Real Time Scheduling of Data Transmission Sessions in a Microsatellites Swarm and Ground Stations Network Based on Multi-Agent Technology

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Abstract: The problem of designing an effective models and methods for data transmission between group of microsatellites and network of ground stations in the dynamically changing environment is considered. Multi-agent technology for solving the problem by adaptive resource allocation and scheduling is proposed. It is shown that solution of the considered complex problem evolutionary emerges from interaction and trade-offs of many agents which continuously self-organize themselves and change decisions to improve their objectives and the objectives of the system as a whole. The advantages of multi-agent solution are high adaptability, flexibility and efficiency of services. The main classes of agents, ontology of problem domain, interaction protocols, results of first experiments with system prototype and key benefits of proposed system are discussed.

1 INTRODUCTION

Recent achievements in miniaturization of satellites components made easy access to space for SME and universities. As the result, a new class of satellites called small-scale have appeared. The current classification of such satellites has formed by their weight characteristics: pico-satellites - under 1 kg, nano-satellites - from 1 to 10 kg, microsatellites - from 10 to 100 kg, mini-satellites - from 100 to 500 kg and small SC - from 500 to 1000 kg.

New trend of small satellites industry is characterized by designing microsatellites swarms, capable of continuous earth surface monitoring, resolve navigation and telecommunication issues, etc. The small satellites swarms can dramatically change the market of space systems and provide new low-cost services comparing to the ones that are implemented today (Zinchenko, 2011, Global Navigation Satellite Systems, 2012). On the other hand, increased number of microsatellites in orbit results in overload of management systems and the necessity to process large amounts of target information. Under these circumstances, a problem of scheduling the timely data transfer from microsatellites to the ground stations becomes one of the most urgent.

In this paper the multi-agent technology for solving the problem by adaptive resource allocation and scheduling is proposed. It will be shown that solution of the considered complex problem could evolutionary emerge from interaction and trade-offs of many agents which continuously change decisions to improve their objectives and the objectives of the system as a whole.

The paper is organized as follows. First part will formalize the problem statement and give method of scheduling based on multi-agent technology. The second part will consider the architecture of multi-agent system for problem solving including specific classes of agents and protocols of their interaction. The third part will present results of first experiments with software prototype of the system.

At the end the key benefits of proposed system and future steps will be discussed.

2 PROBLEM STATEMENT

Let's consider a swarm of microsatellites that belongs to different types of users (e.g. several universities, SME, ERS operators, etc.) and focused on getting the information from microsatellites and on data transceiving to the ground stations.

Microsatellites swarm functionality can change in time (some of them break down, the new ones are launched, etc.). Each microsatellite can have constraints of technical, organizational, financial or of any other character on the data transmission to the ground stations that belong to different developers. Therefore there is a group of available stations for data transfer and the group of temporary available stations. Let's assume that all ground stations have an ability to transmit the received information to another station with the use of Internet. Data transmission task is a task to transmit the specified data amount from one particular microsatellite in a given time period. Data transmission to the ground station should be proceeded by a communication sessions which need to be scheduled properly. It is necessary for the implementation of some preliminary work on the station, including the computation of target destinations for antenna aiming to a certain satellite, preparation of engineering software tools for processing of incoming information, etc.

The main idea of the suggested development is to design a method of real time scheduling for microsatellites data transmittion sessions to ground stations system with dynamic constraints. Duration of communication sessions between microsatellites and ground stations is one of the key factors that affect monitoring performance and data delivery efficiency. Therefore, data delivery to the ground stations optimization influences directly satellites efficiency.

The main objective for sarm is to provide the efficient data transmittion from microsatellites at the required time with the minimum delay from the moment of on-board data receipt. At the same time, system should adaptively correct schedule for each station, considering the unpredictable events: failures on a satellite, station equipment failure, new VIP user request on data receipt, etc. If unexpected events have occurred on one of the stations, its tasks should be redistributed between other stations of the network.

The considered problem of data transmission sessions scheduling between many microsatellites and ground stations can be more formally formulated in the following way. There must be provided data flow Φ maximization in the microsatellites system N on the time horizon T for M stations:

$$\Phi = \sum_{j=1}^{M}\sum_{i=1}^{N}\int_{0}^{T} rate_{ij}(t)\cdot link_{ij}(t)\cdot schedule_{ij}(t)dt, \qquad (1)$$

where $rate_{ij}(t)$ is a speed of data transfer from microsatellite i to ground station j, $link_{ij}(t)$ is a mutual data transfer efficiency from microsatellite to ground station, $schedule_{ij}(t)$ – duration of data transfer between the i-th microsatellite and j-th ground station, planned according to the intervals of their mutual visibility.

Therefore, a solution of the above problem requires coordinated real time scheduling of tasks in the stations and microsatellites network.

3 MULTI-AGENT TECHNOLOGY FOR PROBLEM SOLVING

Traditional centralized planning is based on classical mathematical methods, for example, linear and dynamic programming, discrete optimization, constraint programming, etc.

But it is well-known that such type of problems is NP-hard and that is why a number of a new heuristic and metaheuristic scheduling models, methods and algorithms appeared, such as greedy methods and other various methods of local optimization, neural networks and genetic algorithms as well as other evolutional computations, simulated annealing, tabu search, ant search, mixed miscellaneous metaheuristics and many others (Leung, J. YT. (ed .), 2004).

However, there is still a gap with the market requirements because all orders and resources need to be known in advance and processed in batch mode which it is not a case in real life.

Multi-agent technologies allow to solve complex problems evolutionary on the fly, according to new unpredictable events coming in a real time (Wooldridge, 2009, Rzevski, Skobelev, 2014).

In developed approach,system will receive orders in real time as well as a flow of other unpredictable events: order cancellations, unavailability of resources, failures or delays etc.

The plan for resource usage has to be dynamically formed and continuously and adaptively revised taking into consideration individual set of criteria, characteristics, preferences and constraints of orders and resources. The full cycle of satellites and stations management must include fast reaction to new events, allocation of orders to resources, scheduling of orders/resources, optimization of orders (if time is available), communication with users, monitoring of plan execution, re-scheduling in case of a growing gap between the plan and reality.

The revision of the schedule must be made by the allocation of operations to open time slots or by solving conflicts between operations that can be shifted to previously allocated resource or re-allocated / swapped to the new resources.

Communication with users means supporting a dialogue with the users via mobile phones or other tools initiated by either side at any time.

The developed approach is based on a "holon" concept of PROSA system (Brussel, 1998) where specific classes of agents of "orders", "products" and "resources" were introduced as well as a "staff" agent which monitors results and advises other agents when required.

To make this approach more flexible and efficient the concept of Demand-Supply Networks (DSN) was introduced where agents of demands and supply are competing and cooperating on Virtual Market (VM). In the concept any agent (holon) of physical or abstract entity can generate "small" demand and supply agents, which follow the specific requirements.

As a result, the schedule can be formed as a kind of requirement-driven network of operations which can be easily adapted by events in real time (Skobelev, Vittikh, 2003, Skobelev, Vittikh, 2009).

The core part of the method of adaptive scheduling can be identified as the following:

1. The number of classes of demand and supply agents represents specifics of the problem domain with the required level of granularity.
2. Satisfaction function and function of bonuses / penalties are represented by linear combination of multi-criteria objectives, preferences and constraints of each agent.
3. Protocols are defined which specify how to identify conflicts and find trade-offs with the open slots, shifts and swaps of operations.
4. A schedule formed in the process of DSN agents self-organization is based on decision-making and interaction of agents.
5. Special event procession protocols are triggered when new events occur (for example, arrival of a new demand):
    a. An agent is allocated to a demand as it arrives into the system. The Demand Agent sends a message to all agents assigned to available resources stating that it requires a resource with particular features and it can pay for this resource with a certain amount of virtual money.
    b. All agents representing resources with all or some specified features and with the cost smaller or equal to the specified amount of money, offer them to the Demand Agent.
    c. The Demand Agent selects the most appropriate free resource from those on offer. If no suitable resource is free, the Demand Agent attempts to obtain a resource, which has already been linked to another demand, by offering to that demand some compensation.
    d. The Demand Agent who has been offered some compensation considers the offer. It accepts the offer only if the compensation enables it to obtain a different satisfactory resource and at the same time increase the overall value of the system.
    e. If the Demand Agent accepts the offer, it reorganises the previously established relationship between that demand and resource and search for a new relationship with resource increasing the overall value of the system.
    f. The same process is running for Resource agents which are able to generate Supply agents with specific context-based requirements.
6. The above process is repeated until all resources are linked to orders and there is no way for agents to improve their current state or until the time available is exhausted.

To achieve the best possible results agents use the virtual money that regulates their behaviour. The amount of virtual money can be increased by getting bonuses or decreased by penalties depending of their individual cost functions. The key rule of the designed VM is that any agent that is searching for a new better position in the schedule must compensate losses to other agents that change their allocations to resources, and propagation of such wave of changes is limited by virtual money (Skobelev, Vittikh, 2009).

Therefore, the final schedule is built as a dynamic balance of interests (consensus) of satellites and stations agents that negotiate for their position in the network schedule and plan their work by shifting and reallocating time slots with the view on their objectives and interest of the whole swarm.

4 MULTI-AGENT SYSTEM FOR SESSIONS SCHEDULING

4.1 Architecture of the System

Architecture of multi-agent system for communication sessions scheduling between microsatellites and ground stations network is sown in the Figure 1.

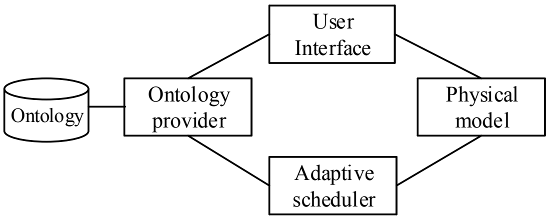

Figure 1: Architecture of multi-agent system for communication sessions scheduling.

The key components of the system include:

- Physical Model – a simulation component that is designed for Earth rotation simulation, calculation of satellites orbits and visibility intervals for microsatellites and ground stations.
- Adaptive scheduler – scheduling system, responsible for the forming and adaptive change of the data communication sessions schedule. Adaptive scheduler is based on the multi-agent technology and is implemented in Java Agent Development Framework (JADE) according to FIPA standards for intellectual agents (FIPA, 2014).
- Ontology provider – a component that allows to formalize problem domain knowledge by defining concepts and relation of the domain area represented in a form of semantic network;
- User Interface – provide possibility to make settings and visualize results of scheduling.

All components are developed in Java.

4.2 Ontology of Small Satellites and Ground Stations

An ontology is used to formalize the knowledge that is necessary for the agents to take decisions. According to our approach, knowledge should be separated from the program code of the system and kept in the ontology that represents a network of concepts and relations of the problem domain area (Huhns, 1997, Skobelev, 2012).

More specifically ontology in the developed approach hels to specify requirements for satellities and stations to make matching. Fragment of ontology of small satellities and networks is shown in the Figure 2 where it mainly includes microsatellite, ground station and tasks scheduled for the system.

Ontology helps to configure parameters of tasks, microsatellites and ground stations and set the rules of planning sessions between microsatellites and ground stations.

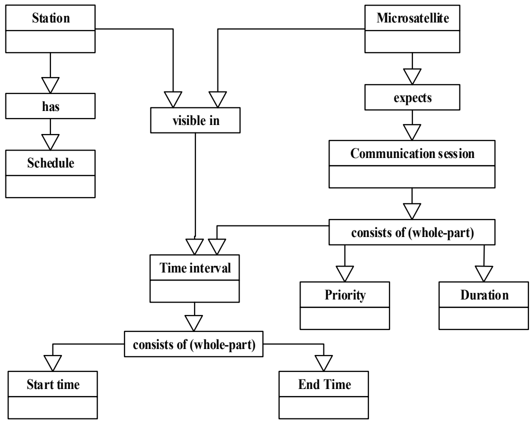

Figure 2: Ontology fragment of the multi-agent system for communication sessions scheduling.

According to this structure, each ground station has individual schedule where planned communication sessions with microsatellites and station operation schedule are displayed. Each communication session is characterized by priority, duration, performance status and time period when it need to be executed. Communication sessions can be possible only in certain time intervals, during which a direct visibility between a microsatellite and a station is maintained.

4.3 Agents Functionality

Each ground station is associated with a resource agent. Resource agent objective is to maximize profit and schedule maximum of sessions with the preference of own microsatellite tasks and providing minimum idle run of the equipment.

Each communication session is associated with a task agent. Task agent objective is to allocate to the best ground station, which parameters fully satisfy problem constraints with minimum costs. Task agent can react to the events, addition/removal of ground stations and tasks cancellations.

Satellite agent create session agents and is trying to maximize its own efficiency – to provide as much useful information as possible.

To provide the economy-driven reasoning, virtual market is introduced, where all decisions of agents are linked with virtual money. Each agent has an objective and bonus/penalty function.

The objective function represents satisfaction of the agent depending on the achievement of the objectives. Bonus/Penalty function sets a bonus for achieving ideal target objectives or a penalty for missing targets.

Each agent tries to maximize its satisfaction and increases the profit (virtual money) that he can spend for shifting other agents in the case of a conflict, which he tries to resolve in the interests of the system as a whole. Objective function of the system is calculated as the sum of satisfaction of all its existing agents (Figure 3(a)). Scheduling problems is solved iteratively in evolution way by the step-by-step increase (local improvement) of the objective functions values of each agent.

When the task is initialized its agent gets the initial sum of virtual money according to its priority. This money can be used as a payment for allocation on the chosen resource and for the compensation of the expenses of the tasks shifted during the allocation. Objective and penalty functions are built considering time limits for the task agent and considering the loading on the certain scheduling interval fort the resource agent. T – time horizon, KPI – key performance indicator (Figure 3 (b)).

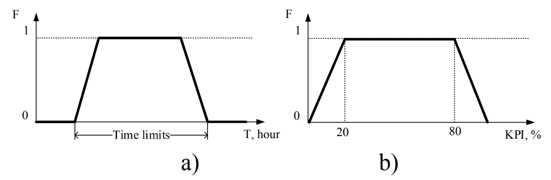

Figure 3: An example of the task (a) and resource (b) objective function.

The key rule of the designed VM is that any agent that is searching for a new better position in the schedule must compensate losses to other agents that change their allocations to resources, and propagation of such wave of changes is limited by virtual money.

4.4 Agent Interaction Protocols

Scheduling process includes two phases which continuously repeated:

1) Initial allocation of tasks to the resources considering both preferences and time constraints;

2) Proactive improvement of tasks and resources by their rescheduling.

Agent interaction protocol for the first phase is shown in the Figure 4. This protocol is a modification of Contract Net interaction protocol implementation, specified by the FIPA standard.

Arrived task agent defines a list of available and appropriate for the allocation resource agents and then it sends a message-request CFP (Call for Proposal) to each of the, which contains satellite name and time interval, during which a communication session should be scheduled.

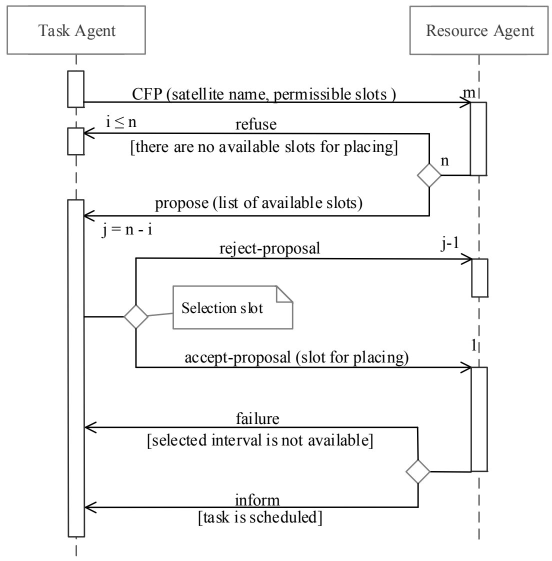

Figure 4: First phase of agents interaction protocol in case of a new task arrival.

Each resource agent that received this message, forms a visibility intervals analysis in the specified time slot. The calculations are only performed on request, because visibility intervals calculation between microsatellite and a station is a resourceful operation. Then from the obtained list of the possible task allocation intervals those time slots are excluded during which station is busy according to its schedule. If there are no time slots available for allocation, resource agent sends a response “refuse”, otherwise – message “propose” that contains a list of the available intervals.

When resource agent receives an “accept-proposal” message, it checks the specified scheduling time slot for occupation by other tasks. If the interval is free then a responding message “inform” is sent, resource agents gets a payment for the allocation and task information is recorded in the schedule. Otherwise, a “failure” message is sent and when task agent receives it, it tries to be allocated on the other resource.

Then an phase of proactive improvement of task agent satisfaction is initiated. Task agent with the smallest objective function value starts the improvement process first. Proactive task asks the appropriate resources, defining the allocation cost in the different time slots.

Among the tasks already planned on this resource, two tasks one on the left and one right side of the slot are selected. Agents of these tasks receive a request on shift on the specified time. Recursive shifting of the tasks affected by the shift continues until one of the tasks can move to the new position without conflicts, the displacing task still have means to compensate the expenses or a counter that limits recursion depth equals zero. A process of agent interaction when shifting the tasks in the ground station schedule is shown in Figure 5 where solid arrows represent messages with the shift request and response messages of the shifted tasks are shown as dotted lines.

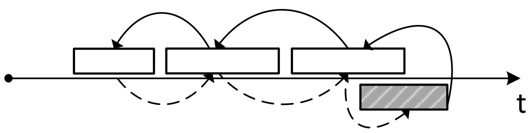

Figure 5: Recursive task shifting.

From the set of possible allocation positions those options are excluded, which confirmation will not let to improve the system objective function value, and the best option is chosen from the ones that are left.

The task that remains unscheduled is out in the list of tasks that wait for the scheduling. New attempt of scheduling for these tasks will be made in case of arising new events of adding new resources or schedule changes of the existing ones.

The designed system implements models, methods and algorithms that were earlier developed for the multi-agent swarm of satellites (Sollogub, 2013), where the incoming tasks adaptively reschedule tasks of satellites.

4.5 Example of Scheduling

Let us consider an example of communication sessions scheduling for 5 ground stations.

In the traditional approach the data from satellites will be transmitted only to their own ground stations (Table 1). In these case the KPI of all the involved stations is defined as the ratio between the total data receipt time (~2720 sec) and the length of the considered scheduling interval (24 hours) and it will be equal about 3%.

Table 1: Tasks allocation on its own stations.

Satellite	Ground Station	Sessions number	Total connection time, sec	Data volume, Mb
CubeSat XI	Kashima11	11	2200	2.64
HamSat	Neustrelitez	17	3400	4.08
Mozhayets	Kourou11	12	2400	2.88
ECHO	Wallops14	15	3000	3.6
CubeSat V	Malindi	13	2600	3.12
			Total	**16.32**

With the use of multi-agent scheduling system for the the same number of tasks it will be enough to use only two stations. It allows not only to reduce the maintenance cost of ground infrastructure and increase stations KPI up to 20%, but also increases the volume of transferred data from 16,32 to 20,64 Mb (with the data transfer speed 9600 bit/s).

Table 2: Communication sessions scheduling with stations of the network.

Satellite	Ground Station	Sessions number	Total connection time, sec	Data volume, Mb
CubeSat XI	Kashima11 Neustrelitez	11	3000	3.6
HamSat		17	4600	5.52
Mozhayets		12	2800	3.36
ECHO		15	3600	4.32
CubeSat V		13	3200	3.84
			Total	**20.64**

Volume increase of the data transferred from the satellite is shown in the Figure 6 that is achieved by communication sessions scheduling in the network of ground stations, comparing to the traditional approach.

The results is showing the high value which could be provided by bio-inspired models and methods for real time scheduling based on fundamental principles of self-organization and evolution.

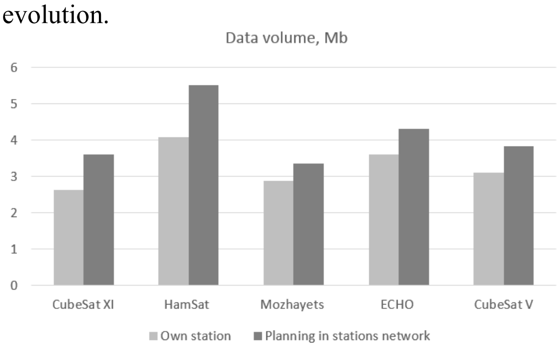

Figure 6: Transferred data volume.

Next steps in the R&D work will be focused on industrial version of the solution for modeling EU Cubsat50 program and other applications.

5 CONCLUSIONS

The papers presents developed approach for adaptive scheduling of data transmission sessions for group of small satellites and ground stations.

It is shown that solution of the considered problem evolutionary emerges from interaction and trade-offs of many agents which continuously self-organize themselves and change decisions to improve their objectives and the objectives of the system as a whole.

The advantages of developed multi-agent solution are high adaptability, flexibility and efficiency of future satellite services.

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