Cognitive Route Selection and Frequency Allocation for CubeSat Swarm

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Content

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- Comparison of different weights
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CubeSat swarm

Inspired by the swarming behaviors of animals in nature [1]

The swarm-based satellite system:

Many pico-class, low-power, and low-weight satellite units working together for space exploration tasks [2][3].
The Master CubeSat can *sense the changes* about the internal and external environment of the CubeSat swarm, proactively *regulates and optimizes* the communication network employing the *adjustable inter-satellite routing decisions* for the CubeSat swarm.

### Notation[5]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$K$</td>
<td>Number of data flow</td>
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<tr>
<td>$k$</td>
<td>The $k^{th}$ data flow, $1 \leq k \leq K$</td>
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<tr>
<td>$x_{ij}^k$</td>
<td>The route selection from $U_i$ to $U_j$ at $k^{th}$ data flow</td>
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<td>$\eta_{ij}^k$</td>
<td>The energy efficiency of the inter-satellite links from $U_i$ to $U_j$ of $k^{th}$ data flow</td>
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<td>$T_{ij}^k$</td>
<td>The time delay of the inter-satellite links from $U_i$ to $U_j$ of $k^{th}$ data flow</td>
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Choose the route between CubeSat $i$ to CubeSat $j$ based on the different route weight metric.
A : Route weight: Energy efficiency

Only consider transmission power

Slave CubeSat transmission power 1 W
Master CubeSat transmission power 5 W
Energy efficiency between two CubeSat

\[ \eta_{i,j}^k = \frac{R_{i,j}^k}{P_{i,j}^k} \]

\[ R_{i,j}^k = \frac{G_{i,j} R_{i,j}^{k-1}}{k_s T_s (E_b/N_0)} \]

\[ \eta_{i,j} = \frac{R_{i,j}}{P_{i,j}} \]

\[ R_{i,j} = \frac{G_{i,j} L_{i,j}}{k_s T_s (E_b/N_0)} \]

\[ \text{[4][5]} \]

\( \eta_{i,j}^k \): The energy efficiency of the inter-satellite link between \( U_i \) and \( U_j \) of \( k \text{th} \) data flow

\( R_{i,j}^k \): The throughput of satellite \( U_i \) to \( U_j \) of \( k \text{th} \) data flow

\( P_{i,j}^k \): The transmit power of satellite \( U_i \) to \( U_j \) of \( k \text{th} \) data flow

The threshold is about 526km.
Less than 526km, we choose 353THz as our operation frequency.
Larger than 526km, we choose 60GHz as our operation frequency.
The transmission power do not affect energy efficiency

\[ \eta_{i,j} = \frac{R_{i,j}}{P_{i,j}} = \frac{G_T G_R P_{i,j} L_{i,j}}{k_s T_s (E_b/N_0)} = \frac{G_T G_R L_{i,j}}{k_s T_s (E_b/N_0)} \]
Consider CubeSat swarm in a plane

Two Examples:
Euclidean Distance scale $1 : 10^5$ (the same as follows)
M: represent master CubeSat
S1: represent the #1 slave CubeSat

We want to find the route from satellite $U_i$ to $U_j$ at $k^{th}$ data flow, which can achieve maximum energy efficiency.
The route selection from slave to master

Orange represents optical frequency (353THz)
Green represents mmWave (60GHz)

#0 slave CubeSat to master CubeSat
Route Path is [0, M]
Operation frequency is [353THz]

#1 slave CubeSat to master CubeSat
Route Path is [1, 4, M]
Operation frequency is [60GHz, 353THz]

#3 slave CubeSat to master CubeSat
Route Path is [3, 2, M]
Operation frequency is [353THz, 353THz]
Energy efficiency comparison (#1 slave CubeSat to Master CubeSat)

Without route selection: #1 slave CubeSat directly transmit to Master CubeSat
With route selection: based on maximum energy efficiency, Route Path is [1, 4, M]

Route Path is [1, M]
Operation frequency is [60GHz]

Route Path is [1, 4, M]
Operation frequency is [60GHz, 353THz]

Energy efficiency from Slave #1 to Master

Without route selection

With route selection

68%
The route selection from slave to slave

#0 slave CubeSat to #4 slave CubeSat
Route Path is [0, M, 4]
Operation frequency is [353THz, 353THz]

#1 slave CubeSat to #2 slave CubeSat
Route Path is [1, 4, M, 2]
Operation frequency is [60GHz, 353THz, 353THz]

#3 slave CubeSat to #0 slave CubeSat
Route Path is [3, 2, 0]
Operation frequency is [353THz, 353THz]
Energy efficiency comparison (\#0 slave CubeSat to \#4 slave CubeSat)

Without route selection: \#0 slave CubeSat directly transmit to \#4 slave CubeSat
With route selection: based on maximum energy efficiency, Route Path is [0, M, 4]

Route Path is [0, 4]
Operation frequency is [353THz]

Route Path is [0, M, 4]
Operation frequency is [353THz, 353THz]

Energy efficiency from Slave \#0 to \#4

Without route selection

With route selection

17%
#3 slave CubeSat to other CubeSats

Without route selection

Operation frequency is [353THz]

Operation frequency is [353THz]

Operation frequency is [353THz]

Operation frequency is [60GHz]

Operation frequency is [60GHz]

With route selection

Operation frequency is [353THz]

Operation frequency is [353THz, 353THz]

Operation frequency is [353THz, 60GHz]

Operation frequency is [353THz, 353THz, 353THz]

Operation frequency is [353THz, 353THz, 353THz, 60GHz]
Energy efficiency improvement with distance between the source CubeSat and destination CubeSat

The energy efficiency improvement will decrease when the distance between two CubeSats become larger.
C: Route weight: Time delay

\[ \min_{x_{i,j}^k} T_{i,j}^k \]

We want to find the route from satellite \( U_i \) to \( U_j \) at \( k^{th} \) time slot, which can achieve minimum time delay.

\[ T_{i,j}^k = \tau_{i,j}^k + t_{i,j}^k \]

\( \tau_{i,j}^k \): The transmission delay of satellite \( U_i \) to \( U_j \) of \( k^{th} \) data flow

\( t_{i,j}^k \): The propagation delay of satellite \( U_i \) to \( U_j \) of \( k^{th} \) data flow

Example two:
Euclidean Distance scale 1 : \( 10^5 \)
M: represent master CubeSat
S1: represent the #1 slave CubeSat
Time delay

\[ T_{i,j} = \frac{V_{i,j}}{R_{i,j}} + \frac{d_{i,j}}{c} = \frac{V_{i,j}}{G_TG_RP_{i,j}L_{i,j}} + \frac{d_{i,j}}{c} \]

- \( \eta_{ij} \): The energy efficiency between \( U_i \) and \( U_j \)
- \( R_{ij} \): The throughput of satellite \( U_i \) to \( U_j \)
- \( P_{ij} \): The transmit power of satellite \( U_i \) to \( U_j \)
- \( d_{ij} \): The distance from satellite \( U_i \) to \( U_j \)
- \( L_{ij} \): The loss from satellite \( U_i \) to \( U_j \)
- \( V_{ij} \): The data flow from satellite \( U_i \) to \( U_j \)

Fix the operation frequency is 353THz, transmission power is 1 W

\[ T_{ij} = \frac{V_{ij}}{R_{ij}} + d_{ij} = \frac{V_{ij}}{G_TG_RP_{ij}L_{ij}} + d_{ij} \cdot \frac{L_{ij}}{c} \]

Different data flow affect the transmission delay.
The route selection from slave to master

#0 slave CubeSat to master CubeSat
Route Path is [0, 8, M]
Operation frequency is [353THz, 353THz]

#1 slave CubeSat to master CubeSat
Route Path is [1, 7, 13, 10, M]
Operation frequency is [353THz, 353THz, 353THz, 353THz]

#3 slave CubeSat to master CubeSat
Route Path is [3, 12, 13, 10, M]
Operation frequency is [353THz, 353THz, 353THz, 353THz]
Time delay comparison (#3 slave CubeSat to Master CubeSat)

Without route selection: #3 slave CubeSat directly transmit to Master CubeSat
With route selection: based on maximum energy efficiency, Route Path is [3, 12, 13, 10, M]

Route Path is [3, M]
Operation frequency is [353THz]

Route Path is [3, 12, 13, 10, M]
Operation frequency is [353THz, 353THz, 353THz, 353THz]
Comparison of route selection between CubeSat swarm

(Maximum energy efficiency or minimum time delay)
Comparison (route weight: energy efficiency and time delay)

The route selections are different when we consider different weight for route selection.

Route selection based on minimum time delay will select less hop than route selection based on maximum energy efficiency.
Route selection with consideration of energy efficiency and time delay together

\[
\begin{align*}
\max_{x_{i,j}} & \quad \eta_{i,j} \\
\text{s.t} & \quad T_{i,j} \leq \Delta T
\end{align*}
\]

Derivation:

\[
\eta_{i,j} = \frac{R_{i,j}}{P_{i,j}} = \frac{G_T G_R L_{i,j}}{k_s T_s (E_b/N_0)}
\]

\[
T_{i,j} = \frac{V_{i,j}}{R_{i,j}} + \frac{d_{i,j}}{c} = \frac{G_T G_R P_{i,j} L_{i,j}}{k_s T_s (E_b/N_0)} + \frac{d_{i,j}}{c}
\]

\[
\frac{V_{i,j}}{\eta_{i,j} P_{i,j}} + \frac{d_{i,j}}{c} \leq \Delta T
\]

\[
\eta_{i,j} \geq \frac{c V_{i,j}}{P_{i,j} (c \Delta T - d_{i,j})}
\]

Based on maximum time delay constraint, we can find the minimum boundary for energy efficiency

\[
\begin{align*}
\min_{x_{i,j}} & \quad T_{i,j}^k \\
\text{s.t} & \quad \eta_{i,j}^k \geq \eta_{\text{min}}
\end{align*}
\]

Due to the duality, based on minimum energy efficiency constraint, we can find the maximum boundary for time delay.

\[\eta_{i,j} \text{ The energy efficiency between } U_i \text{ and } U_j\]

\[R_{i,j} : \text{ The throughput of satellite } U_i \text{ to } U_j\]

\[P_{i,j} : \text{ The transmit power of satellite } U_i \text{ to } U_j\]

\[d_{i,j} : \text{ The distance from satellite } U_i \text{ to } U_j\]

\[L_{i,j} : \text{ The loss from satellite } U_i \text{ to } U_j\]

\[V_{i,j} : \text{ The data volume from satellite } U_i \text{ to } U_j\]

\[\Delta T : \text{ The maximum time delay from satellite } U_i \text{ to } U_j\]
When we fix the data flow and transmission power, energy efficiency and time delay are likely to be reciprocal.

Large energy efficiency achieve the small time delay. Large time delay achieve small energy efficiency.
Conclusion

1. Energy efficiency will have different threshold when we consider circuit power consumption or not.

2. Based on maximum energy efficiency, we can find the optimal route in CubeSat swarm and achieve improvement of energy efficiency for CubeSat swarm.

3. Based on minimum time delay, we can find the optimal route in CubeSat swarm and achieve decrease of time delay for CubeSat swarm.

4. Route selection will be different when considering minimum time delay with different transmission data volume.

5. Route selection will be different when considering maximum energy efficiency or minimum time delay.
Future Work:

• Consider the queue, data storage and service processes of CubeSats (Markov states)

• Consider the route selection from CubeSat swarm to ground stations

• Based on real data and using machine learning to choose optimal route for CubeSats
Reference


