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ENGAGING THE WORLD

StarStream: Live Video Analytics over Space Networking

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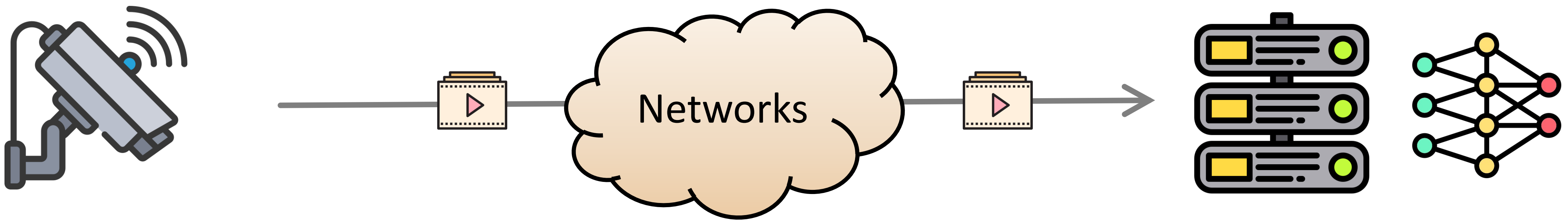
BACKGROUND

❖ Live Video Analytics (LVA) Streaming

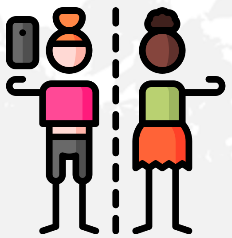


Cameras typically do not have sufficient resources for in-situ analytics.

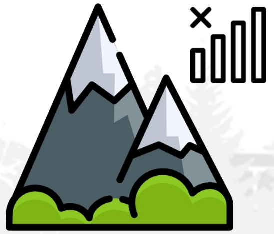
Resource-rich edge/cloud servers

Status: Almost all existing LVA systems are built over terrestrial networks.

1/3 of the earth's population remains disconnected.



Many remote and rural areas have not been covered.



Disruptions from extreme weather, natural disasters, etc.

BACKGROUND

❖ LEO Satellite Networking (LSN): A Game-Changer

Low Orbit altitudes at below 2,000 km vs. GEO 35,786 km

Lower network latency. Reduced signal travel distance to Earth (LEO vs. GEO: 25+ vs 600+ ms)

Smaller coverage. Truly global coverage with mega-constellation, e.g., Starlink has launched more than 7,000 satellites up to date.

STARLINK

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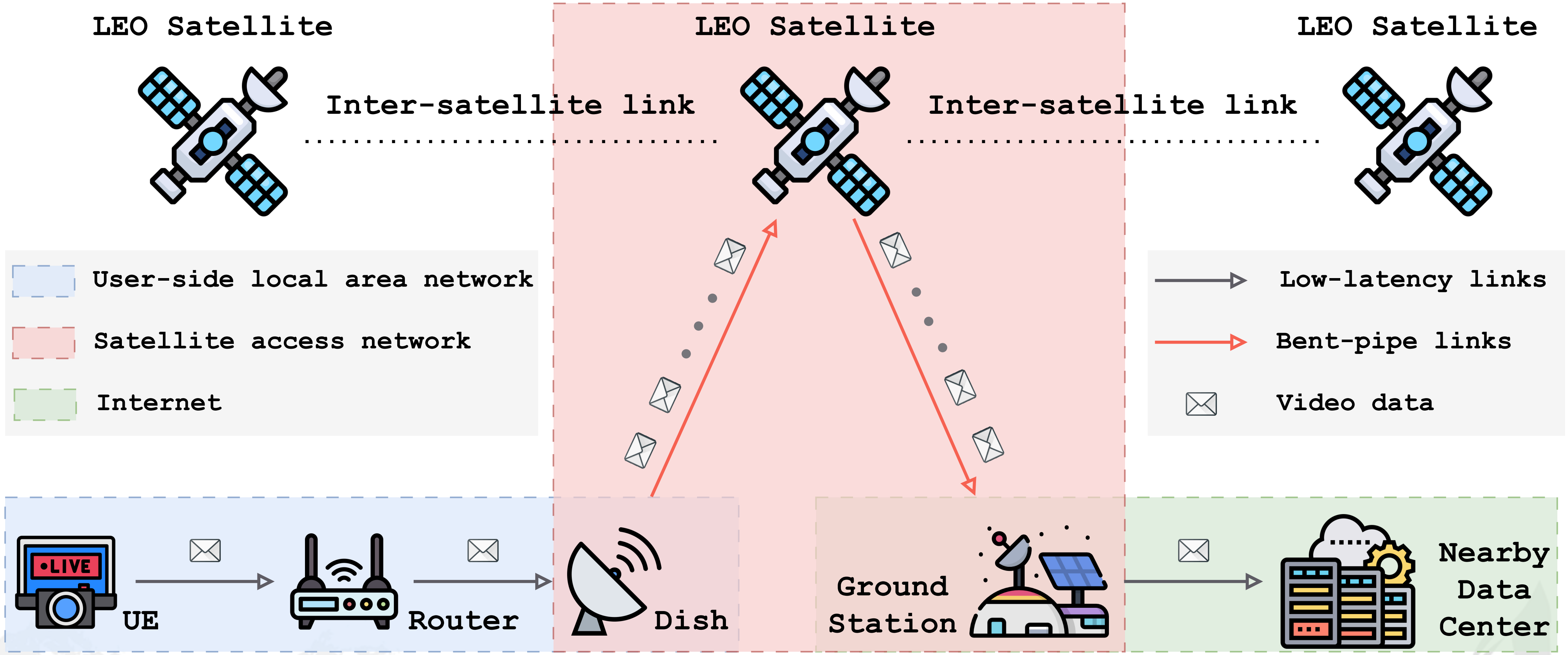
Higher network throughput. LEO vs. GEO: 178 vs 82 Mbps median download speed [1].

Relative motion to Earth. The orbital period of LEO satellites is typically 90-120 minutes; Handovers can happen as frequently as every 15 seconds [2].

[1] Michel, François, et al. "A First Look at Starlink Performance." in Proceedings of IMC'22.

[2] Ma, Sami, et al. "LEO Satellite Network Access in the Wild: Potentials, Experiences, and Challenges." IEEE Network, 2024.

OVERVIEW



An Overview of LSN-enabled LVA

LSN ACCESS NETWORK PERFORMANCE

- **LEO Internet service provider:** Starlink
- **Mobile device:** Raspberry Pi 4 Model B
- **Edge servers:** AWS and Google Cloud Platform
- **Throughput measurement tool:** IPerf3 utility
- **RTT measurement tool:** Ping utility

Network performance metrics	gc-server	aws-server
Download throughput (Mbps)	83.4 ± 60.5	110.1 ± 57.5
Upload throughput (Mbps)	8.1 ± 3.3	8.4 ± 5.2
Round-trip time (RTT, ms)	46.9 ± 14.4	40.5 ± 16.4

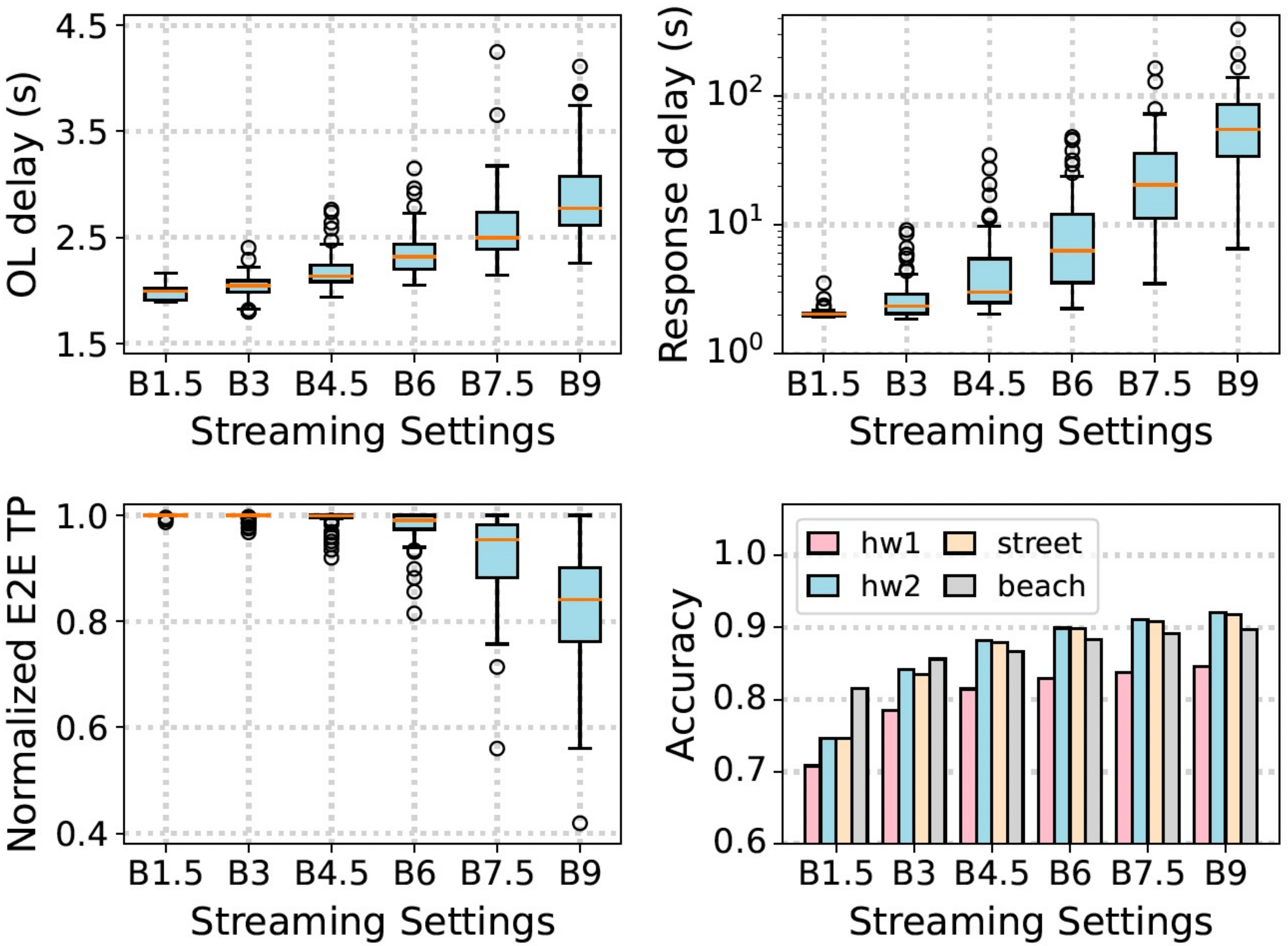
Decent network latency. Comparable to LTE (34.9 - 47.6 ms)[1]

Download-centric design. Download throughput / upload throughput > 10

Mean upload throughput << LTE (53.4 Mbps) and 5G mmWave (52.8-131.8 Mbps)[1]

[1] Ghoshal, Moinak, et al. "An In-Depth Study of Uplink Performance of 5G mmWave Networks." in Proceedings of the ACM SIGCOMM Workshop, 2022.

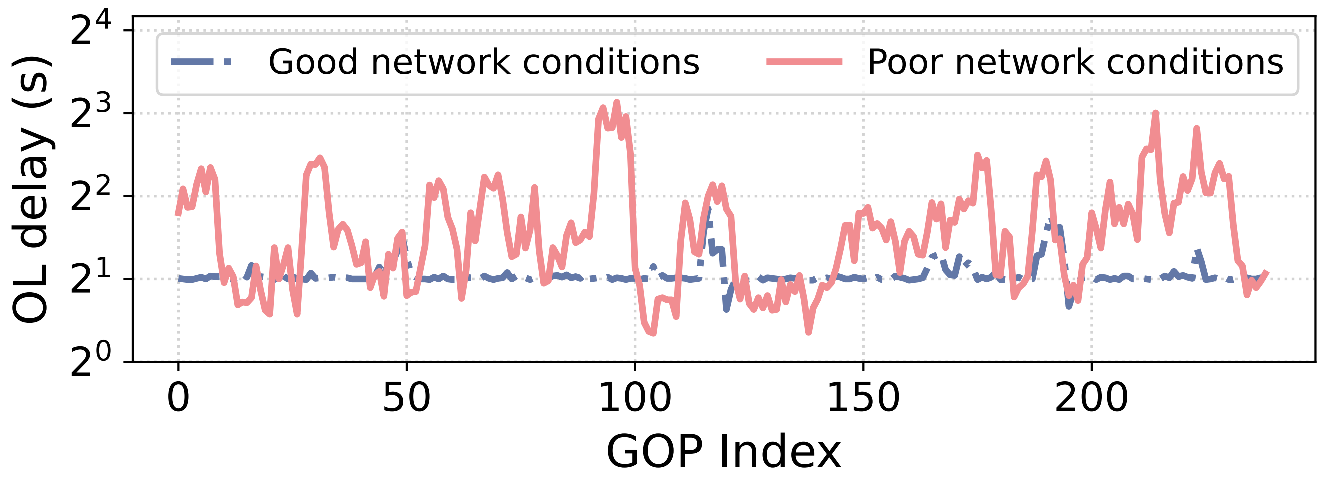
IN-THE-WILD LVA PERFORMANCE OVER STARLINK



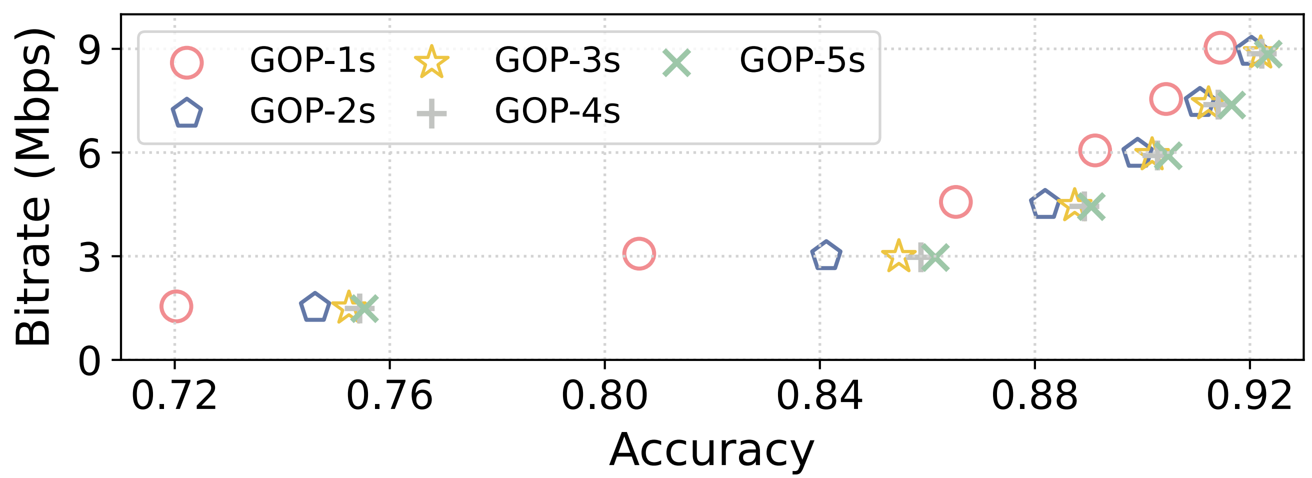
- It is still challenging for today's LSN to support real-time LVA streaming at bitrates higher than 6 Mbps.
- The dynamics in underlying network conditions can dramatically affect the LVA-perceived performance.

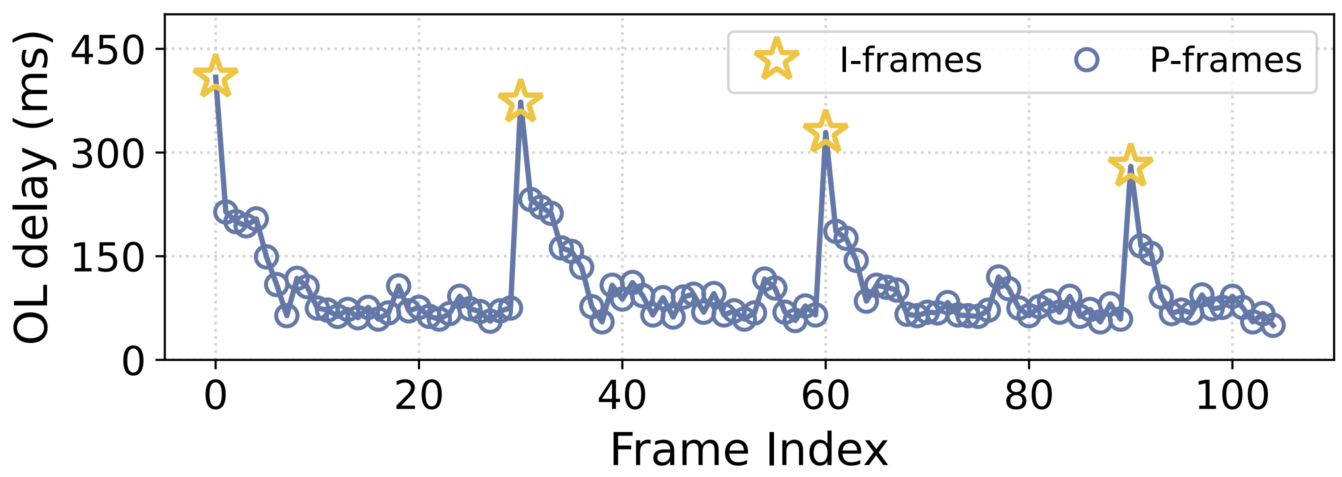
OL delay: Offloading delay over LSN (GOP: 2 seconds)
E2E TP: End-to-End throughput
B#: Streaming with H.264 and RTMP at the bitrate of # Mbps

IN-THE-WILD LVA PERFORMANCE OVER STARLINK

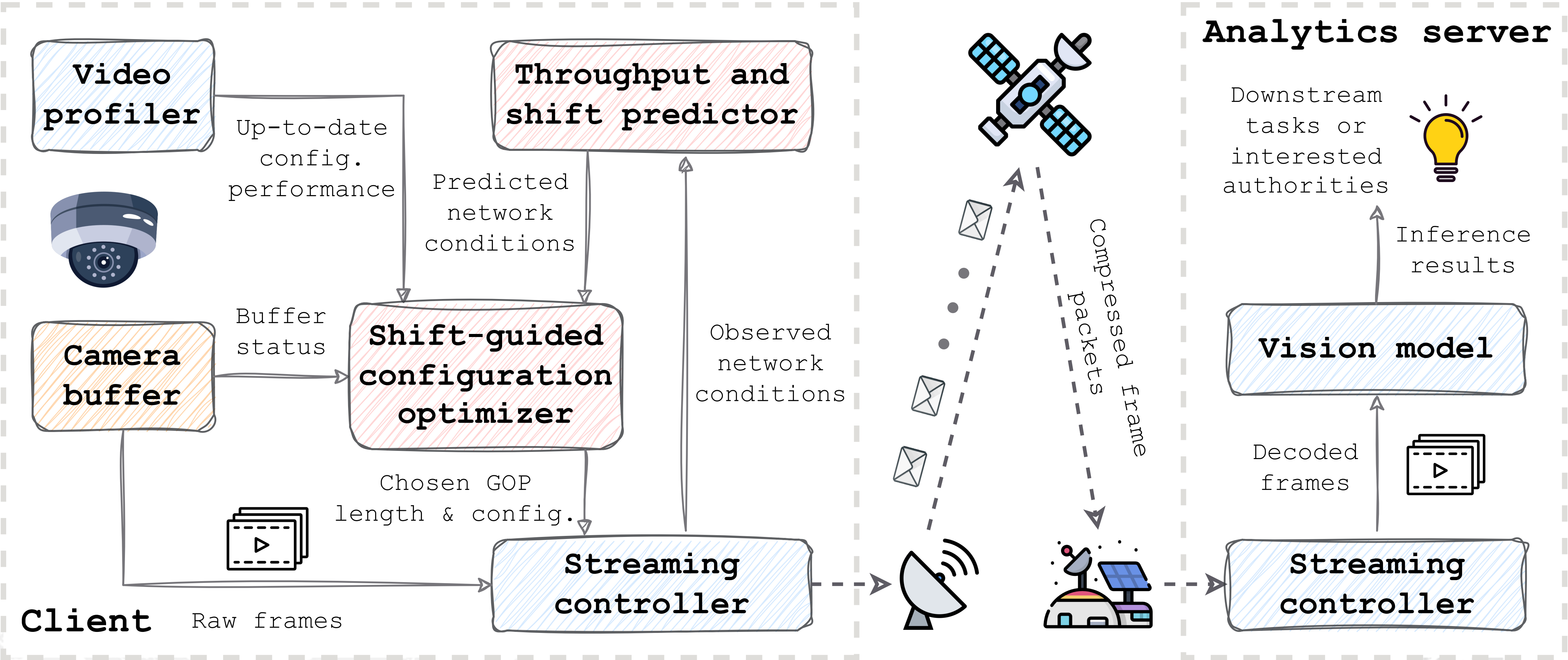


❖ Coarse-grained adaptation is adequate for good network conditions, while poor network conditions necessitate fine-grained adaptations.





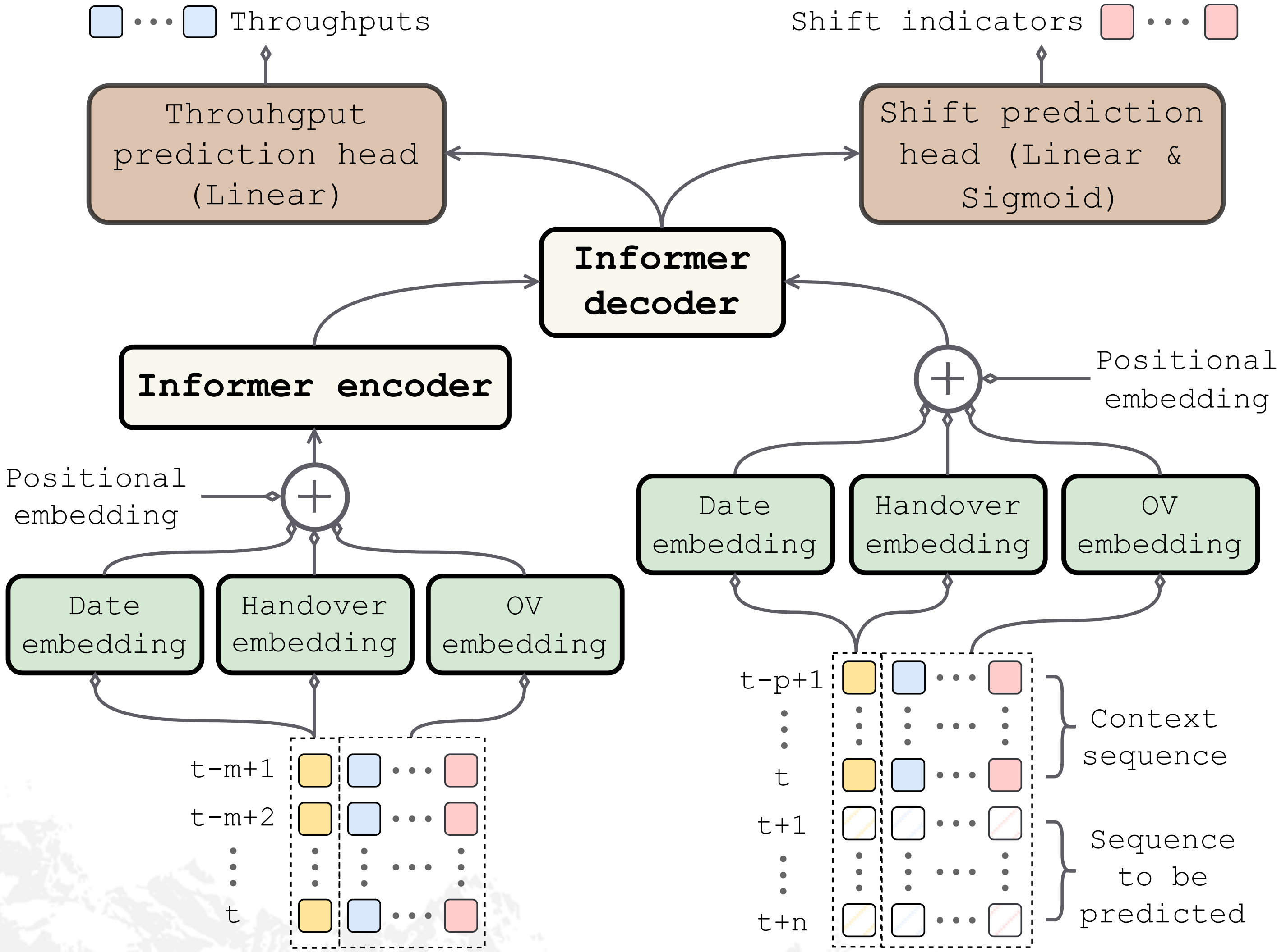
❖ Increasing GOP length can both benefit accuracy and delay stability.



System Overview of StarStream

LSN UPLINK PERFORMANCE PREDICTION

- A throughput shift occurs at time step t if the difference between the throughput b_t and b_{t-1} is greater than a predefined threshold.



Observable Variables (OV): Past throughputs and their shifts, as well as TCP connection statistics.

Architecture of the proposed LSN throughput and shift predictor

SHIFT-GUIDED CONFIGURATION OPTIMIZATION

GOP length selection Based on the predicted throughput shifts indicators.

$$\underset{c_{k1},\cdots,c_{k2}}{\arg\max} \quad \sum_{k=k1}^{k2} \alpha A_k(c_k) - \beta Q_k$$

$$s.t. \quad \begin{cases} \bar{b}_k = \frac{1}{t_k - t_{k-1}} \int_{t_{k-1}}^{t_k} b_t \, dt \\ t_k = t_{k-1} + \sum_j e_j(c_k) + \frac{\sum_j d_j(c_k)}{\bar{b}_k} + \Delta t_k \\ Q_k = Q_{k-1} + (t_k - t_{k-1}) - L_k \\ c_k \in C, \qquad \forall k = k1, \cdots, k2 \end{cases}$$

Performance objectives: Maximizing the analytics accuracy and minimizing the lag by choosing an encoding configuration for each GOP, where lag is defined by the number of queued-up frames that wait to be processed.

Key solution ideas

- Content-aware configuration performance estimation.
- Solving the problem using a dynamic programming algorithm that follows the MPC paradigm.

EVALUATION

❖ Evaluation of Network Predictor

Network traces: Fine-grained LSN upload network traces collected from real-world setups, covering various times, locations, and weather conditions.

Baselines: Historical observation-based methods (HM, MA), classic machine learning methods (RF), neural network-based methods (FCN, LSTM, Seq2seq).

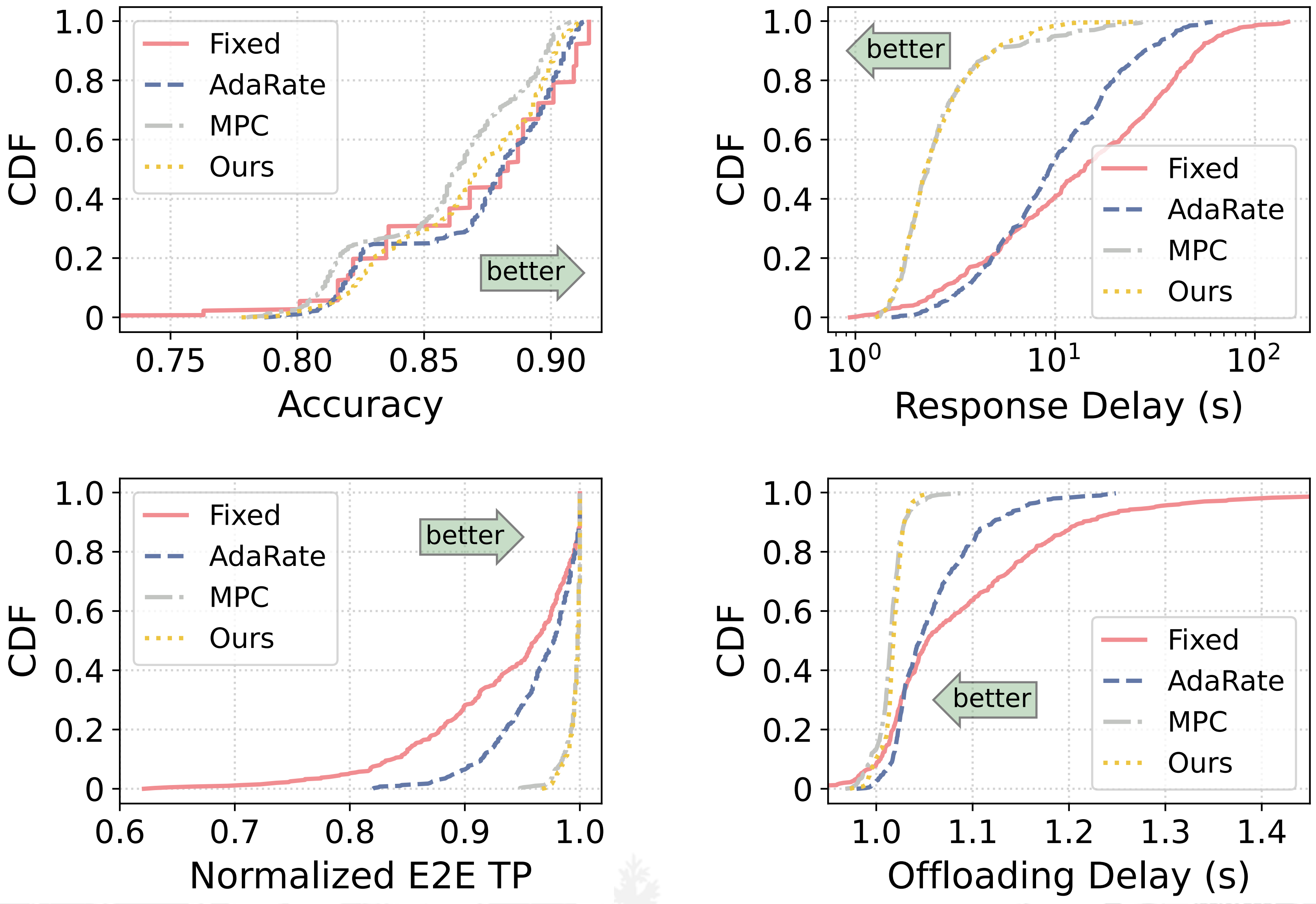
Methods	Throughput				Shift indicator	
	MAE	RMSE	MAPE	R^2	Accuracy	F1
HM [36]	4.019	5.275	57.095	−0.709	0.670	0.074
MA [15]	3.166	4.045	52.173	−0.005	0.671	0.065
RF [1]	2.577	3.388	42.695	0.295	0.682	0.025
FCN [34]	2.493	3.302	41.042	0.330	0.684	0.040
LSTM [12]	2.472	3.281	40.513	0.339	0.684	0.041
Seq2seq [20]	2.463	3.274	40.383	0.342	0.685	0.053
Ours	2.435	3.248	39.244	0.352	0.706	0.467

Our predictor achieves the best performance on all evaluation metrics. This can be attributed to the introduction of the attention mechanism and embeddings of exogenous information.

❖ Evaluation of StarStream

StarStream achieves near real-time E2E processing and noticeable accuracy improvements compared with baselines at low system overheads.

Ablation studies further verify the effectiveness of our system component designs.



Overall performance comparisons of various methods on different videos

SUMMARY

- ❖ LVA applications built upon LSN show great potential in enabling otherwise challenging services, such as disaster response and relief and maritime surveillance.
- ❖ The uplink resources of LSNs are scarce and highly dynamic, preventing upper-layer applications from delivering consistent quality of experience.
- ❖ It remains hard for today's LSN to support high-quality real-time LVA streaming without network adaptations.
- ❖ With specialized designs tailored for LSN, StarStream enhances LVA performance and bridges the gap between LSN and traditional LVA solutions.

THANK YOU