Analysis of Delays in Medical Applications of Nanonetworks

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***Abstract* — Nanonetworks is the innovative direction of Internet of Things (IoT). Nanonetwork's technologies promises extensive opportunities for creating innovative applications and it is attracts researchers from different fields of science. Healthcare is one of the fields in which nanonetworks promise technological spurt. For the effective functioning of the medical applications of nanonetworks it is necessary to provide high quality of service (QoS) for end-to-end traffic. In this article we analyzed network delay — one of the most important QoS parameters. Maintenance of low delays especially important for real-time medical applications. The article examines the factors that defines requirements to delay for real-time medical applications as well as components of delay at various levels of the network.**

Keywords—nanonetworks; IoT; delays; medical applications

I. INTRODUCTION

The advances of current medicine in sphere of patient's health monitoring in real-time mode are integrally related to recent achievements in sphere of telecommunication, in particular to development of Internet of things [1]. Different solutions in sphere of self-organized networks and body area networks (BANs) allow integrating separate applications into one and provide the possibility of complex evaluation of a significant number of dynamic medical-biological parameters of functioning of a macro organism [2, 3]. However, these applications are still facing limits in sphere of unfolding and cannot perform operations or collect data inside a human body.

A new telecommunication paradigm Nanonetworks [4] will allow expanding the limits of possibilities of medical applications. Nanonetwork technologies allow developing medical applications of a new level. It is assumed that application of a new type will have three-level architecture and will be able to unfold within contexts: inside a biological object, at contact (on the surface of a biological object), in personal space surrounding a biological object (regarding human, it can be a house, a transport means, a work place, and regarding a patient it can be a ward or mobile ICU) [5]. Even today huge steps are being taken towards the development and implementation of this concept: models of sensor nanonetworks on textile basis were developed [6], not yet manufactured samples of nanomachines, which can perform various tasks inside a biological object: deliver drugs, collection of bioptates of tissues and biological fluids, perform in vivo monitoring and other, were created [7, 8, 9]. All these applications on modern level of technology development have relatively simple structure. The next step aimed at implementation of a paradigm of Nanonetworks shall be development and implementation of more sophisticated and complex solutions that will merge separate nanosolutions into a unified system and provide the possibility of centralized control [10]. Such kind of architectures allows dealing with a wide range of tasks, yet together with the new possibilities new tasks on provision of the required level of quality of service will arise. Meanwhile, criteria of quality of service had not yet been established in detail for nanonetworks. This circumstance complicates the designing of medical nanonetwork real-time applications. Requirements to parameters QoS end-to-end will impose constraints, including on the method of communication between devices on nano level. One of the methods of transferring data on nano level is a molecular communication [11, 12]; this type of communication is rather specific. As another and more familiar method of transferring data on nano level can be named communication on the basis of electromagnetic emission in THz band [13, 14]. We shall also mention communication by means of biological neuron networks [15, 16] which have as basis physiological activity of functionally interconnected neurons of central and/or peripheral nervous system. All these methods of communication quite differ one from another, including by characteristics of communication channel. Different applications can impose certain constraints on parameters of data transfer, due to which at designing of nanonetwork real-time applications one should have a possibility of calculation these parameters.

In this article we offer to review medical nanonetwork applications from the point of one of the most important criteria QoS – delay. The purpose of the article is to understand what defines the delays in work of medical nanonetwork applications and how to find the maximum allowed level of delays for a certain application. This knowledge will help at designing nanonetwork real-time applications.

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The paper is organized as follows. In Section 2 we reviewed the requirements to delay in nanonetwork real-time applications and offered an event-oriented method for definition of the maximum allowed delay for medical nanonetworks real-time applications. Section 3 provides an analysis of delay at transferring message from body gateway to a remote server, and also a review of different locations of a server and priorities of traffic. Section 4 provides a review of modes of operation of a body gateway and their influence on delay, as well as a mode of operation of sensors based on discrete reports. Section 5 provides a comparative analysis of communication technologies of nano level by criterion of delay. Section 6 is the conclusion of the paper.

II. Requirements to Delay in Real-time Medical Applications

The main parameters characterizing transfer of data in communication networks include delay, jitter and packet losses. Requirements to these parameters are defined by applications. To operate correctly, certain applications need to be provided with especially good parameters of network transfer. As classic examples of such applications can be named telephone connection, dynamic online games and video conferences. As nanonetworks develop, the list of applications keeps increasing. First of all, these are real-time medical applications. Some medical applications using nanonetworks allow detecting negative events or their predictors (markers) with the help of nanosensors, which are located in a living macro organism (inside it or at contact), and influence the processes within the organism with the help of nanoactuators [10]. Such applications need persistently high parameters QoS, primarily minimum delays. Big delays will prevent correct operation of applications, which may lead to detrimental effects, at occurrence of a negative event. By analyzing such events, we will be able to define requirements to delays. At occurrence of a negative event in an organism, it is important to take measures as soon as possible, thus preventing the development of irreversible changes, as shown on Figure 1.

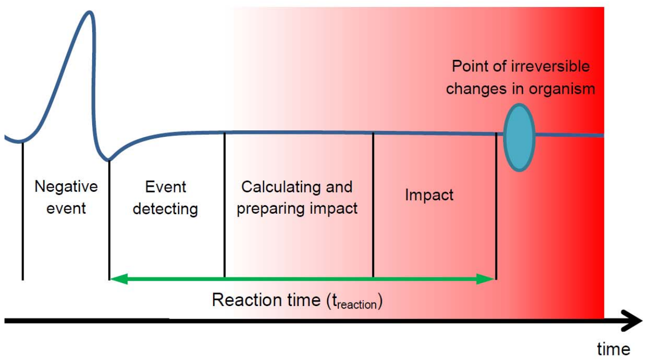
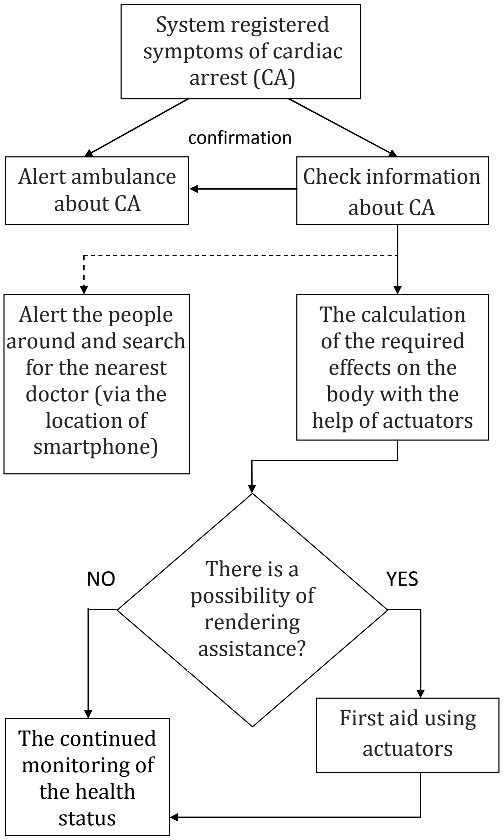


Fig.1 Reaction to the negative event in organism

As an example of a negative event having a fatal consequence, we can analyze a sudden cardiac arrest in human. Consequences of cardiac arrest depend exclusively on time of providing emergency aid to a patient. It is possible to keep full functioning of central nervous system (CNS) and mental functions if time of complete arrest of brain circulation and therefore acute dyscirculatory hypoxia and loss of neurons did not exceed, on average, 3-3.5 minutes (without adjustment for temperature of environment, temperature of human body, functional reserves of CNS, etc.) [17]. The later blood circulation is recovered, the more the probability if short-term



(fatal outcome) and long-term (failure/loss of functioning of organs and systems) negative consequences. A general algorithm of operation of a medical application based on the system “Biodriver” at cardiac arrest is given on Fig. 2.

Fig. 2 Operating procedure of nanonetwork medical applications at cardiac arrest.

Therefore, our purpose is to minimize the time consume during realization of this algorithm. The communication scheme of nanonetwork medical applications is given on Fig. 3. The system includes nanodevices integrated in a controlled environment (nanosensors and nanoactuators), body gateway providing transfer of data between nanodevices and Internet, and a remote computing center (server), which in its turn provide processing and analysis of data from nanosensors as well as accumulation of data for further detection of prognostic (predictive) factors influencing the state of health of a patient [10].

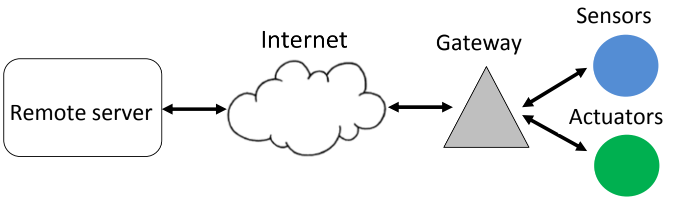


Fig. 3. Communication scheme of nanonetwork application

Based on the architecture, the value of total delay can be represented as:

$$T_{full} = t_{nano} + t_{gw} + t_{web} \quad (1)$$

where T_{full} – delay at transfer of data from nanodevices to the server; t_{nano} – time spent for transfer of data from the sensor (actuator) to the gateway; t_{gw} – timespent by the gateway for processing and conversion of a message into a format applicable for transfer through traditional communication networks; t_{web} – time spent for transfer of a message from the gateway to a remote server.

Now let's consider each of the constituents of a total delay T_{full}.

III. Delay in Internet

Mostly, we use Internet to transfer information from the gateway to the remote server. Value of a delay on Internet depends on many parameters: traffic priority, productivity and congestion of intermediate nodes, intermediate nodes, changes of bandwidth and other factors. From the side of application we can't improve characteristics of the intermediate nodes or communication channels. However, we can change the priority of traffic and geographical location of the computer centre (the server). On figure 4 presented results of the delay measurement for data package transfer to the server for three different variants of its geographical locations. In this case we considered traffic priority by speed of delivery and reliability. For each variant we did 100 measurements.

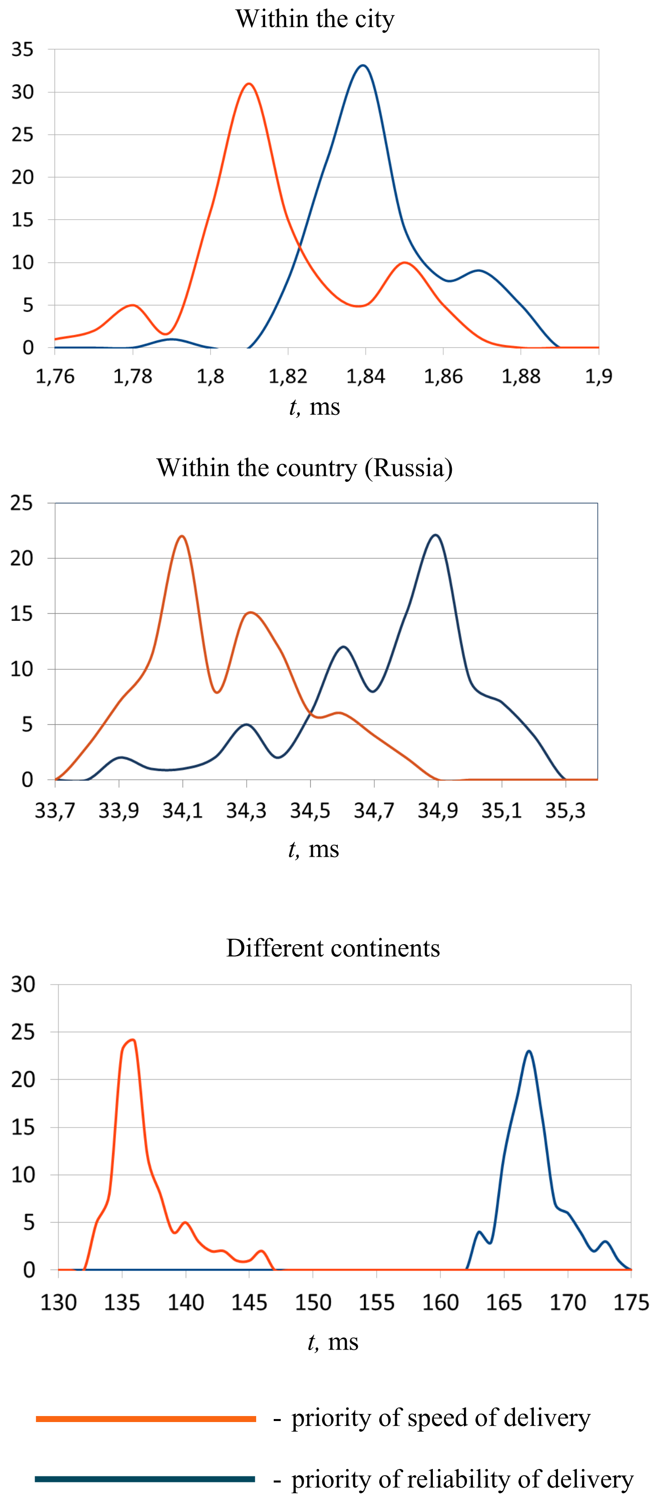


Fig. 4 Delay of message transfer from gateway to server

In presented experiment, for change the priority of traffic we changed the value of the parameter TOS (Type Of Service). Note that not all nodes can support the TOS parameter.

In case A, the route traffic was limited to the urban network and does not affect trunk, which as we know can be "a bottleneck" at route. The route is consist of 4 to 6 hops. In case B, traffic is passed via trunk lines connecting different regions of Russia. The number of intermediate nodes was in the range of 8 to 10. For case C, the number of intermediate nodes was 14. IoT device during experiment was connected to internet using Wi-Fi access. From Figure 4 it can be seen that we can reach a minimum delay in case when a server location is geographically close and when traffic has the highest priority by speed of delivery. Subject to the priority of reliability of delivery and large enough geographical distance to server, delay may become too high for real-time applications.

The results of the experiment presented as an example of differences in delay for different server locations under standard conditions. Depending on the technology used, the results can differ, for example the use of satellite communications may lead to large delay, even if the server is located geographically nearby.

IV. Body Gateway Delay

Time of message processing by the gateway (t_{gw}) will depend on the message processing algorithms, performance of gateway device, frequency of messages. Frequency of incoming messages to the gateway depends on the number of sensors deployed in networks and frequency of queries to them. These characteristics should be researched personally for each medical application and model for the number of sensors required for accurate diagnosis of various events in the human body needed to be created. So, firstly we need to choose the mode of gateway works:

1. Without processing at gateway messages from the sensors
2. With processing at gateway messages from the sensors

In mode "without processing messages from the sensors", the gateway forwards all messages received from the sensor directly to the remote server. This mode allows us to reduce the delay caused by the processing of the message, which in this case will consist only of the time spent to message conversion from nanodevices format to formats of conventional network. The gateway which works in this mode will be with more simple architecture, lower volume of buffer and performance. To the disadvantages of such a mode the increased load on the communication channel between the gateway and the remote server can be attributed. Load in this case is characterized by lots of packages with a minimum data field.

Message processing mode of sensors involves the accumulation and processing of information from sensors before it is sent to the remote server. Such mode increases the efficiency of network resources during information exchange between the gateway and the server due to the proportion of data in packages is becoming significantly more and in addition decreases the frequency and number of messages. In comparison to the first mode the delay increases mainly due to the additional time required for accumulation and processing of data from sensors. Gateway architecture in this case becomes more complicated due to the increased system requirements.

When analyzing traffic generated by nanosensor devices, you should be aware of restrictions on energy supply of such devices. Because of these limitations sensors usually cannot pass on information in continuous mode, as it requires significant energy costs. More preferred is a discrete sensor model, where instead continuous measurements are uses sequence of samples that correspond the value of the measured parameter at point in time (Fig. 5).

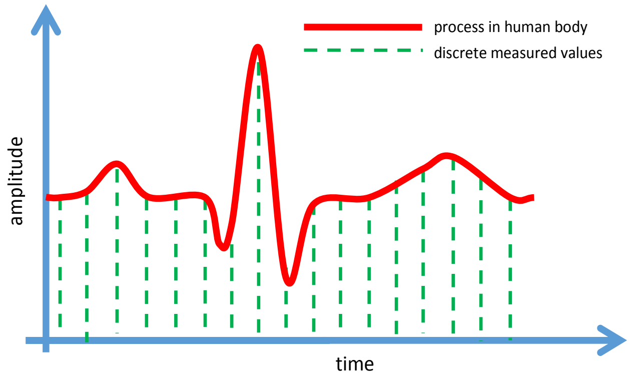


Fig. 5 Discrete measurement of process characteristics

We should choose the frequency of counts enabling to restore the characteristic researched process. In accordance with the Kotelnikov theorem (also known as Nyquist-Shannon theorem), the sampling frequency (f_d) should satisfy the condition:

$$f_d \geq 2f_{max} \tag{2}$$

where f_{max} – is the maximum possible frequency controlled process in humans body (excluding noise).

V. Delay in Nanoscale Communications

Network delay of message between the gateway and nanodevices primarily depends on the chosen method of communication at the nanoscale. Today, it invited a lot of ways of transmitting data in nanonetworks. Requirements, that apply to medical applications data characteristics, can impose restrictions on the use of certain technologies. In our case, we consider communication technology from the standpoint of network delay requirements.

We start with the technology that is most similar to ordinary telecommunication systems – electromagnetic communication in nanonetworks. Electromagnetic communications involve the use of electromagnetic waves to transmit messages, one of the most promising directions in this field is the use of THz frequency range. Taking into account the high rate of propagation of electromagnetic waves, it is possible to assert with confidence that the network delay in data transmission using this technology is so small that it can be ignored. Nanomachines using THz electromagnetic wave range can theoretically have a sufficiently small size that they can be inserted into the body by injection.

However, there is one major drawback of electromagnetic waves in the terahertz range – high losses in the tissues and body fluids of microorganism. When the signal propagates several millimeters, thelossesin blood are about 120 dB, inskin – about 90 dB and in fat – about 70 dB [13]. In this connection, the usage of repeaters is requiredfor communication with nanodevices, remote from the gateway to a distance for a couple of millimeters.

Neuronal communication is a more specific way to communicate, however remotely it resembles the wired telecommunications network. Neuronal communication is based on the transmission of electrochemical pulses. According to the classification Erlanger-Gasser, there are six types of nerve fibers in the human body. The characteristics of these fibers are given in Table 1.

TABLE I. CLASSIFICATION OF NERVE FIBERS

Type	Function in organism	Diameter, micron	Pulse velocity, м/s
Aα	Afferent — muscle spindles, tendinous organs; efferent — skeletal muscles	10-20	60-120
Aβ	Afferent — tactile feeling; collaterals Aα fibers to the muscle fibers intrafusal	7-15	40-90
Aγ	Efferent — musclespindles	4-8	15-30
Aδ	Afferent — temperature, rapid holding of pain	3-5	5-25
B	Sympathetic, preganglionic; postganglionic fibers of the ciliary ganglion	1-3	3-15
C	Sympathetic, postganglionic; afferent — conducting slow pain	0,3-1	0,5-2

As far as we can see from the table, the network delay of communication between the gateway and the nanodevices using neural communication can be represented as a function of:

$$t_{neuro} = \sum_{i=1}^{m} l_i \cdot v_i \qquad (3)$$

where l_i – the length of the i-th section of the neural link between the gateway and nanodevices; v_i - the speed of the nerve impulse at the i section of the channel between the gateway and nanodevices. The advantage of the neural communication is the presence in the body of higher vertebrates, including man, a huge number of neurons forming biological neural networks, through which nerve impulses are transmitted to various areas of the body. However, the biological neural networks are still poorly studied for implementing the full data channel [15].

Bacterial conjugation communication is based on the bacteria's ability to share copies of the plasmid – mobile DNA molecules, containing certain genes that allow bacterial cells to acquire new competencies (properties). This method involves the communication, including transmission of information by artificially introducing plasmids, containing genetic information into the bacteria, which are subsequently introduced into macroorganism. According to studies [18], the speed of propagation of information between two nodes, located a distance of 180 microns, is about 300 seconds, and if there is an intermediate node, it is increased to more than 100 times. This latency does not allow bacterial conjugation communication for medical applications in real time.

Molecular communicationis based on transmission information that is contained in a material different substances (electrolytes, hormones, cytokines, peptides, etc.), between certain cells and/or various divisions of microorganism. Communication channels in this case are the body fluids (blood, lymph, intercellular substance, liquor and others.). Integration of cells into internet was reviewed in [19]. The diffusion coefficient of the particles is about 10-8 m^2/s. The effect of the impact on the target of the same substance in the dynamics in conditions of constantly changing microorganism can differ ceteris paribus the time of exposure and the dose of the active substance that is designated as a "dose-dependent" and "time-dependent" effects. This type of interaction is the basis of humoral regulation of the body, where, in general, the setting or regulation of effector/maintenance of vital functions of the whole organism is performed by the endocrine glands. However, a significant impact on data transfer using molecular communication processes have a permanent base (noise) necessary to maintain the viability of each cell. Each cell of the microorganism through a variety of mechanisms maintains the concentration gradient of various substances inside and outside cells. For example, to maintain the concentration gradient of sodium and potassium ions, sodium-potassium ATPase constantly operates, carrying out the transfer into cells potassium, sodium - into the extracellular space. In turn, the uneven distribution of ions inside and outside the cell creates an action potential, which is the basis of electrophysiological processes in the body (cardiac automatism, neural transmission). One of the significant factors, affecting the success of molecular communication, is noise. There are four kinds of noise: recurrent noise, source noise, destination noise and system noise. Concentration of substance,which should be created to overcome the noise, increases with increasing distance between the source and the receiver [20]. This leads to a significant network delay in the transmission of information. This method of communication also contains the traditional difficulties, associated with the originality and diversity of the living world, in particular on individual sensitivity of the organism.

One alternative method of communication in nanonetworks is the use of ultrasound – there are two main roles of ultrasound in nanonetworks medical facilities. In the first case, the ultrasound is a factor, activating the work nanonetworks structures [21] or as a technology, by which sensors perform echographic diagnosis of various organs of the patient [22] (However, the diagnosis of the organs and systems of the body by means of ultrasound is facing a certain complexity – reduction in the ability of penetrating waves in the air, which requires a specific static position sensor (s) in contact with the surface of the body and / or the use of special materials that enhance the penetration of waves.) For this kind of manipulation, prolonged exposure of ultrasound waves to nanonetworks device (about 30 seconds) is required. Another area of use of ultrasound is the transfer of information through short duration pulses. Use of short duration pulses enables to reduce reflection and scattering effects, as well as to reduce the impact of any harmful thermal and mechanical effects. Today, this technology is the most complete, for it has already been developed and the models of the physical and data link (MAC) level are described [23]. Maximum range of signal propagation depends on the frequency and varies from a few millimeters to a few centimeters, which can be considered as an ultrasonic communication technology conditionally suitable for data transmission between the gateway and nanodevices.

Thus, from the examined technologies for data transmission between the gateway and nanodevices with acceptable network delay, it is more preferable to use an electromagnetic, ultrasonic or neuronal communication, and their combinations.

VI. Conclusion

Implementation of real-time medical applications is a significant milestone in the development of the concept of the Internet of Things. The importance of this point is due to the transition from entertainment tasks to the socio and vital tasks. In this context, requirements for many aspects of functioning of the application arestrengthened, first of all,these areinformation security and speed application response to various events. In this paper, we reviewed one of the important parameters of the functioning of medical nanonetworks applications – the delay between the event in the body and the application reaction. The analysis makes it possible to understand how to determine the maximum network delay value, at which it is possible to ensure the effective operation of a particular medical application, as well as gives an idea of what the basic components will shape retention. To achieve the minimum network delay, it is necessary to:

• Ensure the highest priority on the Internet for real-time medical application's traffic.

• Minimize the distance between the gateway and nanodevices.

• Use electromagnetic communications for communication on nanoscale level.

• Use gateway mode "without message processing from the sensors"

The findings can be useful in the development of medical nanonetworks real-time applications.

In future work, we plan to explore the further network delays in multi hop nanonetworks, as well as to solve the following tasks:

• Research the impact of medical real-time applications traffic on the QoS parameters of other types of traffic.

• Solve the problem of load optimization on the channel of Internet, caused by a large number of messages at the gateway in "without message processing" mode.

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