Energy Efficient Network Strategy for Nanosatellites Cluster Flight Formations

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Abstract: *This research aims to establish a network strategy with energy efficient considerations for cluster formations, which comprise a number of nanosatellites to coordinate for scientific missions. Nanosatellites are constrained in size and power, hardly providing adequate energy for long transmission distance and high transmission rate. Hereby we propose a multiple hopping relay methodology to deliver the scientific data in the cluster or to the ground terminals with the optimal energy balance of the entire network. Accordingly, we first analyzed power constraint in the network related to link budget and energy dissipations of maintaining intersatellite links with necessary data rates at desired frequency. Then we formulated the network as a space-time graph due to nanosatellite relative motions. A minimum spanning tree was searched to fulfill the global connectivity of low energy cost over the space-time graph. Simulation results show that the minimum spanning tree over the space communication is optimal for the cluster formations with high energy efficiency.*

Keywords: *Network Energy Efficiency, Cluster Flight Formation, Intersatellite Links, Nanosatellites.*

1. Introduction

Nowadays nanosatellites win great popularity in scientists and researchers for the benefits as low budget cost, short manufacturing timeline, flexible design ideologies and influential educational significance. Many missions have been proposed following this trend, such as QB50 mission, which aims to establish an international network of 50 CubeSats for multi-point, in-situ measurements in the lower thermosphere and re-entry research [1]. Also the main theme of annual Interplanetary CubeSat Workshop held in New York, 2012, was to find the possibilities in sailing nanosatellites in formation to deep space for scientific explorations [2]. This concept was presented by fractionated spacecraft project aiming to distribute the functionality of a traditional monolithic spacecraft into a number of nanosatellite modules through wireless links. These merits have highlighted nanosatellites as strong candidates to establish a large scale network for remote sensing and space explorations.

A cluster formation is a collection of independent satellites that coordinate to perform a task and work as a firmly cooperative system. This system usually consists of a number of satellites with wireless communication links. After deployment from the launcher, the satellites fly on their own orbit and operate for mission purposes. Different satellite orbits result in relative motions, which can provide long baselines and contribute to unprecedented high resolution and ability to view research targets from multiple angles or at multiple times.

Similar with other satellites, nanosatellites use solar cells to convert solar radiations into electricity to charge the batteries and supply subsystems. However, traditional power management is not applicable to current nanosatellites. Power gained from solar cells is determined by solar cell area and the angle between sun vector and the orthogonal of solar panels. Analysis in [3] shows that average power gained from sun per orbit for a nanosatellite with a size of $182 \times 127 \times 186$ mm^3 in a sun synchronous orbit with maximum eclipse is usually no more than 2.1 watts, even with high efficiency cells. Even for a larger nanosatellite, with dimensions of $182 \times 127 \times 414$ mm^3, results in a typical power generation per panel of about approximately 4.5 watts, if errors and losses are considered. There is another method to increase the area. Deployable solar arrays can mount more solar cells to generate more power. But, as large flexible appendages, they cause extra momentum torque disturbance, undermine the attitude stability and also increase complexity for nanosatellite attitude control system. Therefore, existing energy constraint makes it desirable to find an economic way of using the limited energy on the nanosatellites. [4] shows the power budget analysis of one 2U nanosatellite in a 330 km sun synchronous orbit. This nanosatellite uses Ultra High Frequency for 10 Kbps telecommand uplinks and telemetry downlinks with estimated power consumption of 400 mwatts. From the power budget, we can see communication system always play a critical role in the energy consumption even though current data rate is inefficient for downloading large amount of data from space to ground stations.

In the cluster formation, we can hardly expect each nanosatellite to own direct and high-speed links with ground stations, due to the analysis above. In this paper, we suggest a network architecture using multiple hopping relay channels to deliver the scientific data in the cluster or to the ground terminals. Our major work is summarized as follows: We first define the network with multiple hopping paths for data transmissions in the cluster formations. Then we model the dynamic network configured by intersatellite links in the cluster formations as a space-time graph incorporating both spatial links and temporal links. Both links are discussed for the contributions in energy efficiency. In order to reduce the energy cost of network communications, we propose to search the network minimum spanning tree (MST), which is considered as the shortest path of global connectivity. Moreover, a method of MST is discussed over the space-time graph for efficient energy utilization. All the methods proposed in the paper are verified by simulations. Results demonstrate the efficiency of the methods. Finally the paper concludes with a recommendation of using the proposed efficient energy strategy for nanosatellite cluster formations.

2. Multiple hopping path and intersatellite network

Nanosatellites are extremely small with harsh power budget. Hence it is not feasible to support high speed downlinks on each nanosatellite in the cluster formation. Energy insufficiency is not only a crucial issue for cluster formations with nanosatellites. Many ground networks such as wireless sensor network and pocket mobile network face the same problem. Current solution for this problem is to use short distance links instead of long distance links. Such a strategy provides multiple hopping links from one node to another in the network. For example, data packages from source node to terminal node can be delivered and forwarded among the nodes in the network. Multiple hopping links reduce energy consumption and also helps to extend network lifetime. Similar with these ground networks abovementioned, we propose a multiple hopping strategy in the cluster formations to manage energy efficient communication and download scientific data from payload to ground stations.

In our strategy, we assign a number of nanosatellites in the cluster formation as masters. Nanosatellites considered as masters are assumed to have (i) large storage capacity, (ii) capability of establishing satellite-ground links (uplinks and downlinks), and (iii) intersatellite links to communicate with other satellites in the same formation. That is to say, a master satellite can act as a relay node to send the messages to the target destinations and forward the information from ground terminal to other nodes. Masters can be elected from slaves based on the energy sufficiency or assigned by ground stations. Related to masters, all the other nanosatellites are defined as slaves, who usually lack enough power for the downlinks, only connect and communicate with masters or other slaves through intersatellite links within its limited communication range (or called visible distance).

As a result, majority of nanosatellites in the cluster formation do not have to establish direct satellite-ground links, as shown in Fig. 1-(a). Alternatively, as shown in Fig.1-(b), they just need to connect with masters through intersatellite links, which are shorter than direct satellite-ground links.

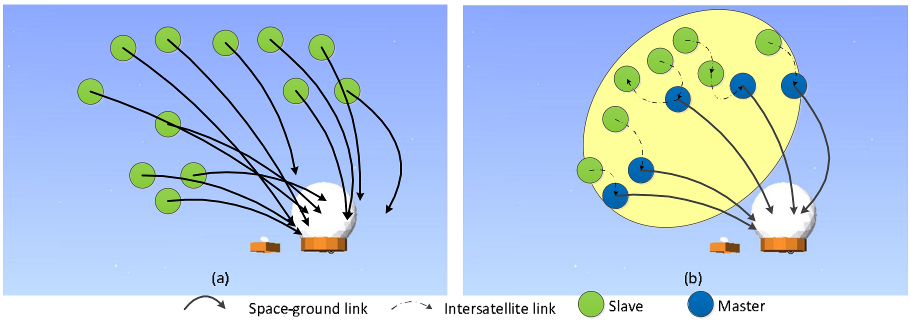

Figure 1. Multiple Hopping Paths between nanosatellites and ground stations

The path from a slave to ground stations consists in space-ground links and intersatellite links. Energy consumed for this path also includes the consumptions of both space-ground links and intersatellite links. Energy consumption by space-ground links is determined by orbit height. Energy consumption of intersatellite links depends on the number of hopping and the distance summation of the path from the source slave to the master.

3. Dynamic topology

In this section, we adopt graphs to describe paths of data spreading over the network, which are widely used by other network topology study. Each nanosatellite in the cluster formation can be regarded as a node with wireless links and similarly the cluster forms a network connected by wireless communication. Nevertheless, unlike ground networks, the network established by nanosatellites involves dynamic node motions caused by spacecraft orbit dynamics. In this section, we model the network with consideration of spacecraft orbit dynamics and give solutions to energy efficient connectivity of the network.

3.1. Space-time Graph

Nanosatellite orbit in the cluster formation is represented in the earth-centered inertial reference frame by Keplerian orbital elements, expressed as $(a_j, e_j, t_j, \Omega_j, \omega_j, u_j)$, which sequentially denote semi-major axis, eccentricity, inclination, right ascension of the ascending node, argument of perigee, and mean argument of latitude. Relative motions between nanosatellites in the cluster formation can be expressed in the orbital frame centered on any nanosatellite. The relative motion of this nanosatellite, when other nanosatellites are moving in a circular orbit, can be described by Hill's equations or Clohessy-Wiltshire Equations [5]. Fig. 2 shows an example of relative motions among three satellites in a cluster formation. Considering the existence of trigonometric items in the solution of these equations, relative motions follow a periodic law, seen in Fig. 2.

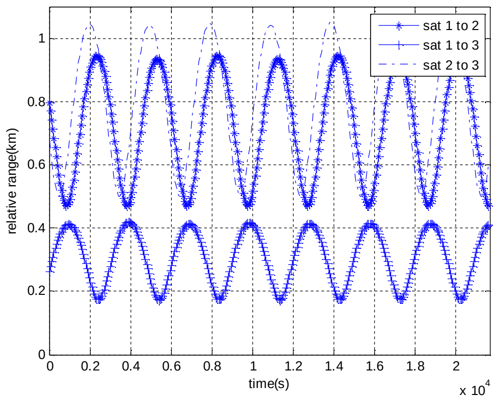

Figure 2. Relative motions among three nanosatellites in a cluster formation

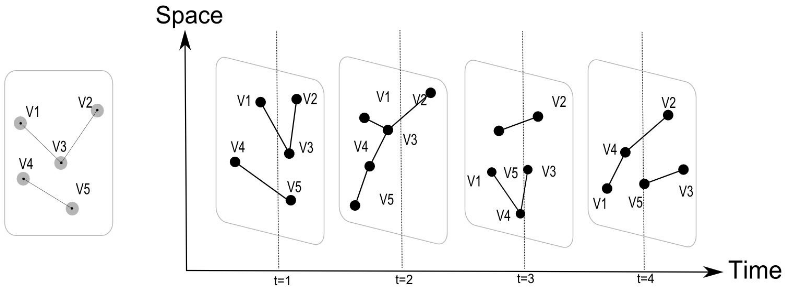

Figure 3. Time evolution of network topology

Considering the periodic relative motions between any pair of nanosatellites, network topology evolves over time. The connectivity between two nanosatellites is determined by transmission distance. Traditional static graph cannot describe such an evolution. However, each static graph can be considered as a snapshot of the evolution in a specific time interval and thereafter the dynamic network topology can be represented by a sequence of static graphs over a period of time among nanosatellites in the cluster, as described in Fig 3. Here, we name this sequence of static graphs, space-time graph, which is an ideal tool to model the dynamic network.

Assume that the time duration is divided into discrete and equal time slots, $T=\{t_1, \cdots ,t_N\}$. Let $V=\{v_1,\cdots,v_n\}$ be the vertex set of all the nanosatellites in the network. Let $G^t=\langle V^t,E^t\rangle$ be a graph representing the snapshot of the network at time slot t and $v_i^t v_j^t \in E^t$ be the link budget from v_i to v_j at time slot t. Based on the relative motions, we consider the network as a set of graphs $\{G^t \mid t=t_1,\cdots,t_N\}$, over time t. For a certain time, the topology is depicted by adjacent matrix. For any slot in this period, each slot has the corresponding adjacent matrix. Considering the whole period, the adjacent matrix evolves to be a union of all the adjacent matrixes over the time slots in this period.

First, we model the impact of the node mobility and the resulting link failures by representing the network topology at any point in time with an adjacency matrix denoted by $A(t)$, where n is the number of nanosatellites in this network. The matrix is as follows,

$$A(t)=\begin{pmatrix} a_{v_1v_1}(t) & a_{v_1v_2}(t) & \cdots & a_{v_1v_n}(t) \\ a_{v_2v_1}(t) & a_{v_2v_2}(t) & \cdots & a_{v_2v_n}(t) \\ \vdots & \vdots & & \vdots \\ a_{v_nv_1}(t) & a_{v_nv_1}(t) & \cdots & a_{v_nv_n}(t) \end{pmatrix}, \quad a_{v_iv_j}(t)=\begin{cases} 1, d_{v_iv_j}(t)\le R_{max} \\ 0, otherwise \end{cases} \tag{1}$$

where $d_{v_iv_j}(t)$ is defined as the real distance between satellite nodes v_i and v_j at time t, R_{max} is denoted as the maximum transmission distance between two nanosatellite above. Hence, dynamic network topology due to the relative motion is reflected in the adjacency matrix by changing the value in $d_{v_iv_j}(t)$ with time. When the satellite nodes are approaching each other, if the distance is less than R_{max}, $a_{v_iv_j}(t)$ shows the connectivity by converting from 0 to 1. When the distance between the two nodes exceeds the coverage of the link, $a_{v_iv_j}(t)$ will return to 0 from 1.

From the definitions above, we can discover that the proposed space-time graph model includes both the space and time evolutions of the network topology. The space evolution demonstrates delivering a message from node v_i to v_j in the tth time slot. The temporal evolution represents caching the message at node v_i from the tth time slot to the $t+1$th time slot. We use spatial links and temporal links to demonstrate the connectivity in both space and temporal evolutions. The total cost of this path can contain cost of all the temporal links and space links.

The cost of maintaining the link before $v_i(t_m)$ and $v_j(t_n)$ is denoted as $c(a_{v_iv_j}(t_m,t_n)), m,n \in \{1, \cdots, N\}$. Therefore, the total cost of a space-time graph is the sum of all links in graph $\{G^t \mid t = t_1, \cdots, t_N\}$, denoted as,

$$c(G) = \sum_{t=t_m}^{t_n} \sum_{v_i \in V} \sum_{v_j \in V} c[a(v_i(t_m) v_j(t_n))]. \tag{2}$$

Given the cost of the links, we can define the shortest path as the path with the least cost from one nanosatellite $v_i(t_m)$ to another nanosatellite $v_j(t_n)$ in the space-time graph.

3.2. Link Energy dissipations

Wireless links in the cluster formation, no matter used for inter-satellite links or satellite-ground links, follow the first order radio model referred in [6]. The cost for transmitting l-bit message at a distance d is demonstrated as follows:

$$E_{tx}(l,d) = l \cdot E_{elec} + l \cdot \varepsilon_{amp} \cdot d^2 \tag{3}$$

and for receiving end, we have,

$$E_{rx}(l) = l \cdot E_{elec} \tag{4}$$

where E_{elec} is the energy dissipated on the transmitter or the receiver circuit for communicating one bit, ε_{amp} depends on the transmitter amplifier model, and d is the distance between the transmitter and receiver. As summarized in [6], $E_{elec} = 50\text{nJ/b}$, $\varepsilon_{amp} = 100\ \text{pJ}/(\text{b} \cdot \text{m}^2)$, for the radio wireless systems at ISM 2.45GHz, capable of transmitting up to 1 Mb/s.

Before the target link creating, messages need to be cached for a nanosatellite waiting the chance for transmitting. Energy is consumed by reading the packet data and writing it into memory. For l bit message, the energy consumed on caching is evaluated by,

$$E_{cache} = E_{write} + E_{read} = \frac{l \cdot V_{sup}}{8}(I_{write}T_{write} + I_{read}T_{read}) \tag{5}$$

where E_{write} is energy consumption for writing data, E_{read} is energy consumption for reading l bit packet data, I_{write} and I_{read} are current for writing and reading procedures, V_{sup} is the voltage supply. T_{write} is the time duration of flash writing and T_{read} is the time duration of flash reading. [8] shows the configuration of these parameters used in the model. I_{write} and I_{read} are on average 25 mA at frequency of 50 MHz and 12 mA at frequency of 30MHz. Thereafter, it is estimated that,

$$E_{cache} = \varepsilon_{cache} \cdot l \tag{6}$$

where $\varepsilon_{cache} = 400\,\mathrm{pJ/b}$.

According to the analysis above, we can consider that if the length of message is known, as distance increases, E_{tx} consumes more than the sum of E_{rx} and E_{cache} . Particularly, E_{cache} is quite insignificant in contrast to E_{tx} .

3.3. Global connectivity of lowest energy cost

The network in the cluster formation requires global connectivity with energy efficiency concerns. The connectivity should cover all the nanosatellites in the network at the lowest energy cost. Equation (3-6) described the energy consumption for wireless links. Given the length of messages, energy consumption is only determined by distance between the transmitter and the receiver. Hereby achieving the global connectivity at lowest energy cost is to find a subgraph, which connects all the nodes in the graph together with the minimum summation of the distance on the links. Each slave should find its closest master over the subgraph for downloading the data.

Many efforts have been made in searching for the shortest paths in the network. For example, Dijkstra's algorithm and Floyd–Warshall algorithm can provide solutions for the shortest path problem between any pair of nodes for a graph with non-negative edge path costs [9-10]. Accordingly, we can find the shortest paths between masters and slaves over the network in the cluster formation. However, as defined above, masters are variable. The evolution of masters makes it better to focus on the shortest distance of global connectivity instead of studying just the distance between a master and a slave. As a result, we use minimum spanning tree (MST) to form the subgraph with global connectivity of lowest energy cost.

A MST can provide lowest total cost of network connectivity among all the vertices. Here is an example of using MST to achieve the least sum of edge weights for the graph in Fig. 4-(a). In such a graph of seven vertices, an optimum connectivity is ensured by MST and connectivity result is given by Fig. 4-(b).

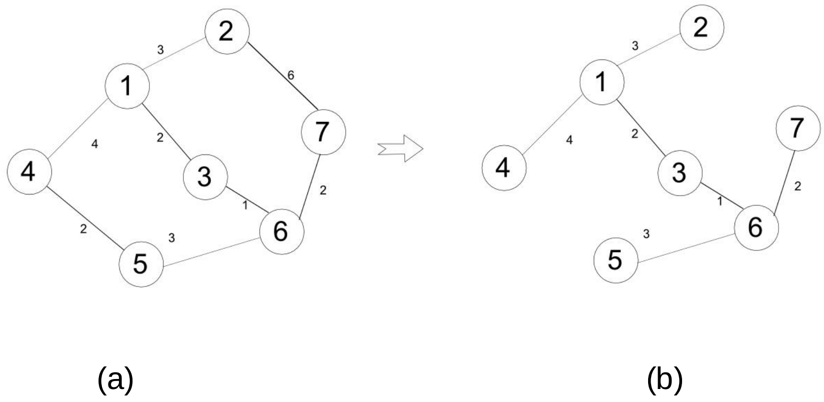

Figure 4. MST algorithm

From the result in Fig. 4-(b), all the seven nodes are connected by a set of links, $\{v_4v_1, v_1v_2, v_1v_3, v_3v_6, v_5v_6, v_6v_7\}$. These links provide the lowest energy cost for global connectivity. But for the individual node in the network, it may not connect with the closest neighbor node, such as node v_4 has a link with node v_1 at the cost of 4, instead of having a link with the closest neighbor node v_5 at the cost of 2. Energy efficiency is a global issue over the entire network. The results of MST make it optimal to keep the total energy cost over the network in balance.

4. MST Solution over Space-time graph

As discussed above, MST provides a global consideration of energy efficiency when producing a tree with all the nanosatellites in a static graph. However, the network topology is time varying and the corresponding MST also varies over time. Traditional MST determination algorithms like renowned Prim and Kruskal algorithms fail to provide a time varying solution, as they are capable only in the static graph. We need to find the MST over a space-time graph, as it represents the lowest cost of global connectivity in the cluster formation.

Considering the relative motions, each nanosatellite is able to find the closest position during a period of time. It is apparent that transmitting messages at the closest position is the best choice to improve energy efficiency. Meanwhile, in Section 3.1, both spatial and temporal links were defined. A spatial link represents delivering a message from node v_i to v_j in the tth time slot and a temporal link is defined as caching the message at node v_i in the tth time slot. Based on the analysis in Section 3.2, we assume that spatial links consume on-board energy and while caching messages via temporal links does not consume the energy. This is to say, each nanosatellite can cache messages until the closest position to the target is reached terminal. At that moment, this nanosatellite can transmit the messages to the target at an economic energy cost. As a result, we propose to use temporal links to find the energy efficient MST over the time.

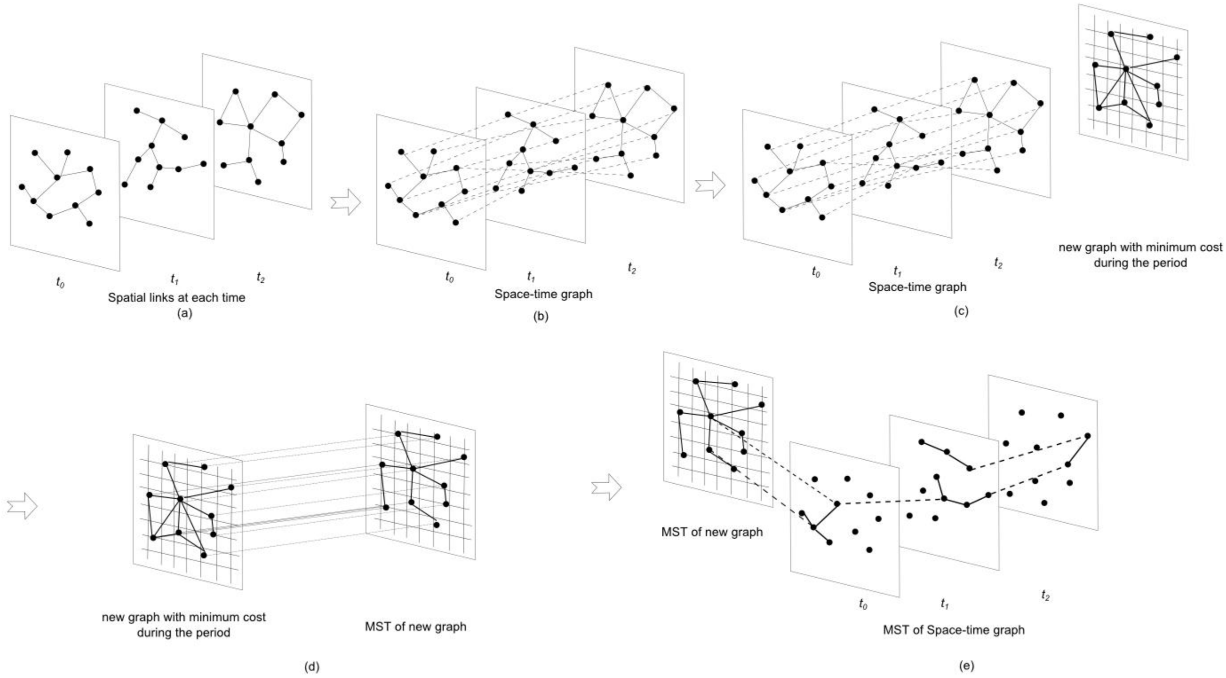

Figure 5. Mapping the space-time graph into static graph

The essence of the proposed algorithm is to use closest distance as the graph edges. Assuming that temporal links consumes negligible energy, all the energy consumptions result from spatial links. So we first construct a new graph $\zeta = <V, E'>$ with same number of nodes. Secondly, we search for the closest distance between any pair of nanosatellites in the space-time graph, for example, to find $\min[d(v_i(t_m), v_j(t_{m'})], m, m' \in \{1, \cdots, N\}$ as the cost for the edge between node v_i and v_j in the new graph in any time slot. This means, E' is assigned by new costs between vertices with $\min[d(v_i(t_m), v_j(t_{m'})], m, m' \in \{1, \cdots, N\}$ between node v_i and v_j. It is also expressed as,

$$c(v_i, v_j, t_1, \cdots, t_N) = \min[d(v_i(t_m), v_j(t_{m'})], m, m' \in \{1, \cdots, N\} \quad (6)$$

When all the nodes are visited, ζ is ready for finding a MST. Fig.5 shows the construction of new graph ζ. From Fig 5-(a), we know each time can have a snapshot of the space-time graph. Each snap has its own MST, which is lowest cost at current time and may not be the lowest over the entire network. In Fig 5-(b), dotted lines shows the temporal links, which represents the nanosatellite would cache the data without transmission. Fig5-(a) and (b) form the space-time graph. As for Fig. 5-(c), the space-time graph is mapped to generate the graph ζ, the edges of which are replaced with minimum cost edges according to Eq (6). In Fig. 5-(d), the MST over new graph ζ is searched. The cost summation of ζ is the lowest cost of this space-time graph. The following step shown in Fig. 5-(e) is to constructing the path in the original space-graph graph. We find the corresponding edge in the space-graph graph for each edge in the

MST over ζ. If the corresponding edge is found in one time slot, then we consider a spatial link existing between two nanosatellites. If a nanosatellite is both connected in two time slots, then we consider there is a temporal link between two time slots. All the corresponding spatial and temporal links are connected to fulfill the global connectivity.

Following the proposed MST of space-time graph, we do not have to evaluate the MSTs of all the snapshot graphs but discover the lowest cost of the edges over the space-time network among these nanosatellites through the period. The MST of the newly formed graph reveals the solution of low energy cost over the space-time graph.

Algorithm 1 MST of Space-time graph

1: $G^t = \langle V^t, E^t \rangle$, $t \in \{t_1, \ldots, t_N\}$
2. for $t \in \{t_1, \ldots, t_N\}$
    for $i \in \{1, \ldots, n\}$
        for $i \in \{j, \ldots, n\}$
            find minimum cost of edge $v_i v_j$
        end for
    end for
end for
3: construct a new graph $\zeta = < V, E' >$ with same number of nodes, cost of edge $v_i v_j$ in E' is marked as $c(v_i, v_j, t)$
4: find the MST over ζ, edges of the MST is denoted by set E_{MST}
5: for $t_m \in \{t \mid t = 1, \cdots, T\}$
    If $v_i v_j \in E_{MST}$
        $v_i v_j$ is the spatial link in the MST of $G^t = \langle V^t, E^t \rangle$, $t \in \{t_1, \ldots, t_N\}$
    end if
    if v_i appear more than once,
    $v_i(t) v_i(t + \Delta t)$ is the temporal link in the MST of $G^t = \langle V^t, E^t \rangle$, Δt is the time shift between the different appearance.
    end if
end for
6: connect all the temporal links discovered to form the MST of $G^t = \langle V^t, E^t \rangle$

5. Numerical simulations

To verify the validity and efficiency of our scheme for energy efficiency problem in the cluster formations, a numerical simulation is performed. We create a scenario for 360 minutes with 5 nanosatellites and the orbit parameters of the nanosatellites in the simulation are listed in Tab 1. Each time slot is one minute.

In the cluster formation defined above, Kruskal algorithm is used to find the MST for the snapshot graph in each time slot. Cost summation of the MST for each time slot is calculated and depicted in Fig. 9. In Fig. 9, the cost summation calculated by MST at each time slot varies between 1.35 to 1.51 Km. However, with the MST over the space-time graph, the cost summation is, in Fig. 10, less than the average cost for wireless links in the cluster formation in Fig. 9. In Fig.10, the connectivity includes spatial links, $v_1v_5, v_2v_4, v_3v_4, v_3v_5$ and temporal links, $v_1(0,49), v_5(49,91), v_3(90,91), v_4(65,90)$. The total cost is only 0.9729 Km.

Table 1. Orbit elements of nanosatellites

	Semimajor axis /km	Eccentricity	Inclination /deg	Argument of Perigee / deg	RAAN/ deg	Mean Anomaly /deg
1	7078.13	0.00104247	98.1904	2.7068	189.893	-2.70646
2	7078.14	0.001	98.19	0	189.891	0
3	7078.13	0.00106176	98.1921	1.90632	189.892	-1.90615
4	7078.13	0.00101465	98.1904	3.93141	189.893	-3.93106
5	7078.14	0.00104681	98.1916	2.96316	189.893	-2.96289

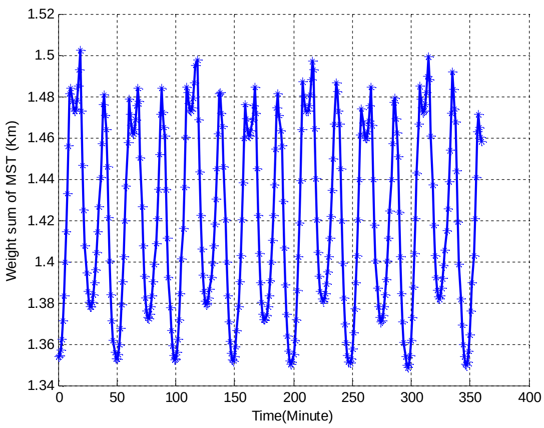

Figure 9. Weight sum of MST at each time

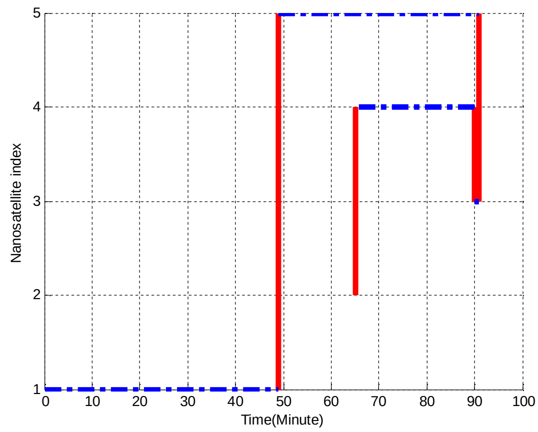

Figure 10. MST for the space-time graph(dotted lines: temporal links, real line: spatial links)

5. Conclusions

In this paper, we introduced an energy efficient strategy for nanosatellite cluster formations. The strategy proposed a network architecture using multiple hoppping relay channels to deliver the scientific data in the cluster or to the ground terminals. The paper explicitly illustrated the time varying characteristic in topology. Moreover, a method to search the shortest route in the time-varying network to maintain the optimal energy utilization based on Minimum Spanning Tree is specified. Then each snapshot in the space-time graph was mapped to a static graph with minimum cost during the period as the weight of this new graph. Energy efficient solutions can be found in the new graph with MST. Our conclusion is that this distributed network topology for flying formations is a promising way of optimizing energy utilization which may greatly benefit the design and operation of nanosatellite missions in future.

6. Acknowledgements

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