Cognitive Route Selection and Frequency Allocation for CubeSat Swarm

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Content

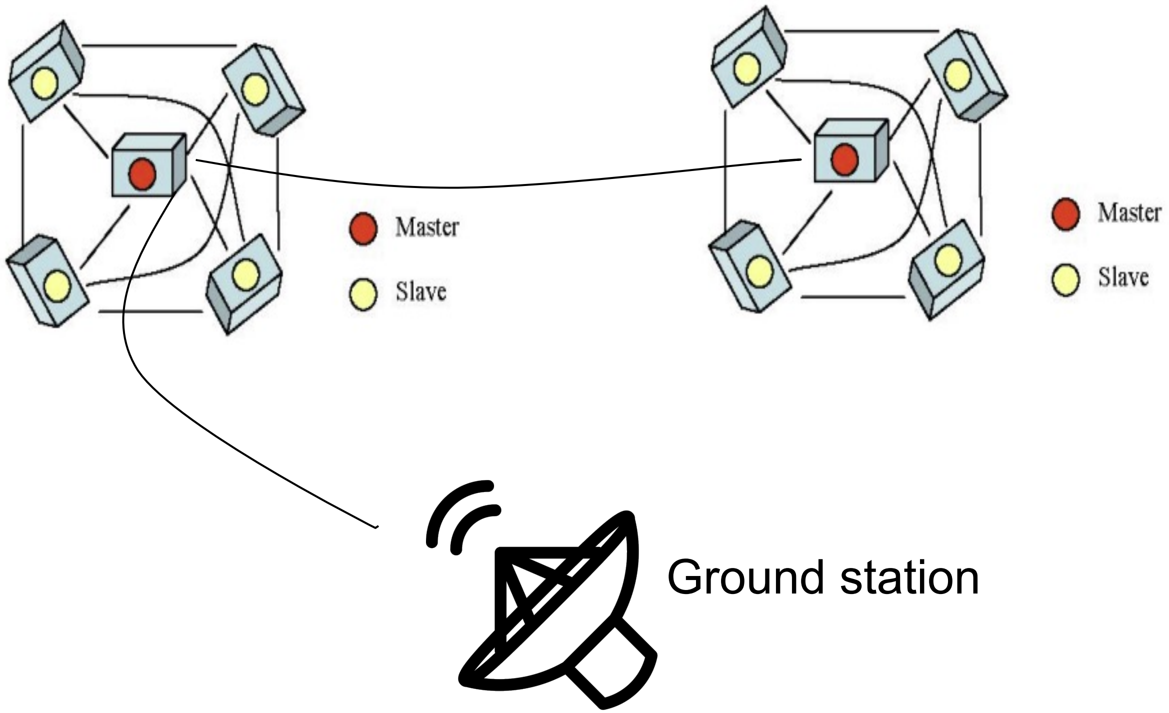
- Introduction
- Two different route weights and results
- Comparison of different weights
- Future work

CubeSat swarm

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

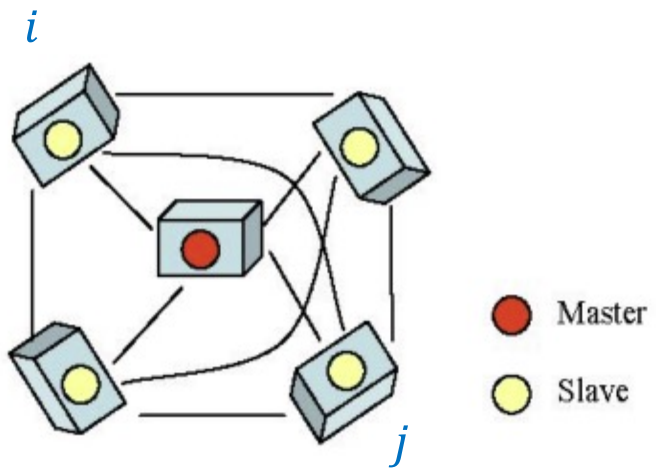
The swarm-based satellite system:

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]	
K	Number of data flow
k	The k^{th} data flow ,1≤ $k \le K$,
$x_{i,j}^{k}$	The route selection from U_i to U_j at k^{th} data flow
$\eta_{i,j}^{k}$	The energy efficiency of the inter-satellite links from U_i to U_j of k^{th} data flow
$T_{i,j}^{k}$	The time delay of the inter-satellite links from U_i to U_j of k^{th} data flow



Choose the route between CubeSat i to CubeSat j based on the different route weight metric

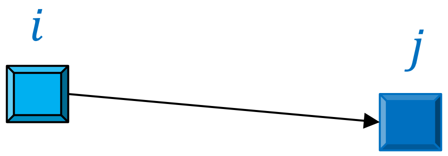
A：Route weight: Energy efficiency

Only consider transmission power

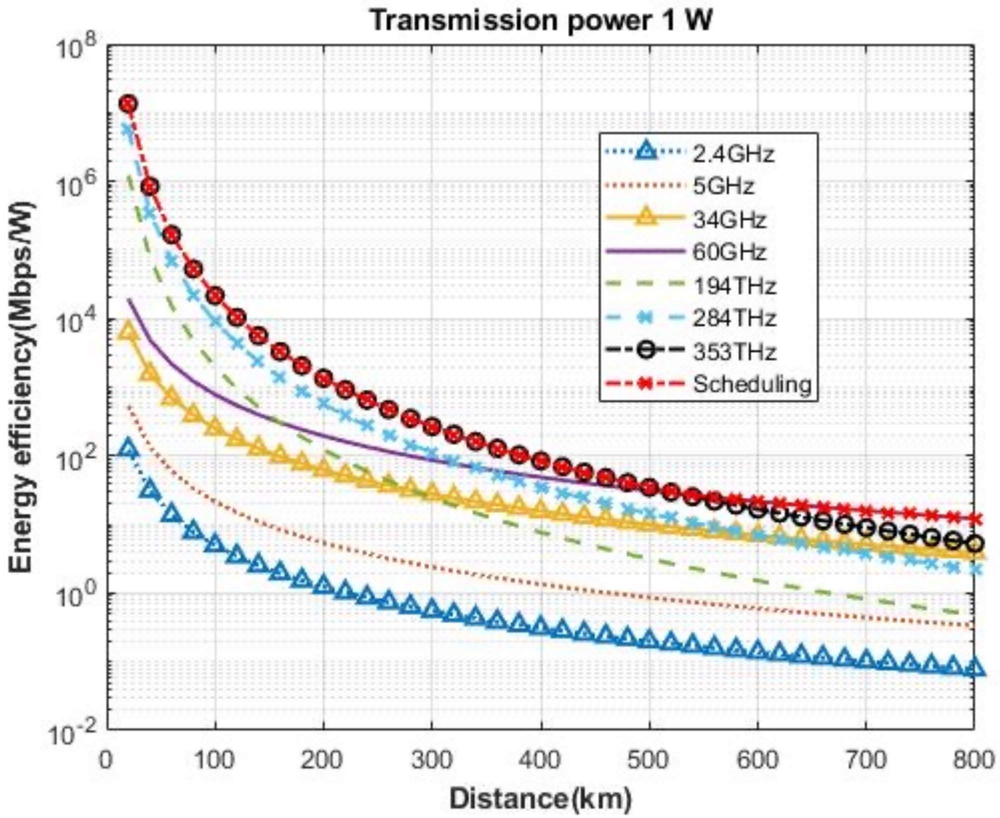
Slave CubeSat transmission power 1 W
Master CubeSat transmission power 5 W

Energy efficiency between two CubeSat

$$\eta_{i,j}^{k} = \frac{R_{i,j}^{k}}{P_{i,j}^{k}} \qquad R_{i,j}^{k} = \frac{G_T G_R P_{i,j}^{k} L_{i,j}^{k}}{k_s T_s (E_b/N_0)}$$

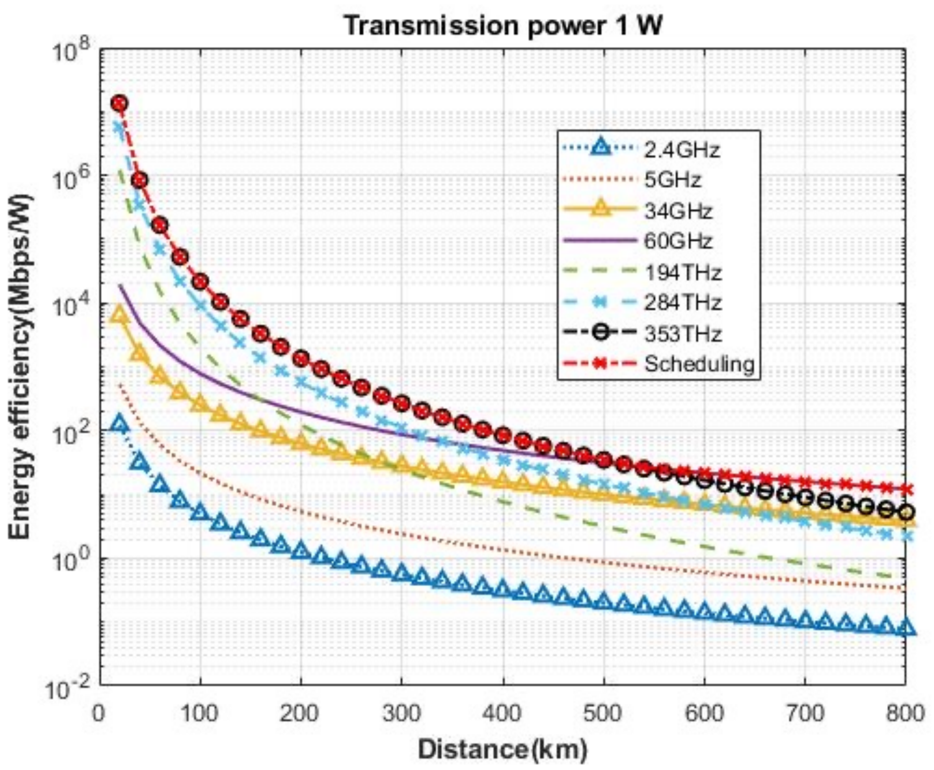


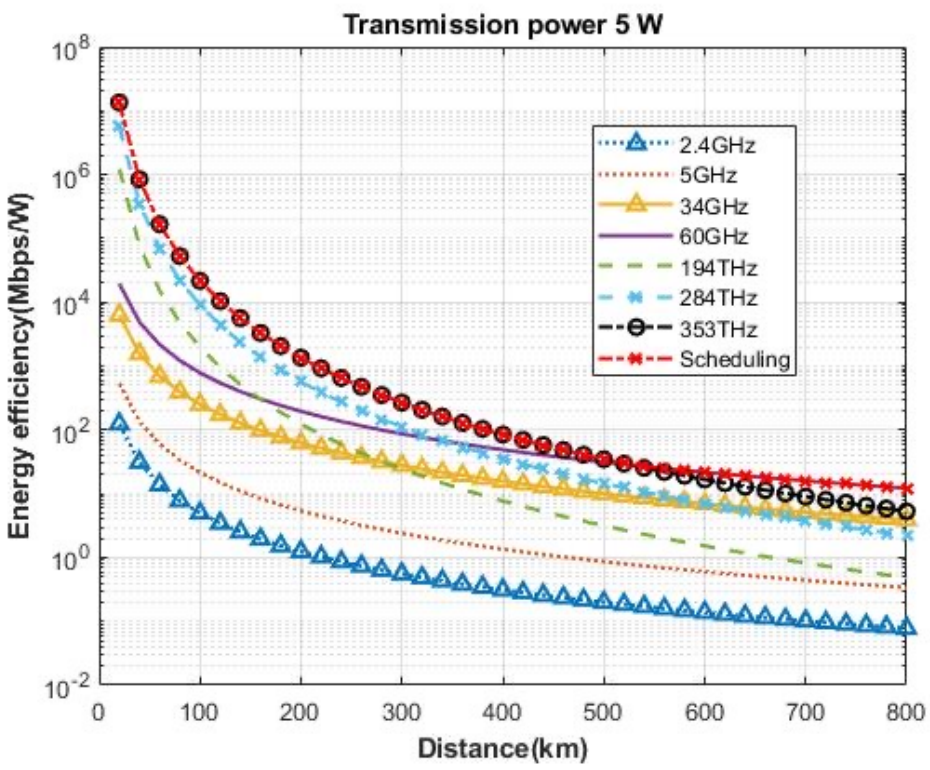
$$\eta_{i,j} = \frac{R_{i,j}}{P_{i,j}} \qquad R_{i,j} = \frac{G_T G_R P_{i,j} L_{i,j}}{k_s T_s (E_b/N_0)}$$ [4][5]



$\eta_{i,j}^{k}$: The energy efficiency of the inter-satellite link between U_i and U_j of k^{th} data flow
$R_{i,j}^{k}$: The throughput of satellite U_i to U_j of k^{th} data flow
$P_{i,j}^{k}$: The transmit power of satellite U_i to U_j of k^{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.

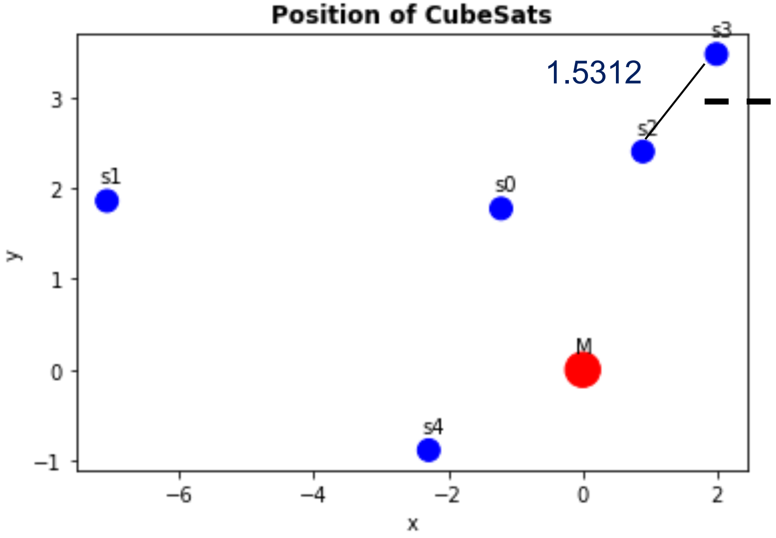




$$\eta_{i,j} = \frac{R_{i,j}}{P_{i,j}} = \frac{\frac{\mathrm{G_T G}_R P_{i,j} L_{i,j}}{\mathrm{k_s} T_\mathrm{s}(\mathrm{E_b/N_0})}}{P_{i,j}} = \frac{\mathrm{G_T G}_R L_{i,j}}{\mathrm{k_s} T_\mathrm{s}(\mathrm{E_b/N_0})}$$

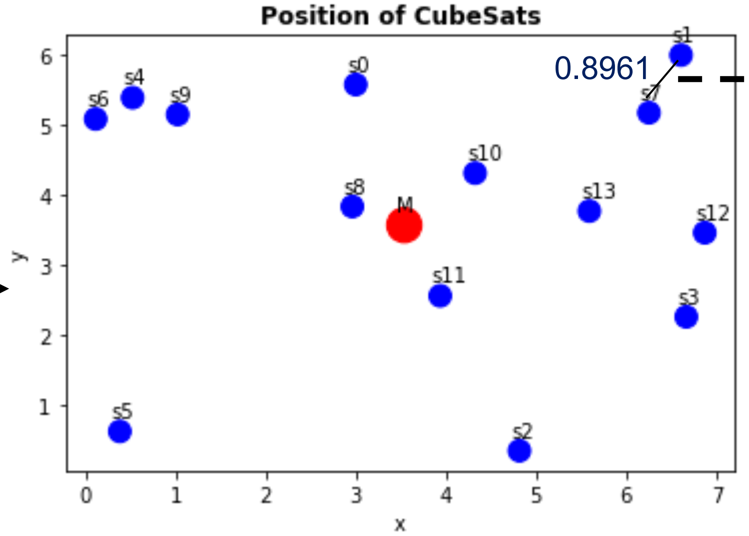
The transmission power do not affect energy efficiency

Consider CubeSat swarm in a plane



153.12 km

More slaves
More crowded



89.61 km

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

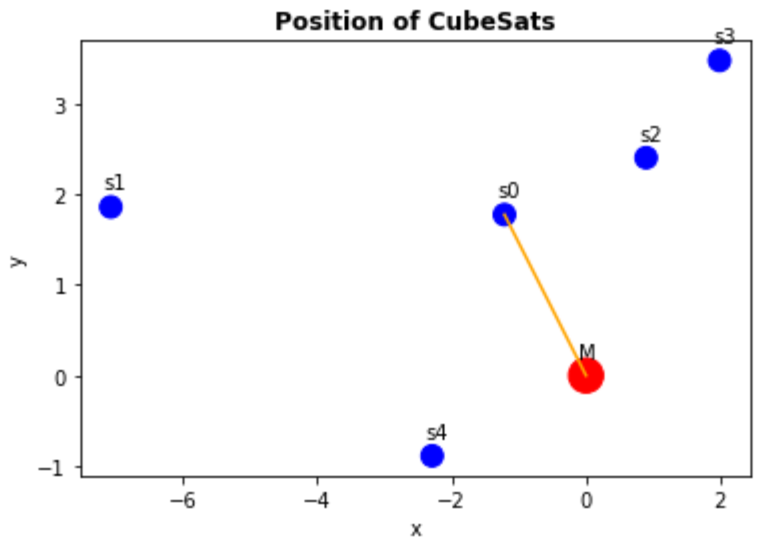
$$\max_{x_{i,j}^k} \quad \eta_{i,j}^k$$

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

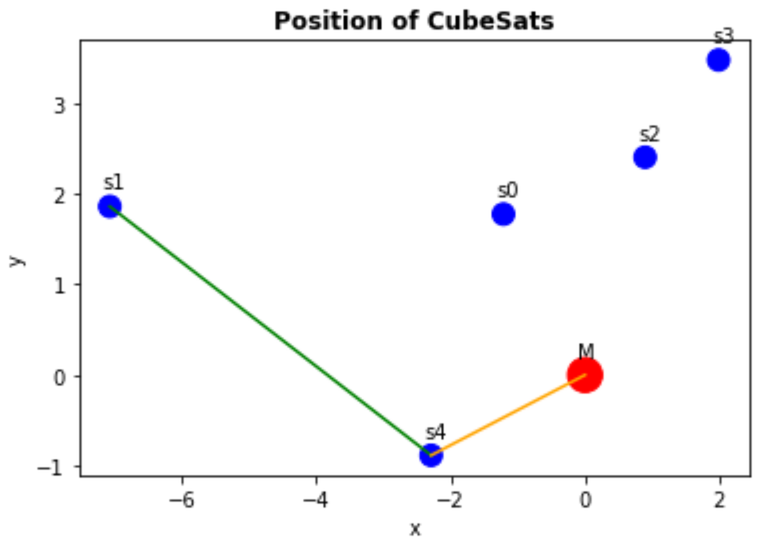
Orange represents optical frequency(353THz)
Green represents mmWave(60GHz)

#0 slave CubeSat to master CubeSat



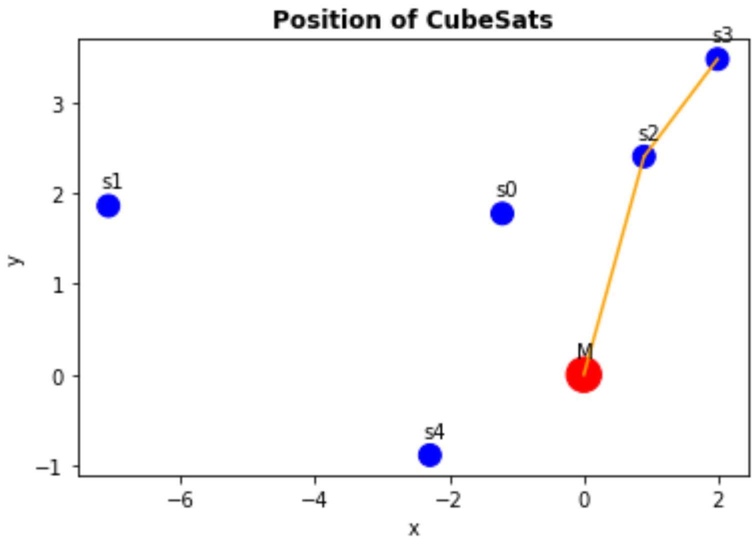
Route Path is [0, M]
Operation frequency is [353THz]

#1 slave CubeSat to master CubeSat



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

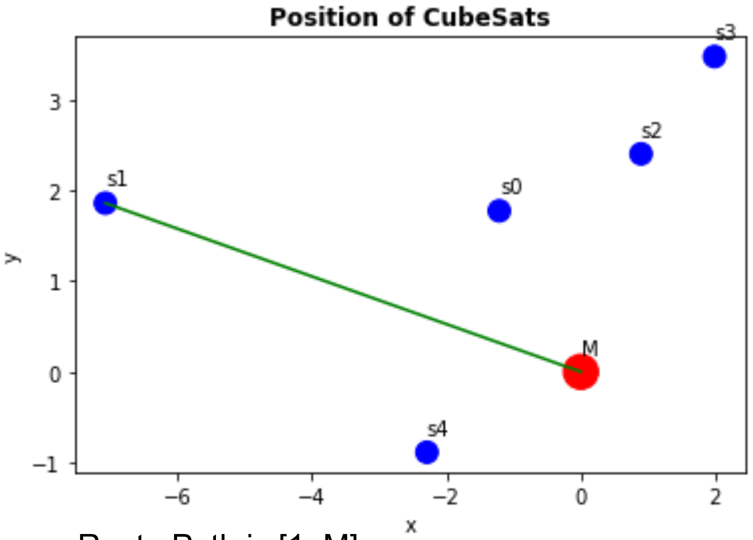
#3 slave CubeSat to master CubeSat



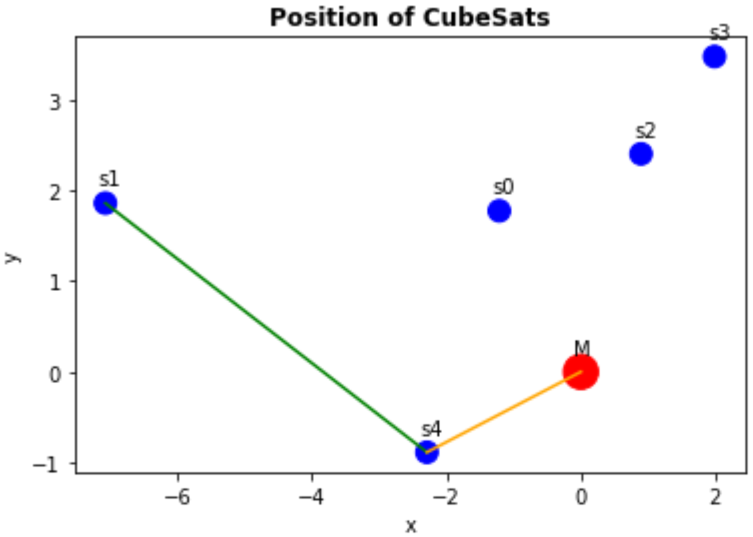
Route Path is [3, 2, M]
Operation frequency is [353THz, 353THz]

Energy efficiency comparison (#1 slave CubeSat to Master CubeSat)

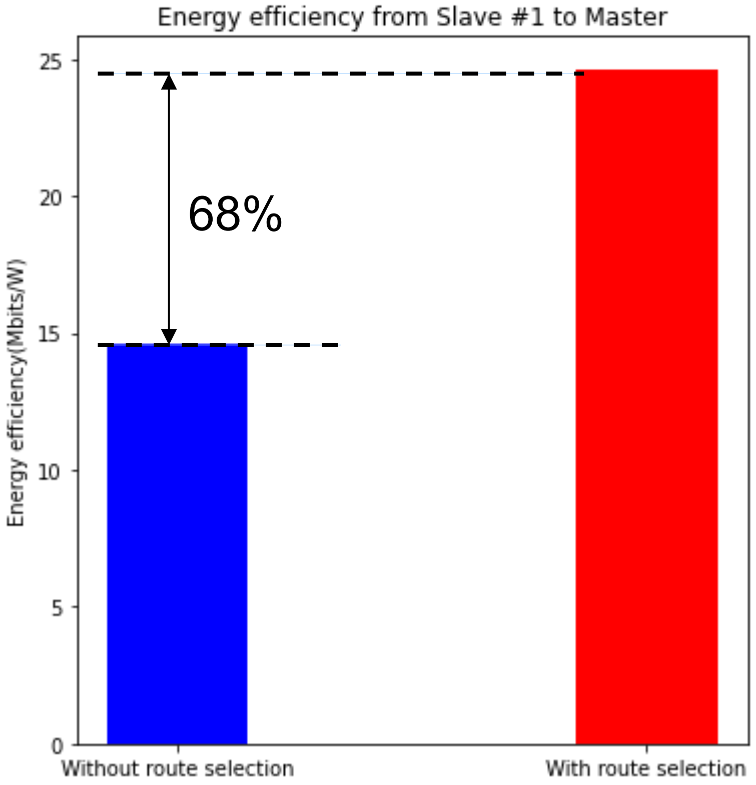
Without route selection: #1 slave CubeSat directly transmit to Master CubeSat
With route selection: based on maximum energy efficiency, Route Path is [1, 4, M]



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

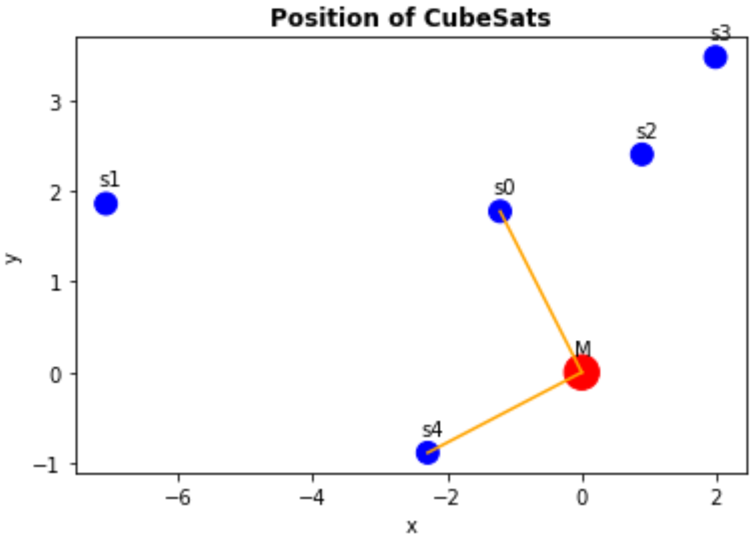


Route Path is [1, 4, M]
Operation frequency is [60GHz, 353THz]



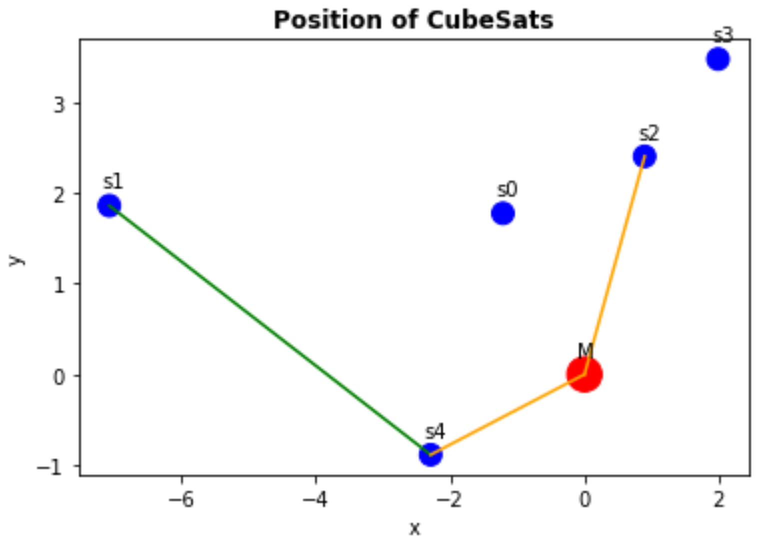
The route selection from slave to slave

#0 slave CubeSat to #4 slave CubeSat



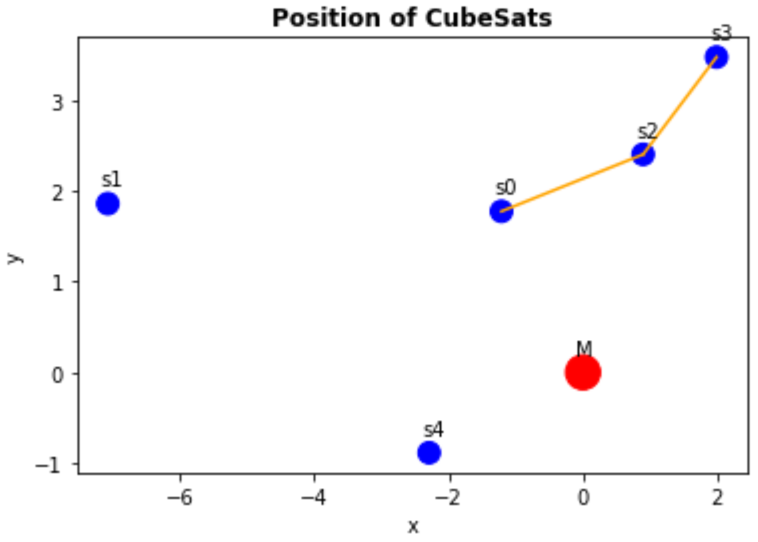
Route Path is [0, M, 4]
Operation frequency is [353THz, 353THz]

#1 slave CubeSat to #2 slave CubeSat



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

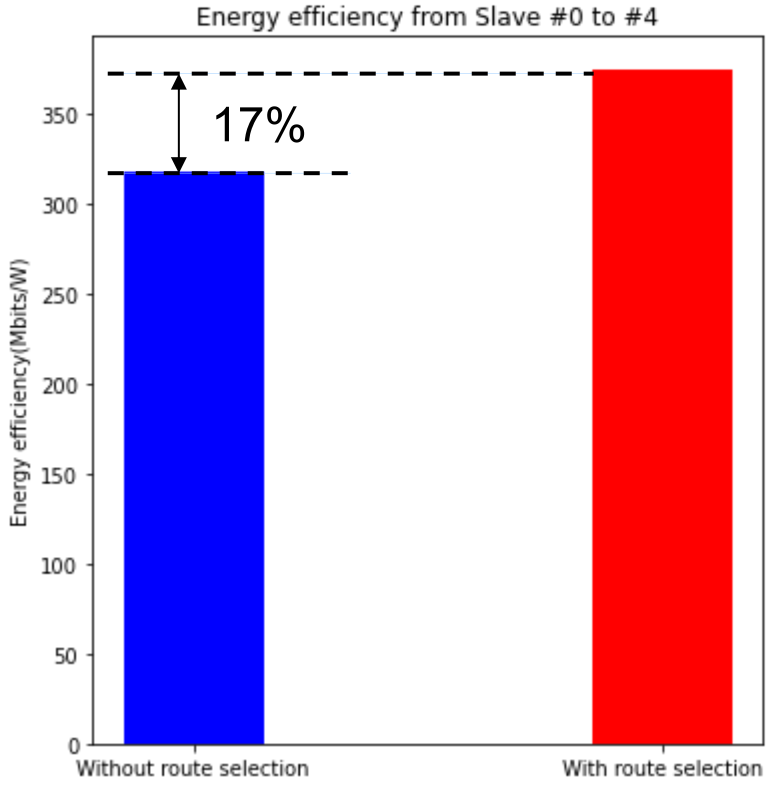
#3 slave CubeSat to #0 slave CubeSat

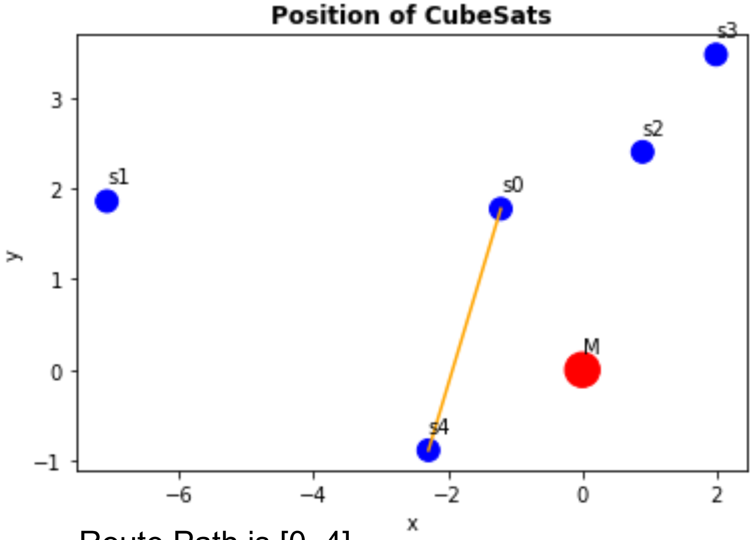


Route Path is [3, 2, 0]
Operation frequency is [353THz, 353THz]

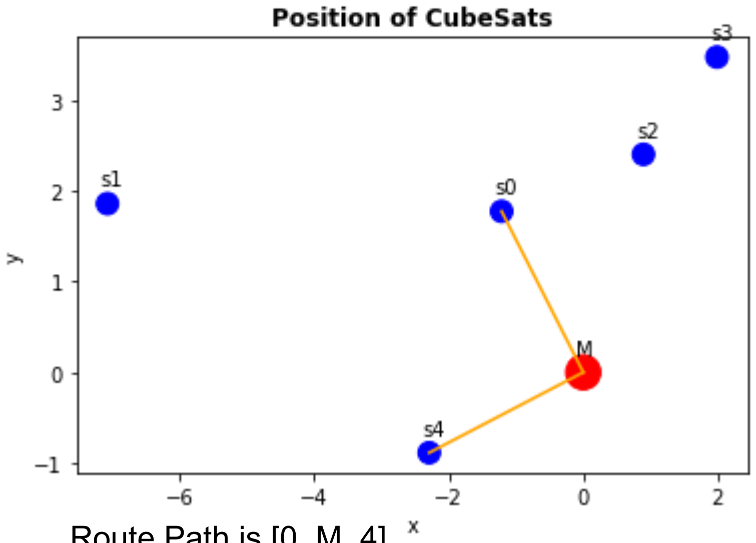
Energy efficiency comparison (#0 slave CubeSat to #4 slave CubeSat)

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]





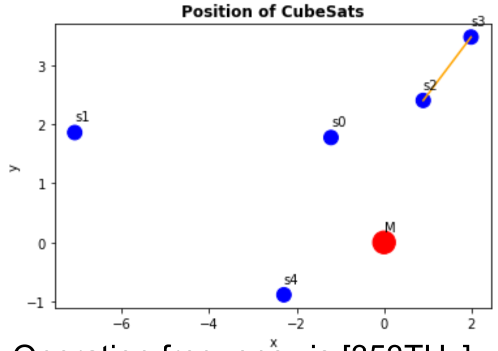
Route Path is [0, 4]
Operation frequency is [353THz]



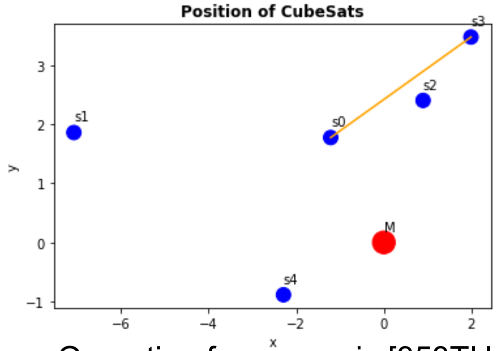
Route Path is [0, M, 4]
Operation frequency is [353THz, 353THz]

#3 slave CubeSat to other CubeSats

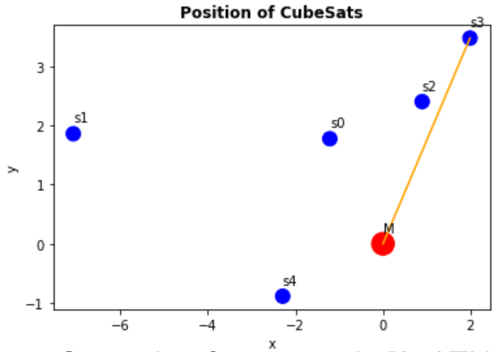
Without route selection



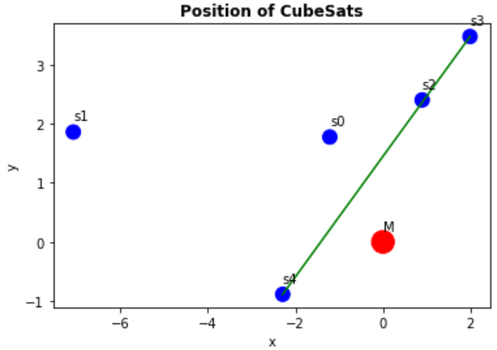
Operation frequency is [353THz]



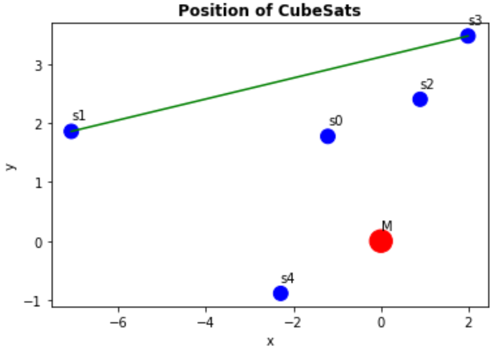
Operation frequency is [353THz]



Operation frequency is [353THz]

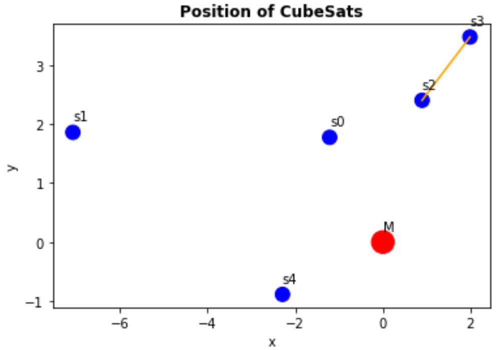


Operation frequency is [60GHz]

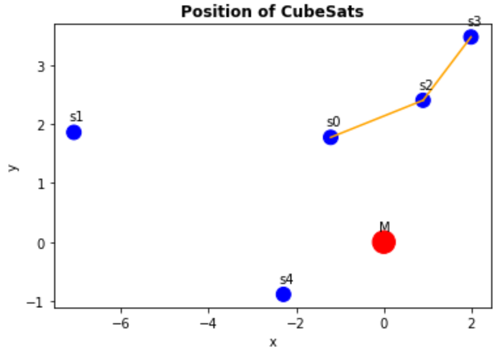


Operation frequency is [60GHz]

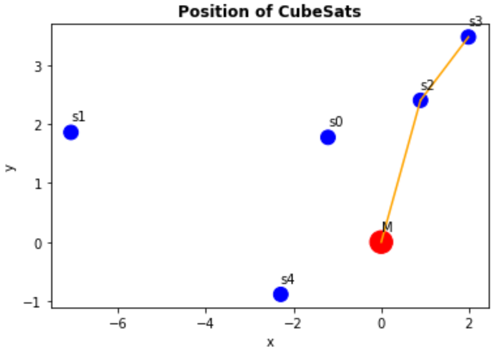
With route selection



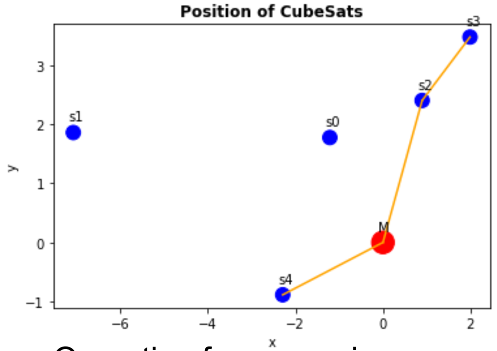
Operation frequency is [353THz]



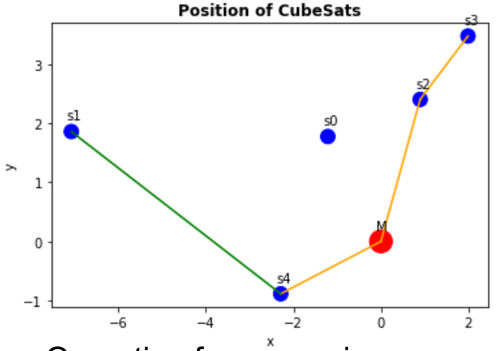
Operation frequency is [353THz , 353THz]



Operation frequency is [353THz , 353THz]

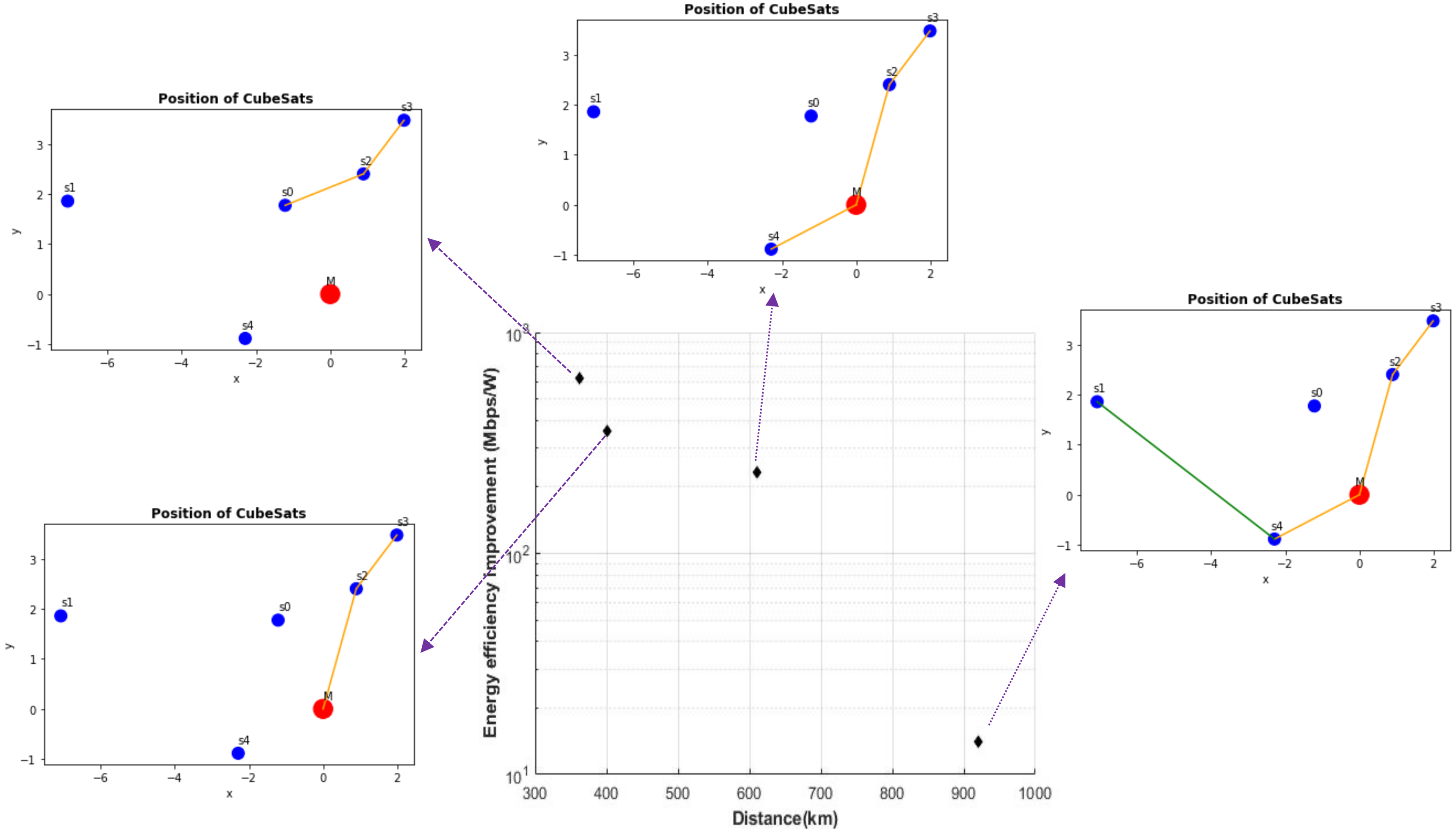


Operation frequency is [353THz, 353THz, 353THz]



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

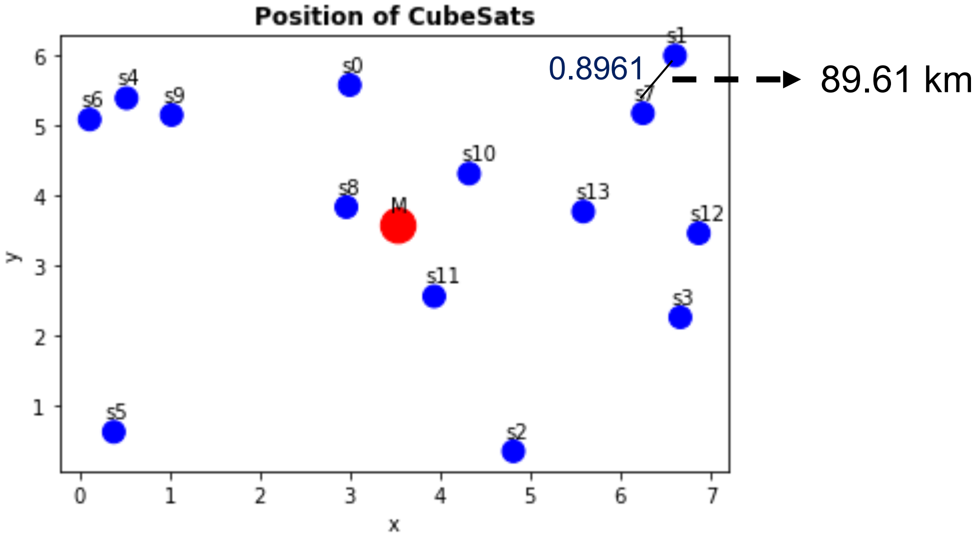
C: Route weight: Time delay

$$\min_{x_{i,j}^k} \quad T_{i,j}^k$$

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



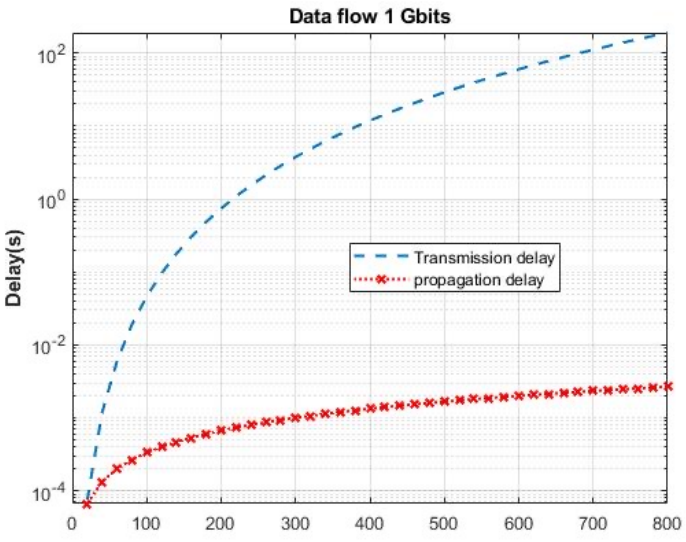
Example two:
Euclidean Distance scale 1 : 10^5
M: represent master CubeSat
S1: represent the #1 slave CubeSat

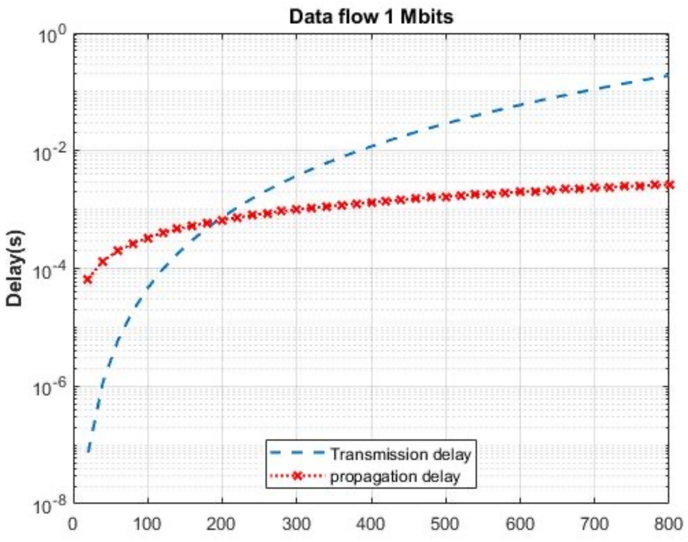
Time delay

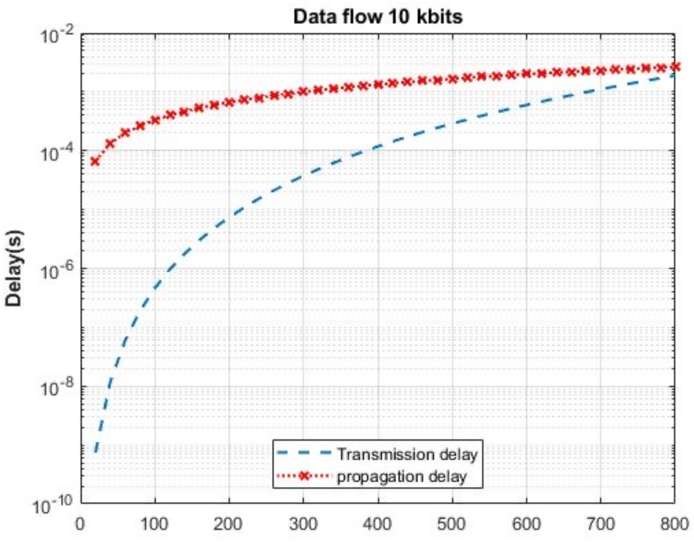
$$T_{i.j} = \frac{V_{i.j}}{R_{i.j}} + \frac{d_{i.j}}{c} = \frac{V_{i.j}}{\frac{G_T G_R P_{i,j} L_{i,j}}{k_s T_s (E_b/N_0)}} + \frac{d_{i.j}}{c}$$

$\eta_{i.j}$ The energy efficiency between U_i and U_j
$R_{i.j}$: The throughput of satellite U_i to U_j
$P_{i.j}$: The transmit power of satellite U_i to U_j
$d_{i.j}$: The distance from satellite U_i to U_j
$L_{i,j}$: The loss from satellite U_i to U_j
$V_{i.j}$: The data flow from satellite U_i to U_j

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



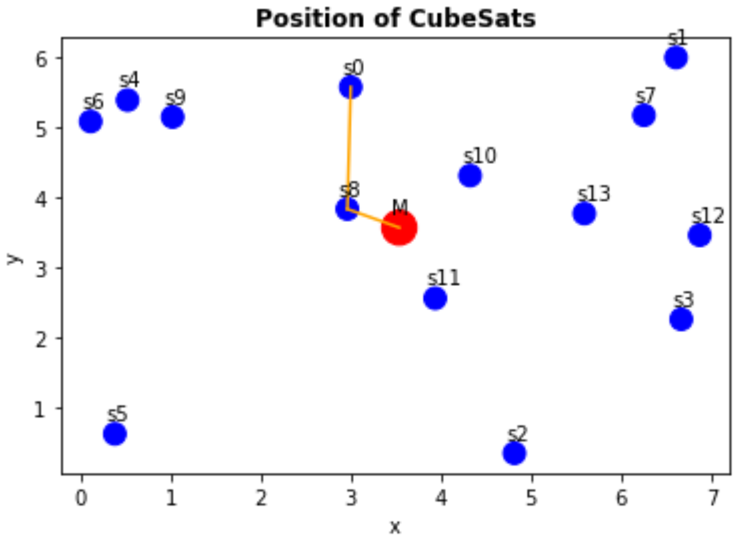




Different data flow affect the transmission delay.

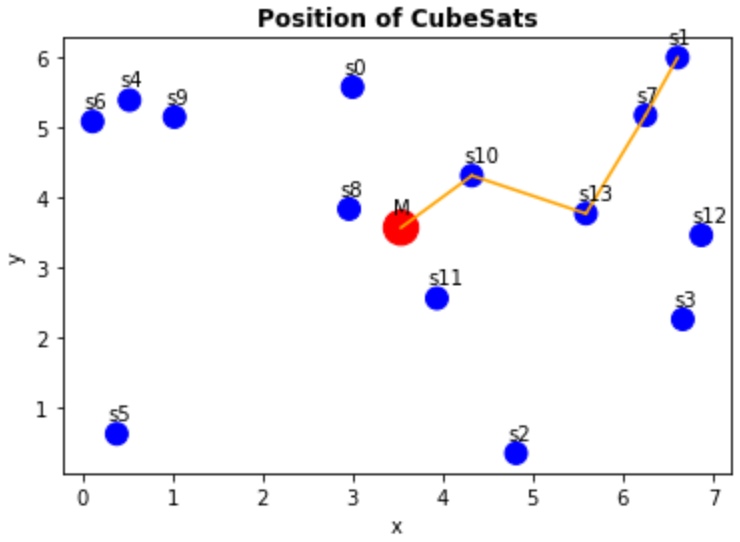
The route selection from slave to master

#0 slave CubeSat to master CubeSat



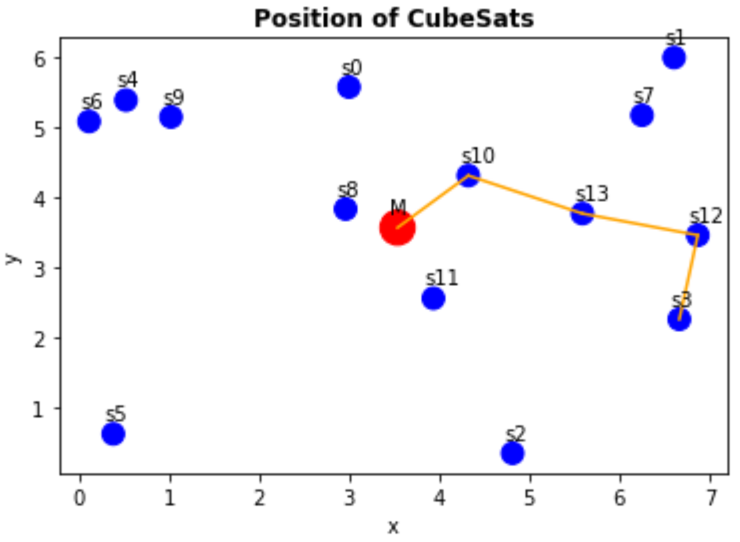
Route Path is [0, 8, M]
Operation frequency is [353THz, 353THz]

#1 slave CubeSat to master CubeSat



Route Path is [1, 7, 13, 10, M]
Operation frequency is [353THz, 353THz, 353THz, , 353THz]

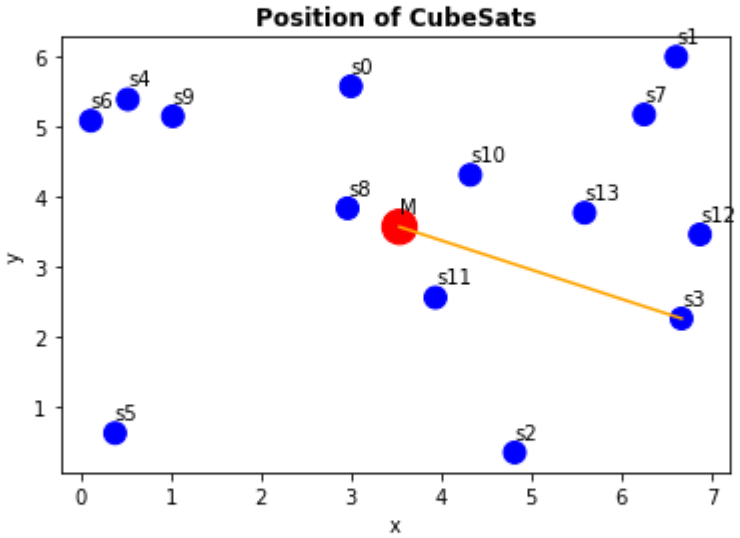
#3 slave CubeSat to master CubeSat



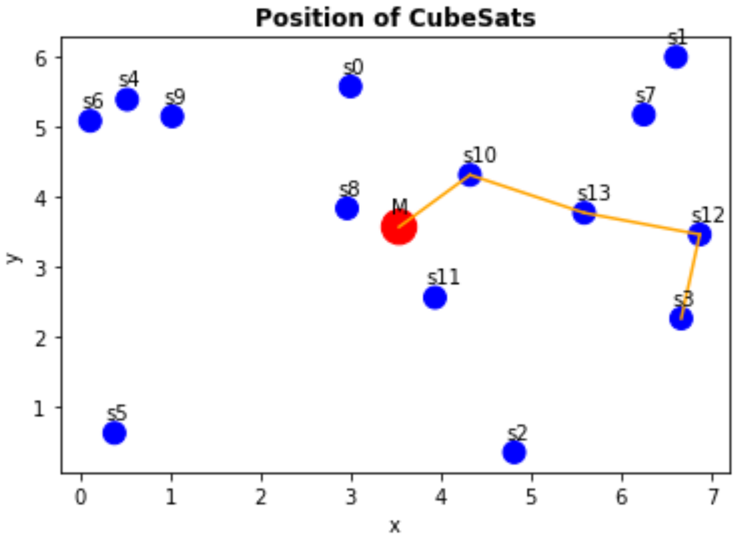
Route Path is [3, 12, 13, 10, M]
Operation frequency is [353THz, 353THz, 353THz, 353THz]

Time delay comparison (#3 slave CubeSat to Master CubeSat)

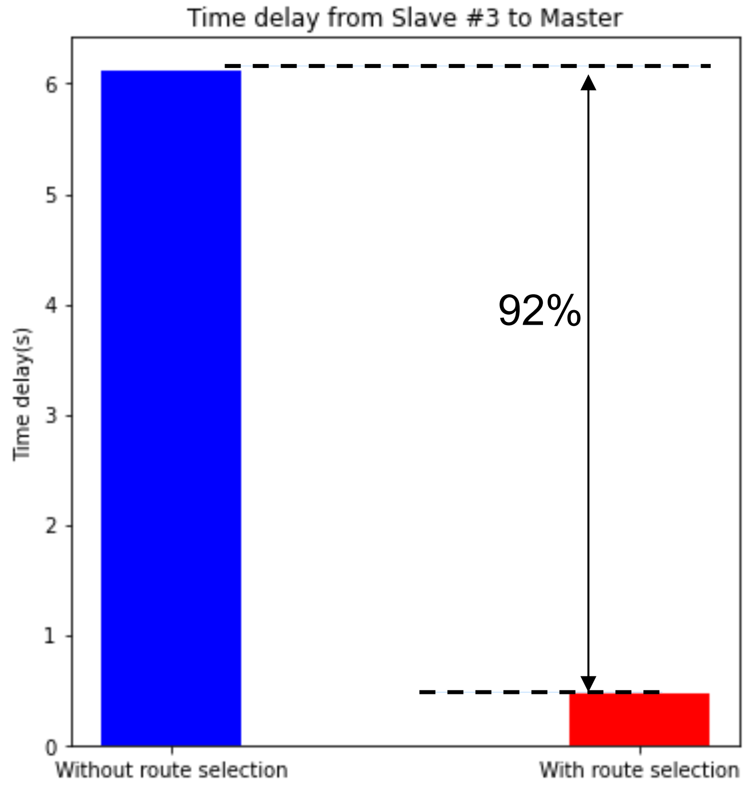
Without route selection: #3 slave CubeSat directly transmit to Master CubeSat
With route selection: based on maximum energy efficiency, Route Path is [3, 12, 13, 10, M]



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



Route Path is [3, 12, 13, 10, M]
Operation frequency is [353THz, 353THz, 353THz, 353THz]

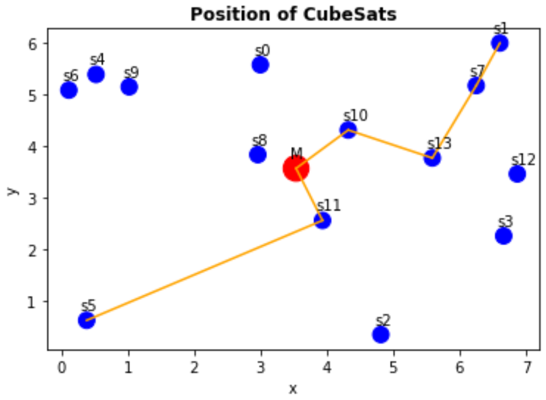


Comparison of route selection between CubeSat swarm

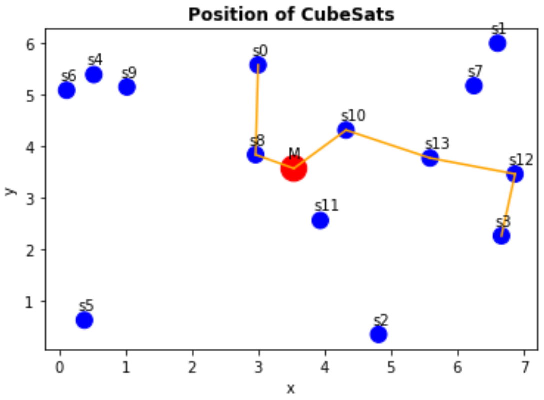
(Maximum energy efficiency or minimum time delay)

Comparison (route weight: energy efficiency and time delay)

energy efficiency

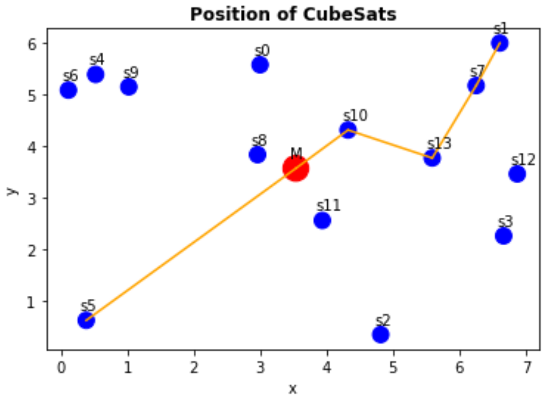


Route Path is [1, 7, 13, 10, M, 11, 5]
Operation frequency is [353THz, 353THz, 353THz, 353THz, 353THz, 353THz]

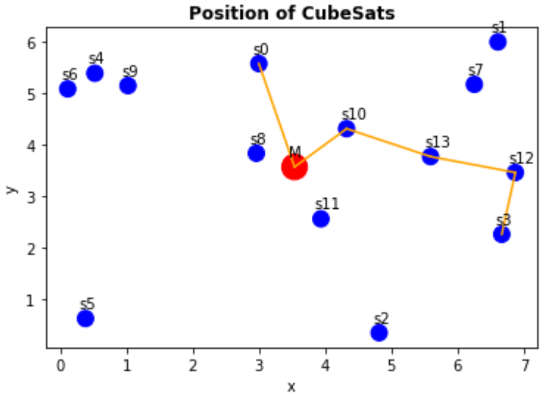


Route Path is [3, 12, 13, 10, M, 8, 0]
Operation frequency is [353THz, 353THz, 353THz, 353THz, 353THz, 353THz]

time delay



Route Path is [1, 7, 13, 10, M, 5]
Operation frequency is [353THz, 353THz, 353THz, 353THz, 353THz]



Route Path is [3, 12, 13, 10, M, 0]
Operation frequency is [353THz, 353THz, 353THz, 353THz, 353THz]

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

$$\underset{x_{i,j}}{Max} \quad \eta_{i.j}$$

s.t $\quad T_{i.j} \leq \Delta T$

Derivation:

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

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

$$\frac{V_{i.j}}{\eta_{i.j} P_{i.j}} + \frac{d_{i.j}}{c} \leq \Delta T$$

$$\eta_{i.j} \geq \frac{cV_{i.j}}{P_{i.j}(c\Delta T - d_{i.j})}$$

$\eta_{i.j}$ The energy efficiency between U_i and U_j

$R_{i.j}$: The throughput of satellite U_i to U_j

$P_{i,j}$: The transmit power of satellite U_i to U_j

$d_{i.j}$: The distance from satellite U_i to U_j

$L_{i,j}$: The loss from satellite U_i to U_j

$V_{i.j}$: The data volume from satellite U_i to U_j

ΔT: The maximum time delay from satellite U_i to U_j

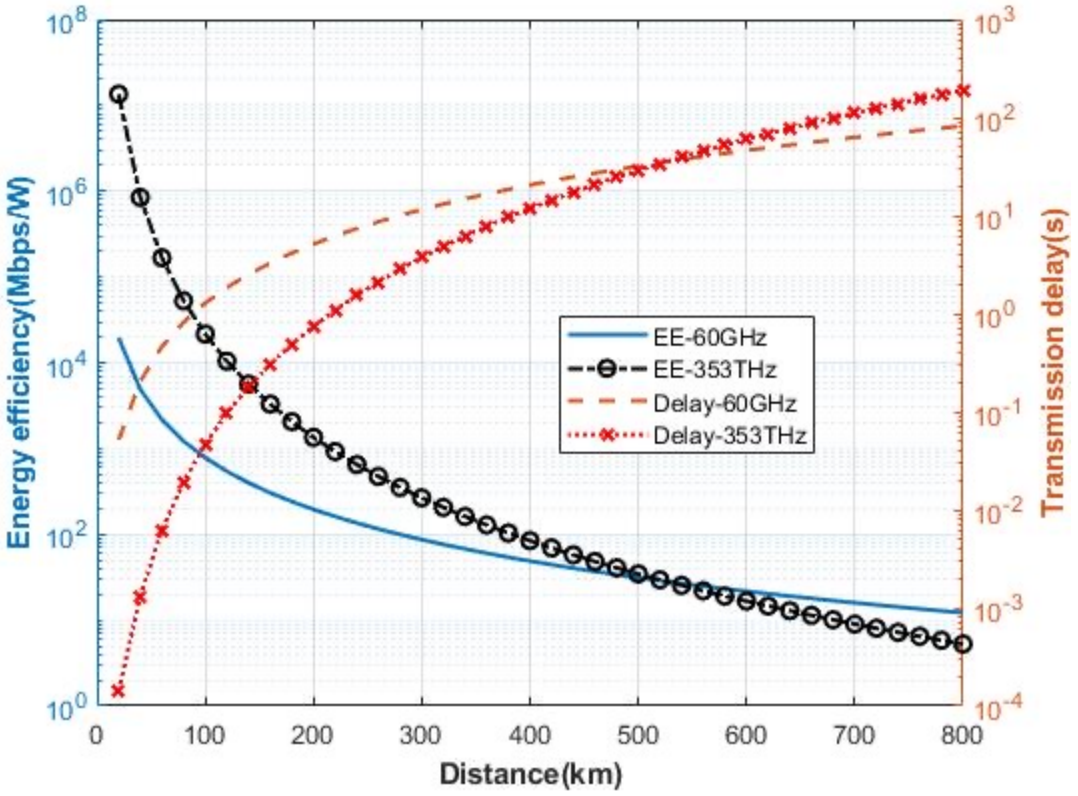
Based on maximum time delay constraint, we can find the minimum boundary for energy efficiency

$$\underset{x_{i,j}^k}{Min} \quad T_{i,j}^k$$

s.t $\quad \eta_{i,j}^k \geq \eta_{min}$

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

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

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