modelling readiness and fulfilment with features have been checked with developed collision-free MAC protocol implementation there.

The designed system's approbations has been done by system's each level design in a prototype model. Dissertation appendix contain MAC protocol's source code (1 appendix); gateway software with code for data acquisition and packing (2 appendix); main computer software as a source code (3 appendix).

Theses to be defended

1. It is possible to organize collision-free inter-cluster communication in wireless sensor networks.
2. Utilization of the new collision-free medium access control protocol does not limit count of WSN clusters.
3. Autonomous cluster formation can be achieved with the same collision-free MAC protocol just extending it with a new state.
4. Utilization of gateway nodes with proposed transport algorithm in a WSN enables network self-healing and extension in count of clusters.

Scientific publications

Available in SCOPUS database:

- Taranovs R., Zagurskis V. Medium Access Protocol for Efficient Communication in Clustered Wireless Sensor Networks // 19th Telecommunications Forum (TELFOR): Proceedings of Papers, Serbia, Belgrade , 22-24 November, 2011 - 582-586 p-s.

- Taranovs R., Zagurskis V., Morozovs . Heterogeneous Collision-Free Clustered Scheme for Wireless Sensor Networks // Proceedings of 2010 IEEE 26th Convention of Electrical and Electronics Engineers in Israel (Digital), Israel, Eliat , 17-20 November, 2010. - 000282.-000285 . p.

Published in the "Scientific Journal of RTU" proceedings:

- Zagurskis V., Bļizņuks D., Taranovs R. Pilot Signal Detection in Wireless Sensor Networks // RTU scientific articles. 5 issue, Computer science. - 48 vol. (2011), 36-40. p-s.

- Zagurskis V., Bļizņuks D., Taranovs R. Self-Organization Paradigm at Critical Time Systems Functioning // Scientific Journal of RTU. 5 series, Computer science. - 46 vol. (2011), pp 40-45.

- Miezītis G., Taranovs R. Passive Wireless Sensor Network Analyzing at Medium Access Level // Scientific Journal of RTU. 5 series, Computer science. - 48 vol. (2012), p-s 56-62.

- Kļaviņš Ē., Taranovs R. Attālinātā robotu vadība ierobežotā telpā izmantojot web kameru (Remote Web Camera Based Robot Control in Bounded Space)// RTU scientific articles. 5 issue, Computer science. - 48 vol. (2011), 63-68 p-s.

- Miezītis G., Zagurskis V., Taranovs R. Multiple Mobile Gateways in Wireless Sensor Networks // RTU scientific articles. 5 issue., Computer science. - 13 vol. (2012), 38-42 p-s.

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- Miezītis G., Taranovs R.Object Tracking in Wireless Sensor Network: Survey// RTU scientific articles. 5 issue., Computer sciencwe. - 42 issue. (2010), 45-52. p-s.

Scentific conferences

- RTU 50th International Scientific Conference, 12. - 16. October, 2009.
- IEEE 26-th Convention of Electrical and Electronics Engineers in Israel, Eilat 17 – 20 November, 2010.
- RTU 51st International Scientific Conference. 11. - 15. October, 2010.
- RTU 52nd International Scientific Conference. 13. - 16. October, 2011.
- 19th Telecommunications Forum (TELFOR), Serbia, Belgrade. 22. - 24. November, 2011.
- RTU 53rd International Scientific Conference. 11 - 12 October, 2012.

Participating in projects

- Latvian Council of Science research grant Nr.09.1564 - ”Simulation and computational intelligence methods for logistics and e-business optimization”.
- Latvian National Research Program ”Scientific Foundations of Information Technology” in project ”Development and research of original signal processing methods for creation of a competitive IT technology”.
- Latvian Council of Science research grant Nr.09.1541 - ”Development and energy consumption optimization of embedded and RFID systems based on innovative DSP technologies”.
- Volunteering in the international project ”Open System for Tractors’ Autonomous Operations — STRATOS”, ERA-NET program.

Structure and extent of the thesis

In the first chapter information concerning wireless sensor nodes is provided, including structure of nodes and main components, their functions. There are explained wireless sensor network protocol stack, its characteristics and specificity of the investigated area, and given an explanation on the general characteristics of WSN.

In the first sub-chapter of the second chapter are studied existing MAC layer protocols that are used in clustering algorithms as the first part of the system's level. There are provided explanations necessary for research for cluster formation approach and related benefits, where along with the cluster formation is explained on the CH node peculiarities and provided clustering attributes, with the help of which any clustering algorithm and its specificity may be described. Further, after the described classification of algorithms in accordance with the methodology set there are proposed researches on existing MAC protocols and clustering algorithms. In the second sub-chapter is proposed methodology for studying the existing system and its application in practice. Researched systems were chosen as the most corresponding to the task set and related limitations. In the end of sub-chapters conclusions about researched objects were made.

The third section offers a two-level hierarchical model of the system. It is made with MDA approach with the help of SysML assistance. There are offered two types of diagrams. The first type is diagram of use. It can display system component interoperability, i.e., how each of the components uses other system component. Diagram also makes it possible to carry out an in-depth analysis of each component and to determine objects operating out of the system, from which, for instance, are gained data. Diagrams of use are deepened in order to show inseparable components of cluster parameters and end-system. The second type of the diagram displays the proposed system consisting of blocks with certain relations towards each other. This type of diagram allows explaining how separate parts of the system are created and united, for example, it can be seen which parts wireless sensor node or GW consists of. Both diagrams are extended till terminal blocks.

In the fourth chapter is offered TDMA based MAC protocol ensuring system's first level inter cluster communication. Along with description of the protocol is offered structure of a MAC packet and is explained protocol adjustment for usage, i.e. it is explained how to act in case there arise necessity in implementation of MAC protocol. There are proposed guidelines, for instance necessary capacity of the data memory, and adjustment to the hardware. In the end of the chapter are offered results of analytic analysis of MAC protocol.

The fifth chapter focuses on issues related to the second or gateway level. Chapter is divided into two sub-chapters. In the first sub-chapter are examined issues and provided solutions to the above set GW requirement. Access to data transport from the cluster to TCP / IP networks, as well as the necessary gateway software are provided. Implemented sensor nodes data transport protocol and data processing algorithm are described. In the second sub-chapter is offered an algorithm of autonomous cluster formation. Algorithm description includes the original MAC protocol changed parts and its description, as well as contains description of the gateway algorithm supplementation.

In the sixth chapter are described and offered opportunities of system computing capabilities. Thus is offered such system model , which displays expected speed of data transmission according to system configuration that was chosen. Configuration contains two main parts. The first one is inter cluster parameters configuring part. In this case parameters are connected with the chosen hardware and WSN, for instance, size of network or amount of sensor nodes in the cluster. The second is gateway software parameters and algorithm installation configuring part. There were checked several gateway platforms by fulfilling the data processing algorithm at different network sizes. In the end of the chapter computing example with real gateway object is provided.

In the end of the present paper are conclusions and list of references.

1. ANALYSIS of CURRENT SITUATION. SYSTEM ARCHITECTURE

1.1. Wireless Sensor Networks

Wireless sensor networks consist of wireless sensor nodes. Their number can reach tens, hundreds and even thousands. Moreover, sensor nodes can be homogeneous or heterogeneous in terms of their construction, use of communication protocols and type of power supply. But their main aim is to send data to data sink. Routing is often used to deliver the data from the node to the data sink if the source is at a distance of a few hops from the sending node. But sometimes it happens that the routing between nodes is not necessary, especially when building a multi-level architecture of a wireless sensor network. In this case, messages are transmitted by specially designated nodes in the network, such as gateways.

Wireless sensor nodes are limited by several parameters:

- *Computational power* - microcontrollers used to build sensor nodes, with ultra-low power consumption resulting in limited clock speed up to a few MHz, as well as the bitness of 8, 16-bit.
- *Storage capacity* – in order to reduce power consumption, the storage capacity is within several kilobytes, which are built in a microcontroller.
- *Power supply* - Wireless sensor nodes are powered by batteries, which allows to use them in the hard-to-reach locations.

Thus, the wireless sensor node has the following properties:

- *Small size* - Sensor nodes should be portable in order to achieve a larger area of placement. Also, sensor networks may be placed on a person, and if sensor nodes are big it could be problematic for their transportation.
- *Low cost* - As it was mentioned before the sensor network can consist of dozens, hundreds, or even thousands of nodes, so their cheapness is also important when building such a network. In the future, the price of the wireless sensor node will be about 1$ [2].
- *Low power consumption* - Each sensor node is considered to be a disposable device WSN, when the replacement of batteries in nodes is completely unprofitable in comparison with

their re-placement, especially in large-scale networks. Therefore, low power consumption contributes to more savings and allows the system to be active over a longer period of time.

The figure 1.1 shows a diagrammatic representation of the main components of a sensor node. When released into the environment, the wireless sensor node begins to perform its task, mostly it is sensing of environment. The data about the environment is converted to a digital format by a sensor located in the sensor node, then the data is processed by a microprogram in the microcontroller and transmitted to other network parties using the chip transceiver and the antenna.

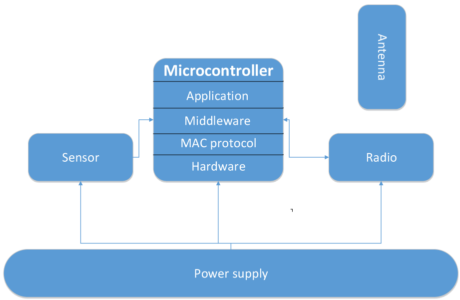

Figure 1.1: The main components of a wireless sensor node

As can be seen in the figure, a microcontroller is the central component of a sensor node, as it provides the performance of the task and implements the network protocol stack. The paper under review proposes to divide a protocol stack into three levels - physical, medium access control, and application. Application performs operations related to sensing and/or transmission of the impact on an object or environment. The interfaces to channel MAC layer are determined by means of middleware. It provides multiple accesses of sensor nodes to the environment. MAC layer, after forming MAC packet implements its transmission to the physical layer via the corresponding interfaces.

1.2. Two-level system architecture

This paper reviews the interaction of sensor nodes in a clustered structure of wireless sensor network in a two-layer system. This system has a clustered sensor network on the first level, and the gateways (GW), coupled with their clusters on the second . The figure 1.2 shows the architecture of the proposed system, created in accordance with the stated goals of the paper.

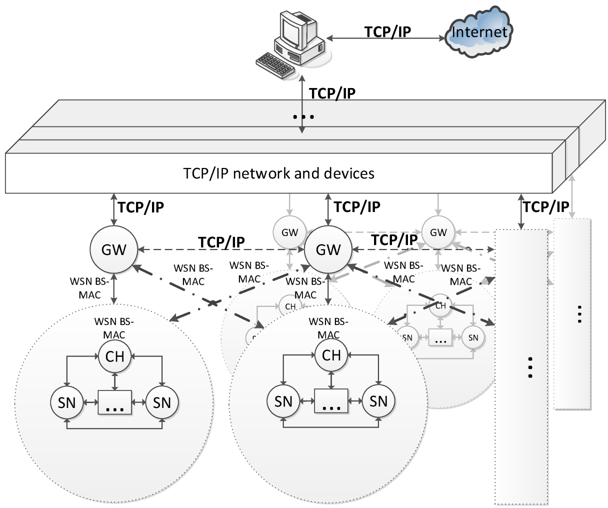

Figure 1.2: Architecture of a two-level clustered WSN system

The first level consists of a WSN, divided into clusters. There are two types of sensor nodes inside each cluster, they are usual sensor nodes (SN) and a cluster head (CH). Moreover, both types of nodes use the same software and are structurally identical. The developed collision-free MAC protocol - WSN BC-MAC is used to ensure communication within the cluster. The second level system consists of gateways, where each of them is connected to a particular cluster. The gateways have two interfaces - for working with a WSN and for transmitting the data from the cluster to TCP/IP network, which allows to integrate the system into the existing network infrastructure. The gateways perform transport algorithm for transmitting the data to the host computer and for exchanging the service information between the gateways.

The architecture also describes the links between its components which are possible in the system. The continuous lines show the main data path from sensor nodes in the system. It includes the data transmission from each sensor node and cluster heads, as well as the transmission of the accumulated and processed data from the gateways to the host computer. Another type of the connection is an inter-cluster connection via GW, in the Figure 1.2 shown by dotted lines. This connection is used by the gateways for exchanging service information.

The clustered scheme of a wireless sensor network has been chosen because it has a number of advantages over a non-clustered scheme [34], namely:

- *Decrease in the flow of resources to ensure communication* - sensor nodes do not need to contain routing tables, they only have to take care about their connection with the cluster head. Only CH from each cluster are involved in the organization of the intercluster interaction, other sensor nodes in the cluster can not be aware of the network topology and its composition.

- *Grouping sensor nodes* - used for forming the clusters to serve the needs of a specific task. Also, grouping may be used to provide any required bandwidth of the cluster.

- *Tasks division between sensor network nodes* - allows to transfer tasks of processing the sensor data from SN to CH nodes to reduce the power consumption in sensor nodes. Moreover, if the system is hierarchical, the tasks of data processing can be transmitted to the gateways, thus increasing the service life and CH nodes.

- *Simplifying the control for WSN* – the cluster are controlled by CH, transmitting the configuration messages for them from other nodes or cluster control signals may come directly from the cluster heads. Moreover, in this case other sensor nodes are involved only in executing tasks to the received control signals.

In addition to the outlined advantages of the clustered sensor network, the paper also reviews the additional advantages, which are possible due proposed two-level system of organization:

- *Providing of the deterministic distributed data collection* – since the intersensory communication in clusters is provided by the collision-free MAC protocol, it is possible to ensure the speed of data transmission in the cluster at its known configuration. Thus, by limiting the number of sensor nodes we can set the speed of data transmission, and as a result it guarantees the time for receipt of sensor data.

- *Self-organization of sensor nodes* - which in addition to autonomous self-organization of sensor nodes into clusters allows to realize self-treatment of a wireless sensor network. Using the second level - the gateways it is proposed to exchange service messages to detect the cluster which requires the replacement of the faulty sensor node.

- *Self-organization of clusters* which in addition to self-organization at the cluster level allows you to organize the group of clusters by combining some of them under the control of one GW. Thus, an increasing number of sensors connected to the network job processing facility at a constant data rate in these clusters.

Before carrying out further studies on the proposed two-level system on its levels the paper investigates the existing MAC protocols with the clustering algorithms for wireless sensor networks, it also proposes the methodology for comparing the existing hierarchical systems with the proposed one.

1.3. The analysis of the existing situation

For the analysis of the existing MAC protocols with clustering algorithms we have proposed to compare them according to the following criteria:

- *Protocol type* - defines its scope.
- *Important points of the protocol* – provides a short description of the main functions and peculiarities of the protocol. It is used for comparison with the necessary functions of the first level of the system.
- *Application* - describes the restrictions of the protocols on communication in a network or a cluster.
- *Quality of connection* - as well as the security used to describe the quality of the service provided by the protocol under review.

The study addressed the following protocols with clustering algorithms: LCA [5], CLUBS [22], FLOC [9], ACE [7], WCA [8], DWEHC [10], LEACH [13], HCC [6], HEED [35].

The studies have shown that the considered protocols meet most of the requirements to the first level of the system. We offer the following table 1.1 to compare the results of the study. Unfortunately, none of the considered protocols provides the collision-free communication within the cluster, and it has been established that there are collisions in the communication between the nodes and they have to be reduced. As a result, none of the discussed existing MAC protocols can guarantee the deterministic speed of the data transmission within a cluster. There is also no information about the possibility of their use in hierarchical wireless sensor networks.

Table 1.1: A Summary of the Study on MAC protocols

Protocol	**Mobility**	**Energy-efficiency**	**Restore**	**Balance**
LCA	Possible	Yes	Yes	Yes
CLUBS	Possible	No Information	Yes	Yes
FLOC	Possible	No Information	Yes	Yes
ACE	Possible	No Information	Yes	Yes
WCA	Possible	Yes	No Information	Yes
DWEHC	No	Yes	No Information	Yes
LEACH	BC fixed	No	Yes	Yes
HCC	Possible	No Information	Yes	Yes
HEED	No	Yes	No Information	Yes

After studying MAC protocols for clustering in a wireless sensor network we have proposed to investigate the existing hierarchical systems for WSN integration in TCP/IP networks. As in the case with the study of MAC protocols, the systems are studied to reveal approaches to implementing the objectives set for the proposed system.

This paper proposes the methodology developed for investigating hierarchical systems. It consists of two parts. The first part proposes to carry out a research in accordance with the four-layer model which is specific to this type of two-level wireless sensor networks:

- *Channel (MAC) layer* - MAC protocol and algorithms, its extensions are defined.
- *Clustering formation level* – the clustering algorithms are investigated at this level.
- *Network layer* – it analyses the ability of the system to transmit data packets within the clusters, as well as to provide intercluster data transmission. In addition, at this level we also investigate the possibilities of the considered systems to transmit messages from WSN to TCP/IP network.
- *Application level* - which investigates the services which can be provided by each of the considered systems.

In the second part of the research methodology and comparison of the hierarchical systems we propose to compare them with the system architecture shown in the Figure 1.2. For that each system should be divided into two levels. The first - this is the level of a clustered wireless sensor network, and the second – this is the level uniting the gateways.

The research has been carried out on the following systems: CDC-DSA [19], MARWIS [32], CWSNLECC [4], MLCASLAAS [36]. As a result it has been stated that the MAC protocols for all systems do not meet all the requirements, that is, the result of the analysis is the same as with the analysis of the common MAC protocols discussed above.

However, the analysis of the second level of the system has given the results for its designing. For example, the part of the gateway in the system MARWIS working on a WSN is built from the common sensor node, while in the other system the gateway performs the algorithm for processing the data before sending it to the TCP/IP network. At the same time, the second level of the proposed systems is used to interface WSN with TCP/IP infrastructure.

2. MODEL of TWO-LEVEL SYSTEM

This chapter dwells upon the proposed model of a two-level network, built using the modeling language SysML [23, 33]. This model is built in accordance with the previously discussed restrictions and functions of the system. Building of this model is also based on the analysis of the existing hierarchical systems for wireless sensor networks. Modelling is performed in accordance with the proposed system architecture shown in Figure 1.2.

It should have five characteristics to ensure the usefulness and adequacy of the model. They are as follows: the first characteristic is to ensure abstraction that is to avoid excessive detailing unnecessary at this level of the analysis. The second characteristic is intelligibility providing an opportunity to understand the principles of the system without any technical and protocol specifics. The third is the accuracy; the model must accurately reflect the modeled system. The fourth characteristic is predictability when it becomes possible to predict the behavior of the system without running an experiment. And fifth is the low cost of the development in comarison with the development of the modeled system or its prototype [26].

Developing complex systems, it is necessary to pay attention to their restrictions, functionality and requirements. Since these systems have an increased number of connections between the elements of the system and the possible transitions between its modes - such features complicate the perception of the system without the additional tools and approaches. Therefore such models as abstractions of physical systems are used. In general, modeling is used to improve or simplify the perception of the system, to determine its behavior boferehand and to check its implementation [33].

The proposed model of the system consists of two parts. The first part is the use case diagram, which determines the interaction of the subjects with the system components. The figure 2.1 shows the use case diagram of the first part of the general model of the proposed two-level system. This diagram shows the interaction of several acting subjects with the proposed system. Thus, the collision-free communication in WSN is conducted at two levels of the system. The first level of communication realizes the communication within clusters of the sensor network, while the second level - the intercluster communication for grouping and sending messages to the host computer and for exchanging data with other nodes of the second level.

There are two main tasks in the system, i.e. setting and collecting sensor data from the environment. This task includes both data collection and data store operation. If you save the data by copying it to the host computer, the collection of data from the sensors is restricted by the system requirements and the chosen hardware platform of the sensor nodes.

The second task of the system is monitoring and controlling by setting the parameters in accordance with the requirements. The clusters are managed in the system by the host computer which sends the gateways the new parameters of clusters and their tasks.

The paper further describes each of the previously mentioned case laws in more detail with their respective diagrams.

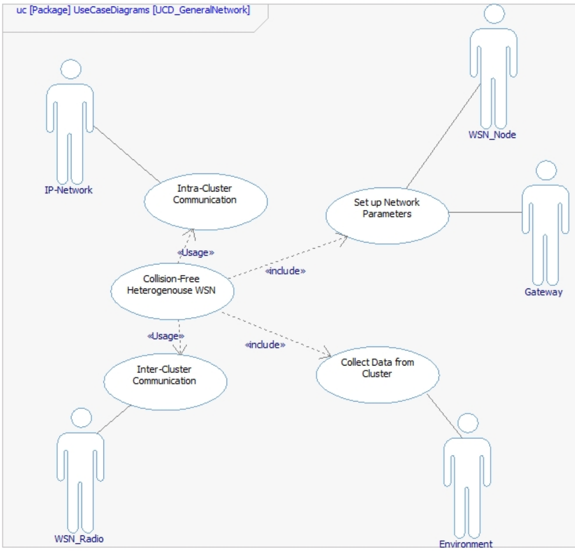

Figure 2.1: The first part of the system model. Use case diagram

The second part of the proposed system model is a block diagram type. This diagram shows the connections of separate elements-blocks of the system with each other, and also defines the interfaces and dependencies of such connections.

The figure 2.2 shows a block diagram for the collision-free system, consisting of two parts - cluster and non-cluster elements. Each element of the system is connected to another via interfaces-ports by typified connections, the relationships of one element to another are also specified.

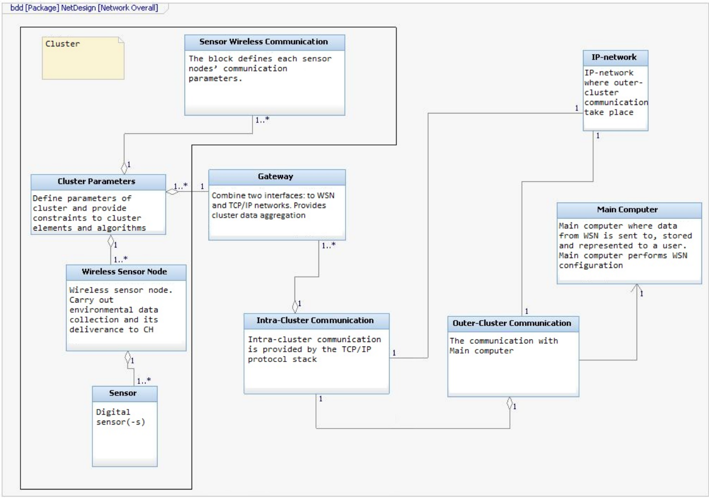

Figure 2.2: The second part of the system model. Block diagram type

There is a wireless sensor module in the center of the cluster, which collects the environmental data. One or more digital sensors are connected to it – it is evidenced by the ratio "one to one" or "one to many" *1 - 1 .. **. The sensor node collects the data and sends it to the gateway of the cluster in which it is located. This delivery happens with the help of the original protocol stack proposed in this paper for this kind of systems.

Each wireless sensor node in the cluster is influenced by the element *Cluster parameters*. This element includes restrictions on sensor nodes, wireless communication and gateways. Thus, it is the central element of each cluster, which regulates the interster communication.

Intercluster communication is provided on the second level of the system. The gateways when collecting the sensor data from the nodes of their cluster use the element *Intercluster communication*, connecting via the second interface. This element determines a protocol stack for such communication and also algorithms for their implementation. In such implementation of the system intercluster communication is performed in IP-networks, as it is shown by the corresponding diagram element.

Communication with other objects in the system, as *Main computer* is also conducted in IP-based networks, but limited by other data transport algorithm specified in the element *Intercluster communication*. However, the protocol stack remains unchanged in our case TCP/IP.

3. COLLISION-FREE INTER-CLUSTER COMMUNICATION

This paper proposes to use a collision-free clustered wireless sensor network as a basis of the proposed hierarchical system. Each cluster is separated from its neighbour using a different frequency channel of data transmission for communication. Thus the radio ranges of the clusters consisting of sensor nodes may be overlapped without negative effect of collisions. Along with other features of the proposed system, it is necessary to provide collision-free, deterministic communication between the nodes of each cluster, which will guarantee the bandwidth in the sensor network and pinpoint possible delays in the data transmission. We propose a new MAC protocol of the level to meet this requirement.

The proposed collision-free MAC protocol is based on the principle of time division between transmission nodes - TDMA. This approach provides the conflict-free data transmission from the cluster nodes. However, TDMA frame requires to generate or initialize the sensor nodes within the cluster by specifying the time slots - when they are allowed to initiate the data transmission. Moreover, the cluster head - CH is responsible for the initialization of sensor nodes. To conclude: the collision-freeness on the first level of the system should be maintained at the three stages of the MAC protocol: the CH selection, the initialization of new cluster members, and the communication within the TDMA frame. Therefore, the following MAC protocol algorithms are used to ensure the collision-free initialization of new participants of the TDMA frame and to select the CH. They are based on the ID system of sensor nodes. Each node in a sensor network has a unique identifier or ID.

The MAC protocol offers three modes of operation, because the requirements to the system and its capabilities are subject to change depending on a task as well as for energy saving. In the first or default mode, one time slot is assigned to each sensor node. In the second mode, the CH may allocate one or more additional time slots to a particular sensor node - this mode is called high speed mode or the further allocated time slot. The third mode ensures energy saving, which is achieved by placing the initialized participants in the sleep state.

In order to select the cluster head the MAC protocol performs inter-cluster algorithm for self-organization. Though the initialized TDMA frame consists of the nodes of two types, they are chosen from the structurally identical components. Moreover, the choice of the CH is provided in a collision-free manner, i.e. the collision-freeness is maintained at all stages of the MAC protocol, starting from the initialization phase and up to the phase of the initialized work of the network. This is a unique feature of the proposed method of multiple access to environment, as the previous papers describe cases when the collision-freeness is maintained in the initialized network, but at the time of its initialization it is not guaranteed .

The proposed MAC protocol provides the robustness of the cluster, which is achieved with the help of an appropriate algorithm, divided into three parts. Its first part provides the cluster nodes' control over the CH existence. If the sensor nodes do not receive a message from the CH for a certain period of time, they start re-initializing. In the second part, the cluster head in its turn provides control over the state of the cluster. It means that the CH can identify which sensor cluster nodes are inactive, and it can generate corresponding messages for the second level elements and for the host computer. Finally in the third part of the cluster robustness algorithm the host computer or the system operator can react to changes in the status of the cluster, depending on the set task. The MAC protocol with its specific algorithms is proposed in the form of the machine - see Figure 3.1 with certain states and transitions.

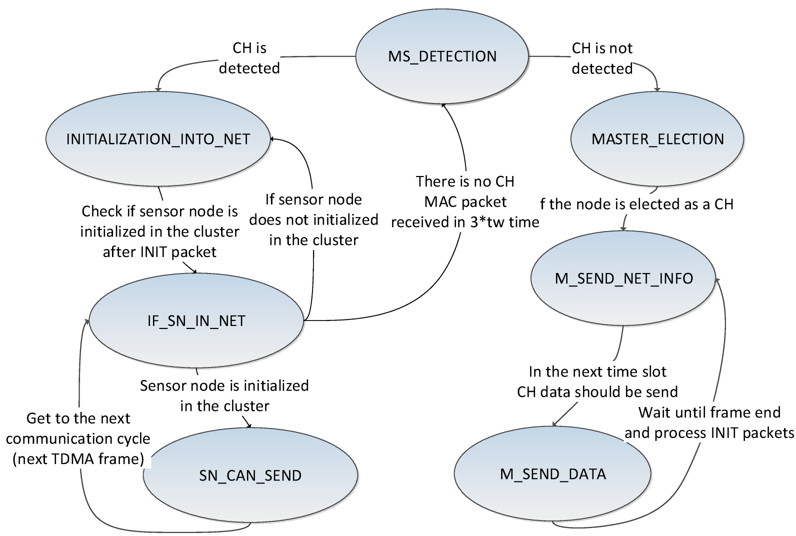

Figure 3.1: Collision-free MAC protocol as a machine

The following states are realized in the MAC protocol:

- *MS_DETECTION* - detection of the CH time slot.
- *INITIALIZATION _INTO _NET* - state of the sensor nodes, in which they participate in their initialization into the network.
- *IF_SN _IN _NET* - state in which a sensor node checks whether it is initialized into the network.
- *SN_CAN_SEND* - in this state of a sensory node it is allowed to transmit data only in a strictly allocated time slot.
- *MASTER_ELECTION* - if the CH is not detected in the state it MS_DETECTION, cluster nodes start the process of CH election in this state.
- *M_SEND_NET_INFO* - in this state, the elected sensor node CH sends the network information, thus initiating a new TDMA frame.
- *M_SEND_DATA* - next state of the CH after it M_SEND_NET_INFO, in which it sends the data received from a sensor(s).

This form of description of the algorithm has been chosen because it is used to implement it on the selected components of sensor nodes. This approach allows us to extend the protocol, which has been created earlier, by modifying or adding new states and determining the conditions for transitions. Then this structure of the protocol allows us to investigate it for the existence of the logical contradictions. The initialized communication in the cluster is organized as a TDMA frame, consisting of three types of time slots, as shown in Figure 3.2.

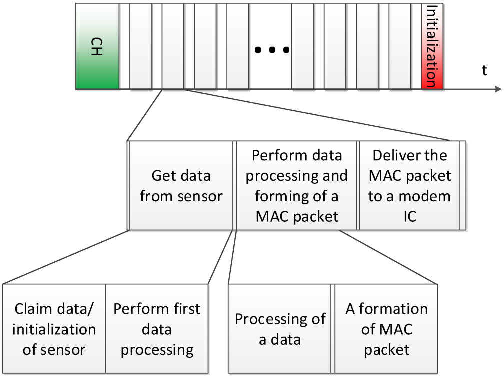

Figure 3.2: TDMA frame of the proposed MAC protocol with three types of slots

The first type of slots belongs to the elected cluster head and consists of two parts. In the first part the CH sends the data about the cluster as a MAC packet having a data field structure shown in Figure 3.3.

Figure 3.3: The data field structure in the MAC packet when sending the cluster information from the CH

The data field contains the information about the CH node - its ID and the number of the slots in which it can transmit packets, and also about other network participants in the cluster. Each participant, or the initialized sensor node is registered in the structure and separated by the symbol *";"* from the other nodes. The time slots assigned to the appointed sensor node are specified after its ID and are separated from it by the symbol *"|"*. The frame ends with the ID number of the next sensor node which can pretend to initialize into the cluster.

The second type of slots belongs to sensor nodes, it is shown as empty in Figure 3.2, and the number of slots is limited by the cluster size and hardware restrictions of the sensor nodes. Having received the CH packet each sensor node starts a timer and sets its check on the interval equal to the time slot number received from the CH packet with the cluster information. Thus, only one sensor node may transmit in one time unit.

Each sensor time slot is divided into three phases: receiving data from a sensor, processing and formation of a MAC packet and sending it to a modem microchip. After all slots are assigned to sensor nodes, the TDMA frame completes the initialization slot, it is designated with the text *Initialization* on Figure 3.2. This time slot is allocated in order not to allow uninitialized sensor nodes hinder the communication of the elected cluster when sending the initialization packets. In order to achieve completely collision-free MAC protocol, sending of the initialization packets is regulated by the CH in the information package about the cluster.

The proposed protocol offers three modes of the cluster operation. The first mode provides equal access of all initialized sensor nodes to the environment by assigning one time slot to each node. The expected data transmission rate of the sensor node *n* can be expressed by the formula:

$$V_n = \frac{t_{tx}}{t_{MS} + 2t_g + (n-1) \cdot (t_s + t_g) + t_{init}} \cdot V, \tag{3.1}$$

where V – the data transmission rate of the chosen sensor nodes platform, for example, the platform eZ430-RF2500 developed by Texas Instruments is able to transmit data at a rate up to 500kBs [15]; it t_{tx} – the time required to transmit data from a microprocessor of a sensor node to a modem microchip and to transmit data on air; *m* – a number of sensor nodes in the clusters; t_g - the size of the secure gap between adjacent slots.

$$V_{n_j} = \frac{t_{txa_j}}{t_{MS} + 2t_g + \sum_{i=2}^{n} \frac{t_{sa_i}}{t_s} \cdot (t_s + t_g) + t_{init}} \cdot V, \tag{3.2}$$

where t_{txa_j} - the total time of a node in all slots when sending data to a modem microchip and transferring it on air; $\sum_{i=2}^{n} \frac{t_{sa_i}}{t_s} \cdot (t_s + t_g)$ – the total length of slots (with additional allocated slots) of all nodes in the cluster, except for the CH, and the corresponding number of gaps.

The last proposed mode of the protocol operation is saving mode when all the cluster sensor nodes sleep for the time t_{sleep} after the communication cycle - TDMA frame. In this case, the data transmission rate of a sensor node can be expressed by the formula:

$$V_n = \frac{t_{tx}}{t_{MS} + 2t_g + (m-1) \cdot (t_s + t_g) + t_{init} + t_{sleep}} \cdot V. \tag{3.3}$$

When transmitting a message from a sensor node to a modem microchip it is transmitted as a generated MAC packet, which structure is shown in Figure 3.4.

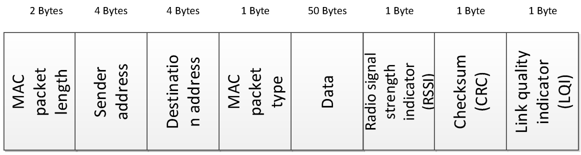

Figure 3.4: Structure of the MAC packet of the proposed MAC protocol

The MAC packet contains data about the sender and the receiver of the packet, as well as its type, by which it is possible to determine how the packet shall be processed. For example, the packet type field indicates the CH-type, i.e. this packet contains the data about the network within the cluster. In this case, the appropriate algorithm should be used for reading the data, and the protocol state should be changed. In other case the packet type indicates a data packet then the scalar data will be processed in accordance with the cluster task.

The MAC packet contains length of the data field and keeps its value at the beginning of the packet to determine the size of the data field. This approach allows us to go to the next group of the MAC protocol fields in one command. This group contains indicators of the transmitted signal quality.

4. THE SECOND LEVEL OF THE SYSTEM. AUTONOMOUS CLUSTERING

The previous chapter described the first level of the proposed system, which ensured the collision-free communication, in other words, the collective interaction of sensor nodes in a wireless sensor network. However, according to the system architecture shown in Figure 1.2, there is also the collective interaction of nodes on the second level. It has gateways, whose main task is to transform protocols from a wireless sensor network to TCP/IP network. In addition, the extension of a sensor network by adding the second level results in the following improvements:

- *Autonomous Clustering.*
- *Delivery of sensor data for TCP/IP network.*
- *Ensuring cluster management.*
- *Sending data processing tasks from CH to gateways.*

Next, we are going to consider each of the points of improving the functions of the system with the second layer.

4.1. Autonomous clustering

The autonomous clustering algorithm proposed in the paper is foreseen for work on the first level of the system and it is also a part of the collision-free MAC protocol. The autonomous clustering allows you to introduce self-organization into the sensor network not only within clusters, but also direct clustering without any operator. It is also possible to provide self-healing of a network by determining a target cluster for a new or already initialized sensor node. This feature is particularly important in critical tasks of data collection, when it is necessary to receive a certain amount of sensor information per time unit. Besides, the autonomous clustering allows you to extend the sensor network according to the tasks to be performed by limiting the size of clusters, as well as by uniting the existing clusters or initiating their re-clustering for a specific task.

- All wireless sensor nodes start working with a certain preset communication frequency.
- There are new types of MAC packets as shown in Figure 3.4:

– MAC service packet of CH, which informs about the necessity to join another cluster.

– MAC packet for the communication of the CH with the gateway.

- gateways, in turn, share service information.

Changes to the original MAC protocol have been made in accordance with the described approach - adding a new mode and describing the transition modes. So, we have added the mode *INITIALIZATION_CHECK*, as shown in Figure 4.1 in which an uninitialized sensor node checks whether it can be initialized by the cluster head on the selected communication frequency.

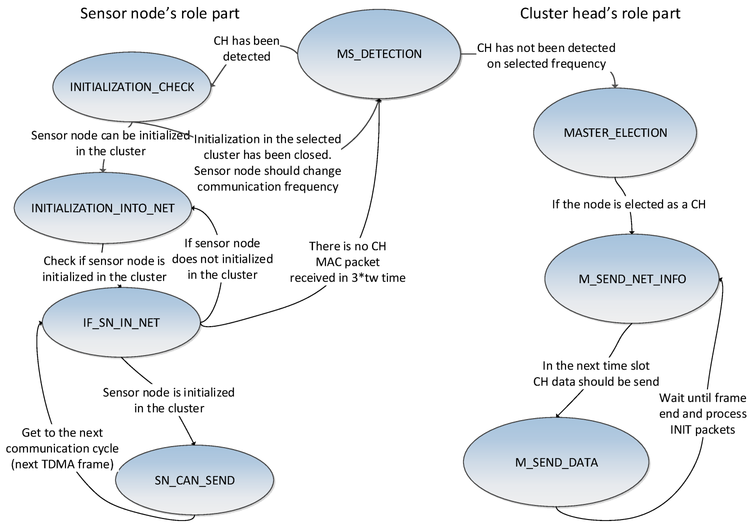

Figure 4.1: MAC protocol algorithm with an autonomous clustering algorithm

Being in the mode *INITIALIZATION_CHECK*, the sensor node continuously changes the communication frequencies looking for the clusters which are free for the initialization. In order to speed up this process the service information exchange between the gateways is provided. They exchange messages about the mode of their cluster, which is further forwarded to the CH nodes. This information includes the following data: the cluster head ID, the number of sensor nodes in the cluster, the number of free slots in the cluster, the number of damaged sensor nodes, the tasks for the cluster, the cluster communication frequency. Thus, uninitialized sensor nodes receive the data on the clusters which are free to initialize. An additional time slot is added to exchange messages between the clusters and the gateway, as shown in Figure 4.2.

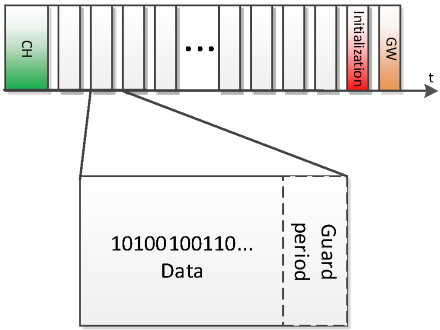

Figure 4.2: The TDMA frame of the MAC protocol with an autonomous clustering algorithm

The messages from the gateway are processed within this slot. The proposed two-level system has got configuration parameters of the cluster to ensure the solutions of its tasks, as well as the data on free clusters, in which new members of the clustered sensor network should be initialized.

4.2. The exchange of the service and sensor data between the gateways

We'd like to remind you that the primary function of the gateways in the proposed system is providing the delivery of sensor data from the clusters to the TCP/IP network. In order to ensure this function the gateway consists of two parts, as shown in Figure 4.3.

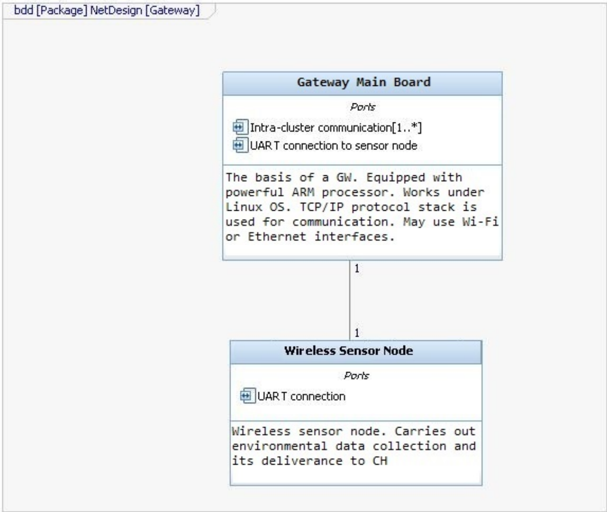

Figure 4.3: The components of the gateway

The first part is the basis of the gateway which converts the clustered wireless sensor network protocol stack into the TCP / IP protocol stack. In addition, the gateways on the second level of the system transport the data from the clusters to the host computer by means of the developed transport protocol. Since the use of such units in the system reduces the load of data processing in the CH, the sensor network data processing algorithms are carried out in the gateways. This is possible due to the continuous power supply of these nodes. The second part of the gateway node is shown in Figure 4.3 and it is the interface for the sensor network. We propose to use the same wireless sensor node, as during the clustering, since it can provide the consistency of the wireless communication between the same nodes at the hardware level, and as a result it increases the system reliability. In order to link both parts of the gateway, we propose to use the UART interface. This interface has been chosen because of its availability in the microprocessor technology and the proposed functions: the configuration of the data rate, the error check.

The data processing can be carried out by means of the corresponding algorithms, which have been programmed and run on the gateways. The paper proposes four commonly used sensor data processing algorithms, their description and an example of their use on the general software. In accordance with the proposed approach, the other algorithms according to the system tasks may be applied and installed in the gateways.

Following the processing of the sensor data from the cluster, the gateway according to the transport protocol illustrated in Figure 4.4, transmits the data to the host computer. The algorithm is divided into three logical parts. The first part is responsible for the connection of the basic part of the gateway with the second part, i.e. the interface for the sensor network, and also for the registration of the gateway in the system. After the successful registration, the gateway receives the data on the system mode: the number of sensor nodes in the clusters, their mode, and the mode of other gateways. The gateway also receives the control messages from the operator in this part. The second part of the transport protocol is performed, if it is necessary to support the clusters, where the gateways are out of order. Thus, in addition to the collection, processing and transmission of the data to/from the sensor network, the algorithm supports the damaged elements of the system. The gateway, which has been elected as a support provider collects the sensor data from the clusters sequentially, and sends the data to the host computer or other gateways. The cluster processing procedure is performed on the cluster of the gateway In the third part of the algorithm.

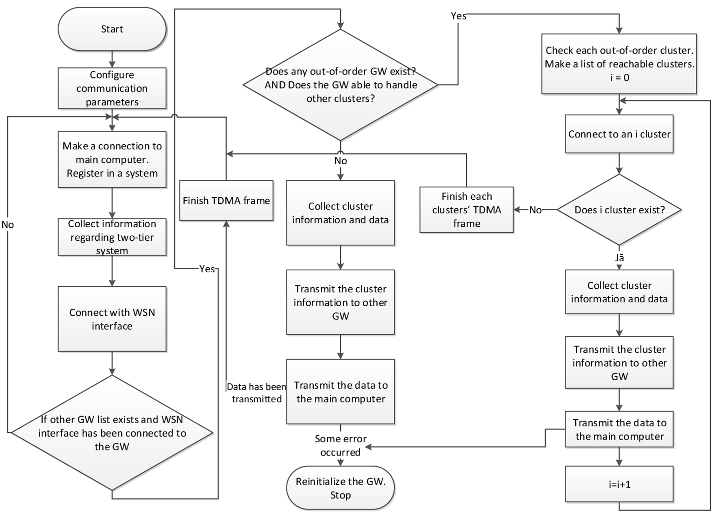

Figure 4.4: The transport protocol of the gateway

4.3. *The technique of designing the two-level system*

After the detailed description of the protocols, algorithms, and capabilities of the system this paper proposes the technique for designing such systems.

The technique consists of two methods: the method for designing the first level of the system – the clustered sensor network and the method for designing the second level of the system. We offer two block diagrams corresponding to the two methods to illustrate the proposed approach (see Figure 4.5).

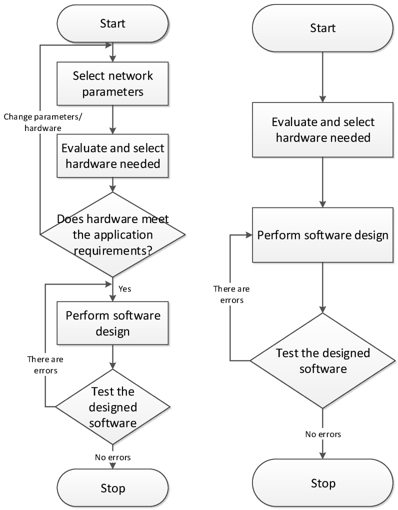

Figure 4.5: The technique of designing the two-level system

We propose to start designing with the first level of the system, since the network settings or tasks govern the choice of the hardware portion of the first level, since the sensor nodes themselves are limited in the resources. The next step is to select the hardware portion for the first level. If the check for compliance of the hardware with the system restrictions is successful, you can proceed to the next step - the development of the software. The paper offers some recommendations on how to develop the software in terms of the limited resources. After developing the software for the sensor nodes we propose an approach to testing the received results in this paper: we have indicated some points which require your attention, and which have to be verified for accuracy. In case of the successful test, the first method is completed and the designing moves on to the development of the second level of the system.

The second part of the designing technique is the method for designing the second level of the system. Since according to the recommendations for the designing of the first layer, the task parameters are known and are adapted to the specific platform, it is not necessary to make the repetitive steps and the compliance testing. After selecting the hardware platform we propose to move to the next step , i.e. writing the software for the gateways. Then test it according to the directions described in the work.

5. TWO-LEVEL SYSTEM MODEL FOR ANALYSIS OF DATA PROCESSING DELAYS

Since the proposed two-level system is complex, i.e. it consists of two parts; it is necessary to have possibility of conducting preliminary performance analysis without its installation. The task of the system is data collection and management of objects by sensor nodes, thus it is necessary to know the ability of proposed system architecture to fulfill such tasks. As a rule, under performance of such systems is meant amount of transferred data per time unit, and also amount of possible delays while system nodes are processing sensor data. In the present paper is offered a statistical model for evaluation of performance and possible delays while data processing while their transfer from sensor nodes to TCP/IP network. The model is shown in the picture 5.1.

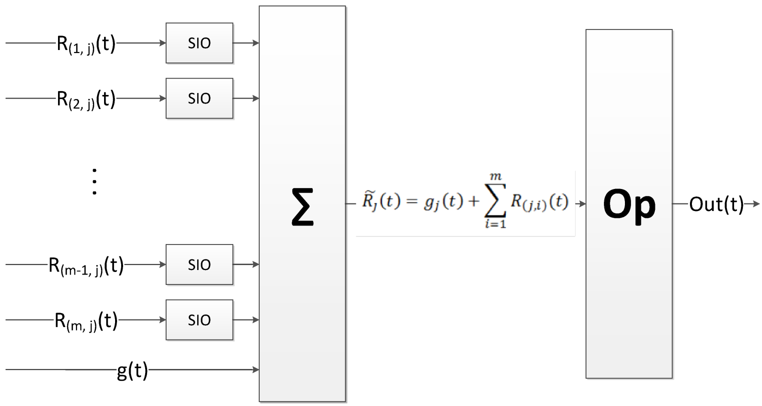

Figure 5.1: Non-collisional MACprotocol in the automatic form

The model includes both system levels. Thus to its input are supplied data streams from *m* sensor nodes from *j* cluster. All streams pass from a serial data communication unit *SIO*, in accordance with MAC protocol. Each received stream is summarized in cluster gateway into common data mass dividing according sensor types. Along with the data received from sensor nodes to the summing unit are transferred data from the neighboring gateways. Summarized stream is transferred to the processing unit model *Op*, after the work of which in the output is displayed resulting processed data stream from two-level system. Further, resulting data stream *Out(t)* is transferred through interface into TCP/IP to the host computer.

The present model allows verifying chosen hardware base to solve the task stated without its launching in the real system. Description of each unit model should correspond to its real description. Thus for the unit *SIO* should be defined its bandwidth, and processing unit should be checked by means of execution of the program simulating its work. Thus, this model is meant not only for the analysis of delays in data processing, but also for verification of the correctness of choice system parameters. Hardware of basic gateway part because of its complexity will use OS, for instance, Linux. In such a case a developer will be provided with development tools and interfaces for the network subsystem, and gateway hardware in the most convenient form, i.e. without their binding to a specific hardware platform. However, because of the multi-tasking required to ensure opportunities provided by the OS, program's run-time may vary. If using this approach for the design of the second system level, the selected hardware platform must be assessed in terms of the critical time, if required. Using the program that simulates gateway's work on the chosen hardware platform, it is proposed to record statistical data about expectation of the execution of the program for different number of units in cluster, and standard deviation in every experiment point. Obtained statistical data are proposed to be used for evaluation of the stability of the programs of the selected platform. In the case of a satisfactory evaluation, it is proposed to use earlier obtained data in the *Op* unit model.

As an illustration here is an example shown in the picture 5.2, case of improperly selected system parameters, namely *SIO* unit.

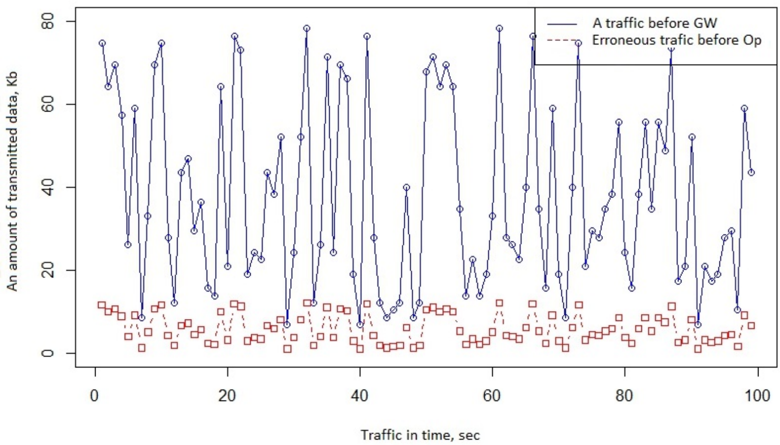

Figure 5.2: Transferred data amount at varying number of senders before processing in the gateway. Incorrectly configured unit *SIO*

Here we can see correct summing data stream from sensor nodes, data stream is shown in the picture as firm line. However, due to improperly selected or improperly configured block *SIO* only a part of data is transferred, and there is not enough time to transfer the second part of data to the basic part of the gateway, thus only a part of the data is available. Therefore, we believe that the use of the model before designing such a system is necessary for clarification, the selection of the platform and identification of errors.

MAIN RESULTS AND CONCLUSIONS

In the promotion theses was proposed and examined two-level wireless sensor network. In the first level are located wireless sensor nodes, which measure the environment or an object, instead of sensors there might be actuators as well. Namely, the first level consists of resource limited wireless sensor nodes that cooperate with the environment. Wireless sensor nodes are organized in clusters. For inter cluster communication was developed collision-free media access control protocol. It is based on TDMA principle with a specific TDMA frame initialization and maintenance algorithms. Wireless sensor nodes are divided into clusters using self-developed autonomous clustering algorithm. This arrangement of wireless sensor network provides several advantages, such as: self-arranged clusters, determined data collection help to reduce resources used, and to reduce use of power supply energy etc. Each cluster contains general sensor nodes and among them chosen head node. Head node is the node, which performs main functions in the cluster supporting. Actually CH node is cluster transporter that is responsible for uninitialized inclusion of sensor nodes into cluster and initial TDMA frame expression by sending the information about cluster configuration.

Proposed second system level consists of gateway nodes. They are facilitated with more resources than wireless sensor nodes. Gateways have bigger amount of memory, in computing more powerful processor, and they may also be connected to a constant power supply. These features are ensured by the GW performed tasks where the main task is to carry out the transformation of protocols from wireless sensor network or cluster to the TCP / IP-networks. As additional tasks they are to perform data processing, which removes this load from CH node, as it is made in several other systems. In order to perform this operation it is necessary to have at least TCP/IP protocol stack, which would be organized for software type, and process switching algorithm. In this case Embedded Linux operating system was selected, namely, necessary specific hardware resources for its correct launching and correct action.

When the system operates correctly GW is determined for every cluster, but during system's operation times both GW as well as sensor nodes can fail operating. In order to prevent such cases it was also proposed to use gateways. Algorithm supporting several clusters allows avoiding cases when a cluster becomes inactive or data from it is not transmitted to the TCP/IP network. Then other GW nodes try to connect inactive cluster as additional cluster. The other source of errors is replacement of inactive sensor nodes. GW nodes exchange information about their clusters in which they transmit message about requirements to include/ replace sensor noes. From this GW the information is transferred to cluster heads and for a new, non-initialized sensor node it will be available in the initialization stage. Such GW feature allows introducing not only self-recovering of two-level network, but also fast integration of new participants. For the design of two-level system the methodology was proposed. It was decided to divide design methodology into several stages. Such a division helps the system engineer to develop a system for the selected platform or to perform system reconfiguration. It is achieved with help of references in thesis text, as the result an engineer may find explanations he is interested in by following the references. The design methodology includes guideline by selecting hardware, by program development and testing. The design methodology was developed for the first system-level development, and for the development of the second or gateway level.

In the present thesis also network computing was offered. It consists of two parts. The first part being cluster communication part in which throughput of MAC protocol is simulated. Thanks to collision-free communication and conflict-free initialization algorithm, it is possible to create inter cluster determined data transmission, i.e. it is possible to use such wireless sensor network in time-critical tasks. For determination of throughput and data transmission time there are offered 3 equations which describe operating regimes. It is proposed to use them in network computing model, where every data flow from wireless sensor network is summarized and passed for processing to the next part of the model, to GW node, which is based on use of statistic data for determination of data processing delay on GW. For the other part of the model necessary statistic data are collected. It is shown with the help of example that network computing model can be used when analysing throughput of the system for specific configuration cluster and gateway.

A network calculation has been proposed in the work based on acquired information about system, MAC protocol and other algorithms. It consists of two parts. In the first part is about cluster communications, in it the MAC protocol throughput has been modelled. Due to collision-free and conflict-free nature of an initialization algorithm becomes available to form intra-cluster determinate data transmission, or rather, it enables the proposed WSN utilization in time critical tasks. Throughput and data transmission time determination is done with three different modes' descriptive equations. There is proposed to use them in network calculation model, where data flows from each sensor node are computed together and transferred to next model processing part - GW node. It is based on data processing and GW delay statistical data utilization. Thus a needed statistical data is gathered for second part of a model. In the thesis an example of the model usage is shown - it is aimed to analysis of the system's throughput when cluster has s known configuration on its elements as well GW configuration is known.

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