Energy Efficient Network Strategy for Nanosatellite Cluster Flight Formations

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Network in Nanosatellites cluster formation

Multiple hopping path strategy

Dynamic topology

MST Solution over Space-time graph

Numerical simulations & Conclusions
Nanosatellite benefits

- low budget cost
- flexible design ideologies
- significant educational roles
- Short manufacturing timeline
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QB50

An International Network of 50 double and triple CubeSats

in a string-of-pearls configuration for multi-point, in-situ, long-duration exploration of the lower thermosphere (90 – 320 km),
for re-entry research and for in-orbit demonstration of technologies and miniaturised sensors.
Power constraints

Average power per orbit is 2.1-4.5 watts

S-band downlinks, 1 Mbps

UHF downlinks, 10 kbps
Link budget

- Use short distance links instead of long distance links;
- Provide multiple hopping links from one node to another in the network

![Graph of BER vs. Eb/No](image1)

![Graph of free space path loss vs. frequency](image2)

![Diagram of network with multiple links](image3)
Network in Nanosatellites and Cubesats

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Network architecture

<table>
<thead>
<tr>
<th>Masters</th>
<th>Slaves</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ large storage capacity;</td>
<td>only connect and communicate with masters or other slaves</td>
</tr>
<tr>
<td>➢ capability of establishing satellite-ground</td>
<td>through intersatellite links within its limited communication range</td>
</tr>
<tr>
<td>links (uplinks and downlinks);</td>
<td>(or called visible distance)</td>
</tr>
<tr>
<td>➢ intersatellite links to communicate with</td>
<td></td>
</tr>
<tr>
<td>others;</td>
<td></td>
</tr>
</tbody>
</table>

Masters voted from slaves based on the energy sufficiency or assigned by ground stations.
Multiple hopping path

Independent space-ground links
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Space-time graph

Nanosatellite orbit in the cluster formation

Hill’s equations or Clohessy-Wiltshire Equations
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Space-time graph

Nanosatellite orbit in the cluster formation

Hill’s equations or Clohessy-Wiltshire Equations

![Space-time graph](image)
Network topology evolves over time.

Nanosatellite orbit in the cluster formation

Hill’s equations or Clohessy-Wiltshire Equations

Space-time graph
Space-time graph

\[ G = \{V, E\} \]

\[
A(t) = \begin{pmatrix}
    a_{v_1v_1}(t) & a_{v_1v_2}(t) & \cdots & a_{v_1v_n}(t) \\
    a_{v_2v_1}(t) & a_{v_2v_2}(t) & \cdots & a_{v_2v_n}(t) \\
    \vdots & \vdots & \ddots & \vdots \\
    a_{v_nv_1}(t) & a_{v_nv_2}(t) & \cdots & a_{v_nv_n}(t)
\end{pmatrix}
\]

\[
a_{v_i,v_j}(t) = \begin{cases}
1, & d_{v_i,v_j}(t) \leq R_{max} \\
0, & \text{otherwise}
\end{cases}
\]

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

\[ G' = \{V', E'\} \]

\[ \{G' \mid t = t_1, \ldots, t_N\} \]

\[ \text{min}[c(G)] \]
Link dissipation model

\[ E_{tx}(l,d) = l \cdot E_{elec} + l \cdot \varepsilon_{amp} \cdot d^2 \]

\[ E_{cache} = E_{write} + E_{read} = \frac{l \cdot V^{sup}}{8} (I_{write}T_{write} + I_{read}T_{read}) \]

\[ E_{rx}(l) = l \cdot E_{elec} \]

if the length of message is known, as distance increases,
The connectivity should cover all the nanosatellites in the network at the lowest energy cost.

Find a subgraph, which connects all the nodes in the graph together with the minimum summation of the distance on the links.

Dijkstra’s & Floyd–Warshall algorithm
- Provide solutions for the shortest path problem between any pair of nodes for a graph with non-negative edge path costs
- Find the shortest paths between masters and slaves over the network in the cluster formation.

- Minimum spanning tree to form the subgraph with global connectivity of lowest energy cost.
- 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.
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Spatial links consume on-board energy: proportional to square of distance.

Temporal links: caching messages via temporal links does not consume the energy.

each nanosatellite can cache messages until the closest position to the target is reached. transmit the messages to the target at an economic energy cost

use temporal links to find the energy efficient MST over the time
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Algorithm 1 MST of Space-time graph

1: \( G' = \langle v', E' \rangle, t \in \{ t_1, \ldots, t_N \} \)
2: for \( t \in \{ t_1, \ldots, t_N \} \)
   for \( i \in \{ 1, \ldots, n \} \)
      for \( j \in \{ 1, \ldots, n \} \)
      find minimum cost of edge \( v_i v_j \)
      end for
   end for
end for
3: construct a new graph \( \zeta = \langle V, E' \rangle \) 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 \( \zeta \), edges of the MST is denoted by set \( E_{\text{MST}} \)
5: for \( t_m \in \{ t | t = 1, \ldots, T \} \)
   if \( v_i v_j \in E_{\text{MST}} \)
   \( v_i v_j \) is the spatial link in the MST of \( G' = \langle v', E' \rangle, t \in \{ t_1, \ldots, t_N \} \)
   end if
   if \( v_i \) appear more than once,
   \( v_i(t_i v_i(t + \Delta t) \) is the temporal link in the MST of \( G' = \langle v', E' \rangle, \Delta t \) is the time shift between the different appearance.
   end if
end for
6: connect all the temporal links discovered to form the MST of \( G' = \langle v', E' \rangle \)
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<table>
<thead>
<tr>
<th></th>
<th>Semimajor axis /km</th>
<th>Eceentricity</th>
<th>Inclination /deg</th>
<th>Argument of Perigee / deg</th>
<th>RAAN/ deg</th>
<th>Mean Anomaly /deg</th>
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<td>-2.96289</td>
</tr>
</tbody>
</table>

**Graph 1:**
- **Time (Minute):** Range 0 to 408
- **Weight of MST (Km):** Range 1.34 to 1.52

**Graph 2:**
- **Time (Minute):** Range 0 to 100
- **Normalized Index:** Range 1 to 5
Spatial links:

\( v_1 v_5, v_2 v_4, v_3 v_4, \)

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.
Conclusion

- Introduced an energy efficient strategy for nanosatellite cluster formations.
- Defined a network architecture using multiple hopping relay.
- Illustrated the time varying characteristic in topology.
- Proposed a MST for Space-time graph.

This network strategy for cluster formations is a promising way of optimizing energy utilization which may greatly benefit the design and operation of nanosatellite missions in future.
Acknowledge

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