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Scientific and Technological Experiments on Automatic Space Vehicles and Small Satellites

Multi-agent planning of the network traffic between nanosatellites and ground stations

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Abstract

Multi-agent technologies application for adaptive planning of communication sessions establishment requests with nanosatellites in the ground stations network in response to the arising events, considering constraints, is considered. Mathematical problem statement of adaptive communication sessions scheduling is given. Method of coupled interactions extension based on the demand-resource networks model for operative requests allocation for communication sessions between ground stations and nanosatellites implementation is described.

Peer-review under responsibility of organizing committee of the Scientific and Technological Experiments on Automatic Space Vehicles and Small Satellites (SPEXP2014)

Keywords: multi-agent technology, nanosatellite, communication session, ground station, planning (scheduling).

1. Introduction

Space service market growth caused by an increasing information demand that is necessary for decision making in different areas of business activities, results in the increased competition between its participants, which have to provide their services promptly, with high quality and low costs. Therefore, creation and application of multi-satellite orbit groups that consist of small-scale spacecrafts becomes one of the most promising trends.

The number of projects based on the small-scale spacecrafts (nanosatellites) is constantly growing, because nanosatellites groups application allows to solve current problems on the whole new level, opening new

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development prospects for space-based global services that are often called "space Internet". QB-50 project is a typical example, started by Von Karman Institute (VKI) with European space agency support and EU Seventh Framework Program financing. This project contemplates orbit group of 50 nanosatellites creation, designed for Earth thermosphere condition monitoring [1].

In order to provide target operation for created space systems, it is necessary to solve problems of communication sessions establishment for real time data receipt and commands transfer. Approaches used today are centralized and static and for each nanosatellite there is a ground transceiving station and communication sessions order is defined beforehand. There is an alternative solution – dynamic communication sessions allocation to a ground stations set. This approach will allow to adaptively reallocate tasks for communication sessions establishment in reaction to the arising events, such as new ground station appearance or urgent task for datadump from satellites.

2. Problem statement

In this paper, communication sessions adaptive planning is a process of ground transceiving station rescheduling in response to the arising events and considering the constraints. Let there be given a set of ground transceiving stations (GTS) from nanosatellites group. Each GTS can have several transceiving antennas with different characteristics for connection establishment with nanosatellites of the correspondent type. GTS can have communication session with only one nanosatellites at a time. GTS have its operation schedule and one or several operators service it. GTS operation schedule consists of shifts. A shift is a fixed time interval that defines GTS operation start and ending (e.g. Shift 1: starts July 15, 2014 at 8 a.m. local time, ends: July 15, 2014 at 6 p.m. local time). Each shift is formed according to the schedule (e.g. GTS works only working days from 8 a.m. till 6 p.m. local time). GTS set has a dynamic structure and its elements can join or leave the common network at any time. Requests for communication sessions with nanosatellites come into GTS network. A request is an assignment of receipt/transition of the set data amount to a nanosatellite with the specified time interval when this task should be performed. Execution time of communication session request can be different for each GTS, because it depends on the equipment type used on the GTS and nanosatellite. The request can only be performed during one GTS shift. It is necessary to operatively adapt the GTS operation schedule for communication sessions establishment for data transmitting/receipt with nanosatellites in response to the arising events and considering all the constraints so the communication sessions are performed in the short term, providing the maximum workload of each GTS shift.

List of the arising events:

- new request for data transmitting/receipt with nanosatellite;
- planned request for data transmitting/receipt from nanosatellite is deleted;
- new GTS appearance;
- GTS deletion;
- changes in the GTS operation schedule.

List of constraints:

- technical characteristics of the transceiving devises of GTS and nanosatellite (communication session is only possible if the transceiving devices technically match);
- GTS and nanosatellites visibility intervals;
- antenna complex targeting time on the certain nanosatellite, preparation time for the engineering software tools of data processing;
- GTS operation schedule.

Mathematical problem statement can be formulated as following:

$$I = K_p \frac{\sum_{j=1}^{M} I_j^M}{M} + (1\text{-}k_p)\frac{\sum_{j=1}^{S} I_j^S}{S} \to max, \quad (1)$$

Where I is system's objective function, $k_p \in [0.1]$ is a balance coefficient between communication sessions efficiency and GTS shifts workload; j – request number, M – amount of the submitted requests for communication sessions; S – number of GTS shifts, that are engaged in the communication sessions performance; I_j^M - satisfaction

criterion of request *j* execution:

$$\begin{cases} I^M = 1 - \dfrac{t_p - t_s}{t_f - t_s}, \text{если } t_p \in [t_s, t_s - p_k] \\ \text{иначе } I^M = 0 \end{cases}, \quad (2)$$

Where t_p is a planned communication session starting time; t_s - left border of the interval; t_f - right border of the interval; p_k - request performance time on the chosen GTS. If the request for communication session is not scheduled on any of the GTS, then t_p is not defined.

GTS shift workload criterion can be represented as:

$$I^S = \frac{\sum_{k=1}^{W} p_k}{T}, \quad (3)$$

Where W is a number of the planned requests in the GTS shift; p_k - performance time of the scheduled request on the GTS; T – time interval for which the shift workload is calculated, e.g. GTS shift duration.

Request execution time on GTS depends on the equipment type of the ground station and nanosatellite and can be represented as following:

$$p_k = F(M, S), \quad (4)$$

Where $F(M, S)$ is a display function, which sets up a correspondence between a pair "ground station – request" and request execution time. Request execution time includes antenna complex targeting time on the certain nanosatellite and preparation time for the engineering software tools of GTS data processing.

This problem statement initially contains a conflict between the aims of the two main entities: requests for communication sessions and GTS shifts: the requests try to be executed as soon as possible and GTS shift wants maximum workload on the specified time interval.

Therefore, it is required to develop such models, methods and algorithms, which depending on the balance coefficient between communication sessions efficiency and GTS workload and incoming in real time events would allocate the requests for communication sessions between a set of ground stations as soon as possible in order to satisfy the given criteria of requests execution efficiency and GTS shifts workload.

3. DRN-model for communication sessions scheduling problem solution

Real-time resource allocation, scheduling and optimization problem is a typical example of complex and dynamic problems that are barely solved or not solved at all by the traditional mathematical methods and tools, characterized by the high uncertainty, have to operate in the constantly changing environment, they are badly structured and formalized, often have wrong data as the outcome, etc. For these tasks solution it is suggested to use multi-agent technologies based on the demand-resource networks (DRN) [2, 3].

There are demand and resource agents (roles) in the DRN that represent entities with the opposing interests. They operate on the virtual market of the system based on the economic reasoning and can both compete and cooperate with each other (e.g. two ground stations can compete for one request or one request for a big data amount transmission can require several ground stations cooperation). The demands and resources of its elements (in the simplest case - orders and resources that want to find each other and set the connections) form DRN-network.

DRN-model complexity can increase by the introduction of new classes of agents that represent interests of different physical or abstract entities, which are necessary for network operation, and by with the increase in umber and diversity of classes of agents communication protocols [4].

Center of agents' interaction lies in the common virtual market, where agents can buy or sell their services, based on the economic feasibility. Constant activity of the network agents, both from the demands and resources sides, causes multi-party negotiations on the virtual market that go on in a quasiparallel mode. Agents decision-making and connections establishment between the for tasks solution that continuously appear when a new event arrives, cause changes in the operation conditions for other agents and therefore it defines the process of system self-organization that leads to the rescheduling in response to the events.

In the ground stations management model, there can be singled out entities that have demands (e.g., a request for communication session wants to be successfully scheduled considering all the constraints and be executed as soon as possible) and resources (e.g. ground station can perform communication sessions with the satellites of the corresponding types and to have a maximum workload). Each demand or resource can be associated with a program agent. Agents form the DRN-network that represents a self-organized resource allocation schedule (GTS shifts) by tasks (requests), open to any corrections. When a new event occur, demand and resource agents adaptive reconnection can happen in the DRN-network, which ends when a trade-off between agents is found and no agent can improve the situation. An ability to adaptively build and execute schedules, when the schedule is not built every time when a new event comes (as it is done in the classical optimization methods), but it is corrected in rea time when the events arrive.

Method of coupled interactions for DRN-network support is developed in the course of the multi-agent approach [3].

This method can be applied to the dynamic resource scheduling of any kind [5, 6].

4. Method of communication sessions adaptive scheduling

As a development of the method of coupled interactions, a method of operative requests allocation for communication sessions between ground stations is suggested for satisfaction of the given criteria of requests execution efficiency and GTS shifts workload [7, 8].

As applied to the problem of workload distribution between the ground stations? There can be singled out the following list of main agents:

1. Request agent for communication session that is responsible for the search and choice of GTS that meets the set criteria and constraints, has the following characteristics:
   - type – demand agent;
   - purpose – schedule a communication session with the satellite as soon as possible, bu in the specifies time interval;
   - preferences and constraints: GTS with the acceptable transceiving device type are required for the execution.
2. Ground station agent that is responsible for shift agents creation. Its purpose is to provide constraints connected to the creation of GTS shifts agents that do not fit in the GTS operation schedule.
3. GTS shift agent that is responsible for the requests allocation, shift schedule design, GTS shift workload and has the following characteristics:
   - type – resource agent;
   - purpose – to have a maximum workload;
   - preferences and constraints: operation duration (e.g. 8-hours working day).

Basic principles of the suggested method of operative requests allocation for communication sessions between ground stations for satisfaction of the given criteria of requests execution efficiency and GTS shifts workload are the following:

1. Agents of the corresponding types are created for each communication session request, ground station and GTS shift.
2. When new events connected to the unscheduled requests arrival (new request input, request removal from the GTS shift) occur, their operative allocation happens with the goal of the fast receipt of the first version of communication sessions schedule.
3. Requests allocation for communication sessions between ground stations is divided into several sub-processes that are executed concurrently by the objective function formula:

- sub-process of location of objective function maximum for each request by the operability of communication session performance (2);
- sub-process of location of objective function maximum for each GTS shift by the GTS shift workload (3).

4. Request agents are responsible for the location of objective function maximum for each request (2) by negotiations, discovering and resolution of conflicts with GTS shifts agents.
5. GTS shifts agents are responsible for location of objective function maximum for each GTS shift (3) by negotiations, discovering and resolution of conflicts with request agents.
6. Request agents choose only those GTS shifts agents for negotiations, whose working hours intersect with request execution period.
7. GTS shifts agents choose only those request agents for negotiations, whose time intersect with GTS shift working hours.
8. The key rule for GTS operation schedule changes is a condition, which stated that the total amount of all the improvements must exceed or minimize the total amount of the deteriorations, caused by the new event.
9. After the occurrence of new events, only those request and GTS shifts agents are trying to improve their position, who have the interests on the specified time interval, where the event has occurred,
10. Workload distribution process between ground stations network is considered complete when none of the request of GTS shift agents can improve their state (the request cannot be scheduled for the earlier date; GTS shift cannot increase its workload).

5. Agents interaction scheme during the operative unscheduled requests allocation in the ground station network

1. A Unscheduled request agent collects information about the existing GTA shifts agents and requests possible allocation intervals from them.
2. After receiving the request about allocation intervals, GTS shift agent calculates visibility intervals for communication session, determines compatibility of the transceiving devices, subtracts intervals that are already occupied by the current requests from the visibility intervals and sends the resulting intervals back to the request agent.
3. Analyzing the resulting allocation intervals, request agent calculates communication session time for each GTS and sends a request to that GTS shift agents, which will provide request allocation in accordance with the fast execution criterion.
4. GTS shift agent that received a request allocation inquiry, checks the possibility of changing the operation schedule of GTS shift. If it is impossible to allocate the request in the given interval or it was successfully allocated in the shift schedule, then GTS informs the correspondent request agent.
5. If request agent cannot find the appropriate GTS shift for allocation, it collects the information about the existing GTS station agents and requests possible allocation intervals.
6. After receiving allocation intervals request, GTS station agent analyzes the amount of time that is necessary for the communication session and creates a correspondent GTS shift agent. After that, it redirects the request about possible allocation intervals to it.
7. It in the search process request agent cannot find the possible allocation intervals, then the request remains unscheduled and the search algorithm is initiated in case of the new events occurrence (new station appearance, removal of the other scheduled request, other request reallocation.

Agents interaction scheme during the operative unscheduled requests allocation in the ground station network is shown in the Figure 1.

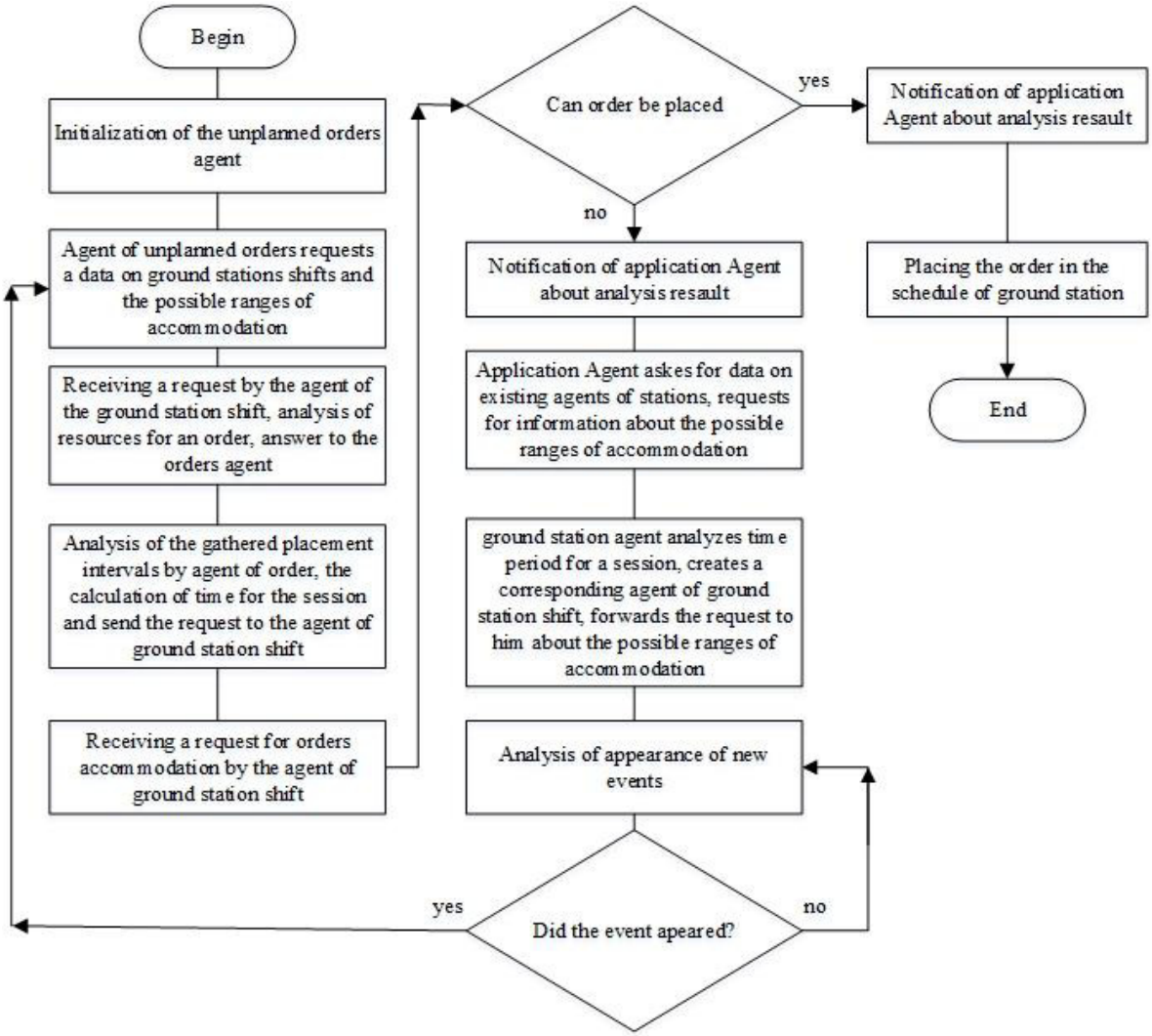

Fig. 1 - Agents interaction scheme during the operative unscheduled requests allocation in the ground station network

6. Agents interaction scheme during the location of the objective function maximum by the communication session performance operability

1. Ack In order to optimize system's objective function value (1), scheduled request agent sends a request to the GTS shifts agents about available allocation intervals for the early scheduling considering the constraints.
2. After receiving the available in the other GTS shift allocation intervals, request agent calculates its objective function value (2).
3. If request agent finds allocation interval in the other GTS shift that improves its objective function (2), then it sends a request to the GTS shift, which has a scheduled request, demanding to give a value reduction evaluation (3) when the request is taken off the GTS shift, considering current workload balance coefficient.
4. After receiving the value reduction evaluation (3) of the GTS shift, which had the allocated request, request agent evaluates the benefits of the transition by the system's objective function value (1).

5. If the request transition increases system objective function value (1), then new GTS shift agent receives an inquiry on this request allocation.

6. After receiving the allocation inquiry about the new request, new GTS shift agent checks if the situation changed during the negotiations with the request agent. If the situation changed, then there is a conflict and request agent receives a rejection in new allocation, otherwise, the request is allocated in the new GTS shift and it is removed from the old one.

7. If GTS shift agent have no more scheduled communication sessions, then it finishes its operation.

8. If there occurred events, connected to the condition changes in the interval that is a part of the request performance interval, the objective function optimization process by the operability of the communication session is repeated (Figure 2).

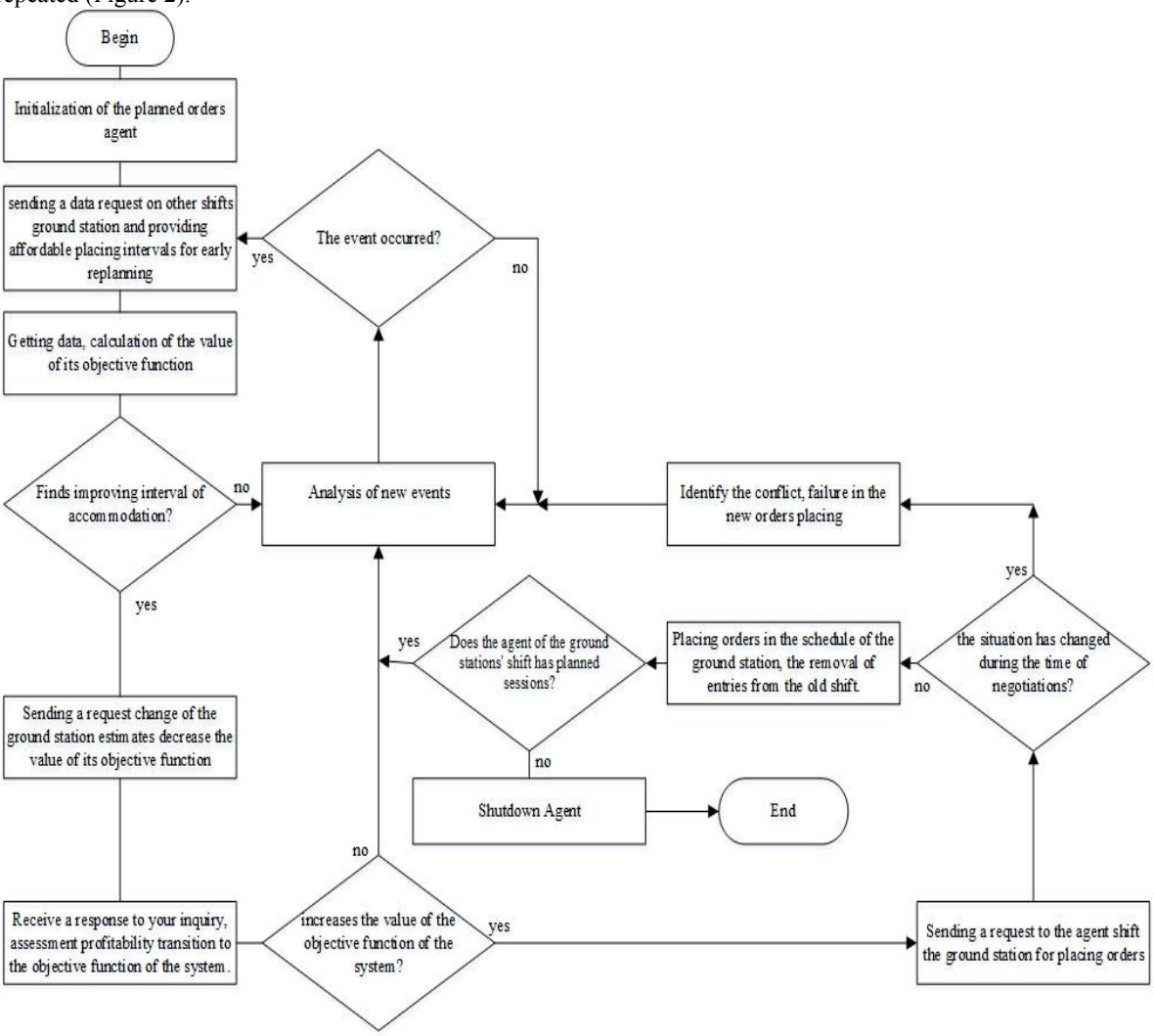

Fig. 2 - Agents interaction scheme during the location of the objective function maximum by the communication session performance operability

7. Agents interaction scheme during the location of the objective function maximum by the GTS shift workload

1. In order to optimize the value of the system objective function (1), GTS shift agent sends an inquiry to the other GTS shift agents about their workload.
2. After receiving workload values from other GTS shifts, GTS shift agent determines the shifts that are loaded less than his are and sends them its intervals.
3. Based on the received from other shifts available intervals, GTS shift agent evaluates the possibility to transfer all its requests to other shifts.
4. If it is possible to transfer all the requests to other shifts, then each request objective function reduction value (2) is evaluated in connection with transfer.
5. If the total amount of the objective function reductions of the shift (2), connected to the transfer, is less than the profits from the shift "removal", then the requests are transferred and this shift is deleted.
6. If the events, connected to the conditions changes on the interval that is a part of the shift working hours, occurred, then objective function optimization process by GTS shift workload is repeated (Figure 3).

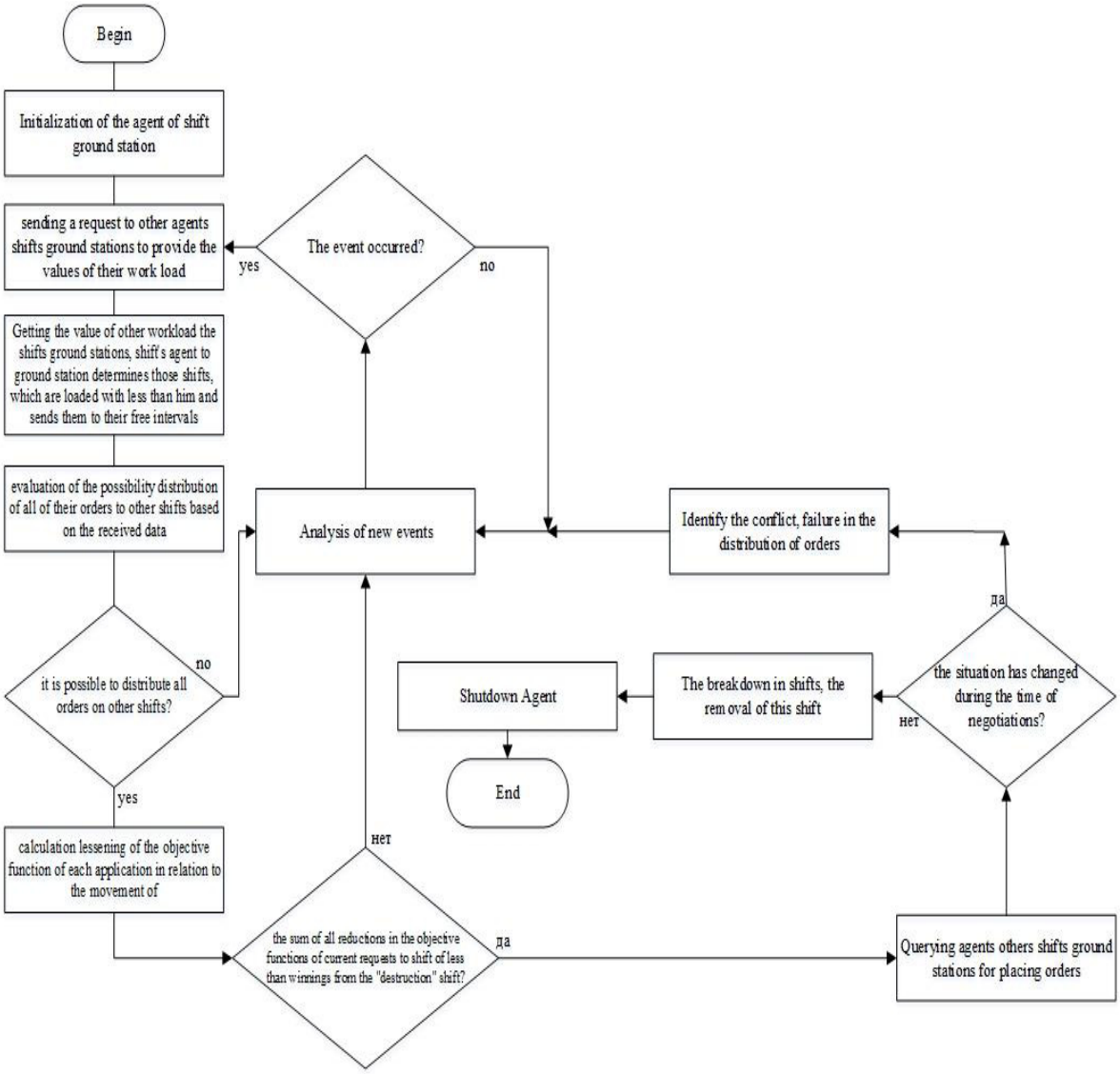

Fig. 3 - Agents interaction scheme during the location of the objective function maximum by the GTS shift workload.

8. Multi-agent system description

Ac For the implementation of multi-agent methods for planning of communication sessions between nano-satellites and ground stations that transmit/receive data is created an experimental model (EM) of multi-agent system, built on an open multi-agent platform JADE. This EM allows to calculate the orbit of any nanosatellite, the data for which is presented in the system NORAD in TLE format. EM contains the database of the source data for the calculation of the orbits of nanosatellites. In order to maintain the current state of nanosatellites orbit the database is updated periodically with the NORAD server. From this database, you can select the interesting nanosatellites for modeling. There is a database for the ground stations (about 100 known locations of ground stations). From this database, a needed network of ground stations can created. Ground stations can also be created, by manually entering their coordinates (name, longitude, latitude, altitude). EM allows you to simulate the motion of

nanosatellites selected from the database. Simulation can be performed in real time, if necessary to determine the position of nanosatellite at the current time, or in the model time if necessary to determine the position of the satellite at the specified date in the future or in the past. All trajectories of the orbits of the selected nanosatellites and ground stations are presented using 3D-visualization based on the engine JAVA WorldWind. EM allows to calculate the intervals of sight between ground stations and nanosatellites, presenting this information in the form of a Gantt chart. According to the statement of the problem, EM allows to enter the orders to host the session, defying the time interval when it should be performed. Applications based on the entered showtimes communication between ground stations and nanosatellites.

EM of multi-agent system allows to build a work schedule stations to serve orders for communication sessions on the basis of negotiation agents. For each of the ground station selected from the database creates a corresponding agent of ground station and for selected order - the agent of order. These agents communicate with each other to meet their needs, for example if a new order appears or it removed from any ground station, the agent of the application begins to carry out negotiations with all the agents of the ground stations, with a view to optimal placement. These negotiations are based on the ContractNet interaction protocol, described in the specification of FIPA multi-agent platform. Using EM multi-agent system, the emergencies can be simulated related to the failure of the ground stations, with the assessment of the possibility of rescheduling of the applications for other ground stations.

Figure 4 shows the main window of the multi-agent system for scheduling the communication sessions between nano-satellites and ground stations.

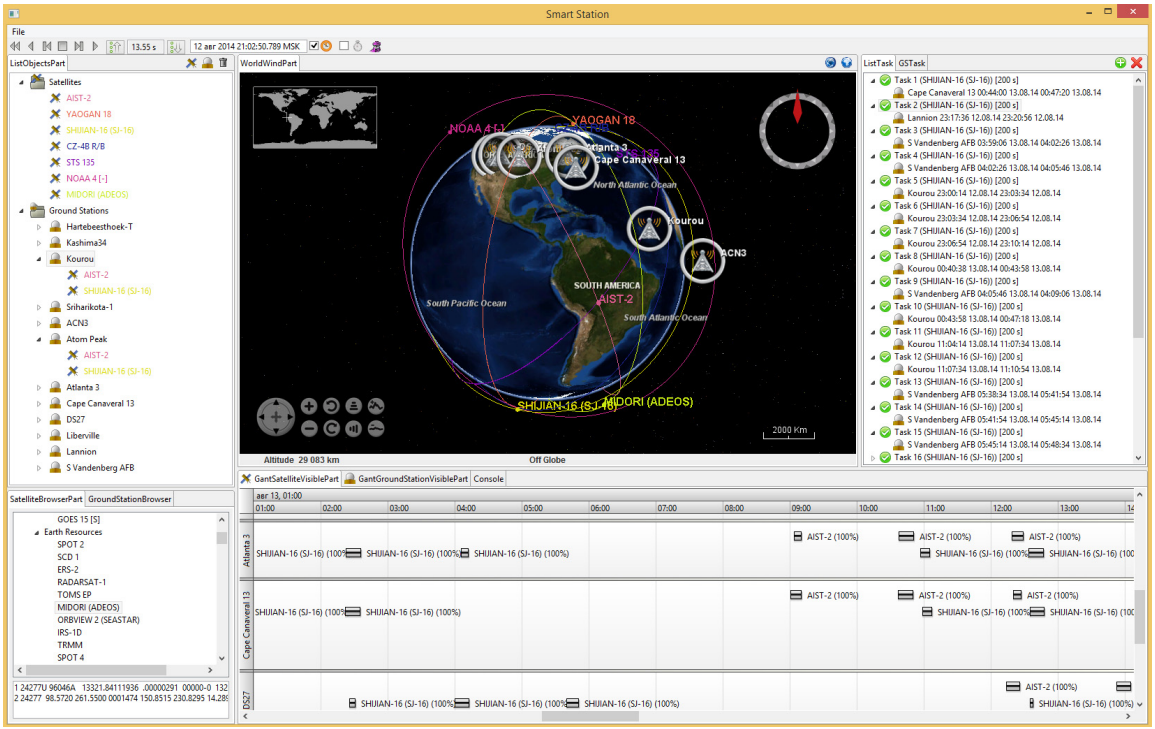

Fig. 4 - The main window of the multi-agent system for scheduling of communication sessions between nanosatellites and ground stations

9. Results of experiment

A To test the described methods of planning the experiment was conducted in which assessed the efficiency of the EM on the scheduling of communication sessions between three spacecraft and two ground stations. In addition, for comparison, we considered two ways to construct the desired schedule: using the algorithm of multi-agent planning described above and by complete enumeration of options to deploy elements of the plan. The cyclogram of

visibility of selected spacecraft and ground stations is shown on Picture 5.

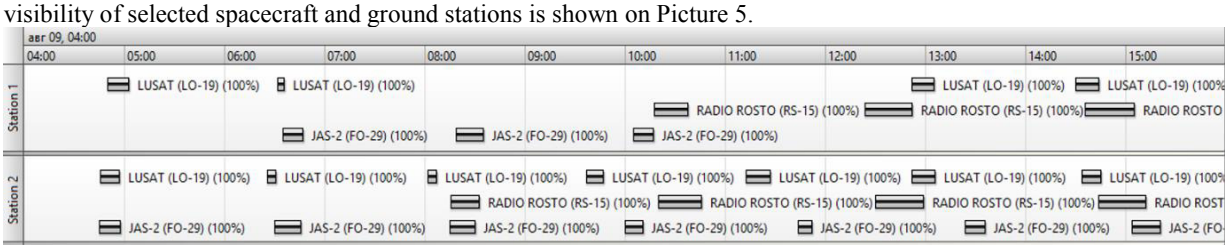

Figure 5 – The cyclogram of visibility of nano-satellites and ground stations

The comparison of the schedules obtained in the course of the experiment was performed in accordance with the criterion of efficiency of communication sessions with $k_p = 1$, the duration of each shift on ground station was 12 hours. The experiment was conducted alternately with planning 1-10 orders; parameters are listed in Table 1.

Table 1 – Orders parameters

№	Nani-satellite	Time of occurrence	Data amount, KB
1	JAS-2	2014.08.09 6:45	950
2	RADIO ROSTO	2014.08.09 6:42	300
3	RADIO ROSTO	2014.08.09 7:21	500
4	RADIO ROSTO	2014.08.09 7:05	400
5	LUSAT	2014.08.09 7:46	800
6	LUSAT	2014.08.09 7:55	700
7	JAS-2	2014.08.09 7:10	600
8	LUSAT	2014.08.09 7:32	900
9	JAS-2	2014.08.09 6:30	500
10	RADIO ROSTO	2014.08.09 6:40	700

The experimental results are shown in Table 2.

Table 2 - Results of experiment

Number of tasks	The objective function value		Schedulling time, sec	
	MAS	Exhaustive search	MAS	Exhaustive search
1	0,837	0,837	0,33	0,15
2	0,847	0,847	0,36	0,31
3	0,784	0,82	0,41	0,5
4	0,78	0,81	0,5	0,7
5	0,784	0,831	0,85	1,6
6	0,785	0,824	0,89	1,9
7	0,77	0,803	1,2	2,3
8	0,744	0,79	1,6	4
9	0,746	0,79	2,1	18
10	0,755	0,78	2,4	89

The chart of dependencies between objective function value and amount of orders is shown on Figure 6.

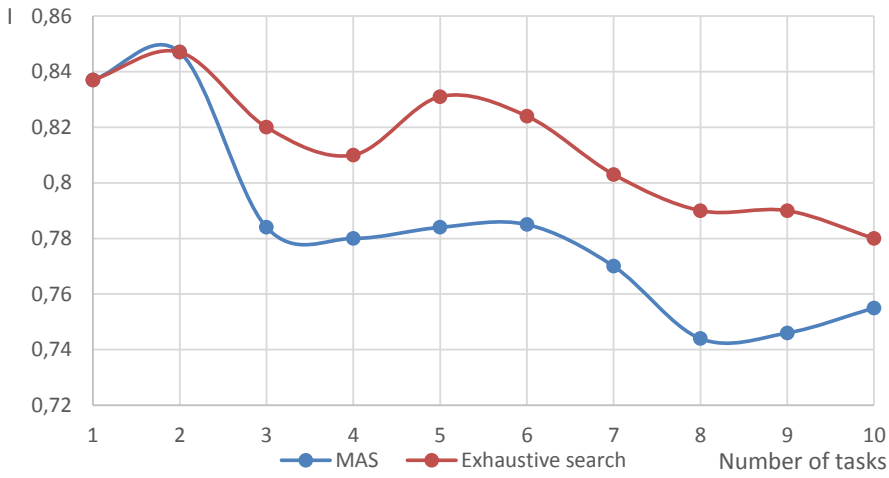

Figure 6 – The chart of dependency between objective function value and amount of orders

The dependency between scheduling time and amount of orders is shown on Figure 7.

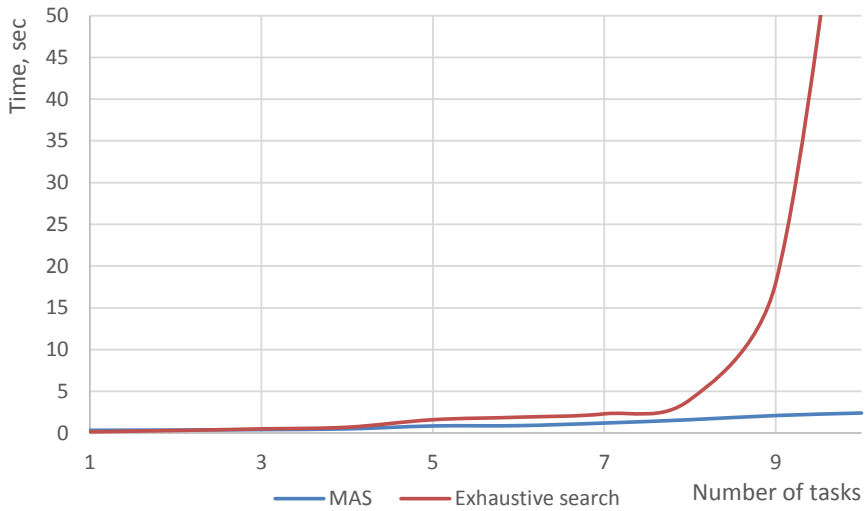

Figure 7 – The dependency between scheduling time and amount of orders

Based on these data, we can make the following conclusions:

1. Multiagent scheduling algorithm of communication sessions allows us to find approximate solutions, slightly lower than optimal (obtained after complete enumeration of options).

2. Using the multi-agent algorithm can significantly reduce the time spent on the construction of a suitable schedule, even with an increase in dimension of the problem, which distinguishes this method from a solution by complete enumeration.

Conclusion

On the basis of these methods and algorithms an experimental model of multi-agent system is developed on the base of JADE platform, to evaluate the use of multi-agent technology to solve the problem of adaptive reallocation of orders for communication sessions in a network of ground stations. The solution of this problem will allow to achieve high flexibility and efficiency in the service of space nanosatellites systems, especially with apriori uncertainty in the changes of supply and demand on the transferred amount of data and high-level dynamics in the occurrence of unanticipated events, complicating the use of traditional methods of optimization.

Acknowledgements

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