DNN-Controlled Multi-Technology Platooning

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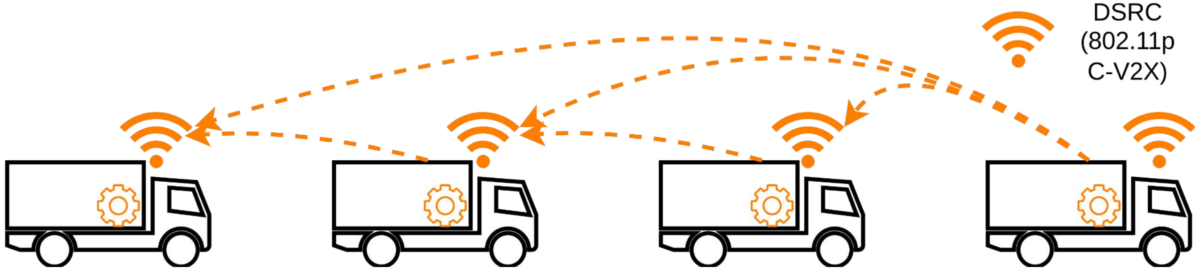
Platoon communication systems

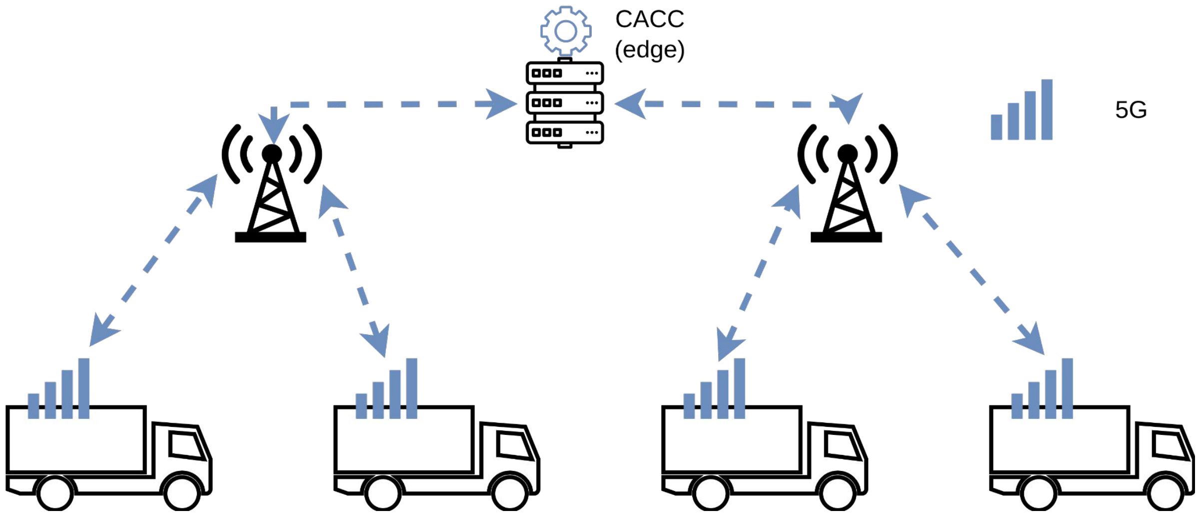


Distributed coordination through DSRC

Onboard control law computation

Limited radio range

Uncoordinated radio access



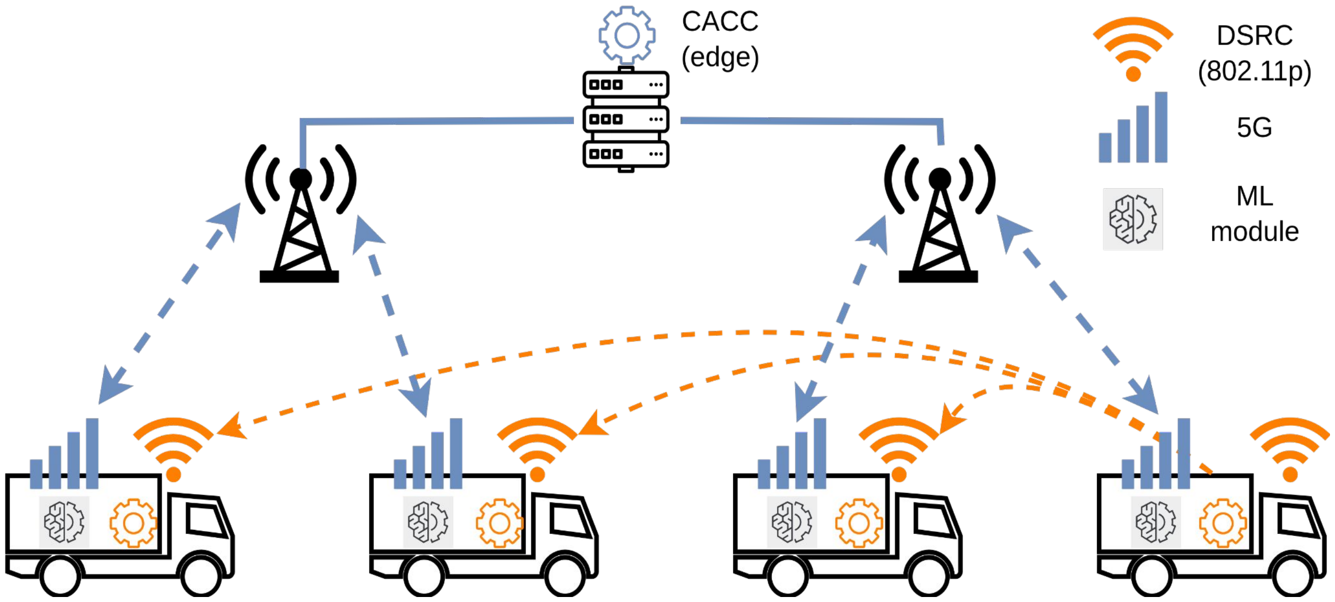
Centralized coordination

Edge control law computation

Infrastructure radio coverage (5G- Uu)

Highly variable channel conditions

Multi-RAT platooning



Operational modes (always running):

5G-Edge Centralized Cooperative platoon (CACC)
DSRC Distributed Cooperative platoon (CACC)
Standalone Non-Cooperative (ACC)

ML-based reliability evaluation

Local monitoring and evaluation using only **onboard information** (sensors + from platoon systems)

Reliable operational mode selection:
5G-Edge / DSRC / Standalone

Independent decision

No broadcasting to the other platoon members

Reliability measure

Ideal instruction (instruction computed without network delays) represents **the best coordination instruction**

The reliability of a platoon system is the **difference** between the **instruction** provided ***$a^s(t)$*** and the **ideal instruction *$a^*(t)$***

$$r^s(t) = a^s(t) - a^*(t)$$

Goal

Inferring the system reliability in the next future using past observation

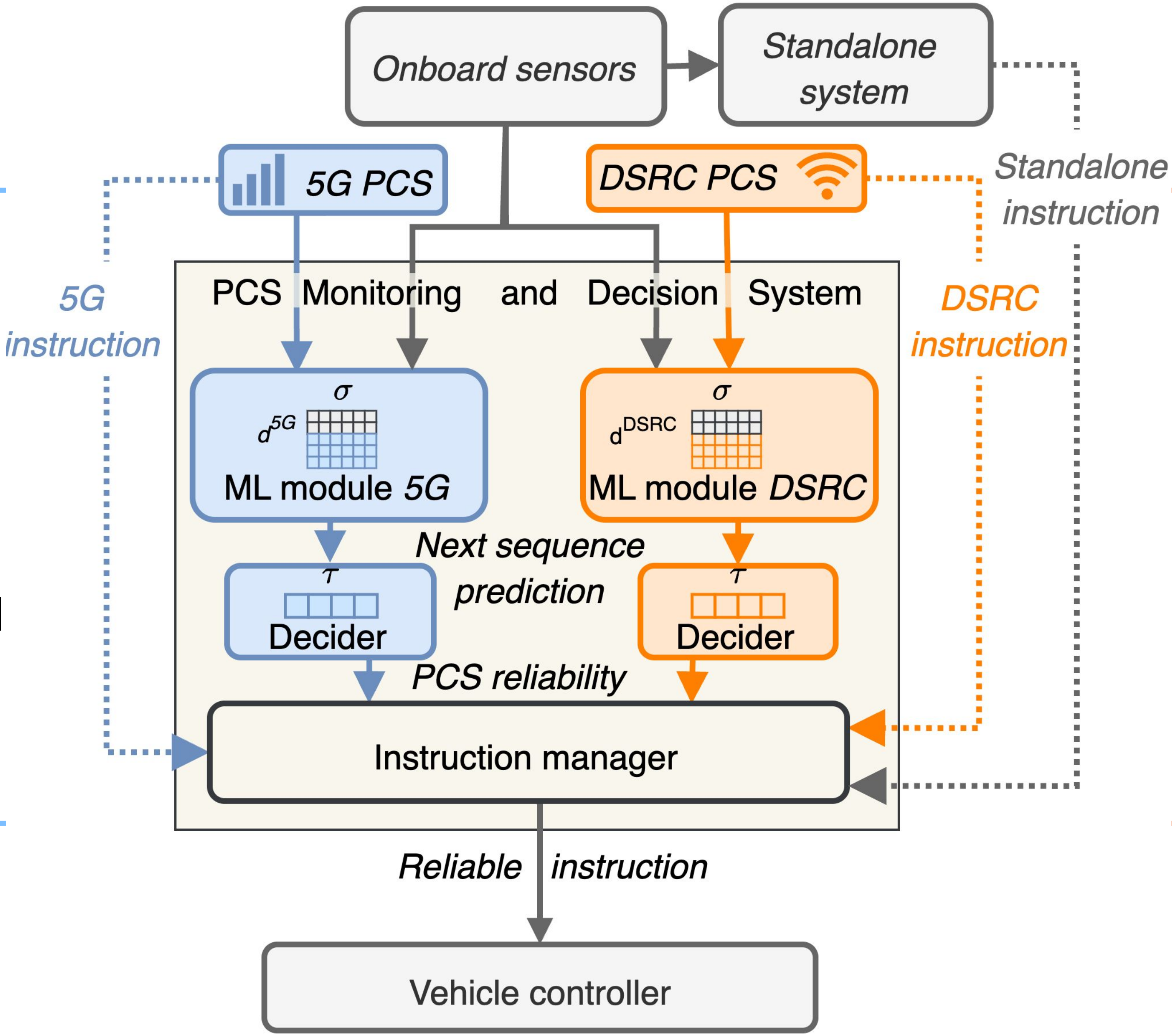
$$\langle r^s(t), \ldots, r^s(t+\tau) \rangle = f(\langle \mathbf{x}^s(t-\sigma, \ldots, \mathbf{x}^s(t) \rangle | \boldsymbol{\theta}^s)$$

Future reliability *Past data observation*

ML Onboard system

5G-Edge features

- CQI UL/DL
- RTT
- AoI of status information and instructions



DSRC features

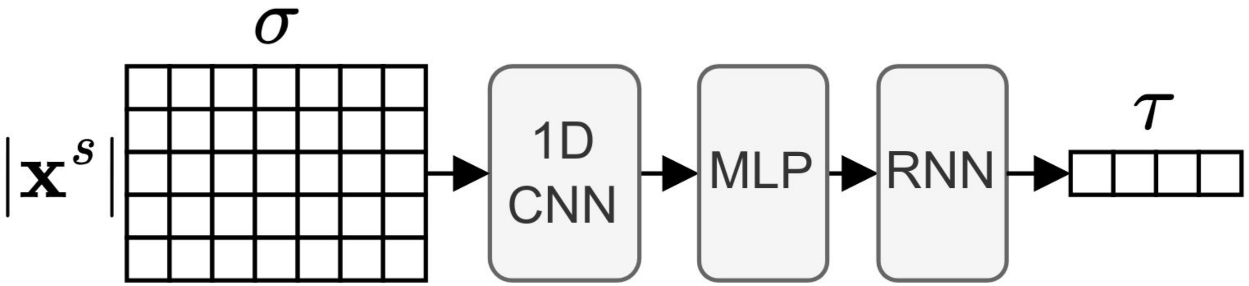
- AoI of status information
- Packet loss
- RX power
- MAC queuing time

ML Onboard system

Regression task: *next instructions difference*

$$\langle r^s(t), \dots, r^s(t+\tau)\rangle = f(\langle \mathbf{x}^s(t-\sigma, \dots, \mathbf{x}^s(t)\rangle | \boldsymbol{\theta}^s)$$

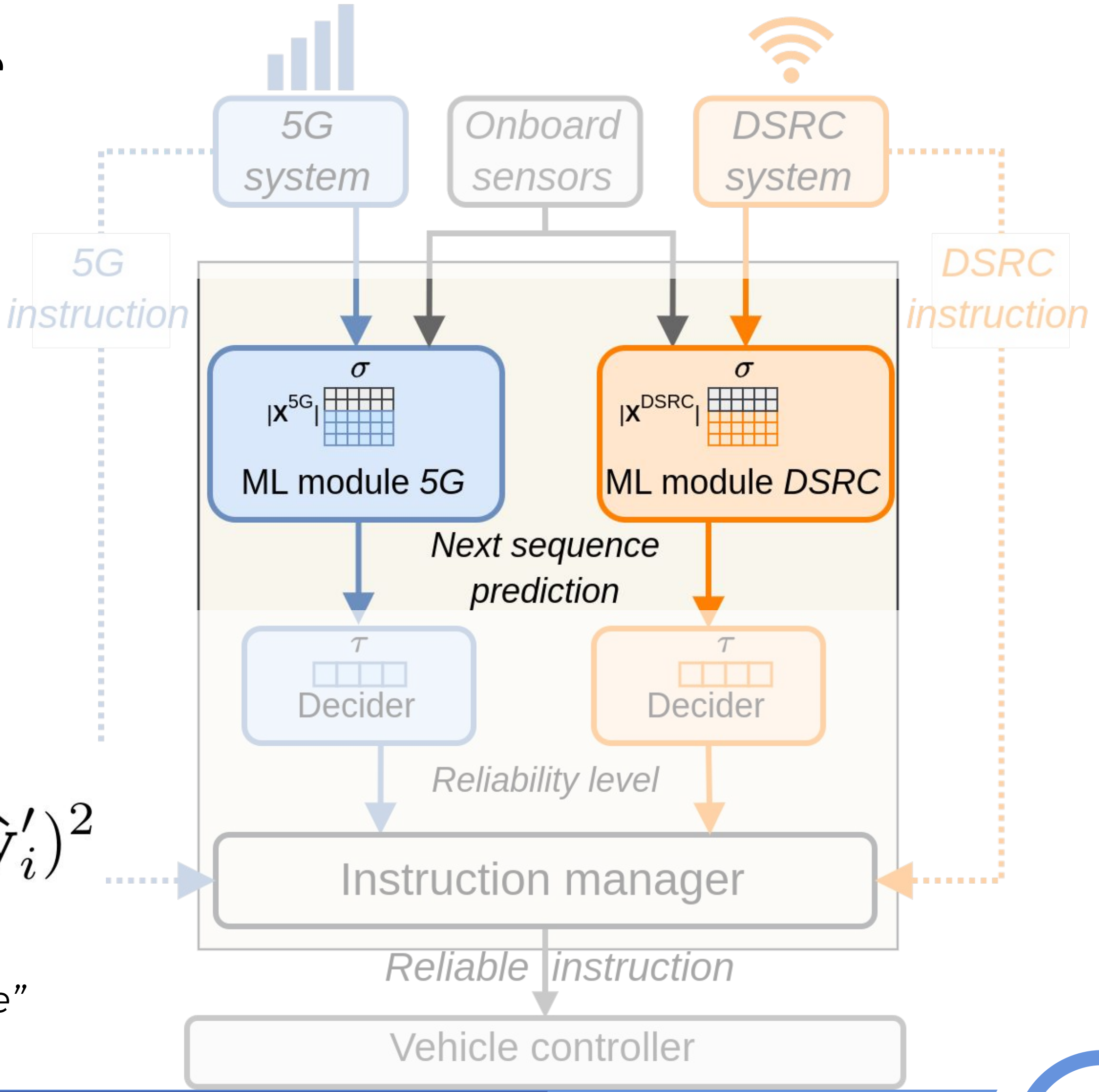
Model architecture:
two independent models, same architecture



Custom loss function

$$L(\mathbf{y}, \hat{\mathbf{y}}) = \frac{1}{n}\sum_{i=1}^{n} |\mathbf{y}_i - \hat{\mathbf{y}}_i| + \alpha \frac{1}{n}\sum_{i=1}^{n} (\mathbf{y}'_i - \hat{\mathbf{y}}'_i)^2$$

"Reliability Mean" *"Reliability Shape"*

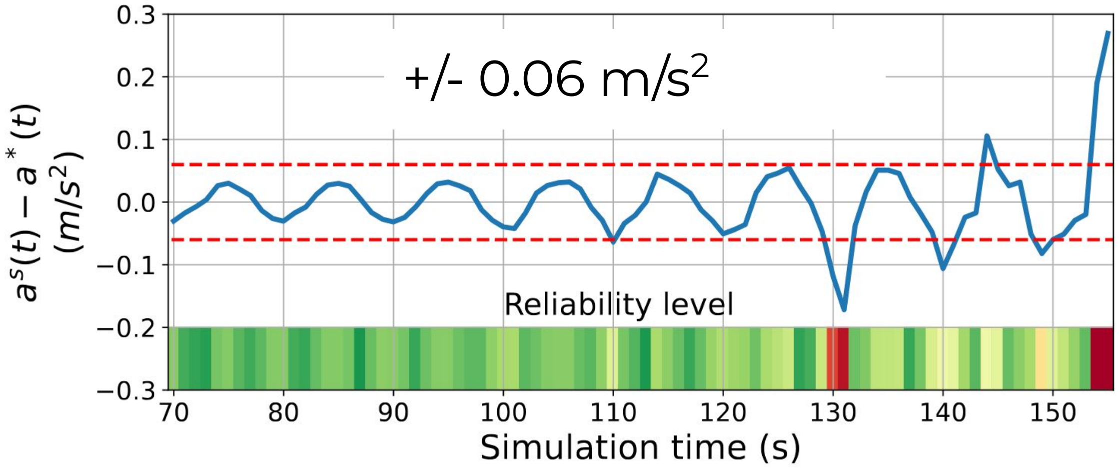


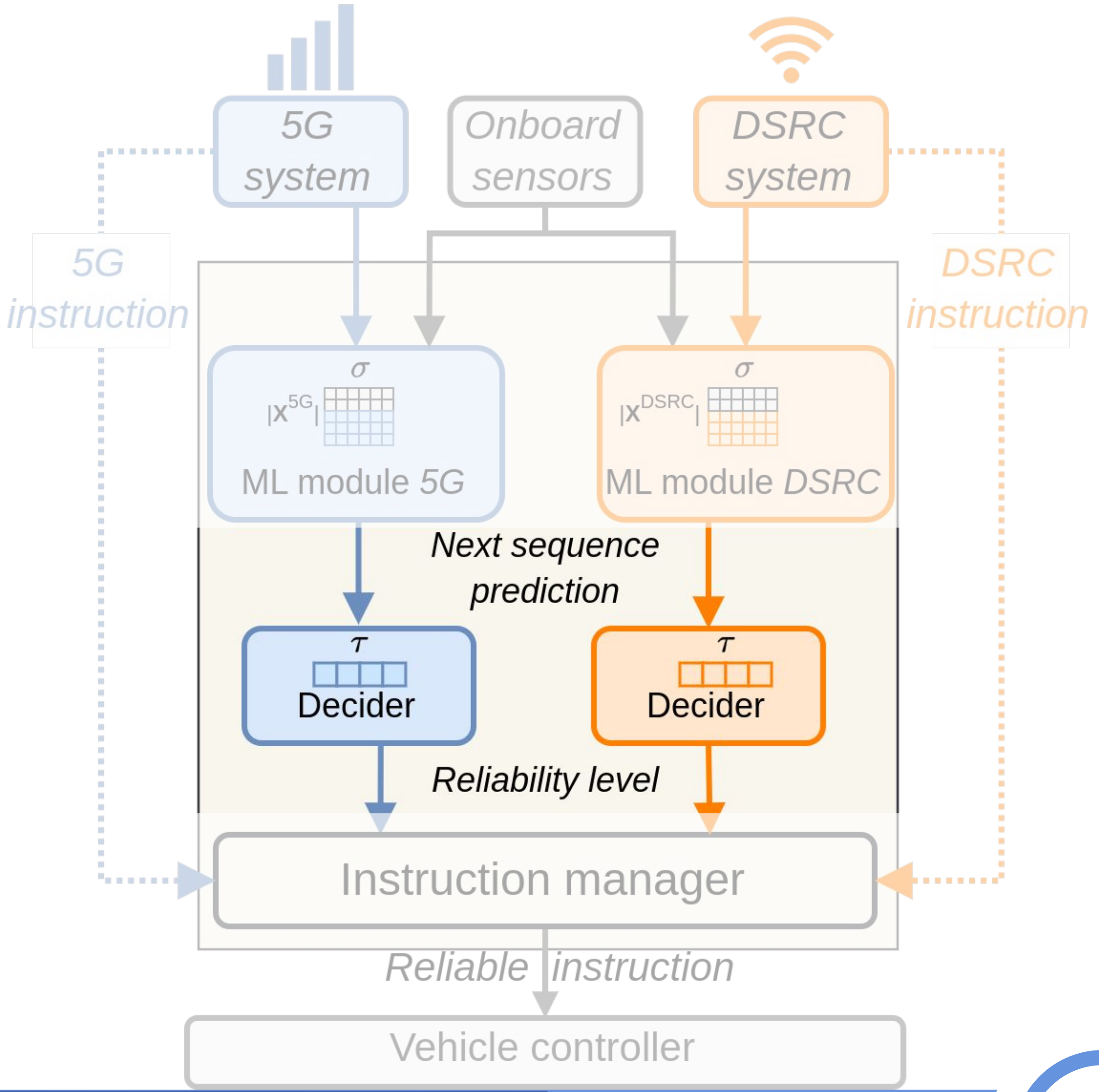
ML Onboard system

Is the platoon system *s* reliable?

Heuristic-based binary decision based on threshold applied to the *next sequence prediction*

$$\langle r^s(t), \ldots, r^s(t+\tau) \rangle \rightarrow \text{Yes/No}$$





ML Onboard system

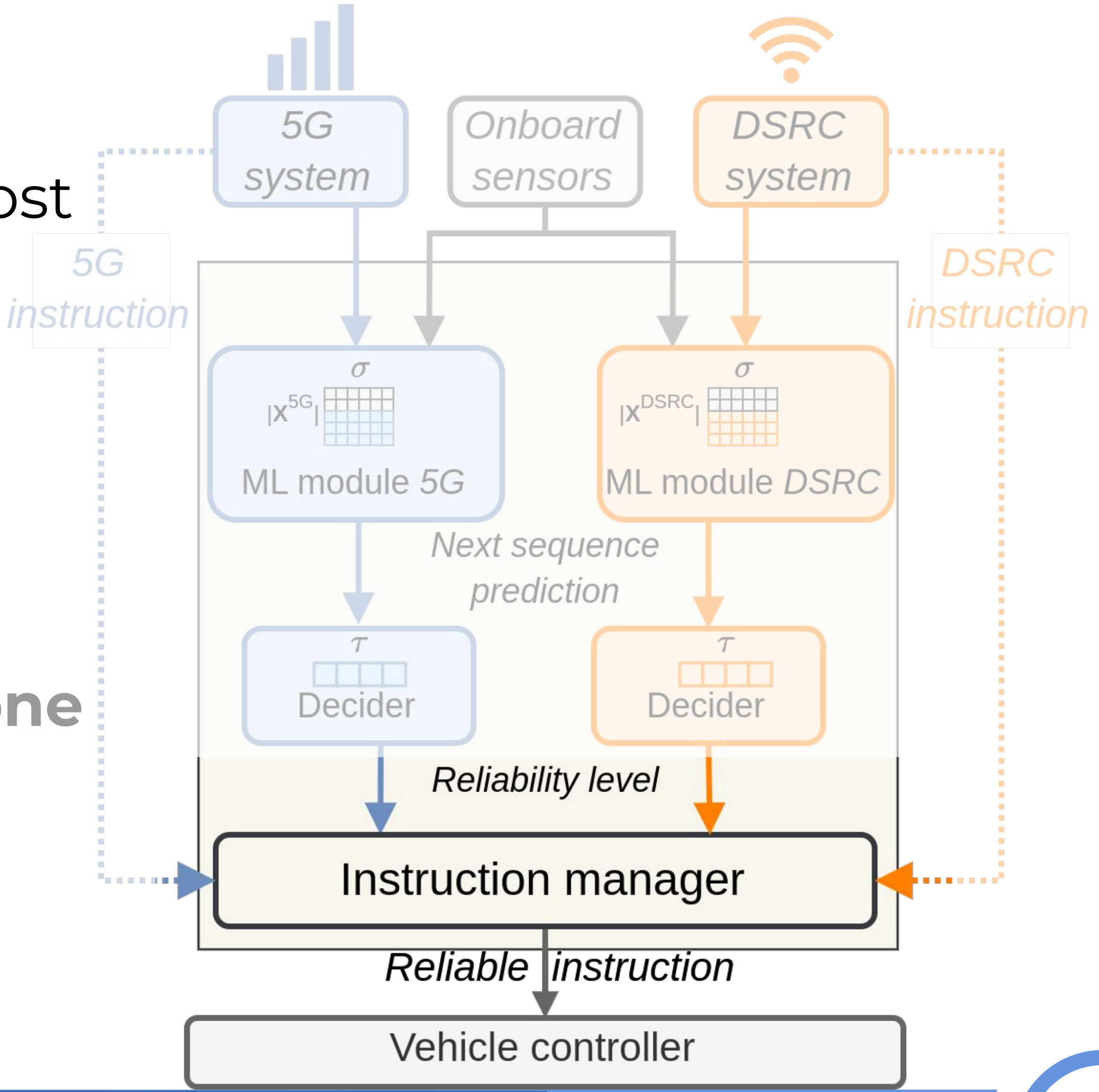
Based on the reliability of the systems the **Instruction manager** selects the most suitable operation mode

5G reliable → **5G-Edge**

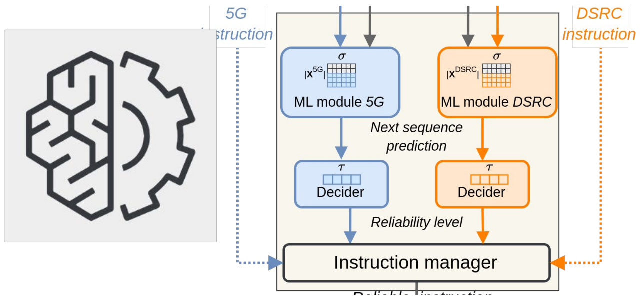
5G unreliable & **DRSC reliable** → **DSRC**

5G unreliable & **DSRC unreliable** → **Standalone**

Hysteresis parameter to prevent continuous switches



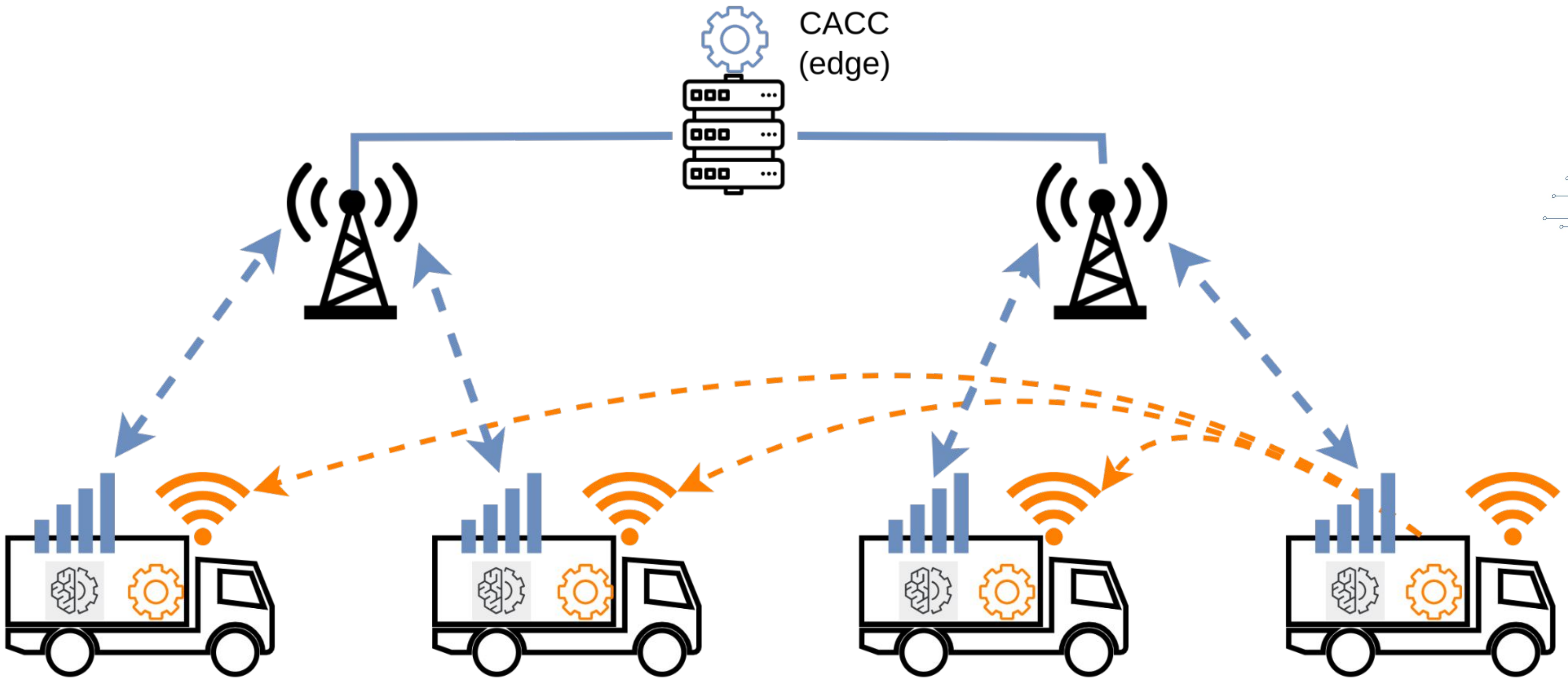
Simulation framework



PyTorch

scikit learn

OMNeT ++



SIMU5G

veins
Vehicles in Network Simulation

SUMO

Simulation of Urban MObility

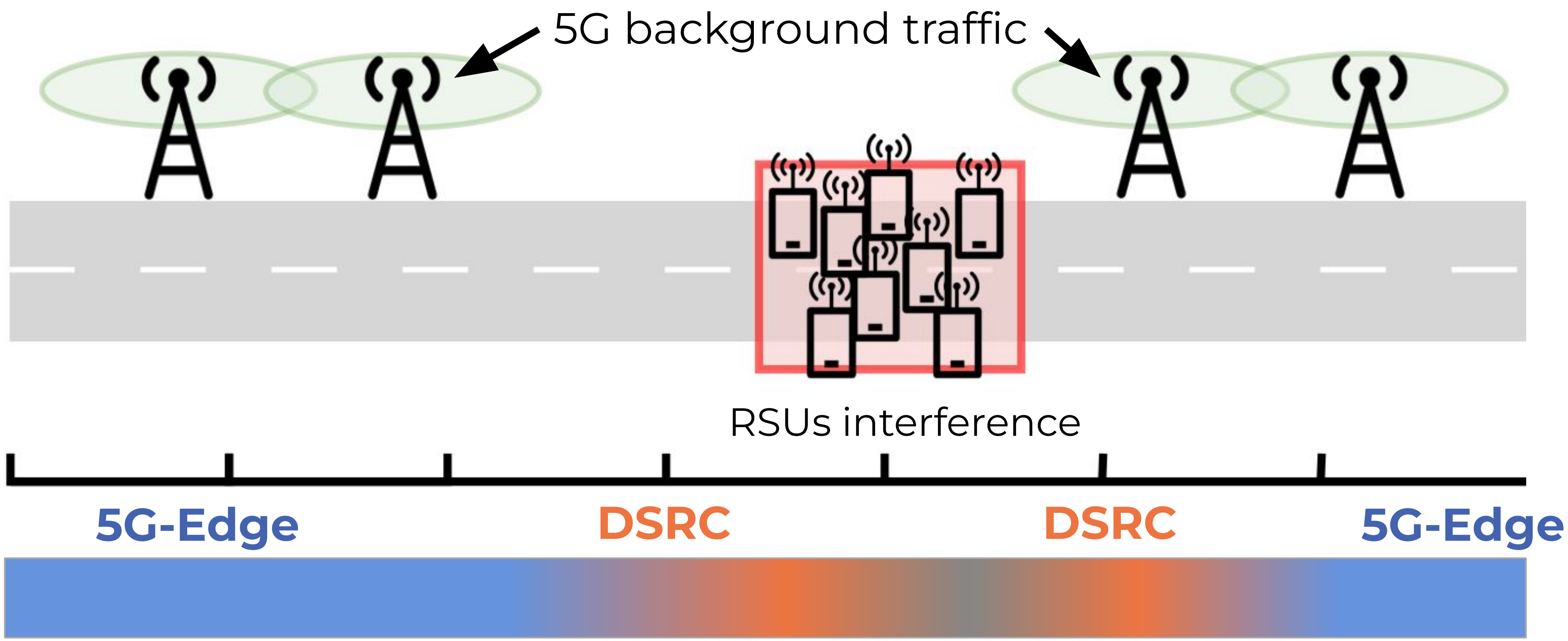
Evaluation setting

8 vehicles platoon

Leader speed:
Sinusoidal
90km/h +/- 5km/

Target distance:
15m

ML module:
5 seconds observation
5 seconds prediction
2Hz evaluation frequency



Standalone

ACC → larger inter-vehicle distance

Baselines

PDR-Based: packet delivery ratio based baseline

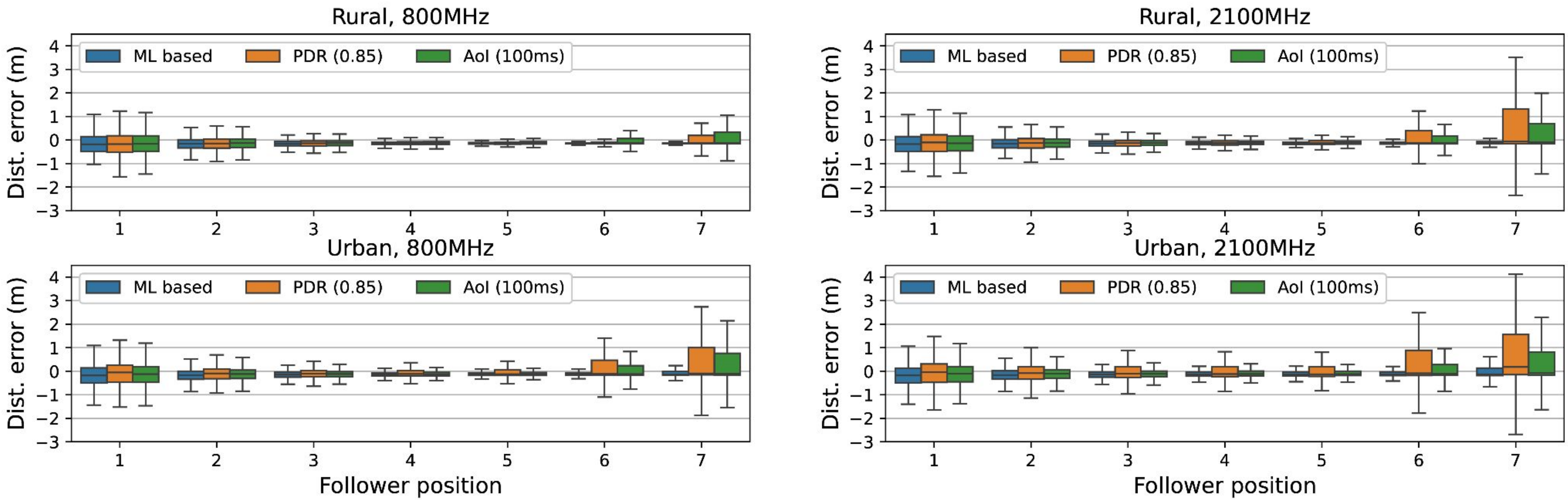
- Exponential smoothing of PDR
- PDR < 85% → Platoon system unreliable
- Approach based on [1]

AoI-Based: age of information based baseline

- Avg. of AoI of CAMs
- Exponential smoothing of avg. of AoI
- Avg. AoI > 100 ms → Platoon system unreliable

[1] M. Segata et al., "Multi-Technology Cooperative Driving: An Analysis Based on PLEXE," in IEEE Transactions on Mobile Computing, vol. 22, no. 8, pp. 4792-4806, 1 Aug. 2023,

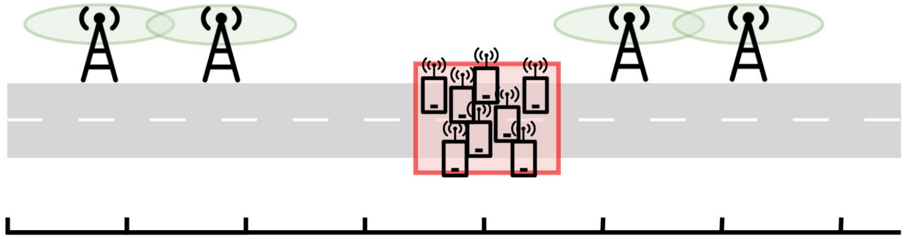
Results - Platoon stability

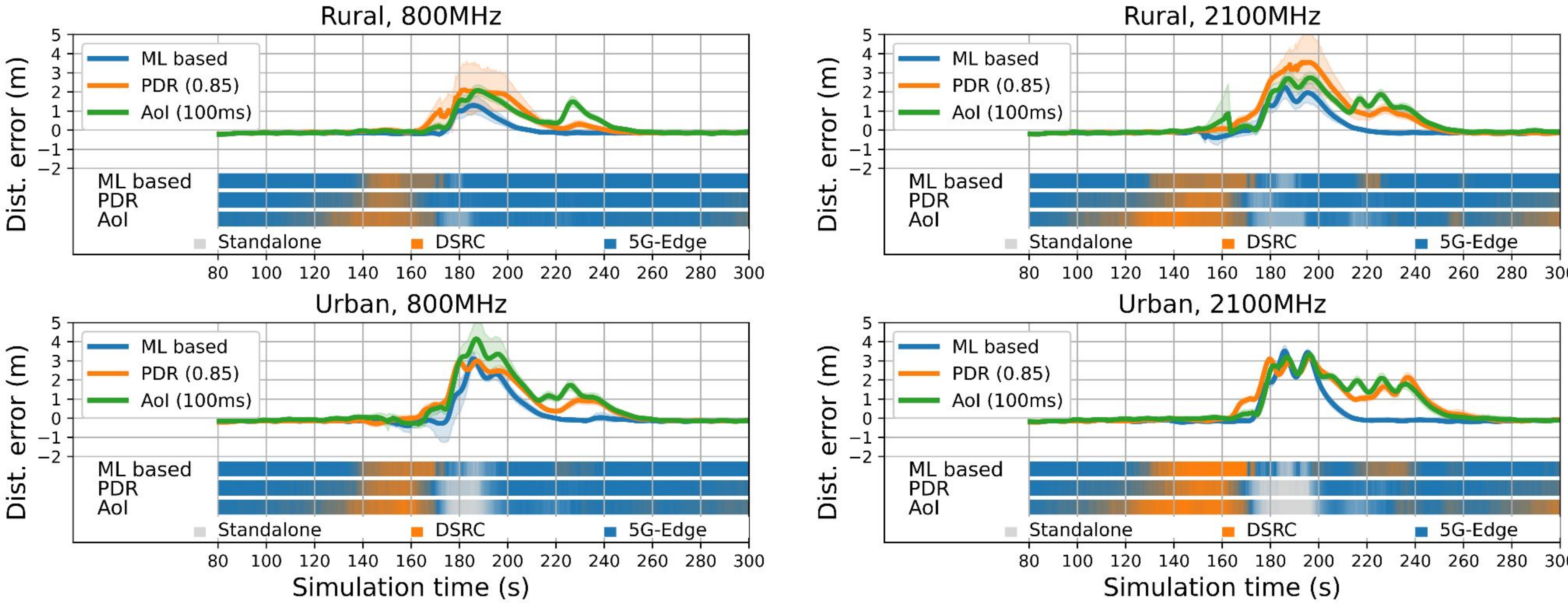


ML based guarantees more strong platoon string stability than the baselines

Results - Error distance over time

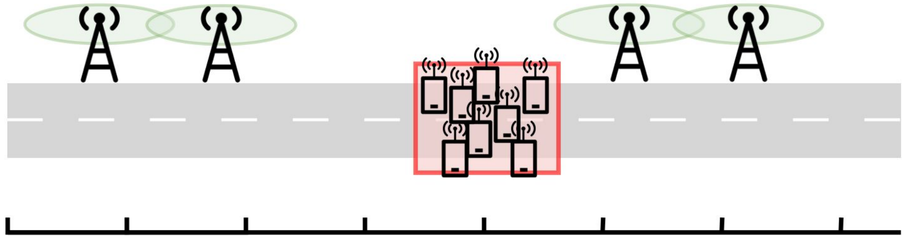
6th follower

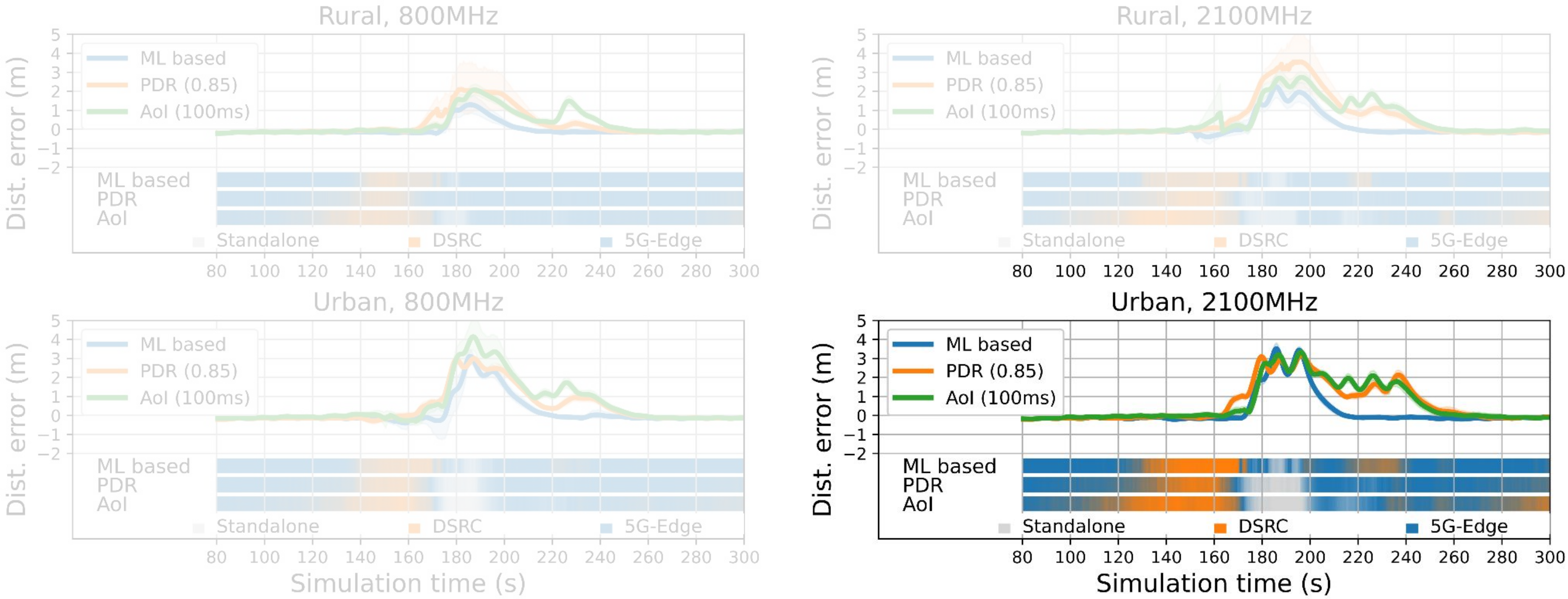




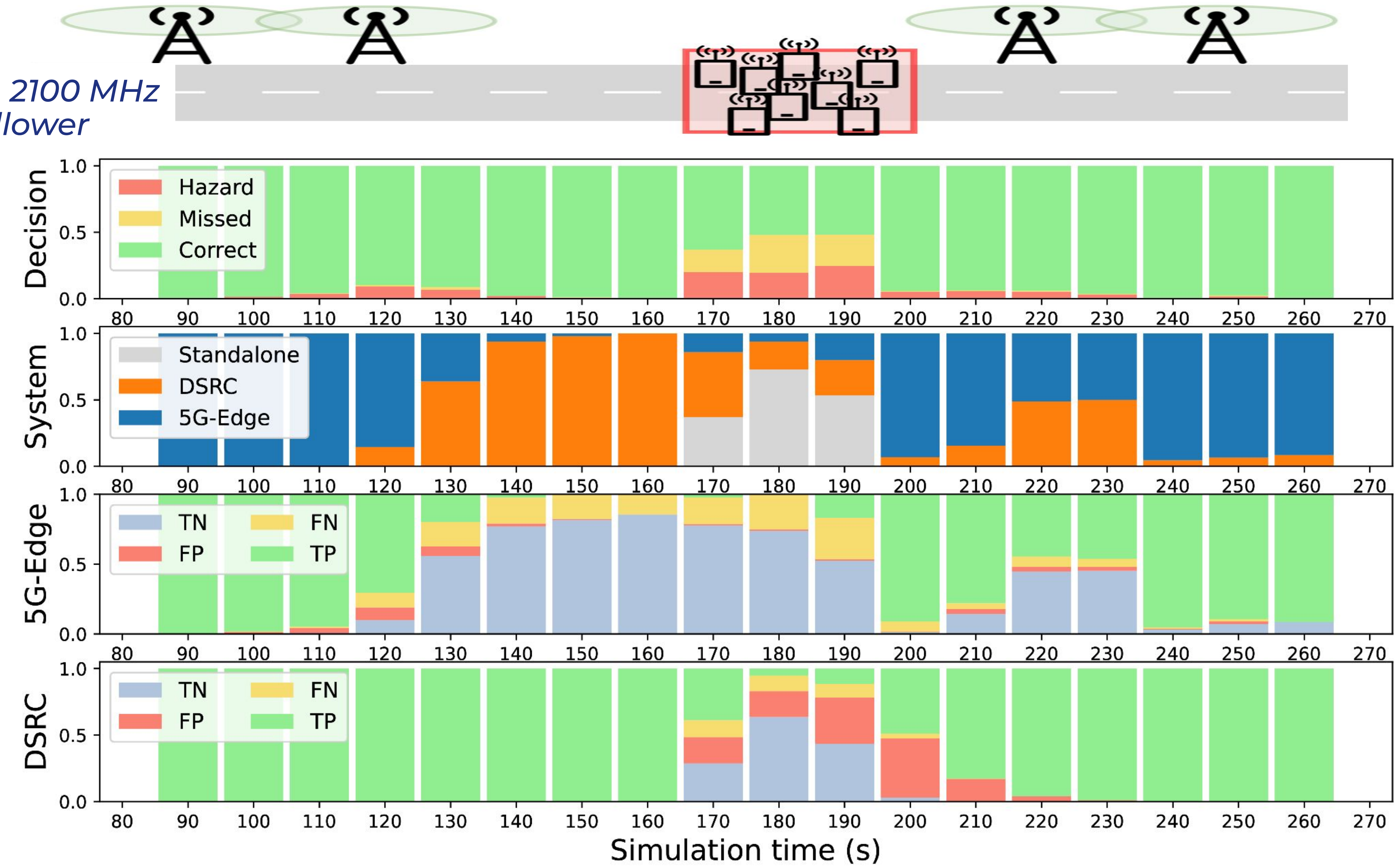
Results - Error distance over time

6th follower

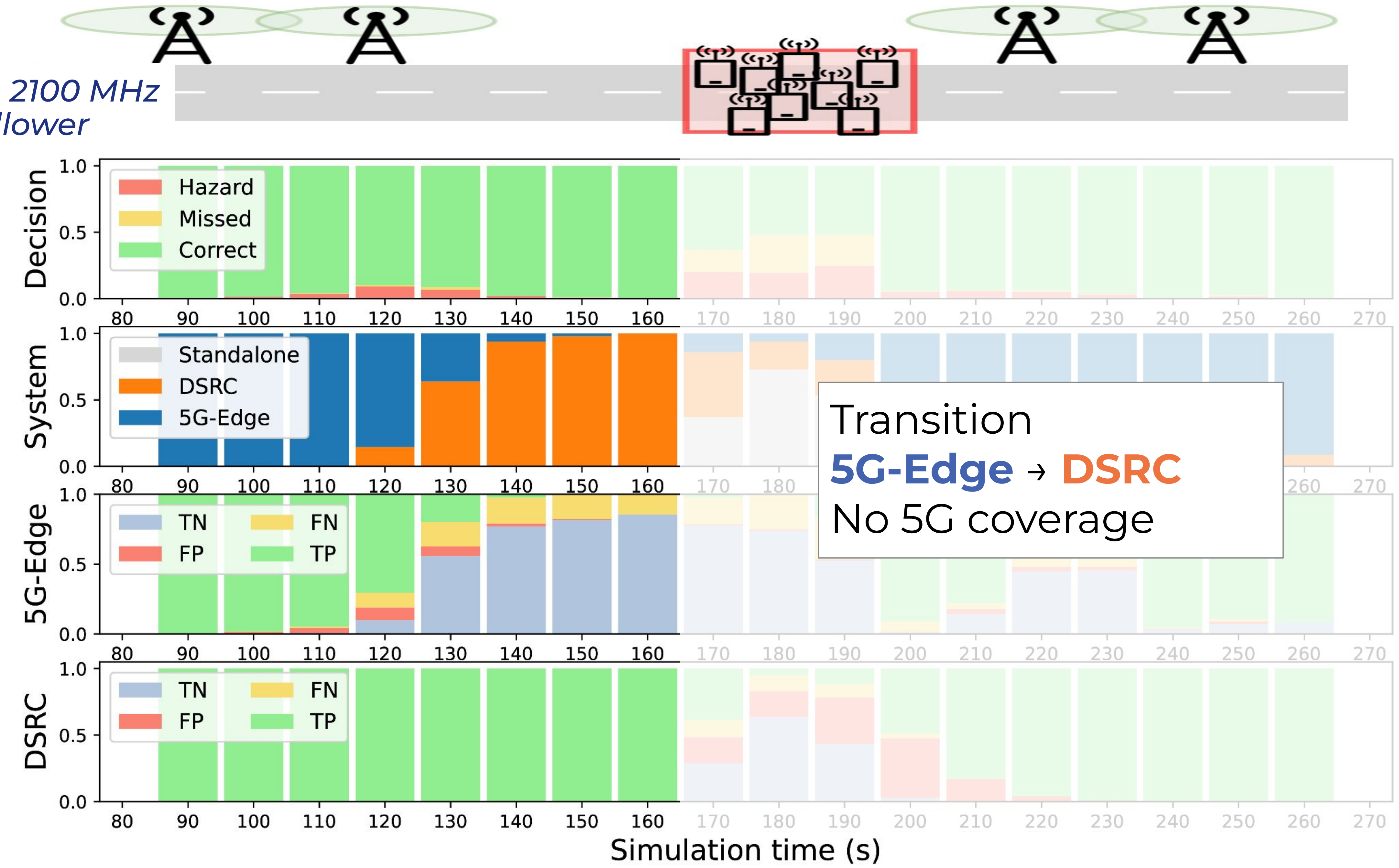




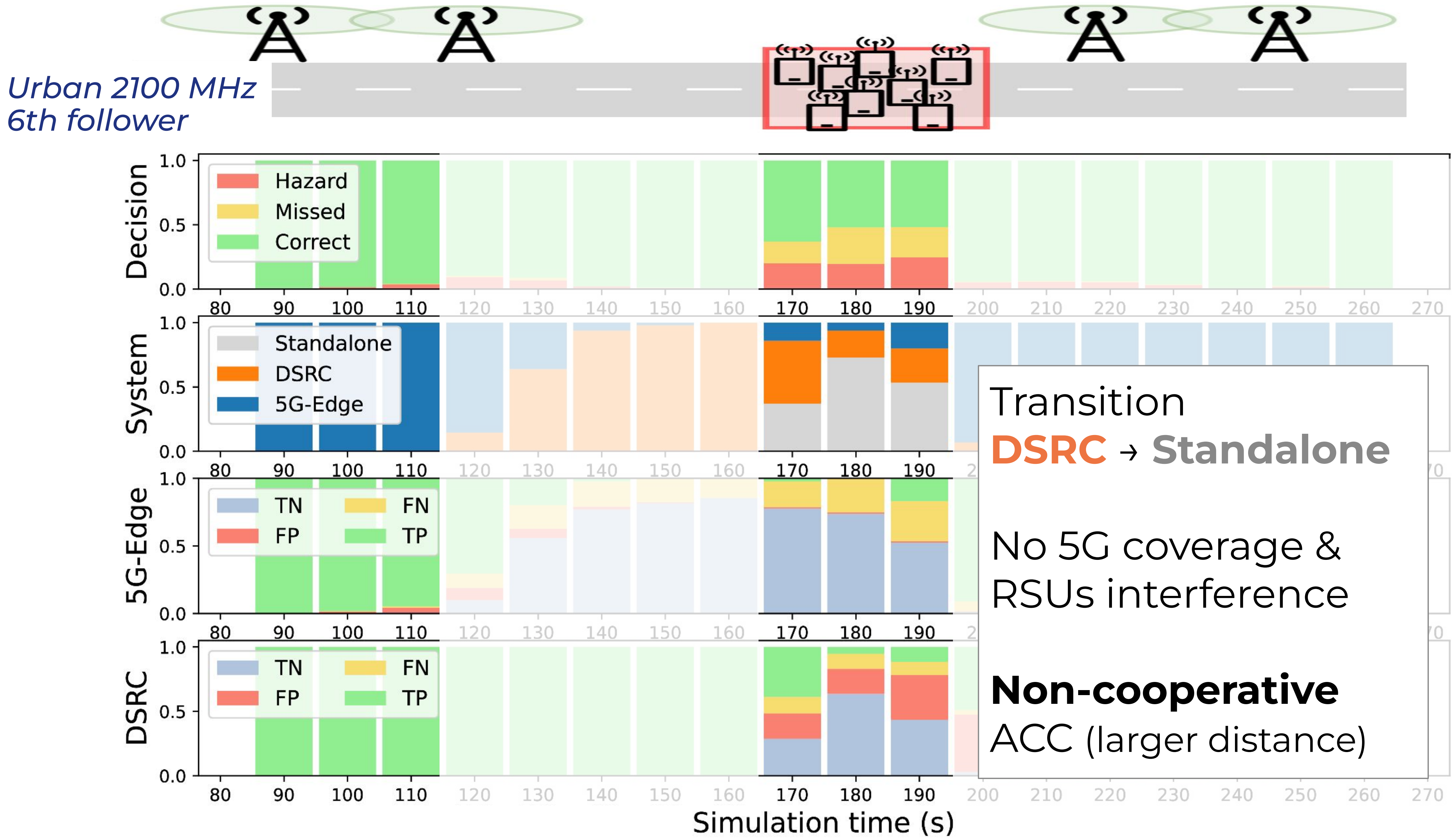
Urban 2100 MHz
6th follower

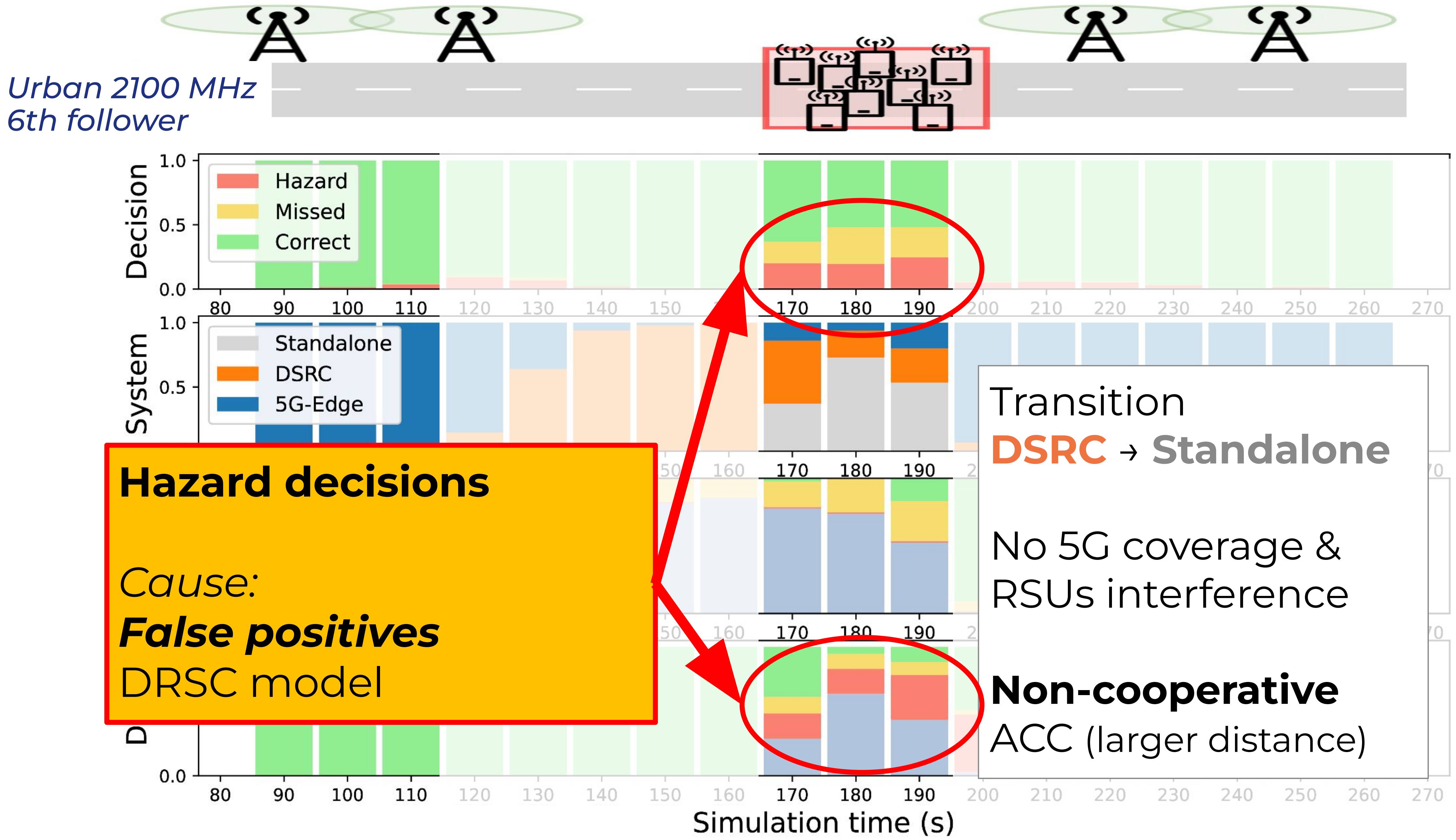


Urban 2100 MHz
6th follower

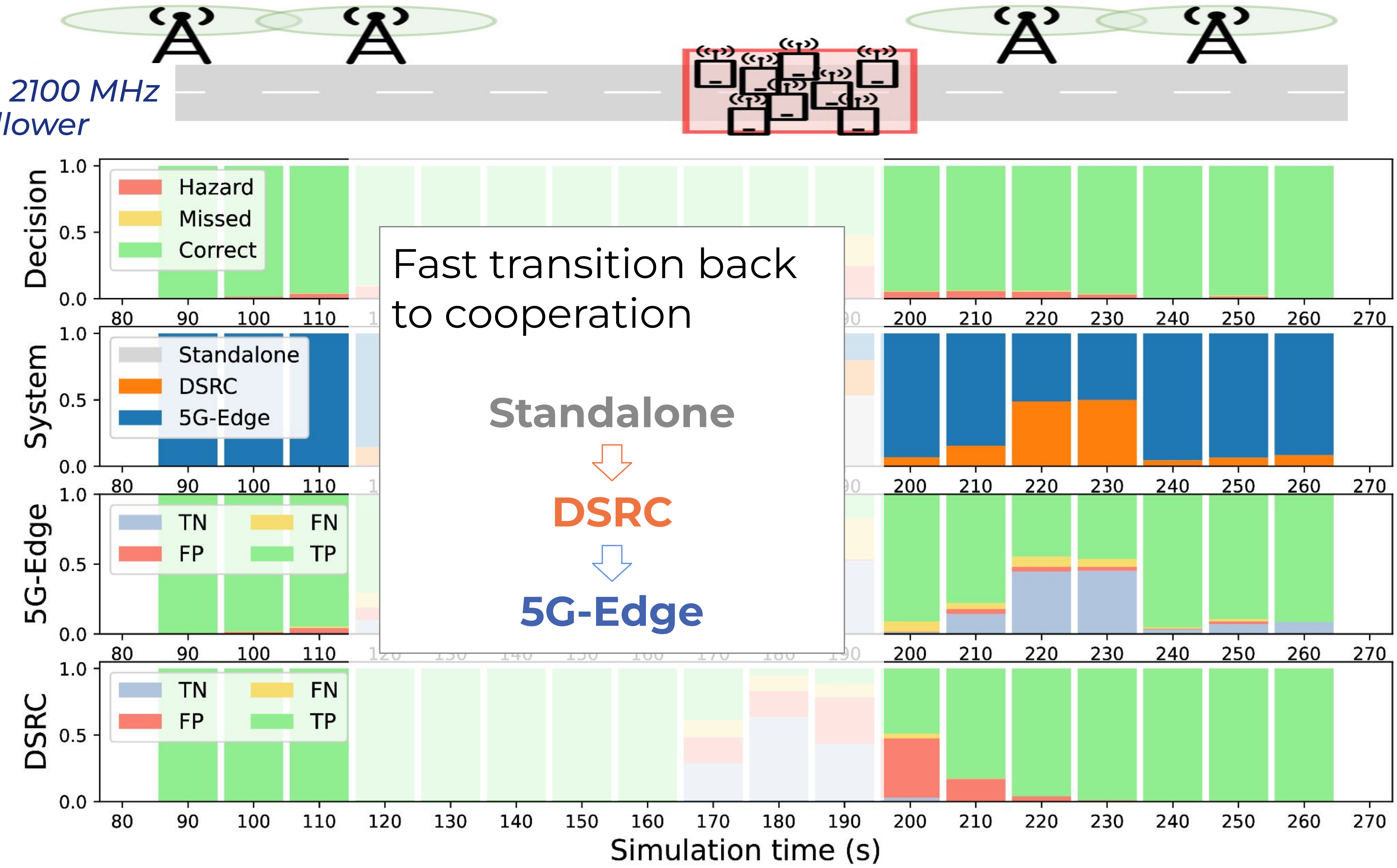


Transition
5G-Edge → DSRC
No 5G coverage


Urban 2100 MHz
6th follower
Decision
Hazard
Missed
Correct
System
Standalone
DSRC
5G-Edge
5G-Edge
TN
FN
FP
TP
DSRC
TN
FN
FP
TP
Simulation time (s)
Transition
DSRC → Standalone
No 5G coverage &
RSUs interference
Non-cooperative
ACC (larger distance)


Urban 2100 MHz
6th follower
Decision
Hazard
Missed
Correct
System
Standalone
DSRC
5G-Edge
Simulation time (s)
Hazard decisions
Cause:
False positives
DRSC model
Transition
DSRC → Standalone
No 5G coverage &
RSUs interference
Non-cooperative
ACC (larger distance)

Urban 2100 MHz
6th follower



Fast transition back to cooperation

Standalone

⇩

DSRC

⇩

5G-Edge

Decision system accuracy

Rural	800 MHz			2100 MHz		
	Correct	*Missed*	*Hazard*	*Correct*	*Missed*	*Hazard*
ML based	97.4	0.5	2.1	95.1	1.1	3.8
PDR (0.85)	91.0	2.1	6.9	87.2	4.5	8.3
AoI (100ms)	95.0	3.7	1.3	93.2	5.5	1.3

Urban	800 MHz			2100 MHz		
	Correct	*Missed*	*Hazard*	*Correct*	*Missed*	*Hazard*
ML based	94.4	1.4	4.2	92.7	2.2	5.1
PDR (0.85)	88.6	6.3	5.1	82.0	9.2	8.8
AoI (100ms)	91.7	6.7	1.6	90.1	8.2	1.7

Conclusion & Next steps

ML approach for selecting platoon operational mode

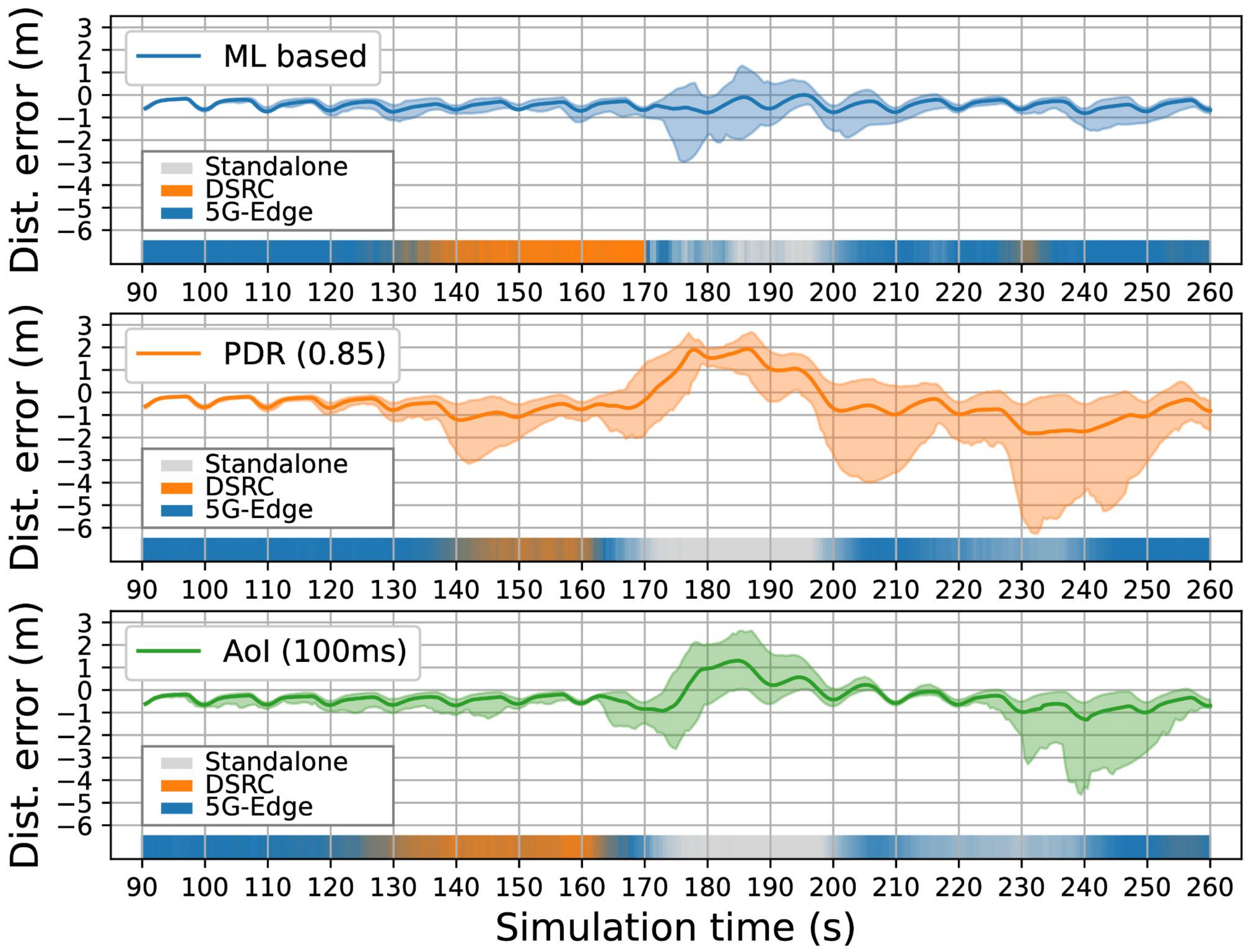
Reliability measurement of divergence w.r.t. ideal instructions

The approach shows good performance
- Operational mode transition
- Handling challenging scenarios

<u>What's next</u>
- DSRC model needs *fine tuning* to prevent false positives
- Testing other leader speed patterns
- More sophisticated and precise decision function
- Explainability

Thanks for your attention

Platoon safety



Min. front distance across the whole platoon

ML based approach benefits from more agreement among vehicles

Baselines:
Mix of cooperative and non-cooperative operational modes

Model input features

Common kinematics features:

- Vehicle acceleration
- Distance from the preceding vehicle
- Relative position of the vehicle within the platoon

5G-Edge features:

- Channel quality indicator (CQI) UL and DL
- Round-trip time (RTT),
- AoI of the status information: Leader, Preceding and Self vehicles
- AoI of platoon instruction

DSRC features:

- MAC layer queueing time
- Packet drop events,
- RSSI of the leader and preceding vehicle messages
- AoI of the status information: Leader, Preceding vehicles

Heuristic-based binary decision

A platoon system is reliable if the predicted sequence satisfies both conditions:

1. The mean of absolute values of reliability levels is below a threshold δ
   In this work δ == 0.06 m/s²

2. The average of the subset of predicted values that exceeds δ is lower than a second threshold Δ > δ
   In this work Δ == 0.08 m/s²

Simulation parameters

General parameters	
Simulated road	Straight 3-lane highway
Simulation time (repetitions)	300 s (60 s of warm-up time) (10 repeats)
Platoon parameters	
Number of platoon members	8
Leader speed pattern	Sinusoidal 90 km/h (± 5 km/h), 0.1 Hz
CACC spacing policy	Constant space (15 m)
ACC spacing policy	Constant ahead time (0.7 s)
Decision system parameters	
Input time window size (σ)	5 s (20 time steps)
Prediction time steps (τ)	5 s (20 time steps)
Decider thresholds (δ, Δ)	$\delta = 0.06m/s^2$, $\Delta = 0.07m/s^2$
DSRC configuration	
TX power, Radio sensitivity	20 dBm, -95 dBm
Pathloss model	Rician (k = 8 dB)
Obstacle loss	Model from [16]
Channel band (bandwidth)	5.9 GHz (10 MHz)
Number of RSUs (area size)	0, 10, 20, 30 (250 m x 40 m)
RSUs traffic	3kB, exponential(20 ms)

5G network configuration	
Base station physical resource	3 RBs per TTI (1 ms)
UE Tx power (gain)	26 dBm (+0dBi)
Base station Tx power (gain)	46 dBm (+18dBi)
Carrier frequency	800 MHz, 2100 MHz
Base station model	*ITU-Urban* & *ITU-Rural* macrocell
Pathloss model	Rural: Free Space $\alpha = 2.5$ Urban: Free Space $\alpha = 3.5$
Base station scheduler	Max Channel Indicator
Number of background devices	0, 40 UEs
Packet size (UL/DL)	10, 500 byte
Packet frequency (UL/DL)	20 pkt/s (UPD Constant Bit Rate)
Generation starting/ending time	U(120 s, 150 s) / U(220 s, 250 s)
Congestion-free 5G-Edge RTT	20 ± 5 ms