U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

HELIOCOMM: A Resilient Wireless Heliostats Communication System

HelioCon PI: Prof. Eirini Eleni Tsiropoulou
University of New Mexico

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conceptual design • components • integration • mass production • heliostat field

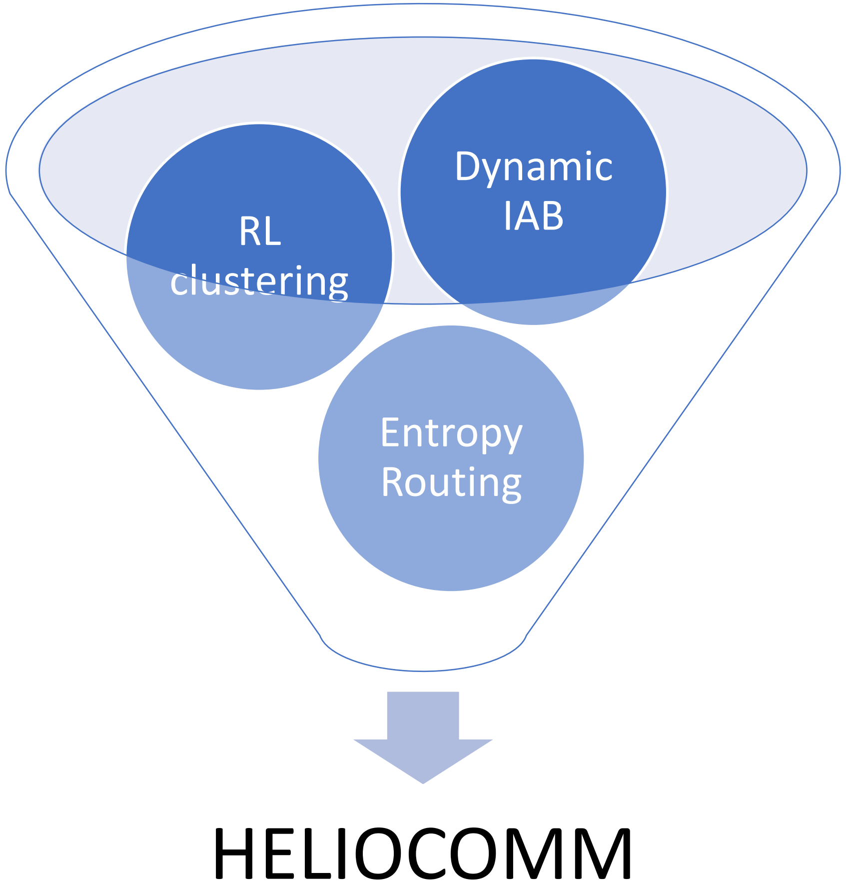
Team Members

Aisha B Rahman
arahman3@unm.edu

Md Sadman Siraj
mdsadmansiraj96@unm.edu

At a glance

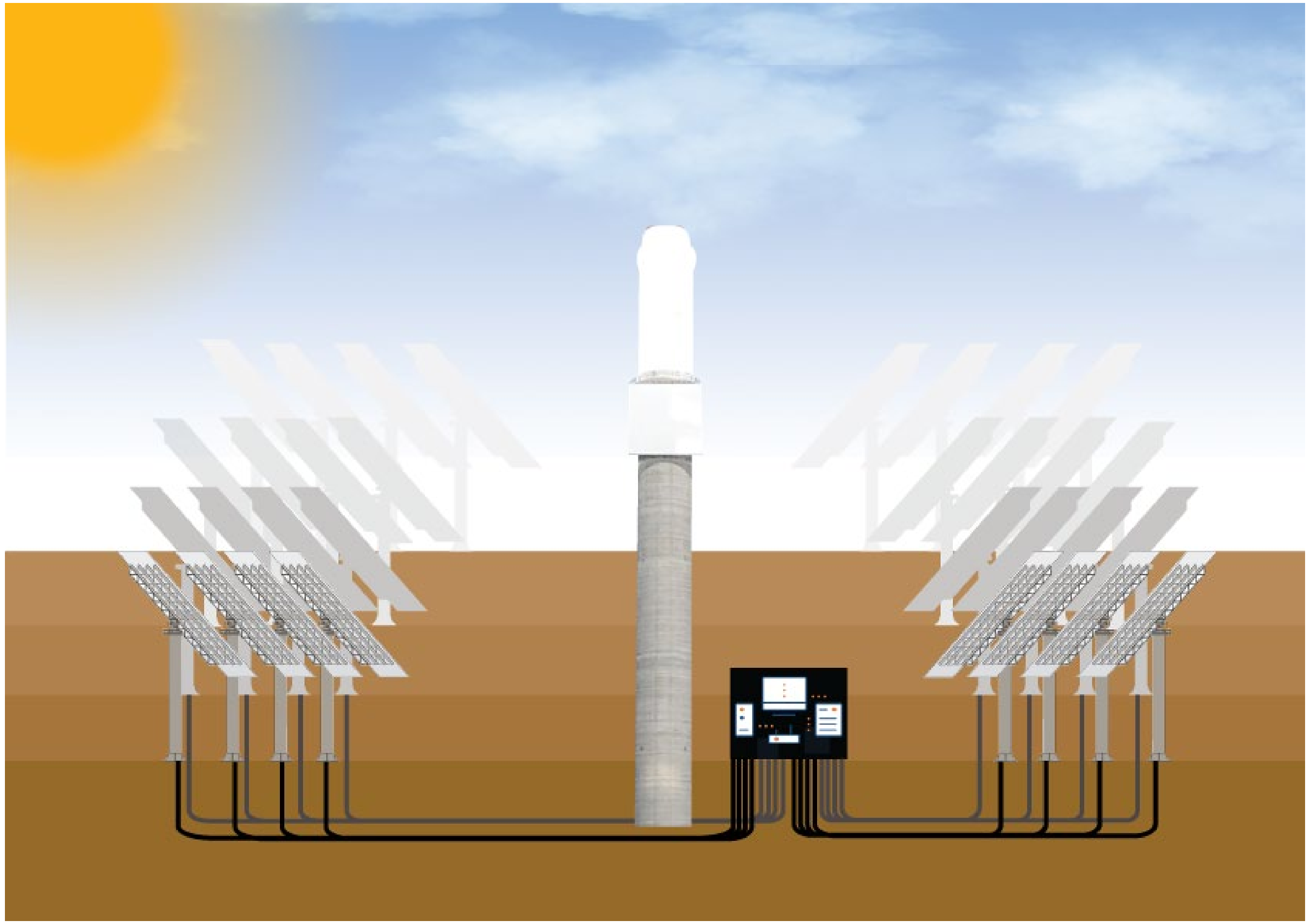
- Design of Integrated Access and Backhaul (IAB)-based robust wireless network.
- Perform dynamic spectrum management in the access and wireless backhaul.
- Dynamic clustering-based network reconfiguration.
- Design an entropy-based routing.
- Test the model through simulation and emulation-based experiments.
- Partial HELIOCOMM validation at Sandia National Laboratories (SNL) National Solar Thermal Test Facility (NSTTF).



Current Status

Wired communication solutions

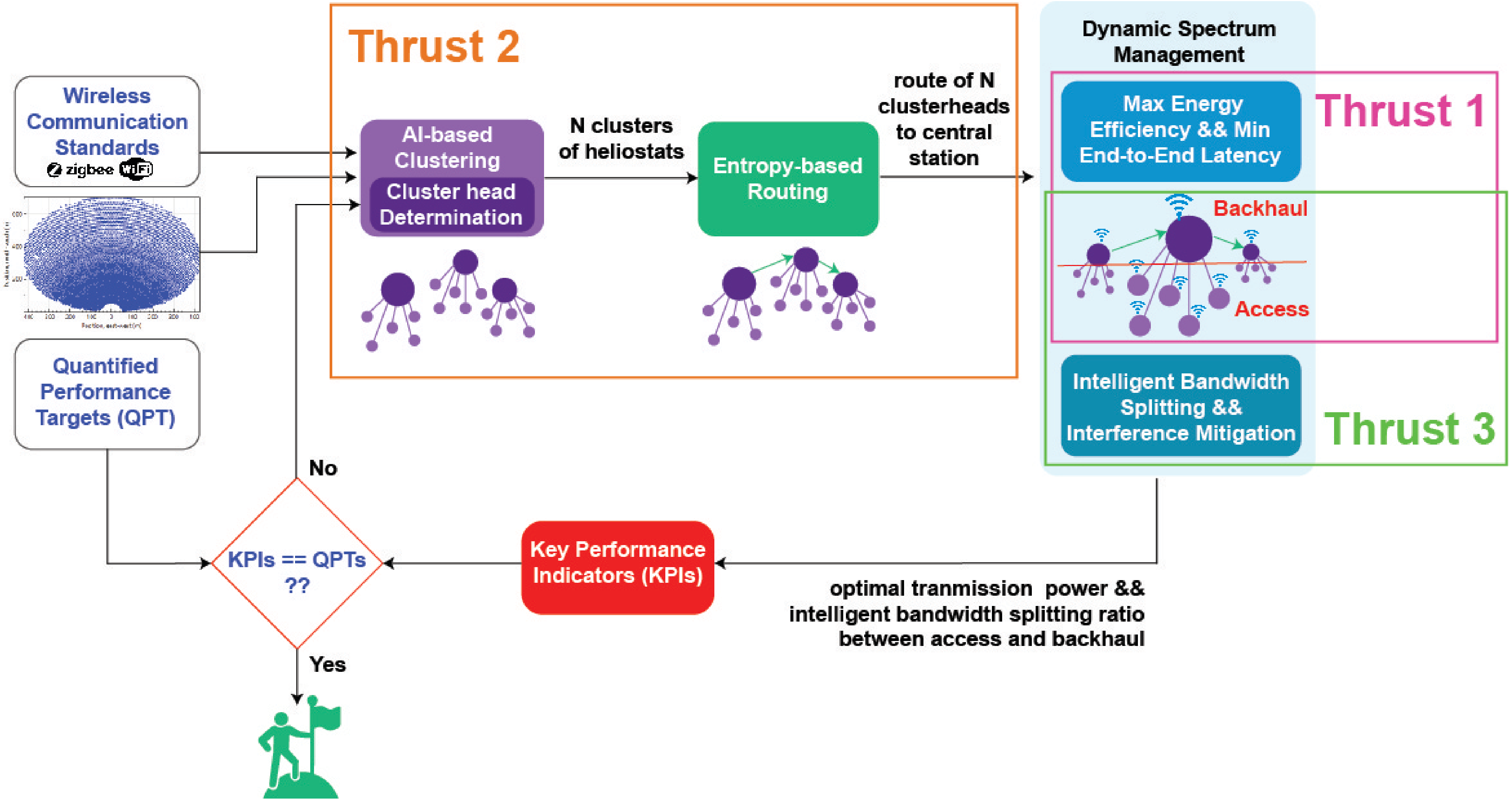
- buried copper or fiber optic links
- high cabling-related cost (installation, maintenance, operation-related costs)



Why switch to wireless?

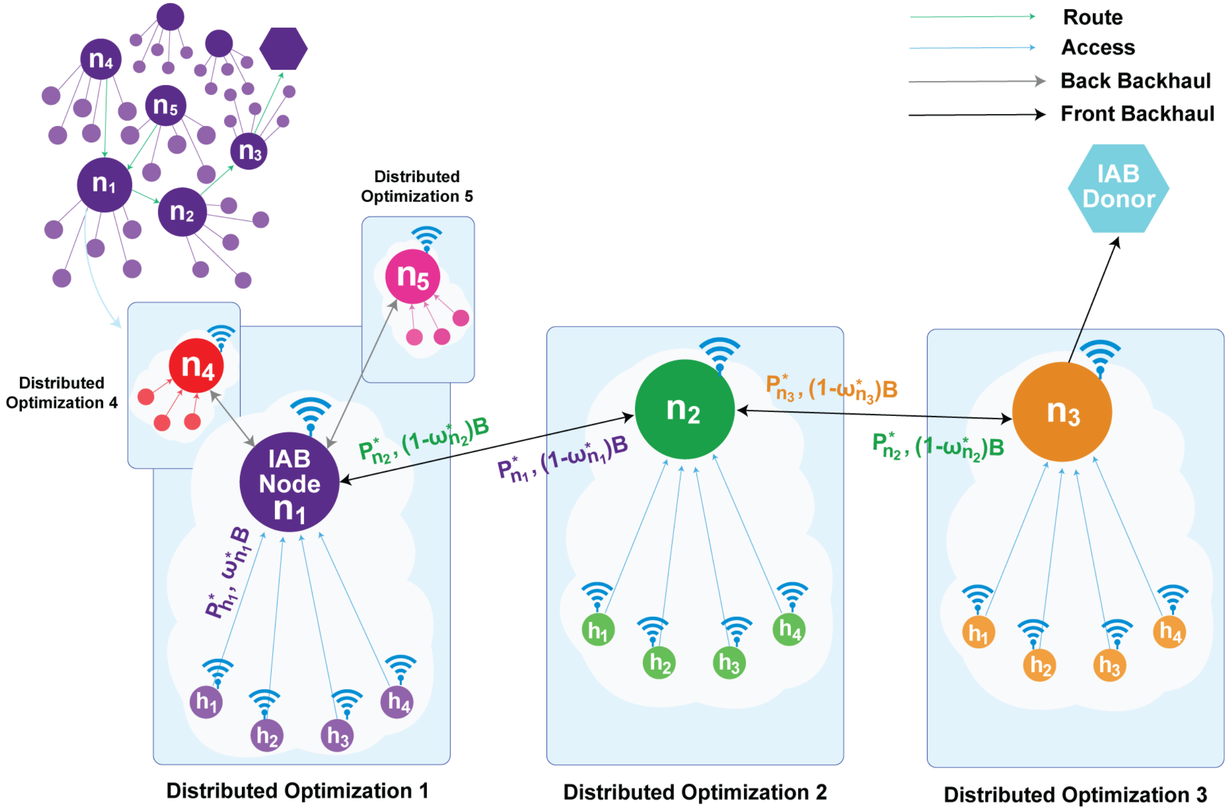
- Cost
  - Installation
  - Maintenance
- Reconfigurability
- *Requires Optimal Resource Management – transmission power, latency, bandwidth, etc.*

HELIOCOMM System Overview



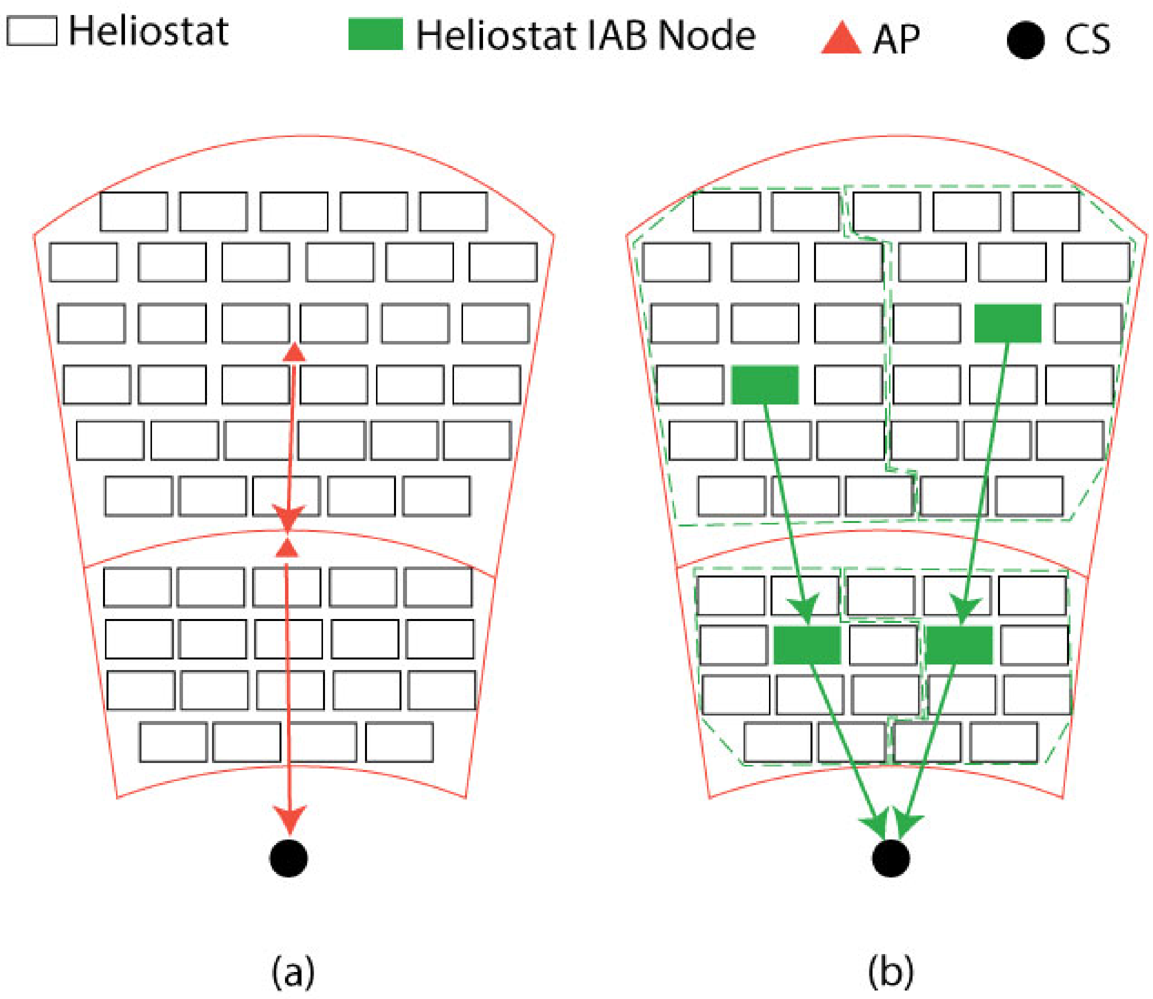
Integrated Access and Backhaul Technology

- Maximize energy efficiency and minimize end-to-end latency.
- Determine optimal uplink transmission power and bandwidth allocation.
- Dynamically allocate the limited ISM spectrum.



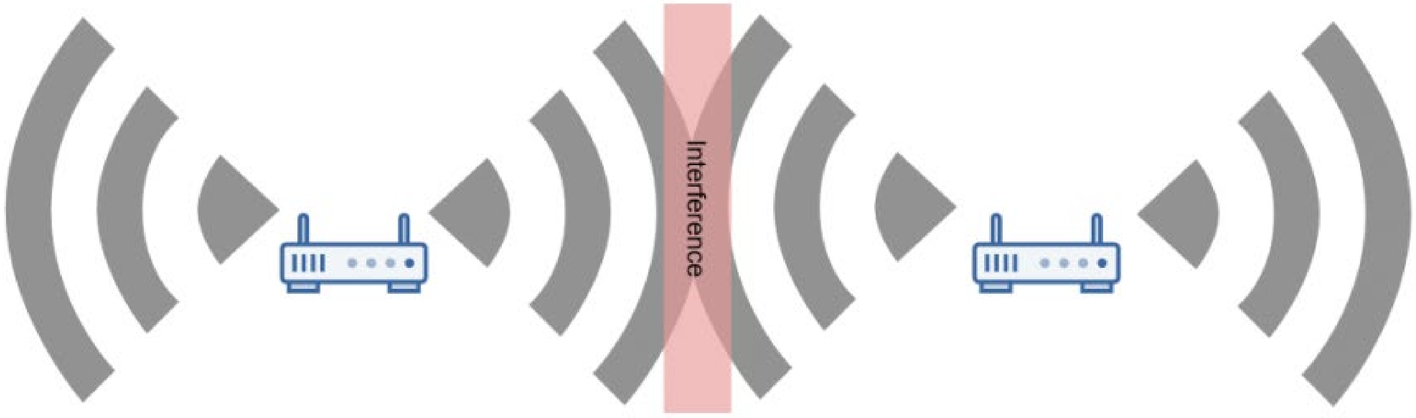
Artificial Intelligent Network Reconfiguration and Routing

- Dynamic clustering-based network reconfiguration.
- **Reinforcement Learning** (RL)-based clustering based on **distance** and **channel gain** analysis.
- Intelligent **cluster-head selection** based on **closeness centrality**.
- Entropy-based routing to balance traffic propagation through the network.



Dynamic Spectrum Management and Interference Mitigation

- Interference mitigation component on the maximization of energy efficiency and minimization of end-to-end latency problem.
- Minimizing the intra- and inter-cluster interference.

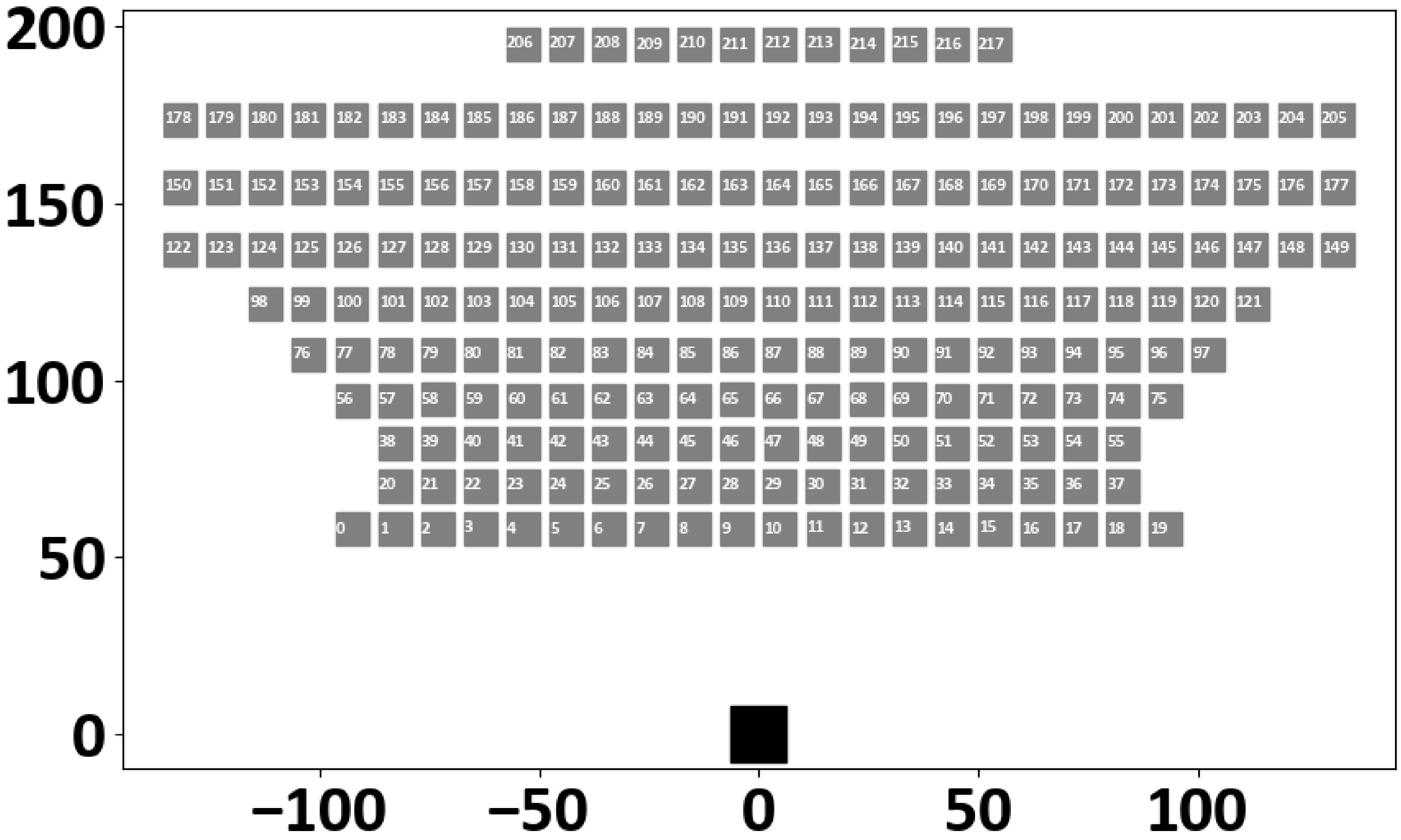


Testing & Validation

- Modeling and *simulation* for realizing diverse scenarios and scalability analysis.
- *Emulation*-based experiments using OMNET++ to test the networking aspects.
- Partial HELIOCOMM validation at Sandia National Laboratories (SNL) National Solar Thermal Test Facility (NSTTF).

Accomplishments from Year 1 up to Present

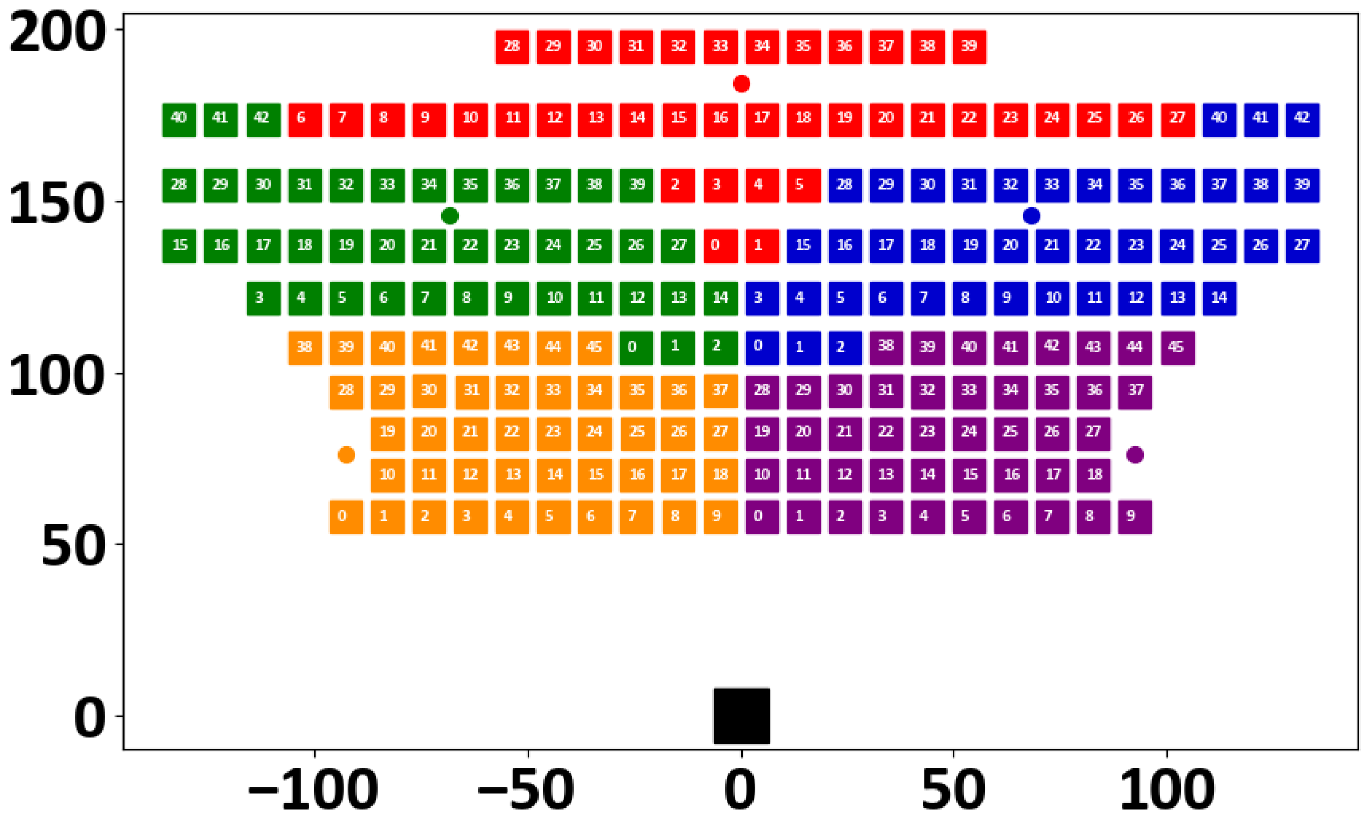
NTTF@SNL Topology



Segmentation in NSTFF@SNL topology

- Heliostats are grouped into five segments and each segment is assigned an AP acting as the IAB node.

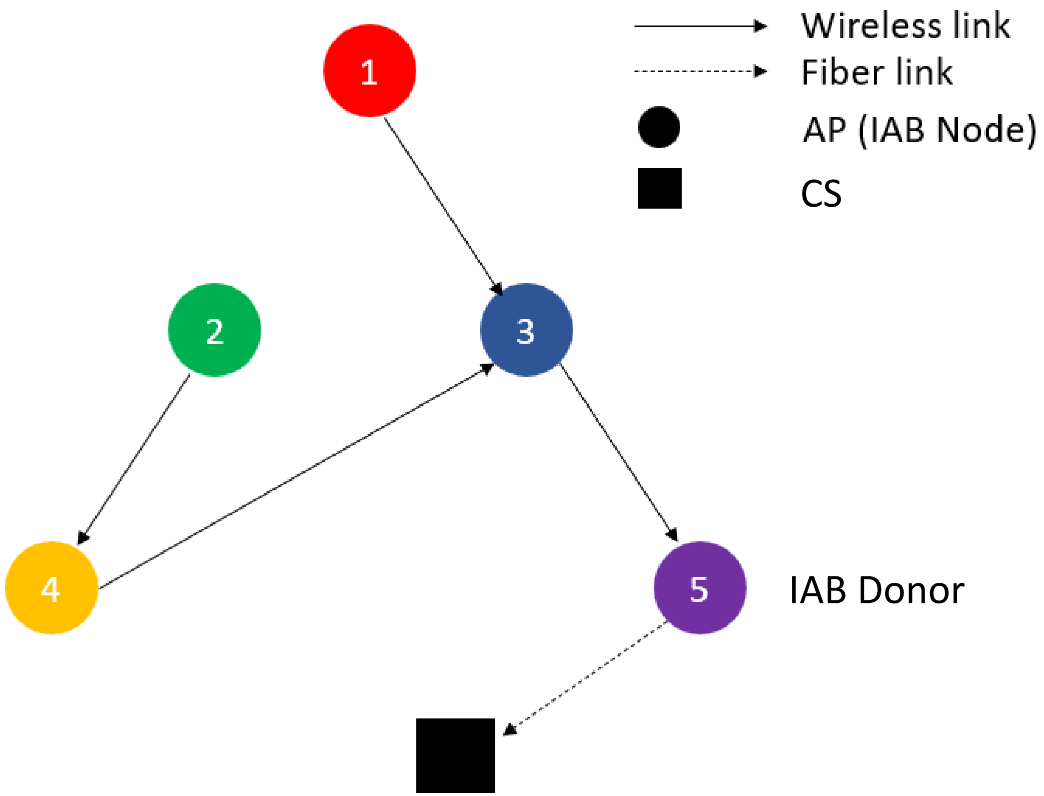
- The heliostats are identified with a unique ID based on the channel condition (path loss) between the heliostat and the corresponding IAB Node.



Routing in NSTFF@SNL topology

- The optimal route is determined following the Dijkstra's algorithm based on the lowest total cost.

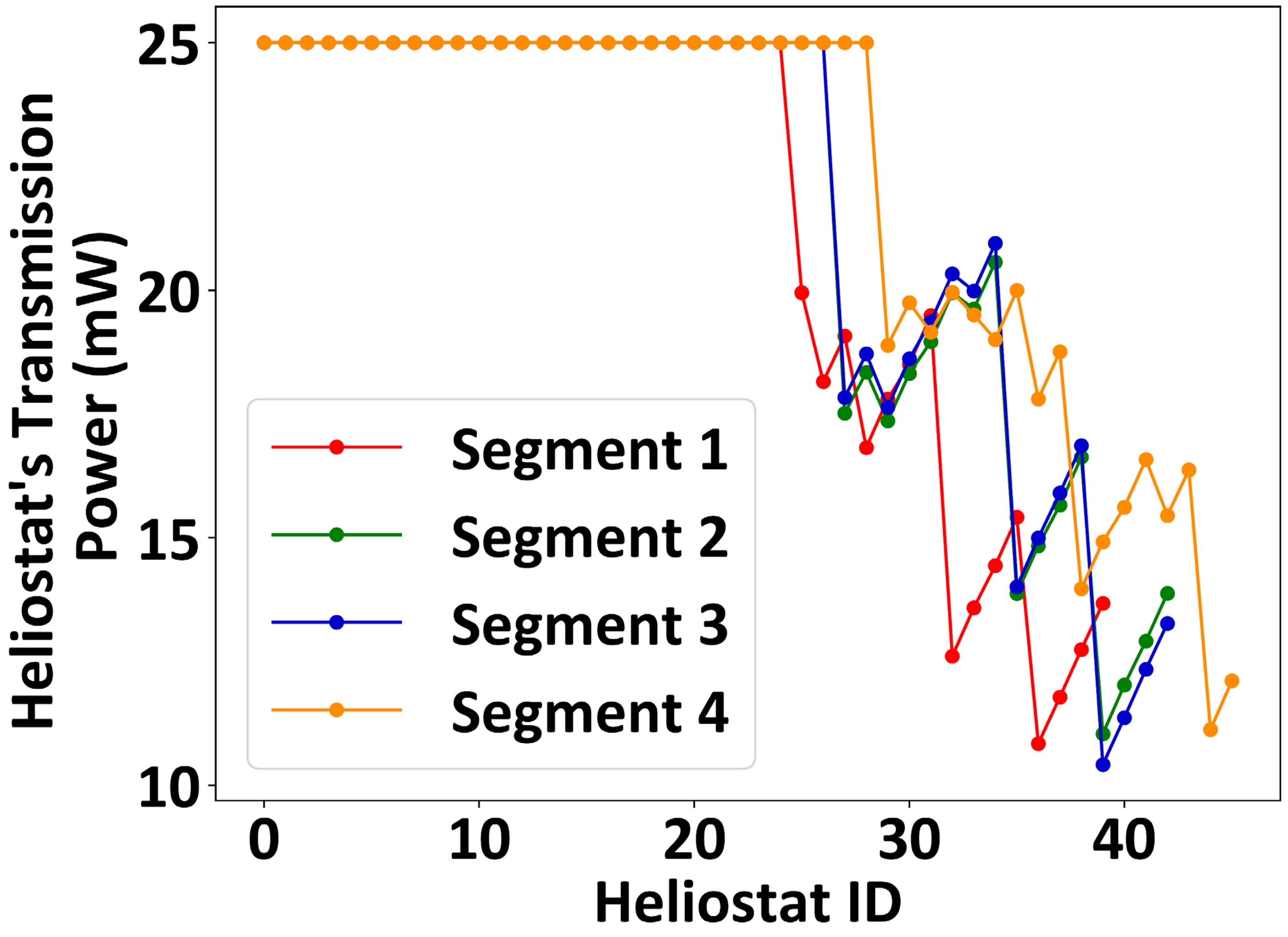
- In this application, the **cost** is taken to be **path loss** determined with the 3GPP model and the optimal route is the end-to-end path with the lowest path loss.



Transmission Power

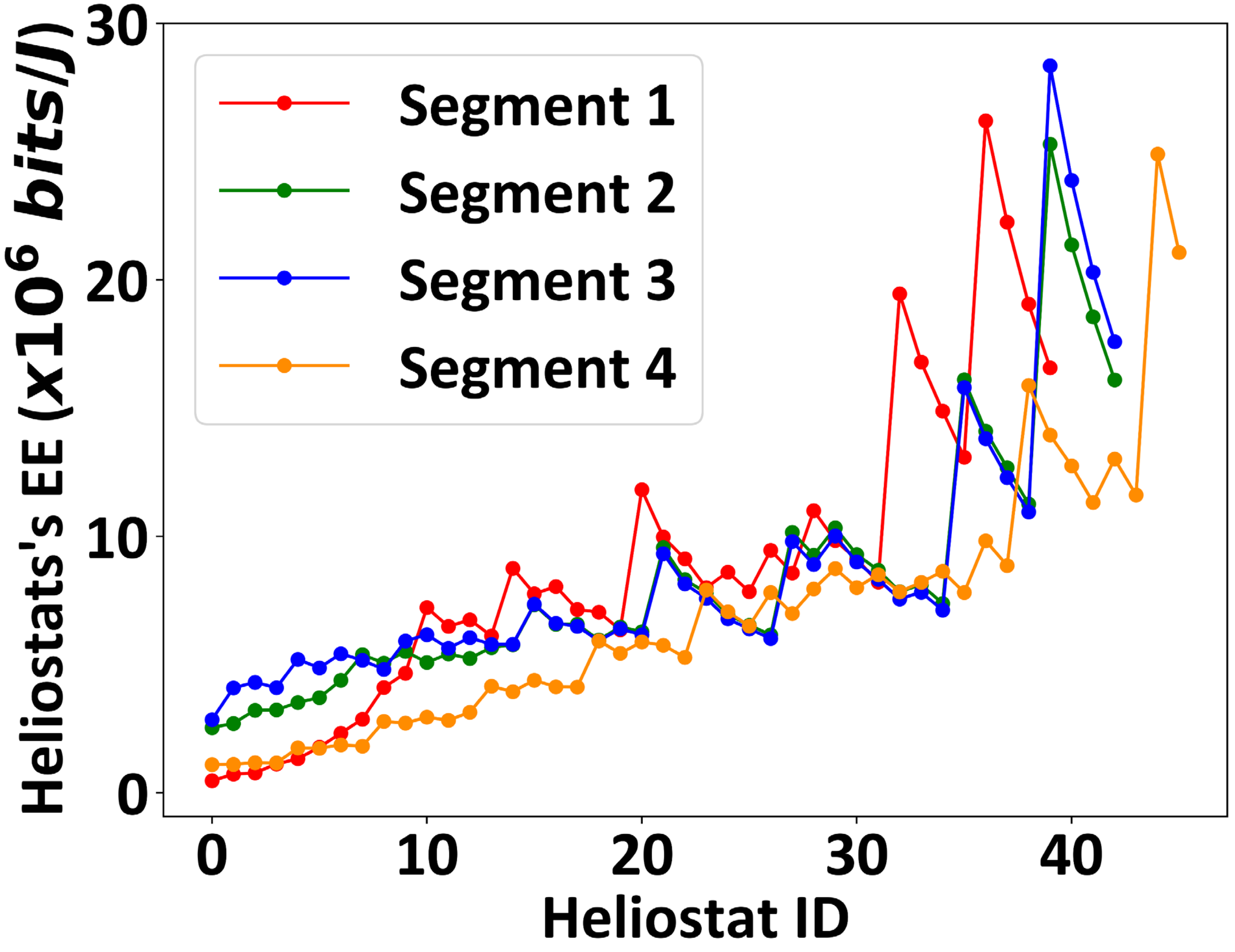
- Considering the transmission power bound of the modules TI CC1312R and TI CC1352R, the maximum transmission power is set to 25mW.

- The higher the ID of a heliostat in a segment, the higher is its channel gain with the IAB node. This results in a lower transmission power required for a heliostat with higher IDs.

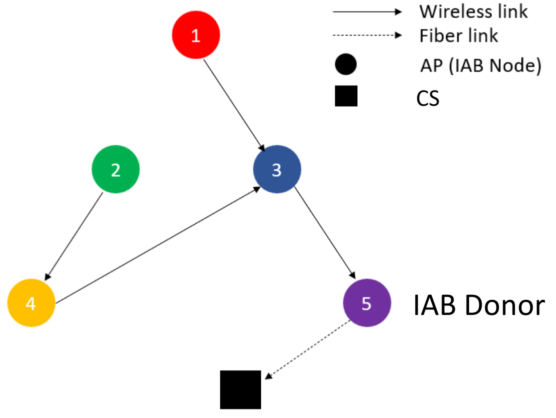


Energy Efficiency

- The higher the transmission power, the lower is the achieved energy efficiency. Hence, the downward trend of transmitting power results in an upward trend for the energy efficiency.

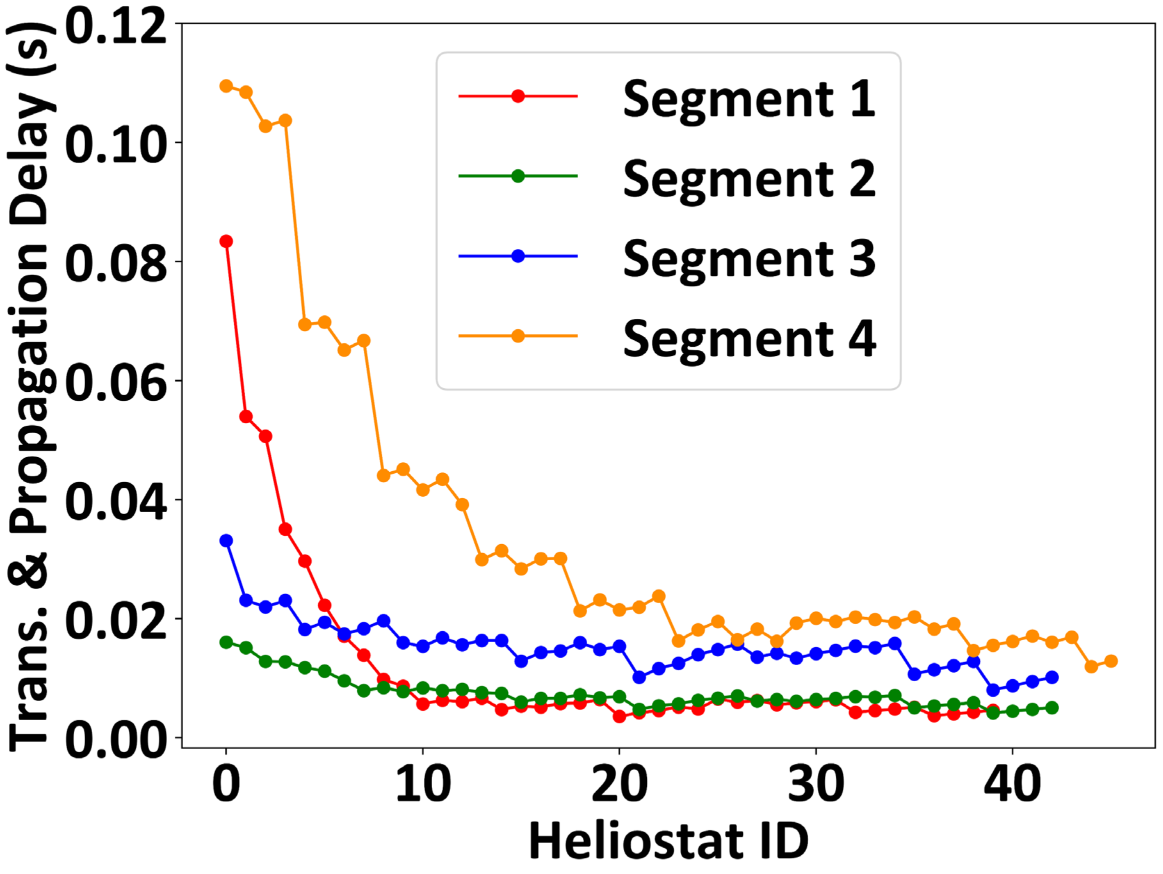


Latency



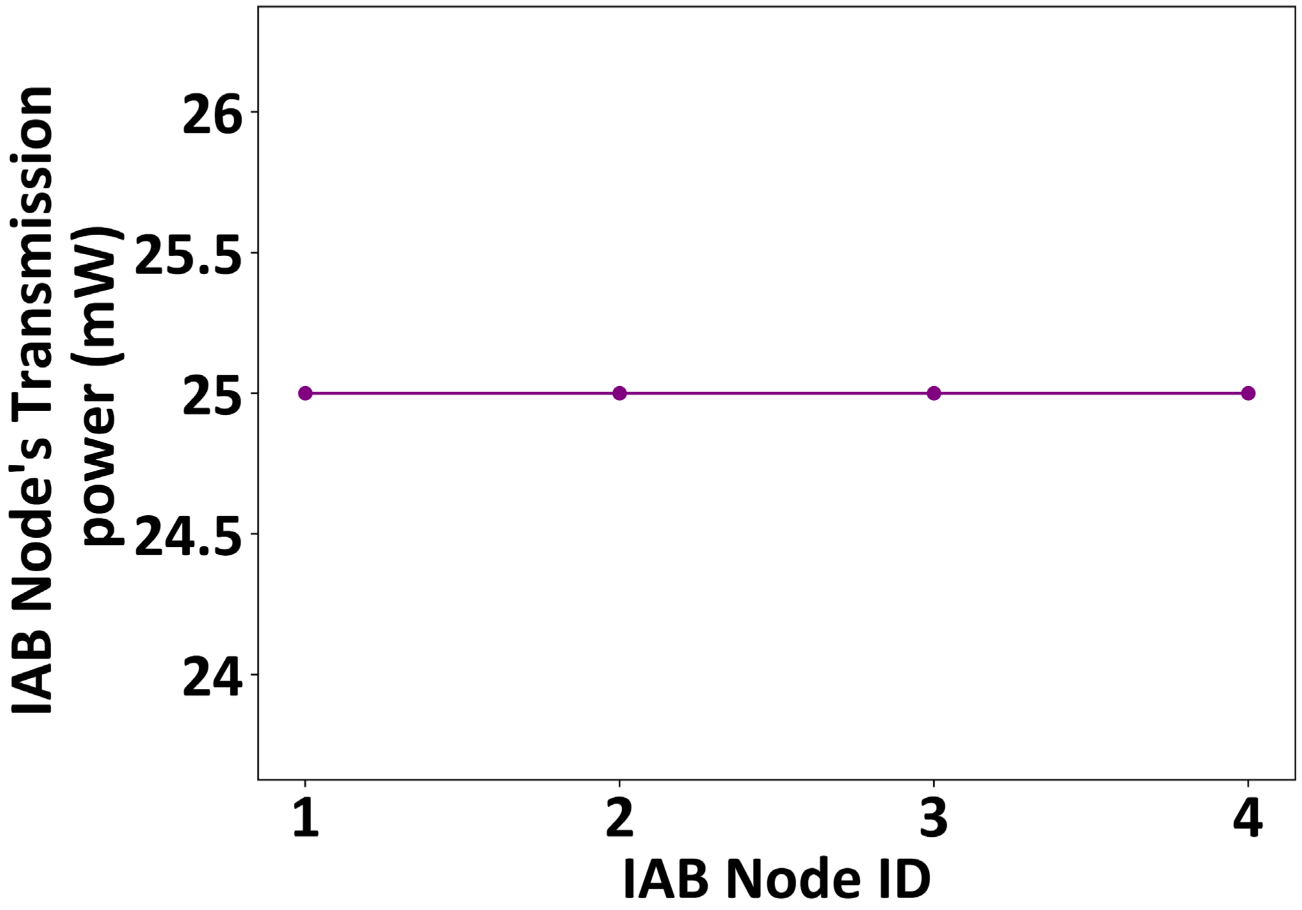
- Segments 1 and 2 have no backhaul links to relay traffic coming from other segments, hence, the heliostats in those segments experience lower latency.

- Segments 3 and 4 both have backhaul connections, resulting in 43(heliostats)+ 2(backhaul) = 45 total connections and 46(heliostats) + 1(backhaul) = 47 total connections, respectively, resulting in a higher latency for the heliostats in segment 4.

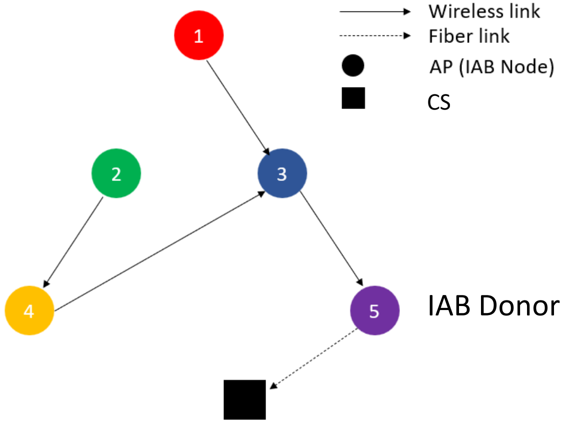


IAB Node Transmission Power

- In order to transmit the data collected from the heliostats, all the IAB nodes are required to transmit with the maximum transmission power, i.e., 25 mW, as indicated by the hardware specs of the wireless modules (TI CC1312R or TI CC1352R).

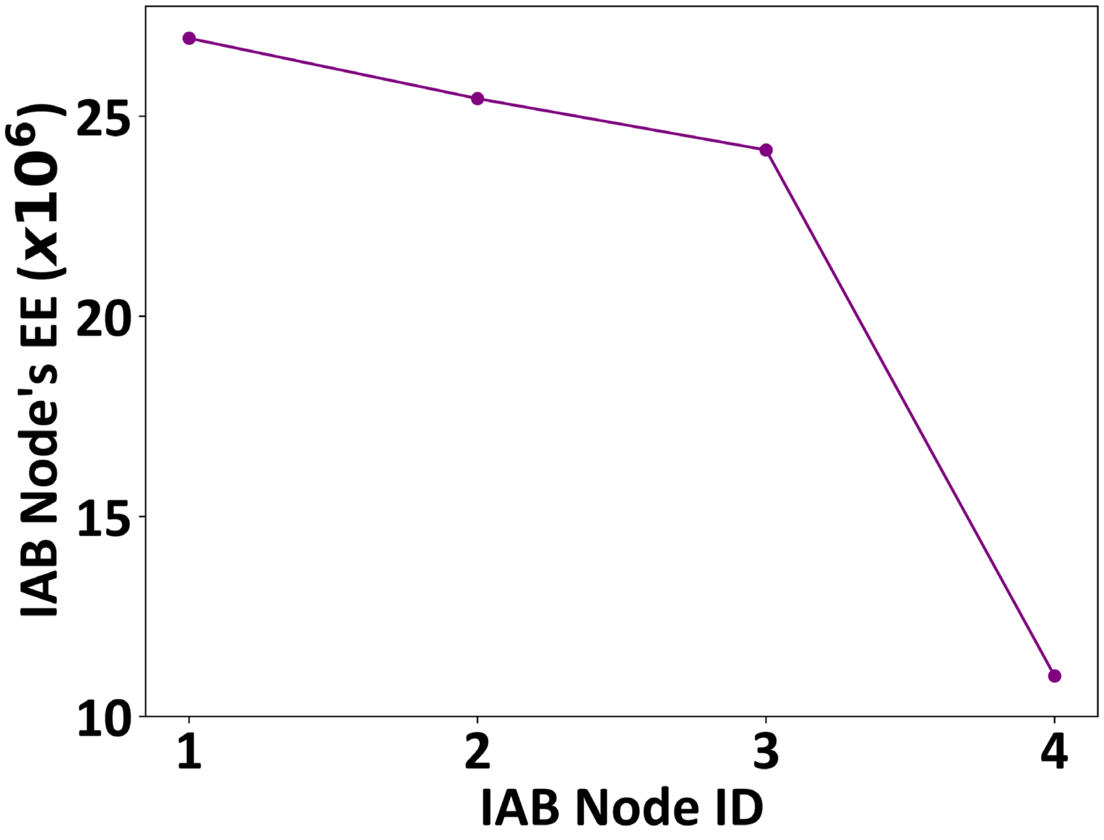


IAB Node Energy Efficiency

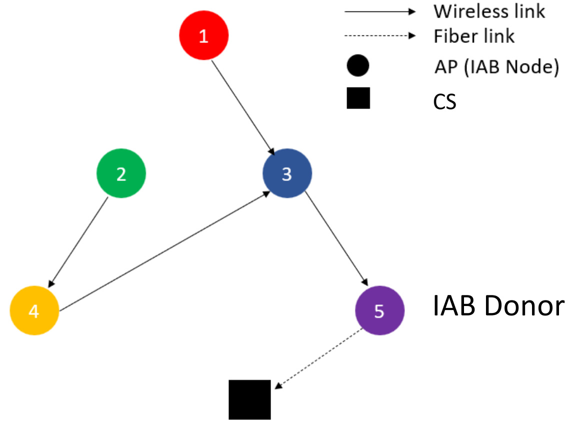


- IAB nodes 1 and 2 have higher EE as both the APs only serve the heliostats in the cluster and have no backhaul connections. However, IAB Node 2 has larger number of heliostats in its access compared to IAB Node 1, hence the EE of IAB node 2 is lower than IAB node 1.

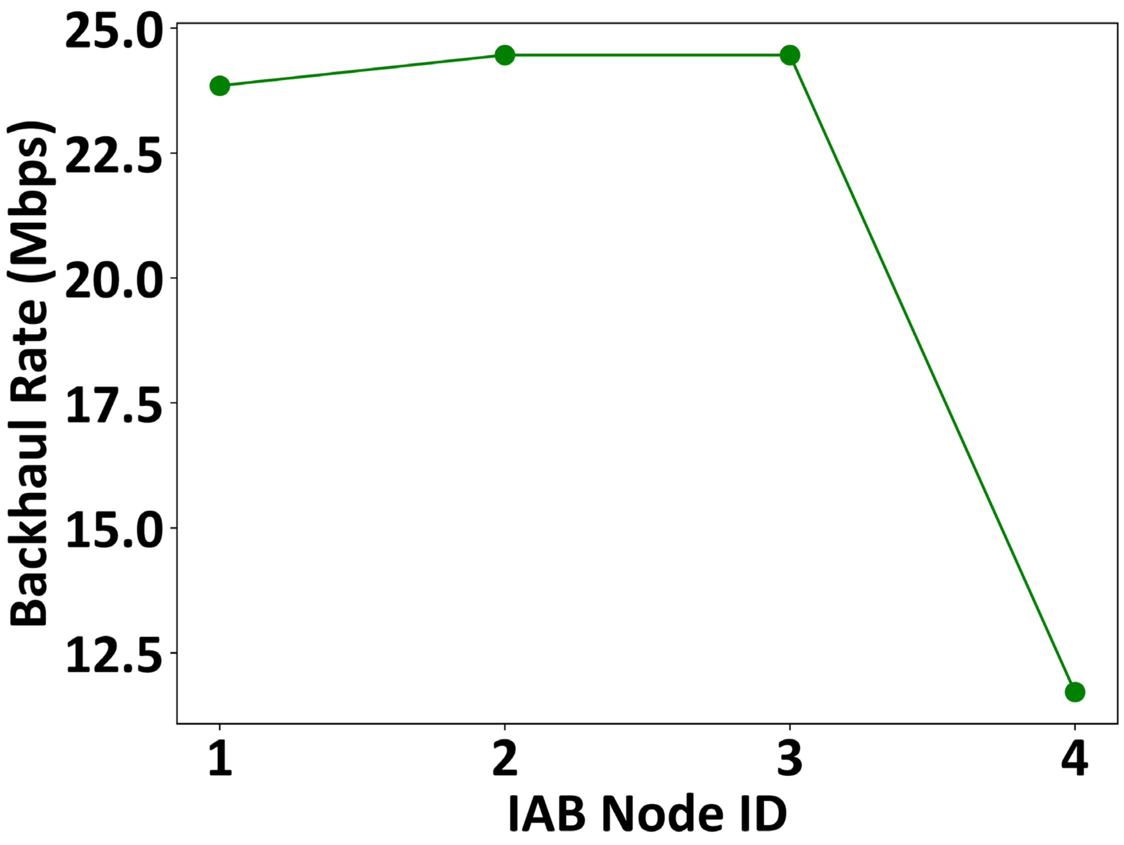
- IAB nodes 3 and 4 both have backhaul connections, resulting in 43 (heliostats) + 2 (backhaul) = 45 total connections and 46 (heliostats) + 1 (backhaul) = 47 total connections, respectively, resulting in lower EE.



Backhaul Rates

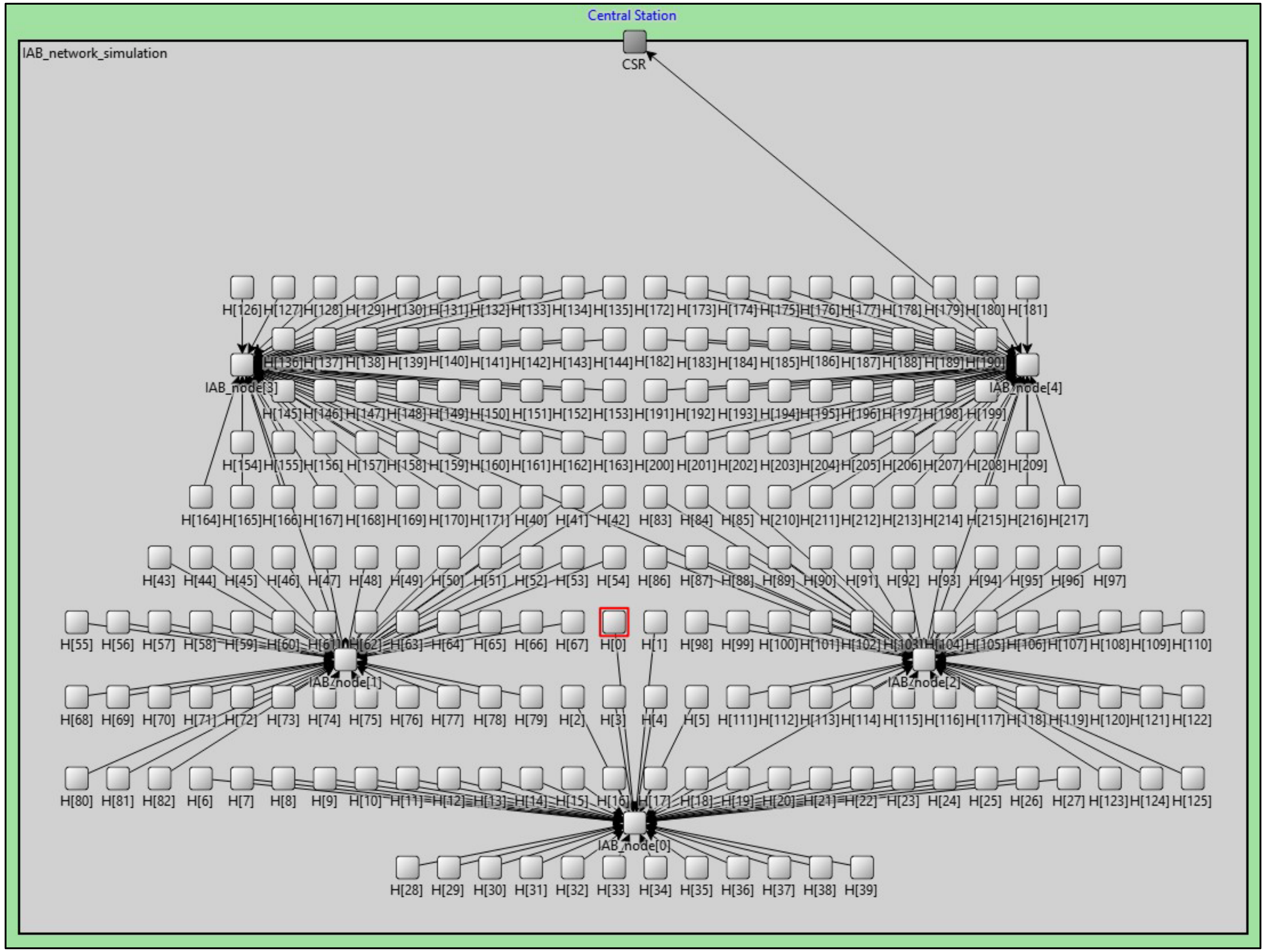


- The achievable data rates in the backhaul depend on the channel through which the data propagate.
- In the current topology, the path loss in the channel between 4 and its next hop destination, i.e., 3 is the maximum, resulting in the lowest backhaul rate.
- In the current topology, the path loss in the channel between 1 and its next hop destination, i.e., 3 is the second maximum, resulting in the second lowest backhaul rate.



Emulation: OMNET++ Experiments

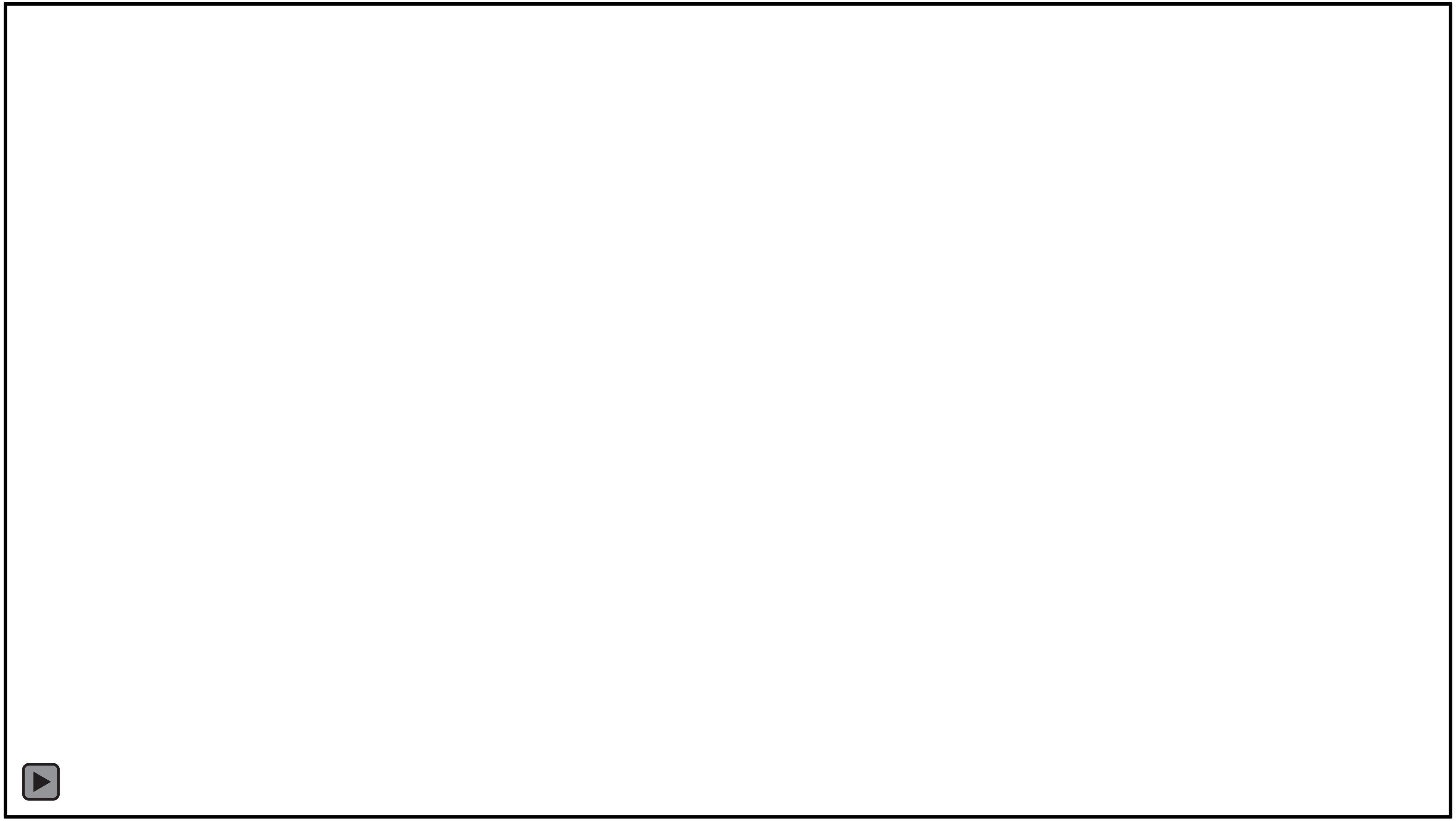
- Sandia's NSTTF topology is taken as the test topology to perform experiments in OMNET++ as it has a comparatively lower number of heliostats.
- A wired IAB network architecture is established initially for two major reasons.
- A wired network of the test topology can provide a basis of comparison for the emulation results obtained from the wireless implementation of the test topology.



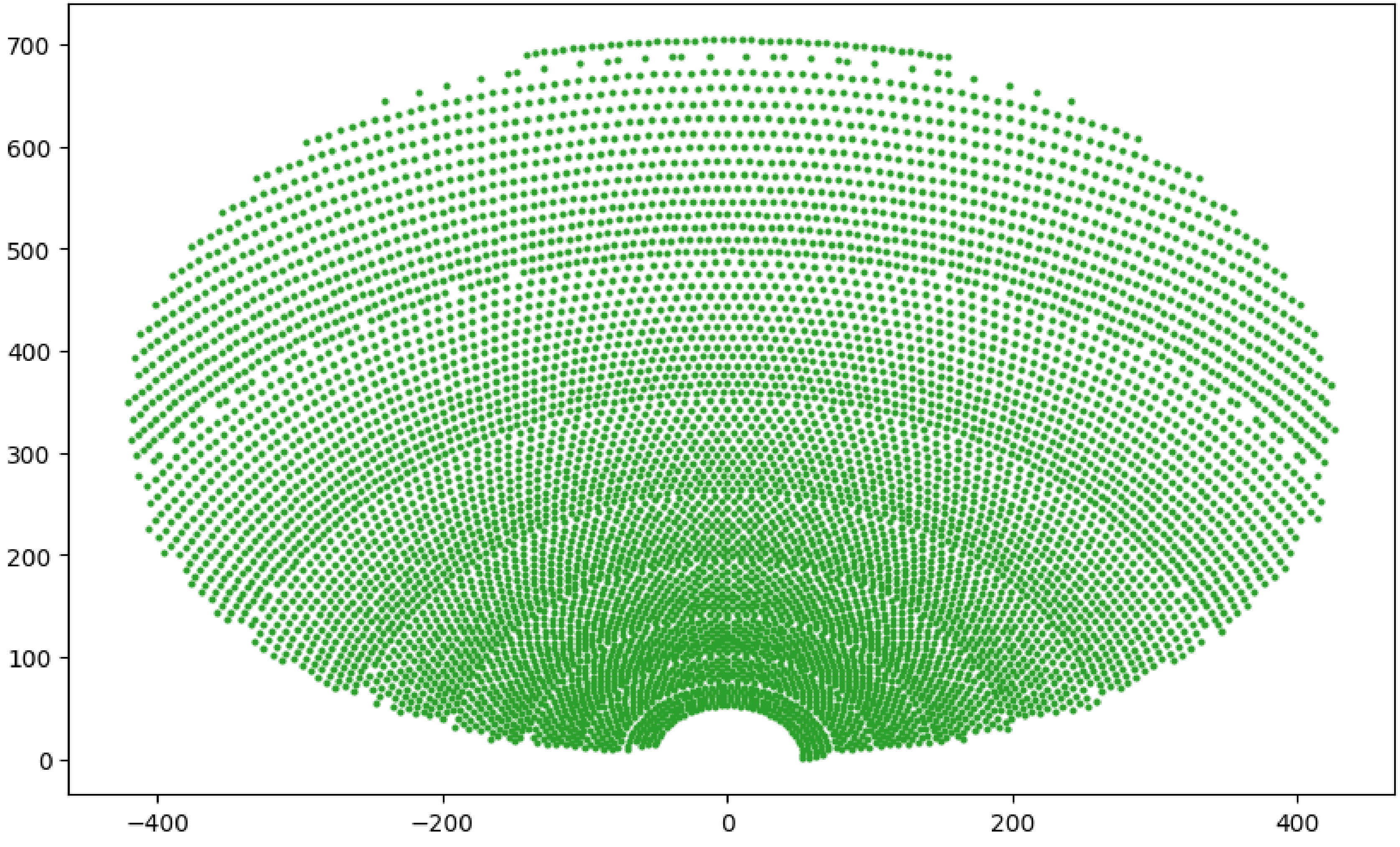
Data Uploading Phase

Data Concatenating Phase

Data Forwarding Phase



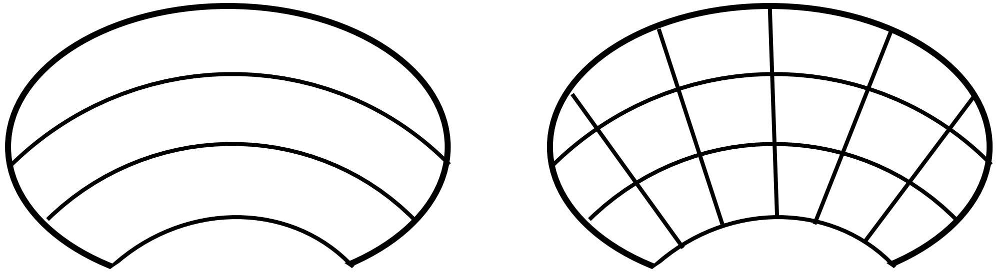
HELIOCON Baseline Topology

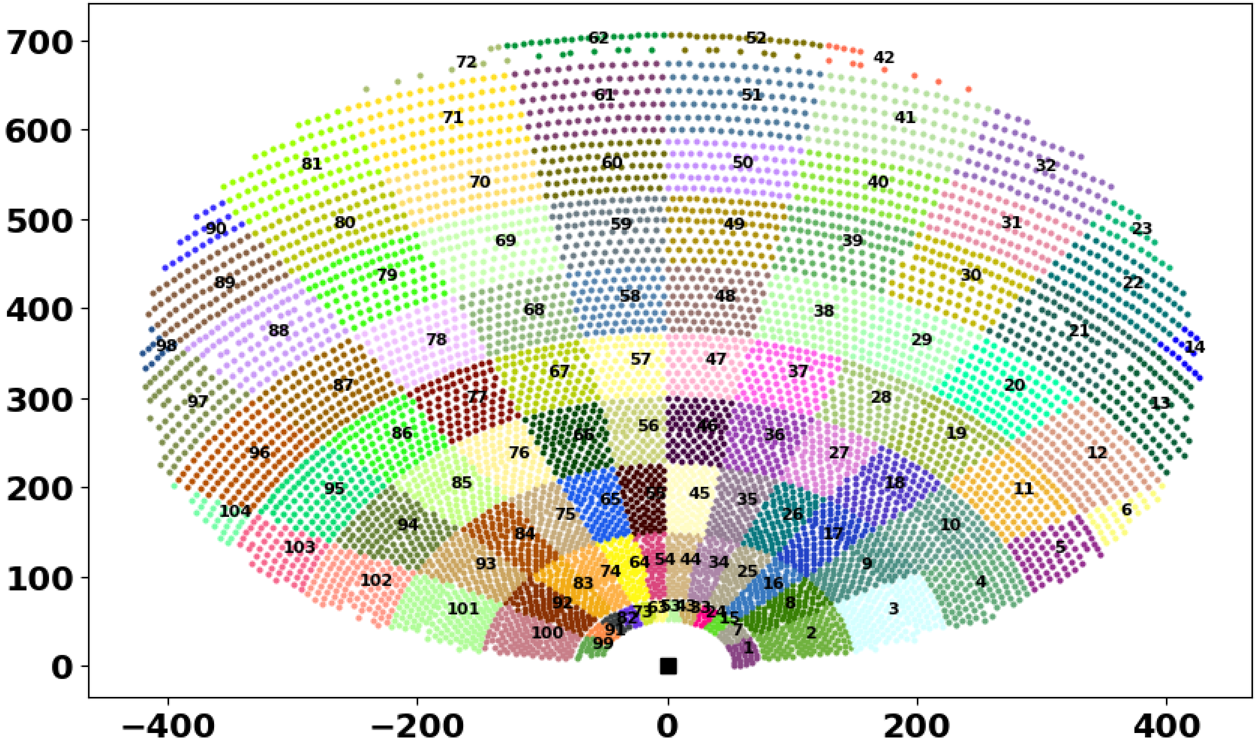


Segmentation

- Heliostats are grouped into multiple segments to efficiently handle the communication among the access heliostats, IAB nodes (segment-heads) and the central station.

- Segmentation is done in two ways. Firstly, a vertical segmentation is done considering a fixed communication range from the central station. Then, a horizontal segmentation is done on top that based on the angular orientation with respect to the central station.

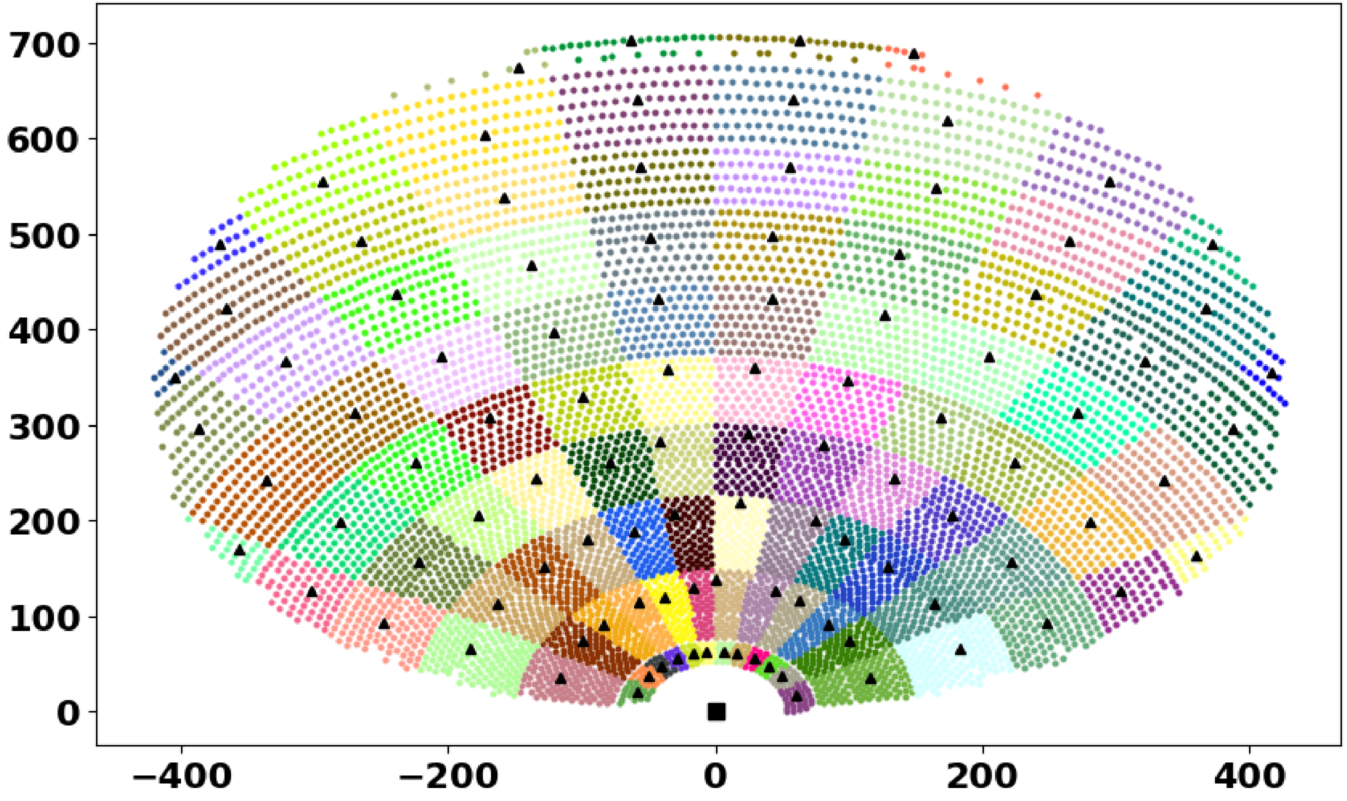




Segment-heads

- **Segment-heads** are determined based on the scoring criteria which is a function of the **closeness centrality and energy availability**.

- Each access heliostat within a segment has a score based on the closeness centrality and energy availability and the access heliostat with the highest score is chosen to be the segment-head of the concerned segment.

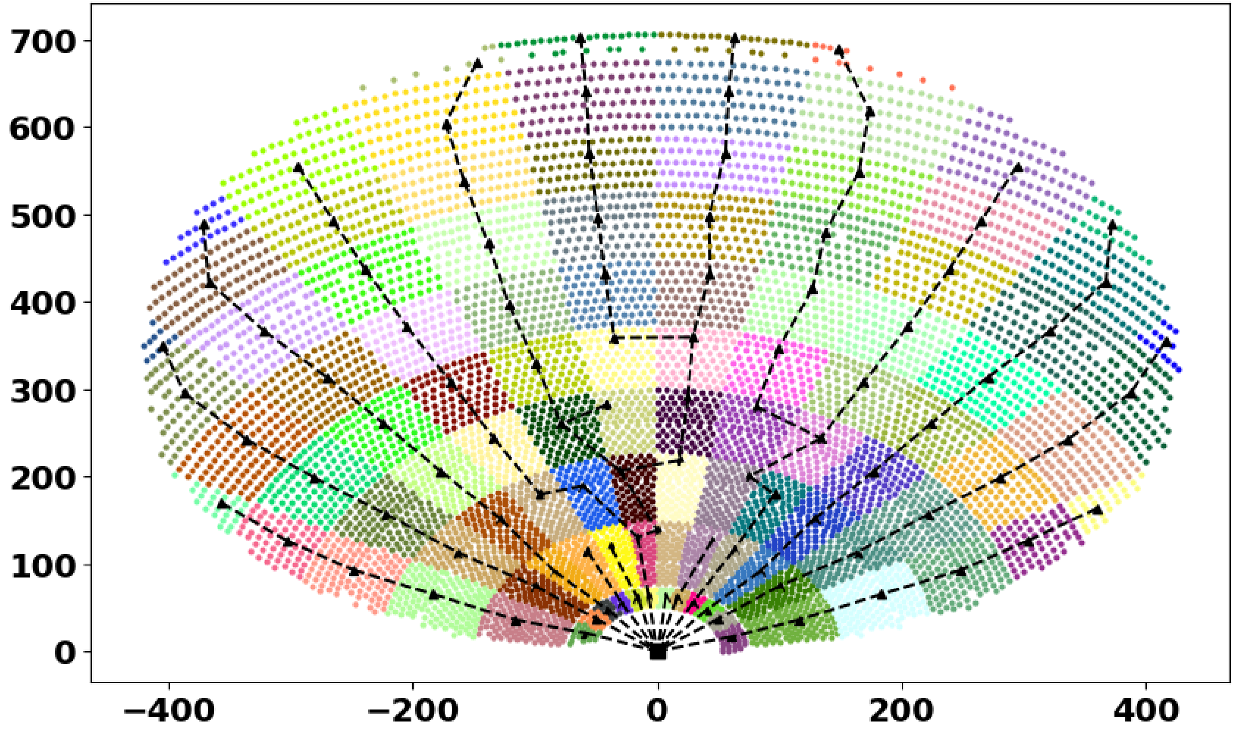


Routing

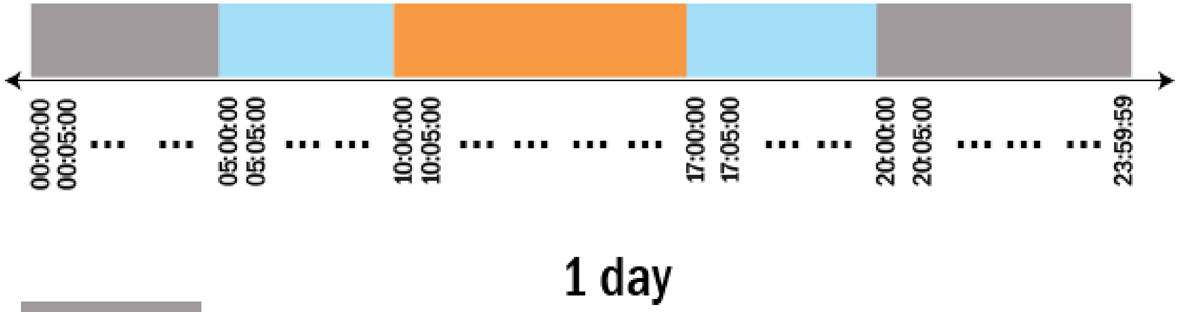
- To find the optimal routes to the central station for each segment-head by using Dijkstra's algorithm, potential routes with the corresponding minimum values of the cost function are determined.

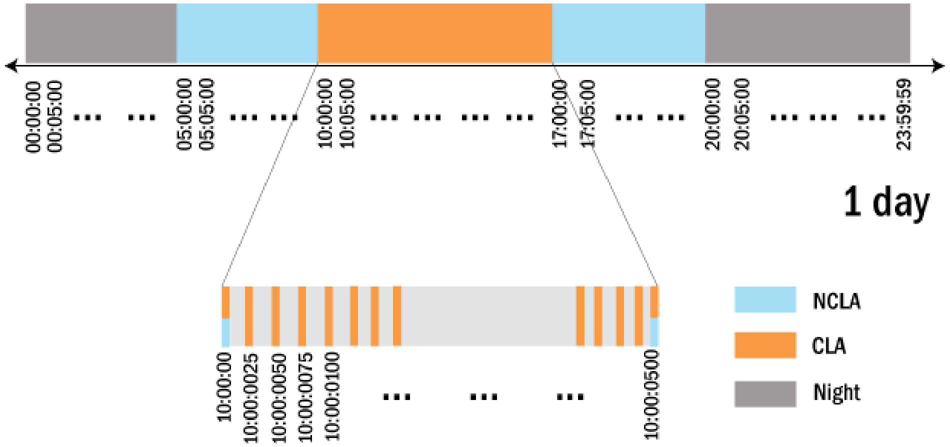
- The cost function is the path loss between a pair of segment-heads or between a segment-head and the central station.

- A segment-head has the central station as the destination in its optimal route by choosing other segment-heads comparatively closer to the central station.



CLA-NCLA





No communication, consume the very minimum of the device electronics

No closed-loop-autocalibration (N-CLA) – 1 signal/4999 msec = 0.017 **sps** with 2 sec *latency*

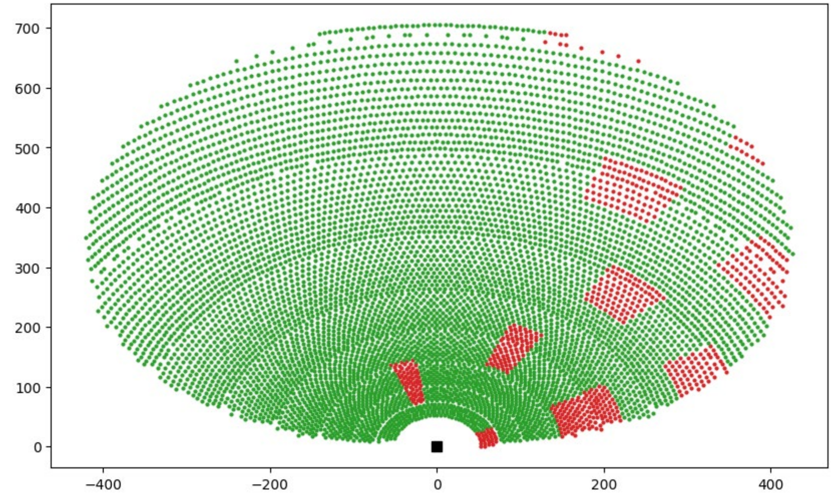
Closed-loop-autocalibration (CLA) – 1 signal/251 msec = 4×10^{-5} **sps** with 250 msec *latency*

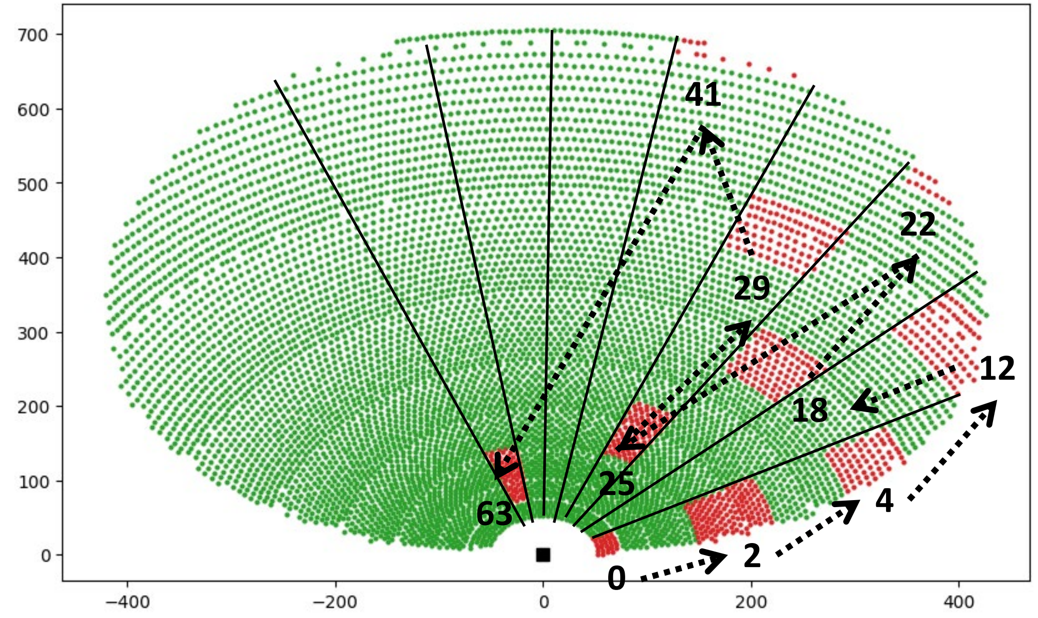
- The need for CLA and NCLA transmissions at different timestamps has been identified to **prevent incidents where IAB nodes receive CLA and NCLA packets simultaneously**.

- During CLA signal transmissions, the NCLA segment heads, will function as relays, as their access networks (NCLA) will be in sleep mode during CLA transmission, and vice versa.

Grouping of CLA Segments

- We start with the segments sequentially from the first vertical segmentation and each segment is allowed to choose another lowest id non-grouped segment from the horizontal segmentations.
- Each of the segments in the vertical segmentations form CLA groups in a sequential manner and then we move to the segments in the next arc.
- The algorithm terminates when there are no new groups that can be formed.





CLA Group 1: [0, 2, 4, 12, 18, 22, 25, 29, 41, 63]

Grouping of CLA Segments

(a) Total Number of Heliostats in a CLA group: ~1000

```
CLA Group 1 Segment IDs: [0, 2, 4, 12, 18, 22, 25, 29, 40, 46, 48, 60, 63, 89, 97]
CLA Group 1 Heliostat Number: 983
CLA Group 2 Segment IDs: [6, 3, 5, 13, 19, 26, 30, 37, 41, 49, 54, 61, 66, 68, 80]
CLA Group 2 Heliostat Number: 996
CLA Group 3 Segment IDs: [14, 8, 10, 20, 31, 35, 38, 50, 57, 64, 69, 71, 96]
CLA Group 3 Heliostat Number: 1000
CLA Group 4 Segment IDs: [23, 9, 11, 21, 28, 34, 39, 47, 51, 59, 65, 77, 91]
CLA Group 4 Heliostat Number: 1083
CLA Group 5 Segment IDs: [32, 16, 27, 55, 58, 70, 78, 83, 85, 102]
CLA Group 5 Heliostat Number: 771
CLA Group 6 Segment IDs: [42, 17, 44, 56, 79, 84, 86, 103]
CLA Group 6 Heliostat Number: 586
CLA Group 7 Segment IDs: [52, 1, 36, 67, 74, 87, 94, 100]
CLA Group 7 Heliostat Number: 731
CLA Group 8 Segment IDs: [62, 45, 75, 88, 95, 101]
CLA Group 8 Heliostat Number: 496
CLA Group 9 Segment IDs: [72, 7, 76, 92]
CLA Group 9 Heliostat Number: 300
CLA Group 10 Segment IDs: [81, 15, 93]
CLA Group 10 Heliostat Number: 199
CLA Group 11 Segment IDs: [90, 24]
CLA Group 11 Heliostat Number: 85
CLA Group 12 Segment IDs: [98, 33]
CLA Group 12 Heliostat Number: 88
CLA Group 13 Segment IDs: [43, 99]
CLA Group 13 Heliostat Number: 178
CLA Group 14 Segment IDs: [53]
CLA Group 14 Heliostat Number: 51
CLA Group 15 Segment IDs: [73]
CLA Group 15 Heliostat Number: 67
CLA Group 16 Segment IDs: [82]
CLA Group 16 Heliostat Number: 69
-----------------------------------------------------------------------
Total Number of Heliostats performing CLA: 7683
```

(a)
Groups: 16 → 160 min CLA
Standalones: 3
Less Balanced

(b) Total Number of Heliostats in a CLA group: ~600

```
CLA Group 1 Segment IDs: [0, 2, 4, 12, 18, 22, 25, 29, 41, 63]
CLA Group 1 Heliostat Number: 664
CLA Group 2 Segment IDs: [6, 3, 5, 13, 19, 26, 30, 37, 51, 71, 89, 73]
CLA Group 2 Heliostat Number: 666
CLA Group 3 Segment IDs: [14, 8, 10, 20, 31, 35, 38, 97, 82]
CLA Group 3 Heliostat Number: 662
CLA Group 4 Segment IDs: [23, 9, 11, 21, 28, 34, 40, 91]
CLA Group 4 Heliostat Number: 687
CLA Group 5 Segment IDs: [32, 16, 27, 39, 47, 54, 59, 61, 103]
CLA Group 5 Heliostat Number: 588
CLA Group 6 Segment IDs: [42, 17, 44, 46, 48, 50, 68, 70]
CLA Group 6 Heliostat Number: 599
CLA Group 7 Segment IDs: [52, 1, 36, 49, 64, 66, 69]
CLA Group 7 Heliostat Number: 572
CLA Group 8 Segment IDs: [62, 45, 57, 60, 74, 76, 78, 80]
CLA Group 8 Heliostat Number: 569
CLA Group 9 Segment IDs: [72, 7, 55, 58, 77, 79, 83]
CLA Group 9 Heliostat Number: 545
CLA Group 10 Segment IDs: [81, 15, 56, 84, 86, 88, 102]
CLA Group 10 Heliostat Number: 510
CLA Group 11 Segment IDs: [90, 24, 65, 67, 87, 92, 94]
CLA Group 11 Heliostat Number: 588
CLA Group 12 Segment IDs: [98, 33, 75, 95, 100]
CLA Group 12 Heliostat Number: 425
CLA Group 13 Segment IDs: [43, 85, 96, 99, 101]
CLA Group 13 Heliostat Number: 443
CLA Group 14 Segment IDs: [53, 93]
CLA Group 14 Heliostat Number: 165
-----------------------------------------------------------------------
Total Number of Heliostats performing CLA: 7683
```

(b)
Groups: 14 → 140 min CLA
Standalones: 0
More Balanced

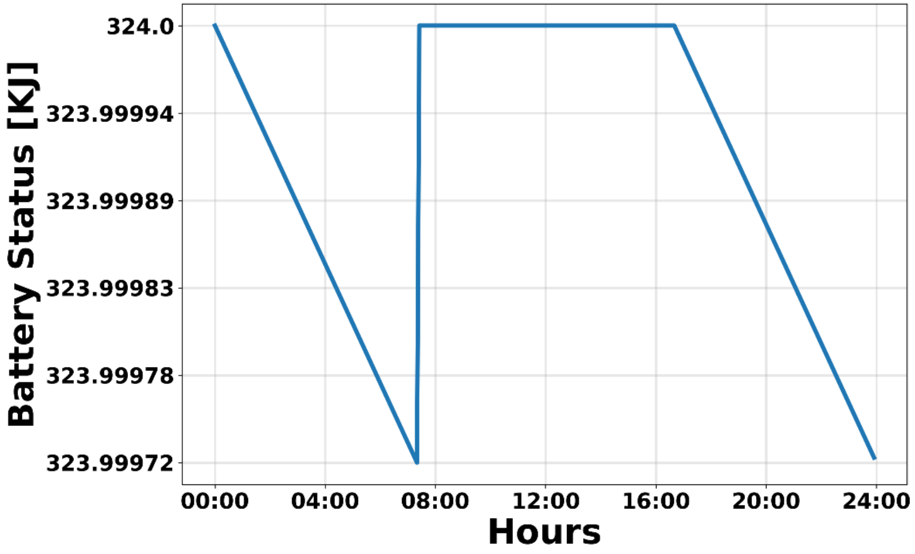
Grouping of CLA Segments

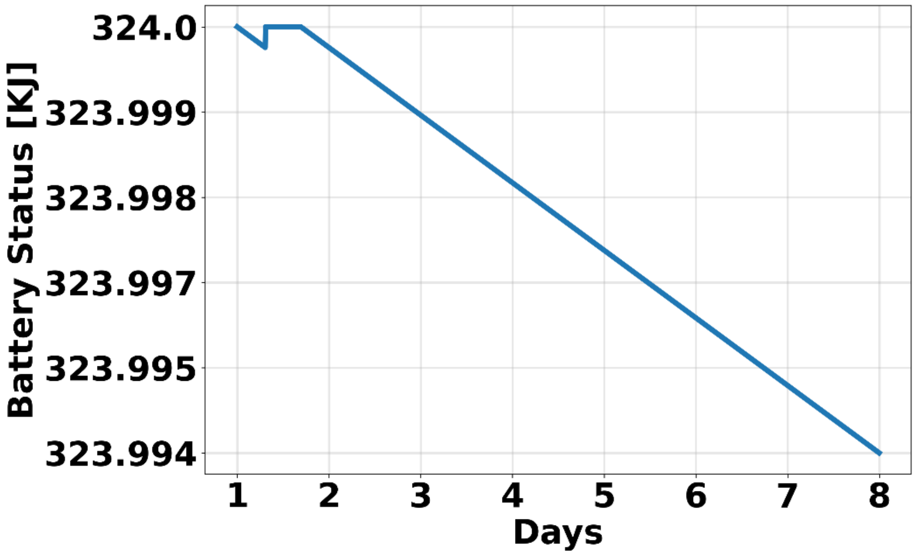
Total Number of Heliostats in a CLA group: ~600

Selected segments need to be 75m apart to avoid interference

Battery Status

- The energy consumption of the RF modules during the transmission is significantly smaller than the energy harvested.
- We also performed an analysis for a week where energy harvest occurs only on Day 1 and no harvest occurs in the next consecutive 6 days.
- Even in such worst-case, the charge of the battery did not drain enough to drive the heliostats RF module incapable of waking up.



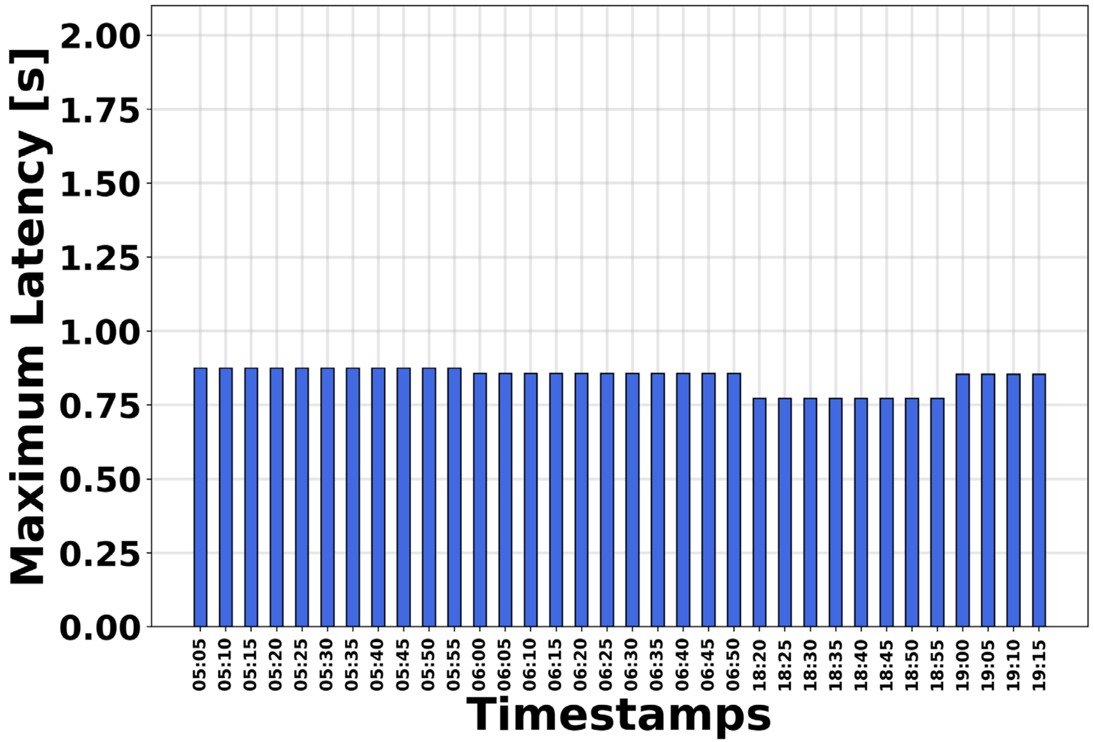


NCLA Latency Analysis

- Simulation for a timeframe of **1 day**.

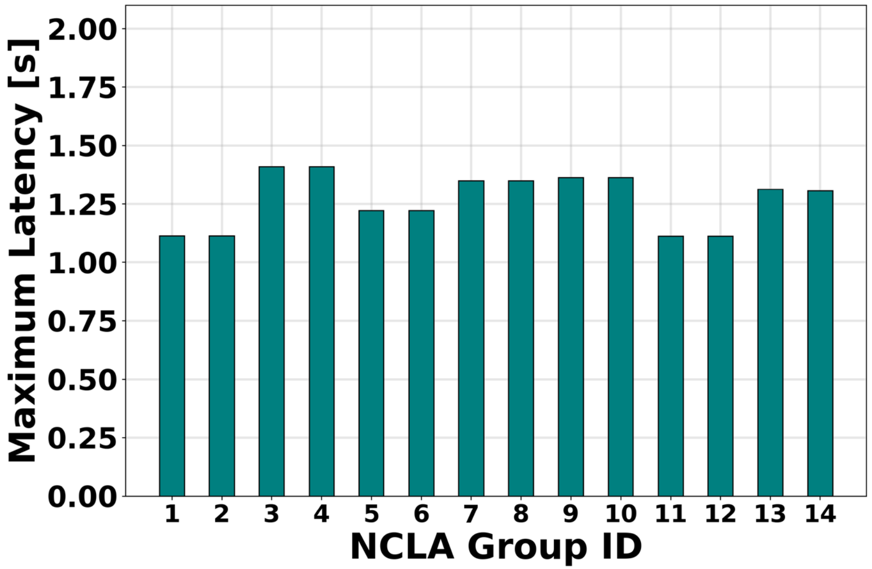
- Analysis of achieved end-to-end latency in all the events where all the heliostats are performing regular communication (referred to as 'NCLA only' events) and no CLA operation is performed (CLA is performed when DNI>=500).

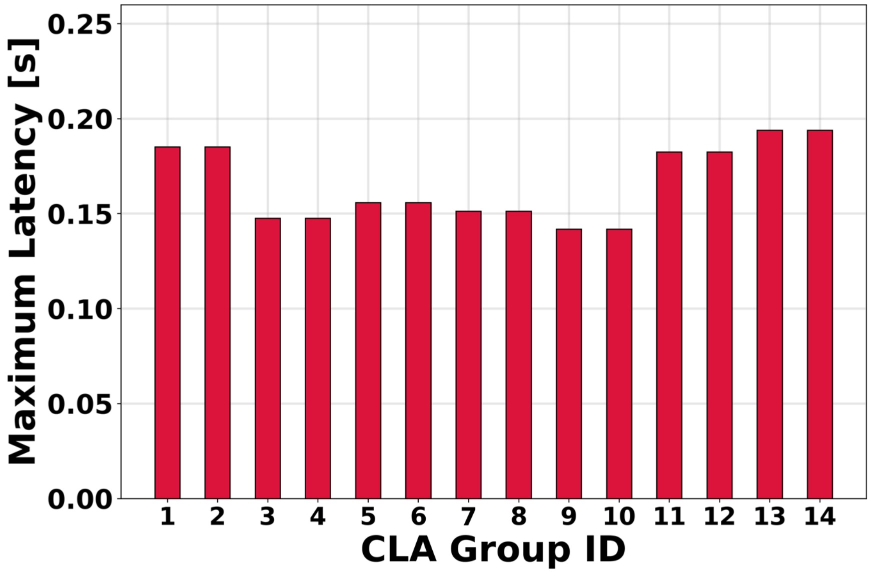
- We have concluded to not having any heliostats requiring an end-to-end latency more than the latency constraint, for the 'NCLA only' events, which have latency constraints of 2 sec.



CLA Latency Analysis

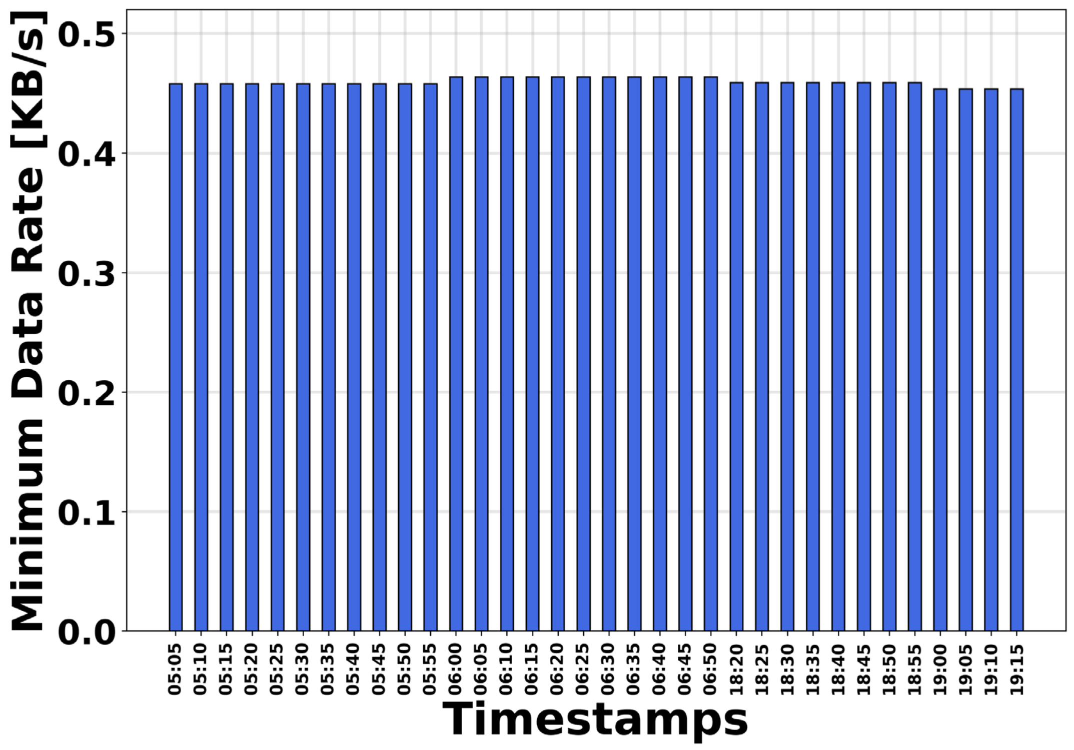
- Simulation for a timeframe of **1 day**.
- Analysis of achieved end-to-end latency in every possible CLA segment group performing CLA simultaneously and the corresponding NCLA segment group performing NCLA.
- We have concluded to not having any heliostats requiring an end-to-end latency more than the latency constraint, both during CLA events and NCLA events, which have latency constraints of 250 msec and 2 sec, respectively.





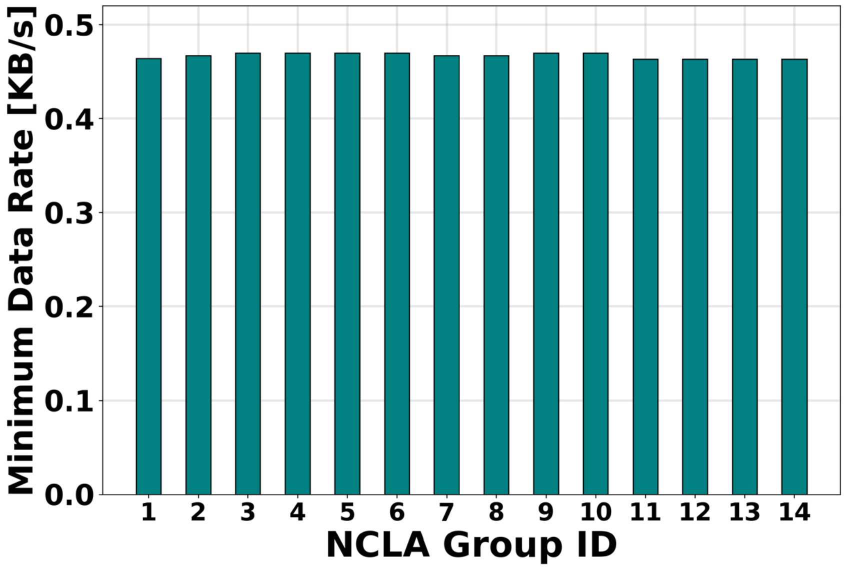
NCLA Data Rate Analysis

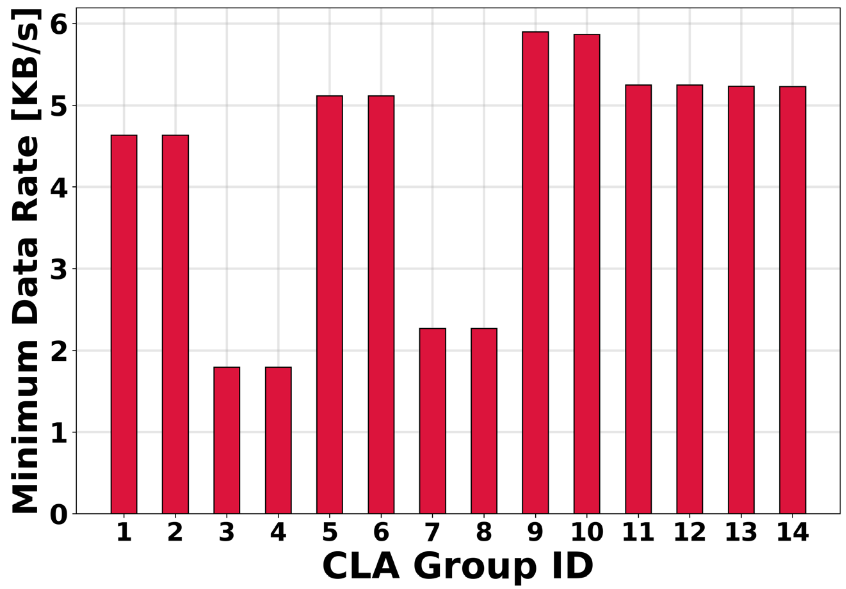
- Simulation for a timeframe of **1 day**.
- Analysis of achieved data rate in all the events where all the heliostats are performing regular communication (referred to as 'NCLA only' events) and no CLA operation is performed.
- We have reached to a conclusion that by having **95 Bytes to transmit**, the achieved data rate is high enough for transmission, during the 'NCLA only' events.



CLA Data Rate Analysis

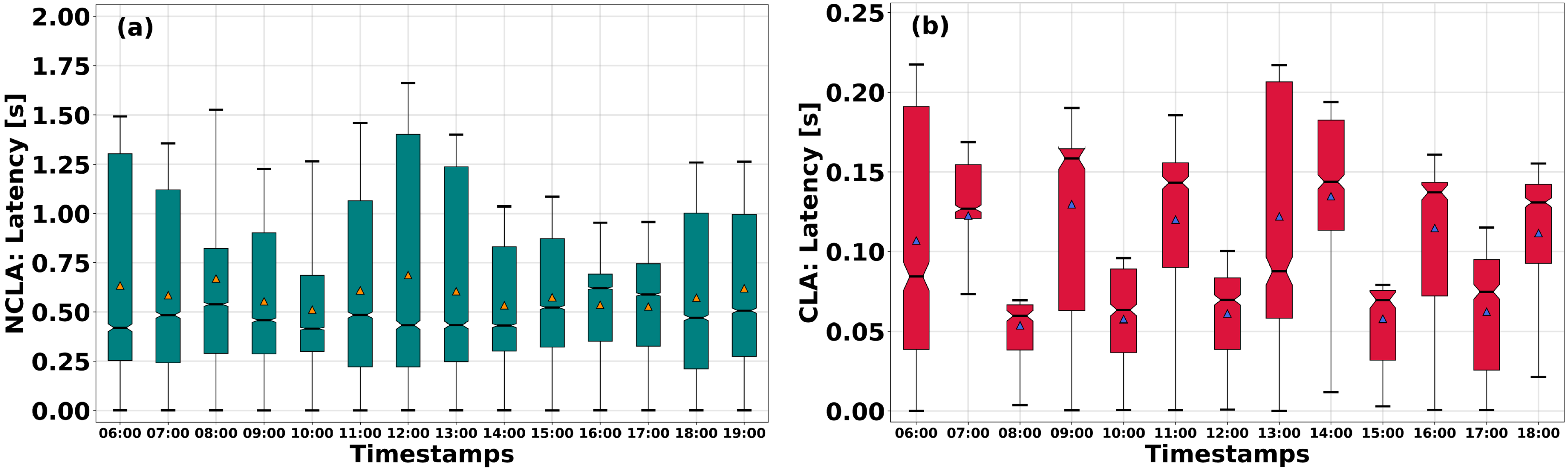
- Simulation for a timeframe of **1 day**.
- Analysis of achieved data-rate in every possible CLA segment group performing CLA simultaneously and the corresponding NCLA segment group performing NCLA.
- We have reached to a conclusion that by having **95 Bytes to transmit**, the achieved data rate is high enough for transmission, both during CLA events and NCLA events.





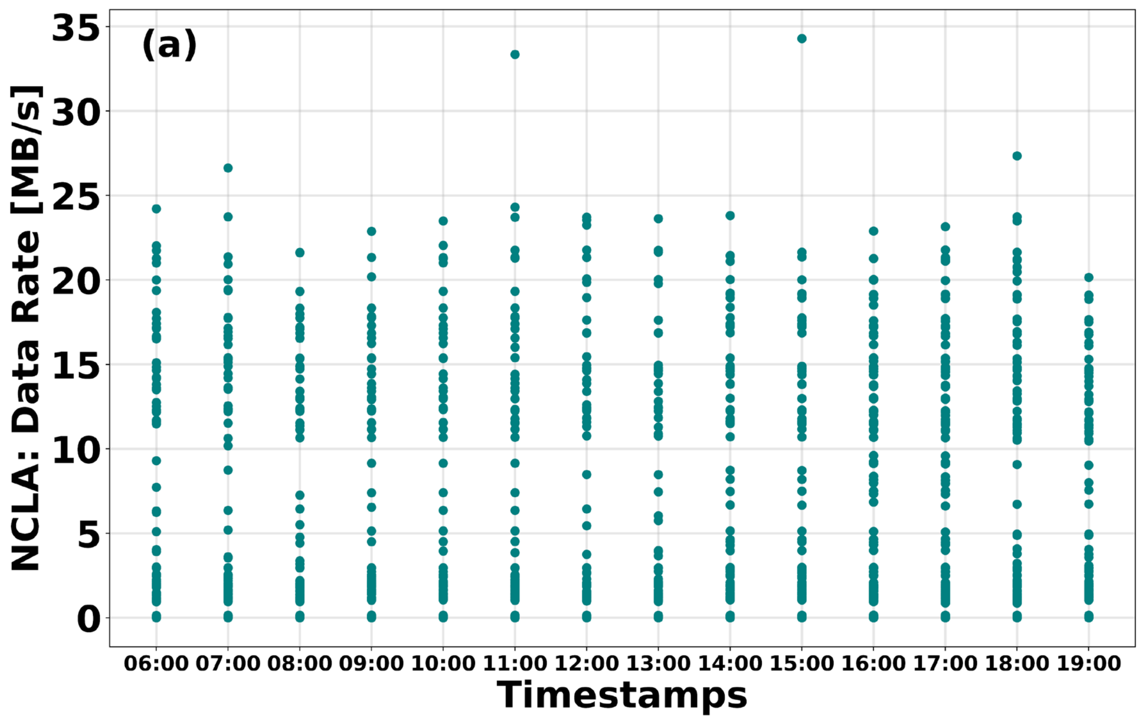
NCLA & CLA Latency Analysis

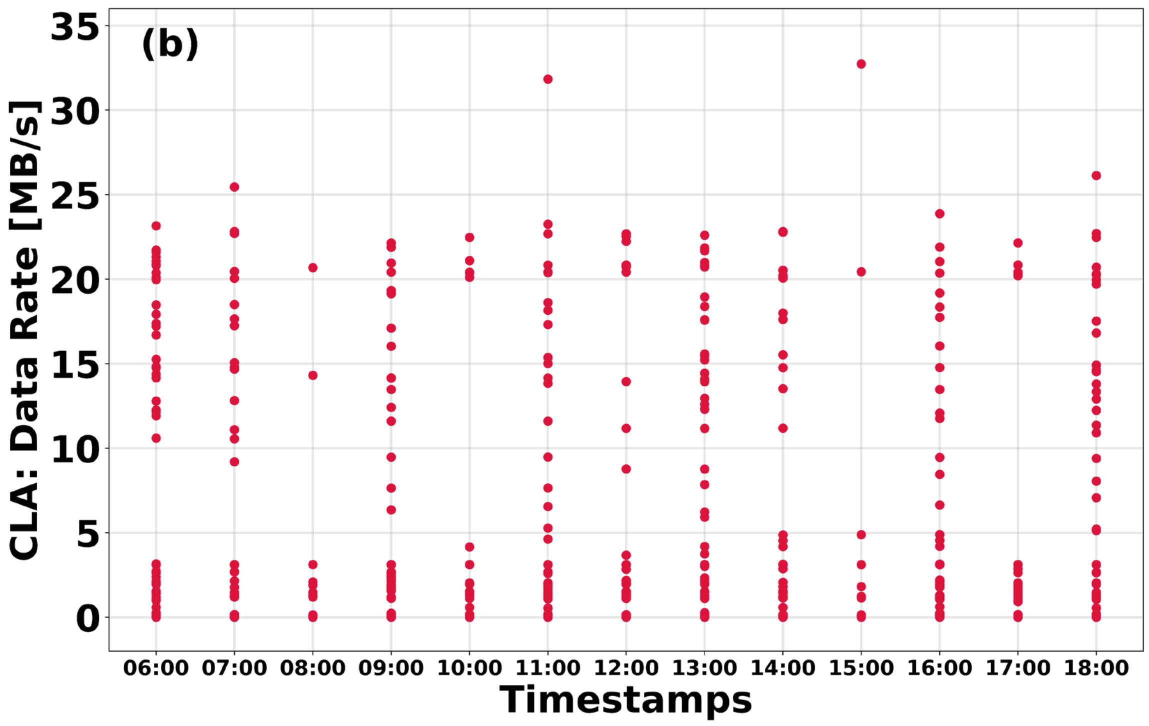
- Simulation for a timeframe of **1 day**. Analysis of achieved end-to-end latency for CLA and NCLA operations across all the timestamps in the day when DNI is non-zero.



NCLA & CLA Sampling of Data Rate Analysis

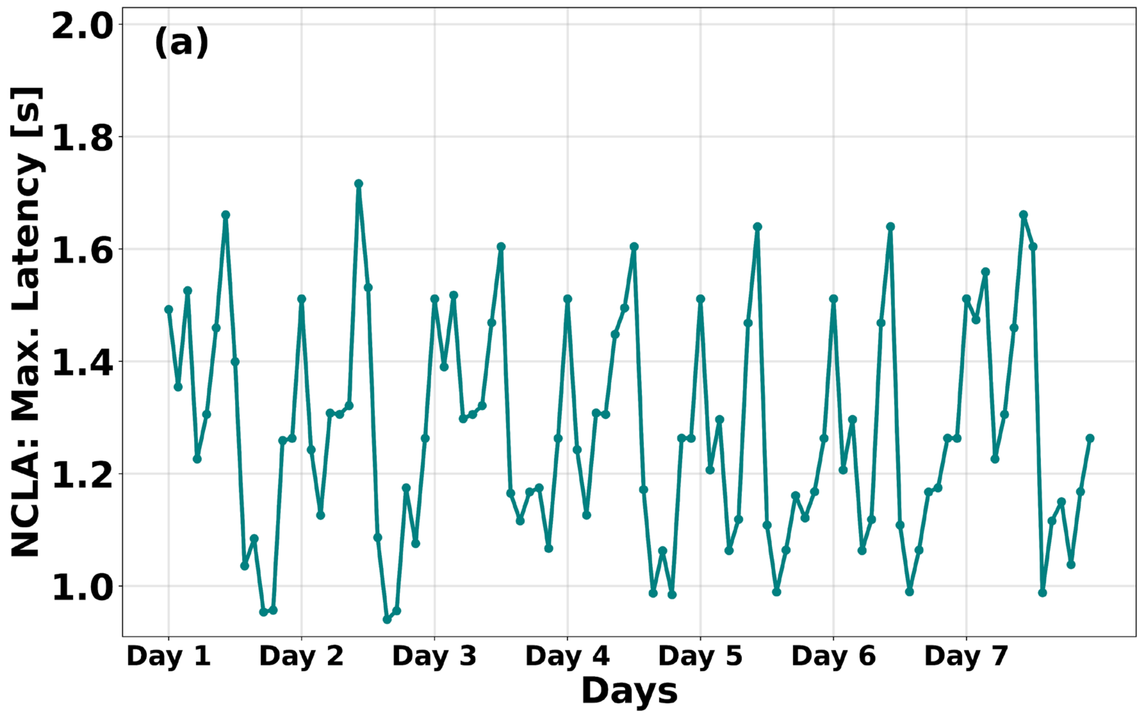
- Simulation for a timeframe of **1 day**. Analysis of achieved date rate for CLA and NCLA operations across all the timestamps in the day when DNI is non-zero.

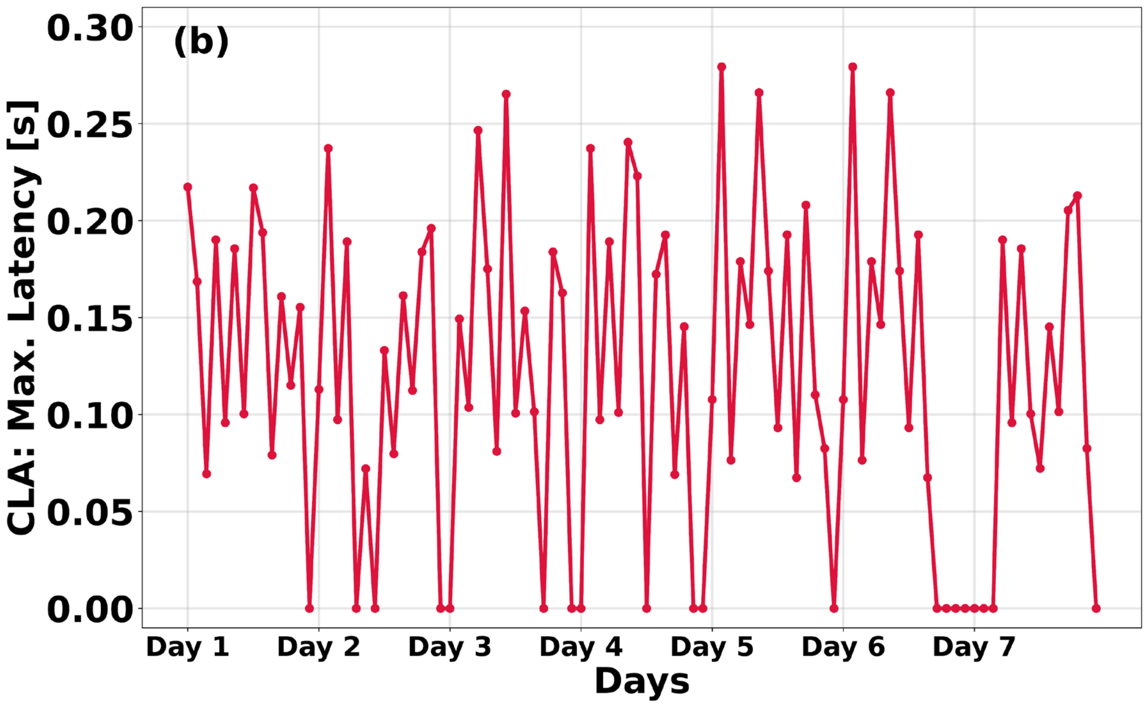




Maximum NCLA & CLA Latency Analysis

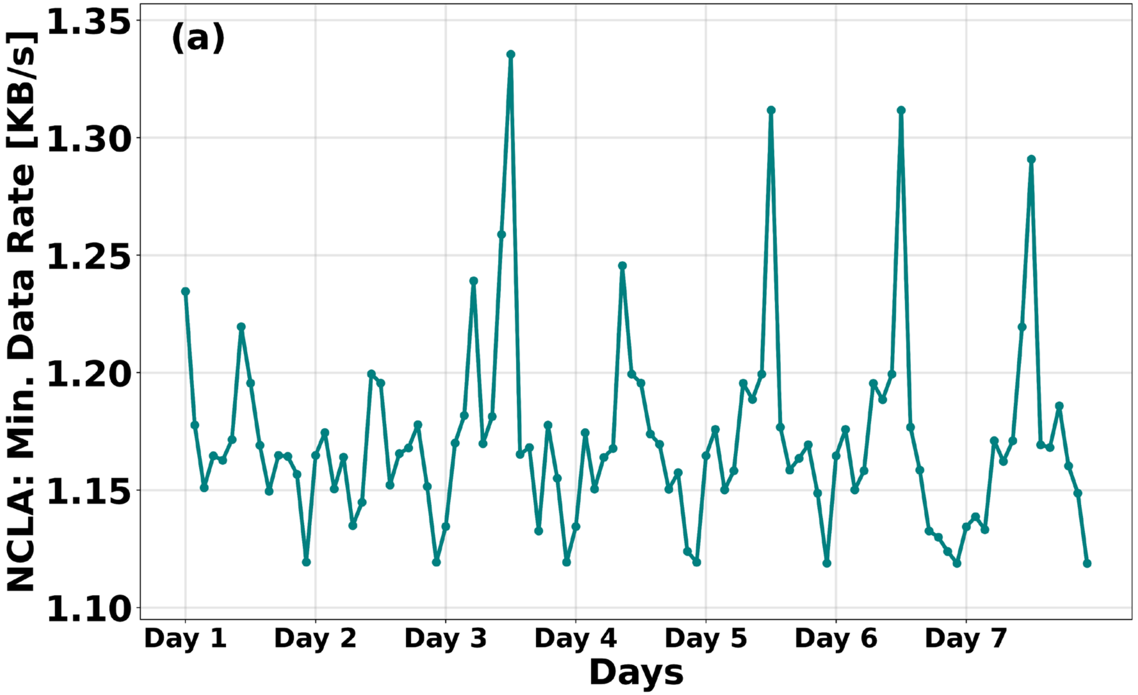
- Simulation for a timeframe of **1 week**. Analysis of the maximum achieved end-to-end latency for CLA and NCLA operations for all the timestamps in each day when DNI is non-zero (CLA is performed when DNI >=500).

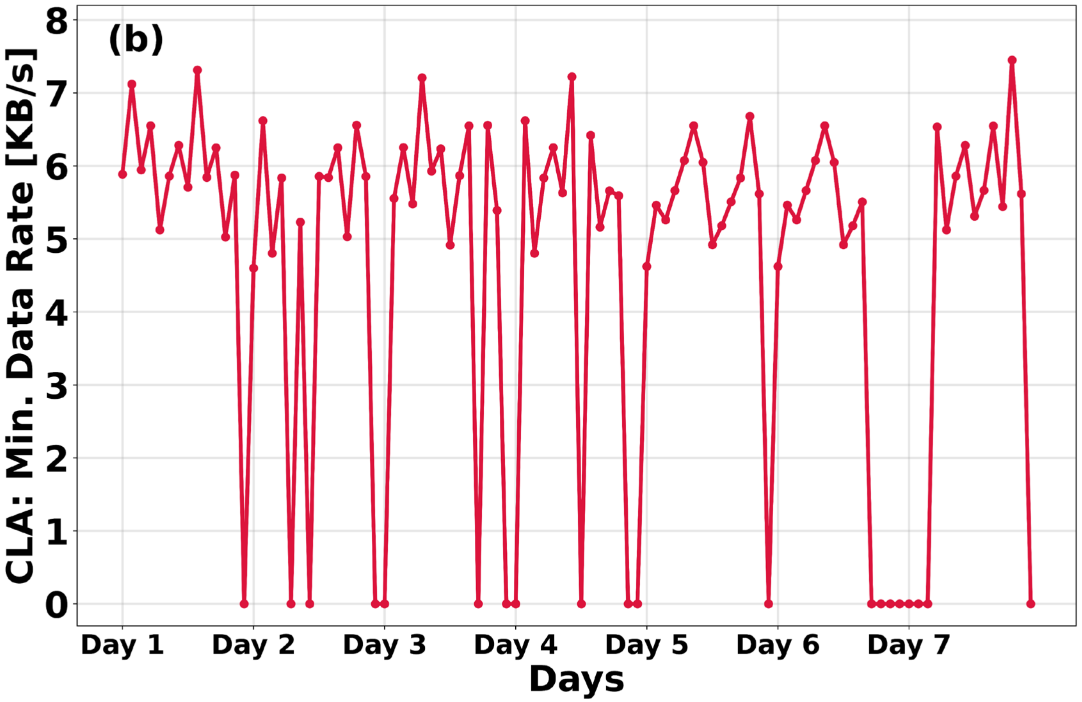




Minimum NCLA & CLA Data Rate Analysis

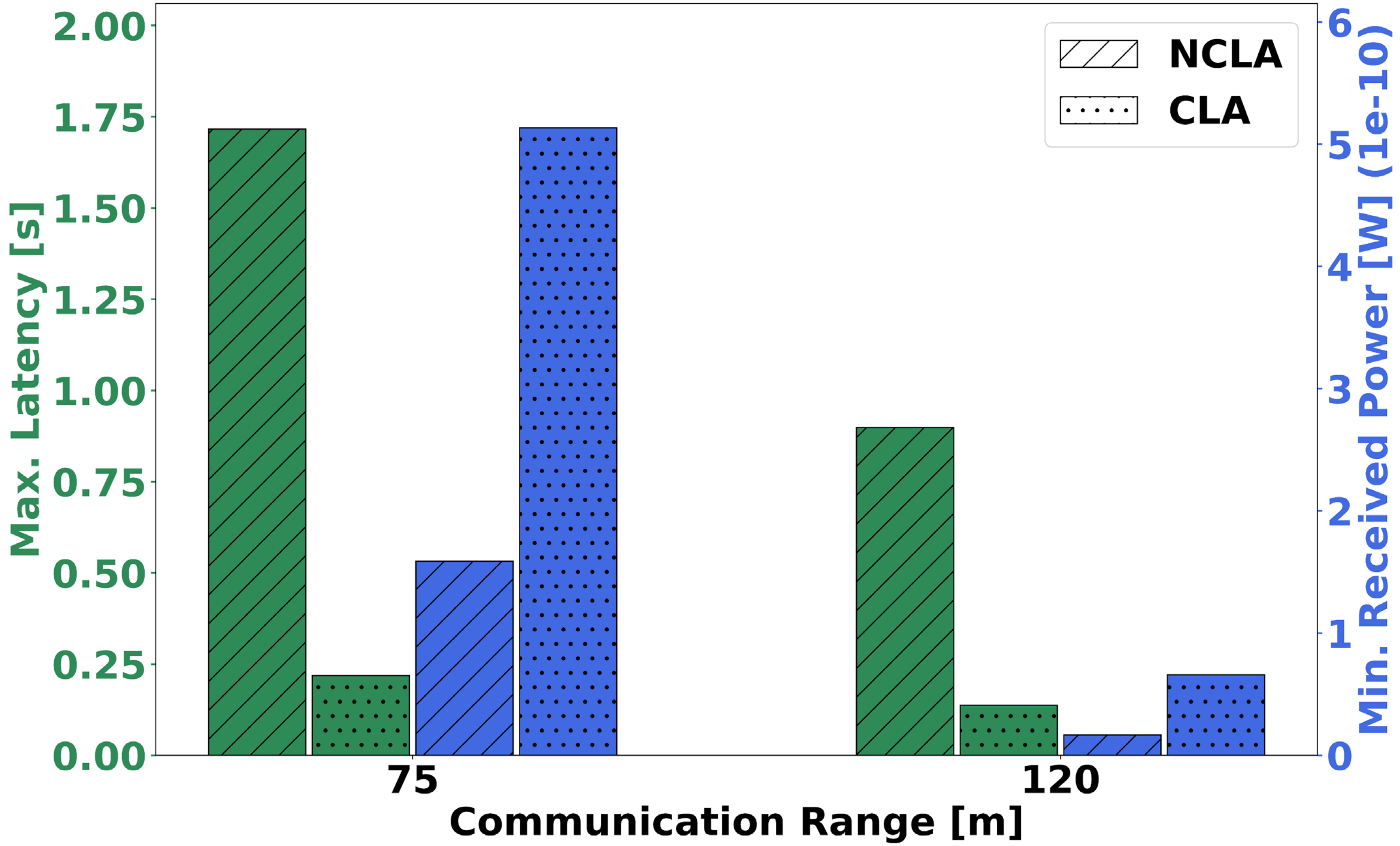
- Simulation for a timeframe of **1 week**. Analysis of the minimum achieved data rate for CLA and NCLA operations for all the timestamps in each day when DNI is non-zero.





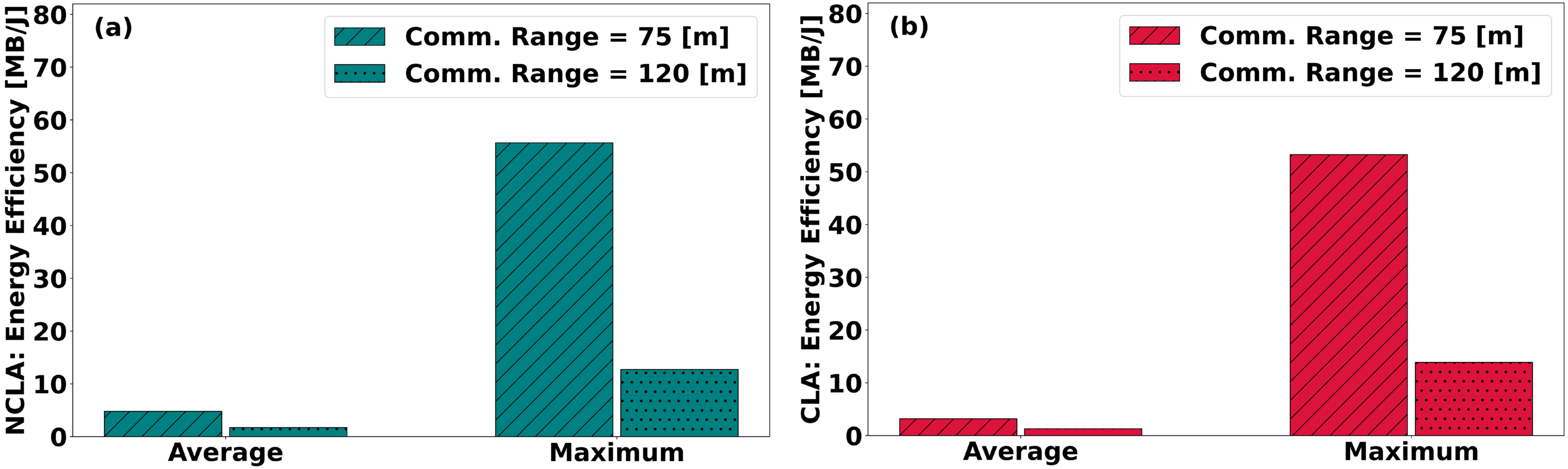
Comparative Analysis for Different Communication Range

- Considering different wireless modules supporting 75 m and 120 m communication range.



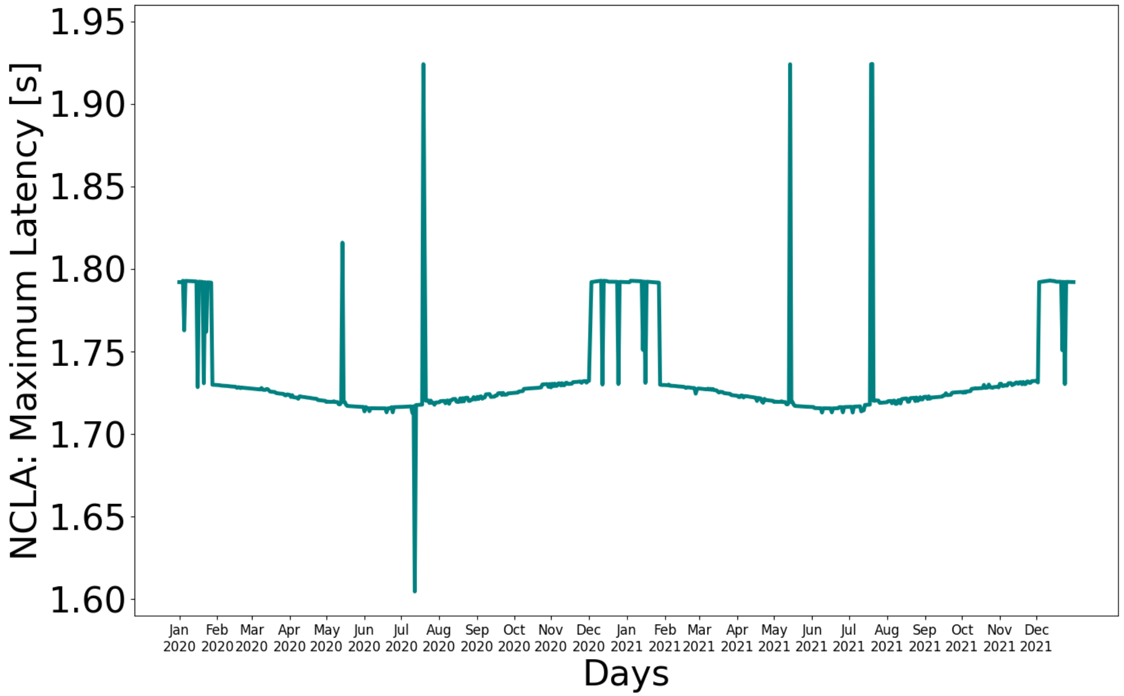
Comparative Analysis

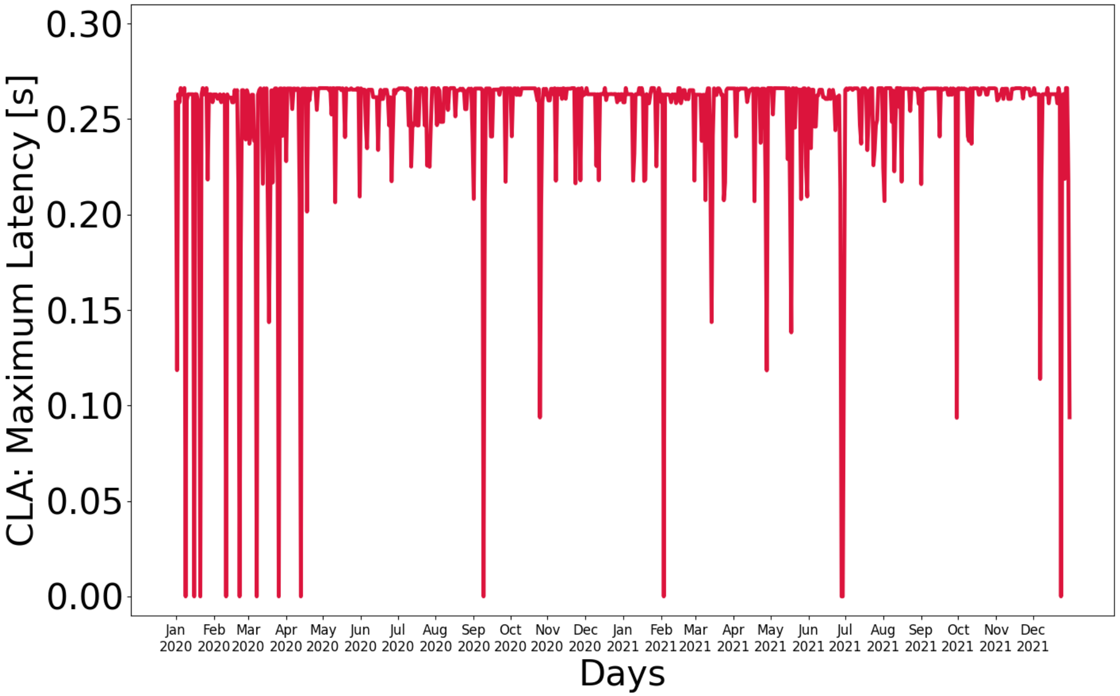
- Considering different wireless modules supporting 75 m and 120 m communication range.



2 Years Latency Analysis

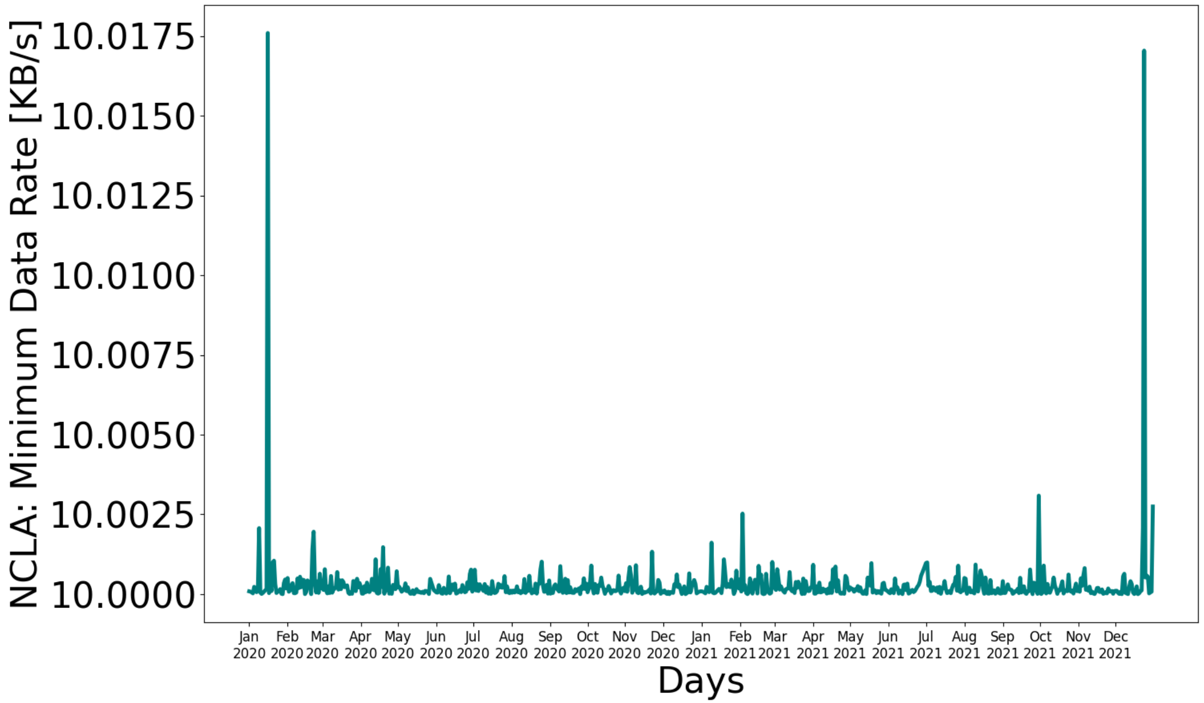
- Simulation for a timeframe of **2 years**. Analysis of the maximum achieved end-to-end latency for CLA and NCLA operations each day across the 2-year simulation duration.

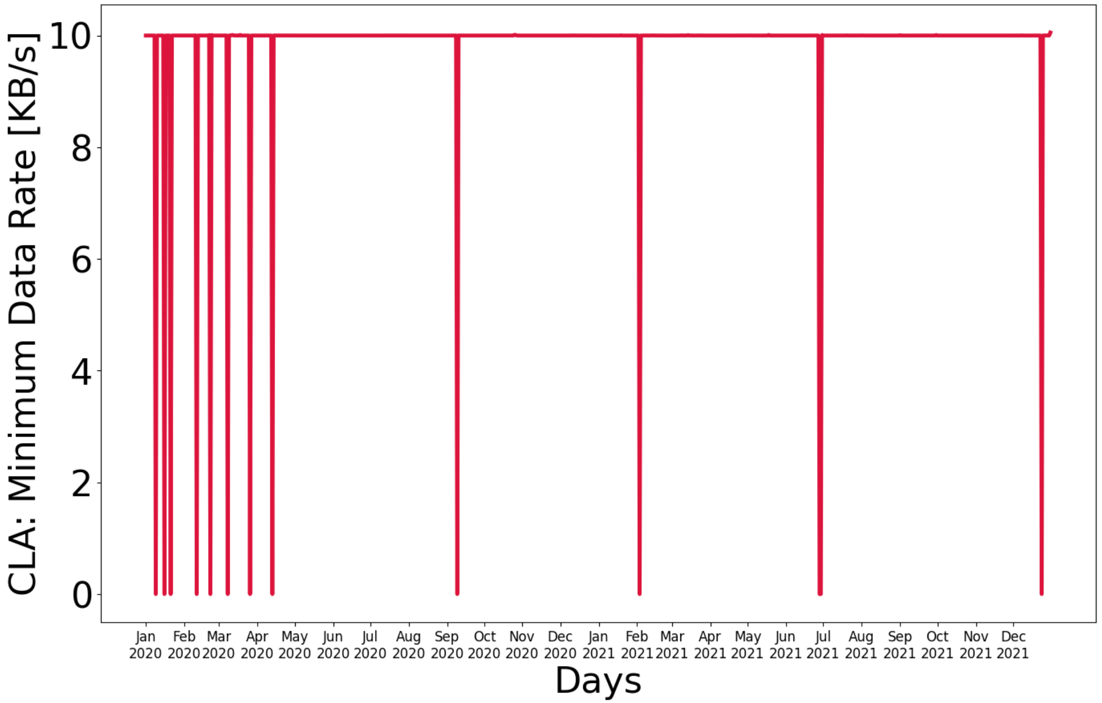




2 Years Data Rate Analysis

- Simulation for a timeframe of **2 years**. Analysis of the minimum achieved data rate for CLA and NCLA operations each day across the 2-year simulation duration.

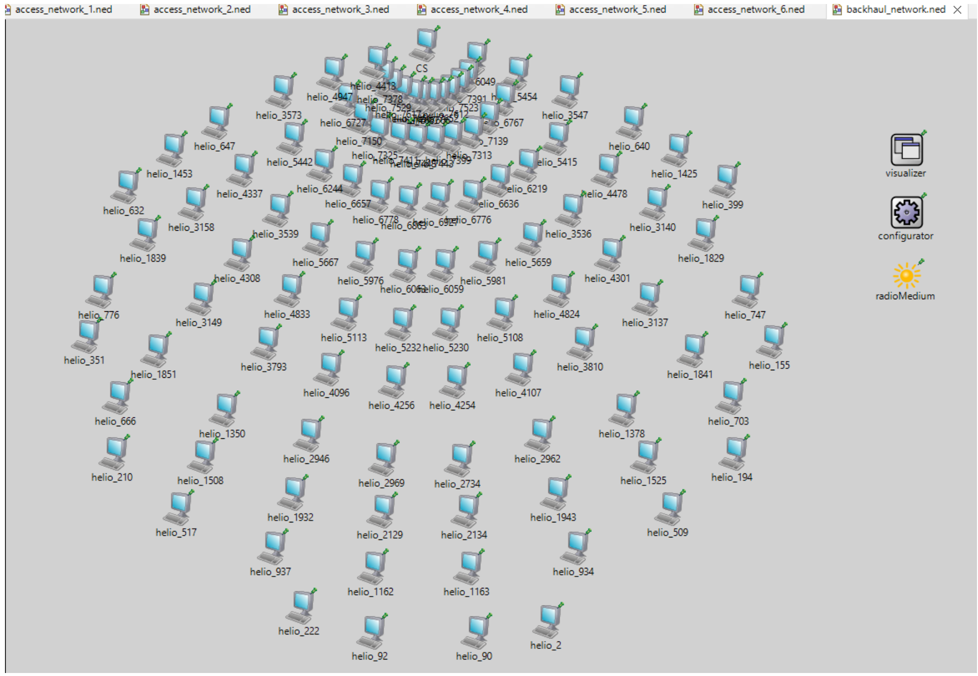




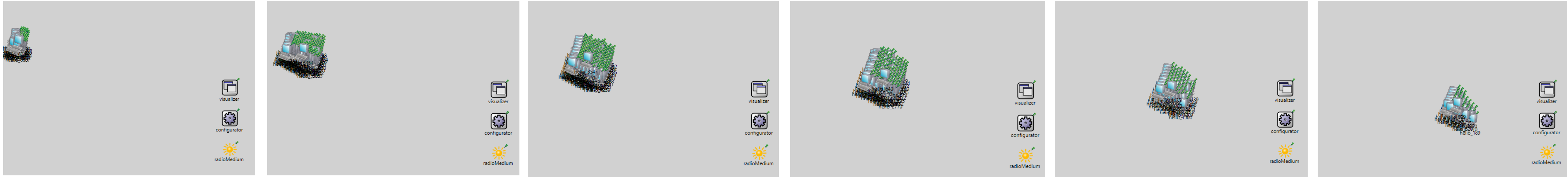
Emulation in OMNET++

- We have built our own radio module to consider our system model components including path loss, personalized transmission power, data rate, etc.
- We have built our own UDP (User Datagram Protocol) Application for the IAB nodes to collect packets from the access network and forward it to the next-hop destination.

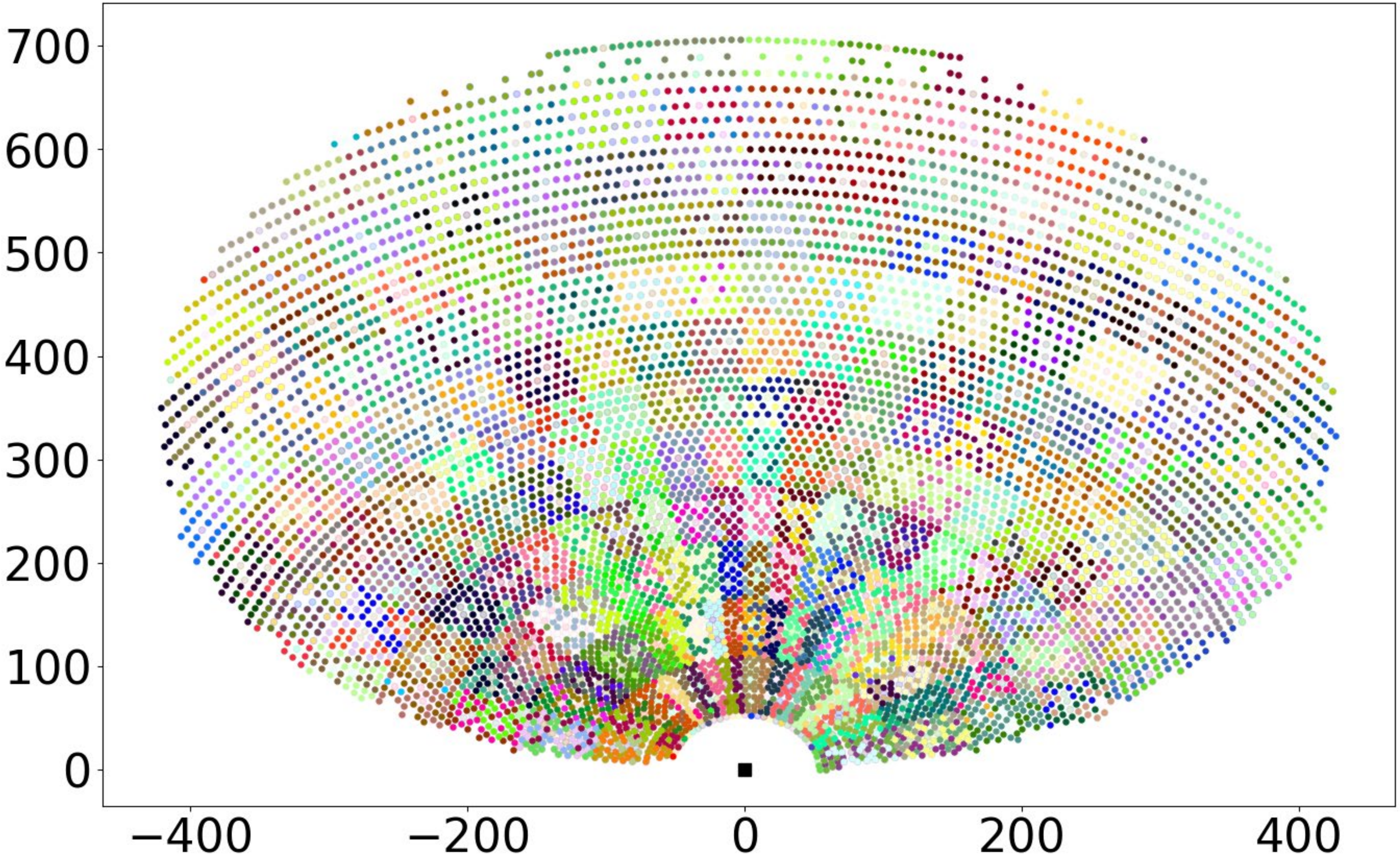
Backhaul Network



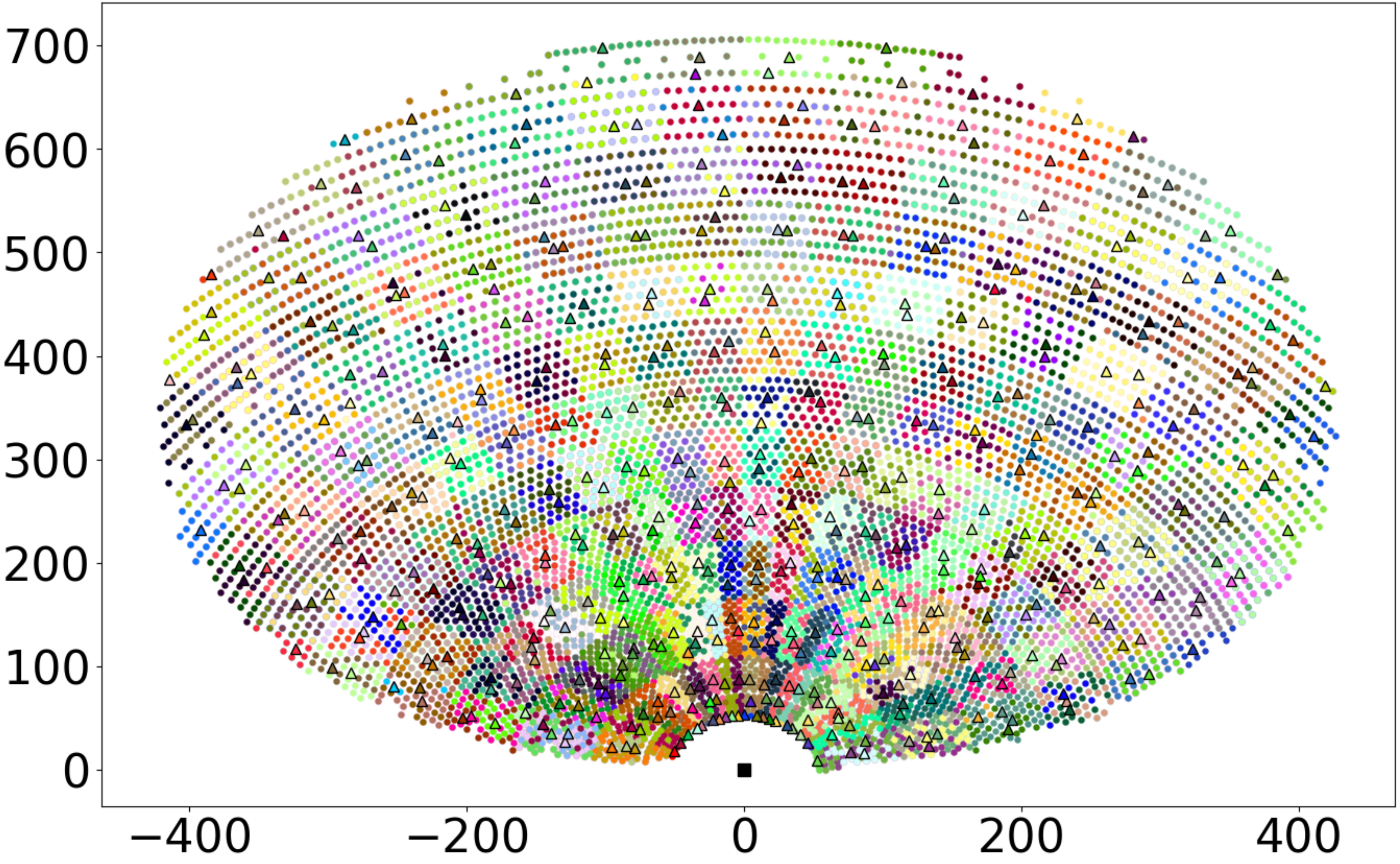
Access Networks



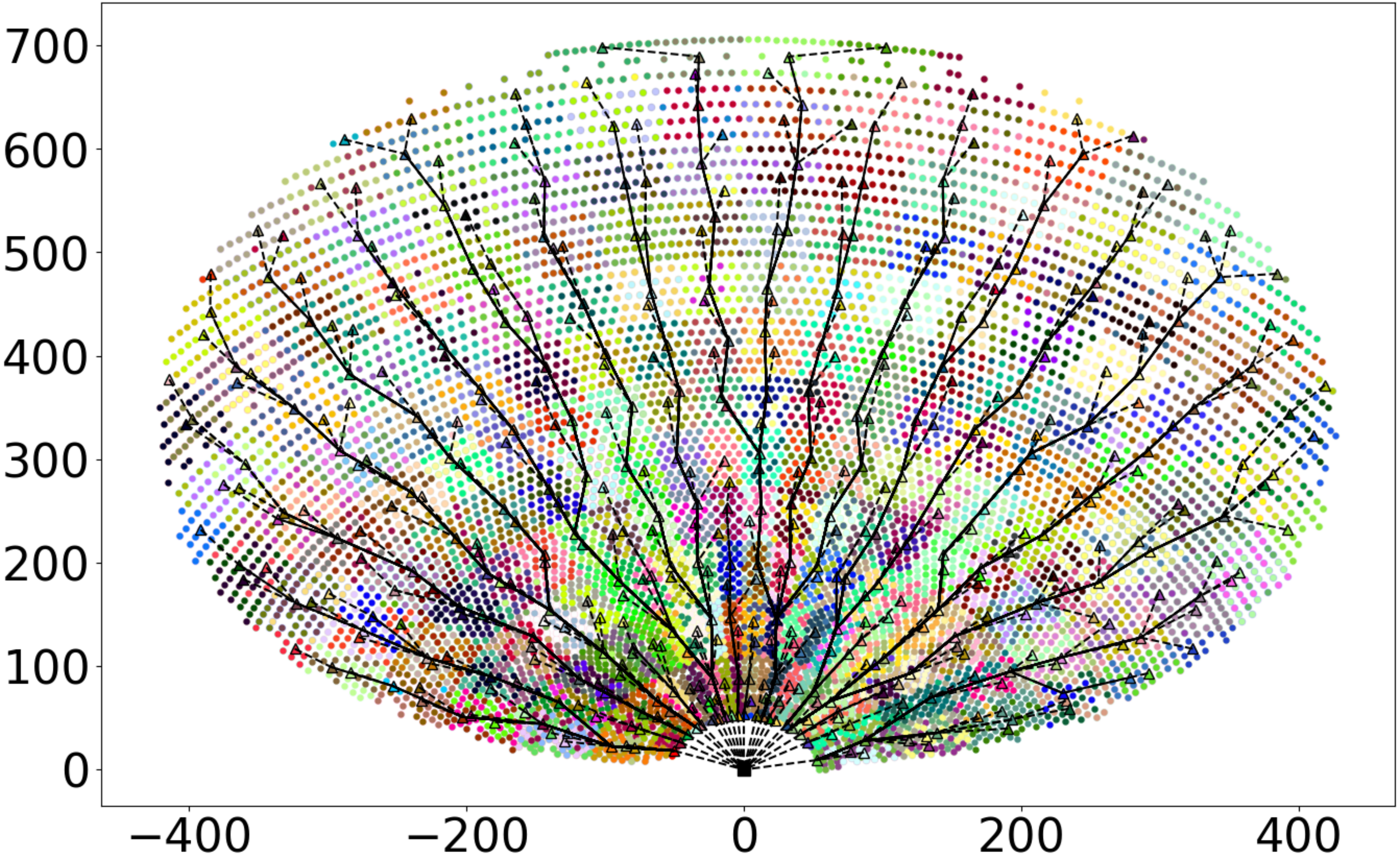
HELIOCON Baseline Topology: Clustering



HELIOCON Baseline Topology: Cluster-heads



HELIOCON Baseline Topology: Routing



Thank you!

Aisha B. Rahman
Graduate Research Assistant at University of New Mexico, USA

Md Sadman Siraj
Graduate Research Assistant at The University of New Mexico

Questions?

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APPENDIX

NSTFF@SNL topology: EE Optimization

Energy efficiency optimization for <u>IAB nodes</u> within sub-second latency

- The optimization problem of the IAB nodes is formulated as follows.

$$\max_{\omega_c, P_{N_c}} EE_{N_c}(\omega_c, P_{N_c}) = \frac{R_{N_c}^{BH}}{\sum_{\forall h \in \mathcal{H}_c} P_{h_c} + \sum_{\forall c' \in \mathcal{N}_{N_c}^{BH}} P_{N_{c'}} + P_{N_c}}$$

$$\begin{aligned} s.t.\ \boldsymbol{c1}&: 0 \leq \omega_c \leq 1 \\ \boldsymbol{c2}&: P_{N_c} \leq P^{max} \\ \boldsymbol{c3}&: P_{N_{c+1}}^{S} \geq P^{s} \\ \boldsymbol{c4}&: t_{h_c}^{E2E} \leq t^{max}, \forall h_c \in \mathcal{H}_c \end{aligned}$$

- The resulting data rate achieved at the backhaul by IAB node N_c is given as:

$$R_{N_c}^{BH} = (1 - \omega_c) B_c \log_2\left(1 + \frac{g_{N_c} P_{N_c}}{\sum_{\forall i \in \mathcal{I}_{N_c}} g_i P_i + (1 - \omega_c) B_c N_0}\right)$$

NSTFF@SNL topology: EE Optimization

Energy efficiency optimization for access heliostats within sub-second latency

- The single-variable optimization problem of the access heliostats is formulated as follows:

$$\max_{P_{h_c}} EE_{h_c}\left(P_{h_c}, P_{-h_c}\right) = \frac{R_{h_c}^{AC}}{P_{h_c} + P_c}$$

$$\boldsymbol{c1}: P_{h_c} \leq P^{max}$$

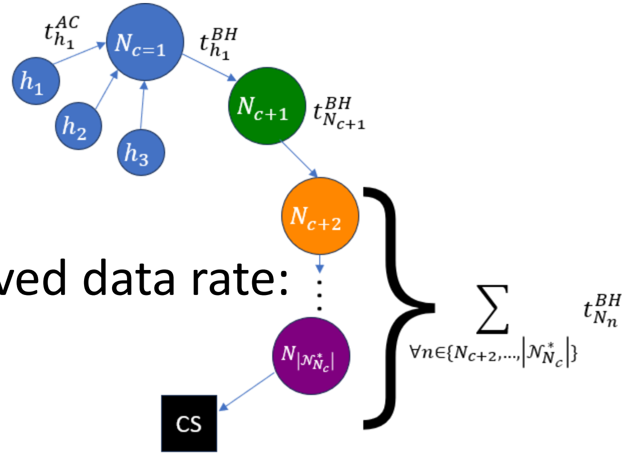
$$\boldsymbol{c2}: P_{h_c,N_c}^{S} \geq P^{S}, \forall h_c \in \mathcal{H}_c$$

$$\boldsymbol{c3}:\ t_{h_c}^{E2E} \leq t^{max}, \forall h_c \in \mathcal{H}_c$$

- The resulting data rate achieved at the access network by heliostat h_c is given as:

$$R_{h_c}^{AC} = \omega_c B_c \log_2\left(1 + \frac{g_{h_c} P_{h_c}}{\sum_{\forall i \in \mathcal{I}_{\hbar_c}} g_i P_i + \omega_c B_c N_0}\right)$$

NSTFF@SNL topology: EE Optimization



Energy efficiency optimization within sub-second latency

- The corresponding transmission delay experienced by heliostat h_c with the achieved data rate:

$$t_{h_c}^{E2E} = t_{h_c}^{AC} + t_{h_c}^{BH} + t_{N_{c+1}}^{BH} + \sum_{\forall n \in \{N_{c+2},\ldots,|\mathcal{N}_{N_c}^*|\}} t_{N_n}^{BH} \leq t^{max}, \forall h_c \in \mathcal{H}_c$$

- Where, the delay experienced in the access network and the backhaul network of its own segment is given by $t_{h_c}^{AC} = \frac{D_{h_c}}{R_{h_c}^{AC}}$ and $t_{h_c}^{BH} = \frac{D_{h_c}}{\frac{R_{h_c}^{AC}}{\sum_{\forall h_c \in \mathcal{H}_c} R_{h_c}^{AC} + \sum_{\forall c' \in N_{N_c}^{BH}} R_{N_{c'}}^{BH}} R_{N_c}^{BH}}$, respectively.

- The rest of the term $t_{N_{c+1}}$ and $t_{N_n}^{BH}$ capture the latency experienced at the backhaul of the subsequent segment-heads within the route of data transmission from heliostat h_c to the CS, and are given as

$$\frac{\sum_{h_c \in \mathcal{H}_c} D_{h_c}}{\frac{R_{N_c}^{BH}}{\sum_{\forall h_{c+1} \in \mathcal{H}_{c+1}} R_{h_{c+1}}^{AC} + \sum_{\forall c' \in N_{\mathcal{N}_{c+1}}^{BH}} R_{N_{c'}}^{BH}} R_{N_{c+1}}^{BH}} \text{ and } \frac{D_{N_{n-1}}}{\frac{R_{N_{n-1}}^{BH}}{\sum_{\forall h_n \in \mathcal{H}_n} R_{h_n}^{AC} + \sum_{\forall c' \in N_{\mathcal{N}_n}^{\mathcal{BH}}} R_{N_{c'}}^{BH}} R_{N_n}^{BH}}, \text{ respectively.}$$

HELIOCON Baseline Topology: Segment-heads

Segment-head selection process

- A segment s with heliostats denoted by $\mathcal{H}_s$ is considered.
- Segment-head selection process is initiated with the calculation of weights w_{h_s} of each heliostat h_s with other heliostats h_s' in the same segment.

$$D(h_s, h_s') = -\log_2\left(d(h_s, h_s')\right), \text{ where } d(h_s, h_s') \text{ is the actual distance between } h_s \text{ and } h_s'$$

$$G(h_s, h_s') = -\log_2(g(h_s, h_s')), \text{ where } g(h_s, h_s') \text{ is the actual channel gain between } h_s \text{ and } h_s'$$

$$DG(h_s, h_s') = w_D D(h_s, h_s') + w_G \frac{1}{G(h_s, h_s')}, \text{ where } w_D, w_G \text{ are the weights for the distance and channel gain dependent terms respectively}$$

$$w_{h_s}(h_s, h_s') = DG(h_s, h_s'), \forall h_s' \in \mathcal{H}_s, h_s \neq h_s'$$

- Towards selecting the segment-head sh_s of segment s, the concept of closeness centrality CC is utilized.

$$CC(h_s) = \sum_{\substack{\forall h_s' \in \mathcal{H}_s \\ h_s \neq h_s'}} \left[\frac{w_{h_s}(h_s, h_s')}{|\mathcal{H}_s| - 1}\right]$$

- The score of heliostat h_s as a function of closeness centrality CC and energy availability E in the segment s is defined as follows:

$$score(h_s) = w_{CC} CC(h_s) + w_E \frac{E(h_s)}{E_s^{max}}, \text{ where } w_{CC}, w_E \text{ are the weights for the } CC \text{ and } E \text{ values respectively}$$

- The heliostat with the highest score is the chosen segment-head: $sh_s = \underset{\forall h_s \in \mathcal{H}_s}{\operatorname{argmax}}\{score(h_s)\}$

HELIOCON Baseline Topology: EE Optimization

Energy efficiency optimization for IAB nodes

- The optimization problem of the IAB nodes is formulated as follows.

$$\max_{\omega_c, P_{N_c}} EE_{N_c}(\omega_c, P_{N_c}) = \frac{R_{N_c}^{BH}}{\sum_{\forall h_c \in \mathcal{H}_c} P_{h_c} + \sum_{\forall c' \in \mathcal{N}_{N_c}^{\mathcal{BH}}} P_{N_{c'}} + P_{N_c}}$$

$$s.t.\ \boldsymbol{c1}: 0 \leq \omega_c \leq 1$$

$$\boldsymbol{c2}: P_{N_c} \leq P^{max}$$

$$\boldsymbol{c3}: P_{N_{c+1}}^{S} \geq P^{S}$$

$$\boldsymbol{c4}: t_k^{E2E} \leq t^{max}, \forall k \in \mathcal{H}_c \cup \mathcal{N}_{N_c}^{BH}$$

- $R_{N_c}^{BH}$: *achieved data rate of IAB node* N_c *in the backhaul*
- P_{N_c}: *transmission power of IAB node* N_c *in the backhaul*
- P_{h_c}: *transmission power of access heliostat* $h_c, \forall h_c \in \mathcal{H}_c$
- $P_{N_{c'}}, \forall c' \in \mathcal{N}_{N_c}^{\mathcal{BH}}$: *transmission power of IAB node/IAB relay connected to the backhaul of IAB node* N_c

HELIOCON Baseline Topology: EE Optimization

Energy efficiency optimization for IAB relays

- The optimization problem of the IAB nodes is formulated as follows.

$$\max_{P_{N_c}} EE_{N_c}(P_{N_c}) = \frac{R_{N_c}^{BH}}{\sum_{\forall c' \in \mathcal{N}_{N_c}^{\mathcal{BH}}} P_{N_{c'}} + P_{N_c}}$$

$$s.t.\ \boldsymbol{c1}:\ P_{N_c} \leq P^{max}$$

$$\boldsymbol{c2}:\ P_{N_{c+1}}^{S} \geq P^{S}$$

$$\boldsymbol{c3}:\ t_k^{E2E} \leq t^{max}, \forall k \in \mathcal{N}_{N_c}^{BH}$$

- $R_{N_c}^{BH}$: *achieved data rate of IAB node* N_c *in the backhaul*
- P_{N_c}: *transmission power of IAB node* N_c *in the backhaul*
- $P_{N_{c'}}, \forall c' \in \mathcal{N}_{N_c}^{\mathcal{BH}}$: *transmission power of IAB node/IAB relay connected to the backhaul of IAB node* N_c

HELIOCON Baseline Topology: EE Optimization

Energy efficiency optimization for access heliostats

- The single-variable optimization problem of the access heliostats is formulated as follows:

$$\max_{P_{h_c}} EE_{h_c}\left(P_{h_c}, P_{-h_c}\right) = \frac{R_{h_c}^{AC}}{P_{h_c} + P_c}$$

$$\boldsymbol{c1}: P_{h_c} \leq P^{max}$$

$$\boldsymbol{c2}: P_{h_c,N_c}^{S} \geq P^{S}, \forall h_c \in \mathcal{H}_c$$

$$\boldsymbol{c3}: \ t_{h_c}^{E2E} \leq t^{max}, \forall h_c \in \mathcal{H}_c$$

- P_{h_c}*: transmission power of access heliostat* $h_c, \forall h_c \in \mathcal{H}_c$
- $R_{h_c}^{AC}$*: achieved data rate of heliostat* h_c *in the access*

HELIOCON Baseline Topology: Transmission Delay

- The corresponding transmission delay experienced by heliostat h_c with the achieved data rate:

$$t_{h_c}^{E2E} = t_{h_c}^{AC} + t_{h_c}^{BH} + \sum_{\forall n \in \{N_{c+1}, \ldots, |\mathcal{N}_{N_c}^{*}|\}} t_{N_n}^{BH} \leq t^{max}, \forall h_c \in \mathcal{H}_c$$

- Where, the delay experienced in the access network and the backhaul network of its own segment is given by $t_{h_c}^{AC} = \frac{D_{h_c}}{R_{h_c}^{AC}}$ and $t_{h_c}^{BH} = \frac{D_{N_c}}{R_{N_c}^{BH}}$, respectively.

- The rest of the term capture the latency experienced at the backhaul of the subsequent segment-heads within the route of data transmission from heliostat h_c to the CS.

HELIOCON Baseline Topology: Position Updates

Required parameters:

- Length of the mirror: L
- Height of mirror pivot: h
- Angle of elevation: $\angle e$ [degree]
- Height of the top of the mirror:

$$\sin(90^\circ - \angle e) = \frac{h'}{L/2}$$

$$\Rightarrow h' = L/2 \sin(90^\circ - \angle e)$$

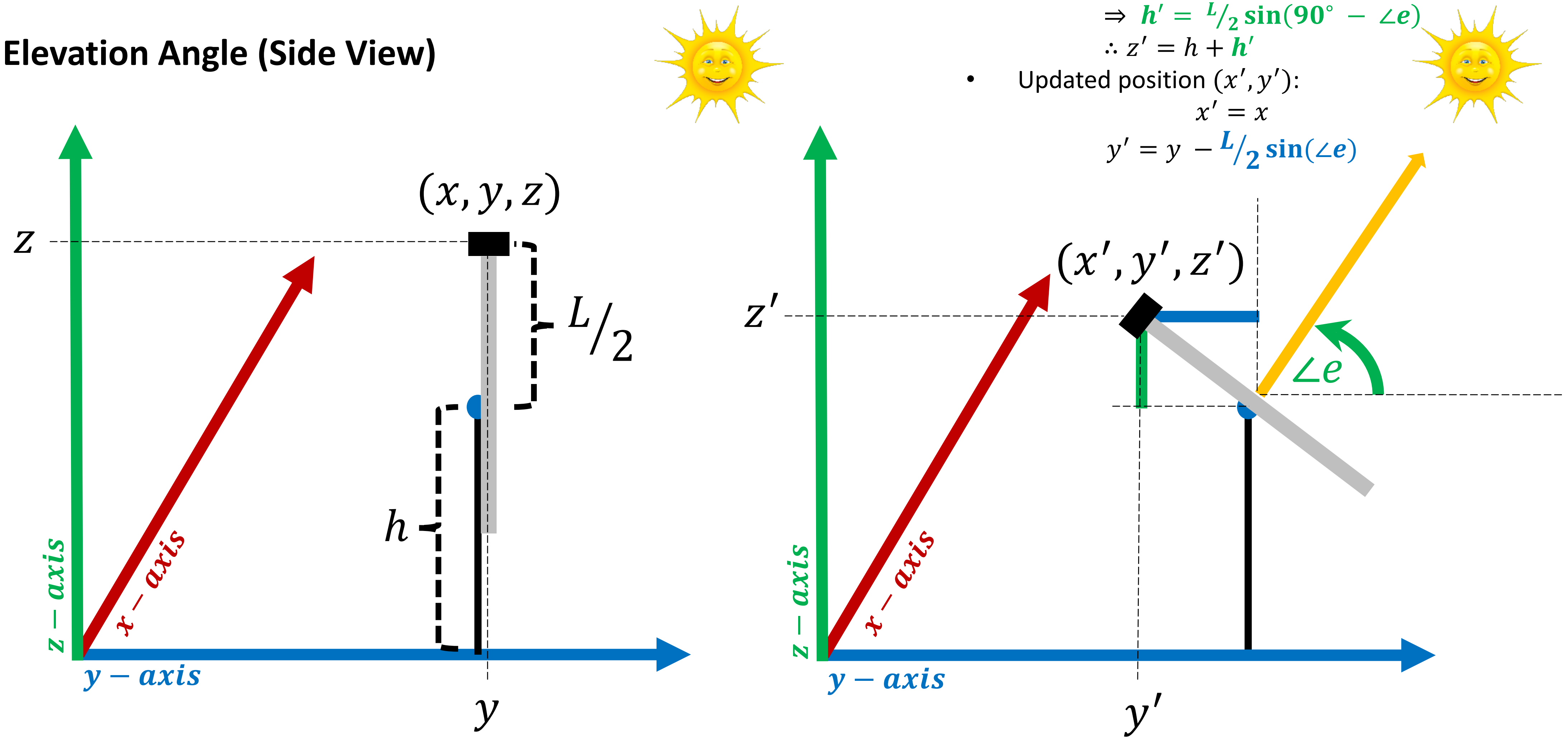
$$\therefore z' = h + h'$$

- Updated position (x', y'):

$$x' = x$$

$$y' = y - L/2 \sin(\angle e)$$

Elevation Angle (Side View)



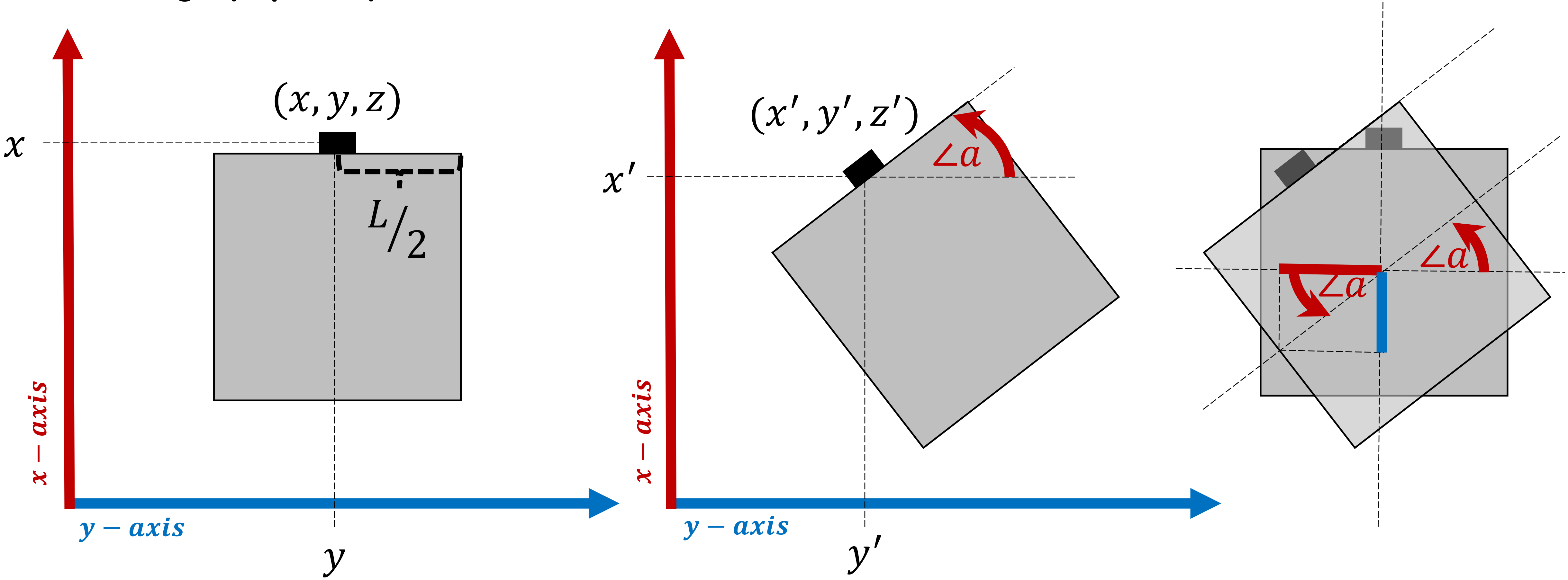
HELIOCON Baseline Topology: Position Updates

Required parameters:

- Length of the mirror: L
- Angle of azimuth: $\angle a$ [degree]
- Updated position (x', y', z'):

$$x' = x - {}^{L}/_{2} \sin(\angle a)$$
$$y' = y - {}^{L}/_{2} \cos(\angle a)$$
$$z' = z$$

Azimuth Angle (Top View)



HELIOCON Baseline Topology: Energy Availability

- In the 24-hour timeframe, the energy and DNI (Direct Normal Irradiance) data are taken as input after every 5 minutes to determine the mode of the heliostats.
- The heliostat can be in one of the two modes: "STANDBY" or "ACTIVE".
    - **STANDBY** mode: Heliostats are not transmitting and only the "$\boldsymbol{energy_{standby}}$" in consumed.
    - **ACTIVE** mode: Heliostats are transmitting by consuming "$\boldsymbol{energy_{transmission}}$" and "$\boldsymbol{energy_{active}}$".
- In ACTIVE mode and for a particular timestamp, heliostats are performing "NCLA" or both "CLA" and "NCLA" depending on the DNI in this timestamp.
- The battery status of each heliostat is logged at every step of the simulation (at an interval of 5 minutes).

HELIOCON Baseline Topology: Energy Availability

Simulation Parameters

$$\boldsymbol{time\_interval = 5 * 60\ [s]}$$

- $V_{DDS} = 3.6\ [V]$
- $I_{CORE}^{standby} = 2.92 * 10^{-6}\ [A]$
- $\boldsymbol{energy_{standby} = V_{DDS} * I_{CORE}^{standby} * time\_interval}$

- $V_{DDS} = 3.6\ [V]$
- $I_{CORE}^{active} = 2.89 * 10^{-3}\ [A]$
- $I_{PERIPHERAL} = 750.1 * 10^{-6}\ [A]$
- $V_{SENSOR} = 3.0\ [V]$
- $I_{SENSOR} = 808.5 * 10^{-6}\ [A]$
- $\boldsymbol{energy_{active} = \left(V_{DDS} * \left(I_{CORE}^{standby} + I_{PERIPHERAL}\right) + V_{SENSOR} * I_{SENSOR}\right) * time\_interval}$

- $\boldsymbol{battery_{max} = 324\ [KJ]\ \#\ 100\%}$
- $\boldsymbol{battery_{min} = 65\ [KJ]\ \#\ 20\%}$

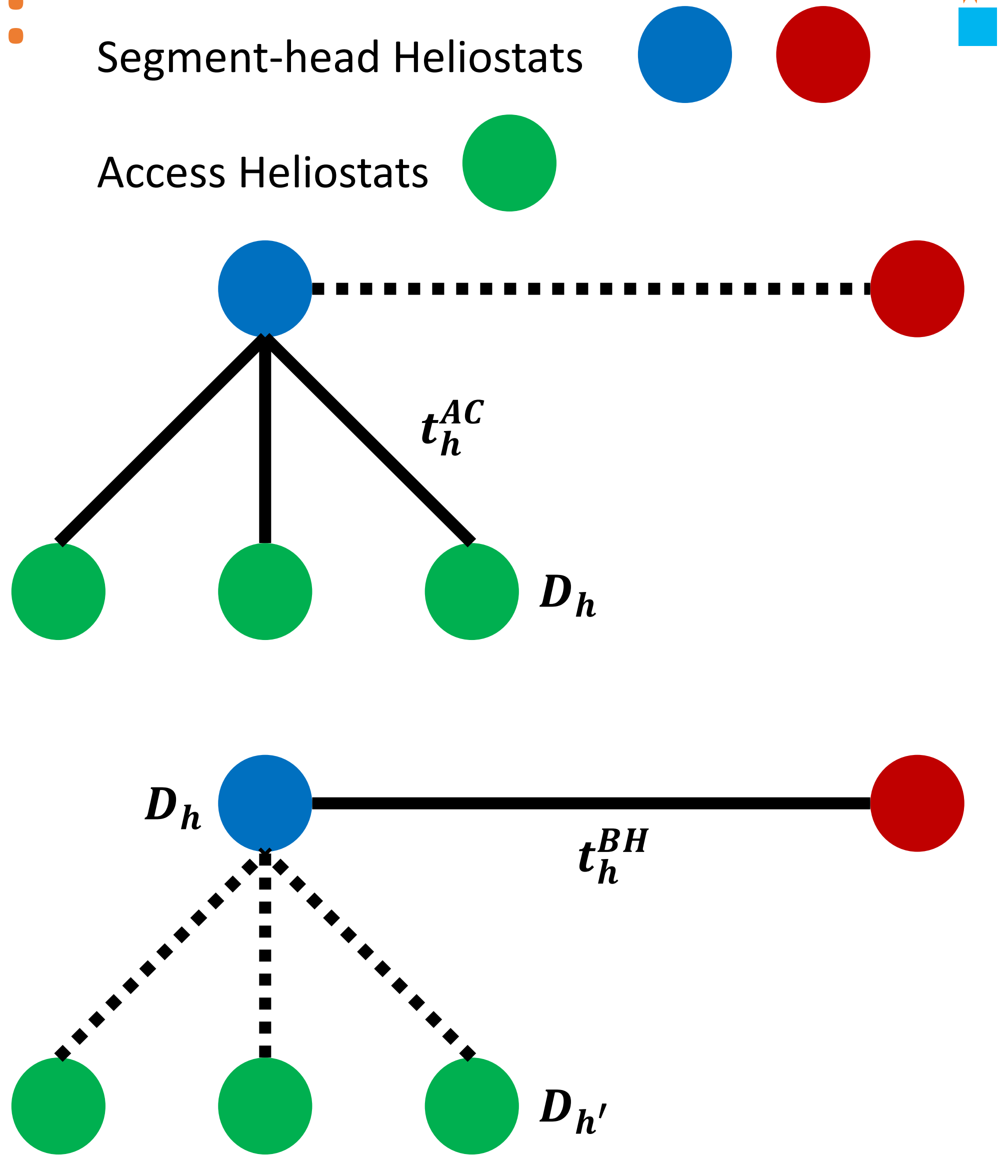
Reference: TI CC1312R, Pages: 12, 62

HELIOCON Baseline Topology: Energy Availability

Simulation Parameters

- *Access Heliostats*:
  - $energy_{transmission} = P_{transmission} * t_h^{AC}$ [J]
  - $t_h^{AC} = \frac{D_h}{R_h^{AC}}$ [s]

- *Segment − head Heliostats*:
  - $energy_{transmission} = P_{transmission} * t_h^{BH}$ [J]
  - $t_h^{BH} = \frac{D_{h+\sum_{\forall h'} D_{h'}}}{R_h^{BH}}$ [s]



HELIOCON Baseline Topology: Energy Availability

Simulation Overview

- timestamp after every 5 mins

  $energy_{harvested} = energy[timestamp]$

  $energy_{consumed} = [0, \dots, 0]$

- if DNI[timestamp] = 0

  mode = 'STANDBY', $energy_{consumed} \mathrel{+}= energy_{standby}$

- else

  mode = 'ACTIVE'

  - if DNI[timestamp] >= 500

    event = 'CLA', optimization_CLA(event)

    $energy_{consumed} \mathrel{+}= energy^{CLA}_{transmission} + energy_{active}$

  event = 'NCLA', optimization_NCLA(event)

  $energy_{consumed} \mathrel{+}= energy^{NCLA}_{transmission} + energy_{active}$

- $battery_{status} = battery_{status} + energy_{harvested} - energy_{consumed}$

- The net energy is the difference between energy harvested and energy consumed.
- If there is positive net energy and the battery status is not $battery_{max}$, the surplus energy harvested is added to the battery to have status set to $battery_{max}$.
- If there is negative net energy, we subtract the net energy from the battery status.

HELIOCON Baseline Topology: Clustering

- In order to initiate the RL-based cluster formation subsequent to the segmentation, each heliostat utilizes the distance and channel gain values with other heliostats in the same segment. Each heliostat h (agent) determines the following to select another heliostat h':

$$DG(h,h') = w_1 D(h,h') + w_2 \frac{1}{G(h,h')}$$

where, $D(h,h') = -\log_2\left(d(h,h')\right)$ and $G(h,h') = -\log_2\left(g(h,h')\right)$.

- In each iteration of the RL algorithm, the agent h selects an action a_h^{ite} from its set of actions A_h and subsequently update the Q-value of the selected action to $Q_h(a_h^{ite})$. The Q-value update rule is as follows:

$$Q_h\left(a_h^{ite}\right) = Q_h\left(a_h^{ite}\right) + \alpha * \left(R_h^{ite} - Q_h\left(a_h^{ite}\right)\right)$$

where, R_h^{ite} denotes the reward assigned to the agent for the chosen action.

HELIOCON Baseline Topology: Clustering

- To compute the reward, the silhouette analysis is performed. For each heliostat h in a cluster c, the average similarity with all the other heliostats in the same cluster is calculated as $p_h = \frac{\sum_{\forall h' \in c} DG(h,h')}{|c|-1}$.
- For all other clusters c' within the same segment, the average similarity with all the other heliostats is computed as $q_h = \min\left\{\frac{\sum_{\forall h' \in c'} DG(h,h')}{|c'|}\right\}$.
- The silhouette value of h is then determined as follows:

$$S_h = \frac{p_h - q_h}{\max\{p_h, q_h\}}$$

- If $S_h > 0$ it indicates that heliostat h is appropriately clustered. If $S_h < 0$, it suggests that heliostat h might be more suitably placed in a different cluster within the same segment. When $S_h = 0$ it means the heliostat is positioned between two neighboring clusters.
- The reward R_h^{ite} is calculated based on the silhouette analysis as $R_h^{ite}(a_h^{ite}) = S_h$. To achieve a balance between exploration and exploitation, the ε-greedy strategy is employed with a decay scheme.

$$\epsilon = d^{ite}, \quad d = \sqrt[\tau]{\frac{\epsilon_f}{\epsilon_0}}$$

HELIOCON Baseline Topology: Clustering

- To have more uniform clusters, another RL algorithm has been used which considers the expected reward (first term) and the uncertainty related to the reward (second term). Based on these considerations, the action selection criteria is updated as follows:

$$a_h^{ite} = \underset{a_h^{ite}}{\arg\max}\left[Q_h + c_0\sqrt{\frac{\ln(ite)}{N_{a_h}^{ite}}}\right]$$

where, Q_h is the expected reward, $c_0 \in \mathbb{R}$ is the confidence level, ite is the number of iterations, and $N_{a_h}^{ite}$ is the number of times the action a_h^{ite} has been chosen prior to ite.

- Since, the exploration-exploitation trade-off now stems from the action selection criteria, the ε-greedy strategy has been discarded.

- The remaining sections of the clustering algorithm are similar to the Q-learning inspired RL algorithm where an each heliostat chooses another heliostat to form a cluster with, determines the reward through the silhouette analysis, updates the Q-value and determines the action for the next iteration.

HELIOCON Baseline Topology: Cluster-heads

- A cluster c with heliostats denoted by $\mathcal{H}_c$ is considered.
- Cluster-head selection process is initiated with the calculation of weights w_{h_c} of each heliostat h_c with other heliostats h'_c in the same cluster.

$D(h_c, h'_c) = -\log_2\big(d(h_c, h'_c)\big)$, where $d(h_c, h'_c)$ is the actual distance between h_c and h'_c

$G(h_c, h'_c) = -\log_2(g(h_c, h'_c))$, where $g(h_c, h'_c)$ is the actual channel gain between h_c and h'_c

$DG(h_c, h'_c) = w_D D(h_c, h'_c) + w_G \frac{1}{G(h_c, h'_c)}$, where w_D, w_G are the weights for the distance and channel gain dependent terms respectively

$$w_{h_c}(h_c, h'_c) = DG(h_c, h'_c), \forall h'_c \in \mathcal{H}_c, h_c \neq h'_c$$

- Towards selecting the cluster-head ch_c of cluster c, the concept of closeness centrality CC is utilized.

$$CC(h_c) = \sum_{\substack{\forall h'_c \in \mathcal{H}_c \\ h_c \neq h'_c}} \left[\frac{w_{h_c}(h_c, h'_c)}{|\mathcal{H}_c| - 1}\right]$$

- The score of heliostat h_c as a function of closeness centrality CC and energy availability E in the cluster c is defined as follows:

$score(h_c) = w_{CC} CC(h_c) + w_E \frac{E(h_c)}{E_c^{max}}$, where w_{CC}, w_E are the weights for the CC and E values respectively

Power Sensitivity Analysis

- Simulation for a timeframe of **1 week**. Analysis of the minimum received power for CLA and NCLA operations each day.