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Building Energy Efficient Wireless Sensor Networks

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***Abstract*—This article provides an overview of the existing problems in the construction of wireless sensor networks (WSN), in particular the problem of energy efficiency of the system. In many cases, the WSN is set in places where the connection to the stationary power sources is difficult or impossible. Such situations require the use of autonomous energy sources: traditional (batteries) or alternative (solar panels, wind generators, etc.). Due to limitations in the available system power there is obvious need in efficient use of available energy resources.**

***Keywords*—wireless sensor network, energy efficiency, signals, systems, automated control systems**

I. Introduction

AUTOMATED process control system (APCS) is defined as a man-machine control system that provides automated collection and processing of information necessary for the optimization of technological units in accordance with the criterion. APCS are generally platform components – Company's ACS which, in turn, may be part of the ACS of Corporation or the whole industry (Fig. 1).

It is clear that hierarchical connection affects the architecture, topology, protocols, algorithms and software of automation systems. Corporate, production and research structures of ACS almost always are "closed" systems. Closed, in this context, implies a rigid hierarchical administrative control and monitoring of configuration changes, functions, component specifications, composition and roles of users in ACS, while supporting the widespread use of the components, protocols, and software executed on open international standards.

The reason lies in the fact that the processes which are responsible for the production processes of similar products (for example, automobiles or textiles), but organized by the competing companies, will be controlled by different ACPS. We can conclude that ACPS is usually part of a protected corporate technology and, therefore, unique and not duplicated or poorly replicated system.

The construction of ACS for civil purposes is in many ways similar to the Corporation's ACS, but require, as a rule, a good replication capacity, open and transparent procedures for the operation, the ability to work with the mass consumer taking advantage of public information network resources. Automated systems have penetrated almost all spheres of human life: housing and communal services and networks, medicine, education, buildings and structures for various purposes, trade, entertainment, traffic and agriculture. They can also be defined as the automated engineering systems and facility management system.

The study is part of the project of creation of modern component base for the monitoring and control systems engineering objects for wide purposes. The challenge of building data collection and control systems is relevant now in many application areas. However, usage of traditional wired networks is not always efficient due to high expenses of installation and commissioning works. Technical services are also difficult to maintain. Furthermore, in some cases cable routing is impossible due to technical, economic or organisational reasons. Hence, it follows that wireless data transmission systems are useful for finding solutions to the challenge offered. In spite of this, their application was hampered for a long time by low liability of radio channels, high costs, higher energy consumption and limits to electronic components comparing to wired networks. Installation and customization of the object system may also cause several issues.

Presently, wireless data collection and control systems have become a reality because of development and standardization of wireless network technologies.

Summation of actuators (sensors), transmitters and mechanisms united into a structured, self-organized network by means of radio channels is known as wireless sensor network (WSN). The key requirements to sensor networks are the coverage area and low energy consumption by the devices connected to the network. Despite the fact that technologies using wireless connections based on RFID, ZigBee, Bluetooth, Z-Wave, Insteon including devices with low and ultra-low energy consumption are widespread, their abilities are limited by the amount of devices connected to a single network as well as carrying capacity, their range and other parameters. Applying technologies of urban and regional network such as WiMAX and LTE is also hampered in IoE due to greater energy consumption and quite high expenses.

There is no optimal technology for IoE in the world today. Each of the existing standards has different serious disadvantages.

II. The Concept of an Ideal Sensor Network

In this article, the concept of an ideal sensor network is considered from the position of maximum conformity to the challenges offered to this network based on creating automated control systems. Wherein certain restrictions on parameters of an ideal sensor network are imposed by the legislation of a country of its application. In our case it is the territory of Russia.

The frequency range used by the system is the crucial restriction imposed on a wireless sensor network. It should be permitted and unlicensed in order to create a network of this

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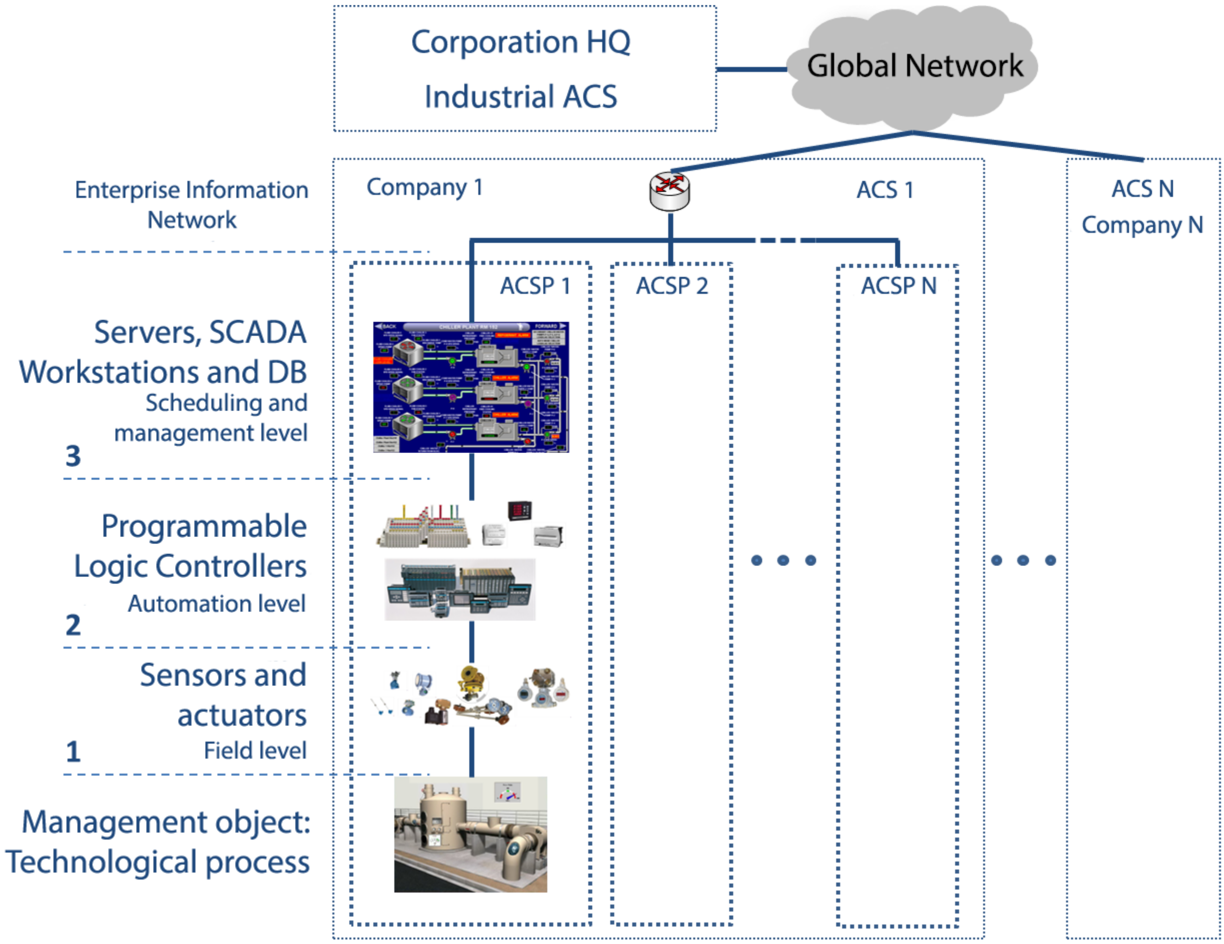

Fig. 1. ACPS hierarchy.

kind in the future and turn it into a commercially successful product.

Another important quality of an ideal sensor network depends on the range of coverage, which should be sufficient for creating the automated system of the required size. In frames of building automation, production facilities and challenges of Internet of Things we may suggest that the range of coverage should be not less than several hundreds of meters. But in order to achieve the required level of network location it should not be too big – not more than several kilometres. Summation of expert opinions concerning this question and comparing them with the aim of this article allows us to set the ideal range of coverage, which is equal to 1 km.

The following quality is also important to maintain the range of coverage and to match the requirements of the sensor network. It determines the number of interacting devices in the network, which are presented at the same time.

This number cannot be low because only a large number of simultaneously functioning devices in the network is able to provide high level of functionality, which is necessary for the modern control systems. According to expert estimates, considering the perspective of wireless technology development, the number of the network members should amount to a few thousands and if the coverage area is 1 km, there should be not less than 8000 devices (in this case, the average distance between them will be around 5 meters).

The necessity of interaction among a large number of the network members also affects indicators such as energy efficiency of interaction, and processing speed. Numerical values of these qualities are difficult to determine precisely. However, they should provide the necessary interaction area and the number of participants. Processing speed is crucial for the main device of the network because it should be able to interact with each member of the network and for peripheral devices, in its turn, the indicator of energy efficiency is crucial because a wireless network suggests absence of conductors that convey information and even absence of power supply (where it is feasible). Hence, an ideal sensor network should have the lowest possible energy consumption and the fastest possible processing speed, which are necessary to find solutions for building Automated Process Control Systems of different kinds.

Parameters of energy efficiency and processing speed are rather antagonistic because if we improve one of them, the other one will be inevitably impaired.

Aside from the mentioned qualities of an ideal wireless sensor network, it should also provide security to data processing. Data encryption in the territory of Russia is regulated by respective GOST’s, which requirements an ideal wireless sensor network should match. It’s worth to point out that increasing the security of data processing leads to an increase in traffic and requires an increase in processing speed, which in its turn reduces energy efficiency of the system.

Devices of an ideal sensor network should be also characterized by reliable electromagnetic compatibility.

Technical and algorithmical solutions to an ideal wireless sensor network should be based on the modern principles and approaches in order to provide its competitiveness for the time of its following commercialization and cost recovery. In this regard, future-proof solutions should be considered with a certain level of caution to make sure that at the current level of technical development, it is feasible to implement some of the mentioned perspective solutions, considering the price requirement, which should be as less as possible to meet the standards of an ideal wireless sensor network.

Hence, we can name the basic requirements for an ideal sensor network in the following way (Table I) from the challenges offered to this network based on creating automated control systems.

TABLE I
PARAMETERS OF AN IDEAL SENSOR NETWORK

Column 1	Column 2
Carrier frequency, GHz	In frames of the allowed network (most probable occurrences: 0,433; 0,868 2,4–2,4835 GHz)
Coverage area, km	1
Number of participants, not less than	8000
Energy efficiency	The higher the better
Processing speed, Mbps	The higher the better
Information security	Yes

III. MAINTENANCE OF THE REQUIRED ENERGY EFFICIENCY

The crucial parameter of a sensor network is energy efficiency of its separate parts. Considering the planned number of the network participants, (more than 8000 units), power supply becomes the most relevant objective. Installation of the system also means installation of transmitters and actuators, which should be connected to the network devices. Wired power supply of each node of the network substantially complicates or even makes impossible its practical implementation. Hence, each of the devices, which is capable of functioning autonomously throughout proper amount of time, should be implemented through wireless power supply.

This requirement contains special demands for power supply of the wireless sensor network devices. Since an increase in data processing also requires an increase in energy consumption for the processing, it follows that instead of reducing energy consumption of field devices of the system, we need to increase their energy efficiency, that is to say, the proportions of processed (meaningful) information and the energy consumed in the process.

Many factors of circuit formation affect energy efficiency and the parameters «number of participants» and «coverage area» listed above. Particular attention should be paid to building hardware solutions for information exchange, architecture, technologies of microcircuit solutions and also for protocols of information exchange in the network. We should take into account, that solutions, which are aimed at energy efficiency objectively, impair parameters of the system such as communication range, its security, etc. and have a system-wide effect on it. Presently, there are no suitable solutions that would match the requirements for energy efficiency necessary for an ideal wireless sensor network.

Hence, we may define the main direction of research in frames of this article: finding and development of technological solutions which would provide energy efficiency of the system considering the required coverage range, number of the network devices, speed and security of information exchange.

IV. THE MEMBERSHIP FUNCTION

The membership function of the networks on energy efficiency parameters based on two qualities: «the maximum power of the transmitter» and «maintenance of power supply mode».

The membership function is used for «the maximum power of the transmitter» characteristic, which meets the requirements for energy efficiency suggested for an ideal sensor network. Taking into consideration energy consumption, the following definition appears: «the less the better». The membership function is even (contains no discontinuities) and based on sinusoidal functions (1).

$$\mu(x)=\begin{cases}1,\ x<c\\ \frac{1}{2}-\frac{1}{2}\cdot\sin\frac{\pi}{c-d}(x-\frac{c+d}{2}),\ c\le x\le d\\ 0,\ x>d\end{cases} \quad (1)$$

Where parameters c and d – set the value limits to reduction area of the membership function. The function is shown in Fig. 2.

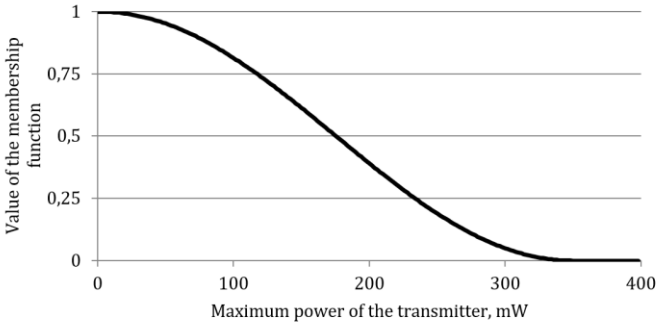

Fig. 2. The membership function for «the maximum power of the transmitter» characteristic.

Parameters for that function are rather tentative; their values are within the limits of the maximum values of the power supply transmitter in frames of existing solutions (c = 1 mW, d = 350 mW). The function serves for ranking the known solutions by this characteristic.

In addition to the previous characteristics, it is necessary to consider the "Baud rate", for which the membership function is introduced. It reflects the requirements for the possibility of simultaneous work with a large number of devices, indirectly reflects the possibility for data protection and encryption, and thus has an antagonistic effect on the energy efficiency characteristics. The behaviour of the membership function corresponding to the semantic rule "the more, the better." The form of the membership function selected smooth (without break points) based on sinusoidal functions, the formula (2).

$$\mu(x)=\begin{cases}0,\ x<a\\ \frac{1}{2}+\frac{1}{2}\cdot\sin\frac{\pi}{b-a}(x-\frac{a+b}{2}),\ a\le x\le b\\ 1,\ x>b\end{cases} \quad (2)$$

Where the parameters *a* and *b* – set the value limits to increase area of the membership function. The function is shown in Fig. 3.

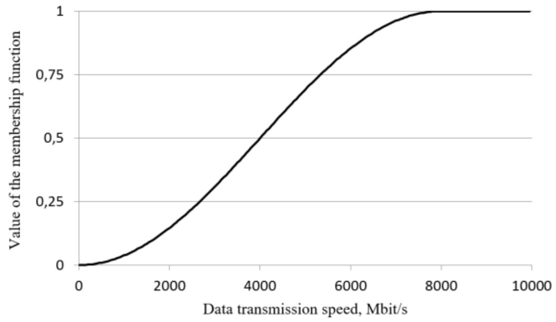

Fig. 3. Membership function for the "Baud rate".

The parameters of this function are selected rather arbitrarily, they provide distinguishing characteristics in values ranging from 1 (parameter *a*) and 8000 (parameter *b*) Mb/s, which are in the range of estimated values for the discussed solutions. The function is introduced to allow ranking of the known solutions in this respect.

«Maintenance of power supply mode» characteristic positively affects energy efficiency of the system. Hence, due to actual binary values of that characteristic, the two values of the membership function are selected: 0,67 in case of supportive presence and 0.33 – in all other cases.

Based on the specific membership function it can be seen that ZigBee type of system and the system based on a potential protocol IEEE 802.11ah have the highest values necessary for the implementation of wireless sensor networks for automation on the complex of matching characteristics. Thus, it is the development of technical ideas embodied in these well-known design, defines the technical basis of the lines of research of this article.

V. Methods of Energy Consumption Optimization in WSN

In many cases, the WSN system is set in places where the connection to the stationary power sources is difficult or impossible in principle. Such situations require the use of autonomous energy sources: traditional (electricity or batteries) or alternative (solar panels, wind generators, etc.), inevitably leads to limitations in the available system power, and hence, to the obvious need to efficiently use the available energy resources.

Since the amount of energy consumption designates lifespan of autonomous sources of power supply and, therefore, allotted lifespan of WSN devices, each of the protocol, algorithmic and instrumental aspect of WSN should be optimized on energy consumption parameter equally to optimization of the main function of the aspect considered.

Generally, energy consumption will be efficient when energy consumption for the data processing from the sender device to the receiver device is as low as possible. Formula of calculation of the energy efficiency indicator (2).

$$C = \frac{N}{D} \qquad (2)$$

Where C – the indicator of energy efficiency of data transmission;

E – energy, consumed by the network's nodes over the time period t;

N – data volume over the same time period;

Theoretical and experimental researches with energy cyclegramms of WSN devices functioning and analysis of energy consumption interrelation are represented in [1]. It may be concluded that the need for providing energy efficient sensor network is expedient from two perspectives:

1) Implementation of the hardware platform of the devices, which constitutes the network. Namely, technology of building electronic components (IC), the level of their integration, peculiarities of circuit solutions (notably, ability to control power consumption and to turn off idle function modules.

2) Implementation of WSN as a system and its peculiarities.

The first perspective implies an algorithm, which was successfully brought in and applied during IC development. This algorithm consists of the following stages:

Stage 1. Developing requirements for the functionality of the research object. (creating terms of reference)

Stage 2. Creating behavioral patterns of the object

Stage 3. Finding out whether the behavioral patterns corresponds to the functional requirements.

Stage 4. Transferring the model to arbitrary technological basis. (the synthesis of an electric circuit, prototyping of topology).

Stage 5. Evaluation of static and dynamic energy consumption in different modes.

Stage 6. Finding out the best, standard (or several standard) and the worst modes regarding energy consumption.

Stage 7. Hierarchical decomposition of the research object and analysis of its compounds in the mentioned modes.

Stage 8. Analysis of the compounds in terms of circuit implementation, function mode, variation of disadvantage and exposure to change of the application conditions.

Stage 9. Modification of the behavioral patterns, the circuit or typology. Proceed on stage 3 or 5 depending on the object of modification.

The algorithm is iterative and allows following the stages consecutively, analyzing elements of one stage and to elicit critical areas in terms of increased energy consumption and to adopt measures for preventing it. Its implementation meets the challenge of increasing IC energy efficiency.

The second perspective implies the analysis of many factors, which affect energy efficiency of WSN, using basic model OSI [2].

Let us determine the factors affecting energy efficiency of WSN at the physical level, that is to say, in radio path, (where transmission and reception of information among WSN devices take place).

- Interference

It is a systematic factor, which affects energy consumption, the higher level of interference is, the more energy for radio path is required. The only tool that may prevent interference is shielding which is inapplicable to this system.

- Applied frequency range.

It is a systematic factor, which affects energy consumption. The level of energy consumption corresponds with an increase in transmission frequency.

Meanwhile, the permitted range of operating frequencies in Russia is regulated by the following requirements (0.433 GHz, 0.868 GHz, 2.4000-2.4835 GHz). Obviously, in terms of an increase in energy efficiency, WSN should use a lower frequency range but in terms of an increase in throughput of the radio channel, it is necessary to select a higher frequency range. The option that may take up the challenge is applying range 0.868 GHz.

- Applied code modulation circuit.

It is a systematic factor, which affects energy consumption. Different kinds of modulations – BPSK (binary phase modulation, the most noise resistant but guarantees lower efficiency of proportional amplifier in communication systems); QPSK (four-position phase modulation, lower level of noise resistance but may provide higher throughput in a radio channel, also provides lower efficiency of proportional amplifier in communication systems); QAM (multiposition quadrature amplitude modulation, requires lower frequency band, has a higher risk of errors in higher order systems and requires a more powerful transmitter); GFSK (two-tier Gaussian frequency shift keying contains Gaussian filter, which makes the forming signal more spectral efficient) – determines the maximum possible data transmission speed and noise resistance and, as a result, also the level of energy consumption.

The selection of a code modulation circuit is affected by an increase in data transmission speed, an increase in noise resistance, reduction of the number of errors and other requirements for providing stable radio communications.

The challenge of increasing WSN energy efficiency will affect, indirectly, by requirements for increasing efficiency of proportional amplifiers, which are used in the selected code modulation circuit.

- Location of the nodes

It is a systematic factor, which affects energy consumption. The level of energy consumption is proportional to the distance on which the nodes of the network are located. Location of the nodes is set by configuration of a concrete projected WSN, which necessitates us to consider the worst outcome possible because of the required coverage area – 1 km.

Let us determine the factors, which affect WSN energy efficiency at the link layer.

The main factor at this level is environmental accessibility (selection of the method for channel separation); it is also a systematic factor, which affects energy consumption. Depending on the kind of channel allocation, (frequent or temporal) the level of energy consumption will change. The method of frequent separation loses in terms of providing higher energy efficiency but its application provides optimal polling cycle due to parallel operation of the devices. In terms of energy efficiency, the method of temporal channel allocation is more preferable but at the same time its application provides extension of the polling cycle and, as a result, complication of providing sufficient number of devices and the required time characteristics of information exchange. The solution to the challenge is combination of frequent and temporal channel allocation.

Let us determine the factors, which affect WSN energy efficiency at the network level:

- Data exchange protocol

It is a systematic factor, which affects energy consumption. In this case, the solution to the challenge is application of the protocols, which have energy saving modes (turning off idle subsystems, scheduled working modes and etc.);

- Network topology

It is a systematic factor, which affects energy consumption. The level of energy consumption fully depends on the network topology, this is to say, on the layout plan (the position in line-of-sight and presence of non-transparent radio waves obstacles); It is a systematic factor, which affects energy consumption. The level of energy consumption fully depends on the network topology or, in other words, on the layout plan (its position in line-of-sight and presence of non-transparent radio obstacles) and it also depends on the distance on which the nodes of the network are located because the necessary power of the transmission device depends on this parameter. Network topology is set by configuration in a concrete projected WSN, which necessitates us to consider the worst possible option in the process of development because of the required coverage area– 1 kilometer.

We need to determine the factors that affect WSN energy efficiency at the application layer.

At this layer, the crucial element is scheduling the functioning of the devices. It is a systematic factor, which affects energy consumption. The level of energy consumption is proportional to the airtime of the device. The possible solution of the objective is turning off transmitters of devices, which airtime is not necessary at that moment or to switch the field device to a «deep sleep» phase and switching it on when an energy independent timer implies.

VI. Conclusion

In this article, we consider the challenges of building wireless sensor networks, which are capable of maintaining simultaneous interaction in information of many devices (thousands of transmitters and actuators) with high energy efficiency which is in demand due to difficulty of providing the devices with a central power supply and because of the limits to the autonomous power supply systems in frames of local coverage area (hundreds of meters).

In particular, the challenge of providing energy efficiency is considered. The basic principles and options for providing the required characteristics of the coverage area are represented.

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