Achieving Predictable and Scalable Load Balancing Performance in LEO Mega-Constellations

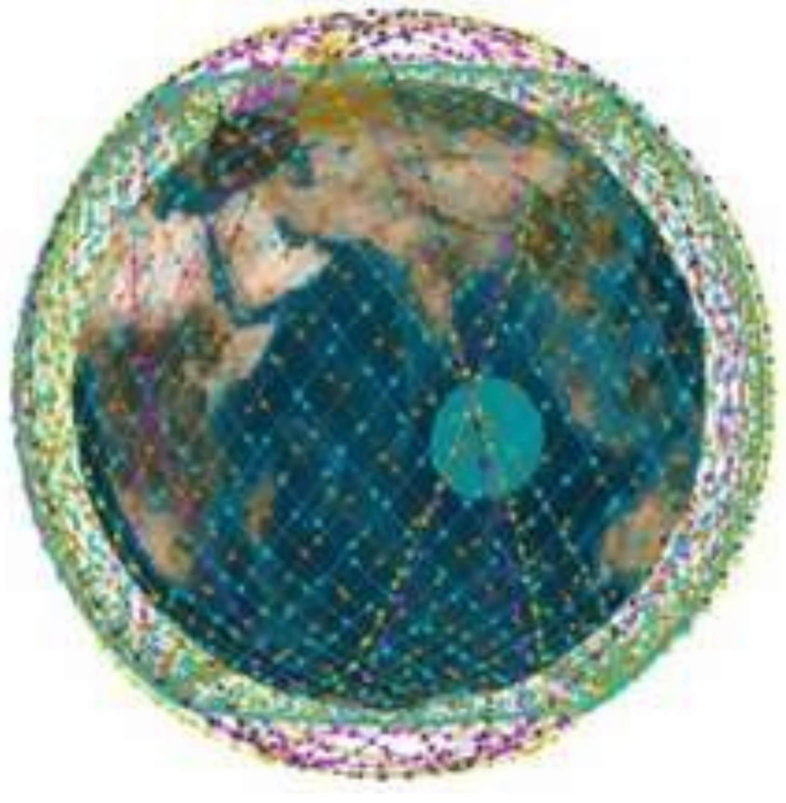
Songshi Dou [*], **Shengyu Zhang** [†], **and Kwan L. Yeung** [*]

[*]The University of Hong Kong, [†]Singapore University of Technology and Design

Emerging LEO Mega-Constellations

- Utilizing mega-constellations consisting of numerous **Low Earth Orbit (LEO)** satellites
  - Increasing number of satellites launched in recent years
  - Providing Internet service from space, particularly in remote areas
  - Mega-constellations: consisting of thousands of satellites in LEO
- Many companies entering the market: **SpaceX**, **OneWeb**, **Telesat**, and **Amazon Kuiper**
  - Functioning as Internet Service Providers (ISPs)
  - Having the capability to offer pervasive Internet connectivity worldwide
  - For example, as of January 2024, SpaceX's Starlink has
    - Over 5,000 Starlink satellites launched
    - More than 2 million subscribers

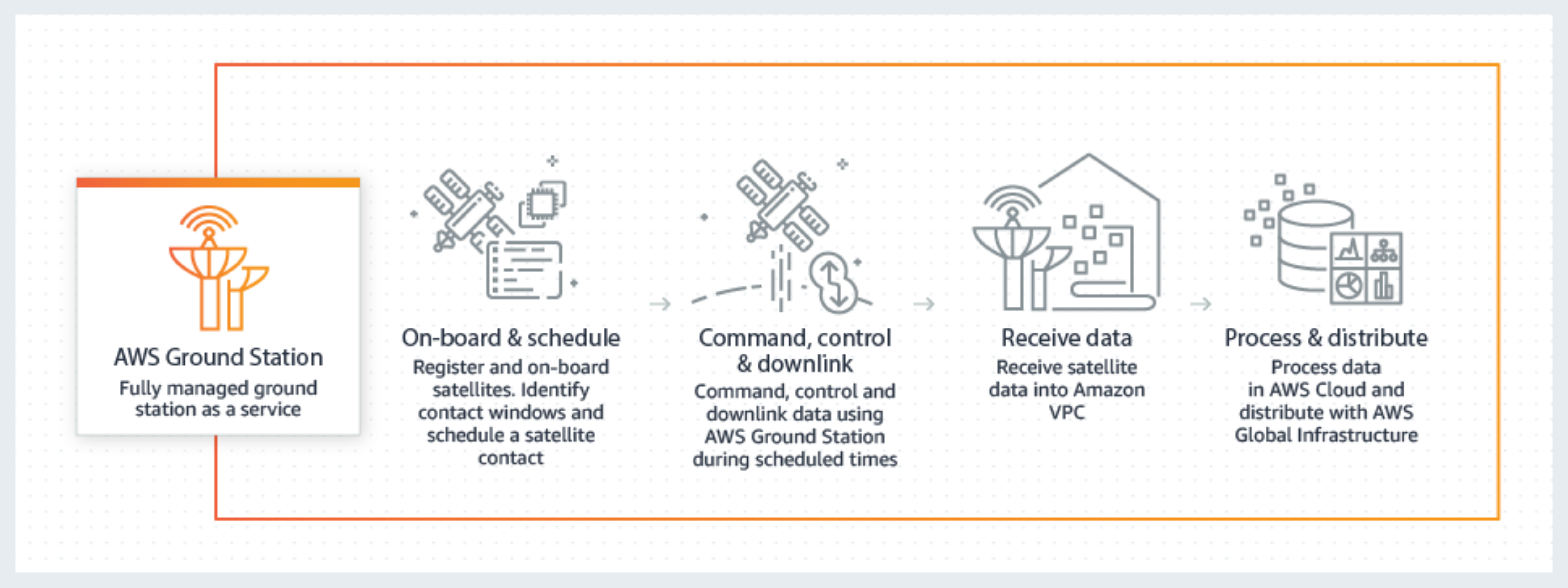
STARLINK



Starlink Constellation

GSaaS Infrastructure

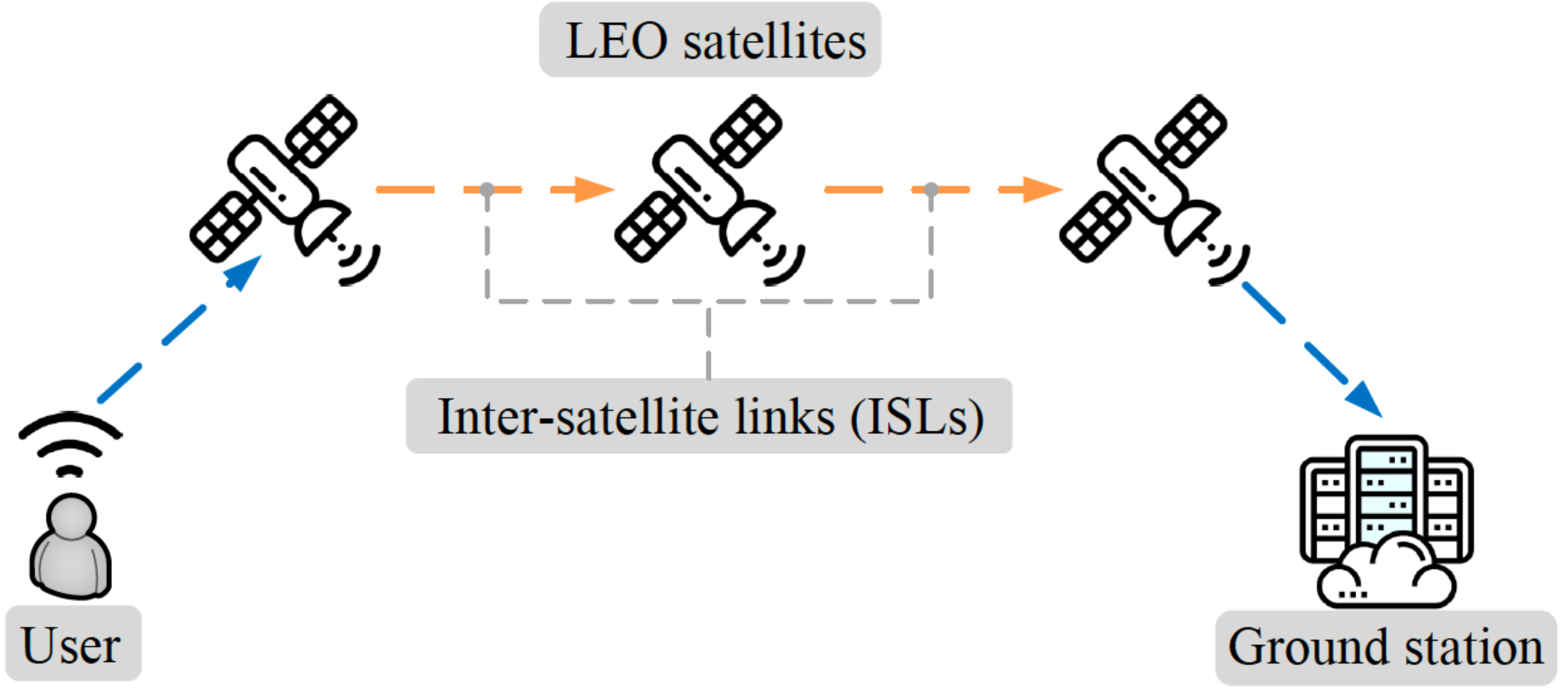
- **Ground-Station-as-a-Service (GSaaS)** infrastructure
  - Aiming to provide cost-effective, flexible, and scalable services
  - For satellite communications, data transmission, and operational management
  - Eliminating the need for organizations to build and maintain their own ground station
- AWS ground station
  - Easily controlling satellites and ingesting data with fully managed GSaaS



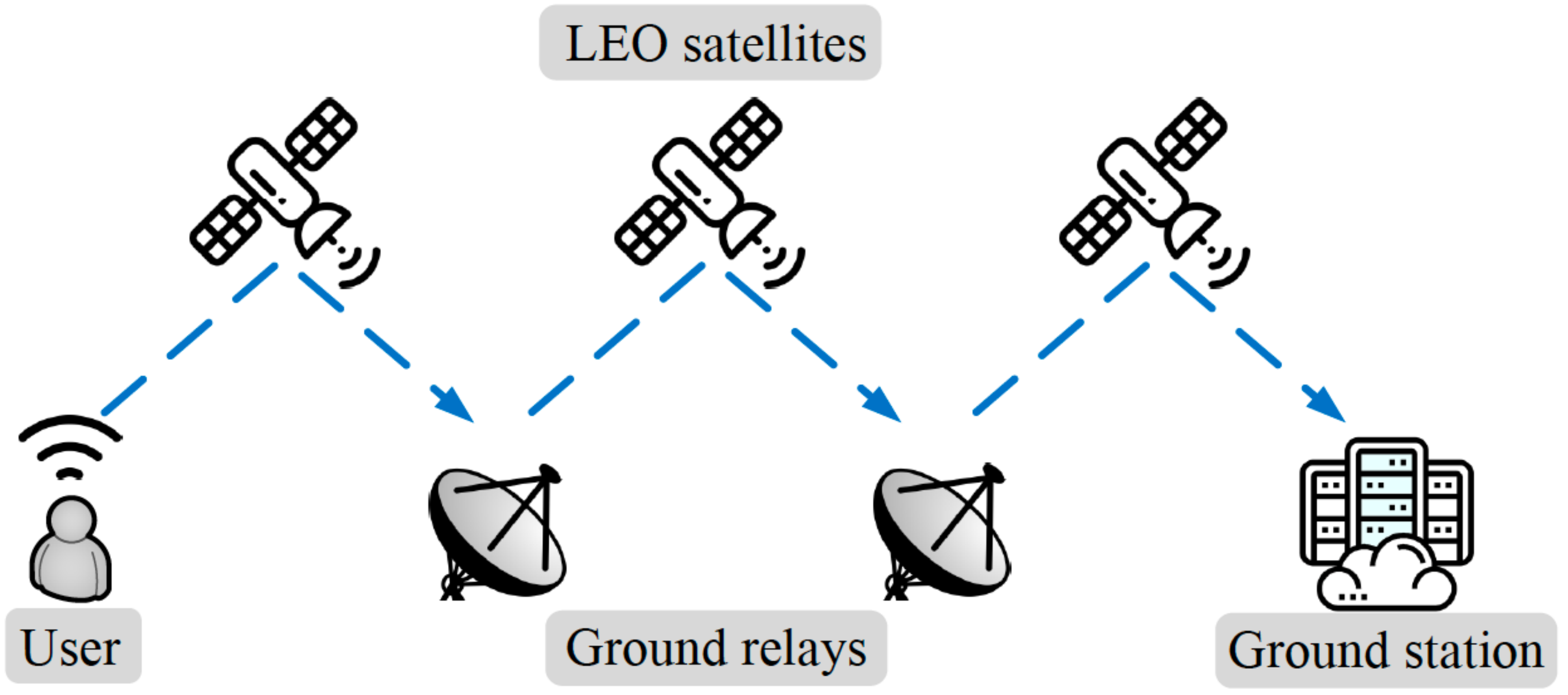
AWS Ground Station, https://aws.amazon.com/ground-station/

LEO Satellite Networks

- Structures of emerging LEO satellite networks
  - **Inter-Satellite Links (ISLs)**-enabled LEO satellite network
    - Utilizing ISLs to establish space routes for long-distance communications
    - First, user data packets are transmitted to the satellites
    - Then, transmitted via ISLs
    - Finally, return the data to ground stations
  - **Bent Pipe**-like LEO satellite network
    - First, user data packets are transmitted to the satellites
    - Then, promptly return the data to ground facilities
    - In a manner resembling a bent pipe
    - Ground relays: intermediaries to interconnect two satellites but do not have direct access to the Internet



(a) ISLs-enabled LEO satellite network design.



(b) Bent Pipe LEO satellite network design.

Challenges

- Differing from traditional terrestrial networks
  - Highly dynamic feature,
  - The availability of satellites for user connectivity varies over time
- Routing in LEO satellite networks
  - Efficiently managing the flow of data between user terminals and ground stations
  - Adapt to topology changes in real time
- Load balancing is important in LEO satellite networks
  - Battery-powered with limited resource
  - Improper routing solution -> Traffic hot-spots -> The surge of traffic load
    - Increasing packet queuing delay
    - A sharp drop in battery power -> Hibernation mode to save power

Motivation

- Load balancing is important in LEO satellite networks
- Existing solutions may not promise satisfactory load balancing performance
  - Not feasible
    - ISLs are not fully supported in current LEO mega-constellations, but current Bent Pipe-like design is not fully considered by existing works
    - Collecting traffic traces among moving LEO satellites in real time may become infeasible
  - Not efficient
    - May not efficiently utilize the network resource without considering load balancing performance
    - Imbalanced traffic load on each satellite may lead to inefficient network resource management
  - Not scalable
    - The end-to-end routing algorithm has to be run periodically due to the time-varying topology
    - With potentially millions of user terminals, the topology scale will continuously grow

Observation & Opportunity

IEEE ICC | IEEE ComSoc

- More satellites become simultaneously visible to user terminals
  - In most terrestrial locations, the number of visible satellites can range from 15-40 if all five groups of Starlink Phase I are fully deployed
  - Multiple choices to assign each user to satellites
  - User-satellite assignment policy (alone) can significantly impact load balancing performance

Phase	Group designation	Orbital shells		Orbital planes[351]			Committed completion date		Deployed satellites 4 November 2023[5]		
		Altitude (km)	Authorized satellites	Incli-nation	Count	Satellites per	Half	Full	Active	Decaying/ deorbited	Satellites needed for completion
1[352]	Group 1[353]	550 km (340 mi)	1584[354]	53.0°	72	22	March 2024 (aimed) 1 August 2022 (achieved)[355]	March 2027	1445	280	139
	Group 2	570 km (350 mi)	720	70°	36	20			403	5	317
	Group 3[356]	560 km (350 mi)	348	97.6°	6	58			233	10	115
	Group 4	540 km (340 mi)	1584	53.2°	72	22			1566	71	18
		560 km (350 mi)	172	97.6°	4	43			0	0	172

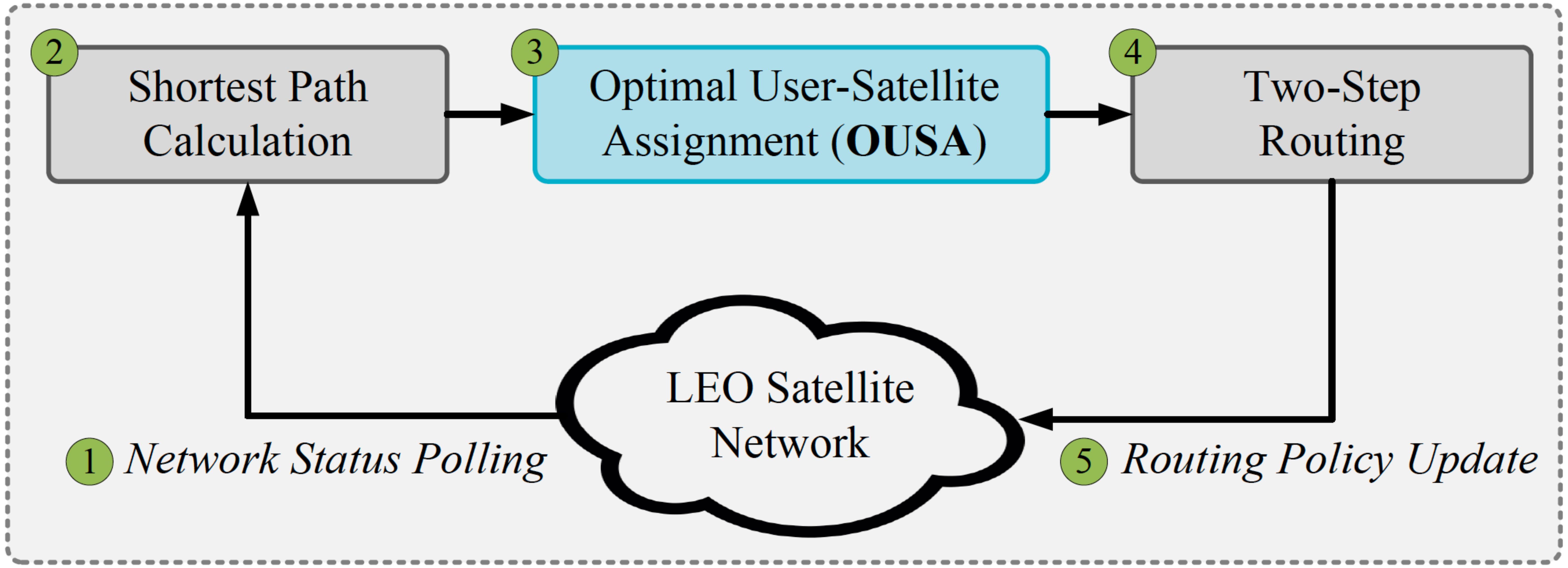
Starlink, https://en.wikipedia.org/wiki/Starlink

Design Overview

- How does our solution overcome these limitations
  - Real-world LEO mega-constellation design
    - Following the current operational Bent Pipe-like design by using ground relays interconnecting satellites
    - Balancing the number of users instead of real-time traffic volume among all satellites
    - Data speeds provided are relatively limited and stable (*e.g.*, from 50 Mbps to 150 Mbps)
  - Load balancing-aware user-satellite assignment
    - First, calculating all shortest paths between each user's visible satellites and its destination ground station periodically
    - Then, deciding proper user-satellite assignments to balance user load among satellites
  - Two-step routing architecture
    - Dividing the routing process into two parts:
      - Assigning the user terminal to a visible satellite
      - Finding a path from the satellite to the nearest ground station
      - A much smaller scale of network topology without involving the end users -> A higher scalability

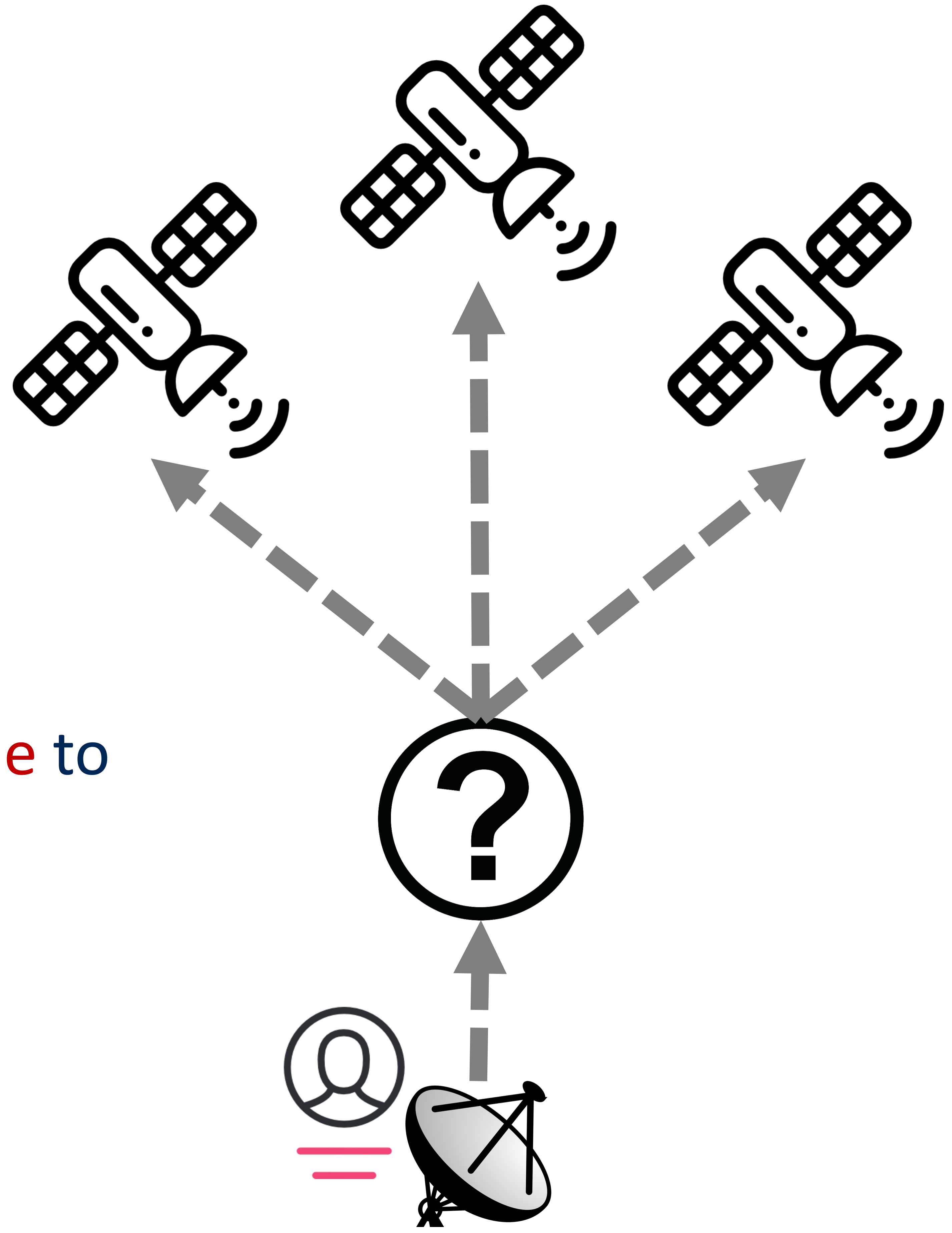
Design Overview

- The processing logic of our proposed solution
  1) Collecting network status (*e.g.*, the visibility between users and satellites) periodically
  2) Pre-calculating all the shortest paths between each user's visible satellites and its destination ground station
  3) Deciding optimal user-satellite assignment strategies by solving our formulated problem
  4) Following pre-calculated shortest paths when forwarding data packets
  5) Updating routing policy in the LEO satellite network



OUSA Problem

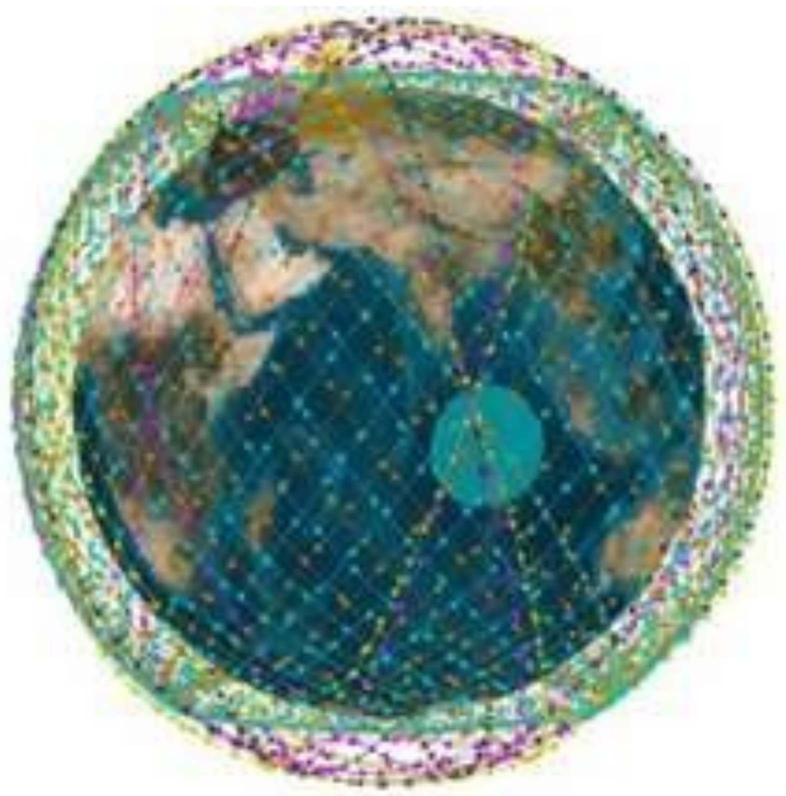
- Optimal User-Satellite Assignment (OUSA) Problem
  - System description
    - Time-slotted system
      - T time intervals
  - Problem constraints
    - User-satellite assignment constraint
      - Each user must be assigned to one satellite at each time interval
    - Connection visibility constraint
      - A user can be assigned to a satellite only when this satellite is visible to the user terminal
    - Satellite load constraint
      - Each satellite's load cannot exceed its capacity
  - Objective function
    - Load balancing performance
      - Minimizing the Maximum Satellite Utilization (MSU) at each time interval



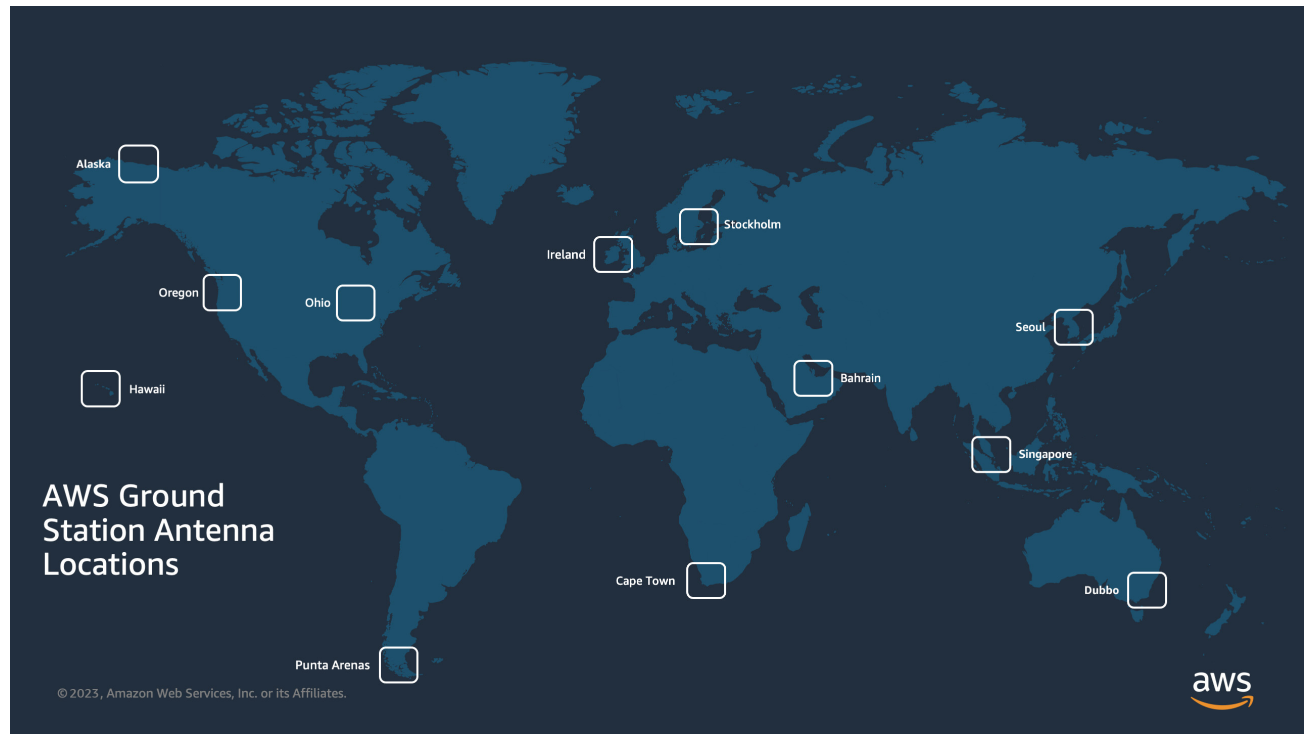
Evaluation

- Simulation setup
  - SpaceX's Starlink (Group I of Phase I) constellation

Primary parameters	Starlink (Shell I of Phase I)
Inclination	53°
Altitude	550 km
Number of orbits	72
Number of satellites	1584
Synodic period	5,731s



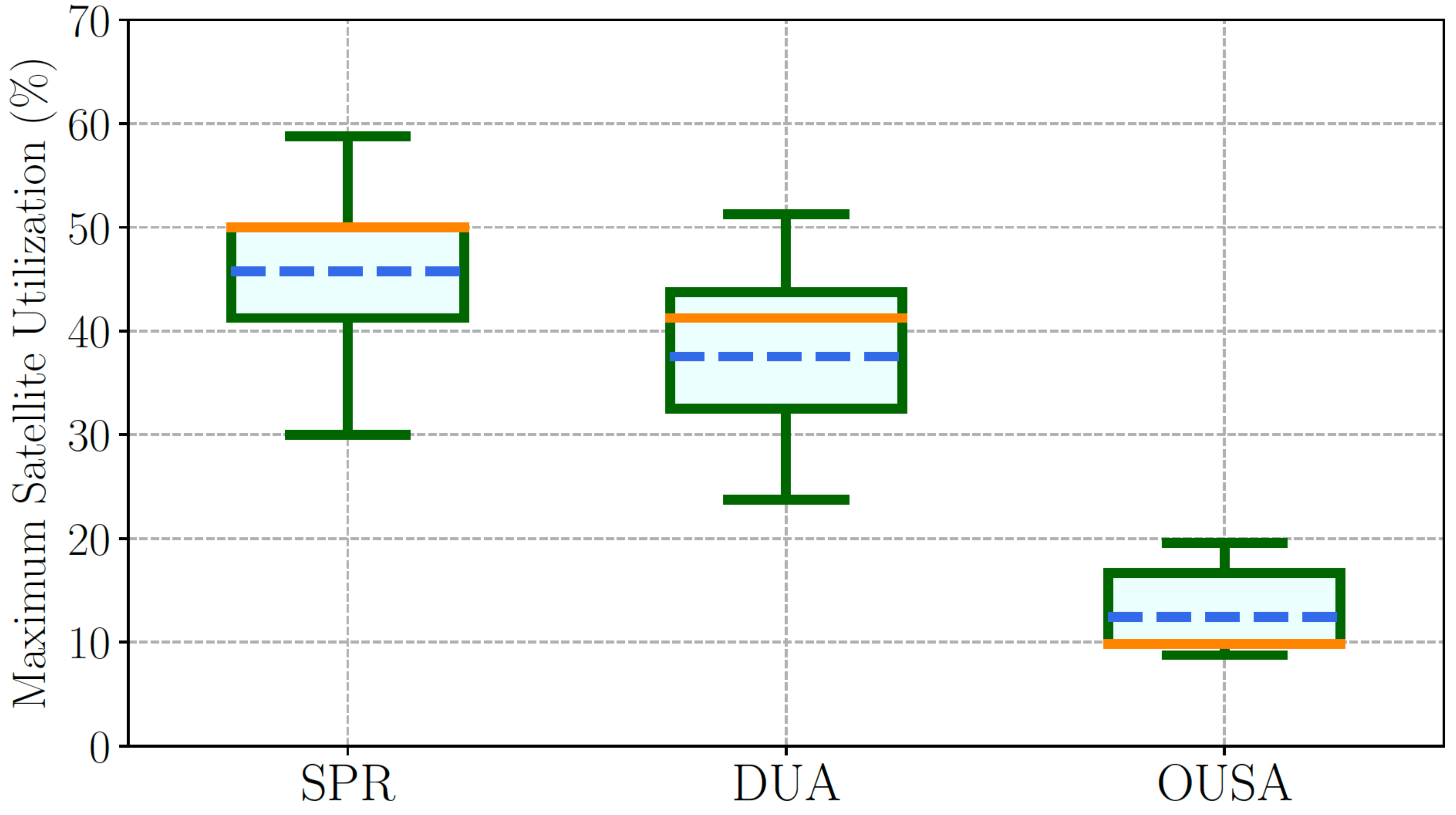
  - 40 representative cities from Starlink's availability map
  - 7,500 active users from these 40 selected cities
  - 11 ground stations worldwide based on Amazon's AWS ground station locations
  - Time interval: 5 seconds; A total of 5,731 seconds



- Comparison algorithm
  - Shortest Path Routing (SPR)
  - Distance-based User-Satellite Assignment (DUA)
  - Optimal User-Satellite Assignment (OUSA)

Evaluation

- Load balancing performance
  - OUSA exhibits the best load balancing performance with a lower median and mean value of the MSU
  - Average MSU
    - SPR: 45.73 %
    - DUA: 37.53%
    - **OUSA: 12.44%**
  - OUSA can improve the average load balancing performance by up to 33.29% compared with SPR



- Scalability performance

Schemes	Scale of the topology
SPR	Users + Satellites + Ground facilities
DUA	Satellites + Ground facilities
OUSA	**Satellites + Ground facilities**

Future Work

- Scalability performance
  - Futuristic larger LEO mega-constellations
  - The need for an efficient heuristic algorithm to achieve the trade-off between the performance and time complexity

- Other important issues
  - User-satellite handover overhead

- Different application scenarios
  - Other current operational LEO mega-constellations
    - OneWeb
    - Amazon Project Kuipers
    - Globalstar
    - …

Summary

- New observation
  - We identify that existing user-satellite assignment solutions are not feasible for today's LEO mega-constellations and also may not achieve good load balancing performance in a scalable manner.

- New problem formulation
  - We formulate the OUSA problem and propose a solution for deciding the optimal user-satellite assignments to achieve predictable load balancing in LEO mega-constellations.

- Evaluation based on real LEO constellation parameters
  - To show the effectiveness of our proposed OUSA, we utilize real-world LEO mega-constellation parameters and ground station information to evaluate the load balancing and scalability performance of OUSA.

Thank you!

IEEE ICC®

IEEE ComSoc® | IEEE