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Enabling Practical and Pervasive Content Delivery From Emerging LEO Mega-Constellations

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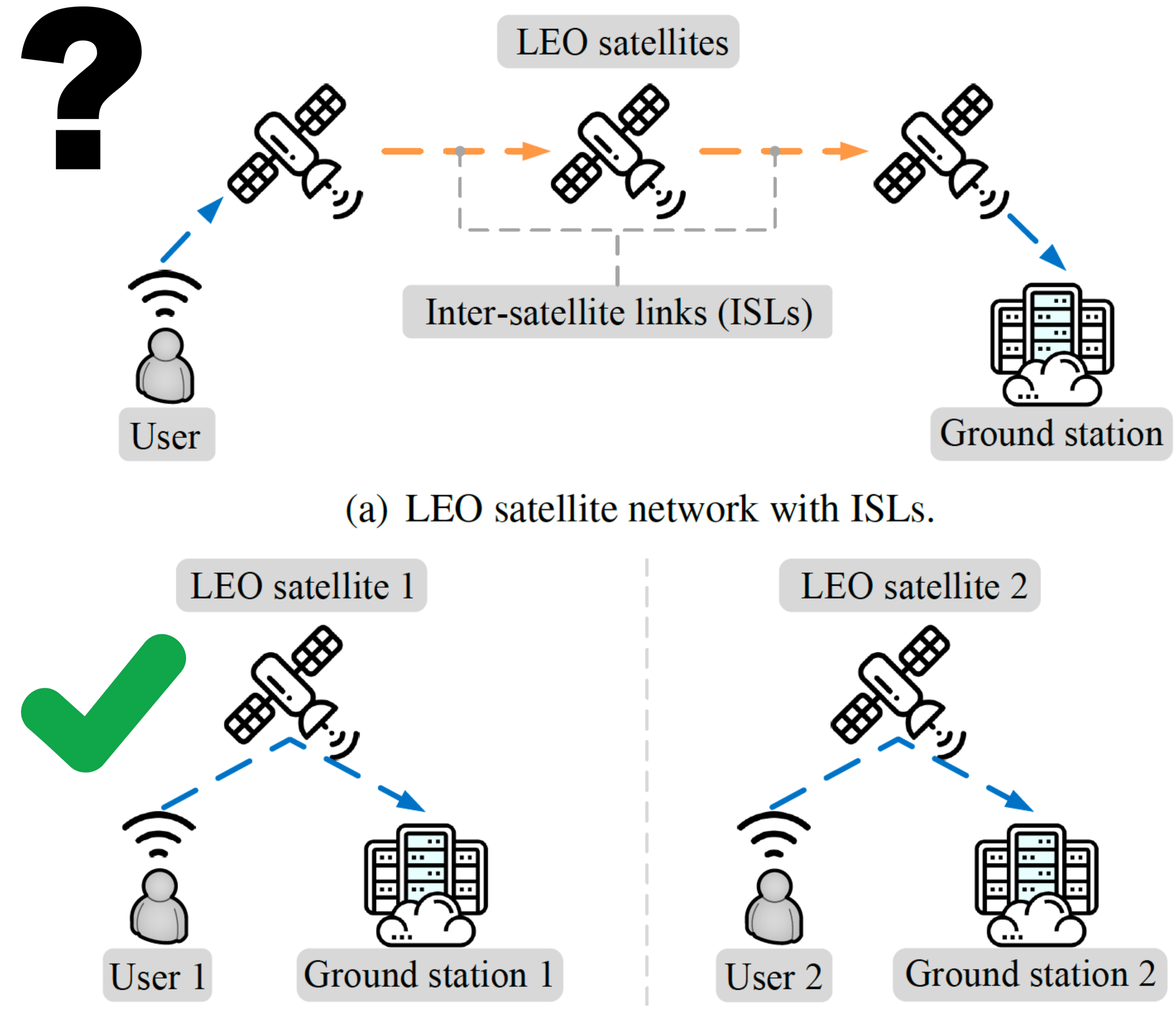
① Introduction

- ***Emerging Low-Earth Orbit (LEO) Mega-Constellations***
  - Constellations with numerous LEO satellites in space can provide global Internet services.
    - Functioning as *Internet Service Providers (ISPs)*.
    - Having the capability to offer *pervasive Internet connectivity* worldwide.
  - However, LEO mega-constellations also face various challenges:
    - Satellites rely on phased array antennas for direct communications with ground stations and user terminals via RF signals – communication *suffers from limited bandwidth*.
    - The traffic demand of users is a dynamic phenomenon that varies over time, which usually follows a tidal pattern – *underutilization of LEO satellites*.
- ***Content Delivery from Space***
  - Constructing Content Delivery Networks (CDNs) in LEO-mega constellations is promising.
    - Wireless bandwidth *can be saved*.
    - Cache satellites *can replace the cached content* when the traffic demand is not heavy.
  - However, enabling practical and pervasive content delivery from space is non-trivial:
    - *Dynamic*. The LEO satellite network is highly dynamic – each ground unit can only communicate with an LEO satellite if the satellite moves into the Line of Sight (LoS).
    - *Expensive*. The cost to upgrade all satellites in a mega constellation, *e.g.*, 5,000+ in Starlink, to support CDN caching is simply not economically feasible.

② Motivation & Challenges

- ***Structures of LEO Constellations***
  - *ISLs-enabled* satellite networks.
    - Utilizing ISLs to establish space routes for long-distance communications
  - *Bent Pipe-like* satellite networks.
    - Packets are transmitted to the satellite and promptly returned to the ground station in a manner resembling a bent pipe.
- ***Challenges***
  - Operational constellations use the Bent Pile-like structure, which is *overlooked by existing works*.
  - How to decide *cache satellite deployment* to ensure that cache satellites can *constantly provide pervasive content delivery* when these satellites are fast-moving.



(a) LEO satellite network with ISLs.

(b) Bent Pipe-like LEO satellite network.

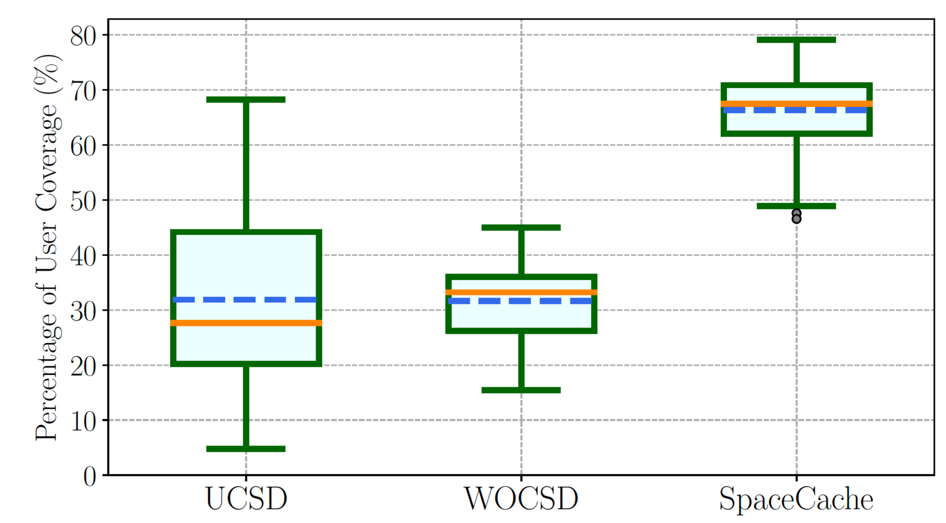
LEO satellite networks with and without ISLs.

③ Solution - SpaceCache

- ***User Coverage-aware Cache Satellite Deployment (UCCSD) Problem***
  - System description.
    - Assume a time-slotted system with multiple time intervals.
  - Problem constraints.
    - **Cache satellite deployment constraint**. Due to the high deployment cost of the cache server on the satellite, a limited number of cache servers can be deployed.
    - **User-satellite connectivity constraint**. Cache satellites can only serve users within their LoS.
    - **Cache satellite coverage constraint**. The coverage of cache satellites at each time interval should be greater than the minimum user coverage ratio.
  - Objective function.
    - Maximizing the cache satellite's coverage at each time interval to enable pervasive content delivery.
- ***Heuristic Algorithm – SpaceCache***
  - High complexity of the formulated UCCSD problem.
  - Heuristic algorithm aiming to provide the trade-off between performance and complexity.
  - Key idea - test and deploy the cache satellite based on the *deployment probabilities* obtained from the *relaxed linear programming* of the UCCSD problem. (Please refer to the paper for more details)

④ Evaluation Results

- ***Simulation Setup***
  - *SpaceX's Starlink constellation*.
    - 1,584 LEO satellites (72 orbits).
    - 165 ground stations.
  - *80 representative cities* with population data.
    - Within Starlink's availability map.
  - *Real CDN traces* (3.9 million records).
    - Cache replacement strategy - caches objects in descending order of their request frequency.
- ***Benchmark Algorithm***
  - Uniform Cache Satellite Deployment (*UCSD*): uniformly deploys cache satellites in the LEO mega-constellation.
  - Weighted Orbital-based Cache Satellite Deployment (*WOCSD*): successively selects the orbit that can cover the highest number of uncovered users and deploys cache satellites in that orbit.



Percentage of the user coverage.

Cache hit ratio from different locations.

Scheme	New York	São Paulo	Rome
UCSD	7.88%	7.91%	16.90%
WOCSD	16.83%	0%	9.14%
SPACECACHE	**27.08%**	**24.83%**	**24.97%**

Total size of hit objects from different locations.

Scheme	New York	São Paulo	Rome
UCSD	3.38 TB	3.41 TB	7.13 TB
WOCSD	7.40 TB	0 TB	3.94 TB
SPACECACHE	**11.63 TB**	**10.84 TB**	**10.74 TB**