Self-Organizing Communication Network of Multi-Agent Robotic Systems

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***Abstract* —The paper proposes a structure of self-organizing communication networks of the multi-robot system. The considered networks are organized on the basis of two radio channels: to transmit control and telemetry data and to transmit data which have the higher bandwidth requirements. The algorithm of self-organizing network is designed and presented on the basis of wideband channel quality control: based on the data of received signal strength indicator (RSSI), the capacity and the packet error ratio (PER).**

I. INTRODUCTION

The communication networks between the agents of multi-agent systems (robots) are designed to provide exchange of control and information messages between elements of the system in order to solve the tasks of agents' management and delivery of the data, which is obtained with the help of video cameras and other sensors, which the system elements are equipped with. Due to the fact that the system components are mobile, and the communication conditions between them are dynamically changeable, the main task of the network self-organization is to ensure stable network performance of its basic functions. Stability of the network performance depends on the network topology and logical structure. For example to provide performance of a wireless sensor network may be used some algorithms for the logical network structure organization [1]. Logical structure of the network affects on the network traffic and quality of service [2]. Topology, logical structure and traffic in the network affect on the power consumption [3, 4]. All these tasks are aimed at solving the main task of ensuring basic connectivity and quality of traffic service.

Therefore, the main tasks of the networks' self-organization are:

- to provide the network connectivity (liaison between the network nodes)
- to provide the Quality of Service (QoS) traffic (maintaining the required quality of service traffic) [5].

II. THE STRUCTURE AND CHARACTERISTICS OF THE CONTROLLED SYSTEM

The proposed solution of a communications network between agents of multi-agent systems (robots) can be constructed using two types of channels:

- control channels;
- information channels.

Purpose of the control channel is sending control messages between network elements.

Purpose of the information channel is sending the traffic which is produced in the elements of the networks.

The main reason to use two different channels is in the different requirements to channel characteristics for information and control messages delivery. The data originated in the network nodes usually require relatively high throughput to provide quality video or tactile information delivery. There are difficulties to provide high throughput in the mobile wireless ad-hoc network, due to the high control traffic, switching of the network structure, interference with other nodes and so on. In common case it is quite difficult to provide stable high throughput high quality channel. If the channel can't deliver control messages, the system can't work and may be lost in the worst case. So the control messages delivery must be reliable as possible. Intensity of the control traffic march more lower then the information traffic intensity. Therefore, for the control of traffic delivery, it makes sense to prefer technology provides greater stability by reducing the channel bandwidth. To use simultaneously both information and control traffic transmitters is necessary to use different frequency bands for them.

For construction of the control channels, it is proposed to use radio communication equipment which operates in the range of 433 or 868 MHz (eg, LoRaWAN technology). This standard [6,7] provide enough bandwidth for the control traffic and high communication range [8] which enough to provide not switched channels between the control unit and each of the elements of the network.

The means of organization of the control channels should provide communication at distances up to 5 km, which provides the organization of the control channels between the control center and each of the elements of the system (robot). Throughput capacity of the control channel is sufficient to transmit commands and data of system management. To construct the information channels, radio communication equipment is used, operating in the 2.4 GHz band (IEEE 802.11n standard) [9]. Information channel obtains a high throughput capacity, ensuring the delivery of information from the elements. Throughput capacity of information channel [10] depends on the radio propagation conditions, including the

distance between the elements. The route of data delivery between elements of the system can include multiple channels (hops) [11]. To arrange the network of the traffic delivery, the algorithm of choice of optimal routes based on channel quality data between the system elements is used. An example of a communication network structure between the elements of the system is shown in Fig.1.

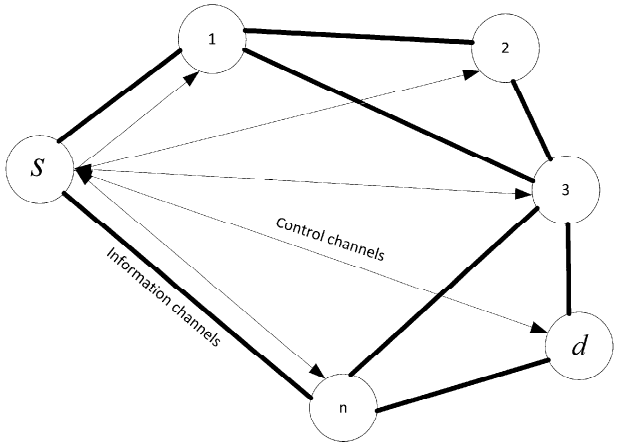

Fig.1. Network structure

The Selection of the network structure is produced dynamically based on data of the channel quality and the quality of services traffic is performed based on the algorithm of self-organizing network. Description of the network self-organization algorithm is given below.

III. Algorithm of Network Self-Organization

Network self-organization algorithm implements algorithms for assessing the quality of the communication channels and select optimal routes for traffic transmission [12-19].

The criterion for the route selection is the optimal (minimum) value of the metric, calculated additively through comprehensive channel quality indicators, included in the route.

The algorithm of selection traffic transmission routes is shown in Fig.2.

The algorithm involves a centralized network management. Network Control Center (further "control center") performs control operations by transmitting control commands with the control elements (node) and by receiving data from the controls elements [20].

The main disadvantage of centralized network management is in the dependence on the control unit reliability and connectivity of control network. The considered network intended to deliver information to the control center. Probability of connectivity of the control network higher then connectivity of the information channels due to the technology characteristics. Therefore in this case the centralized control structure doesn't decrease the network capabilities.

Sending the control commands and receiving the control data from the managed elements is made on the control channel.

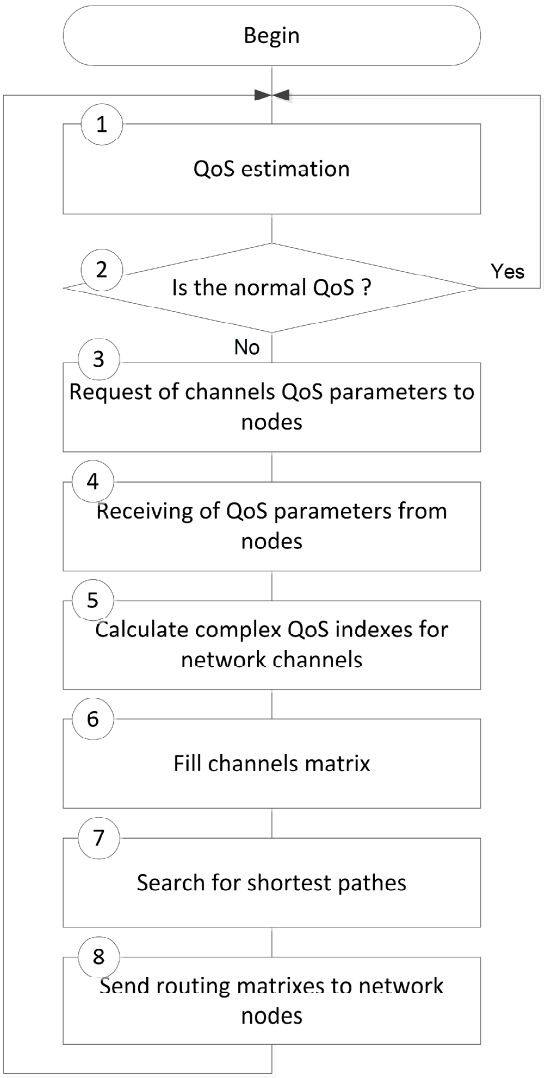

Fig.2. Algorithm of selection traffic transmission routes

1. The control algorithm assumes control of the current quality of service of traffic.

2. If the traffic quality of service does not meet the standard (below a predetermined level), then the request of parameters' value of channels is initiated from the control elements (nodes).

3, 4. Control elements (nodes) collect the necessary data on the channel quality parameters and sent them to the control center.

5. Based on the values of the quality parameters of the channels, which are received from the control elements, the control center calculates the complex quality indicators Q_{ij} channels in accordance with the chosen methodology.

6. Based on the calculated integrated indicators of channel quality, matrix of channel C of n x n is filled, where n - the number of managed elements. Each of the elements C_{ij} matrix is equivalent to complex index of quality Q_{ij}.

$$C_{ij} = \begin{cases} 0 & i = j \\ Q_{ij} & \\ \infty & \text{in the absence of channel} \end{cases}$$

7. On the basis of the data matrix C, search for the shortest paths is produced. To find the shortest paths, Floyd algorithm is used [21].

for $i \in n$

for $j \in n$

for $k \in n$

if $C_{ji} + C_{ik} < C_{jk}$

$C_{jk} = C_{ji} + C_{ik}$

$R_{jk} = i$

As a result, matrix R contains all shortest paths between nodes.

8. On the basis of results of the shortest paths search, the routing table is formed for all nodes in the network and sent to these nodes on the control channel.

IV. The Method of Evaluating the Traffic Quality of Service

The quality of traffic transmission path is estimated on the basis of indicator.

An indicator of the service traffic quality is packet error ratio (PER).

$$PER = \frac{N_{ER}}{N}$$

where N_{ER} - the number of lost packets and packets received with errors,

N - total number of packets transmitted.

Route quality is not satisfactory, if the packet error ratio exceeds PER_{max} characteristic value within the predetermined time interval T.

V. The Method of Weighted Evaluation of a Complex Channel Quality Indicator

Integrated channel quality indicator takes into account the following channel quality indicators:

- q_{RSSI} signal quality (based on the RSSI signal level);
- q_{PER} transmission quality (based on the packet error ratio - PER);
- q_{CAP} throughput (based on bandwidth - Capacity).

These indicators are calculated according to the measurement parameters:

- level signal (RSSI),
- coefficient packet error (PER),
- bandwidth (Capacity).

The values of all the quality indicators are provided to a range from 0 to 1. Where 0 represents the best possible value and 1 – the worst possible value.

$q_{RSSI} = 1\text{-}RSSI/RSSI_{max}$,

$q_{IPLR} = PER/PER_{max}$,

$q_{CAP} = 1\text{-}CAP/CAP_{max}$,

where $RSSI_{max}$ - the maximum possible value of the parameter RSSI;

PER_{max} - maximum value of PER (is determined according to test results, the initial value of 0.5);

CAP_{max} - the maximum possible channel bandwidth.

Integrated channel quality indicator is the sum of these quality indicators with weighting coefficients which take into account their significance. The weighting coefficients are determined by expert assessments and refined on the results of the test layouts.

Integrated channel quality indicator is estimated at Q, which can take values from 0 to 1. The minimum value corresponds to the highest quality channel.

$$Q = k_{RSSI} \cdot q_{RSSI} + k_{PER} \cdot q_{PER} + k_{CAP} \cdot q_{CAP}, \quad k_{RSSI} + k_{PER} + k_{CAP} = 1$$

where k_{RSSI} - weighting coefficient of signal level indicator;

k_{PER} - weighting coefficient of packet error;

k_{CAP} - weighting coefficient of throughput.

The weighting coefficients are determined by expert assessments and refined based on the results of tests layouts (the original meaning of the coefficients 1/3).

VI. Improvement of the Communication Sustainability of the Multi-Agents System with the Control Center

Communication of system agents with control center is provided by the paths, which in general can include multiple hops: control center - one or more hops (agents) - the destination agent. The quality of information channels in the route is determined by the location of system elements in space and state of the frequency channel used for communication (radio interference and congestion external radio systems). Given that IEEE 802.11 standard is selected for organization the information channel, which is widely used for organization the domestic, corporate and public networks PAN classes, in urban conditions its congestion with the external radio systems is of great importance.

Also it is important to take into account the specifics of management challenges and opportunities of technical realization of the system elements. It should be noted that the portion of the route between the control center and the first agent in the route differs significantly from route segments between system agents. This difference is due to the fact that there are quite strict limitations on the size and power consumption of the transceiver device agents. In relation to

communication means of the control center, there are no such restrictions. Therefore, the site of the route "control center - the first agent in the route" potentially has more resources than the other parts of the route.

The main factors determining the operation stability of the information channel are:

- attenuation of a signal in the propagation medium;
- fading caused by multipath propagation of the signal due to reflections from the elements of urban infrastructure;
- interference (noise) of signals from a nearby radio communication systems using the same radio standard.

Fading, which is caused by multipath propagation of the signal due to reflections from the elements of urban infrastructure, lead to a periodic (fast fading) degradation of the channel as a result of errors in data transfer. The most effective methods to combat fading, given the chosen technology communications and facilities of its use, is to change the location of the transceiver device (agent), or selecting a different frequency channel. In the first case the implementation of control functions of agent position is required, depending on the channel quality. In the second case the implementation of analysis functions and selection of frequency channels are required.

Thus, the RF channel selection task and the arrangement of connection between the agent and the control center largely affect the functioning of communication system parameters.

To solve these problems, it is proposed to implement transceiver control center module with two similar transceivers IEEE 802.1 b/g/n standards and two of the same type of antenna devices spaced. These devices are controlled by a controller that selects one of two possible modes of operation: reception and transmission of data and network monitoring (Fig.3).

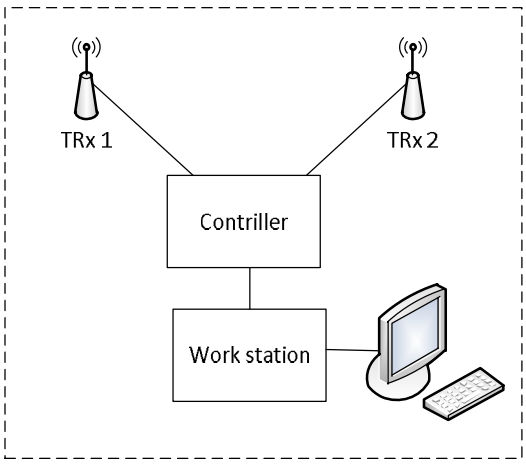

Fig.3. Structure of the means of organizing information channel with the control center

In a data transmission and reception mode, device provides the data delivery from the sources (information channel operation). In a network monitoring mode, device transmits information to the controller on the status of channels' radio frequency and the received signal level of the system elements.

The controller, based on the results of monitoring the data analysis, can decide to move to a different RF channel, as well as to change the functions of devices TRx 1 and TRx 2. To make a decision, the radio data about congestion ρ_i and the level of the received signal (*RSSI*) TRx 1 and TRx 2 devices is used.

Controller solution is based on the forecast of maximum throughput. The projected throughput is roughly estimated based on the received signal strength (*RSSI*), and a channel loading (ρ_i), as:

$$B(RSSI_j, \rho_i) = b(RSSI_j)(1 - \rho_i)$$

where ρ_i - channel loading;

$RSSI_j$ - level of the received signal device j (TRx 1 or TRx 2);

$b(RSSI_j)$ - dependence of the achievable bit rate of the signal level, according to the standard IEEE 802.11 b/g/n).

The decision on the selection of a channel number i and receiving devices j are defined as

$$(j,i) = \arg\max_{j,i} B(RSSI_j, \rho_i)$$

In order to prevent frequent switching, algorithm of changing channel and/or receiving device is performed, when there is a significant reduction in total quality index Q channel information. Functioning algorithm is shown in Fig.4.

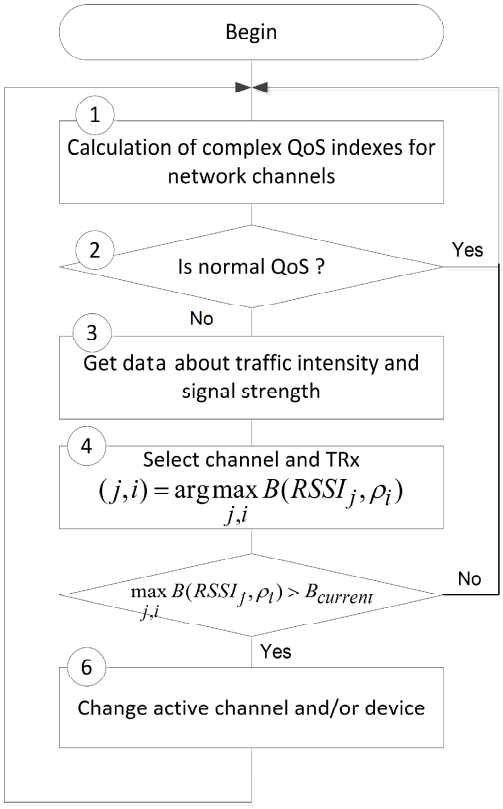

Fig.4 Algorithm of controller operation

The method described above can increase the stability of operation the communication system between the elements of the system by monitoring the conditions and using the methods of operating frequency changes and the location of transceiver antennas of control center.

VII. Future work

Results of our research shown that using of two different channels with different characteristics for control and information traffic service provide higher stability of the network structure and throughput then the ad-hoc network structure with one common channel. So, our future work aimed to improving of such network characteristics as throughput, quality of service and capacity (number of the network elements). To solve these tasks we propose to develop algorithms for optimal or near to optimal routing and power control solutions. We propose to use information about nodes coordinates, speed and movement direction to predict the optimal routing plan and apply it before the quality of channel degradation. On other hand increasing of functionality of the control system brings to the computational resources requirements and increases the control traffic intensity. So the other task is to reach compromise between the functionality of control system and resources requirements. In our opinion this compromise is application specific and may be different for different purposes. The next task is to improve efficiency of energy spending in nodes and control system. The energy consumption problem may be important in many specific applications. So the our future work directed to the system performance optimization for specific applications and requirements.

VIII. Conclusions

The self-organizing communication network between agents of the multi-system which is presented in the article includes the following major decisions:

1. The use of two radio bearers which have different specifications for implementing control tasks and task of information transmission which possesses the higher bandwidth requirements between agents. It is proposed to use radio frequency of 433 or 868 MHz with a bandwidth of up to 250 kbit/s for the organization of the control channel and data telemetry. For data transmission with higher bandwidth requirements, organization wideband channel at 2.4 GHz is proposed, with a throughput of up to 50 Mbit/s.

2. The algorithm of self-organizing network assumes control of wideband channel quality. By reducing the channel quality indicator, it is assumed to rebuild execution procedure of the network structure, in which the network elements (agents) can serve as relay wideband channel.

3. The self-organizing algorithm involves a comprehensive assessment of the quality of functioning channels between network elements (agents). Comprehensive Quality Score is calculated based on the data channel parameters: the level of received signal strength indicator (RSSI), Capacity and packet error ratio (PER).

4. To improve the sustainability of the information channel network monitoring is used and implemented and the functions of selection and change of the working frequency channel are realized as well as the choice of the transceiver and the antenna device as part of the control center.

Acknowledgment

The work is supported by the Russian Ministry of Education in the framework of the Federal Target Program “Research and development on priority directions of scientific-technological complex of Russia for 2014-2020” on the project “Development of methods and algorithms for adaptive motion control of multi spherical robots increased maneuverability in the face of uncertainty and significant external disturbances” (unique identifier project RFMEFI61315X0047).

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