MULTI-PATH TRANSMISSION OF REAL-TIME REMOTE SENSING DATA VIA HETEROGENEOUS LEO INTER-SATELLITE-LINKS

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In This Talk …

- **Fundamentals of remote sensing systems**
- Mega LEO constellation with inter-satellite-links (ISLs)
- Multi-path transmission of remote sensing data via ISLs
- Conclusions

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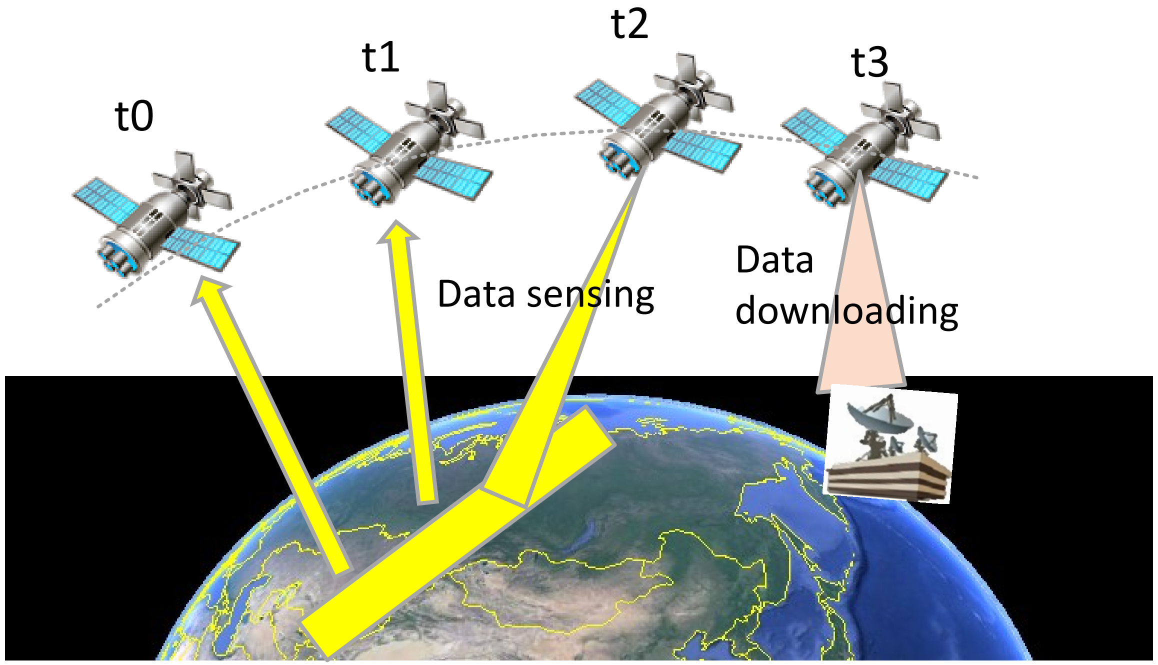
Fundamentals of remote sensing systems

- Basic functions of remote sensing satellites:
  - **observe** Earth surface from orbit
  - **transmit** the sensed data to the ground

It often takes hours or even days for ground stations to receive the remote sensing data.



The workflow of remote sensing systems

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Fundamentals of remote sensing systems

- **Emerging time-critical applications**: Real-time transmission of remote sensing data is crucial for many important time-critical applications, particularly in scenarios like forest fire detection and emergency rescue in remote areas.

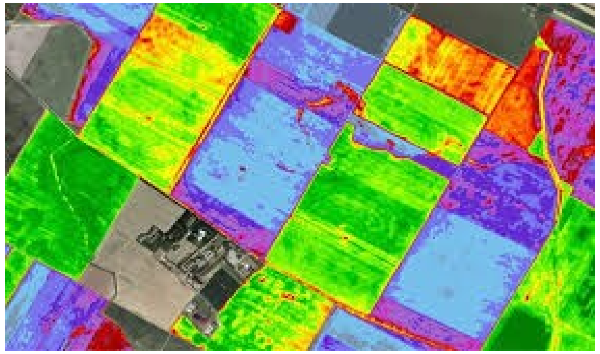
Forest Fire Detection

Landslide Monitoring

Oil Spill Surveillance

Hurricane Surveillance

Earthquake Monitoring



Agricultural Management

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Fundamentals of remote sensing systems

According to the open UCS satellite database, there are **1200+** operational remote sensing satellites in orbit by Aug. 2024.

- **Advancements in Spatial Resolution.** With the enhancement of remote sensing capability, ranging from optical radar (radio detection and ranging), LiDAR (Laser Imaging Detection and Ranging), to multi- spectral/hyper-spectral imaging, remote sensing systems have boosted **spatial resolution from tens of meters to decimeters**.

- **Challenges in Data Transmission:** The increasing volume of sensed data and the demand for high-resolution imaging pose significant challenges in timely transmitting this data from space to the ground. For example,
  - The ESA Sentinel missions acquire ≈12 TB of images per day.
  - NASA missions collectively provide 20-30 TB per day.

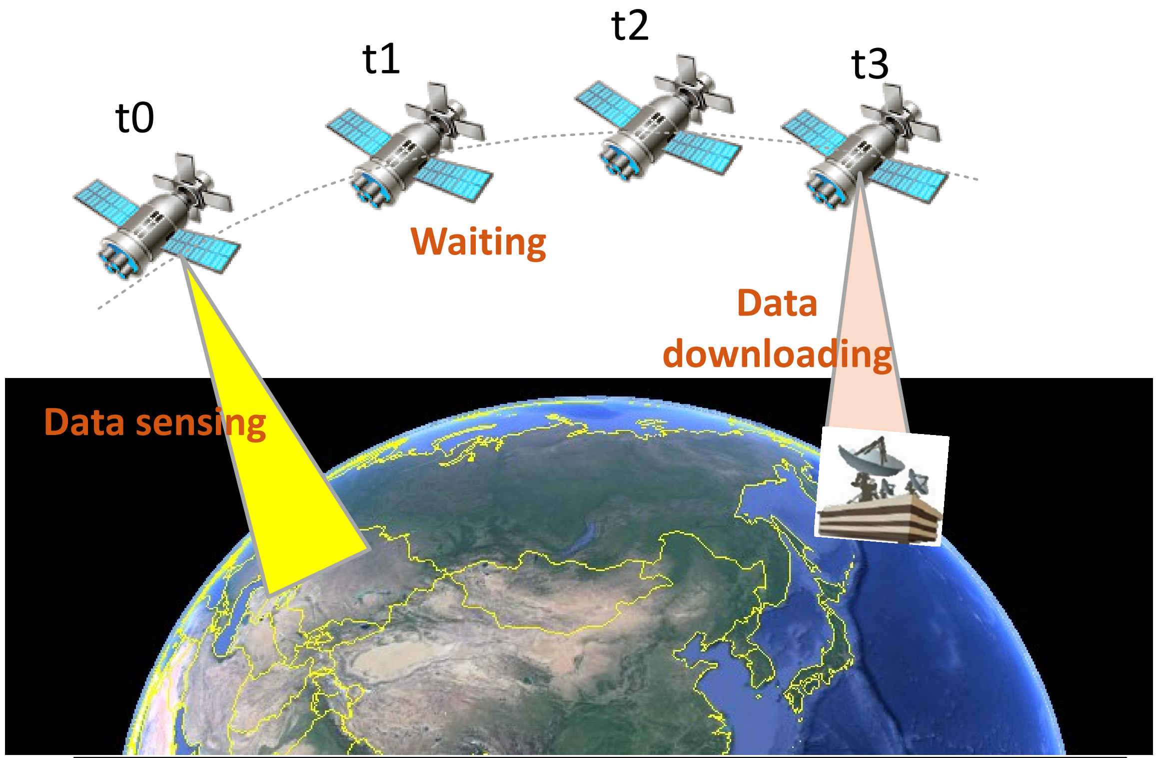
Landsat (15m) | Sentinel-2 (10m) | Blackbridge RapidEye (5m) | Airbus Pleiades (0.5m) | DigitalGlobe WV3 (0.31m)

The higher the spatial resolution, the larger the data volume.

[1] Union of Concern Scientists. UCS Satellite Database. https://www.ucsusa.org/resources/satellite-database.

Fundamentals of remote sensing systems

- What are the key bottlenecks of existing remote sensing systems?
    - **Traditional store-wait-download approach:** Data from today's operational remote sensing satellites must wait in orbit for long periods until satellites pass over ground stations for downloading.
    - **Lack of ground stations**. Current remote sensing satellites are limited to direct communication with ground stations. However, **the total contact period every day between a LEO satellite and any given ground station can be as short as around 1 hour**. Deploying more ground stations at more regions is costly and also faces many restrictions (e.g., legal, environmental).
    - **Scarce spectrum resources v. s .massive data volume**. Given the scarce spectrum (L, S, C, Ku, K, and Ka bands are saturated), supporting the ever-growing remote sensing data volume is challenging.



Data sensed during t0 to t2, have to wait in orbit until t3 (i.e., remote sensing satellite moves over the ground station) , significantly limiting the applicability of remote sensing systems in many time-sensitive scenarios.

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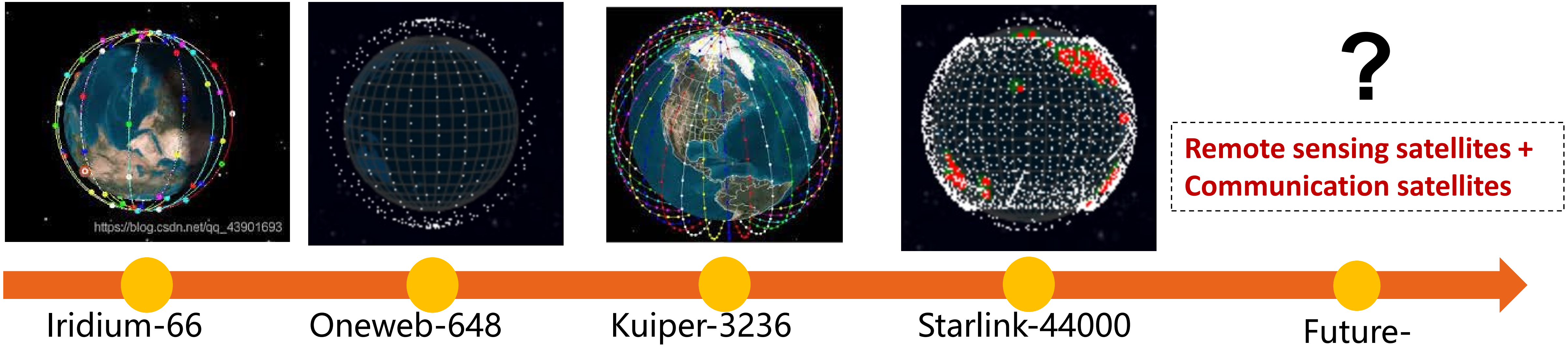
Mega LEO satellite constellation with inter-satellite-links

- **Motivation:** In recent years, commercial enterprises such as SpaceX and Oneweb are building up mega-constellations with thousands of low earth orbit (LEO) satellites to provide global coverage at low-latency and high bandwidth.

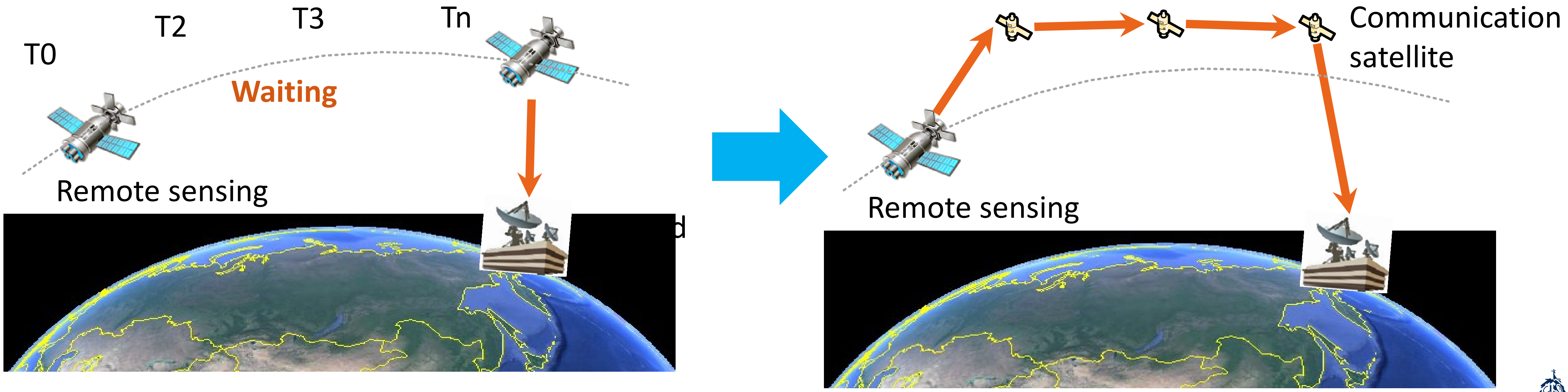


- **One question:** Is it possible/beneficial to transmit remote sensing data through mega LEO satellite constellation with inter-satellite links (ISLs)?

[1] https://satellitemap.space/?constellation=starlink
[2] https://www.ucsusa.org/resources/satellite-database

Mega LEO satellite constellation with inter-satellite-links

- **Our research direction: Remote sensing satellites + Communication satellites**.
- **Advantages**:
  - (a) **Low Latency Communications without long time waiting**. “Store-waiting-download” --> Transmit via inter-satellite links.
  - (b) Enhanced reliability and spectrum efficiency by **combining RF and FSO**.
  - (c) Higher throughput by **multi-path transmission**.



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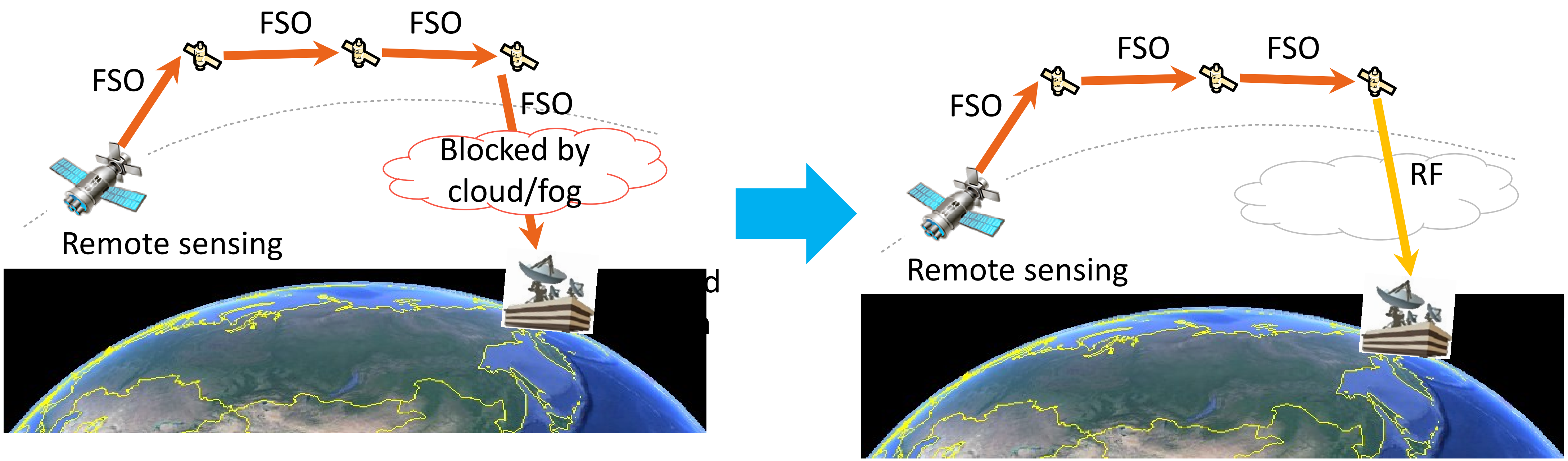

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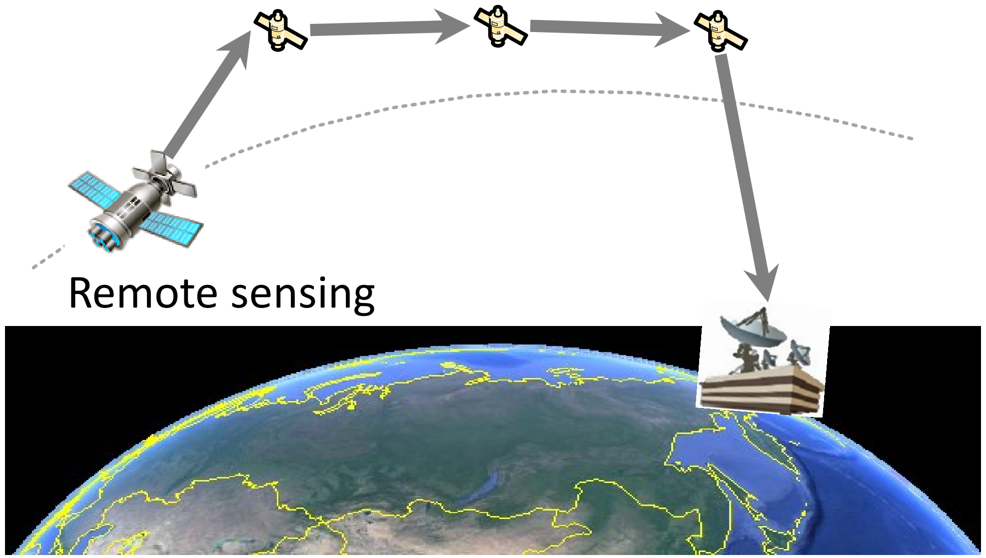
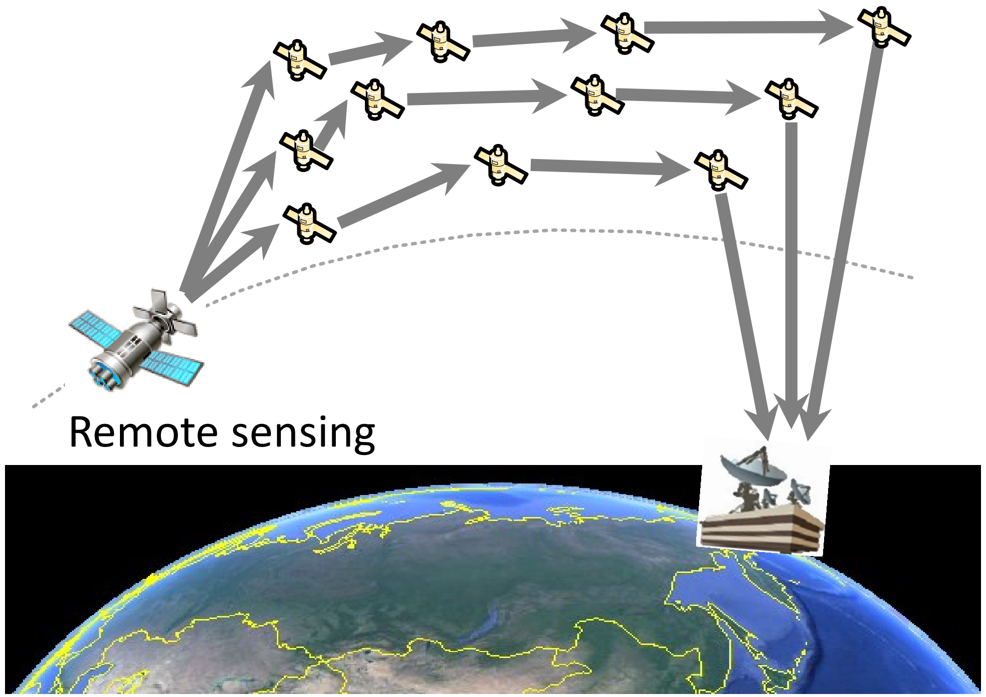
Shortest single-path transmission



Multi-path transmission



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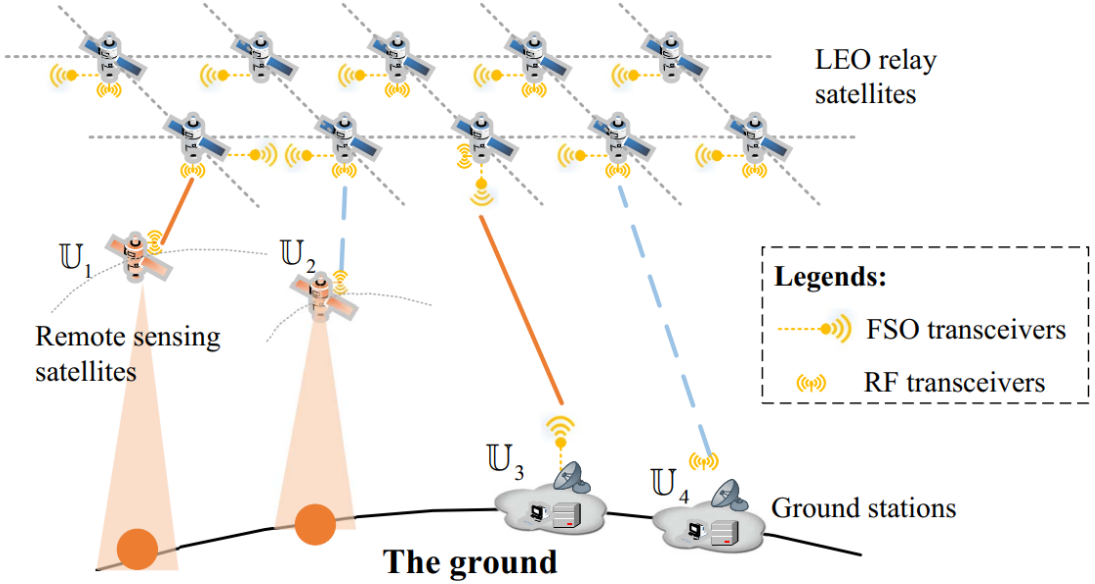
  - (c) Higher throughput by **multi-path transmission**.
- **The research gap**:
  - How to handle LEO satellite network dynamics?
  - How to design routing algorithm?
  - How to schedule heterogeneous transceivers?
  - How to achieve multi-path transmission for higher throughput?

Multi-path transmission of remote sensing data via ISLs

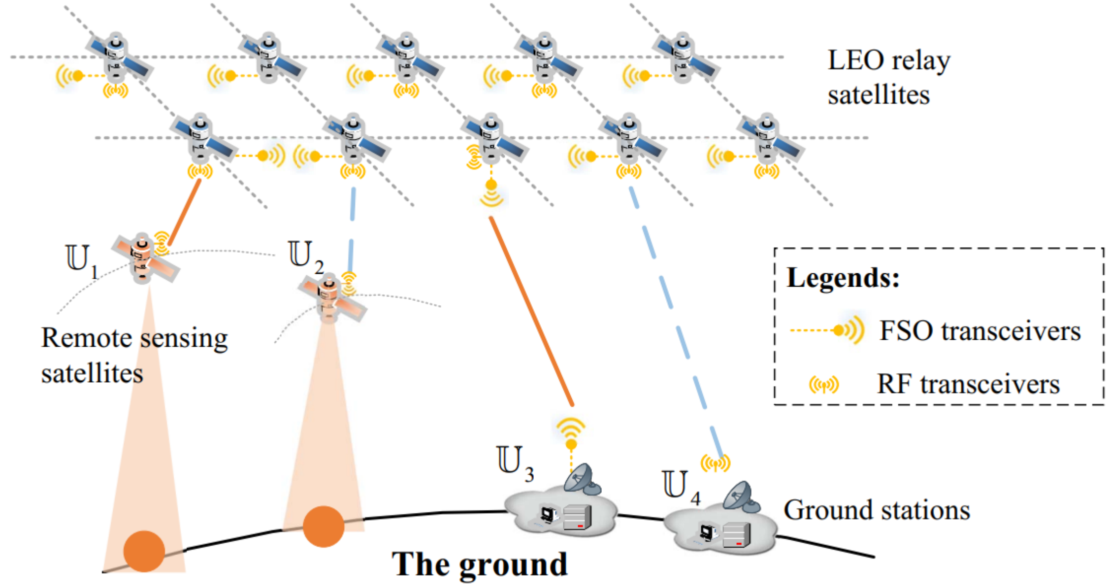
- **System model:**
  - **Satellite network model**: We consider a satellite network of relay satellites, remote sensing satellites and ground stations. Each satellite or UE has heterogeneous transceivers (e.g., RF and FSO) for mixed-mode data transmission.
  - **Real-time remote sensing application model**: A = {Us, Ud} requires data transmission from a source Us to a destination Ud, with the aim of maximizing throughput (Unit: Mbps).



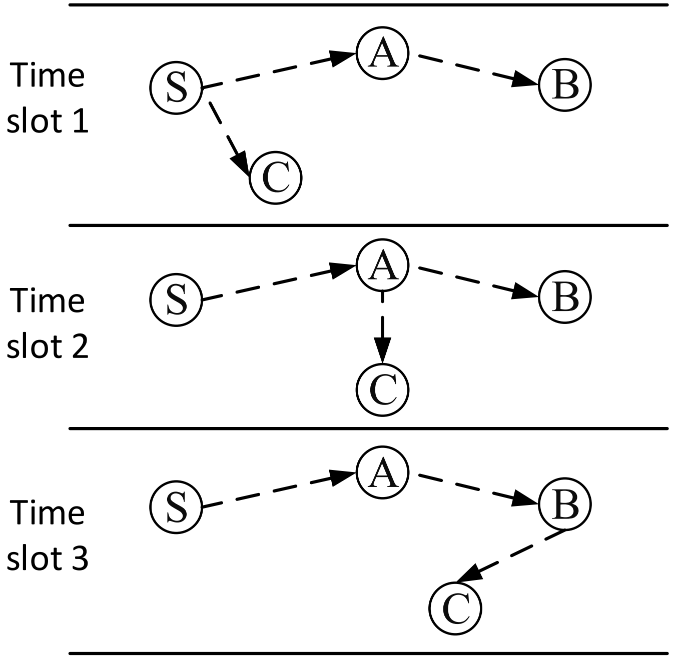
The scenario of satellite networks with heterogeneous LEO ISLs.

Multi-path transmission of remote sensing data via ISLs

- How to model time-varying satellite networks?



Time discretization



Snapshot graphs

The time horizon $T = [0, T]$ is partitioned into time windows of varying durations. Each time window is denoted by $\tau = [t_s, t_e]$.

[1] Binquan Guo, Zheng Chang, Zhu Han, Zehui Xiong, Enhanced Time Discretization for Temporal Graph-Based Continuous Service Provisioning in Large-Scale Satellite Networks, In IEEE Wireless Communications Letters 2024.

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Multi-path transmission of remote sensing data via ISLs

- Model the multi-path heterogeneous-transceiver transmission problem as Linear Programming (LP) problem

Variables: $x^{\tau}_{\mathbb{O}_i,\mathbb{O}_j} \geq 0$ The achievable data rate through the link (O_i, O_j) during time interval τ.

Objective: Maximize the data rate from remote sensing satellite to ground station during time interval τ.

$$\mathbf{P1}: \max\ R^{\tau} = \sum_{\mathbb{O}_k \in \mathcal{V}^{\tau} - \{\mathbb{O}_s\}} x^{\tau}_{\mathbb{U}_s,\mathbb{O}_k} = \sum_{\mathbb{O}_k \in \mathcal{V}^{\tau} - \{\mathbb{U}_d\}} x^{\tau}_{\mathbb{O}_k,\mathbb{U}_d},$$
$$\text{s.t. } (1) - (3), (5),$$
$$x^{\tau}_{\mathbb{O}_i,\mathbb{O}_j} \geq 0.$$

$$x^{\tau}_{\mathbb{O}_i,\mathbb{O}_j} \leq \max\{r^{\tau}_{\mathbb{O}^{f_l}_i,\mathbb{O}_j} | w^{f_l}_{\mathbb{O}_i} = w^{f_l}_{\mathbb{O}_j} = 1, f_l \in \mathcal{F}\}. \quad (1)$$

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$$\sum_{\mathbb{O}_k:(\mathbb{O}_k,\mathbb{O}_\xi)\in\mathcal{L}^{\tau}} x^{\tau}_{\mathbb{O}_k,\mathbb{O}_\xi} = \sum_{\mathbb{O}_k:(\mathbb{O}_\xi,\mathbb{O}_k)\in\mathcal{L}^{\tau}} x^{\tau}_{\mathbb{O}_\xi,\mathbb{O}_k}. \quad (3)$$

$$\exists w^{f_l}_{\mathbb{O}_i} = w^{f_l}_{\mathbb{O}_j} = 1, f_l \in \mathcal{F}, \text{ if } x^{\tau}_{\mathbb{O}_i,\mathbb{O}_j} > 0. \quad (4)$$

Linearize:

$$x^{\tau}_{\mathbb{O}_i,\mathbb{O}_j} \leq M \cdot \sum_{f_l \in \mathcal{F}} w^{f_l}_{\mathbb{O}_i} \cdot w^{f_l}_{\mathbb{O}_j}, (\mathbb{O}_i, \mathbb{O}_j) \in \mathcal{L}^{\tau}, \quad (5)$$

Observation:

- P1 is an LP problem solvable with tools like CVXPY in polynomial time O(|Lτ|^3.5). |Lτ| is the number of links.
- However, this complexity is still high for real-time decision-making in large-scale networks, where computation can take from minutes to days.

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Multi-path transmission of remote sensing data via ISLs

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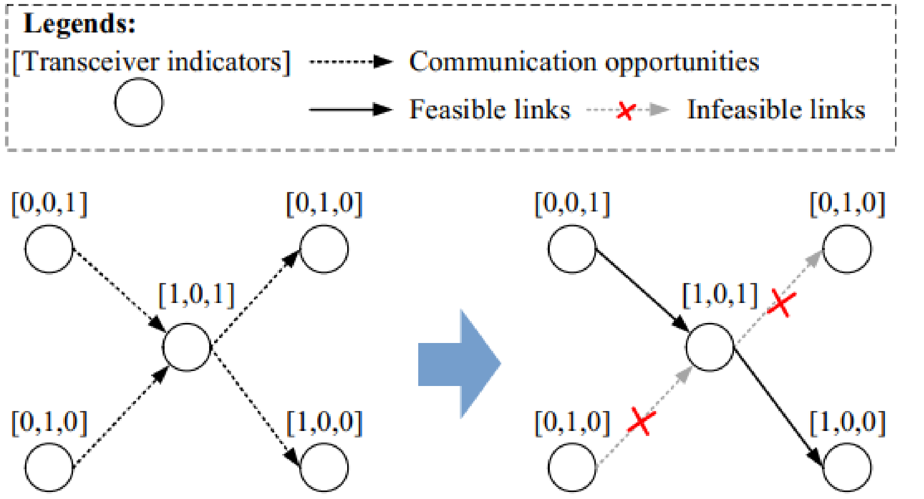
Using standard mathematical optimization method to solve LP problem can be time-consuming when network size is large

Multi-path transmission of remote sensing data via ISLs

- **The proposed graph-based method**
  - Remove redundant links based on transceiver indicators
  - Transform the LP into standard max-flow problem

Transform the LP into standard max-flow problem

Original snapshot graphs



(a) Original snapshot graph with heterogenous transceivers on nodes

(b) Modified snapshot graph with only feasible transmission links

Modified snapshot graphs

Multi-path transmission of remote sensing data via ISLs

- **The proposed graph-based method v. s. the LP-based method**
  - Both methods are polynomial and optimal.
  - The proposed graph-based method is more faster than the LP-based method.

Methods	**Time complexity**	**Optimality**
The LP-based method	$O(\|L\tau\|^{3.5})$	Polynomial and optimal
The proposed graph-based method	$O((\|V\tau\|^2 + \|F\|)\|L\tau\|)$	Polynomial and optimal

- *$|L\tau|$ is the number of links.*
- *$|V\tau|$ is the number of nodes.*
- *$|F|$ is the number of transceiver types.*

Multi-path transmission of remote sensing data via ISLs

- **Simulation Setup**

A. Scenarios

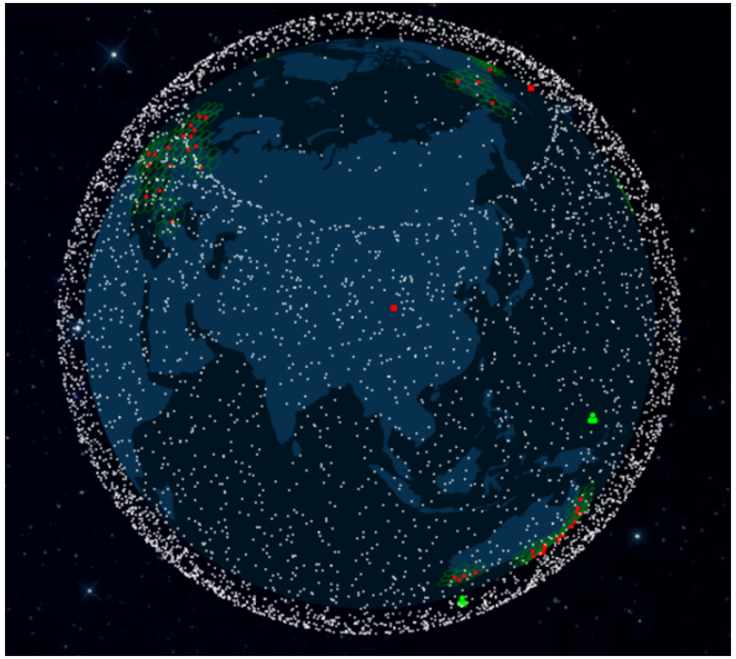
We use 6 Gaofen remote sensing satellites and 2, 000 Starlink satellites.

B. Parameters

- The four ground stations are positioned at :
  - *Beijing (40◦N, 116◦E),*
  - *Xi'an (34.27◦N, 108.93◦E),*
  - *Kashi (39.5◦N, 76◦E),*
  - *Sanya (18◦N, 109.5◦E).*
- Each satellite is configured with two types of transceivers (i.e, RF and FSO) with an availability probability of 0.5.
- The data rate of ISLs and USLs with RF transceivers: [300, 350] Mbps.
- The transmission rate of FSO transceivers: 1.8 Gbps.
- The propagation delays of ISLs and USLs: [5, 15] ms.
- 5,000 applications are simulated.

C. Algorithms

- The LP-based scheme (i.e., Combined RF/FSO-LP solver),
- The proposed graph-based scheme (i.e., Combined RF/FSO-maxflow),
- Two baselines (i.e., Pure RF scheme and Pure FSO scheme).



The simulated satellite network.

Multi-path transmission of remote sensing data via ISLs

1. Running times versus numbers of relay satellites (Starlink satellites)

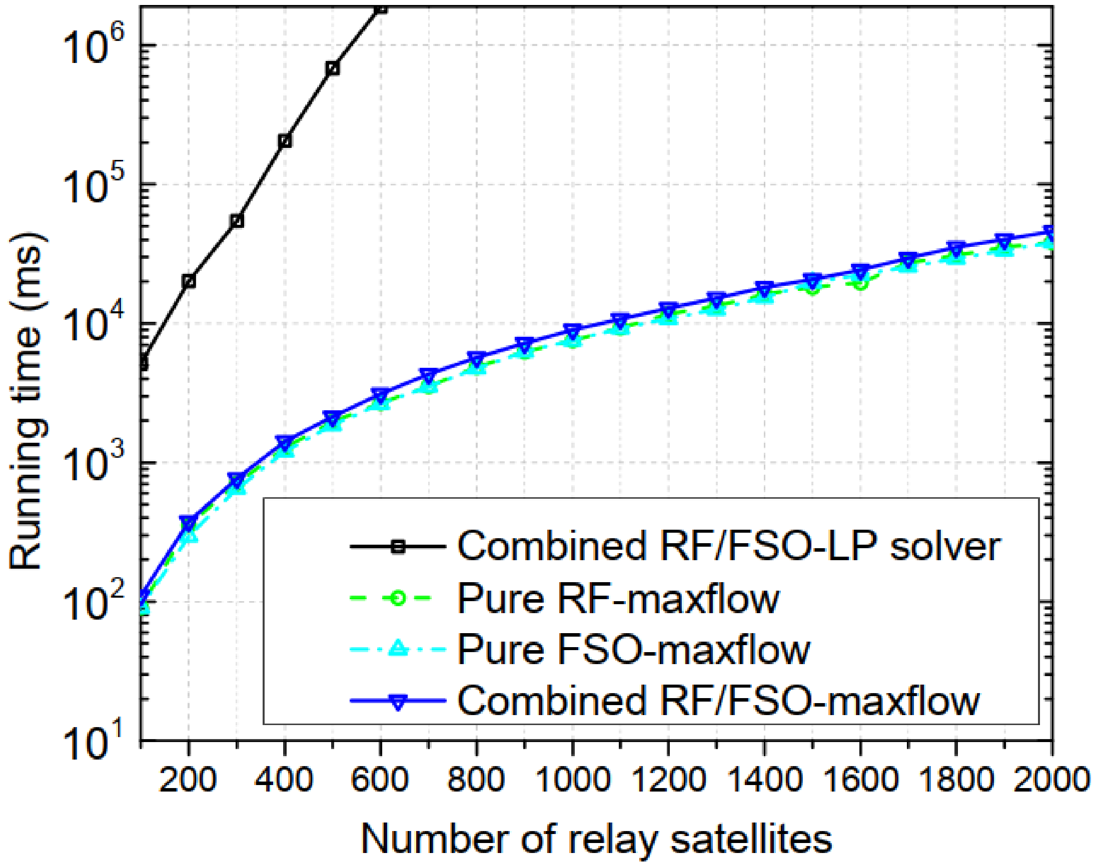


Fig. 3. Running times versus different network sizes.

Observation:
The proposed graph-based algorithm can support multi-path transmission in satellite networks with heterogeneous transceivers without significantly increasing complexity, which is significantly faster than LP-solver.

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Multi-path transmission of remote sensing data via ISLs

2. Average data throughput versus numbers of relay satellites (Starlink satellites)

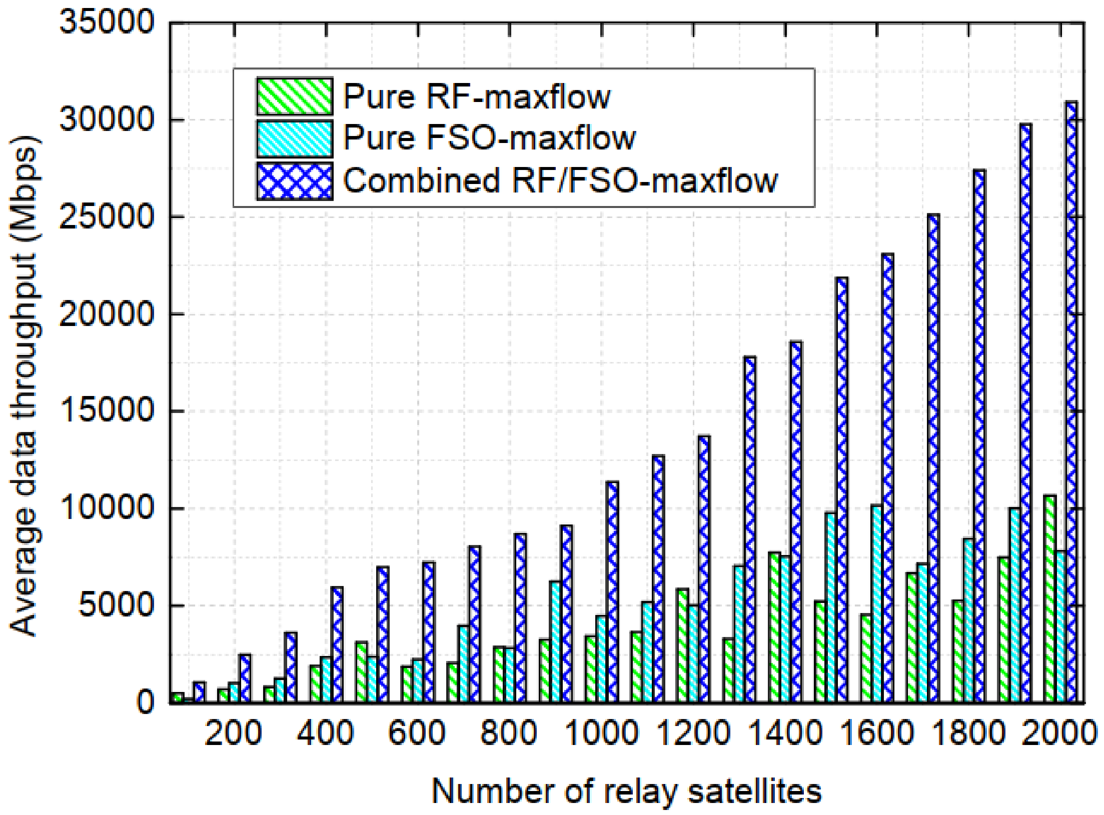

Fig. 4. Average throughput versus network sizes using different methods.

Observation:
As num of relay satellite increases, the proposed graph-based method achieves significant data throughput gains, even surpassing the sum of pure RF and pure FSO.

Multi-path transmission of remote sensing data via ISLs

3. Average path delays versus numbers of relay satellites (Starlink satellites)

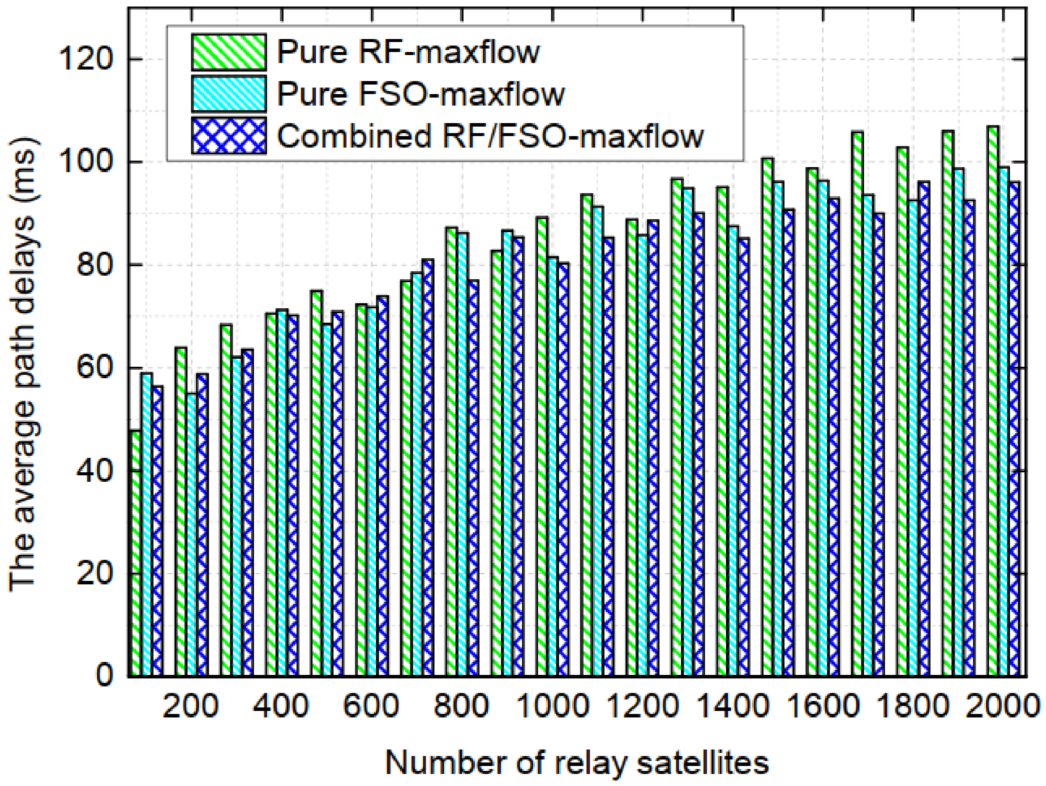

Fig. 5. Path delays versus network sizes under different methods.

Observation:
The increase of relay satellite numbers will roughly cause an increase of average path delays for all the schemes. Under all system parameters, the average path delays of the algorithms are comparable with one another.

Conclusions

- Bottlenecks of existing remote sensing systems
  - Traditional store-wait-download approach.
  - Lack of ground stations. (e.g., high costs, legal and environmental restrictions).
  - The higher the spatial resolution, the larger the data volume.

- Existing efforts to enhance satellite data communication systems
  - Mega LEO constellation.
  - Inter-satellite links (e.g., RF, FSO).

- Using ISLs is the way to go for real-time transmission of remote sensing data
  - Mathematical optimization-based routing approaches.
  - Graph-based routing approaches.
  - AI-based approaches such as semantic communication (future directions).

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For more information: http://www.eng.auburn.edu/~szm0001/

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