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Age of View: A New Metric for Evaluating Heterogeneous Information Fusion in Vehicular Cyber-Physical Systems

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Introduction <u>Background</u>

Vehicular Cyber-Physical System is a key enabler for future ITS

Technologies

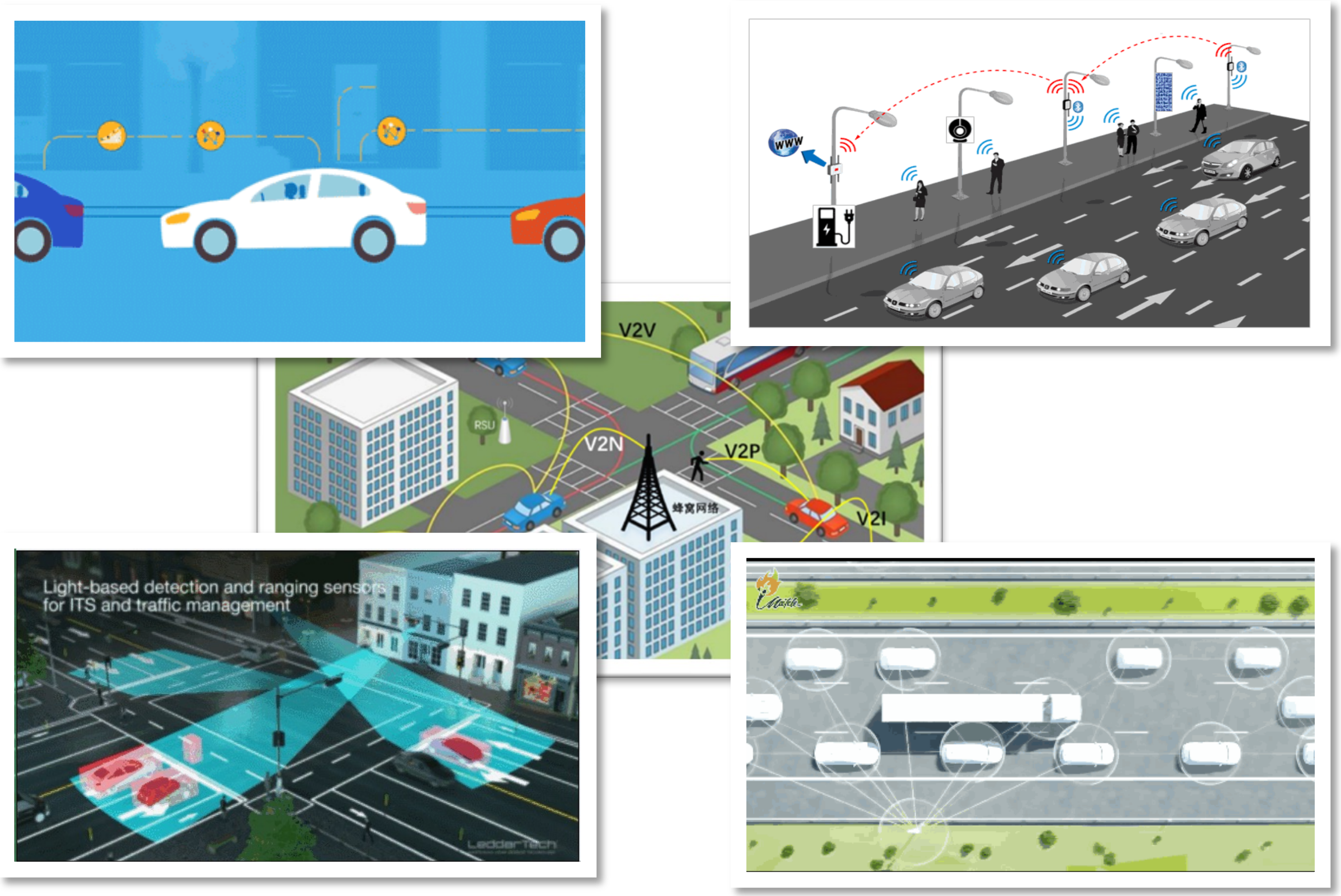
- Vehicles sense everything
- Vehicular communications (i.e., V2X)
- Vehicular edge computing (VEC)

Heterogeneous information

- Traffic lights
- Vehicle locations
- Point cloud data
- Traffic surveillance videos

Logical view

- To reflect the physical environment
- To support emerging ITS applications



Picture sources: http://www.xinhuanet.com//tech/2017-02/08/c_1120429310.htm, http://futureplantechnology.blogspot.com/2009/02/car-speed-control-using-bluetooth.html, https://www.mdpi.com/2079-9292/8/10/1177, https://www.eefocus.com/sensor/421706,

Introduction Scenario

Physical vehicular environment

Vehicles

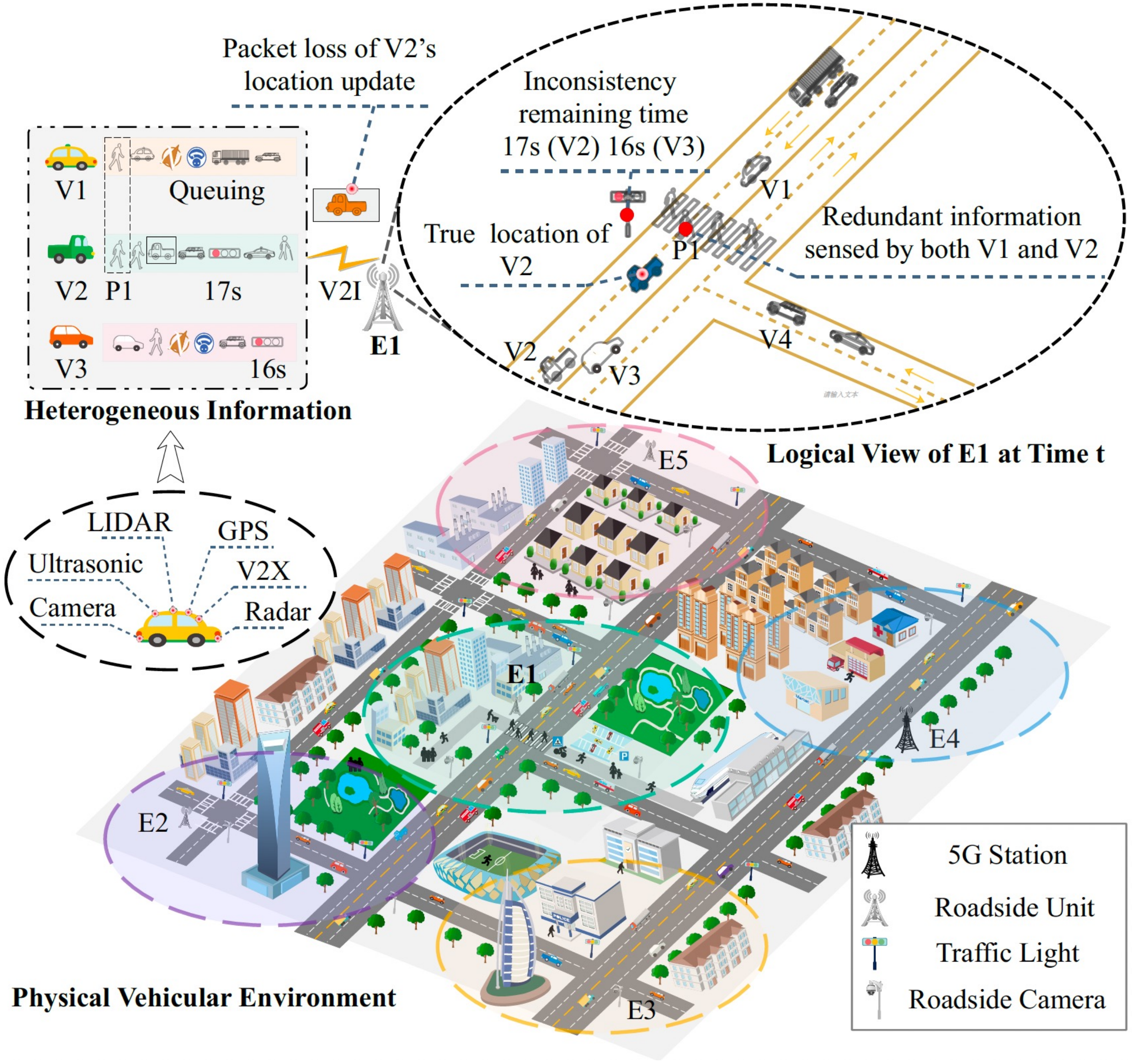
- Multi-class M/G/1 information queue
- Upload via V2I communications

Edge nodes (e.g., 5G stations, RSUs)

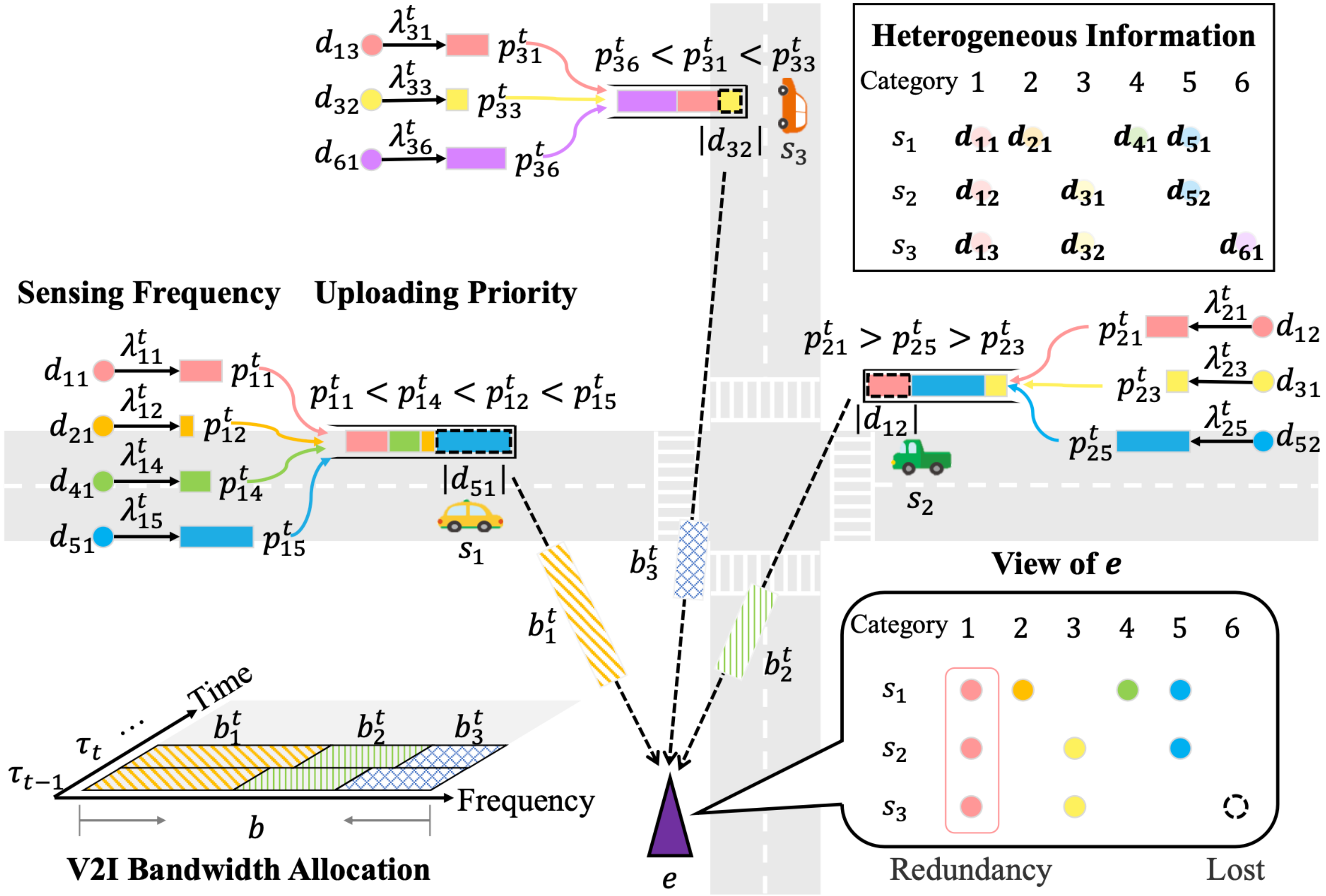
- Heterogeneous information fusion
- Logical view construction at edge

Logical view of edge node

- Information freshness
- Inconsistency
- Packet loss



Age of View Formulation <u>System Model</u>



Vehicles

- Sensing and uploading information
- Sensing frequency
- Uploading priority

Edge nodes

- V2I bandwidth allocation

Age of view (AoV)

- Timeliness
- Completeness
- Consistency

Age of View Formulation <u>Definition</u>

<u>Timeliness of view</u> $\boldsymbol{v_g}$

- Sum of inter-arrival time, queuing time, and transmission time

$$\theta_g = \sum_{\forall v_{ij}^t \in v_g} v_{ij}^t \cdot \mathbb{P}_{ij}^t \cdot \left(int_{ij} + wai_{ij} + tra_{ij}\right)$$

<u>Completeness of view</u> $\boldsymbol{v_g}$

- Ratio between received and required information

$$\chi_g = \frac{\sum_{\forall v_{ij}^t \in v_g} v_{ij}^t \cdot \mathbb{P}_{ij}^t}{\sum_{\forall v_{ij}^t \in v_g} v_{ij}^t}$$

<u>Consistency of view</u> $\boldsymbol{v_g}$

- Quadratic sum of the difference between received time and average

$$\xi_g = \sum_{\forall v_{ij}^t \in v_g} \left| wai_{ij} + tra_{ij} - \frac{\sum_{\forall v_{ij}^t \in v_g} wai_{ij} + tra_{ij}}{\sum_{\forall v_{ij}^t \in v_g} v_{ij}^t \cdot \mathbb{P}_{ij}^t} \right|^2$$

<u>Age of view (AoV)</u>

- Weighted sum of normalized timeliness, completeness, and consistency

$$\mathrm{AoV}_g = \mathrm{W}_1 \hat{\theta_g} + \mathrm{W}_2\left(1 - \chi_g\right) + \mathrm{W}_3 \hat{\xi_g}$$

Age of View Formulation Problem

Minimizing the average AoV in scheduling period $\mathcal{T}$

$$\min_{\mathbf{\Lambda},\mathbf{P},\mathbf{B}} \frac{1}{|\mathcal{T}|}\sum_{\forall \tau_t \in \mathcal{T}} \frac{1}{|V_e^t|}\sum_{\forall v_g \in V_e^t} \mathrm{AoV}_g$$

Determined solution

- Sensing frequencies $\mathbf{\Lambda} = \{\lambda_{ij}^t \mid \forall D_{ij} \in D_i, \forall s_i \in S, \forall \tau_t \in \mathcal{T}\}$
- Uploading priorities $\mathbf{P} = \{p_{ij}^t \mid \forall D_{ij} \in D_i, \forall s_i \in S, \forall \tau_t \in \mathcal{T}\}$
- V2I bandwidth allocation $\mathbf{B} = \{b_i^t \mid \forall s_i \in S_e^t, \forall \tau_t \in \mathcal{T}\}$

Subject to

- Vehicle sensing ability requirement $\lambda_{ij}^t \in [\lambda_{ij}^{\min}, \lambda_{ij}^{\max}], \forall D_{ij} \in D_i, \forall s_i \in S, \forall \tau_t \in \mathcal{T}$
- Uploading priority constraint $p_{ij}^t \in (0,1), \forall D_{ij} \in D_i, \forall s_i \in S, \forall \tau_t \in \mathcal{T}$
- RSU bandwidth capacity constraint $b_i^t \in [0, b_e], \forall s_i \in S_e^t, \forall \tau_t \in \mathcal{T}$
- Queue steady-state guarantee $\sum_{\forall D_{ij} \in D_i} \lambda_{ij}^t \cdot \mathbb{E}[\mathrm{ser}_{ij}] < 1, \forall s_i \in S, \forall \tau_t \in \mathcal{T}$
- Allocated bandwidth constraint $\sum_{\forall s_i \in S_e^t} b_i^t \le b_e, \forall \tau_t \in \mathcal{T}$

Proposed Solution <u>Solution Model</u>

Multi-agent Difference-Reward-based deep reinforcement learning with Greedy Bandwidth Allocation (MDR-GBA)

Components

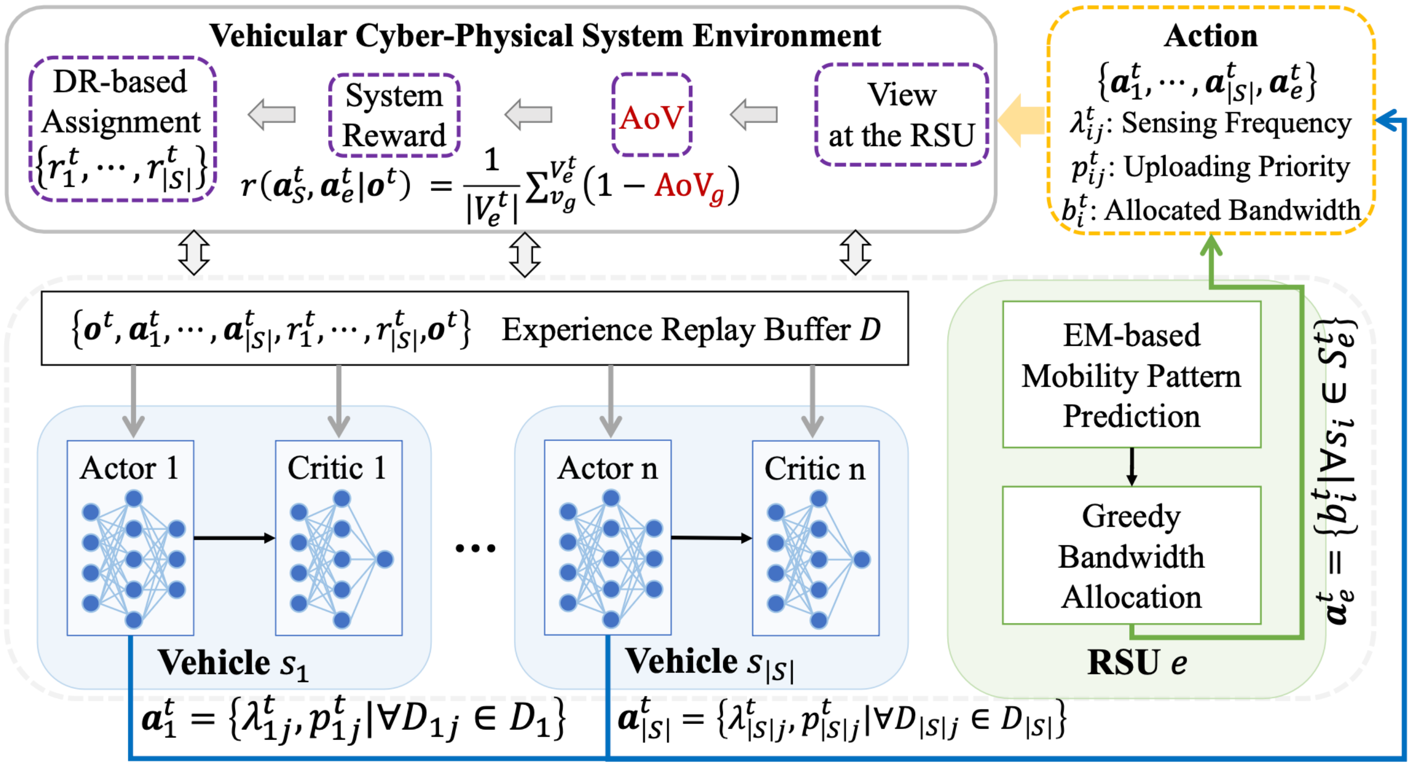
- $|S|$ vehicles and RSU e
- VCPS environment
- Experience replay buffer

Actions

- Vehicle via actor network
- RSU via greedy algorithm

Reward

- Difference reward assignment



Proposed Solution <u>Model Components</u>

System state

- Local observation of the system state in vehicle s_i $\quad \boldsymbol{o}_i^t = \{D_i^t, D_e^t, V_e^t\}$
- System state at time t (RSU observation) $\quad \boldsymbol{o}^t = \{D_1^t, \cdots, D_i^t, \cdots, D_{|S|}^t, D_e^t, V_e^t\}$

Action space

- Vehicle action space $\quad \boldsymbol{a}_i^t = \{\lambda_{ij}^t, p_{ij}^t \mid \forall D_{ij}^t \in D_i^t\}$
- RSU action space $\quad \boldsymbol{a}_e^t = \{b_i^t \mid \forall s_i \in S_e^t\}$

System reward

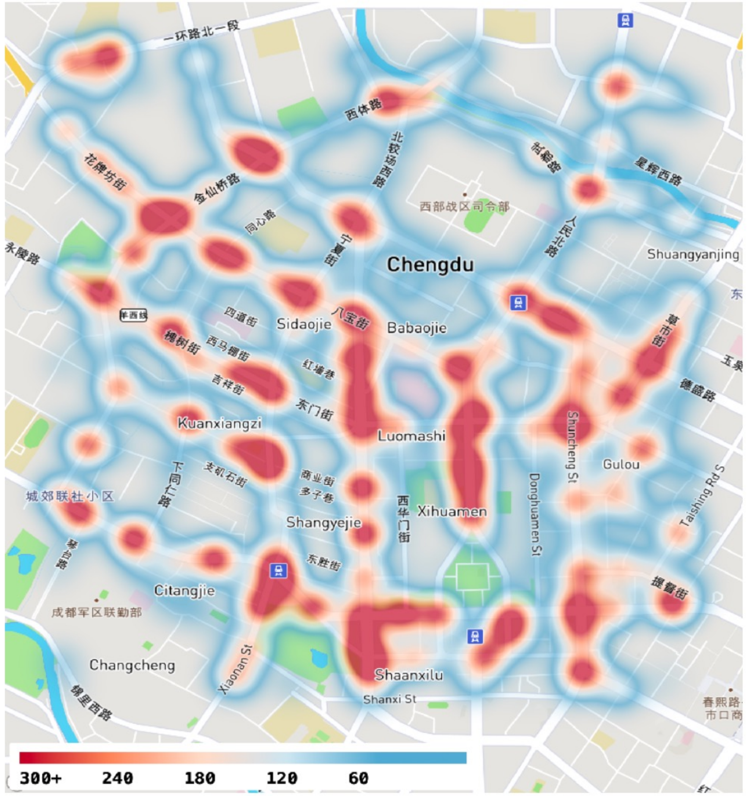
- Average of the complement of AoV $\quad r(\boldsymbol{a}_S^t, \boldsymbol{a}_e^t \mid \boldsymbol{o}^t) = \frac{1}{|V_k^t|} \sum_{v_g}^{V_k^t} (1 - \mathrm{AoV}_g)$
- Reward of vehicle s_i is obtained by different reward assignment

$$r_i^t = r(\boldsymbol{a}_S^t, \boldsymbol{a}_e^t \mid \boldsymbol{o}^t) - r\left(\boldsymbol{a}_{S-i}^t, \boldsymbol{a}_e^t \mid \boldsymbol{o}^t\right)$$

setting null action set of vehicle s_i

Performance Evaluation Settings

Heatmap of vehicle trajectories



- 3 km^2 area of Qingyang district in Chengdu, China from 8:00 am to 8:05 am on 16 Nov. 2016

Default settings

Description	Default Value	Description	Default Value
Information sizes	[100B, 1MB]	RSU bandwidth	3 MHz
Transmission power	1 mW	Channel fading gain	2-mean 0.4-variance
Path loss exponent	3	Noise	-90 dBm

Competitive solution

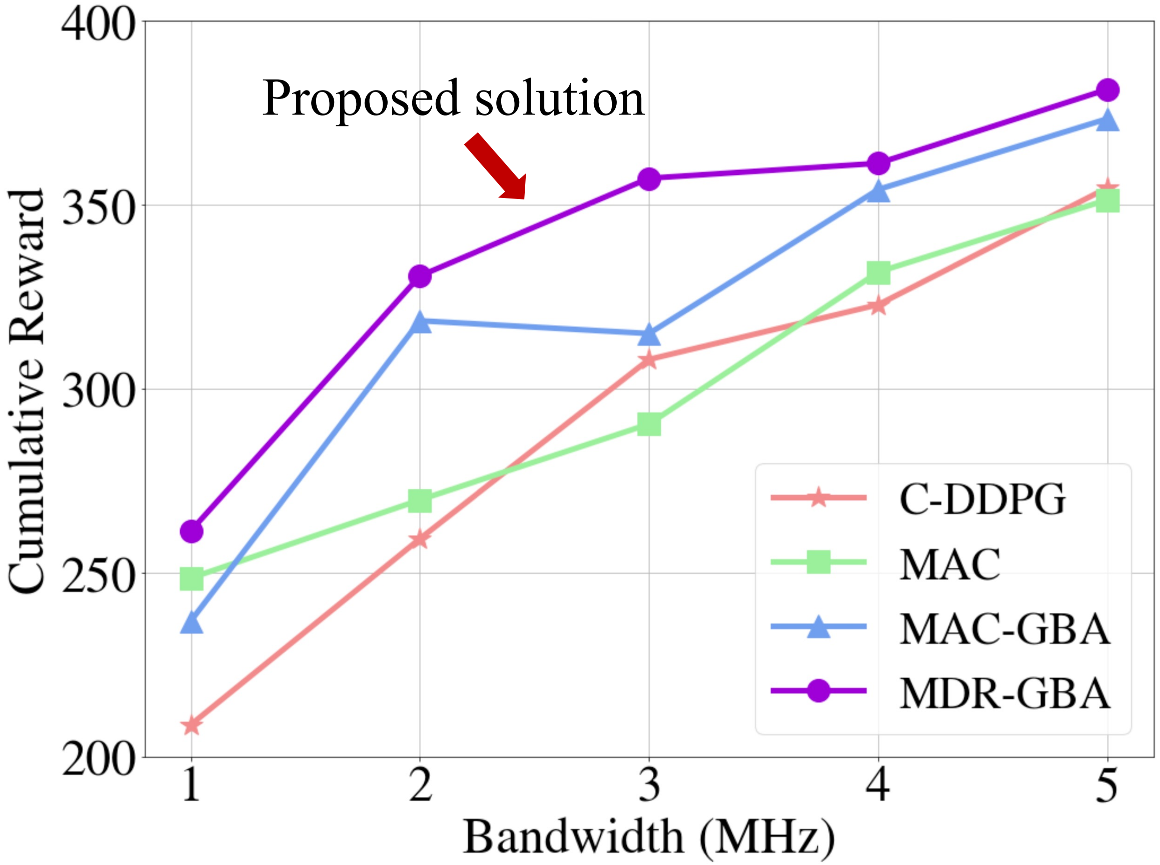
- Centralized Deep Deterministic Policy Gradient (**C-DDPG**)
- Multi-agent Actor-Critic (**MAC**)
- MAC with Greedy Bandwidth Allocation (**MAC-GBA**)

Metrics

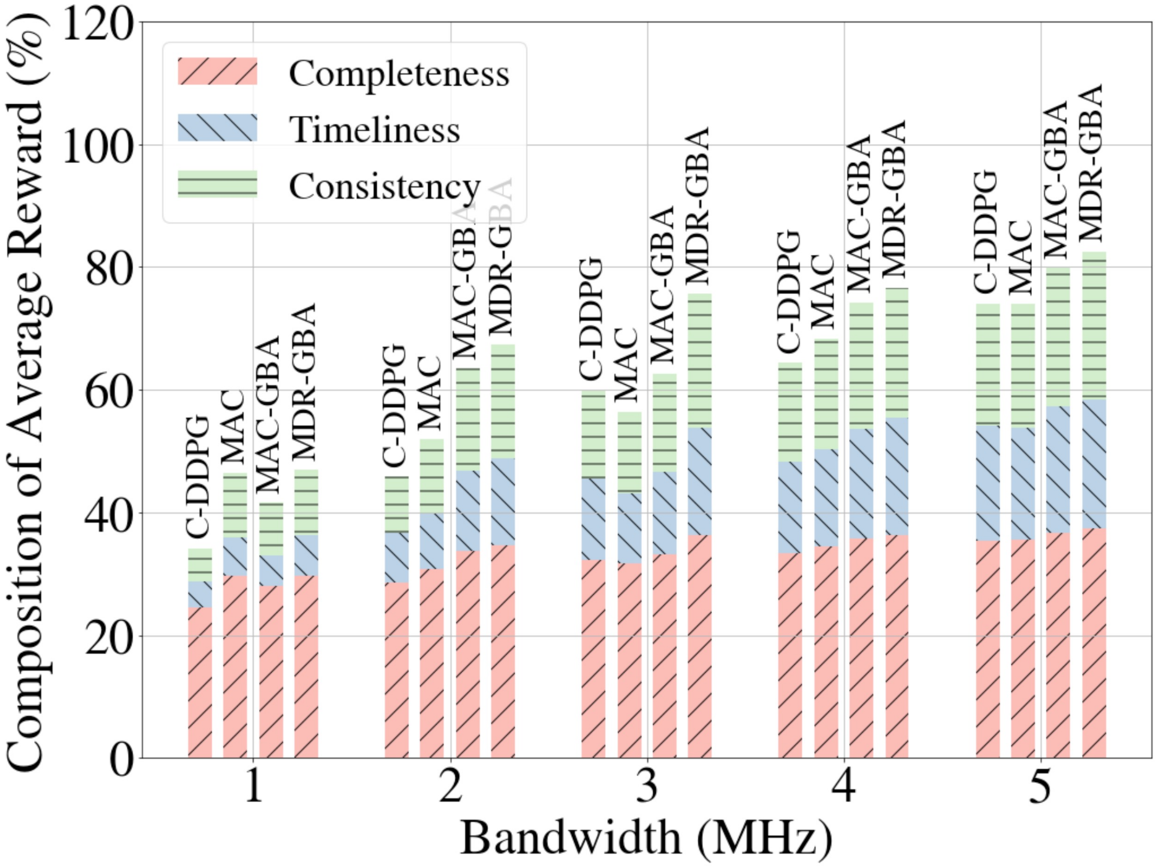
- Cumulative Reward (**CR**)
- Composition of Average Reward (**CAR**)
- Average Queuing Time (**AQT**) & Service Ratio (**SR**)

Performance Evaluation Results

Effect of RSU bandwidth



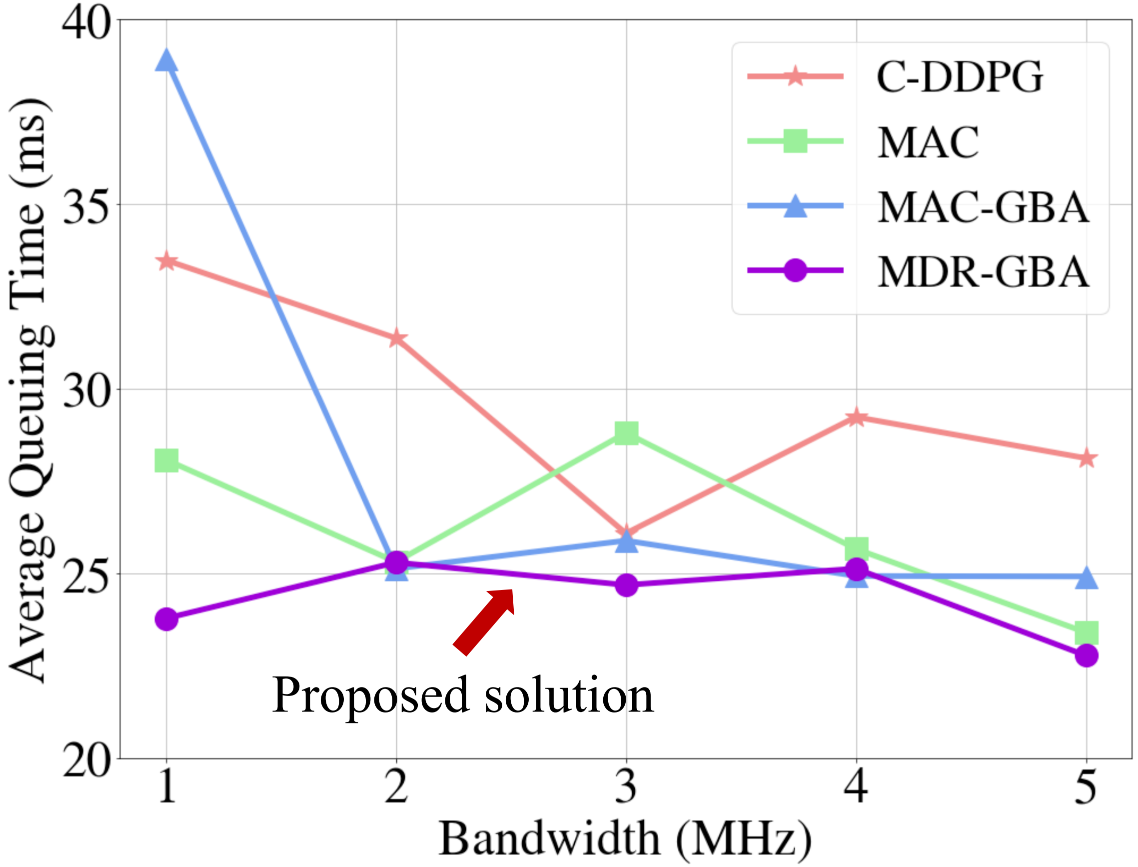
(a) CR under different RSU bandwidth



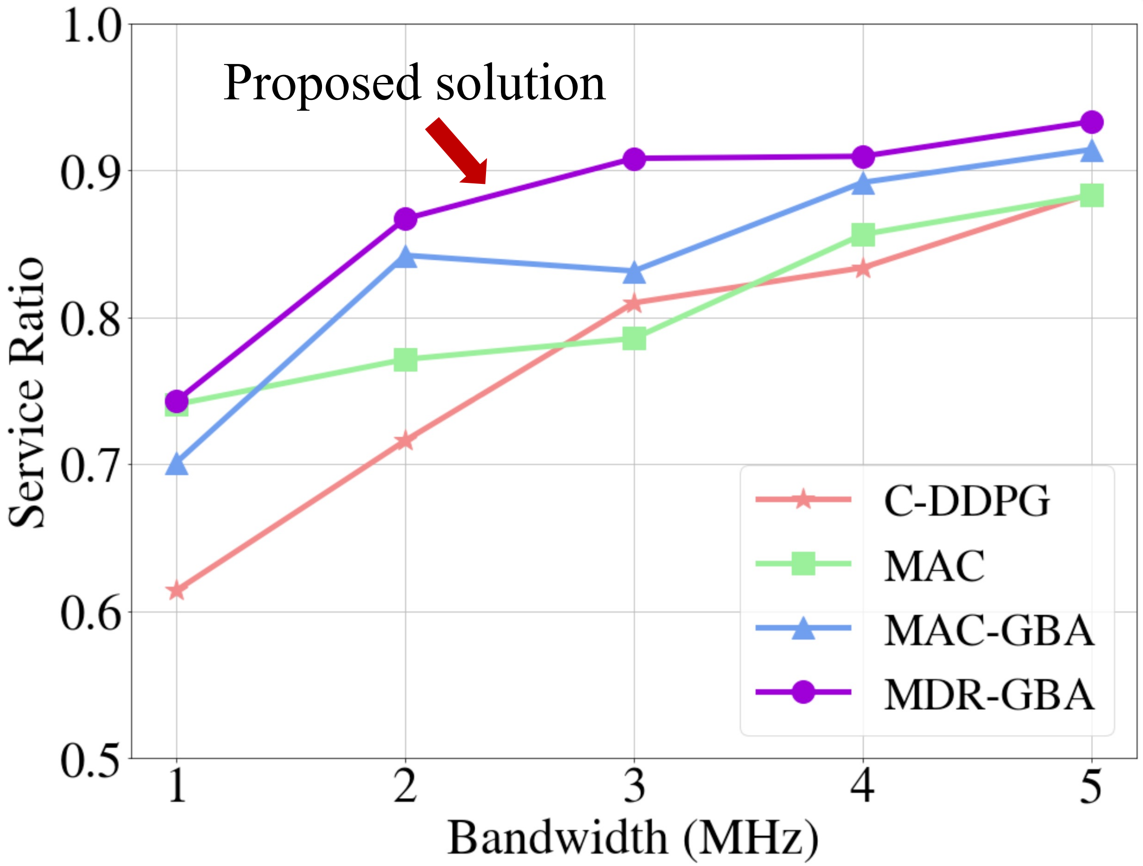
(b) CAR under different RSU bandwidth

Performance Evaluation Results

Effect of RSU bandwidth



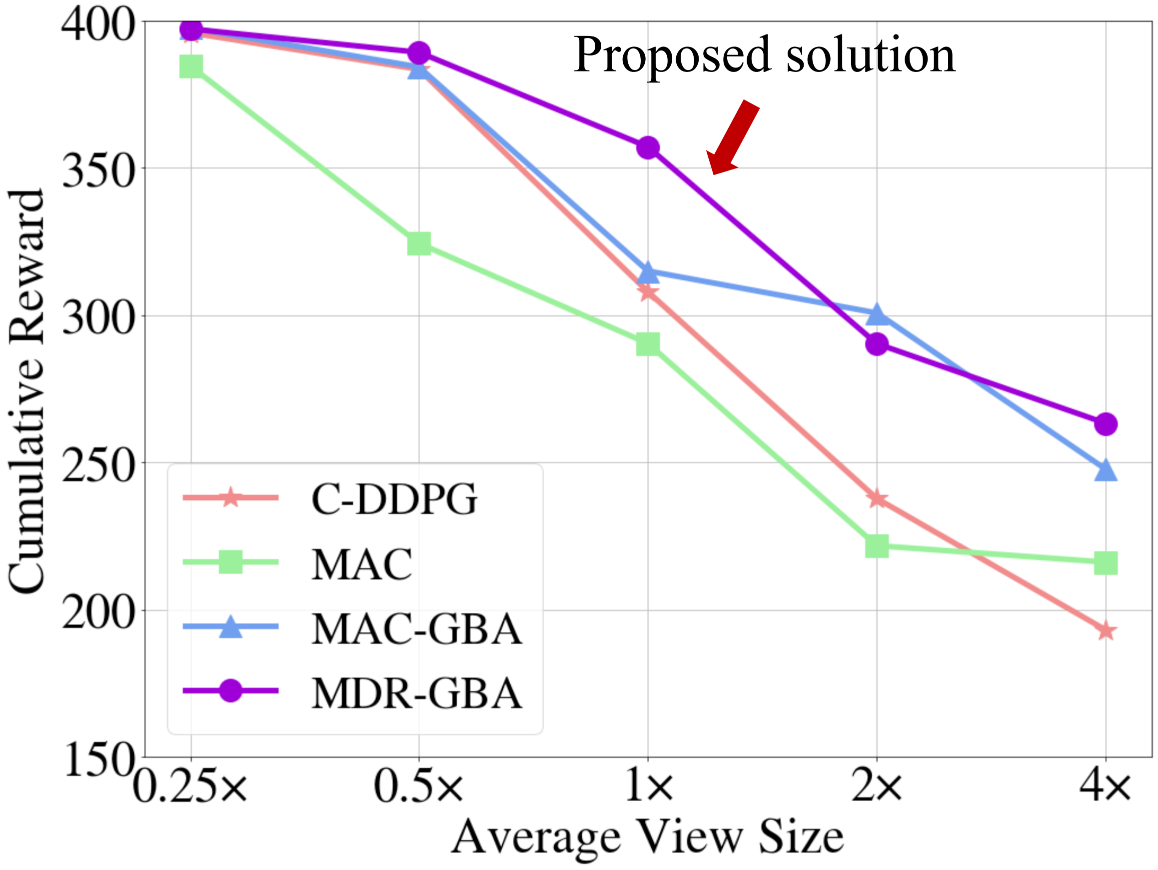
(c) AQT under different RSU bandwidth



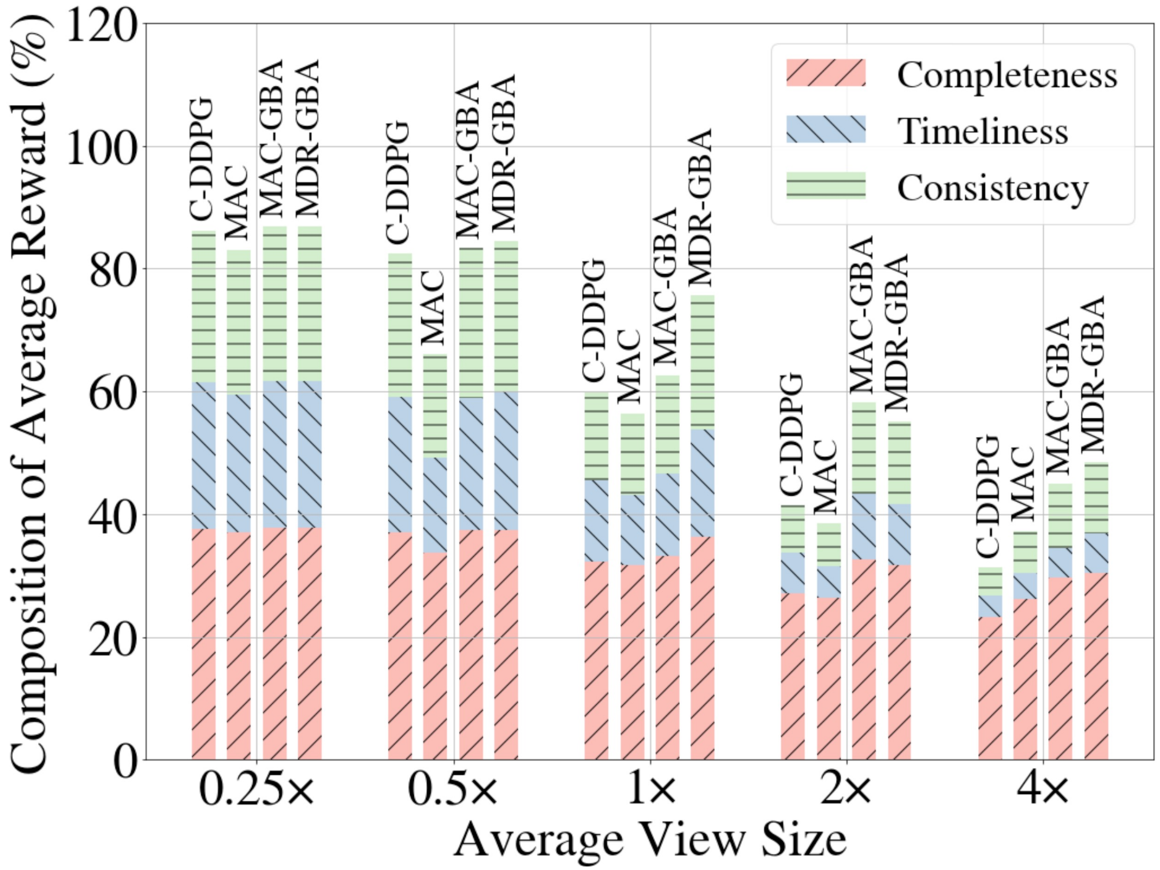
(d) SR under different RSU bandwidth

Performance Evaluation Results

Effect of application requirements on views



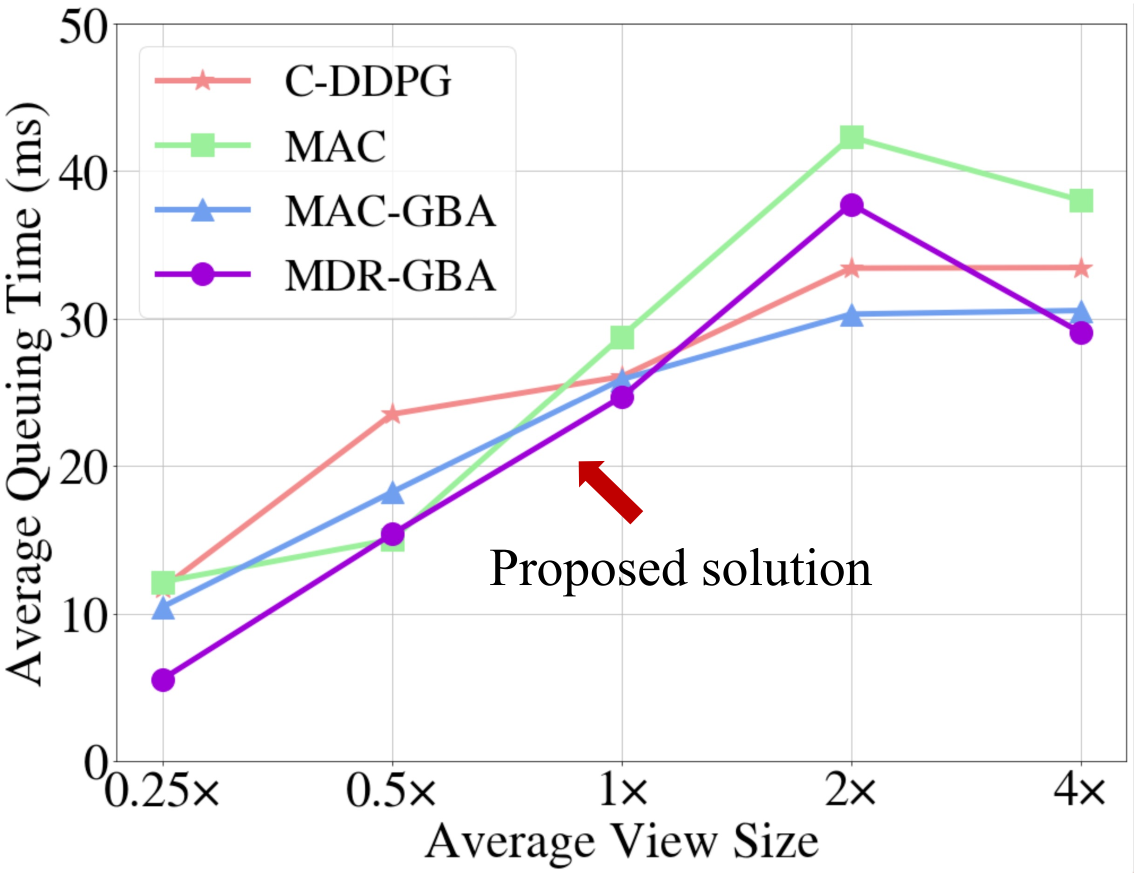
(a) CR under different application requirements



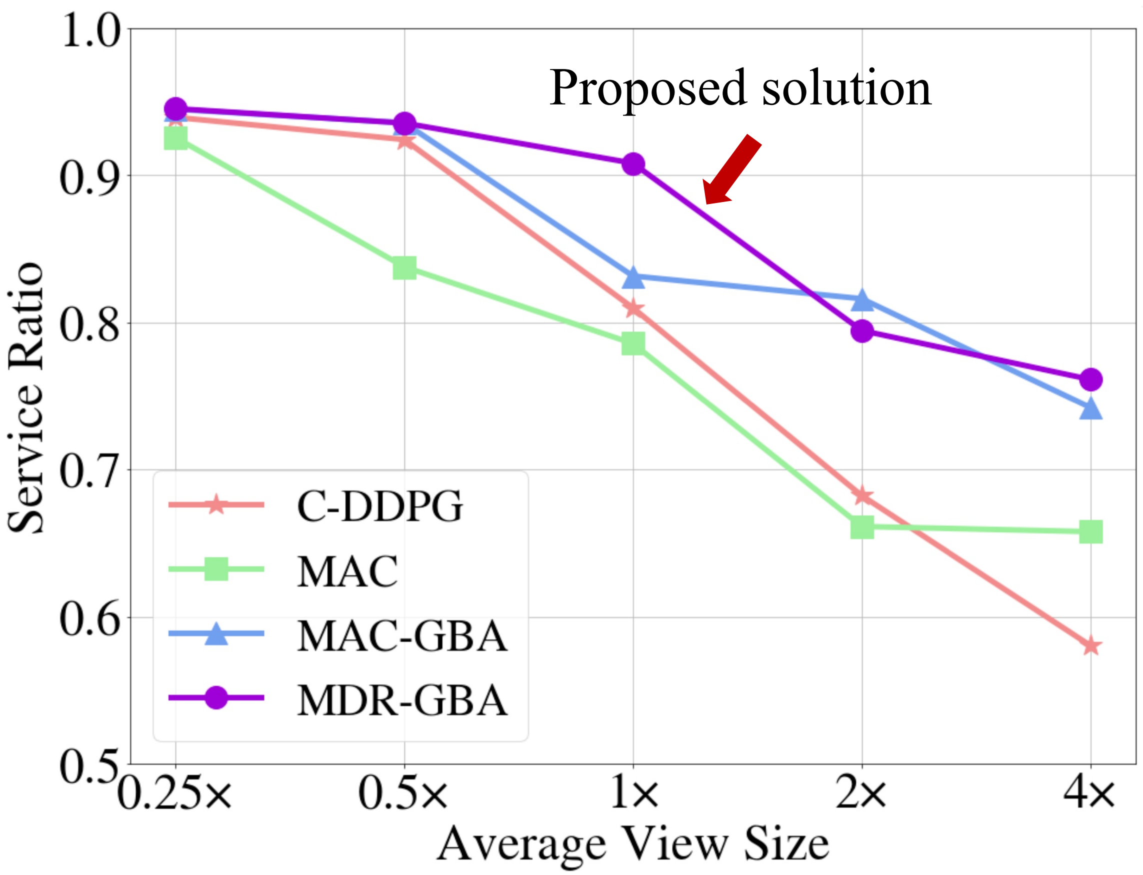
(b) CAR under different application requirements

Performance Evaluation Results

Effect of application requirements on views



(c) AQT under different application requirements



(d) SR under different application requirements

Conclusion

New Metric

- Timeliness of view
- Completeness of view → Age of view (AoV)
- Consistency of view

New Solution

- Multi-agent deep reinforcement leaning
- Greedy bandwidth allocation → MDR-GBA algorithm
- Different reward assignment

Future Work

- Cooperation among edge nodes
- To implement in the real world

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Thanks

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GitHub

https://github.com/neardws