RIGA TECHNICAL UNIVERSITY
Faculty of Computer Science and Information Technology
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APPLYING SENSOR NETWORKS TECHNOLOGIES IN TIMECRITICAL APPLICATIONS

Summary of the Doctoral Thesis

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DOCTORAL THESIS

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To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on November 2, at the Faculty of Computer Science and Information Technology, 1 Setas Street, Room 202.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Dmitrijs Bļizņuks …………………………….(Signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of introduction, 5 chapters, conclusions, bibliography with 130 reference sources, and 2 appendices. It has been illustrated by 65 figures. The volume of the present Doctoral Thesis is 130 pages.

CONTENTS

Theme Relevance

Each year wireless networks conquer the world and spread to new applications [1], [2]. Wireless communication allows creating autonomous and mobile systems, which are not limited by the wire length and flexibility. Despite the widespread occurrence of the wireless networks, still there are numerous problems to solve [24], [55], especially in the field of time-critical applications, where communication parameter stability must be determinate and stable. Widespread wireless networks have a relatively high data rate and high mobility. Still these parameters are not crucial in time-critical applications. The main aim is to provide time related parameter stability and predictability. Information should be transmitted within the predefined time interval and delay boundaries. Therefore, the overall system quality depends not only on values, but also on the time moment, when values are received. By solving such a task, it is possible to apply all advantages of the wireless communications to time-critical systems.

The wireless sensor system used in real application should be able to react within the interval of environment process reaction time. That makes the network real time or time critical. Usually, real environment processes are nonlinear and dynamic. Therefore, formalisation of such a system becomes a nontrivial task. Mathematical models usually are used to formalize either a nonlinear or dynamic system, but not both of them at the same time. The existing formalisation and modelling approaches use static or probabilistic parameters of data streams. Such approaches could be used in a limited number of applications or in the applications, where approximate/probabilistic results are acceptable. To solve these problems, the author proposes an approach that allows using dynamical parameters of input data (packet stream), even if input function is nonlinear. Moreover, the approach allows combining discrete and analogue data in the system input.

One of practical application areas requiring autonomous and mobile control systems is industrial automation. This area is conservative, changes in the existing infrastructure and architecture are expensive as well as stability and fault tolerance requirements are high. That makes the industrial area very conservative to wireless networks. Nevertheless, the current level of technology and recent studies allows fulfilling strict requirements, providing an ability to bring wireless benefits to a new application area — industrial automation.

The Doctoral Thesis solves the above-mentioned problems and proposes hardware and software solutions that allow implementing wireless transmission systems in predefined time bounds. The relevance of the current research is also proved by the fact that there is a tendency of replacing hardware systems with software solutions [58]. It could be explained by an increase in efficiency, when several integrated circuits are replaced by one chip.

The Aim and Tasks

The aim of the Doctoral Thesis is to develop the technology to be used for wireless sensor networks in the time-critical environment, where controlled objects are nonlinear and dynamic.

The tasks are as follows:

1. To define quantitative criteria for the objects of research;
2. To define wireless data transmission problems in time-critical applications;
3. To develop formalisation methods of time-critical system formalisation for nonlinear and dynamic objects;
4. To develop an algorithm for wireless network media access that meets the predefined time requirements;
5. To implement the proposed solutions in real applications;
6. To propose solutions for wireless network security and reliability problems in real life.

Research Subject and Object

The research subject is time-critical wireless sensor networks.

The objects are algorithms for wireless network media access and system dynamics evaluation in time-critical application with nonlinear and dynamical properties.

Thesis Statements to Be Defended

1. Nonlinear and dynamical systems could use wireless transmission for time-critical data transfer;

2. It is possible to create a time-critical wireless network, where transmission delay is small enough for autonomous mobile object control;
3. It is possible to create a protocol of wireless sensor network media access that will combine time-critical data transmission possibility along with data transmission without a central node;
4. Following the defined usage strategy, wireless sensor networks are capable of delivering stable data transmission in harsh (high temperature and humidity) and radio unfriendly environment.

Scientific Methods Used

The Doctoral Thesis uses systems of nonlinear equations, Hammerstein model based decomposition, hardware emulation and dataflow transformation to digital discrete form.

Scientific Novelty

Scientific novelty of the Doctoral Thesis:

1. Problems of wireless transmission in time-critical systems are defined;
2. A nonlinear, dynamic and time-critical system formalisation technology is developed;
3. A wireless media access algorithm is developed. Comparing with the existing solutions, the proposed solution provides greater transmission frequency and interval stability, by using novel algorithmic and hardware techniques;
4. A solution is proposed to increase wireless network simulation precision, for short transmission intervals (<5ms);
5. An approach is developed for automated, fast visualisation and analysis of experimental data.

Practical Application of Research Results

The Doctoral Thesis presents a wireless media access method in combination with nonlinear and dynamic system modelling. Such combination allows creating autonomous and mobile control systems in the specific environment, where cable connections are not possible or not efficient, for example, high explosive or other harsh environments, highly mobile object control. Since industrial applications are conservative to new technologies, there are a number of applications, where wireless networking is still not implemented. Therefore, the proposed solution is relevant and applicable in the industrial area. By using the developed algorithm for hybrid wireless media access, economic benefit could be reached. It is expressed in lowering expenses for network implementation and support. Indirect benefit is also obtained due to higher system stability, which results in lower expenses on support. The latter is especially important in industrial application, where losses due to delays could be much higher than equipment price. Statistics points out that a noticeable number of failures appear due to bad contacts.

The proposed wireless data transmission system allows attaining high timing stability, which is important not only in time-critical tasks, but also in energy efficient solutions. The traditional transmission approach keeps a device turned on while checking if wireless media is free. By using the proposed method, a wireless sensor could turn on only for transmission, since all nodes will be synchronized and there will be a separate timeframe for each transmission. Therefore, node active time will be lowered, which results in increased energy efficiency and the time it could operate on a single battery.

A system capable of transmitting time-critical data could be used as well in audio and video conference systems. Such a system could be created without relying on a central server and that is impossible using the existing techniques.

The proposed solutions were implemented and tested within international FP7 project STRATOS [52]. They were shown to be capable of providing higher transmission frequency and interval stability.

Practical tests were additionally carried out on a real industrial object — a vertical wind tunnel, where the efficiency of wireless transmission was proven in respect to replacement of cabled solution.

The research results have also been used in the following projects: German government project ZESAN [67], FP7 project ProSense [43] and grant No.09.1201 by the

Latvian Council of Science. Research results have been published in 13 science papers and presented at 13 conferences.

Scientific publications

1. Taranovs, R., Jesilevskis, V., Miezītis, G., Bļizņuks, D., Kļaviņš, Ē., Kalniņš, A., Zagurskis, V. An Approach for Meeting Room Activity Monitoring and Analysis. Technologies of Computer Control. Vol.15, 2014, pp.63-68. ISSN 2256-0343. e-ISSN 2256-0351 (*Indexed in: EBSCO, Google Scholar. Author's contribution is introduction section writing and sensor node prototype designing, in total 15%)*

2. Bliznuks D., Zagurskis V., Fantuzzi C. Time Critical Wireless Data Transmission in Autonomous Control Applications // Telecommunications Forum (TELFOR) 21st. — 2013. 196.-199.lpp. ISBN: 978-1-4799-1419-7 (*Indexed in: Scopus, Google Scholar. Author's contribution is main sections writing and experiments implementation, in total 70%)*

3. Bļizņuks D., Zagurskis V. Wireless Time Critical System's Architecture Development Based on Dynamics of Data // Datorvadības tehnoloģijas. Nr.14, 2013, 81.-85.lpp. ISSN 22559108. (*Indexed in: EBSCO, Google Scholar. Author's contribution is main sections writing and experiments implementation, in total 80%)*

4. Bliznuks D., Zagurskis V. Techniques and Architecture Improvements for Fast Data Acquisition in Wireless Networks // Technologies of Computer Control. Vol. 13, 2012, pp.32-37. ISSN 2255-9108 *(Indexed in: Google Scholar. Author's contribution is main sections writing and experiments implementation, in total 80%)*

5. Zagurskis V., Bļizņuks D., Taranovs R. Pilot Signal Detection in Wireless Sensor Networks // Technologies of Computer Control. Vol.48, 2011, pp.36-40. ISSN 1407-7493 *(Indexed in: EBSCO, Google Scholar. Author's contribution is introduction section writing and taking part in algorithms/methods designing, in total 15%)*

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9. Bļizņuks D. Investigation of IEEE 802.15.4 Based Networks with Respect to Industrial Conditions // Scientific Journal of RTU. 5 series, 42 vol. 2010, pp 68-73. *(Indexed in: Google Scholar)*
10. Bliznyk D. Security Issues in Wireless Sensor Networks for Environmental Monitoring // Scientific Journal of RTU. 5 series, 39 vol., 2009, pp. 80-86. (*Indexed in: Google Scholar)*
11. Bliznyk D., Zagursky D. Approach to Verification of Mixed signal Non-linear Objects // Proceedings of the VIII International Conference SICPRO, 2009, pp. 813-821, ISBN 978-5-91450-024-2. *(Author's contribution is introduction section writing and taking part in algorithms/methods designing, in total 20%)*
12. Bliznyk D., Zagursky V. Approach for Wireless Resources Access Control // Proceedings of the 2008 International Computer Symposium, Volume 1, 2008, pp. 141-145. (*Indexed in: Google Scholar. Author's contribution is main sections writing and experiments implementation, in total 80%)*
13. Bliznyk D., Ozols A. Industrial Networks in Time Critical Applications // Scientific Journal of RTU. 5 series, 32 vol., 2007, pp. 51-59. (*Indexed in: Google Scholar. Author's contribution is main sections writing and experiments implementation, in total 80%)*

Scientific conferences

1. International conference IEEE Biophotonics Conference 2015, Florence, Italy, May 20–22, 2015.
2. International conference 21st Telecommunications Forum TELFOR 2013, Belgrade, Serbia, November 26–28, 2013.
3. Riga Technical University 54th International Scientific Conference, Riga, Latvia, October 14–16, 2013.
4. STRATOS project partner's conference, Haifa, Israel, November 25-29, 2012.

5. Riga Technical University 53^{th} International Scientific Conference, Riga, Latvia, October 10–12, 2012.
6. STRATOS project partner's conference, Lugano, Switzerland, February 19-22, 2012.
7. Riga Technical University 52^{th} International Scientific Conference, Riga, Latvia, October 14–16, 2011.
8. International conference The R User Conference 2011, Coventry, UK, August 16–18, 2011.
9. Riga Technical University 51^{th} International Scientific Conference, Riga, Latvia, October 13–17, 2010.
10. Riga Technical University 50^{th} International Scientific Conference, Riga, Latvia, October 12–16, 2009.
11. International Computer Symposium ICS 2008, Taipei, Taiwan, November 13-15, 2008.
12. Riga Technical University 49^{th} International Scientific Conference, Riga, Latvia, October 13–15, 2008.
13. Riga Technical University 48^{th} International Scientific Conference, Riga, Latvia, October, 11–13, 2007.

Structure of the Doctoral Thesis

The Doctoral Thesis consists of five chapters. The first chapter gives a brief overview on wireless sensor nodes, sensor network architecture and specifics. In addition, time-critical systems and their difference from other control systems are reviewed. Data transmission problems of specific time-critical systems are defined. The second chapter evaluates the formalisation methods of existing systems formalisationand proposes the approach for nonlinear system dynamics evaluation.

Since any wireless data transmission system with multiple nodes uses a network media access protocol, the third chapter proposes a hybrid media access protocol. It outperforms the existing protocols in terms of maximum number of nodes and data transmission frequency. Along with the new protocol, methods for node self-organisation and synchronisation are proposed.

The fourth chapter deals with practical implementations. The formalisation method is examined and tested in the vertical wind tunnel control system. Wireless sensor network methods are tested within the international FP7 project — STRATOS [52]. Advantages of the proposed algorithm in respect to the existing algorithms are proven. The proposed algorithm has higher packet transmission frequency and greater timing stability. Full-scale network ability to operate under the defined requirements is proven by using a network simulation model.

The last chapter analyses wireless sensor network security, stability problems and proposes solutions. Sensor networks are analysed in the controlled industrial-like environment. As a result, stability and security definitions have been formulated. To support the test result analysis, a special tool has been developed. The tool allows creating visualisations of large test setup data (> 1 million records), in automatic mode.

1. SPECIFICS OF WIRELESS SENSOR NETWORK DATA TRANSMISSION

1.1. Wireless Sensor Nodes and Networks

The research object — a wireless sensor network definition further will be treated as “spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, pressure, etc. and to cooperatively pass their data through the network to a main location” [62]. Along with that, it is worth mentioning that size of the node is critical. It should be small enough for seamless integration into monitored device/environment. In addition, the price has a limiting role within wide application of wireless sensor nodes.

Wireless sensor specifics are the ability to measure physical parameters and exchange information in wireless manner. Despite the fact that both abilities are trivial and appeared long time ago, creating an autonomous node with combined abilities is not a trivial task. The main limiting factors are physical size and price, which limit processing power and energy source (usually battery) capacity. Modern sensor nodes (as of 2014) are smaller than $1cm^2$. Nevertheless, node size nowadays depends mostly on energy source volume.

During the last year electronic capabilities and price drop allowed creating wireless sensor nodes that are accessible to a wide market. Thanks to mass production it is possible to buy for just 5-50 USD such nodes as “Raspberry Pi”, “LinkitOne”, “Intel Curie”, “esp8266”, “BlackSwift”, etc. [42]. They still have limited capabilities, but the road to wide available wireless sensor networks or the Internet of Things is opened.

Despite wide wireless network usage, the existing standards could not satisfy the demands in respect to wireless sensor nodes. At the time of wireless standard development, there were no plans for using mobile and fully autonomous nodes with limited processing power and energy. Widely used wireless networks (like IEEE 802.11) are used as a universal solution for providing wireless data transmission and cannot satisfy peculiar demands of wireless sensor nodes. One of the important tasks is energy saving. Since the existing power sources (such as batteries) cannot satisfy size/energy demands, the only way to use sensors is energy saving algorithms, which in fact are tightly connected with network control algorithms. Chapter 1.2 examines in detail the demands for the development of special wireless network control algorithms.

Since a wireless sensor node has all of the desktop computer components, it can be treated as a standard PC. Nevertheless, the size of the node is strictly limited. The latest innovations in microelectronics have allowed combining all components in one electronic chip. Such an approach is called System on a Chip SoC (Fig.1.1). All we need is to add the power source and a measuring sensor.

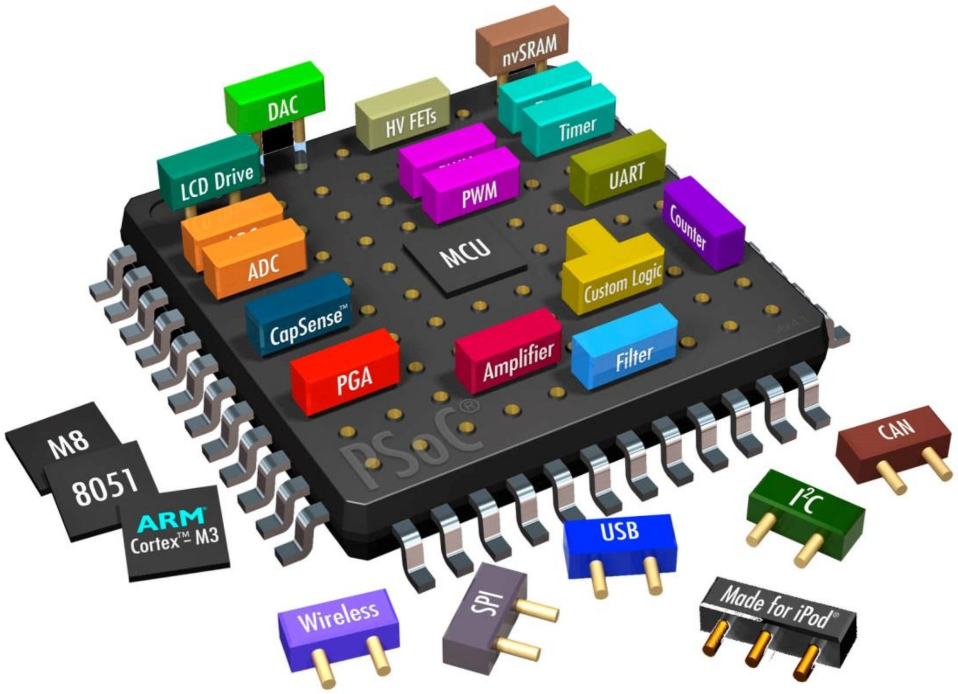

Fig. 1.1 Elements combined in a single chip (SoC) [54].

It is possible to state that size is not constrained any more. Still the power source limits keep wireless sensor nodes from wide use. Batteries are not evolving as fast as electronics. If we compared energy usage of a regular WiFi (IEEE 802.11) node (up to 1000mW) with small size battery (e.g., coin cell) capacity of 50 mAh [21], we could observe the lack of power. The node could be powered only several minutes with such a power source. Even the densest energy power source — lithium batteries are limited to 800 mWh/cm3 [21]. That is still not enough for wide sensor node usage.

To solve energy limitation, it is possible to use special techniques such as IEEE 802.15.4. Their consumption is much lower — 50-100 mW. By combining these techniques with energy saving techniques, it is possible to prolong node lifetime up to several years. By putting a node to sleep state and waking only for short periods, we can prolong node life by several magnitudes. Chapter 3.2 proposes a new media access algorithm that allows using energy saving techniques along with keeping positive aspects of decentralised protocols like CSMA.

1.2. Research of Time-Critical Systems and Data Transmission

Hereinafter the real-time or time-critical system is such a system, the operation accuracy of which depends not only on the obtained value but also on the time moment in which this value has been received [51]. Time-critical nature of the system does not mean that the system is fast; the main point is that its reaction speed corresponds to demands of the medium and of a controlled object. It is important to guarantee that system reaction time does not exceed the predefined threshold in any situation and at any input parameters. This immediately distinguishes the real-time control system from systems of other types, where it is sufficient to ensure system average delay below the value of the previously defined threshold. As an example of a time-critical system we can consider automobile security systems (air bag, anti-sliding system, etc.); they are supposed to ensure the corresponding reaction to external influence in a strictly defined time span. Otherwise, their operation result can be catastrophic. The systems mentioned in the example are considered as hard real-time systems, which in all cases must fit a definite time-limit (Fig. 1.2). There are also systems where it is possible but not desirable to exceed the time-limit as thus the system quality is decreasing. For example, a graphic user interface is considered to be such a system. Delays are admissible, but when they exceed a definite threshold it becomes uncomfortable to work with such an interface. Further, if there are no special remarks all offered systems are considered to be hard type time-critical systems.

In order to emphasise the importance of control system operation in time-critical application, we will consider several examples where the control system cannot fit strict time limits. The STS-1 space ship start was postponed because of synchronicity [32], the crash of Ariane 5 space ship happened because of not observing several time-limits [33], several crashes of Airbus 320 airplanes were caused by errors in communication system "Fly by wire". These accidents show that the time-critical system has also to be able to correspondingly react to errors. A system error must not abort its operation. In case an error occurs, the system must be able to react within a certain time period and return the operation into a certain and stable state. Solutions to these problems will be reviewed in the next section dedicated to self-organisation of wireless nodes.

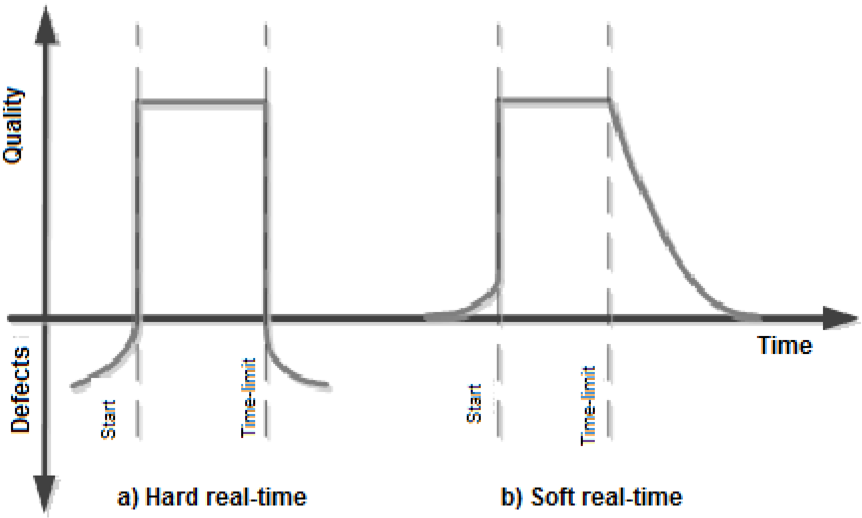

Fig. 1.2 Specifics of "hard" and "soft" real-time systems.

Indeterminate system behaviour can be caused by a number of factors: architecture specifics (data cache memory usage, conveyorization of control commands, interruptions, etc.), algorithmic peculiarities (scheduler of tasks, communication delays, etc.) [12]. One can see that communication can also influence system determinacy. As the cache memory and conveyorization are not used in small built-in systems, communication becomes the main source of indeterminacy. In cases when divided control algorithms are used, indeterminacy is especially critical.

1.3. Features of Time-Critical Tasks and Problems of Data Transmission

The important role of communication stability in time-critical systems has been described above. In these cases, delay and stability become the main communication quality features. Let us define the limits admissible for these delays. Delays that are easier to feel are connected with human sense organs (hearing, eyesight). Sound and video shared insynchronity can be up to 80 ms that is already achieved using existing wireless technologies without application of special algorithms.

The situation is different in the sphere of production of automated control systems. As we can see from Table 1.1, in a number of applications maximum admissible delay is only 10 milliseconds. In several applications (for example, movement control), this delay must not exceed 3-4 ms. Further, it is shown that the wireless sensor system developed by the author is able to process over a hundred of wireless sensors with delay of only 3.3 ms. Moreover, data receipt stability is within the limits of 12 microseconds; and the system is easy to scale. This has been proven using this system in STRATOS project implementation.

Table 1.1

Industrial Application Demands to Delays [23]

Application sphere	Application	Maximum delay (ms)	Cycle time (ms)
Production automatics	Local equipment control	10..20	20..30
	Global control	20..30	30..100
	Diagnostics and supervision	>100	>500
	Safety of mobile operators	10..20	10..30

As transfer delay is considered to be one of the main parameters in time-critical applications, we will review how delay is formed in wireless data processing systems. In Fig. 1.3, it is possible to see that the first data delay is formed at the stage of physical sensor measurement processing. It is followed by data processing and preparation to sending. Data are placed into module radio memory and the transmission procedure is started. Depending on a medium access method, the transmitter can start a translation procedure immediately or after some period of time. When transmitting data, there is a medium delay, which is limited by the speed of radio wave distribution equal to velocity of light. After receiving a signal, the receiver relocates information from the radio module memory to the main memory where data are accessible for processing. All the mentioned delays are static and do not change in time except for medium access. There are a number of medium access algorithms, the greatest part of which before transmission always waits for time defined by a random-number generator. This directly influences the total transmission delay.

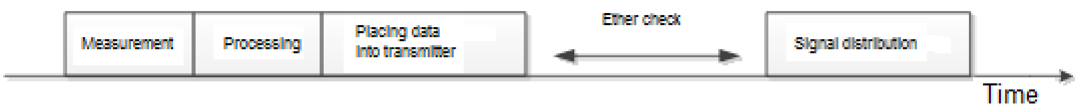

Fig. 1.3 Measurements of transmission delays.

In Fig. 1.4, it is possible to see that the delay is evenly distributed within the limits from 7.5 to 17 ms. This testifies that the main role in delay is played by random numbers. In general, it means that it is necessary to search for medium access protocols that are suitable for time-critical tasks and do not contain random number components. In the following chapters, the existing protocols will be reviewed and a new medium access protocol will be proposed.

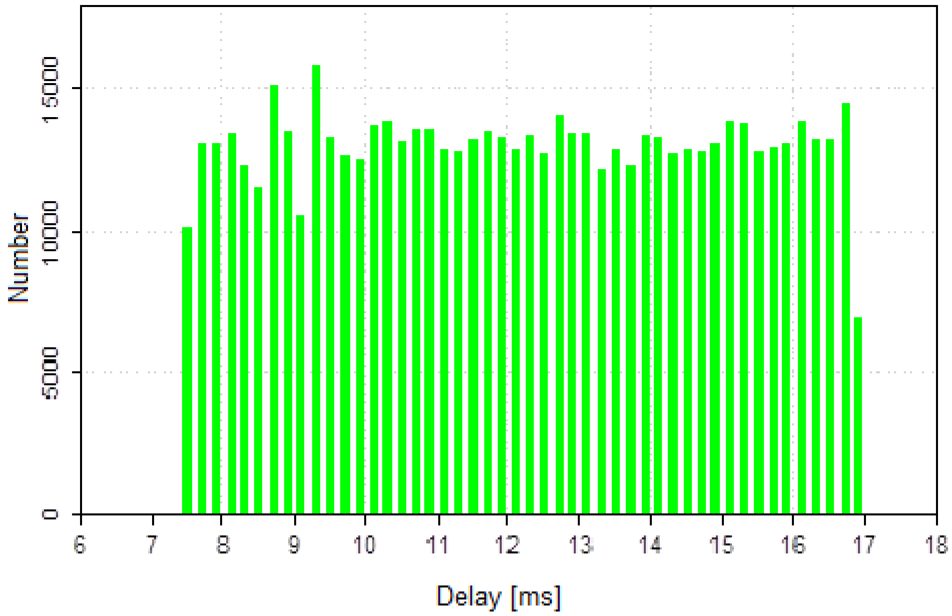

Fig. 1.4 IEEE 802.15.4 CSMA network transmission delay — a typical column diagram.

Of course, safety and security are also important data transmission requirements. The last chapter includes the review of safety and security tasks and problems, and also provides possible solutions to these problems.

1.4. Analysis and Classification of Time-Critical Systems and Transmissions

Considering time-critical systems, it is possible to divide into classes both systems themselves and their generated data flow. Data flow division into classes is often used in widely spread applications both in office and at home. In such applications, usually voice or video stream is separated from other types of packages (HTTP, e-mail), for which delays are not so critical. One of the main problems is to automatically identify the type of a sent package and to appropriate the corresponding priority not decreasing the speed of data transmission. As in such type of applications usually bandwidth is sufficient and the admissible delay border is higher than for industrial type of applications (Table 1.1), it is sufficient to create a row of packages and place the priority package at the beginning of the sending row in order to fulfil the requirements of time-critical applications.

In industrial applications, transmission bandwidth is limited and the value of admissible delay is much lower. But as data packages can be labelled immediately after their generation, the central problem is to ensure the sufficient data exchange speed not exceeding the admissible delay. In order to have a further possibility to formalise a transmission system in general, we will try to formalise and classify delays and the place of its origin.

In order to define the maximum admissible delay time, it is necessary to know the requirements of a particular task or its class. Reviewing actually existing industrial control systems, it is possible to conclude that during their designing no studies of controlled system have been conducted and the value of admissible delay has been defined heuristically. It is admissible in the greatest part of applications as in practice the control systems with a great reserve of reaction time are chosen.

In order not to waste control system resources when choosing the minimum sufficient system high-speed it is proposed to express the admissible delay time summarising the frequency of state changes for the control system and the controlled object. In order to evaluate numerically the frequency of state changes of the controlled object through discrete sensors, it is sufficient to get the number of its active state changes in one time unit. It seems to be impossible to do the same with analogous transmitters as their values are continuous, i.e., defining an endless number of states. However, when operating with real control systems, there are several things significantly limiting the number of evaluated states. Conducting the research and analysing several dozens of control algorithms of time-critical systems used in practice, it has been concluded that they can be divided into the following classes. In the largest part of control algorithms analogous value thresholds are used. It decreases the set of large analogous value states to

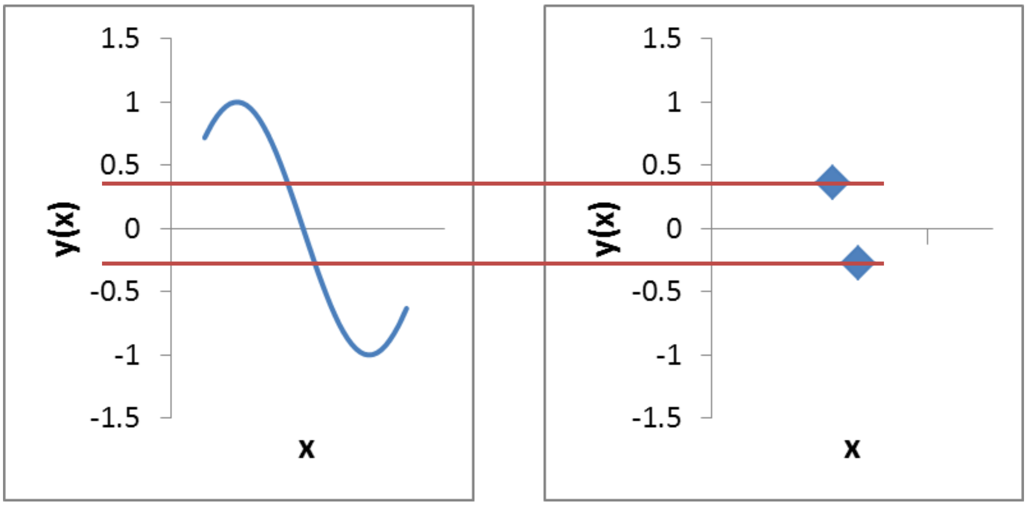

Fig. 1.5 Transformation of analogue signal in a two-points set.

two points, usually these are min/max values (see Fig. 1.5) or a certain point with hysteresis. In this case, it gives a possibility not to consider input signal changes if they do not reach the defined points. The second set includes cases when the control algorithm uses an analogous input value as a feedback. In this case, there are several variants how to define the minimum necessary frequency for processing analogous signals. Firstly, several control algorithms (for example, proportional-integral-derivative control [15]) have their internal cycle time (in a proportional-integral-derivative algorithm — the minimum/shortest integral/ differential time constant), then the necessary frequency corresponds to the algorithm cycle time. In other cases, we can introduce limitations on useful frequencies of analogous signal. The simplest way is not to consider high frequencies of a signal that reflect insignificant signal fluctuations. In practice, it is implemented by installing a hysteresis value.

1.5. Conclusions

The first chapter proves the topicality of the Doctoral Thesis. Wireless sensor node architecture specifics have been examined, as well as difference from existing wireless networks (e.g., IEEE 802.11). The research area has been limited by using data transmission delay time as a main parameter. Specific examples of time delay have been described. Moreover, an approach to time delay evaluation and lowering control time requirements has been proposed.

2. CREATION PRINCIPLES OF TIME-CRITICAL AND WIRELESS DATA TRANSMISSION SYSTEMS

While designing a time-critical system, it is needed to understand its functional parameters. By knowing system formal description, it is possible to define precise transmission parameters (e.g., transmission phase, duration, interval, etc.) and to classify them. Classification allows not only defining specific parameters, but also adopting transmission basic principles (radio frequency, spectral bandwidth, media access, etc.).

2.1. Description of the Existing Formalisation Methods

There are several methods allowing the formalisation of a time-critical control and data transmission system. The greatest part of them has a feature to pass through each of possible system states under the defined conditions. This can guarantee a high credibility degree of the obtained result. But to obtain such a result, large calculation resources are necessary that limit the number of systems that could be formalised. Designer of such systems usually considers a simple control system with a small number of states. But even in these cases the proposed method is not always able to obtain the result.

As the first method we will review a time-critical control system modelling method and tool — UPPAAL [57]. It is often mentioned in scientific papers [60] and is distinguished by good usability for testing transmission systems. It is based on the time automata theory. UPPAAL has gained its popularity mainly because of a specially prepared tool that allows creating a system model in the graphic environment. This tool is one of those used and developed during a long time period (UPPAAL since 1995).

Although the efficiency of UPPAAL and other tools is proven by their long-term and wide usage, they still are not ideal. We can single out several problems that could be important when using them in research. As one of them we can mention high resource consumption of an UPPAAL [57] tool when working with large systems [27]. The researcher needs to find a balance between the accuracy of the modelled system and the processing speed. In real systems, it is difficult to tell, which processes can be united in order to simplify the model.

The so-called time game theory (*timed games* [13]) methods were used to cope with the space of exponentially growing states. Studying time-critical behaviour of objects in circumstances of uncertainty (typical of real life), time game algorithms are able to check both good and bad model scenarios.

In Figure 2.1, the visible regions show the time automaton behaviour in the final abstract way. With this regional time automaton it is possible to save such parameters as attainability and safety. Actually, it is an original time automaton with information on "price" changes between changes of states. Moreover, algorithm complexity is a PSPACE-full task and its analysis is more difficult compared to classic time automaton.

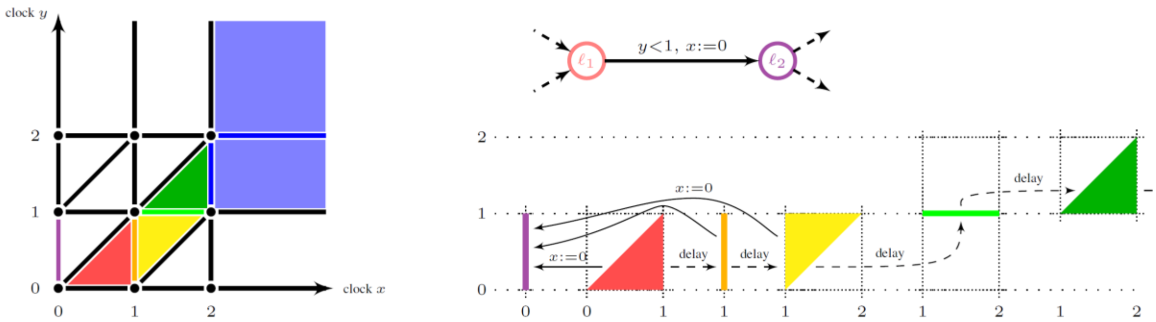

Fig. 2.1 Visualisation of an abstraction in timed automata [10].

Summarising the algorithms considered above, it is possible to see that they have several problems connected to limitation of the modelled algorithm types, their modelling accuracy and general modelling possibility. A number of verification and modelling tools have a state set "explosion" problem when the state set grows exponentially together with the linear growth of model components.

As one of solutions to the previously mentioned problems during last few years there were separate works using the already known scientific basis but applying it in a new sphere. As an example, it is possible to view a data flow in the network with a liquid dynamic model. This approach is known by its ability to describe a network state at any moment unlike other models, the time of which is discrete and the step is big (especially in large systems). The problem of modelling big systems is solved using the liquid model solution with numerical methods [19]. Stepping aside from the discrete space it is possible to simplify a model and work with it. The next chapter shows how to use a nonlinear dynamic system theory for creation of a time-critical wireless data transmission system.

Designing a time-critical system and improving the present one, we should know its functional and structural principles. Knowing system parameters and functions, it is possible to accurately customize data transmission fulfilling the definite demands. Obtaining a system formal description, we can not only set direct transmission parameters. Dividing systems into classes, we can choose not only separate transmission parameters but also basic transmission principles (radio signal frequency, bandwidth, modulation; network access method, routing method).

2.2. Proposal of Methods for Evaluation of System Dynamics

As we can see from the previous chapter, the current methods mainly use discrete methods not changing in time. In small modelling systems like UPPAAL [57], where the number of possible states and inputs is not large, it is possible to test absolutely all system states. Though it is obvious that the check of all possible states requires a lot of time and often this task is not possible to accomplish if calculation resources are not sufficient. To avoid the problem, in other approaches the volume of tested data is limited leaving only parameters characterising an input data flow and the entire system state. Row theory can be considered as an example. For its application, it is sufficient to describe statistical parameters of input data flow, system maintenance time and row capacity (if it is used). This simplifies the system check but it is not sufficient to check stable transmission operation in any state and describe system behaviour with sufficient accuracy at the variable input flow. However, the proposed method will allow analysing dynamic features of transmission system, determining critical situations, freely operating with system components searching for possible solutions to problems.

In order to prevent problems related to the methods described above, it is proposed to use a dynamic formalisation method. In this situation, an input data flow is viewed as a continuous signal with variable amplitude and frequency. In order to transfer from discrete values (data package length and its receipt moment), they are transformed so that package length becomes a signal amplitude and the interval between packages becomes the second parameter — continuous time. The application range of the described methods is limited by applications where data flow corresponds to continuity criteria. In other cases, it is easier to examine the system using the classical row theory methods.

Data flow continuity is expressed by two criteria: interval between packages and their length (time necessary to receive a package). For data flow to be continuous the interval should be smaller than package length. Another applicability criterion is object similarity to the Hammerstein model. Let us consider how we can formalise a real and complex system. From experience, it is known that most objects existing in nature have nonlinear and dynamic character. It is difficult to formalise objects of this type as in this case we need to use a nonlinear system theory. In order to simplify this task, it is proposed to use the Hammerstein model [22], [64]. Applying decomposition of static parameters, it is possible to calculate an input signal from any input signal. For dynamics processing differential equations are used. Model identification occurs in frequency space. As a result, object features can be described by a small set of parameters; moreover, each of them is possible to evaluate experimentally.

According to the Hammerstein model, we will divide a nonlinear dynamic object, hereinafter NDO, into two parts: nonlinear static — ND and linear dynamic — LD. Logically united data flows in the form of x_0 analogous signal are supplied to the system input (Fig. 2.2).

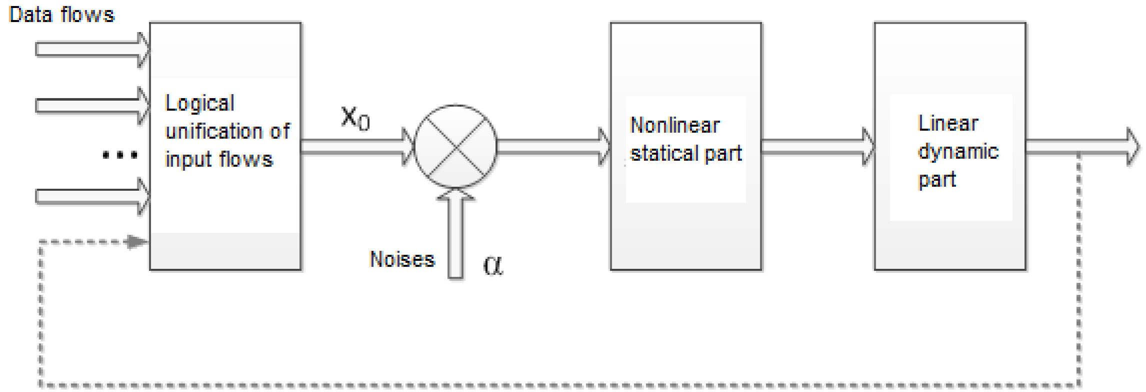

Fig. 2.2 Block scheme of the proposed system.

Together with noise α, the signal is supplied to the first stage of the Hammerstein model:

$$X(t) = x_0 + \alpha \tag{2.1}$$

As the NS part of the Hammerstein model changes the spectrum of input signal, the output reaction of the system is actually the LD part reaction to nonlinear deformed signal. Deformations depend on the chosen operation zone, i.e., signal amplitude and deviation.

Thus, the following questions should be answered:

1) What are the parameters of LD part input signals?

2) How to separate LD reaction only to test signals?

3) How to choose a signal operation zone?

It is possible to extract system nonlinearity applying linear regression to system input-output signals. The curve can be divided into two parts: ideal curve and nonlinearity (2.2). Analytically it can be expressed as follows:

$$y(x_i) = ax_i + b + e(x_i), \tag{2.2}$$

where e(x) — is the difference function that contains all nonlinearities.

In order to get a universal NS part specification, it is proposed to apply the Fourier transform to e(x) function (on condition that it is integrated). The resulting sum of sine curves is divided into two addends: the significant part and the remainder ε(x).

Parameters are amplitude, frequency and phase of the i-th component. The number *k* of significant components (sine curves) should be chosen corresponding to the desired accuracy. Transforming NS part output signal into a system with one linear and *k* sine curve components, we get NS part reaction to input signal:

$$y(t) = y_L(t) + \sum_{i=1}^{k} y_i(t) = \sum_{n=0}^{N} c_n \sin(n\omega + \gamma_n),$$

$$y_L(t) = (ax_0 + b) + (a\lambda)\sin(\omega t + \vartheta),$$

$$y_i(t) = \sum_{n=0}^{N_i} \rho_{n_i} \sin(n\omega + \gamma_n), \qquad (2.3)$$

$$\begin{cases} c_0 = d_0 + (ax_0 + b) \\ c_1 = d_1 - a\lambda \\ c_n = d_n, n = \overline{2, N} \end{cases}$$

where

$y_L(x)$ — the output signal of the linear component,

$y_i(x)$ — the output signal of the i-th sine curve component,

γ_n — the n-th harmonic phase,

d_n — the n-th harmonic amplitude influenced by all sine curves,

c_n — the n-th harmonic amplitude of NS part output signal,

N_i — the last significant harmonic number of the i-th sine curve component,

N — the maximum of N_i.

Thus, in order to calculate NS part reaction to the sine curve input signal, it is necessary to fulfil the following:

- To get the characterisation of nonlinear object static input-output. It must not contain significant nonlinearity;
- To get an ideal curve using linear regression;
- To perform Fourier transform with function part of the nonlinear remainder and to define the significant harmonic border;
- Marking test signal parameters (deviation x_0 and amplitude λ), to calculate output signal spectrum for each sine curve component *i*;
- To calculate amplitude dn for each harmonic n;
- To calculate amplitude cn and phase yn for each harmonic.

In order to formalise linear dynamic (LD) part reaction to the input signal, it is proposed to start with the function of amplitude-phase frequency reactions and separate reaction function ordinates from LD part output signal. As the composite signal reaches LD part output, LD reaction will be sine curve linear combination with different amplitudes and phases. In order to calculate ordinates, it is necessary to solve minimally $M_i > N$ independent equation in each test frequency ω_l.

2.3. Conclusions

As a result, it is possible to evaluate a nonlinear dynamic object with a little set of parameters. Moreover, equations used for calculation could be solved with basic mathematical operations and therefore are easily calculated by microcontrollers [15]. As it has been proven in the first chapter, the main data transmission delay is a media access protocol. By using the proposed evaluation method, it is possible to check if a system is capable of fulfilling the control task by using wireless data transmission.

Industrial application demands are higher than in case of regular everyday wireless network usage (Table 1.1); thus, standard protocols (e.g., IEEE 802.11) are not able to fulfil these demands. Therefore, the next chapter will propose a new hybrid protocol for network media access.

3. WIRELESS SENSOR NETWORK MEDIA ACCESS IN TIME-CRITICAL APPLICATIONS

Delay requirements in typical applications are relatively low in comparison with the specific industrial applications. For example, for using voice conferences, the delay up to 150 milliseconds is admissible, while for industrial use the delay under 3.3ms (see Chapter 4.2 for details) is required for several tasks. The typical office type (IEEE 802.11) wireless network delay is around 30 milliseconds. When the number of network users grows, the delay increases to a few hundred milliseconds [45]. It is obvious that the access mechanism with such parameters cannot be used for critical applications.

3.1. Existing Network Evaluation and Definition of Critical Aspects

Let us examine in practice the current state and define the particular weaknesses in the algorithm. As the research is oriented to wireless sensor networks, the examination of the algorithm will be limited to the access algorithms that are designed for operation in the equipment with low energy and computing power. There are over ten different wireless sensor node (WSN) platforms, which use a variety of operating systems and network access algorithms. As statistical data on WSN are not directly available, the most popular access mechanisms have been defined indirectly. WSN platform operating systems have been resumed and most common network access algorithms have been highlighted.

These are: B-MAC, X-MAC, SS-TDMA [11], [18], [41], [31]. The access of first two protocols to the transmission channel is based on IEEE 802.15.4 standard, applying random numbers for network access sequencing. The choice of random numbers ("*backoff*") depends on the type of application. As the research is related to time-critical tasks, the time was set to minimum. Both algorithms were tested on the TinyOS+telosB [17] platform.

Figure 3.1 presents the delay of two algorithms by transmitting data between two points. One can see that the delay interval with equal distribution has been defined in both algorithms. This proves use of random numbers and presents the minimum possible delay time (6.8 and 8.0 ms, respectively). Taking into consideration the delay of 3.3 ms defined above, it can be concluded that it is not possible to use these algorithms for the defined tasks. Even more, the resulting delays are not determined; they vary over a wide range and are dependent on the number of active network nodes.

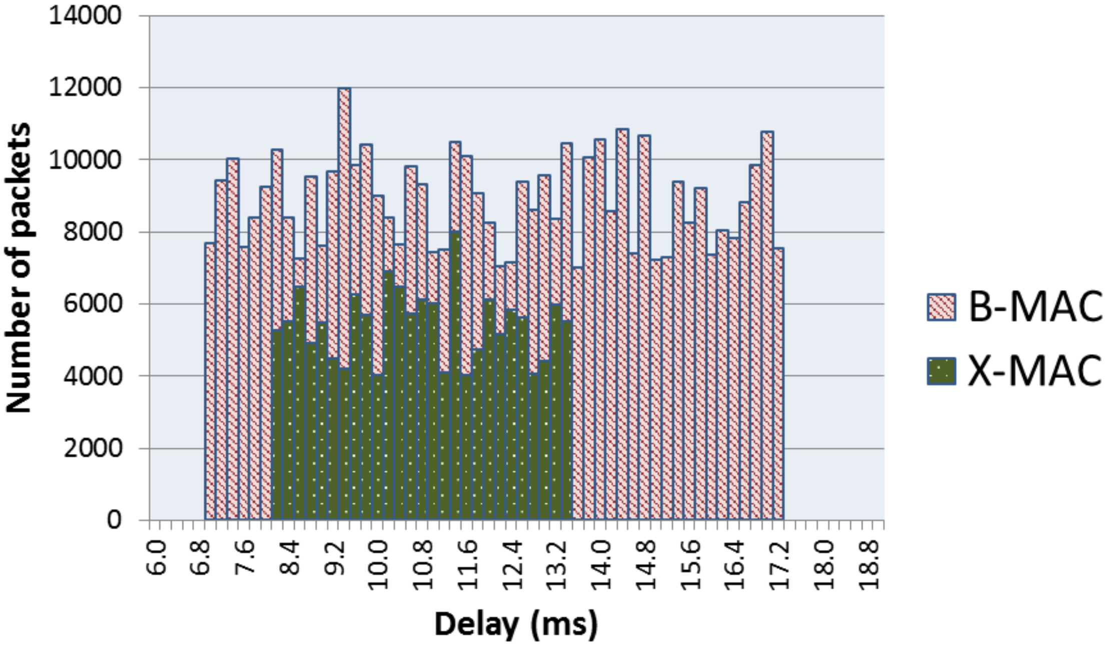

Fig. 3.1 Network transmission delay while using B-MAC and X-MAC media access protocols.

The best result, in comparison with B-MAC and X-MAC, can be obtained by the SS-TDMA algorithm as it is based on time-division principle, which is determined. All that remains is to verify the performance in the process of the real experiment. Similarly to the previous tests, the algorithm was implemented on the TinyOS + telosB [17] platform. Figure 3.2 presents the delay, which is at least three times smaller and several times more stable. One can see that the delay may be applied to the task mentioned in Section 4.2. However, the delay stability ("*jitter*") does not allow using this method directly; more information on it is presented in Section 4.2.

However, conventional TDMA has also several disadvantages. The algorithm requires strict synchronisation between network nodes and the pre-established, fixed network structure. Although TDMA network parameters are stable and do not depend on the number of users, the network utilisation (efficiency) decreases along with the network node activity. Thus, the classic TDMA algorithm is worth being used in applications, where the network structure remains unchanged and the most of the network users continuously send data. Applications that are different from the previously described ones should look for alternative solutions in order to achieve sufficiently low transmission delay.

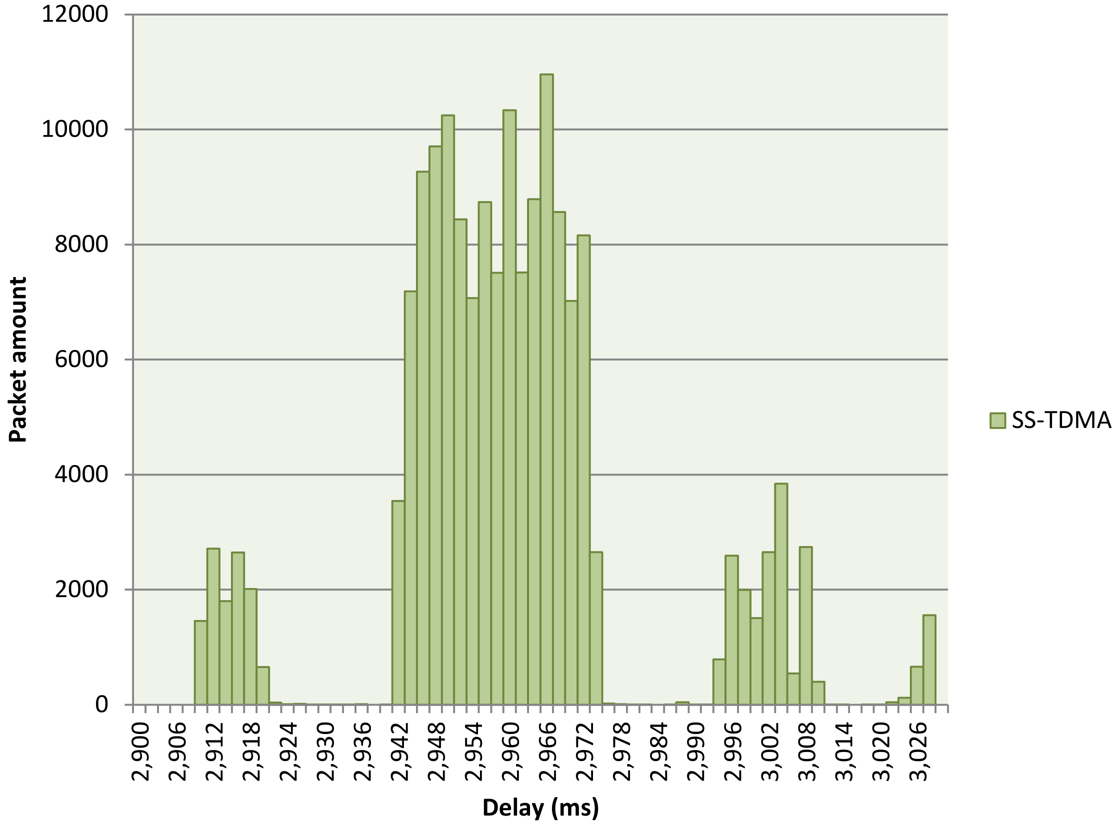

Fig. 3.2 Network transmission delay with the SS-TDMA protocol.

3.2. Proposal of a Hybrid Network Media Access Method

In order to solve the problems described above, a new network access protocol has been offered that will ensure the expected transmission delay in the dynamic environment. The proposed algorithm will combine the best features of CSMA and TDMA algorithms.

The task to devise a new network access method can be formulated as follows:

- The algorithm should ensure stable data traffic with expected delays;
- The opportunity should be provided to attract frame timeslots in order to increase the maximum number of nodes and minimise the delay;
- It is necessary to ensure connection with the routing algorithms in order to reduce data delay by sending data through a series of nodes;
- The opportunity should be provided to freely change the distribution between the Time-Critical (TDMA) and Simple Message (CSMA) types.

The network access method is presented in Figure 3.3. Data traffic is divided into frames. The frame length (duration) depends on several parameters and can be freely set. It is necessary to take into account the following parameters in order to choose the frame length: data rate, node density in space, application requirements to the delay. Each frame is divided into two parts: H-TDMA with the pre-defined transmission sequence and CSMA/CA with random transmission probability. New user initialisation occurs only in the CSMA/CA period. Their task is to synchronise the start of the frame with TDMA and to require timeslots in the CSMA/CA period. The node is allowed to transmit only in its predefined TDMA slot.

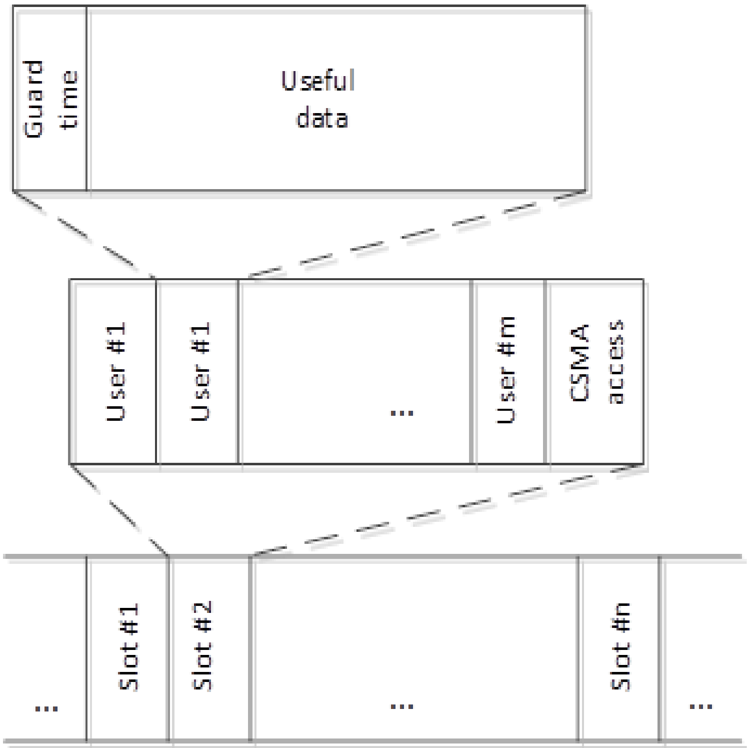

Fig. 3.3 Hybrid media access method scheme.

Figure 3.4 presents the new node initialisation procedure. The node operating conditions in the network are presented in Fig. 3.5.

In this scheme, all packets that come from a new station are transmitted only within the interval CSMA/CA to ensure undisturbed functioning of the TDMA slot. Only when the network contains vacant time slots, the new station is enabled to transmit within the TDMA interval. Stations that have already been initialised keep transmitting their data and transmit responses to the requests of a new station. The delay that will take place before the new station is initialised cannot be guaranteed or predicted since several stations can be initialised simultaneously. However, delays within this interval are not important since the mobility of stations is not high in the industrial usage. As a matter of fact, initialisation of a new station in most cases takes place with one station in case it is modified (for instance, after replacing the battery). Data of the initialised stations are transmitted as shown in the scheme (Fig. 3.5).

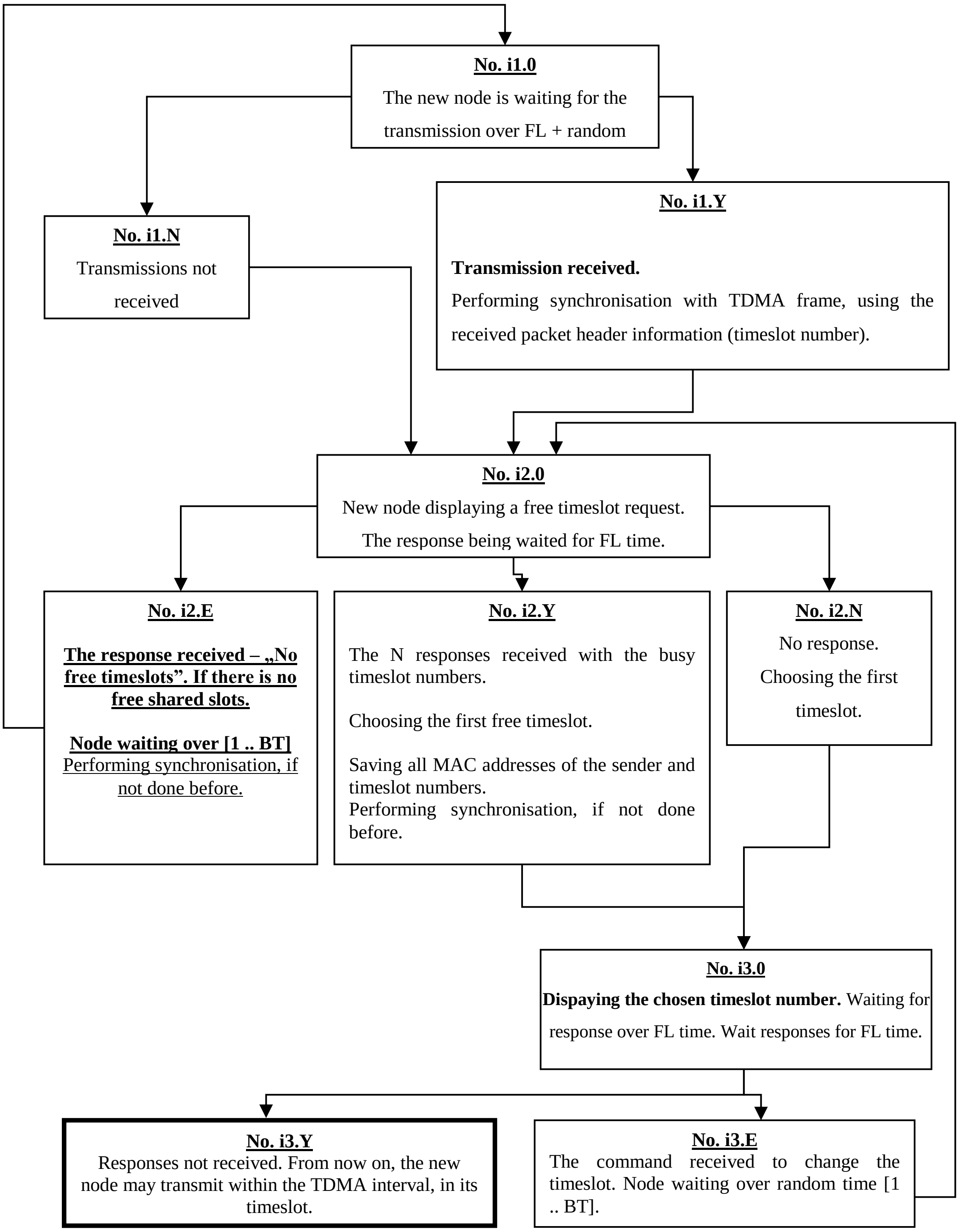

Fig. 3.4 New node initialisation procedure in H-TDMA algorithm

The basic part of the suggested algorithm has been tested in practice while carrying out the project STRATOS [52]. The results are shown in Section 4.2.

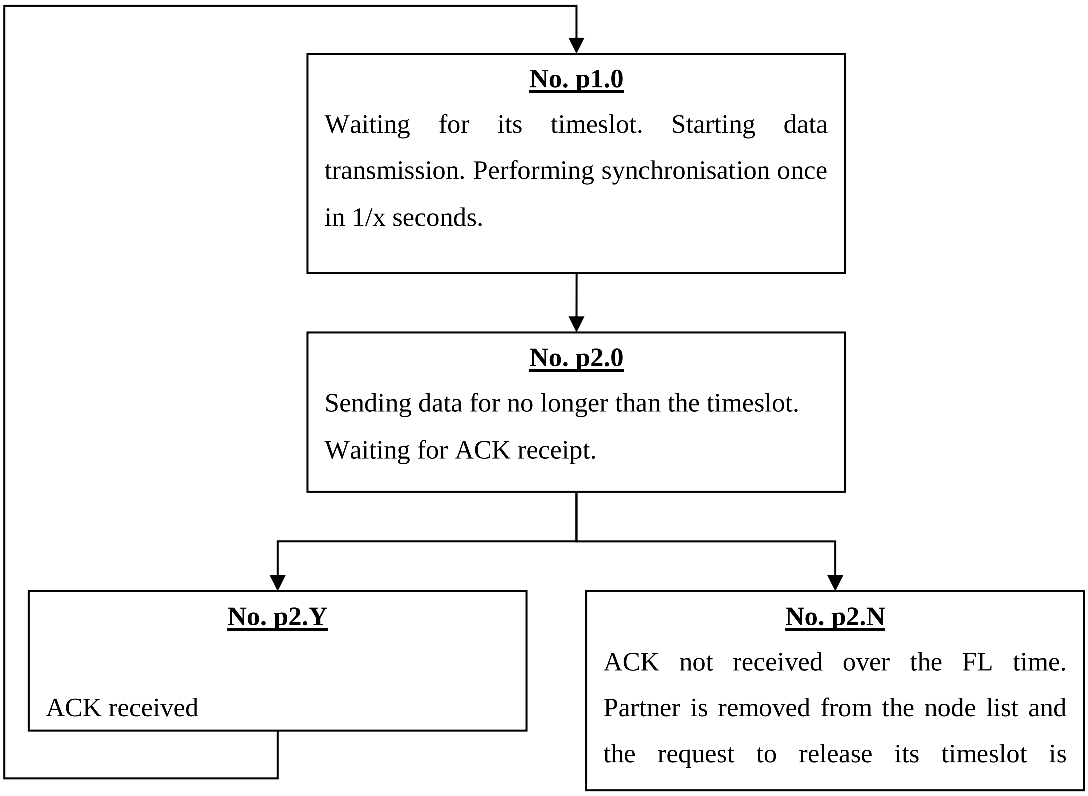

Fig. 3.5 Initialized node actions in the H-TDMA algorithm.

3.3. Issues of Synchronisation and Arrangement, and Solutions Thereof

As observed from the description of the previous method and the results of practical tests, the preciseness of synchronisation is quite important in the suggested method (as well as other algorithms based on TDMA). While using the methods where the speed of data transmission is higher, synchronisation becomes even more important, since it directly influences the stability of the transmission interval of all stations. One of the types of transmission development suggests switching to using particularly broadband signals (UWB [46], [48]). This will make it possible to reduce energy consumption and increase the transmission speed that is particularly important for wireless sensor networks since this will enable creation of autonomous systems, which will not require maintenance at all (there will be sufficient energy for several years, which will be more durable than the durability of the station itself). In order to successfully use a UWB wireless system, a reliable method of establishing the synchronisation signal (pilot signal) is needed. Eventually, it will be possible to use this approach, with a slight modification, also for narrowband signal networks.

It is known that the receiver maintains statistics of screens, integrating the performance of impulses of all screens, and synchronisation is based on the accurate definition of the moment for the signal of the receiver. At the output of the receiver, an impulse signal appears with various noise distributions and types of modulation. The inertia of resolution of the comparator and the threshold of sensitivity in detecting an erroneous signal has been reviewed. It has been proven that the probability of detecting the pilot signal increases along with the signal/noise ratio. Analytical formulas have been suggested for detecting the best threshold of the pilot signal and the comparator.

Summarising the above, it can be concluded that it is possible to successfully apply methods of the probability theory for detecting the pilot signal in wireless sensor networks. As a result, four methods have been outlined, and an analytical description has been suggested for each method. Defining the threshold of the pilot signal ,the comparator has been described analytically.

The methods described above can detect the pilot signals in UWB networks; however, forming a high-quality transmission channel is not sufficient for the network to function. The network must be not only high-speed, but also reliable. Since all possible functioning problems cannot be predicted and prevented, the system must be able to detect the erroneous position and conduct self-arrangement. The basic requirement for successful self-arrangement is a general initiation program. This program is able to improve the system behaviour, increasing the quantity of the information it contains. These functions can be carried out via the middle account or/and in cooperation with another system. The functional description of self-arrangement features was given in the paper [4] as a homeostatic pattern and the same different amplifications were specified in the papers [26], [63]. A comprehensive morphological description was given in the papers [65], [66] and it could be used for design and simulation of various dynamic behaviours. Another approach was suggested in the papers [3], [9], where the real-time systems were described using PTA (priced timed automata). There are limited opportunities for flexible and simultaneous use of the description at different system levels.

3.4. Conclusions

The suggested approach makes it possible to describe various types of systems at various levels. The stochastic automata formalism enables successful generalisation of self-arrangement in the general start program. Improving the system quality, under certain conditions, increasing the volume of information and possibilities of approach to the medium, the stochastic automata formalism, which works in the group, makes it possible to define the critical system in time or the real-time system as a self-arranging time system. The principle of self-organisation was described in paper [4] as well as in papers [36], [37], where Priced Time Automata (PTA) methods were proposed.

The chapter has presented a hybrid network media access method that combines positive aspects of time-critical data transmission along with possibilities of decentralised methods. The next chapter describes practical tests of the proposed algorithm and proves its ability to transmit data in critical manner while keeping transmission delay at low and stable level.

4. PRACTICAL USE OF METHODS AND ALGORITHMS

Before creating and planning a wireless network, it is important to describe the existing practical solutions in order to evaluate the current status and to create a support point. The planned wireless sensor network will be used for industrial needs. For this reason, networks of this branch will be reviewed first. As it has been said before, the manufacturing industry (including agriculture) is rather a conservative branch. Nevertheless, an apparent advantage of wireless networks is its ability to obtain properties of soil remotely, and agriculture has accepted this method. However, its implementation is still somewhat difficult due to high costs. Wireless sensors made it possible to reduce the costs and to increase the accuracy in comparison with weather forecast stations and satellite image processing. Nevertheless, the costs are still high and consist of a purchase price of a sensor station and maintenance expenses, as well as prices of installation of the transmitting infrastructure for the central computer and its maintenance expenses. Completed projects of sensor wireless networks and the existing standards will be reviewed below.

4.1. Review of the Existing Wireless Time-Critical Networks

In the project “Lofar Agro” [5], 150 Crossbow wireless stations distributed throughout the whole agricultural land have been used. Their data are routed from stations with the help of stations themselves to the gateway located in the field. The working cycle is 7 % of the total time. Data are submitted once in ten minutes.

The protocol PEQ [8] (*Periodic, Event-Driven and Query-Based Protocol*) is designed for industrial application and carries out data exchange with the smallest delay of 20 ms, which is sufficient for some applications specified in Section 1.2. However, the suggested protocol concentrates on low-energy consumption and its work is tested in networks with a relatively low intensity of message sending (10 Hz). The protocol GinMAC behaves similarly [53]. When used in oil refining industry, it operates with a data transmission frequency of approximately 1 Hz, in a network of 25 stations. It can be observed that in the reviewed and other applications [20], [47], the intensity of data transmission and the minimum delay do not meet all the set requirements.

Better results are achieved in cooperation between universities of California and Taiwan by whose joint effort the system EcoDAQ [14] is created. Its goal is to obtain data from electric cardiographs. The system has the following characteristics: the number of stations is up to 50; the frequency of data transmission is 200 Hz while the stations are located in the area of 1 sq. km. The author used the method of hybrid time distribution multiple access (TDMA) and a radio receiver with a data transmission speed of 1 Mbps. This meets the delay requirements specified in Section 3.1; however, the next section reveals a broader area of application, which requires even better characteristics.

Reviewing the current status [38], [40], [61] in industrial wireless network standards, three standards can be outlined: Zigbee, WirelessHART and ISA100. The basic idea of these standards is to offer specific algorithms and protocols for using a wireless network for industrial needs. All these standards are based on the standard IEEE 802.15.4 and, thus, use its performance and the delay amount. The delay test results of the standard IEEE 802.15.4 can be viewed in Section 1.3. Although the classical application of the standard does enable creation of a wireless network with the needed delay rates, the features of the said protocol are worth reviewing.

Along with WirelessHART, the ISA100 standard group is destined for close integration with existing industrial standards and applications. ISA100 provides an opportunity to transfer also other protocol packets, creating a virtual "tunnel". The standard also includes safety aspects and the ability to define message priority classes. All this makes it possible to quickly embed the wireless network in the existing infrastructure. Despite the fact that ISA100 uses the standard network access mechanism, which is different from IEEE 802.15.4, its delay factor is not small enough in the work in order to achieve the set target. The developers of the ISA100 standard define it as follows — "This standard is designed for applications with a 100 ms delay" [28].

6LowPAN and Zigbee standards have not been investigated in detail, as they offer extra functionality at the highest OSI model levels and are based on the IEEE 802.15.4 standard. Thus, they are inheriting its performance and the delay factor [16]. In turn, the IEEE 802.15.4 standard delay test results are presented in the previous chapter.

One can see that none of the existing standards and practically implemented sensor networks can resolve the task defined in the Doctor Thesis as the delay time is too large.

4.2. The Implementation of Wireless Network Access Protocol

One of the tasks of a wireless sensor network is to collect and transfer the measurement results to the central node. In low-power sensor networks (IEEE 802.15.4) the data transmission cycle is traditionally measured in seconds or even hours. The introductory chapter shows that in industrial applications the data rate may reach up to 100 Hz (with 10 ms delay). Looking at the existing networks [5], [8], [53], it can be observed that the options are not sufficient. This Thesis presents a solution that will enable collection of data at a frequency of up to 300 Hz. The proposed wireless sensor network reduces energy consumption for nodes to be able to work completely autonomously. The offered system has been tested in practice during the FP7 project. The STRATOS [52] project is aimed at increasing the agriculture efficiency.

As a result of this project, a wireless sensor network with 140 nodes was developed (see Fig. 4.1). It is capable of collecting data in real time at a frequency up to 300 Hz and it is a challenge to low-power computing wireless networks. This is particularly challenging because these nodes have to save as much energy as possible, as they use autonomous power supply. The selected measurement frequency is related to the speed of the agricultural equipment (e.g., tractor). Wireless sensors are located on the tractor trolley and must be able to collect data while in motion and send them to the central node in the real time.

Together with the network access protocol, the structure of the wireless sensor

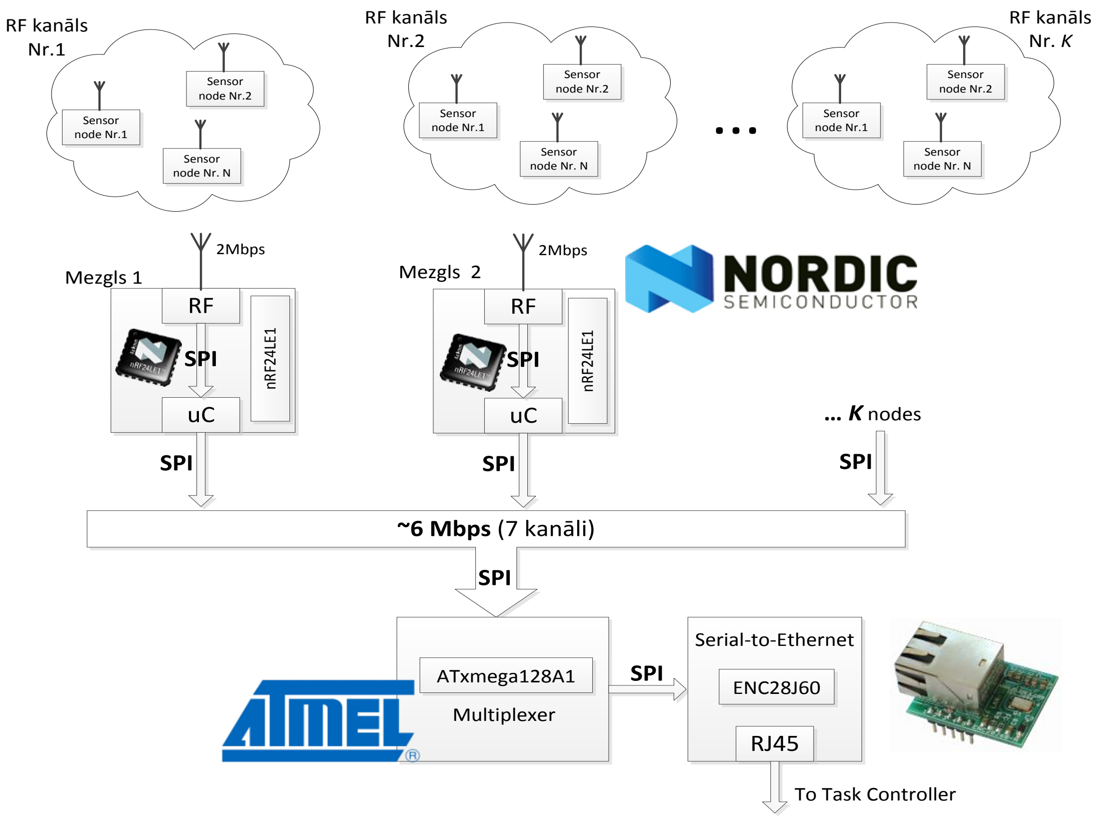

Fig. 4.1 Overall system diagram.

network is described, the connection to the rest of the STRATOS [52] project components is explained, and the environment access method is defined and tested. The network can be used in other fields where data transmission within critical time limitations is needed.

Since the task defines the need to reduce the energy consumption, various existing data transmission technologies have been analysed and the direction with the lowest consumption has been selected.

Devices that are based on WiFi (IEEE 802.11) standard sets do not meet the requirements for energy consumption; in comparison with the IEEE 802.15.4 standard equipment these devices may exceed the energy consumption 20 times. The power source node will be low-powered and without additional equipment it will be unable to provide the required instantaneous power consumption. If two low-power data transmission protocols IEEE 802.15.4 and IEEE 802.15.1 (Bluetooth) are compared, it can be observed that, despite the higher data transmission rates (from 1Mbps to 250kbps), only eight nodes can work in the standard Bluetooth network. If the standards are compared with energy consumption (mJ/MBytes), it is evident that in case of WiFi and UWB (IEEE 802.15.3) it is the lowest. The size of the data transmission is only a few bytes; therefore, the UWB/WiFi standards will not be superior. In addition, the IEEE 802.15.4 standard is less complex [30], which will make it possible to use a microcontroller with a weaker computing power, which will reduce the energy consumption.

As a result, a network was developed and it was based on the IEEE 802.15.4 standard for which the proposed algorithm was used at the network access level. The scheme can be seen in Fig. 4.1. In practical network testing, it was concluded that the proposed solutions were not perfect and there were several problems to be solved. In order to achieve the required measurement frequency (300 Hz) and the total number of nodes (140), the entire available ISM band (2.400 to 2.485 GHz) was used in the beginning. After verifying these settings in the actual environment, the problems of installation were detected.

During the experiments, approximately 2 % of the packets were lost. To check the error source, an external test tool was used. This made it possible to save all the outgoing packets, even if the checksum was incorrect. This leads to the conclusion that the existing WiFi networks interfere with the sensor network. Since all the available bandwidths are occupied by the parallel channels of the sensor network, there is no possibility of sharing the network by the frequency range.

Along with the radio signal interference, there were problems with the quality of synchronisation. This led to a relatively large use of the guard time and consequently increased energy consumption. The solution to the problem is presented below.

The current radio modulation technique uses 2MHz channels with 3MHZ protective band between the channels. Figure 4.2 illustrates how inefficiently the band has been used. In order to increase the efficiency, another transmission technology was chosen based on the GSFK signal modulation method. Consequently, the protection band between the individual channels is not required.

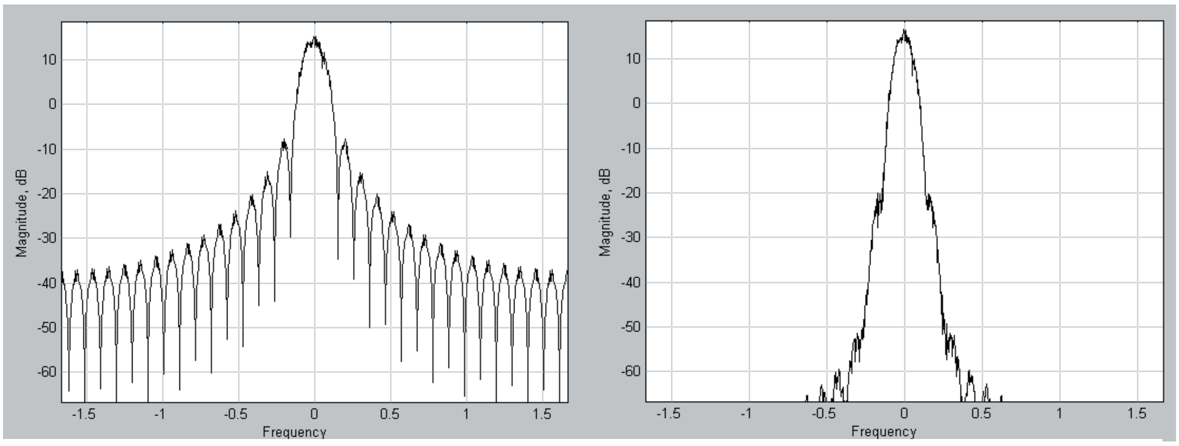

Fig. 4.2 The existing (left) and proposed (right) signal modulation spectrum.

When improving the effectiveness, seven channels occupy only 14 of the total 85 MHz ISM range, so two WiFi channels (Fig. 4.3) can function without interference and they do not disturb the operation of the sensor network. Figure 4.1 contains the overall system diagram, starting with physical sensors to task controllers (TC). For connecting the sensor node

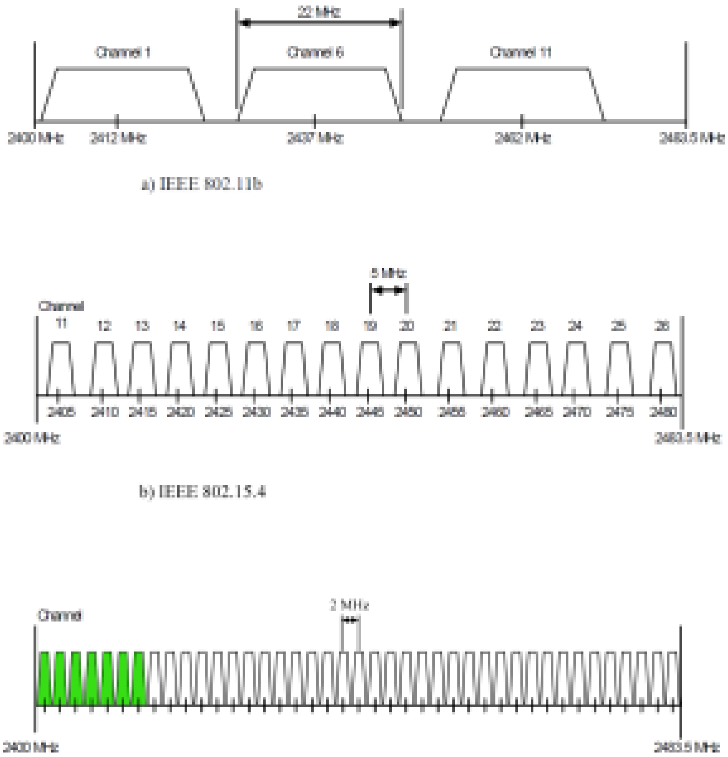

Fig. 4.3 Bandwidths used for three networks.

and the task controller seven nRFGo nodes are used, which function as TDMA conductors. Each node gathers data from its local groups (one frequency channel). Since the nodes are separated by frequency, there is no interference between them. Atmel ATXMEGA128A1 is used as a multiplexer, which collects data received via SPI from each TDMA node. Project partner institutes have examined the intermediary devices (multiplexer and Ethernet converter) and reported on their ability to deliver the required 6 Mbps traffic.

4.3. Wireless Network Simulation Using the Time-Critical Access Algorithm

The network implemented during the STRATOS project requires no less than 140 nodes; it is rather difficult to test such a large network. A network simulation method was used, which was verified with the actual network in a scenario with four nodes.

When choosing the modelling tool, which was supposed to test the network access method, three programs were considered: ns - 2/3 [35], OPNET [37], OMNeT++ [36]. As a result, the Castalia tool (OMNeT++ extension) was selected, which is light enough for training and makes it easy to start the work. Along with that, it has all the features that are planned to be verified in the modelled network, for example:

- The ability to create a radio channel model based on the actual measured data;
- Radio equipment models that are created using the real microchip basis;
- The link with the actual physical size sensors;
- Node time crystal inaccuracies and modelling of the node energy consumption;
- There are several MAC and routing protocols available.

The activity of OMneT++ Castalia simulator was tested and, as a result, the sensor network model was created with 9 channels (groups), with 17 wireless nodes in each. This model shows wireless network structure of the STRATOS project.

To achieve the desired compatibility, the existing equipment model was supplemented with additional features that simulated a delay of data transfer between μCPU and the radio node (see Fig. 4.4).

The delay is calculated using the amount of data that are supposed to be transferred and the data transfer speed of SPI bus. When verification of delay was performed with the actual device, an additional constant delay was added to the model which created time of interruption processing.

As a result of all the changes, differences between the model and the realistic measurements did not exceed 0.2 μs, which accounted for less than 0.15 %. This test led to the conclusion that the model was realistic and could be performed in full network tests.

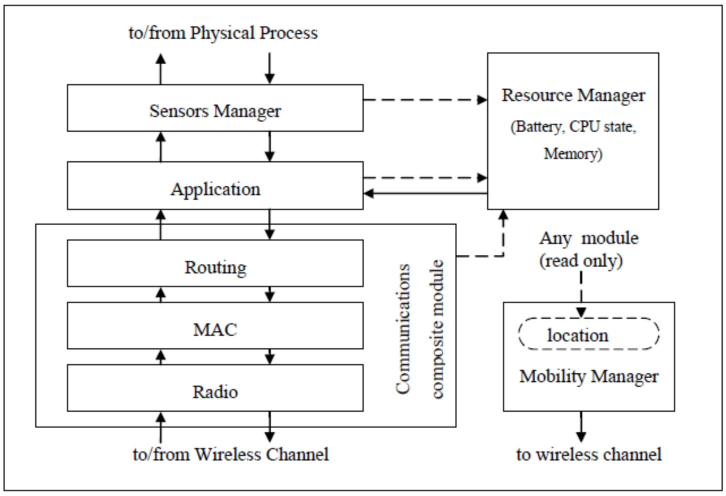

Fig. 4.4 OMnet Castalia network model.

In full network tests, several problems were immediately discovered that could not be foreseen when working with real nodes in the incomplete network. The problem was that the last node in the frame was at times unable to transmit its data. The reason for this was a time crystal inaccuracy ("drift"). The crystals, which are used in time-making are not ideal. The inaccuracy of one node is low when compared to the timeslot duration (1 μs compared to 133 μs). However, when 17 nodes transmit one after another, the total error can be greater than the established protection interval between timeslots (12 μs). The test results showed that the node equipment parameters had an important role in ensuring the TDMA protocol quality, e.g., the accuracy of quartz crystals, the delay of radio node transmitter frequency assembly etc. This leads to the conclusion that the pattern formation is strongly related to the specific equipment, as their influence in TDMA-type algorithms is significant.

4.4. The Formalisation of the System in a Real Industrial Facility

The network access principle and the system formalisation method, featured in Chapter 2.2, were tested in a real object — in the Finnish wind flow tunnel [59]. The existing system has been developed using nodes connected only with cables. Since the system was in the stage of construction, it was possible to test the applicability of the proposed methods without interfering with the use of the system.

Overall, there are 143 discrete and 37 analogue management signals in the management system. In addition, 84 discrete signals are separated from the central management system and form a distributed control system. Together with this, the management is connected with the visualisation system, which implements the higher-level management functions, using 24 analogue values and 260 discrete signals.

Sensors were divided in two classes: discrete (end switches, buttons, starter status, etc.) and analogue (flow meter, speed, etc.). In order to evaluate the changes in the object status through the discreet sensors, it is sufficient to obtain the number of changes in active status in one time unit. It seems impossible to do the same thing with analogue transmitters, because their values are continuous; they can define an infinitely large number of states.

However, when operating with real management systems, there are various aspects that significantly limit the number of states assessed. As it has already been stated in Section 1.4, it is the discretisation of analogue values, which eliminates the problem of infinite state sets. In practice, the number of discretised values is defined with 8 to 16 bits [49]. To further reduce the value of the analogue value state set, the management algorithm has to be assessed.

To obtain specific numerical values, a 34-channel logic analyser *Intronix* was used [1]. During system operation, it was consecutively connected to inputs and outputs of the existing control system. In order to balance the voltage (24V) with the logical analyser threshold (15V) a simple resistor voltage divider is used.

Table 4.1.

Parameters of the Industrial Object (Wind Tunnel)

Input type	Signal description	Frequency type	Max frequency (Hz)
Digital inputs	Operator controlled push buttons	Active state changing frequency	2
Digital inputs	End switches	Active state changing frequency	5
Digital inputs	Encoders	Active state changing frequency	50
Digital outputs	Various	Active state changing frequency	35
Remote station digital inputs	Valve position (opened/closed)	Active state changing frequency	0.05
Remote station digital outputs	Valve position change command	Active state changing frequency	0.05
Analogue inputs	Various	PID algorithm time constant	110
Analogue outputs	Various	Variable frequency drive parameters	150

Furthermore, there is a closer description of each of these blocks. The system input is located at the flow combination unit. Their structure is shown in Fig. 4.5. Taking into account the formalisation schemes, the critical points of the system were obtained.

It has been found that the assignment of sensor groups must be changed in order to separate the signals with wide frequency among different sensor groups. They are signal models of encoders and analogue outputs to frequency converters.

During experiments a lot of statistical material was obtained, which had to be quickly processed to verify the results and adjust the parameters of the next tests. In order to accelerate and facilitate this process, a "FRAD" template on "R" [6,56] language basis was used. FRAD — "Fast Result Analysis and Display" — is a template for automated data visualisation and analysis.

The workflow is simplified to a minimum: copy the data → run the script → get the graphs. The template consists of "R" script files, parameter files, script, run of analysis, the log creation.

Possible tasks that can be performed with the FRAD template:

- quickly obtain the summary of data;
- visually compare data (data string, histogram);
- analysis of large data,
- publication of the results, taking in account requirements of formatting.

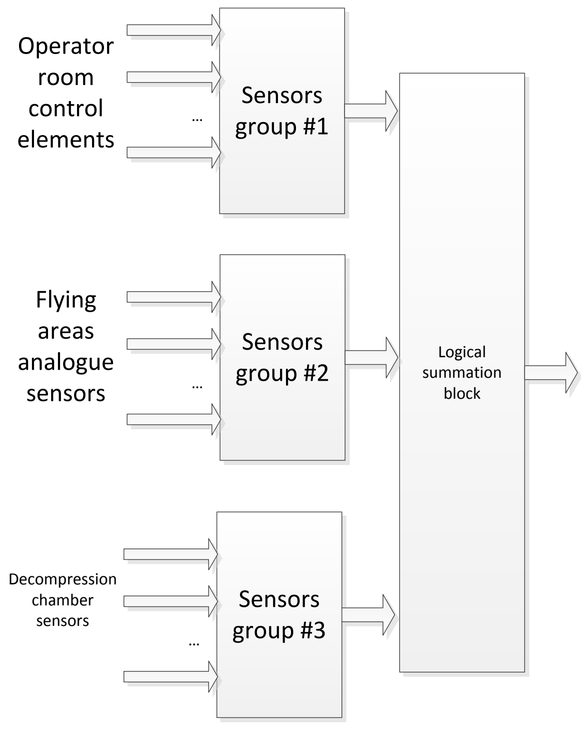

Fig. 4.5. Logical integration block.

The developed tool has been successfully applied to the analysis of the existing tests and in the German Research Institute "ifak" daily trials. As a result, the processing time has been reduced and, as FRAD is an open product, which can be used for free, it can be used by all partners of the Institute to obtain the results and create a single work process.

4.5. Conclusions

The chapter presents the results of wireless network testing that affect practical aspects of the networks. In the beginning, the existing industrial networks have been presented and their problems described.

To prove efficiency of the proposed hybrid method, both practical testing in the laboratory and simulation approach have been used. The simulation program has been improved by implying real hardware parameters. Final algorithm testing has been performed at real industrial facility — wind tunnel. For extensive data analysis a new processing algorithm has been proposed and used.

5. PROBLEMS AND SOLUTIONS TO THE WIRELESS NETWORK DEVELOPMENT AND IMPLEMENTATION

Industrial applications of wireless networks can be used not only for transmitting obtained measurements, but also for managing the facilities. Thus, wireless networks must provide the communication quality requirements. To be able to do experiments and quantitative evaluation of wireless network communication quality, the following criteria have to be taken into consideration: latency, packet loss and jitter.

5.1. Wireless Network Performance Analysis in Industrial Environments

For each predefined test the criteria values were determined using the equipment "Multiface" (Fig. 5.1) specifically designed for this purpose [34]. Packet loss was partially merged with latency. The packet is considered to be lost if the time limit is exceeded (5.1).

Therefore, packets are defined as follows (5.1) :

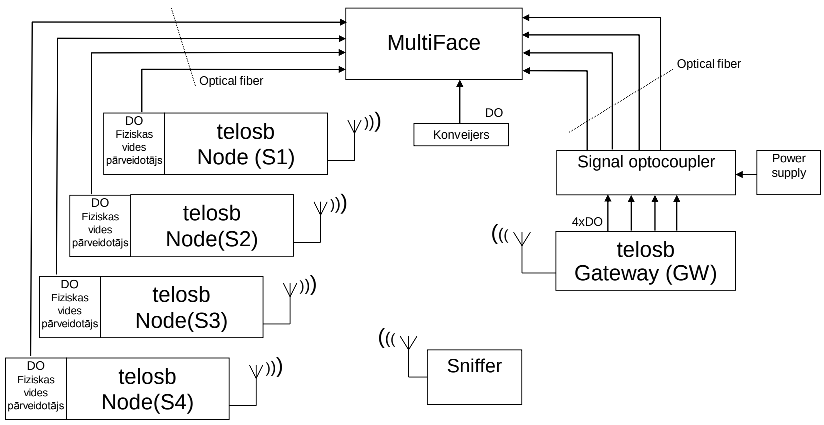

Fig. 5.1. Wireless network test setup.

$$N_{Rx} = \sum_{i=1}^{N_{Tx}} f_{Rx}(i),\ f_{Rx} = \begin{cases} 1: \forall t_{TT_i} \le t_{TT_{max\,UL}} \\ 0: \forall t_{TT_i} > t_{TT_{max\,UL}} \end{cases} \quad (5.1)$$

The test group contains two main subgroups: the scenarios with the moving nodes, where the impact of the motion speed is evaluated, and static node scenarios where different environment conditions and transmission modes are tested. In all the tests routing options are allowed.

Figure 5.1 illustrates the type of equipment connection. There are four senders and one receiver. The optical fibres are connected to the "MultiFace" equipment. Packet receiving timing is recorded with the “MultiFace” equipment according to the signal generated in the *telosb* node.

Brief summary of the test results: (full description can be found in the Thesis). Based on the available literature [29], the instability of frequency was analysed. Two nodes were tested, the recipient was outside the temperature chamber, and the sender was placed in the chamber. Their performance was tested at 20 ºC and 70 ºC. The difference of the defined criteria was below 1 % and a shift in transmitter centre frequency was not detected, suggesting that the nodes functioned steadily within the given temperature range.

Another test examined wireless communications in humidity. In wireless users’ comments it can often be heard about communication problems due to bad weather [39]. Since in production facilities humidity is sometimes possible, it is worth examining its impact on wireless communications. The experiment was set up similarly to the temperature test, but in this case the chamber was instructed to maintain 90 % RH humidity without condensation. No deterioration in the quality of communication was detected.

Quite interesting results were obtained by checking the electromagnetic noise effects on the quality of wireless data communications. German Electrical and Electronic Equipment Manufacturers’ Association published a study on coexistence of wireless communications, which mentioned the interference that might still be common to be met in the industrial environment. As shown in Fig. 5.2, most problems can be caused by arc welding, because the electromagnetic radiant harmonics can reach 1 GHz frequency. However, the study claims that none of the interferences with wireless communication has a frequency less than 2.4 GHz. In the absence of complete information about the conditions under which the experiment was carried out, it was decided to carry out additional experiments. The test examined the source of the electromagnetic noise — a regular electroluminescent lamp. Using a spectrum analyser, electromagnetic noise was measured, which was generated by the electroluminescent lamp being switched off. As a result, it was concluded that the noise, which was generated when the lamp was being switched off, can be as high as 5 GHz frequency. The noise signal power:

– 20 dBm at 430 MHz,

– 10 dBm at 2.4 GHz,

– 2 dBm at 5 GHz.

The noise lasted for less than 0.25μs, so it did not affect the IEEE802.15.4 communication because the transmission time of one bit was 4μs. Redundancy was used for data transmission, because every four bits were encoded with 32 characters that had already been broadcasted on air; because of this the bit was transmitted without errors.

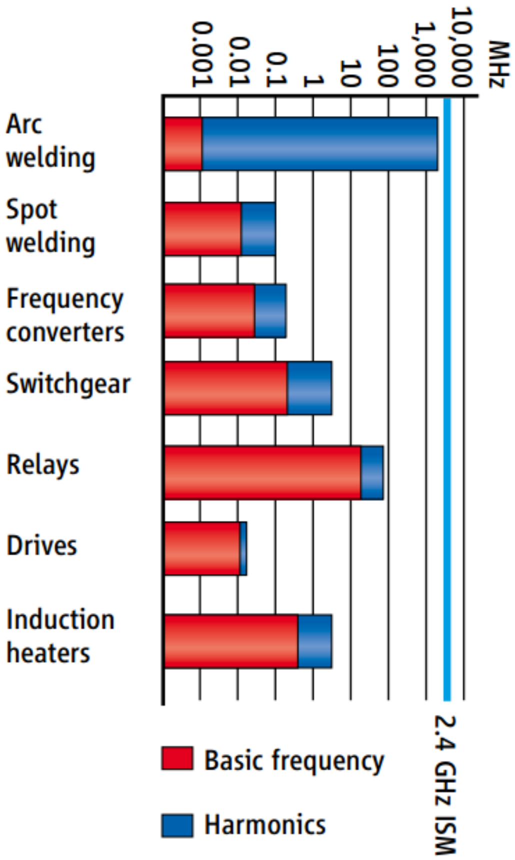

Fig. 5.2 Industrial noise spectrum.

This experiment has resulted in a demand to comply with the noise made by electroluminescent lamps. The noise power is not great; therefore, it is sufficient to place the wireless device one meter away from the lamp and the noise will no longer be interfering. Since the noise occurs only when the lamp is being switched off (when it is being turned on, the noise is considerably weaker), it can be concluded that it is generated by the lamp starter. It is possible to prevent the noise-making using the lamp starter.

In order to draw conclusions, it is necessary to look at the total statistics of all the experiments, which show how many repeated transmissions were necessary to deliver the packet to the recipient. One can see that the packet delivery probability grows exponentially with each subsequent transmission. Three repetitions are sufficient to ensure a 99.8 % probability that the data will be delivered [7].

5.2. Wireless Network Security Problems and Solutions

Developers of wireless sensor networks for environmental monitoring are confronted with a lot of tasks to be solved: choosing hardware, communication protocols, high-level application programming and others. After completing all of the mentioned steps there is still work to be done for making the network applicable in real life. Despite the fact that the network operates perfectly in ideal laboratory conditions, it may be not ready for the harsh real life that is full with natural and even intentional threats. Therefore, wireless sensor networks should be resistant to external influences, especially when such networks are used for environmental monitoring, that is, the obtained data might be important or vital. Some of the applications might involve private data sending over the network. In this case, it is important that this data cannot be seen by unauthorized persons. As appears from the above, a wireless sensor network should be secured and security issues must be taken into consideration at the beginning of network development.

The Doctoral Thesis includes analysis on primary security issues and their solutions in wireless networks. The research was accomplished under the European FP7 project "ProSense" [44]. Test results show specific security issues and solutions for several real life use cases. The Doctoral Thesis has a detailed analysis of each use case, beneath is the summary of security issues and solutions in the scope of the OSI model (Fig. 5.3).

Since secure communication requires extra memory, processing power and communication overhead, there is a need to check the level of impact on network and node performance characteristics. Knowing requirements of the use cases, there is no need in obtaining precise tests values, the main idea is to check if there is strong impact on some performance characteristics or if such impact can be neglected in terms of current use cases. The results are as follows: in the plain scenario maximum initialisation delay was 1 second, in the secured scenario maximum delay increased significantly — up to 8 seconds. Even if the impact is so significant, it should not affect network performance, because it is the delay of initialisation, which is performed only at the beginning of the communication session.

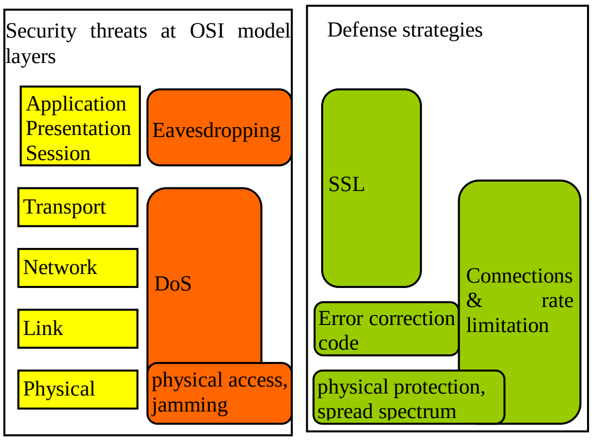

Fig. 5.3 Security threats by OSI layers.

Increase in CPU load due to SSL technique usage could not be measured directly, but there is a possibility to measure communication data overhead. It could be done using a wireless sniffer, a program that is able to capture all wireless transmissions that are sent from SunSPOT nodes. The SunSPOT SDK contains a readymade application for sniffing. Using this program, the node transferred data were captured in SSL and plain communication modes. After capturing data packets it is possible to see the transferred data and therefore obtain message size. The results of this test confirm that data encryption using an RC4 algorithm adds no overhead and SHA (SHA1 - 160 bits) hash produces 20 bytes of overhead. Overhead is not large on the absolute scale (transferring 20 bytes will take less than 1ms). In practice, wireless sensors send small data amounts and effective data size is comparable with overhead; therefore, efficiency of data transfer will be only half from the maximum value. To increase the efficiency, data could be buffered and sent by big blocks using all available packet size (~1.5K bytes at most). In this case efficiency could be >99 %.

To test the influence of increase in CPU load and sent data overhead, battery consumption was measured in SSL and plain text transmission modes. The SunSPOT SDK contains tools to measure battery voltage; therefore, it is possible to determine if there is an increase in energy consumption between two above-mentioned modes. Tests show that in the SSL mode voltage drop is bigger than without encryption by 48 %. As it could be seen, SSL usage increases node battery consumption, main reasons for that are sent data overhead and increase in CPU load for encrypting and hashing the data. It should be mentioned that this test cannot be perfectly accurate, because voltage drop is not linear. Nevertheless, tests prove that it is possible to use secure data transmission in low energy nodes.

Despite all the security measures, the control system should be protected not only from external attacks, but also from erroneous actions from the inside. Typical computer operation systems usually implement user hierarchy, where critical functions have restricted access only for administrators. However, industrial systems often include user (operator) actions that are system and life critical. It is not possible to restrict access to these actions, since they are part of typical system usage. To monitor and control dangerous actions, an operator access control system is used. Similarly to the “dead man’s switch”, wireless operator panels might use the control of operator location, to disallow usage, when there is no direct visual contact with a machine. The Doctoral Thesis proposes a system that extends possibilities of access control, by creating a precise access map.

The task of resource access control could be formulated as follows: to continuously track user’s location while he is using the controlled wireless resource; to manage user rights for accessing resource, using the predefined access zone map, without affecting the initial user’s identification mechanism. User localisation needs to be performed with errors not greater than several tens of centimetres, a distance that is comparable with changes of wireless panel placement at user hands.

During the research stage the following existing systems of wireless user localisation and location based services were examined: “Olivetti Active Badge system”, “AT&T Bats”, “Microsoft RADAR”, “MIT Cricket”, Siemens Mobile Panels. The Thesis has a detailed description of these systems. Here we conclude that none of existing methods and systems is capable of performing contiguous user access control with high localisation accuracy [50]. The proposed approach solves the mentioned problems and thanks to relatively high accuracy it will be possible to create detailed maps of unapproved zones for the operator.

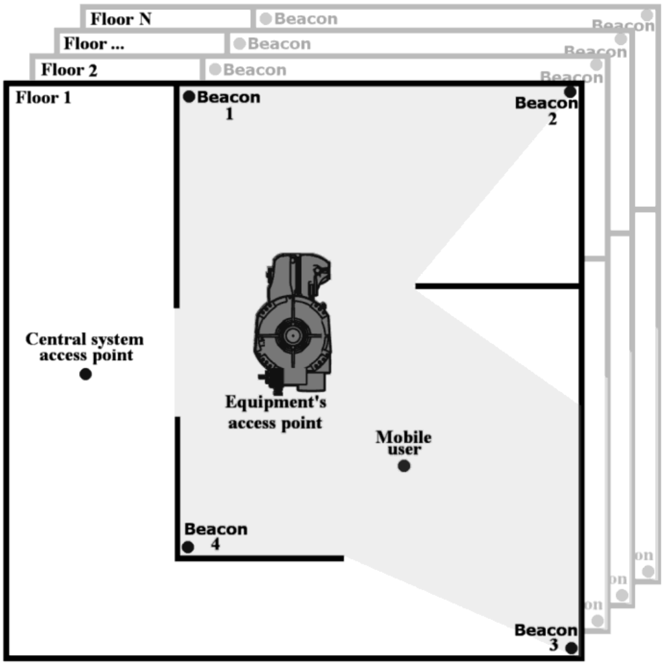

Fig. 5.4 An example of system topology.

Taking into account the information about the examined system topology and the given task, the system topology was proposed. The detailed description could be found in the Thesis. A scheme of one access control area is depicted in Fig. 5.4.

RESULTS AND CONCLUSIONS

The Doctoral Thesis is focused on wireless sensor networks in time-critical applications, for nonlinear and dynamic objects. The research results have been practically tested in real industrial objects and several scientific projects. Results are represented in the form of algorithms, methods and tools.

The main findings of the Doctoral Thesis:

1) Quantitative criteria have been defined for specifying time-critical control system transmissions. Transmission delay was used as the main criterion. The research specifies transmission delay boundaries for the researched application area — industrial systems. Delay boundaries specify systems, where existing wireless transmission technologies cannot be used and the proposed methods should be implemented.
2) Specific time-critical parts of transmission systems have been defined. By examining the existing transmission systems and standards, a media access section has been defined as a bottleneck of the time-critical transmission. Practical experiments have proven that the existing wireless networks are not able to satisfy the predefined time-critical system requirements.
3) A method for formalisation of nonlinear and dynamic objects has been proposed. One of the advantages is the ability to combine discrete and analogue signals at the system input. Moreover, the proposed method uses a relatively low number of variables for system specification. The proposed formalisation uses the Hammerstein method for separating system nonlinear and static part from the dynamically-linear part.
4) A new media access algorithm has been proposed. It combines stability, low and predictable delay with flexibility of the existing transmission standards. The proposed algorithm has been tested within the international project STRATOS [52]. It has shown higher transmission frequency and node number comparing to the existing systems. It has been tested in the network of 140 nodes with the transmission frequency of 300 Hz. However, the existing solutions are able to provide only 200 Hz for 50 nodes.
5) The existing simulation method and tool "Castalia" have been improved for precise handling of the short interval (< 5ms) transmissions. The improvement uses an additional software block for simulating delay between the central processor radio modules. By using the "Castatlia" simulator with the proposed improvements, it is possible to test the full network with 140 nodes and the 3.3ms transmission interval.

6) A tool for experiment result analysis and visualisation has been developed. The tool allows automating experiment result visualisation, without delaying further experiments. Tool efficiency and relevance prove the fact of tool usage in everyday routine of the "ifak" German research institute.
7) Industrial network security and reliability risks have been analysed in real use cases. Previously unknown reliability risks have been found and their solutions specified.

In conclusion, the Doctoral Thesis proves the opportunity of implementing wireless transmission in time-critical systems, with nonlinear and dynamic parameters. By consequent implementation of the proposed system formalisation method and analysis, it is possible to define specific timing parameters. By using the proposed wireless media access algorithm along with the found parameters, it is possible to implement wireless data transmission. Finally, the proposed simulation technique and security methods assure that the system will operate in real-life application.

Future development directions:

- To broaden the implementation area by using the proposed algorithms in large-scale (several hundred nodes) decentralised autonomous control systems;
- To perform the analysis of encrypted transmissions in large-scale wireless sensor networks;
- To analyse routing efficiency in large-scale wireless sensor networks.

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