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A Conceptual Model of Remote Sensing Data Routing in the Grouping of Communication Satellites of a Multi-Satellite Space System

Abstract

The use of low-orbit constellation of small or super-small satellites for solving problems of remote sensing of the Earth is a promising direction for the development of space activities. In order to ensure the communication of these satellites with ground-based points in advanced space systems, it is planned to use groupings of low-orbit communication satellites. At that, a certain formation of this grouping is considered. It is assumed that the satellites are evenly distributed in several orbital planes, and each of them has a connection with two neighboring satellites in its plane and two satellites in neighboring planes. The object of research in the article is the problem of routing, namely, the search for routes for relaying data streams from remote sensing satellites to ground-based information reception points. The proposed approach to solving the routing problem uses the following network specifics. The nodes of the network are remote sensing satellites, communication satellites and objects of ground infrastructure. In this case, you can highlight two fragments of the network. Communication satellites form the first fragment of the network, and the second one — the communication channels of these satellites with ground infrastructure objects and remote sensing satellites. The topology of the first network fragment is static, and the topology of the second fragment is dynamically changing. However, the dynamics of changes in the topology of this network fragment is predictable. It can be calculated based on satellite flight simulations and described as a contact plan that defines the time parameters of satellite communication sessions with ground stations. The solution of the problem is based on an agent-based approach. Satellite agents form the overlay layer of the network and, based on information interaction, provide route search, traffic balancing, and data transmission without delays at network nodes. The article offers information interaction schemes that provide both centralized and distributed route search options.

Keywords: *multi-satellite space system, groupings of remote sensing and satellite communications satellites, routing*

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Концептуальная модель маршрутизации данных дистанционного зондирования Земли в группировке спутников связи многоспутниковой космической системы

Использование низкоорбитальных группировок малых или сверхмалых спутников для решения задач дистанционного зондирования Земли является одним из основных направлений развития космической деятельности. Для обеспечения связи этих спутников с наземными пунктами в перспективных космических системах предполагается использовать группировку низкоорбитальных спутников связи. При этом рассматривается определенное построение этой группировки. Полагается, что спутники равномерно распределены в нескольких орбитальных плоскостях, и каждый из них имеет связь с двумя соседними спутниками в своей плоскости и двумя спутниками в соседних плоскостях. Объектом исследований в статье является задача маршрутизации, а именно поиск маршрутов для ретрансляции потоков данных со спутников дистанционного зондирования в наземные пункты приема информации.

В предлагаемом подходе к решению задачи маршрутизации используется следующая специфика сети. Узлами сети являются спутники дистанционного зондирования, спутники связи и объекты наземной инфраструктуры. При этом можно выделить два фрагмента сети. Первый фрагмент сети образуют спутники связи, а второй фрагмент — каналы связи этих спутников с объектами наземной инфраструктуры и спутниками дистанционного зондирования. Топология первого фрагмента сети является постоянной, а топология второго фрагмента — динамически изменяющейся. Однако динамика изменения топологии этого фрагмента сети является предсказуемой. Она может рассчитываться на основе моделирования полета спутников и описываться в виде плана контактов, определяющего временные параметры сеансов связи спутников с наземными пунктами. В основе решения задачи лежит агентно-ориентированный подход. Агенты спутников образуют оверлейный слой сети и на основе информационного взаимодействия обеспечивают поиск маршрутов, балансировку трафика и передачу данных без задержек в узлах сети. В статье предлагаются схемы информационного взаимодействия, обеспечивающие как централизованный, так и распределенный варианты поиска маршрутов.

Ключевые слова: *многоспутниковая космическая система, группировки спутников дистанционного зондирования Земли и спутников связи, маршрутизация данных*

Introduction

Remote sensing of the Earth (ERS) is currently one of the most demanded space technologies. The growth of a service market in this area is predicted to reach $8.5 billion by 2026 [1]. Further development of ERS technologies is associated with use of small, micro, and mini satellites, and creation of multi-satellite space systems. The development and creation of such systems requires the study of many problems from various subject areas [2]. These include the routing of remote sensing data transmission to the Earth, which is the object of research in this paper.

One of the main factors that determine the choice of approach to its solution is the orbital formation of satellite constellation, the structure and dynamics of changes in the network topology over time, and the type of network connectivity [3].

Depending on the orbital formation and the size of the satellite constellation, the network can be fully connected or non-connected. In the case of connected networks, routing algorithms [4—13] used on the Internet, in terrestrial communication networks, as well as in MANET (Mobile Ad-hock Network) networks are considered. In the case of non-connected networks, technologies that differ from the protocols on which the Internet is built are considered. The development of such technologies led to the development of DTN architecture (Delay-and-Disruption Tolerant Networking) [14]. For data routing in DTN, CGR algorithm (Contact Graph Routing) is considered, which is the object of active research and development [15—22].

The paper is organized as follows. The first section describes a variant of building a space system and setting the routing problem. The second section provides an analysis of the network topology specifics and the dynamics of its changes. The network as a whole belongs to the class of MANET networks. Despite this, the expediency of using a contact plan, which is used in the basis of the CGR algorithm, is justified. The solution of the routing problem involves information interaction. Possible interaction schemes are discussed in the third, fourth and fifth sections of the article.

1. Problem statement

A multi-satellite space system is considered, including groupings of remote sensing and communication satellites. It is assumed that the communication satellites are uniformly located in several orbital planes, and each satellite always has a connection with two neighbors in its plane and two neighbors in adjacent planes. This network formation, in particular, is implemented in the grouping of Iridium communication satellites [23], consisting of 66 satellites, 11 satellites in 6 orbital planes. In the case of such a formation, the network topology has the form of a grid (Fig. 1), and communication satellites can be identified by the indices i and j, where i is the ordinal number of the plane, and j is the ordinal number of the satellite in the plane.

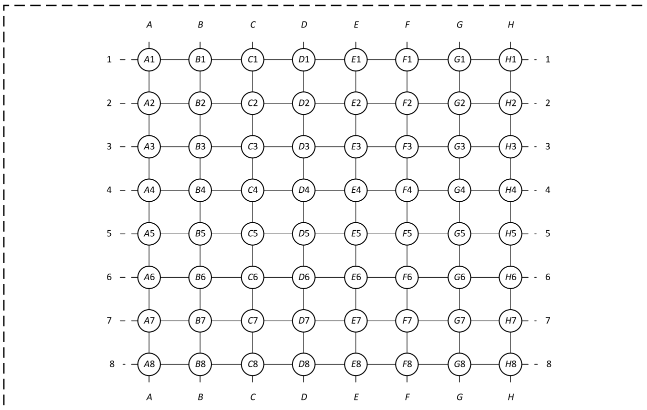

Fig. 1. Identification of communication satellites

The communication satellite for the duration of the communication session with the ground point will be called a terminal or terminal satellite, and the purpose of the task is to find routes to the terminal satellites that have communication sessions with the corresponding ground points. Route search should be performed taking into account the possibility of peak situations and traffic balancing.

The performance of the space system has a limitation: the total volume of data obtained as a result of the execution of ERS requests within a certain period of time should not exceed the maximum volume that can be transmitted within the same period of time within all communication sessions with ground points. This restriction can be taken into account when forming the flow of ERS requests. However, the traffic intensity may fluctuate, and peak situations may occur within some time intervals: the total volume of data held by communication satellites exceeds the capacity of the currently established communication sessions with ground stations.

A terminal satellite can simultaneously relay to the ground station 4 data streams received from 4 neighboring satellites. However, in the case of the network topology under consideration, this restriction may have additional specifics (Fig. 2). In the first case, only 6 streams can be retransmitted instead of 8, in the second case, only 8 streams instead of 12.

The second problem is traffic balancing. If the communication channel is used simultaneously in two routes, then the time of retransmission of streams on these routes is doubled. Thus, the routing problem is considered, which is reduced to the choice of terminals and routes for retransmitting data streams with respect to the restrictions on the intersection of routes and taking into account the possibility of peak situations.

In the case of peak situations, congestions of transmitted data may occur at the network nodes. In this regard, three possible routing strategies can be considered. In the first strategy, data transmission from remote sensing satellites begins only if there is route, the use of which does not cause congestion occurrence at the nodes of the route. In the second strategy, data transfer can occur if congestion can only occur at terminal nodes. In the third strategy, it is allowed that congestion can occur at any intermediate nodes of the route. This article discusses the first of three routing strategies.

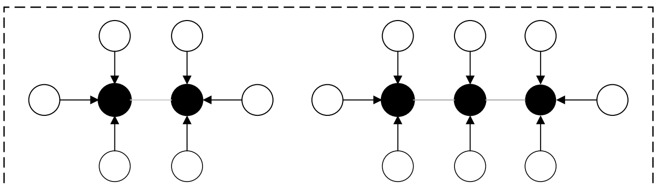

Fig. 2. Specifics of network performance limitations

2. The specifics of network topology and dynamics of its changes

In the case of the formation under consideration, communication satellites form a network with a static topology. However, due to the mobility of satellites, the problem has a dynamic component, which can be explained using Fig. 3.

In this example, it is assumed that the data transmission occurs in the time interval between t^0 and t^4. During this time, the remote sensing satellite has contacts with different communication satellites Sat^1, Sat^2 and Sat^3, and the ground station — with different terminal satellites Sat^{T1}, Sat^{T2} and Sat^{T3}. Thus, the data transmission is divided into 4 time intervals. Within the first time interval $[t^0, t^1]$, the source and destination nodes of data transmission are Sat^1 and Sat^{T1} satellites, respectively, within the second time interval $[t^1, t^2]$ — Sat^2 and Sat^{T1} satellites, etc.

In the case of such changes in the network topology, MANET routing methods assume broadcast distribution of service messages. But in the case of space systems, such changes can be calculated on the basis of satellite flight simulations and described in the form of a contact plan

$$Contact\ plan = \{<Sat,\ node,\ [t^S,\ t^F]>\},$$

that specifies the time intervals $[t^S, t^F]$ of the planned sessions of each communication satellite *Sat* with each other *node* of network: ground station and remote sensing satellite. When using such data, the transmission of service messages about changes in the network topology becomes unnecessary.

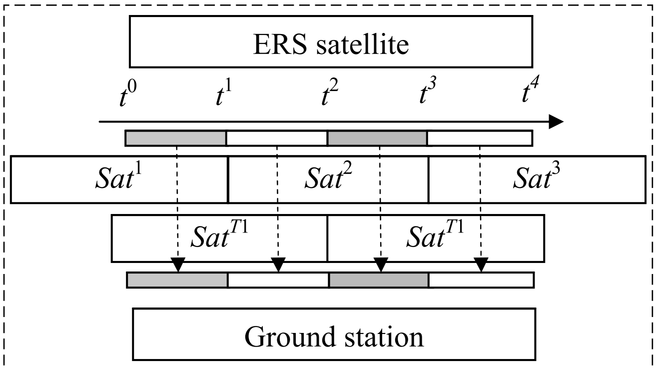

Fig. 3. Dynamics of network topology changes

3. Information interaction of remote sensing and communication satellites

Information interaction between satellites can be implemented on the basis of an agent-based approach. In this approach, it is assumed that each satellite has its own agent. In accordance with this, a multiagent system can be considered as an overlay layer of a communication network. This section discusses the behavior and interaction models of remote sensing satellite and communication satellite agents.

3.1. Behavior model of remote sensing satellite agent

The behavior model of the remote sensing satellite agent in the form of a state chart is shown in Fig. 4.

When observation data appears (1), the agent goes from the data waiting state to the waiting state for contact with a communication satellite. The time intervals when the remote sensing satellite can establish these contacts are available in its contact plan. When the earliest moment of contact start time (2) occurs, it sends a request to the corresponding communication satellite *Sat* to establish contact:

Sat: Communication request.

If a contact is not established for some reason (3), it goes to the waiting state for the next contact, otherwise (4) sends a request to the *Sat* satellite agent to search for a route and transmit data:

Sat: Transmission request.

In accordance with the routing strategy under consideration, data transmission begins on the condition that there is a route that does not cause congestion at the nodes of the route. There may not be such a route in the time interval of the current contact. In this case, when the end time of the current contact occurs (5), the agent enters the waiting state for the next contact.

If the route is found, it receives the message *Transmission is possible* (6) and starts transmitting data before one of the following events 7, 8 or 10 occurs. If the time of the current contact is over (7), it goes into waiting for the next contact. If the *Transmission is interrupted* message is received (8), it enters the data transmission interruption state until the *Transmission is possible* message is received (9) to continue the data transfer. If all data is transmitted (10) before the end of the contact, the agent sends to the *Sat* communication satellite agent a message about this

Sat: Transmission is over,

and goes to the state of waiting for the next data to be transmitted.

3.2. Behavior model of communication satellite agent

The behavior model of the communication satellite agent in the form of a state chart is shown in Fig. 5. In the interaction of the agents of the remote sensing satellite and the communication satellite, the first of them is proactive. Therefore, the communi-

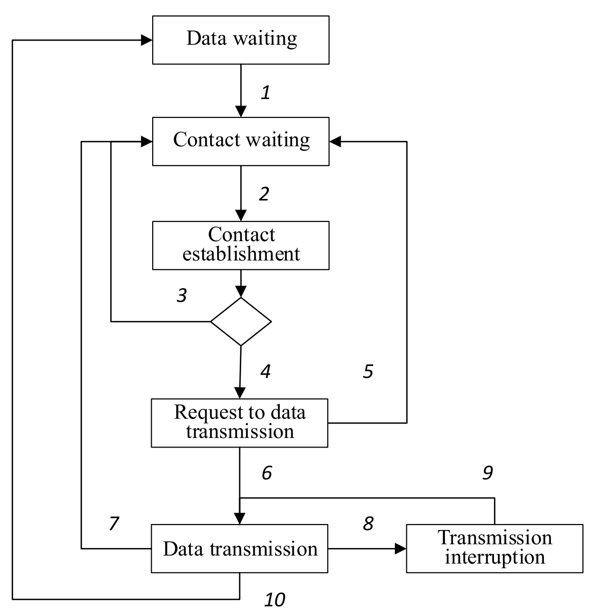

Fig. 4. Behavior model of remote sensing satellite agent

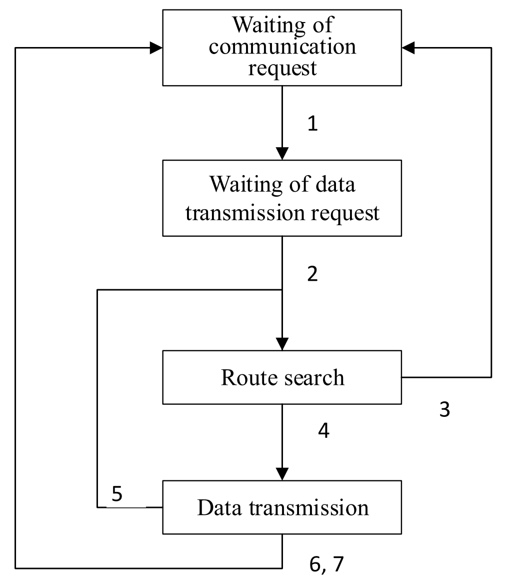

Fig. 5. Behavior model of communication satellite agent

cation satellite agent is waiting for a *Communication request* (1) message to establish a contact. After establishing the contact and receiving the *Transmission request* message (2), it initiates the route search process. This process is described in the next section of the article.

The satellite agent is in the route search state until one of the events 3 or 4 occurs. If the route is not found before the end of contact with the remote sensing satellite (3), it enters the waiting state for a new data request, otherwise (4) sends to the Sat^{ERS} remote sensing satellite agent a message about this

$$Sat^{ERS}\text{: Transmission is possible,}$$

and enters the data transmission state. It is in this state until one of the events 5, 6, or 7 occurs. When the communication session of the terminal satellite with the ground station is over (5), it sends a command to interrupt the data transmission

$$Sat^{ERS}\text{: Transmission interrupted,}$$

based on the contact plan, it determines the next terminal satellite and initiates the process of finding a route to it. When the contact with the Sat^{ERS} satellite ends (6), or the message *Transmission is over* comes (7), the agent of the communication satellite goes to the state of waiting for the next *Communication request.*

4. Interaction scheme of communication satellite agents

Route search can be performed in both centralized and distributed variants. In the first case, an additional *manager* agent is introduced, which searches for routes at the request of the communication satellite agents. In the second case, the communication satellite agents search for routes independently.

The route search is preceded by the choice of a terminal satellite. Initial data for this is the contact plan and the ground point where the ERS data should be delivered. The choice of a terminal satellite also involves information interaction with the agent of this satellite, the purpose of which is to confirm the establishment of a communication session with the ground point.

When searching for routes, we use up-to-date data on the state of inter-satellite communication channels, which are maintained in the *Network load* database. A channel can be in one of two states: it is used in an active route or not. In the centralized model, this database is maintained in the memory of the *manager* agent, in the distributed model — in the memory of the agent of each communication satellite. The route search is performed using Dijkstra's algorithm [24]. The route length metric is the number of communication channels that make up the route.

4.1. Centralized routing model

A possible scheme of agent interaction in the case of a centralized model is shown in Fig. 6.

Here and after, the following designations are used: Sat^0 — a communication satellite receiving data from a remote sensing satellite, Sat^i, $i = 1, ..., k$ — satellites of intermediate nodes of the stream relay route.

In accordance with the scheme, the satellite agent Sat^0 sends the *manager* agent a *Request* to search for a route. After searching and selecting a route, the *manager* agent sends an *Update* message to the agent of each Sat^i route node with a *Route* description in the form of an ordered list of route nodes:

$$Sat^i\text{: Update (Route)}, \ i = 1,...,k,$$
$$Route = \{Sat^j \,/\, j = 0,\ 1,...,\ k\}.$$

Based on the route description, the node agents update their routing tables, and send a *Confirmation* message. After receiving confirmation from the agents of all the route nodes, the *manager* agent registers the new states of the route communication channels in the *Network load* database and sends the *Update* message to the Sat^0 satellite agent:

$$Sat^0\text{: Update (Route).}$$

When a message is received, the Sat^0 satellite agent updates the data in the routing table and sends the *Transmission is possible* message to the remote sensing satellite agent.

After transmitting the data stream, the Sat^0 satellite agent initiates a protocol with a similar scheme (Fig. 6), during which the *manager* agent updates the status of the communication channels

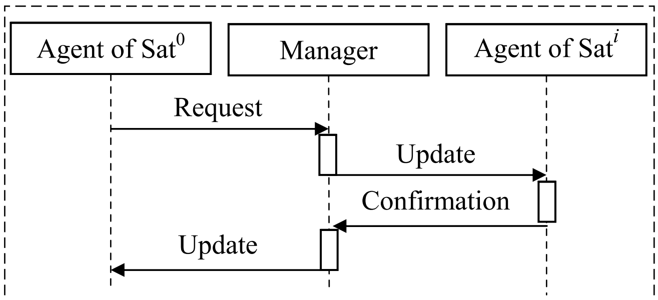

Fig. 6. Interaction scheme in case of a centralized model

used in the route in the *Network load* database, and the agents of the route nodes update the data in their routing tables.

The *manager* agent searches for routes sequentially, in the order in which requests are received. When peak situations occur, a queue of requests for which the route has not yet been found is formed in the memory of the *manager* agent. The search for routes for these queries resumes after updating the data in the *Network load* database due to the termination of the use of any of the existing routes.

In order to ensure reliability, the *manager* agent must have a duplicate agent that operates on another network node and synchronously updates the data in its *Network load* database. If one of these agents becomes unavailable, the other agent remains or becomes the primary agent, creates a new duplicate agent in the other node, sends it a copy of the *Network load* database, and broadcasts the agents of all communication satellites the address of the new duplicate agent.

4.2. Distributed routing model

In the case of a distributed routing model, the behavior scenario of the Sat^0 satellite agent in the "Route Search" state (Fig. 5) can be summarized as follows.

1. It searches for a route. If the route is not found, it resumes the search after waiting and receiving a message about the termination of the existence of an existing route.

2. When the route is found, it initiates the route validation protocol. Participants of the protocol are agents of route nodes, satellites Sat^i, $i = 1, ..., k$. The purpose of the protocol is to check the non-intersection condition of the route and add new data to the routing tables at the route nodes.

3. The result of executing the route validation protocol can be the approval or rejection of the route. If the route is approved, it send the message *Transmission is possible* to the remote sensing satellite agent. If the route is rejected, it learns about the unavailability of the communication channel in the node of the rejected route, updates the state of this channel in its *Network load* database, and, considering this, searches for another route.

The number of nodes in the route determines the number of participants in the route validation protocol. Fig. 7 shows an example of the scheme of this protocol in the special case when the route passes through 3 nodes.

According to the scheme, the *Request* message with the description of the found *Route* is transmitted sequentially to the satellite agents Sat^i, $i = 1, ..., k$. From the *Route* description, the Sat^i satellite agent identifies the Sat^i — Sat^{i+1} communication channel, and determines its current state based on data from its routing table. If this channel is not used for transmitting another stream, it updates data in its routing table, and passes the *Request* message to the agent of the next route node.

If the *Request* message reaches the terminal node, the route is assumed to be approved, and the terminal node agent initiates the broadcast of the *Inform* message on the network with the description of the approved route. The purpose of distributing the *Inform* message is to update the data in the *Network load* databases of all communication satellites. When the Sat^0 satellite agent receives *Inform* message it also sends the *Transmission is possible* message to the remote sensing satellite agent and the data stream transmission begins.

If the Sat^i-Sat^{i+1} communication channel is already used to relay another data stream, the Sat^i satellite agent initiates the rejection of the found route. Route rejection is reduced to the sequential transmission of the *Cancel* message in the opposite direction along the route path (Fig. 7). In this message, along with the description of the rejected route, the Sat^i-Sat^{i+1} communication channel is transmitted. When this message is received, the node agents update the current data in their *Network load* databases and in their routing tables, and the Sat^0 satellite agent also initiates the process of finding and validating a new route.

It should be noted that the Sat^0 satellite agent learns about the use of the Sat^i-Sat^{i+1} communication channel in another route also from the *Inform* message, which is dis-

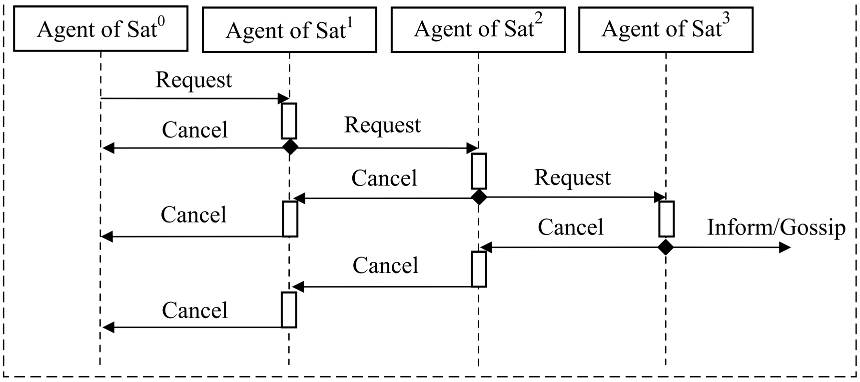

Fig. 7. Protocol of route validation

tributed over the network after the validation of this route. In this case, there are two possible situations: the *Cancel* message is received before or after the arrival of the *Inform* message.

In the first situation, two strategies can be considered. The search and validation of a new route can be performed immediately after receiving the *Cancel* message or with a minor delay after receiving the *Inform* message. The difference between the strategies is as follows. In the first case, the new current data on the use of communication channels in another already approved route is partially known, and in the second case — completely.

In the case of distributed routing, the Sat^0 satellite agent, along with route search and validation also notifies the agents of all communication satellites of the end of route use. In this regard, when it exits the *Data Transmission* state when any of the events 5, 6 or 7 occur (Fig. 5), it initiates the broadcast transmission over the network of the *Inform* message with a description of the route and an indication of the end of its use.

5. Routing in cases of network topology changes

The information interaction schemes of communication satellite agents described in sections 3 and 4 assume that all inter-satellite communication channels are always in operation and the network topology formed by the communication satellites remains constant over time. This section discusses additional tasks of information interaction in cases when some inter-satellite channels fail.

Monitoring of the state of inter-satellite channels can be performed based on the exchange of *Hello* service messages, similar to how it is implemented, for example, in the *OSPF* protocol, which is widely used in practice. A satellite agent that detects a failure of a communication channel transmits a message over the network in broadcast mode with a list of such communication channels.

The behavior model of the Sat^0 satellite agent, when receiving such a message, is as follows. If the channels specified in the message are used in the data transfer route, then it sends a message to the agents of the route nodes about the destruction of the route and initiates the process of searching for a new route in accordance with the interaction schemes described in sections 3 and 4. Route destruction messages are sent for updating the routing tables in the nodes of this route.

The article discusses the routing strategy, according to which data transmission does not involve data congestion in intermediate nodes of the route. In this sense, cases where some communication channel in the route fails can be considered as exceptional ones. A data congestion inevitably occurs at a route node when its communication channel with the next route node fails. In this case, the volume of accumulated data is determined by the length of time that passes after the time when the communication channel fails until the time when the data transmission from the remote sensing satellite is interrupted.

The prototype of the behavior model of the communication satellite agent in this case can be considered the behavior model of the satellite agents Sat^0 (Fig. 5). The difference in the behavior model in this case is only that the source node, from which the data is transmitted, instead of the remote sensing satellite, is the communication satellite itself. At that, the search for a route for data transmission can be performed in accordance with the interaction schemes discussed in section 4.

Conclusion

The object of research in the article is a multi-satellite space system, in which a grouping of communication satellites provides the retranslation of data from remote sensing satellites to ground infrastructure objects. A routing method is proposed that provides data traffic balancing and does not imply the occurrence of data congestion in the network nodes. The software implementation of the proposed routing method is considered as the main component of a complex simulation model designed to study the capabilities of promising multi-satellite space systems.

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