AdaOrb: Adapting In-Orbit Analytics Models for Location-aware Earth Observation Tasks

Zhouyu Li, ***North Carolina State University***

Zhouyu Li, Pinxiang Wang, Xiaochun Liang, Xuanhao Luo,

Yuchen Liu, Xiaojian Wang, Huayue Gu, Ruozhou Yu

North Carolina State University

Outlines

Background and Motivation

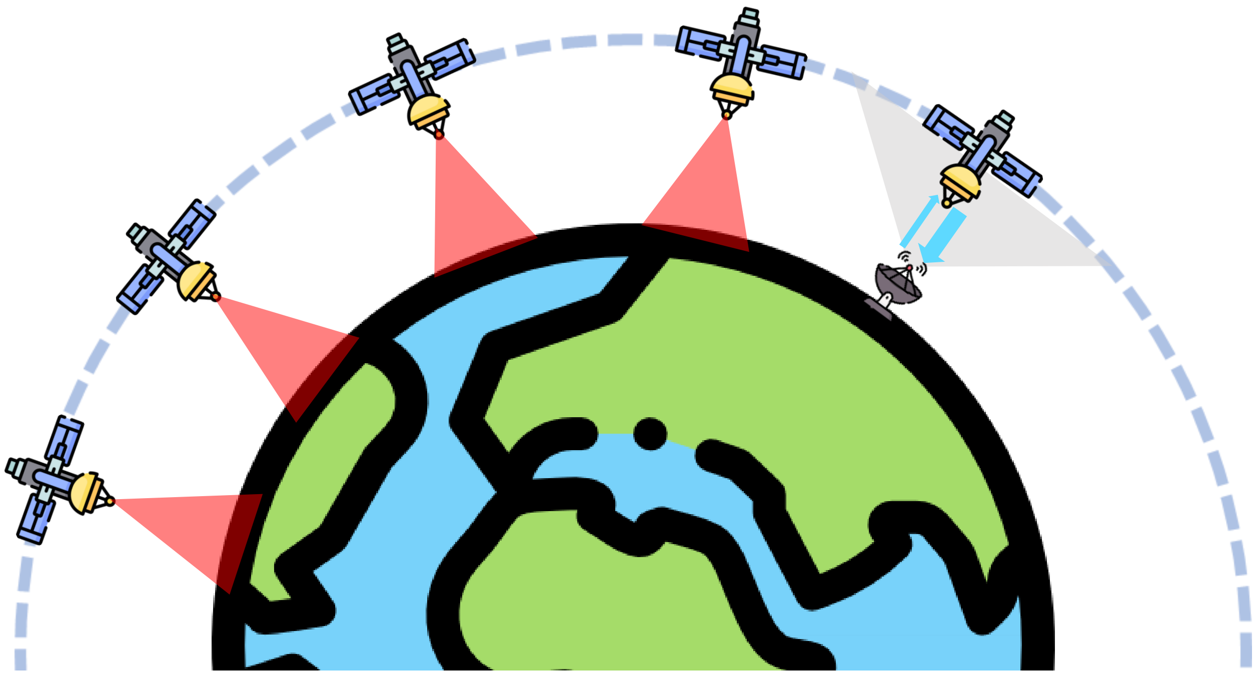
AdaOrb Framework

Performance Evaluation

Conclusions, Future Work

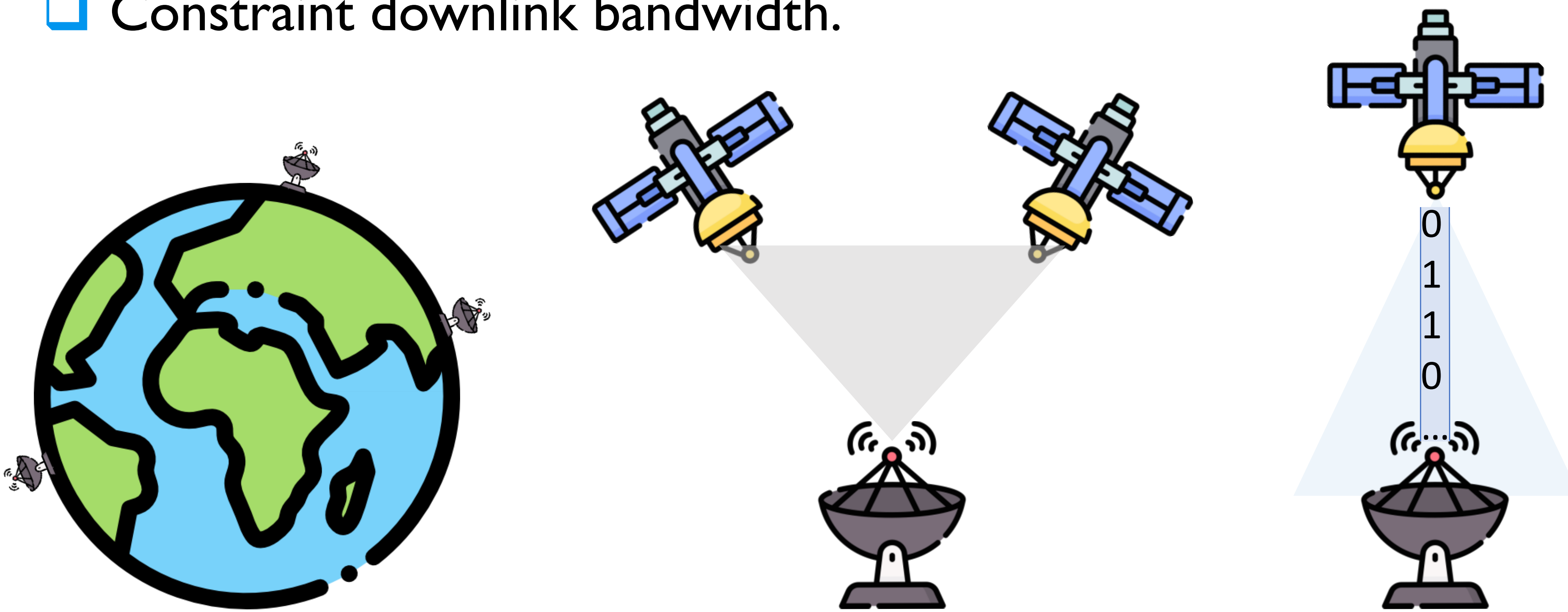
Background
Limitation of Traditional Earth Observation Workflow

- Satellites continuously take images of their ground tracks.
- When a satellite move into the coverage of a ground station, download images for further analysis.



Background
Limitation of Traditional Earth Observation Workflow

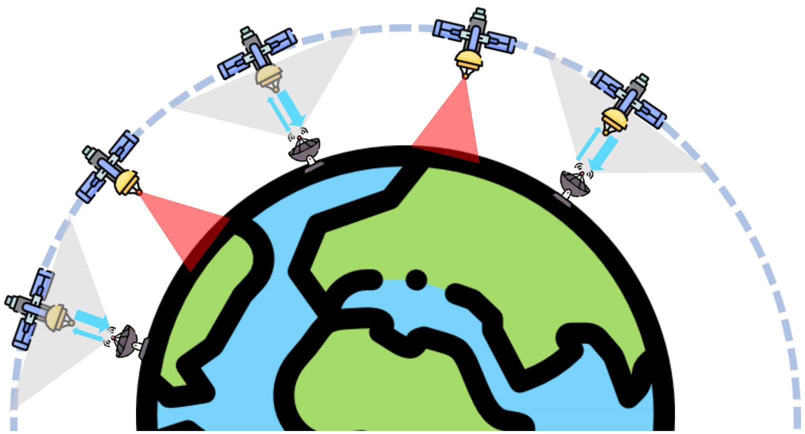
- Limited number of ground stations.
- Short ground-satellite connection duration.
- Constraint downlink bandwidth.

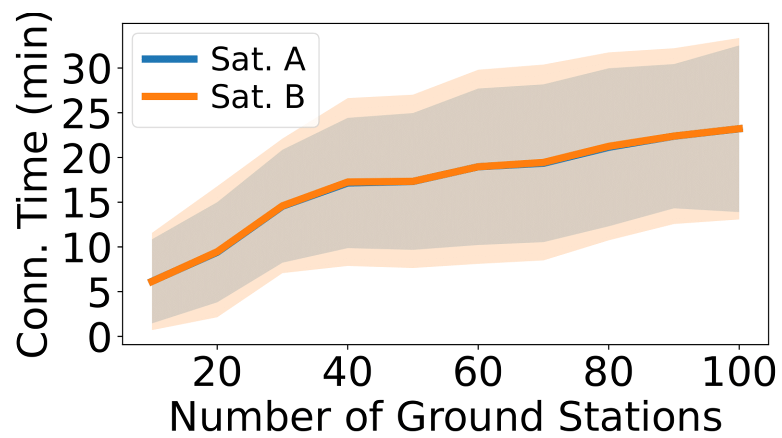


Cannot download all the captured images from satellite.

Background
Limitation of Traditional Earth Observation Workflow

- Will build more ground stations solve the problem?
- Incrementally add ground stations and simulate the ground-satellite connection with two satellites in the Sentinel-2 constellation.
- Record per-revolution connection time v.s. ground station number.



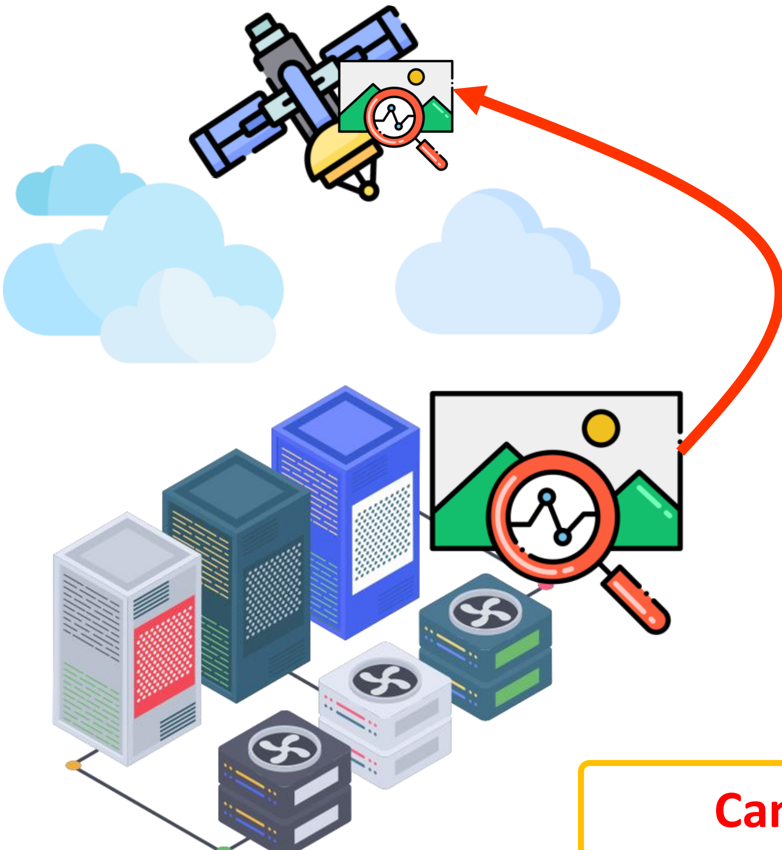


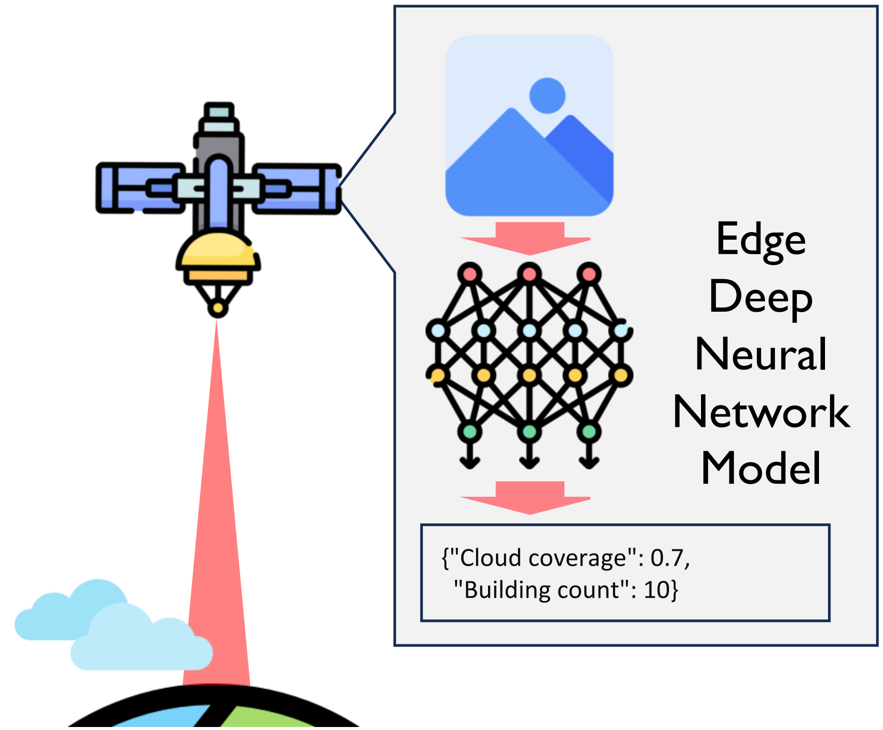
The benefit of building more ground stations decreases.

Simply building more ground stations cannot effectively solve the problem.

Background
Orbital Edge Computing

- Orbital edge computing [1] : put part/full analysis from ground datacenter to satellites in the orbit.



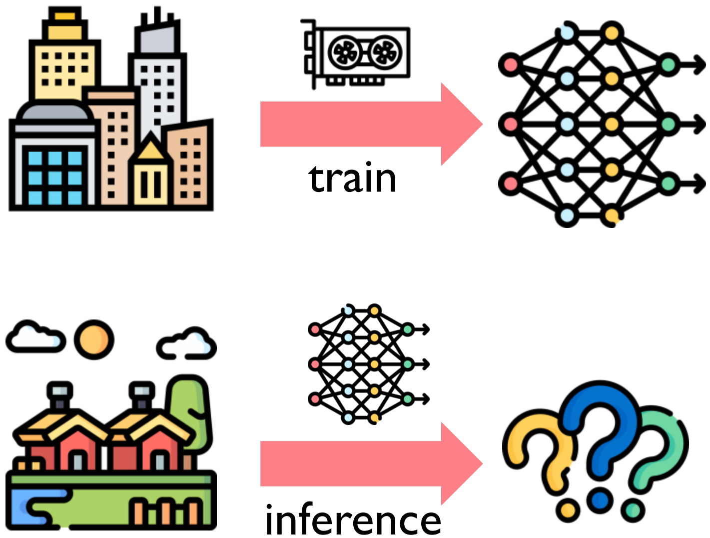


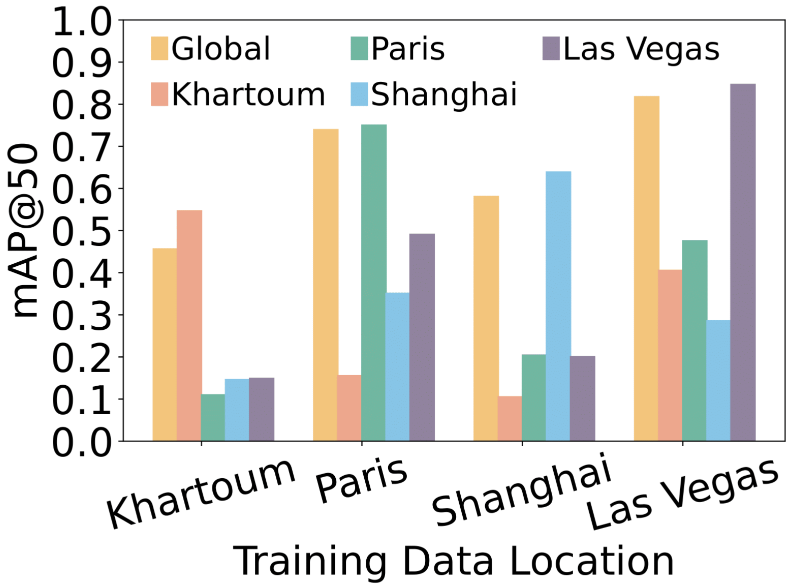
Can we trust the in-orbit analytics results?

[1] B. Denby and B. Lucia, “Orbital Edge Computing: Nanosatellite Constellations as a New Class of Computer System,” ASPLOS 2020

Background - Data distribution shift

- Data distribution shift [2] among different locations that impacts in-orbit model performance.
- Applying models trained on one location to other locations downgrades its performance.





Observation: Location-specific model always has the best performance

[2] E. Rolf, K. Klemmer, C. Robinson, and H. Kerner, "Mission Critical -- Satellite Data is a Distinct Modality in Machine Learning," Feb. 02, 2024, arXiv: arXiv:2402.01444.

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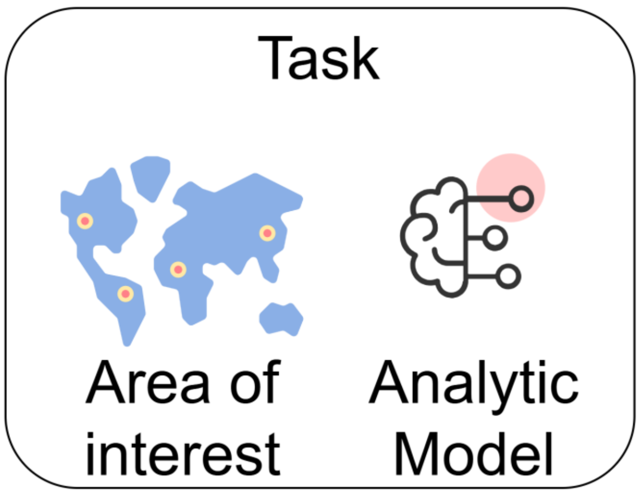
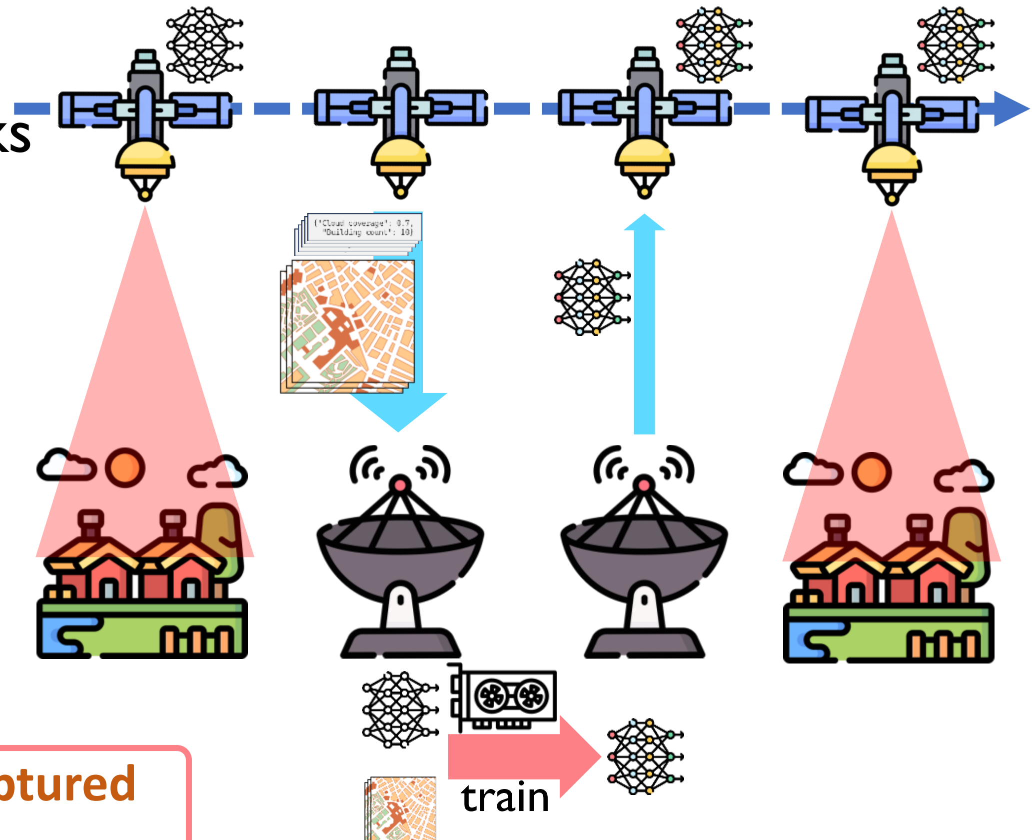
AdaOrb Framework

- **AdaOrb**:Adapt Orbital models to location-specific analytics tasks with scheduled runtime retraining.
- Task: Location + Model
- A satellite hosts many tasks

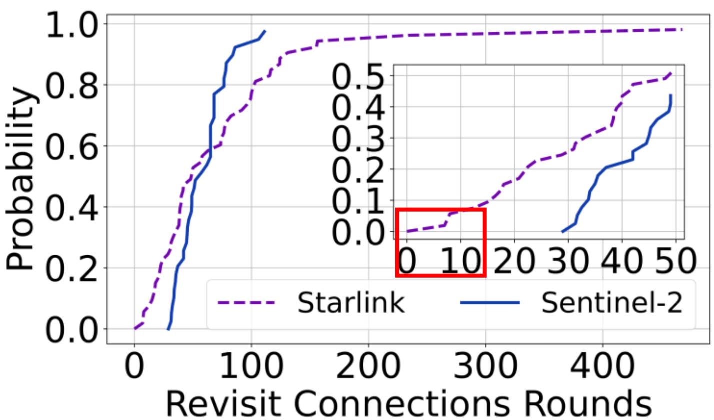


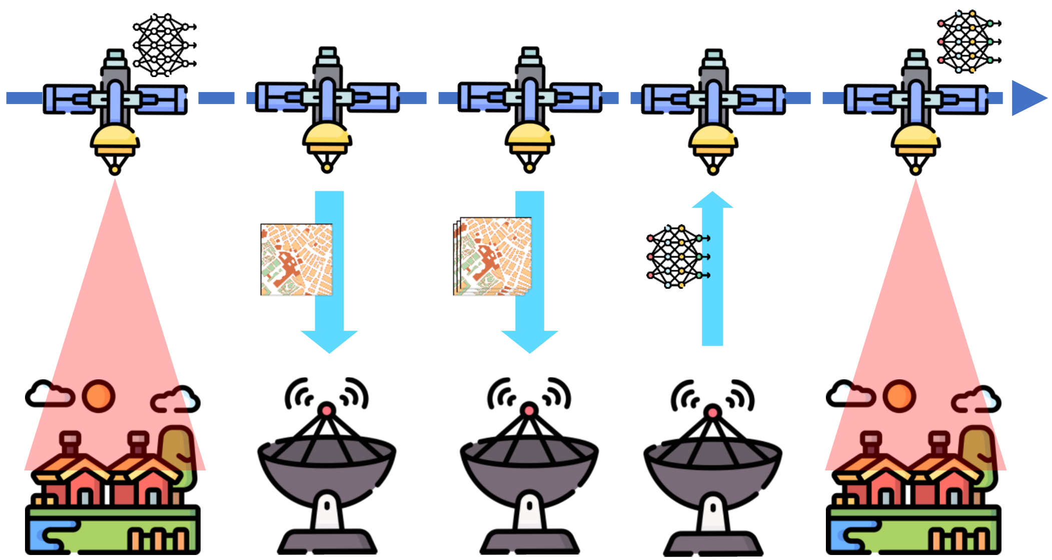


Do we need to download captured data right away?

AdaOrb Framework

- Observation: satellite usually revisit the same place after multiple rounds of ground-satellite connections.
- Allocate downlink channel in each connection for high in-orbit inference accuracy over all the onboard tasks.

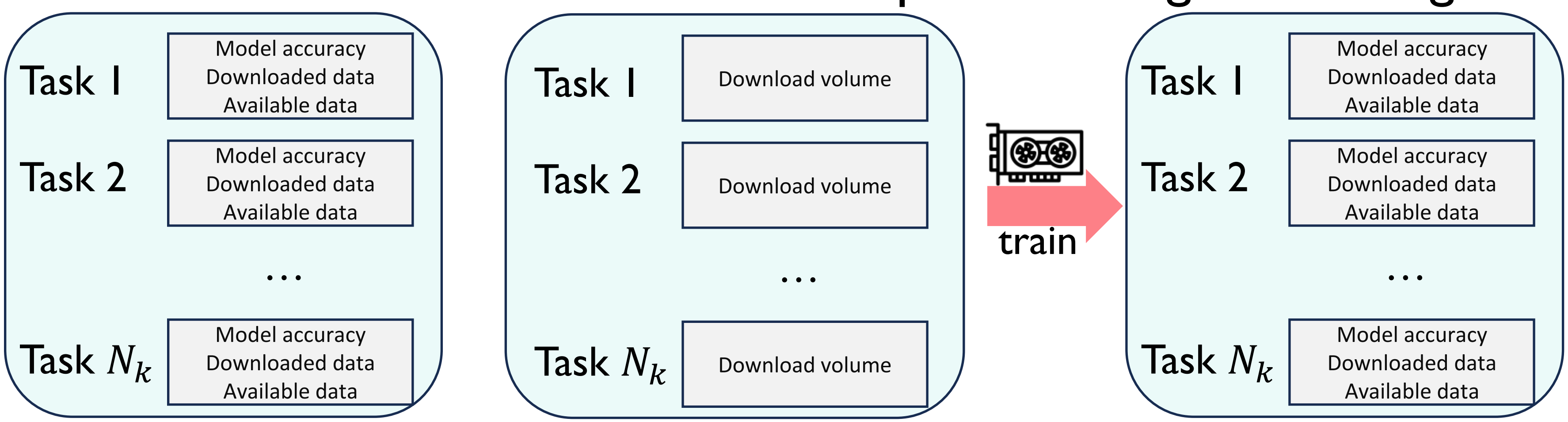




How to schedule downlink channel for model adaption among onboard tasks?

AdaOrb Framework
Represent as Markov Process

- Represent the downlink channel scheduling problem as a Markov process.
- State: model accuracies, num downloaded images, num taken images.
- Action: decide number of images to download for each task.
- State transition: model accuracies update through retraining.

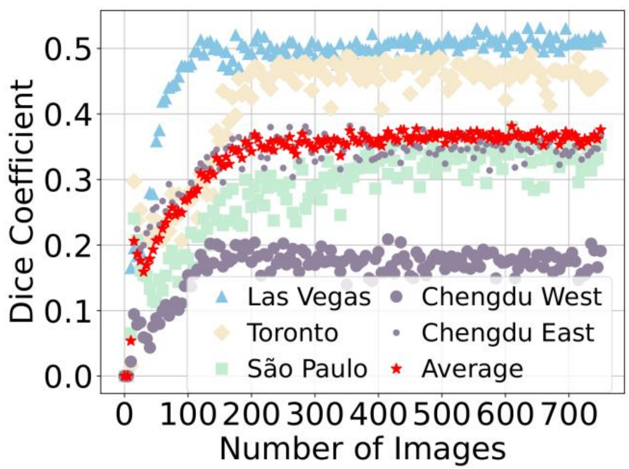


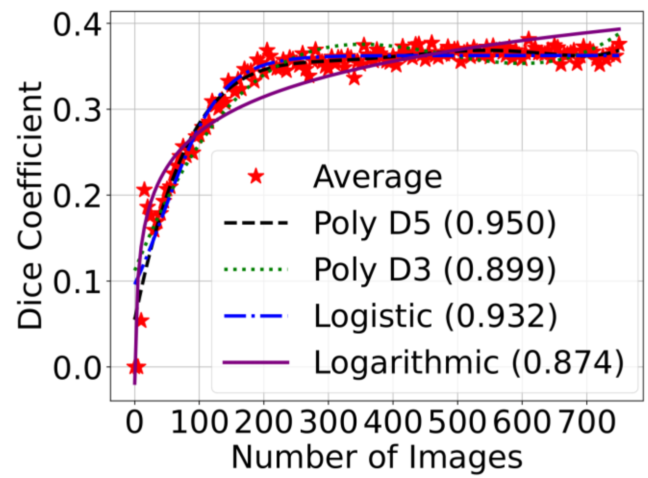
State at the j^{th} connection   Action at the j^{th} connection   State at the $j+1^{th}$ connection

Challenge: how to model the accracy update (state transition)?

AdaOrb Framework
Profiling the state transition

- Profiling: profile 5 locations to get the relationship between model accuracy and number of downloaded images used for retraining.
- Observation: though training curves of different models are different, the accuracy growing patterns (trend) are similar.
- Fitting: fit with a close-form function.





$$\tilde{acc}_j^i = \tilde{\mathcal{F}}\left(d_j^i\right), \forall j \geq 1, k_i \in \mathbf{K}$$

AdaOrb Framework
Solve with Model Predictive Control (MPC)

- Model Predictive Control algorithm for downlink channel allocation.
  - A state transition formula + Not much time for bootstrap.
- State: model accuracy, num. downloaded volume, num. in orbit.

$$\chi_j = \left\{ \left(acc_j^i, d_j^i, v_j^i\right) \middle| i = 1, 2, \ldots, N_K \right\}, \forall t_j \in \mathbf{T}.$$

- State transition: profiled function $\tilde{acc}_j^i = \tilde{\mathcal{F}}\left(d_j^i\right), \forall j \geq 1, k_i \in \mathbf{K}$
- Control inputs: number of images to download for each task at each connection.

$$\boldsymbol{\Delta}_j = \{\delta_j^i | i = 1, 2, \ldots, N_K\}$$

- Cost: Image quantity to inference × (1 − model accuracy)

$$J\left(\boldsymbol{\Delta}\right) = \sum_{i=1}^{N_K} \sum_{j'=j}^{j+N_H} \nu_{j'}^i (1 - acc_{j'}^i).$$

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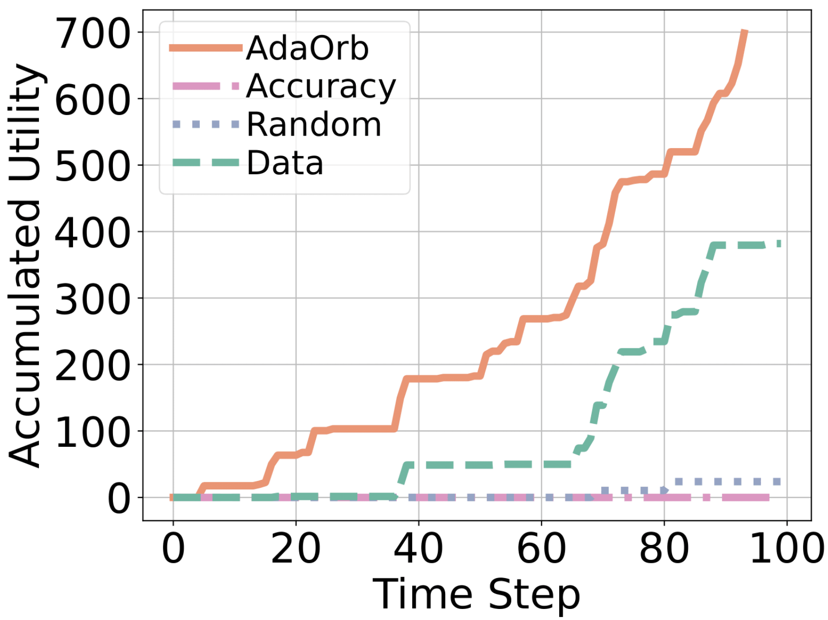
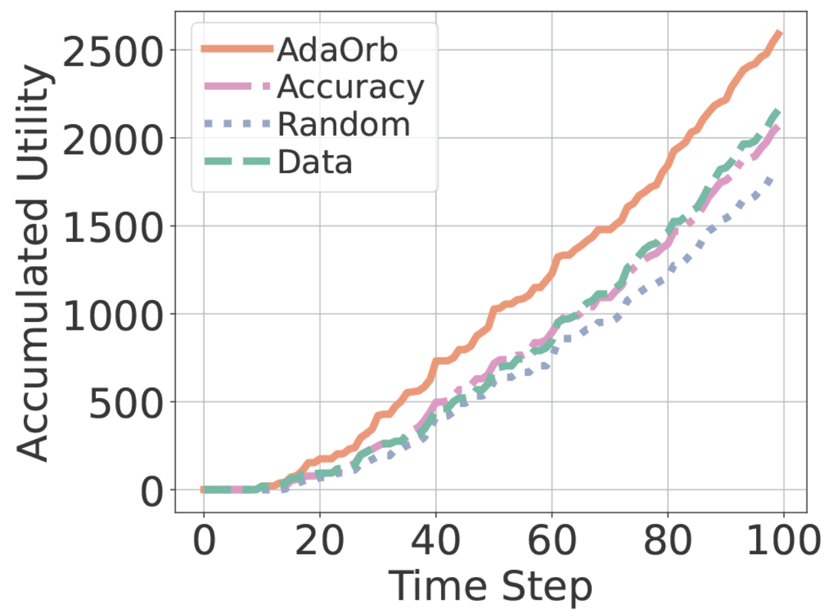
Performance Evaluation
Utility over time

- Utility: the sum of accuracy of all in-orbit predictions.
- Random: randomly splits the downlink channel among all onboard tasks.
- Accuracy: download more images to retrain model with worse accuracy.
- Data: download images to retrain models about to be used.



Sentinel

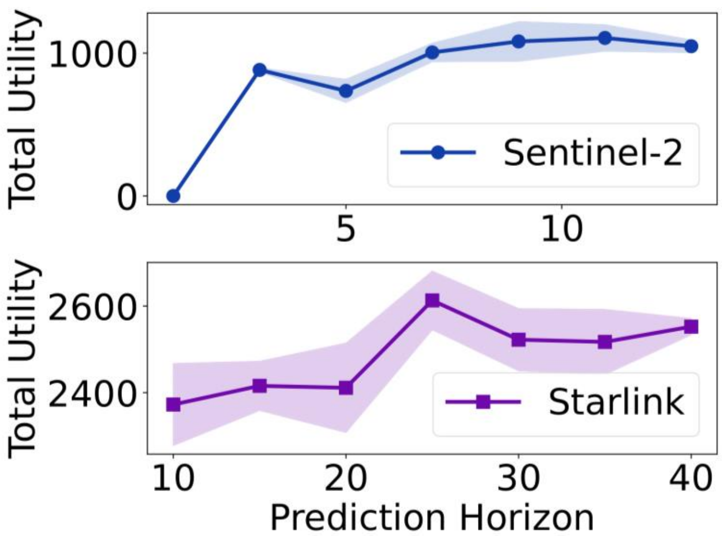


Starlink

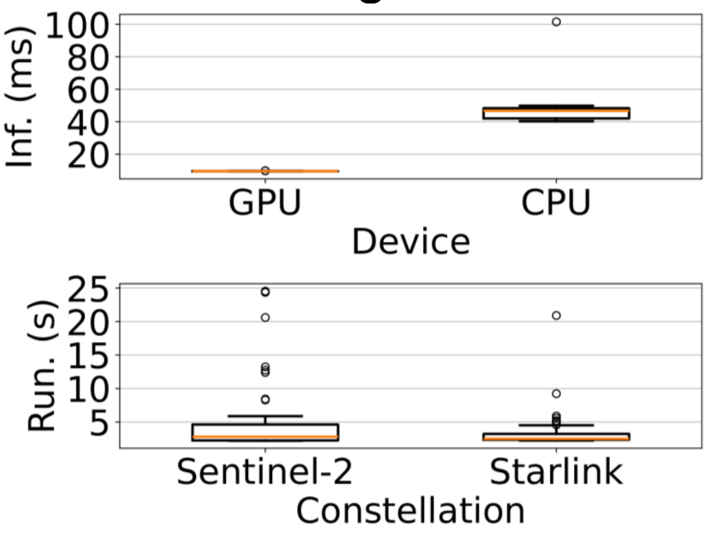
AdaOrb's MPC-based algorithm achieves higher overall utility than the baselines.

Performance Evaluation
Prediction Horizon and Algorithm Efficiency

- How to select MPC prediction horizon:
  - Sentinel and Starlink satellite updates their onboard tasks every 5 and 20 time steps, respectively.
  - Select a prediction horizon marginally longer than the update interval.
- Model and algorithm efficiency
  - AdaOrb uses reasonable edge models and efficient algorithms.



Prediction horizon v.s. utility



Model and algorithm efficiency

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Conclusions, Future work

- AdaOrb
  - Adapt in-orbit analytics models
    to solve
    Location-wise data distribution shift

    } Allocate downlink channel with MPC algorithm

- Future research problems
  - Select data to download for most efficient model training - Active learning
  - Deal with unstable satellite-ground connection
    - Various wheather condition.
    - Cloud blockage.
    - …

    } Download priority
  - Multiple satellite sharing the downlink channel. – Expanded problem size

Thank you very much!

Q&A?