Semantic Communication-Aware End-to-End Routing in Large-Scale LEO Satellite Networks

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Outline

Motivation

- As reported by ITU, $\approx$ 2.9 billion people (37% of the world's population) still do not have access to Internet, and $>$ 70% of the surface of the earth has no terrestrial network. Companies like SpaceX and Amazon are developing large-scale satellite networks (SNs) with inter-satellite links to deliver low-latency services globally.
- Challenges: Given the scarce spectrum (L, S, C, Ku, K, and Ka bands are saturated) and the capacity limitations of Shannon's classical information theory, supporting the ever-growing multimedia communication services poses a challenge for SNs.

One direction: Enabling Semantic Communication (SC) in SNs

- Advantages: SC uses artificial intelligence (AI) to extract and transmit the "meaning" of raw data, reducing bandwidth consumption.
- Research Gap: Routing methods designed for SC in SNs are absent.

Introduction

Semantic Communication-Empowered Satellite Network:

1. **Network resources:** The KBs in the SN is $\Theta = \{\theta_1, \theta_2, ..., \theta_W\}$. $b^{\theta_l}_{\mathbb{I}_i} \in \{0, 1\}$ is defined for each KB $\theta_l \in \Theta$. If $b^{\theta_l}_{\mathbb{I}_i} = 1$, the AI satellite $\mathbb{I}_i$ can support KB θ_l.
2. **App requirements:** $\mathcal{A} = \{\mathbb{S}_a, \mathbb{D}_a, \theta_a, C_a, \sigma_a\}$ denotes an application from satellite $\mathbb{S}_a$ to GS $\mathbb{D}_a$, with transmission rate C_a and KB θ_a and compression ratio σ_a.

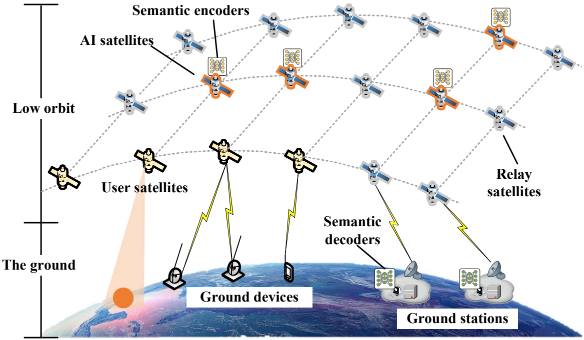

Figure: The system model of semantic communications in SN.

Related work

Category 1: Routing and resource allocation in satellite networks

1. G. Araniti, et. al, "Contact graph routing in DTN space networks: overview, enhancements and performance," IEEE Commun. Mag., vol. 53, no. 3, pp. 38–46, Mar. 2015.
2. Y. Hu, et. al, "Time-deterministic networking for satellite-based internet-of-things services: Architecture, key technologies, and future directions," IEEE Netw., Mar. 2024.

Category 2: AI and Semantic communication in satellite networks

3. B. Al Homssi, et. al, "Artificial intelligence techniques for next generation massive satellite networks," IEEE Commun. Mag., 2024.
4. D. Deng, et. al, "Semantic communication empowered NTN for IoT: Benefits and challenges," IEEE Netw., Apr. 2024.
5. H. Peng, et. al, "Semantic communication in non-terrestrial networks: A future-ready paradigm," IEEE Netw., Apr. 2024.
6. G. Zheng, et. al, "Semantic communication in satellite-borne edge cloud network for computation offloading," IEEE JSAC, 2024.

System Model and Problem Formulation

1. **Network scenario:** We consider an SN includes user/relay/AI satellites and ground stations (GSs), represented as sets $\mathcal{S} = \{\mathbb{S}_1, \mathbb{S}_2, ..., \mathbb{S}_P\}$, $\mathcal{R} = \{\mathbb{R}_1, \mathbb{R}_2, ..., \mathbb{R}_K\}$, $\mathcal{I} = \{\mathbb{I}_1, \mathbb{I}_2, ..., \mathbb{I}_Q\}$, and $\mathcal{D} = \{\mathbb{D}_1, \mathbb{D}_2, ..., \mathbb{D}_N\}$. User satellites transmit raw data to GSs directly when in range, or via relay or AI satellites. Not all satellites can support AI. ISLs are supported.
2. To realize SC, the involved SC encoder and decoder must share the same KB.
3. **Service model:** Denote the set of the deployed KBs in the SN as a set $\Theta = \{\theta_1, \theta_2, ..., \theta_W\}$. $b_{\mathbb{I}_i}^{\theta_l} \in \{0, 1\}$ is defined for each KB $\theta_l \in \Theta$. If $b_{\mathbb{I}_i}^{\theta_l} = 1$, the AI satellite $\mathbb{I}_i$ can support KB θ_l; otherwise, data from source node with KB θ_l can not be encoded.
4. **APP model:** $\mathcal{A} = \{\mathbb{S}_a, \mathbb{D}_a, \theta_a, C_a, \sigma_a\}$ denotes an application from satellite $\mathbb{S}_a$ to GS $\mathbb{D}_a$, with transmission rate C_a and KB θ_a and compression ratio $\sigma_a \in (0, 1]$.

Temporal Graph Model

1. **Time division method**: The time horizon $\mathcal{T} = [0, T]$ is cut into variable length time windows. Each time window $\tau = [t_s, t_e]$.
2. **Snapshot graph**: To capture the dynamic evolution of SN topology in discrete time windows, we utilize snapshot graphs. Each snapshot for the time interval τ is represented by a directed graph, i.e, $\mathcal{G}^{\tau} = (\mathcal{V}^{\tau}, \mathcal{L}^{\tau})$. The node set $\mathcal{V}^{\tau}$, which includes all the satellites and GSs, is defined as $\mathcal{S} \cup \mathcal{R} \cup \mathcal{I} \cup \mathcal{D}$. The link set $\mathcal{L}^{\tau}$ comprises communication links and is defined by $\{(\mathbb{V}_i, \mathbb{V}_j)\}$, including ground-satellite links (GSLs) and ISLs within the time window τ.
3. **Resource attributes**:
   For each AI satellite $\mathbb{I}_i \in \mathcal{I}$, the binary indicators of each KB are collected into a vector $\vec{\mathbf{b}}_{\mathbb{I}_i} = \{b_{\mathbb{I}_i}^{\theta_1}, b_{\mathbb{I}_i}^{\theta_2}, ..., b_{\mathbb{I}_i}^{\theta_W}\}$, where $|\vec{\mathbf{b}}_{\mathbb{I}_i}| = W$. Furthermore, the propagation delay $d_{(\mathbb{V}_i,\mathbb{V}_j)}^{\tau}$ and the transmission rate $c_{(\mathbb{V}_i,\mathbb{V}_j)}^{\tau}$ characterize each link $(\mathbb{V}_i, \mathbb{V}_j)$.

System Model and Problem Formulation

Decision variables

- $x^{\tau}_{\mathbb{V}_i,\mathbb{V}_j} = 1$: signifies that the path allocated for application $\mathcal{A}$ during time window τ includes the link $(\mathbb{V}_i, \mathbb{V}_j)$.

Parameters

- $\mathcal{A} = \{\mathbb{S}_a, \mathbb{D}_a, \theta_a, C_a, \sigma_a\}$: denotes an application originates from satellite $\mathbb{S}_a$ with KB θ_a, targets at GS node $\mathbb{D}_a$, where C_a is the required transmission rate of the raw data, and $\sigma_a \in (0, 1]$ is estimated compression ratio of SC encoder supporting KB θ_a.
- $d^{\tau}_{(\mathbb{V}_i,\mathbb{V}_j)}$: the propagation delay of link $(\mathbb{V}_i, \mathbb{V}_j)$ in time window τ.
- $c^{\tau}_{(\mathbb{V}_i,\mathbb{V}_j)}$: the transmission rate of link $(\mathbb{V}_i, \mathbb{V}_j)$ in time window τ.
- $\vec{\mathbf{b}}_{\mathbb{I}_i} = \{b^{\theta_1}_{\mathbb{I}_i}, b^{\theta_2}_{\mathbb{I}_i}, ..., b^{\theta_W}_{\mathbb{I}_i}\}$: the binary indicators of KBs in AI satellite $\mathbb{I}_i$.

Objective function

- The objective is to minimize the end-to-end delay, i.e.,

$$\sum_{(\mathbb{V}_i,\mathbb{V}_j)\in\mathcal{L}^{\tau}} x^{\tau}_{\mathbb{V}_i,\mathbb{V}_j} \cdot d^{\tau}_{\mathbb{V}_i,\mathbb{V}_j}.$$

A. Basic Constraints

- 1. Source satellite constraint:

$$1 - \sum_{\mathbb{V}_k \in \mathcal{V}^\tau - \{\mathbb{S}_a\}} x^\tau_{\mathbb{V}_k, \mathbb{S}_a} = \sum_{\mathbb{V}_k \in \mathcal{V}^\tau - \{\mathbb{S}_a\}} x^\tau_{\mathbb{S}_a, \mathbb{V}_k} = 1. \quad (1)$$

- 2. Source capacity constraint:

$$\sum_{\mathbb{V}_k \in \mathcal{V}^\tau - \{\mathbb{S}_a\}} (x^\tau_{\mathbb{S}_a, \mathbb{V}_k} \cdot c^\tau_{\mathbb{S}_a, \mathbb{V}_k}) \geq C_a. \quad (2)$$

- 3. Sink GS constraint:

$$\sum_{\mathbb{V}_k \in \mathcal{V}^\tau - \{\mathbb{D}_a\}} x^\tau_{\mathbb{V}_k, \mathbb{D}_a} = 1 - \sum_{\mathbb{V}_k \in \mathcal{V}^\tau - \{\mathbb{D}_a\}} x^\tau_{\mathbb{D}_a, \mathbb{V}_k} = 1. \quad (3)$$

- 4. Sink capacity constraint:

$$\sum_{\mathbb{V}_k \in \mathcal{V}^\tau - \{\mathbb{D}_a\}} (x^\tau_{\mathbb{V}_k, \mathbb{D}_a} \cdot c^\tau_{\mathbb{V}_k, \mathbb{D}_a}) \geq C_a \cdot \sigma_a. \quad (4)$$

B. Relay satellite constraints

- 5. Relay satellite constraint: Therefore, $\forall \mathbb{V}_\xi \in \mathcal{V}^\tau - \{\mathbb{S}_a, \mathbb{D}_a\}$,

$$\sum_{\mathbb{V}_k:(\mathbb{V}_\xi,\mathbb{V}_k)\in\mathcal{L}_\tau} x^\tau_{\mathbb{V}_\xi,\mathbb{V}_k} = \sum_{\mathbb{V}_k:(\mathbb{V}_k,\mathbb{V}_\xi)\in\mathcal{L}_\tau} x^\tau_{\mathbb{V}_k,\mathbb{V}_\xi} \leq 2. \tag{5}$$

- 6. Flow conservation constraints of relay nodes: The incoming flow of each relay node in $\mathcal{V}^\tau - \{\mathbb{S}_a, \mathbb{D}_a\} - \mathcal{I}$ should be equal to its outgoing flow. Thus, $\forall \mathbb{V}_\xi \in \mathcal{V}^\tau - \{\mathbb{S}_a, \mathbb{D}_a\} - \mathcal{I}$,

$$\sum_{\mathbb{V}_k:(\mathbb{V}_k,\mathbb{V}_\xi)\in\mathcal{L}^\tau} c^\tau_{\mathbb{V}_k,\mathbb{V}_\xi} = \sum_{\mathbb{V}_k:(\mathbb{V}_\xi,\mathbb{V}_k)\in\mathcal{L}^\tau} c^\tau_{\mathbb{V}_\xi,\mathbb{V}_k}. \tag{6}$$

C. SC-aware Constraints

- 1. One encoder constraints:

$$\sum_{\mathbb{I}_i \in \mathcal{I}} z_{\mathbb{I}_i}^{\mathcal{T}} = 1. \quad (7)$$

$$b_{\mathbb{I}_i}^{\theta_a} \geq z_{\mathbb{I}_i}^{\mathcal{T}}, \forall \mathbb{I}_i \in \mathcal{I}. \quad (8)$$

- 2. KB matching constraint:

$$\sum_{\mathbb{I}_i \in \mathcal{I}} [(\sum_{\mathbb{V}_k : (\mathbb{V}_k, \mathbb{I}_i) \in \mathcal{L}^{\mathcal{T}}} x_{\mathbb{V}_k, \mathbb{I}_i}^{\mathcal{T}}) \cdot b_{\mathbb{I}_i}^{\theta_a}] \geq 1. \quad (9)$$

If an AI satellite is selected for semantic encoding, its adjacent edges must be included in the path. Using the following constraints, we can bind variable x and z together.

$$\sum_{\mathbb{V}_k : (\mathbb{V}_k, \mathbb{I}_i) \in \mathcal{L}^{\mathcal{T}}} x_{\mathbb{V}_k, \mathbb{I}_i}^{\mathcal{T}} \geq z_{\mathbb{I}_i}^{\mathcal{T}}, \forall \mathbb{I}_i \in \mathcal{I}. \quad (10)$$

C. SC-aware Constraints

- 3.A Semantic encoding constraints:

  Case 1: For $\forall \mathbb{I}_i \in \mathcal{I}$, if $z^{\tau}_{\mathbb{I}_i} = 1$, there is

$$\sum_{\mathbb{V}_k:(\mathbb{V}_k,\mathbb{I}_i)\in\mathcal{L}^{\tau}} (x^{\tau}_{\mathbb{V}_k,\mathbb{I}_i} \cdot c^{\tau}_{\mathbb{V}_k,\mathbb{I}_i}) \geq C_a, \quad (11)$$

$$\sum_{\mathbb{V}_k:(\mathbb{I}_i,\mathbb{V}_k)\in\mathcal{L}^{\tau}} (x^{\tau}_{\mathbb{I}_i,\mathbb{V}_k} \cdot c^{\tau}_{\mathbb{I}_i,\mathbb{V}_k}) \geq C_a \sigma_a. \quad (12)$$

  Case 2: If $z^{\tau}_{\mathbb{I}_i} = 0$, then $\mathbb{I}_i$ only satisfy the flow conservation constraint, i.e.,

$$\sum_{\mathbb{V}_k:(\mathbb{V}_k,\mathbb{I}_i)\in\mathcal{L}^{\tau}} x^{\tau}_{\mathbb{V}_k,\mathbb{I}_i} = \sum_{\mathbb{V}_k:(\mathbb{I}_i,\mathbb{V}_k)\in\mathcal{L}^{\tau}} x^{\tau}_{\mathbb{I}_i,\mathbb{V}_k}, \forall \mathbb{I}_i \in \mathcal{I}. \quad (13)$$

C. SC-aware Constraints

- 3.B Semantic encoding constraints:
  Constraints (11) and (12) in **Case 1** is linearized as, $\forall \mathbb{I}_i \in \mathcal{I}$,

$$\sum_{\mathbb{V}_k:(\mathbb{V}_k,\mathbb{I}_i)\in\mathcal{L}^\tau} (x^\tau_{\mathbb{V}_k,\mathbb{I}_i} \cdot c^\tau_{\mathbb{V}_k,\mathbb{I}_i}) + M(1 - z^\tau_{\mathbb{I}_i}) \geq C_a, \tag{14}$$

$$\sum_{\mathbb{V}_k:(\mathbb{I}_i,\mathbb{V}_k)\in\mathcal{L}^\tau} (x^\tau_{\mathbb{I}_i,\mathbb{V}_k} \cdot c^\tau_{\mathbb{I}_i,\mathbb{V}_k}) + M(1 - z^\tau_{\mathbb{I}_i}) \geq C_a \sigma_a. \tag{15}$$

Then, constraint (13) in **Case 2** is linearized as, $\forall \mathbb{I}_i \in \mathcal{I}$,

$$\sum_{\mathbb{V}_k:(\mathbb{V}_k,\mathbb{I}_i)\in\mathcal{L}^\tau} x^\tau_{\mathbb{V}_k,\mathbb{I}_i} + M z^\tau_{\mathbb{I}_i} \geq \sum_{\mathbb{V}_k:(\mathbb{I}_i,\mathbb{V}_k)\in\mathcal{L}^\tau} x^\tau_{\mathbb{I}_i,\mathbb{V}_k}, \tag{16}$$

$$\sum_{\mathbb{V}_k:(\mathbb{V}_k,\mathbb{I}_i)\in\mathcal{L}^\tau} x^\tau_{\mathbb{V}_k,\mathbb{I}_i} \leq \sum_{\mathbb{V}_k:(\mathbb{I}_i,\mathbb{V}_k)\in\mathcal{L}^\tau} x^\tau_{\mathbb{I}_i,\mathbb{V}_k} + M z^\tau_{\mathbb{I}_i}, \tag{17}$$

System Model and Problem Formulation

SC-aware Routing Problem Formulation

With the goal of minimizing end-to-end delays while ensuring that the SC requirements of application $\mathcal{A}$ are met, the problem is finally formulated as:

$$\textbf{P1}: \min \sum_{(\mathbb{V}_i,\mathbb{V}_j)\in\mathcal{L}^\tau} x^{\tau}_{\mathbb{V}_i,\mathbb{V}_j} \cdot d^{\tau}_{\mathbb{V}_i,\mathbb{V}_j}$$

$$\text{s.t. } (1)-(10),(14)-(17).$$

Analysis and Observation

- **P1** is an integer linear programming (ILP) problem.
- **P1** can be solved by commercial integer programming solvers, such as Gurobi, using the branch and bound (B&B) method.
- The B&B for solving **P1** has a worst-case time complexity of $\mathcal{O}((|\mathcal{L}^\tau| + |\mathcal{I}|) \cdot H^{(|\mathcal{I}|+|\mathcal{L}^\tau|)})$, which grows exponentially with the number of lthe number of links and AI satellites. Thus, it is crucial to devise more efficient solving schemes.

Proposed Schemes

Optional-1: KSP-based Brute-Force Path Searching Method

Input: The snapshot graph $\mathcal{G}^{\tau} = \{\mathcal{V}^{\tau}, \mathcal{L}^{\tau}\}$, and the application $\mathcal{A}$.

Output: The shortest path p_* for SC.

Initialization: $\mathcal{G}^{\tau}_{C_a \cdot \sigma_a} \leftarrow \mathcal{G}^{\tau}$, $k_{\text{threshold}} = \lambda$(e.g., 1000), $k = 0$.

for each $(\mathbb{V}_i, \mathbb{V}_j) \in \mathcal{L}^{\tau}$ **do**

  if $c^{\tau}_{(\mathbb{V}_i, \mathbb{V}_j)} < C_a \cdot \sigma_a$ **then**

    Delete $(\mathbb{V}_i, \mathbb{V}_j)$ from residual snapshot graph $\mathcal{G}^{\tau}_{C_a \cdot \sigma_a}$.

while $k \leq k_{\text{threshold}}$ **do**

  Update $k = k + 1$

  Search for the k-th shortest $(\mathbb{S}_a - \mathbb{D}_a)$ path p_k in $\mathcal{G}^{\tau}_{C_a \cdot \sigma_a}$.

  if $\exists \mathbb{I}_{\xi} \in p_k, b^{\theta_a}_{\mathbb{I}_{\xi}} \geq 1$ **then**

    Update $p_* \longleftarrow p_k$. **break**

return p_*.

Proposed Schemes

The drawbacks of the Brute-Force method

- **Uncertainty:** As **Algorithm 1** operates in a brute-force manner, a appropriate threshold λ must be set to prevent it from not stopping.
- **Sub-optimality:** While **Algorithm 1** is polynomial-time, it can not ensure the optimal solution since it only allow simple paths.
- **Instability:** In "good" cases with sufficient AI satellites and bandwidths, **Algorithm 1** terminates quickly. However, in less favorable scenarios, even after exhaustively exploring K paths, it is possible that a feasible path may still not be found.

Complexity analysis

- In fact, **Algorithm 1** has a worst-case complexity $\mathcal{O}(\lambda(|\mathcal{L}^\tau| + |\mathcal{V}^\tau| \log |\mathcal{V}^\tau|))$, where $\mathcal{O}(|\mathcal{L}^\tau| + |\mathcal{V}^\tau| \log |\mathcal{V}^\tau|)$ is the complexity of KSP computing a single path using the Dijkstra's algorithm. While **Algorithm 1** is polynomial-time by setting the threshold λ, it is sub-optimal.

Proposed Schemes

Option-2: Optimal SC-aware Routing (SGR) Scheme

1. **Input:** The snapshot graph $\mathcal{G}^{\tau} = \{\mathcal{V}^{\tau}, \mathcal{L}^{\tau}\}$, and the application $\mathcal{A}$.
2. **Init:** $\mathcal{G}^{\tau}_{\mathbb{S}_a \to \mathcal{I}} = \mathcal{G}^{\tau}_{\mathbb{D}_a \to \mathcal{I}} = \varnothing$, $\mathcal{I}_{\text{forward/backward}} = \emptyset$, $p_* = \varnothing$, and $D_{p_*} = \infty$.
3. **Step-1.A Forward path pre-computing:**
4. **for** each $(\mathbb{V}_i, \mathbb{V}_j) \in \mathcal{L}^{\tau}$ **do**
5.   **if** $c^{\tau}_{(\mathbb{V}_i, \mathbb{V}_j)} \geq C_a$ **then** Insert edge $(\mathbb{V}_i, \mathbb{V}_j)$ into $\mathcal{G}^{\tau}_{\mathbb{S}_a \to \mathcal{I}}$.
6.   **if** $\mathbb{V}_i / \mathbb{V}_j \in \mathcal{I}$ and $b^{\theta_a}_{\mathbb{V}_i} / b^{\theta_a}_{\mathbb{V}_j} \geq 1$ **then** $\mathcal{I}_{\text{forward}} \leftarrow \mathcal{I}_{\text{forward}} \cup \{\mathbb{V}_i\} / \{\mathbb{V}_j\}$.
7. Run shortest path algorithm from $\mathbb{S}_a$ to every AI satellites within $\mathcal{I}_{\text{forward}}$.
8. **Step-1.B Backward path pre-computing: (The same as Step-1.A)**
9. **Step-2. SC-aware shortest path selection:**
10. **for** each AI satellite $\mathbb{I}_i \in \mathcal{I}_{\text{forward}} \cap \mathcal{I}_{\text{backward}}$ **do**
11.   **if** $D_{p_{(\mathcal{S}_a, \mathbb{I}_i)}} + D_{p_{(\mathcal{D}_a, \mathbb{I}_i)}} = T \leq D_{p_*}$ **then** $D_{p_*} = T$, $p_* = p_{(\mathcal{S}_a, \mathbb{I}_i)} + \bar{p}_{(\mathcal{D}_a, \mathbb{I}_i)}$.
12. **return** The SC-aware shortest path p_*.

Proposed Schemes

The advantages of the proposed SCR algorithm

- **Polynomial:** The SC-aware routing scheme comprises three key steps: forward path pre-computing, backward path pre-computing, and SC-aware shortest path selection.
- **Optimal:** Both simple paths and non-simple paths in feasible solution space are covered. The SC-aware routing scheme is optimal.

Complexity analysis

- Based on the SCR, both of **Step-1.A** and **Step-1.B** require $\mathcal{O}(|\mathcal{L}^\tau|) + \mathcal{O}(|\mathcal{L}^\tau| + |\mathcal{V}^\tau| \log |\mathcal{V}^\tau|) = \mathcal{O}(2|\mathcal{L}^\tau| + |\mathcal{V}^\tau| \log |\mathcal{V}^\tau|)$ operations, where $\mathcal{O}(|\mathcal{L}^\tau| + |\mathcal{V}^\tau| \log |\mathcal{V}^\tau|)$ denotes the time complexity of Dijkstra's algorithm. **Step-2** requires $\mathcal{O}(|\mathcal{I}|)$ operations. As a result, in the worst-case, SCR has a polynomial time complexity $\mathcal{O}(4|\mathcal{L}^\tau| + 2|\mathcal{V}^\tau| \log |\mathcal{V}^\tau|) + |\mathcal{I}|$.

Simulation

A. Scenarios

- We use Starlink constellation with 100-1,200 Starlink satellites.

B. Parameters

- Four GSs located at: Xi'an ($34.27^\circ N, 108.93^\circ E$), Kashi ($39.5^\circ N, 76^\circ E$), Sanya ($18^\circ N, 109.5^\circ E$) and Beijing ($40^\circ N, 116^\circ E$).
- We set the number of KBs $|\Theta| = 3$. The SC encoder compression ratios are randomly selected from $\{0, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}\}$.
- We randomly set starlink satellites as either user satellites, relay satellites or AI satellites with probabilities of 20%, 60% and 20%.
- ISLs and GSLs: bandwidths 300 $\tilde{3}$50 Mbps, and link delays 5 $\tilde{1}$5 ms.
- 5,000 applications with raw data rate between 5 and 100 Mbps.

C. Algorithms

- ILP-based method, KSP-based brute-force method, the proposed SCR, the existing CGR, and "Hybrid SCR+CGR").
- All the algorithms are implemented using Python.

Simulation Results

1. Figure 2 shows average running times versus satellite numbers. Both the brute-force method and SCR are significantly faster compared to the ILP solver, with SCR faster than the brute-force method.
2. Figure 3 compares three methods supporting SC (brute-force, SCR, Hybrid SCR+CGR) with traditional CGR. More satellites bring higher acceptance ratios except brute-force. Compared to CGR, SCR brings significant gain, which can be further enhanced by Hybrid SCR+CGR.

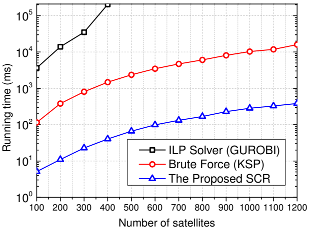

Figure: Running times v.s. numbers of satellites.

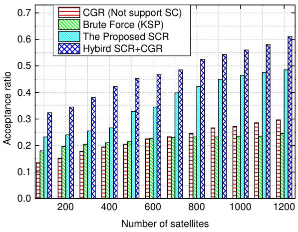

Figure: Acceptance ratios v.s. numbers of satellites.

Simulation Results

1. Figures 4 and 5 plot the data throughput and average path delay versus the number of satellites. All algorithms supporting SC achieve higher throughput and lower path delay than CGR. The brute-force method can achieve higher throughput compared to CGR. However, the lowest path delay achieved by the brute-force compromising acceptance ratios. Meanwhile, the highest throughput achieved by Hybrid SCR+CGR is at the cost of increased path delay.

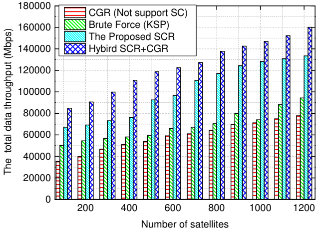

Figure: Data throughputs v.s. numbers of satellites.

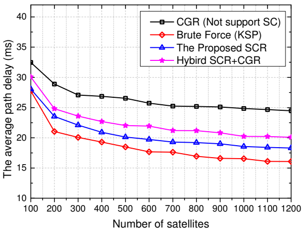

Figure: Average delays v.s. numbers of satellites.

Conclusion

1. We formulate the SC-aware routing problem in SN as an ILP, which incurs $\mathcal{O}((|\mathcal{L}^\tau| + |\mathcal{I}|) \cdot H^{(|\mathcal{I}|+|\mathcal{L}^\tau|)})$ time complexity and is intractable in practice.
2. By adopting a KSP-based brute-force method, the time complexity becomes $\mathcal{O}(\lambda(|\mathcal{L}^\tau| + |\mathcal{V}^\tau| \log |\mathcal{V}^\tau|))$, which is sub-optimal and has drawbacks, resulting in compromised performance in practice.
3. To overcome this, we further design a SC-aware routing (SCR) algorithm, which can obtain the optimal solution in polynomial time with a computational complexity of $\mathcal{O}(4|\mathcal{L}^\tau| + 2|\mathcal{V}^\tau| \log |\mathcal{V}^\tau|) + |\mathcal{I}|$.
4. Simulations conducted on starlink constellation with thousands of satellites demonstrate that the SCR can not only be capable of achieving optimal solutions efficiently, but also can bring significant performance gains compared to existing CGR.
5. Our routing scheme can support the deployment of in-orbit semantic communication over satellite networks in future.

Thank you for listening!

Feel free to contact us via Wechat ↑ or E-mail ↓ if you have any questions.

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