

# Multi Radio Access Technology platooning

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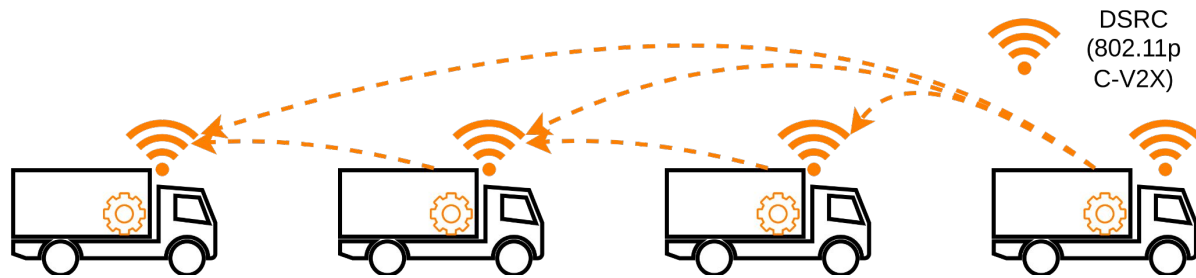


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# Platoon communication systems

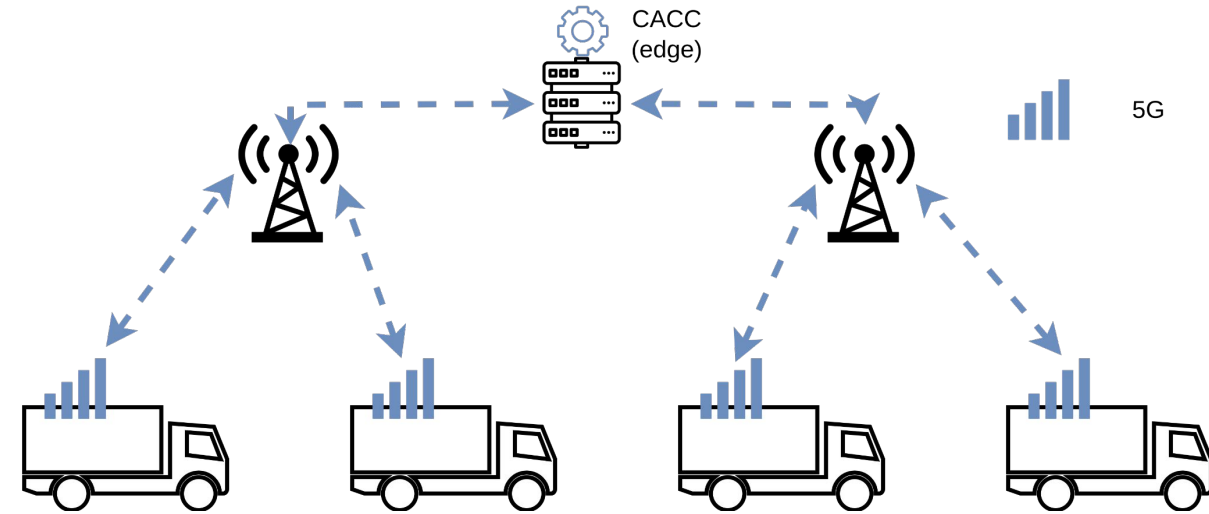


**Distributed coordination** through DSRC

**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**

# Cooperative Adaptive Cruise Control (PATH Project)

$$\ddot{x}_{i\_des} = \alpha_1 \ddot{x}_{i-1} + \alpha_2 \ddot{x}_0 + \alpha_3 \dot{\varepsilon}_i + \alpha_4 (\dot{x}_i - \dot{x}_0) + \alpha_5 \varepsilon_i \quad (\text{B.2})$$

$$\dot{\varepsilon}_i = \dot{x}_i - \dot{x}_{i-1} \quad (\text{B.3})$$

$$\varepsilon_i = x_i - x_{i-1} + l_{i-1} + d_{des} \quad (\text{B.4})$$

$$\alpha_1 = 1 - C_1 \quad (\text{B.5})$$

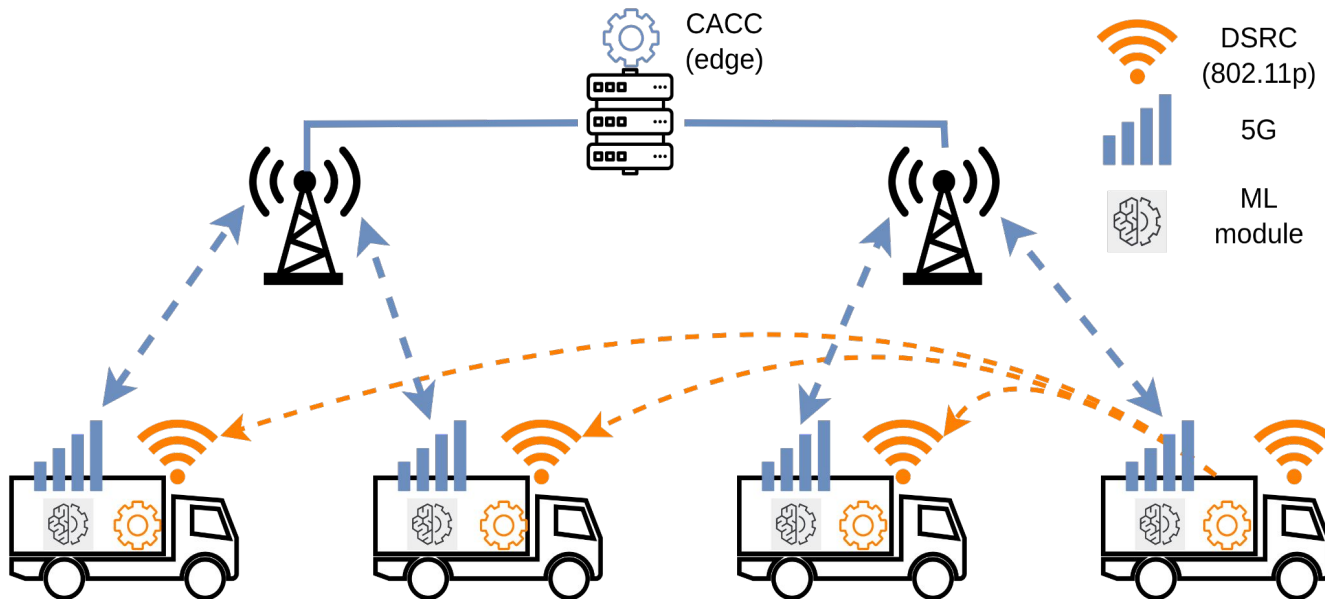
$$\alpha_2 = C_1 \quad (\text{B.6})$$

$$\alpha_3 = - \left( 2\xi - C_1 \left( \xi + \sqrt{\xi^2 - 1} \right) \right) \omega_n \quad (\text{B.7})$$

$$\alpha_4 = -C_1 \left( \xi + \sqrt{\xi^2 - 1} \right) \omega_n \quad (\text{B.8})$$

$$\alpha_5 = -\omega_n^2 \quad (\text{B.9})$$

# Multi-RAT platooning



**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

Operational modes (always running):

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

# 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  $\mathbf{a}^s(t)$  and the **ideal instruction**  $\mathbf{a}^*(t)$

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

## Goal

**Inferring the system reliability in the next future using past observation**

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

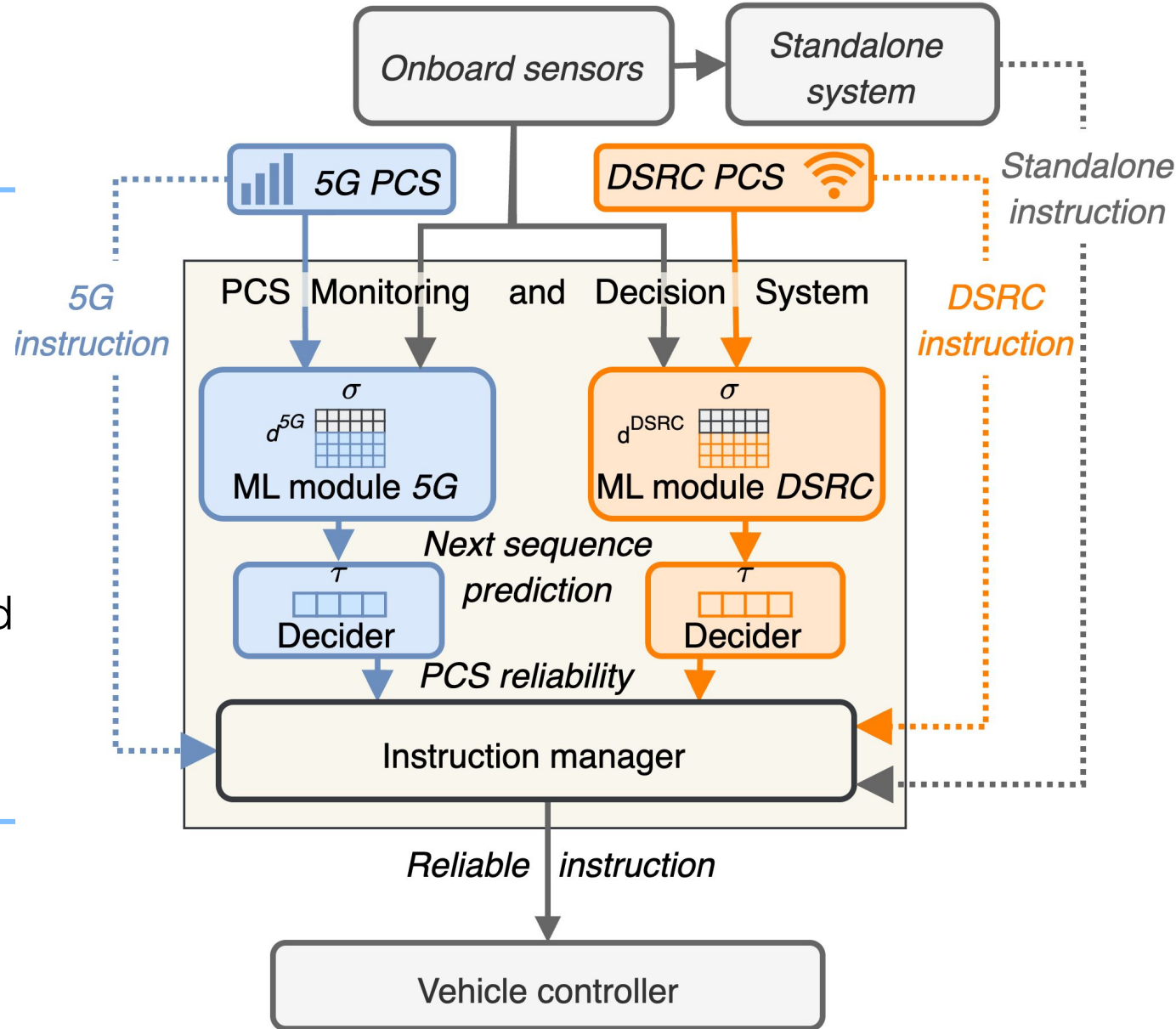
*Future reliability*

*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

# 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),
- Aol of the status information: Leader, Preceding and Self vehicles
- Aol of platoon instruction

## DSRC features:

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

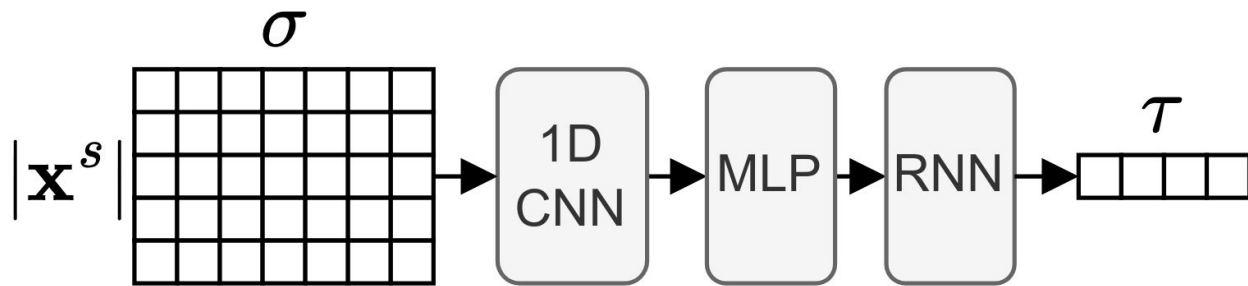
# ML Onboard system

**Regression task:** *next instructions difference*

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

**Model architecture:**

*two independent models, same architecture*

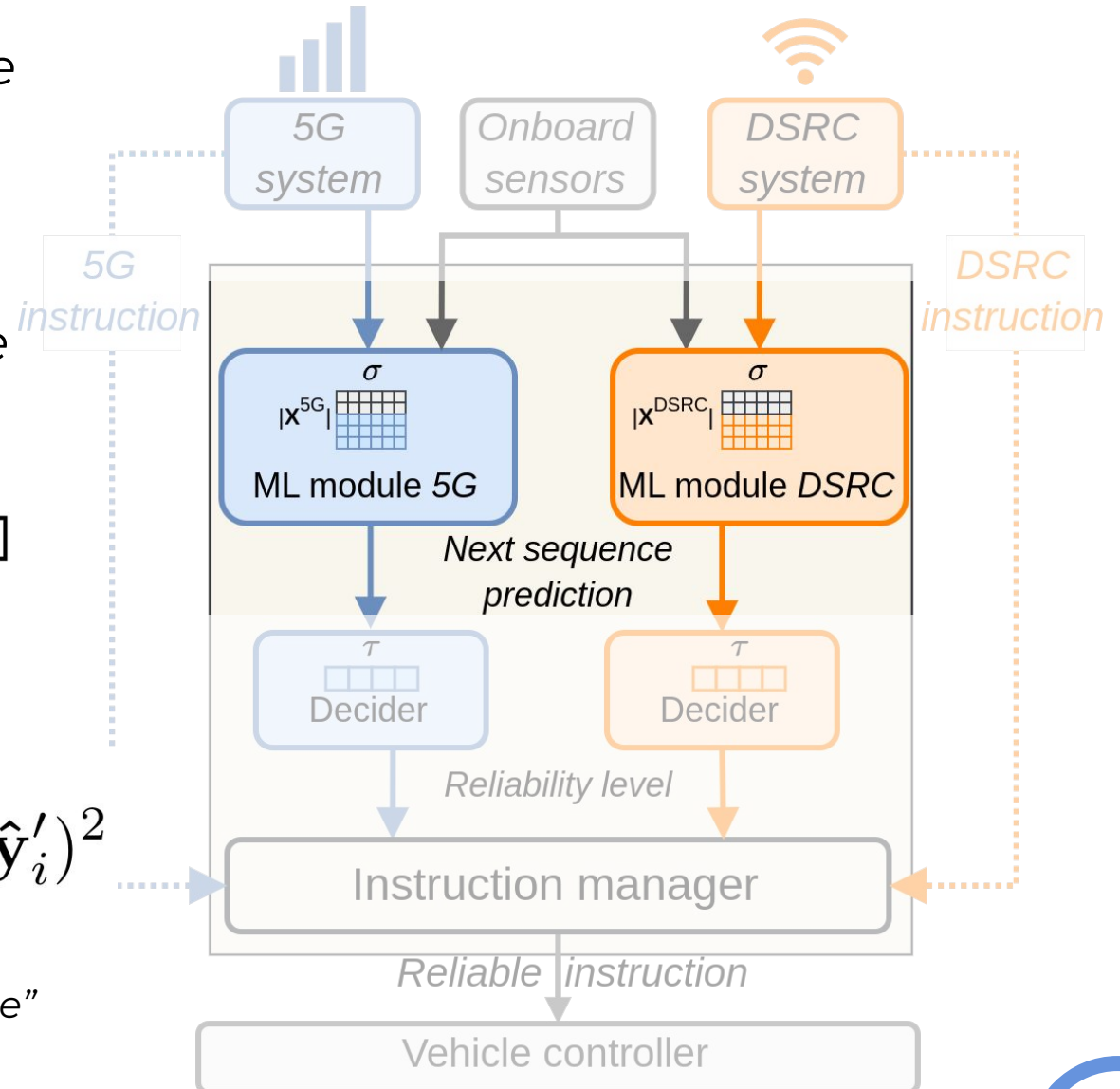


**Custom loss function**

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

“Reliability Mean”

“Reliability Shape”

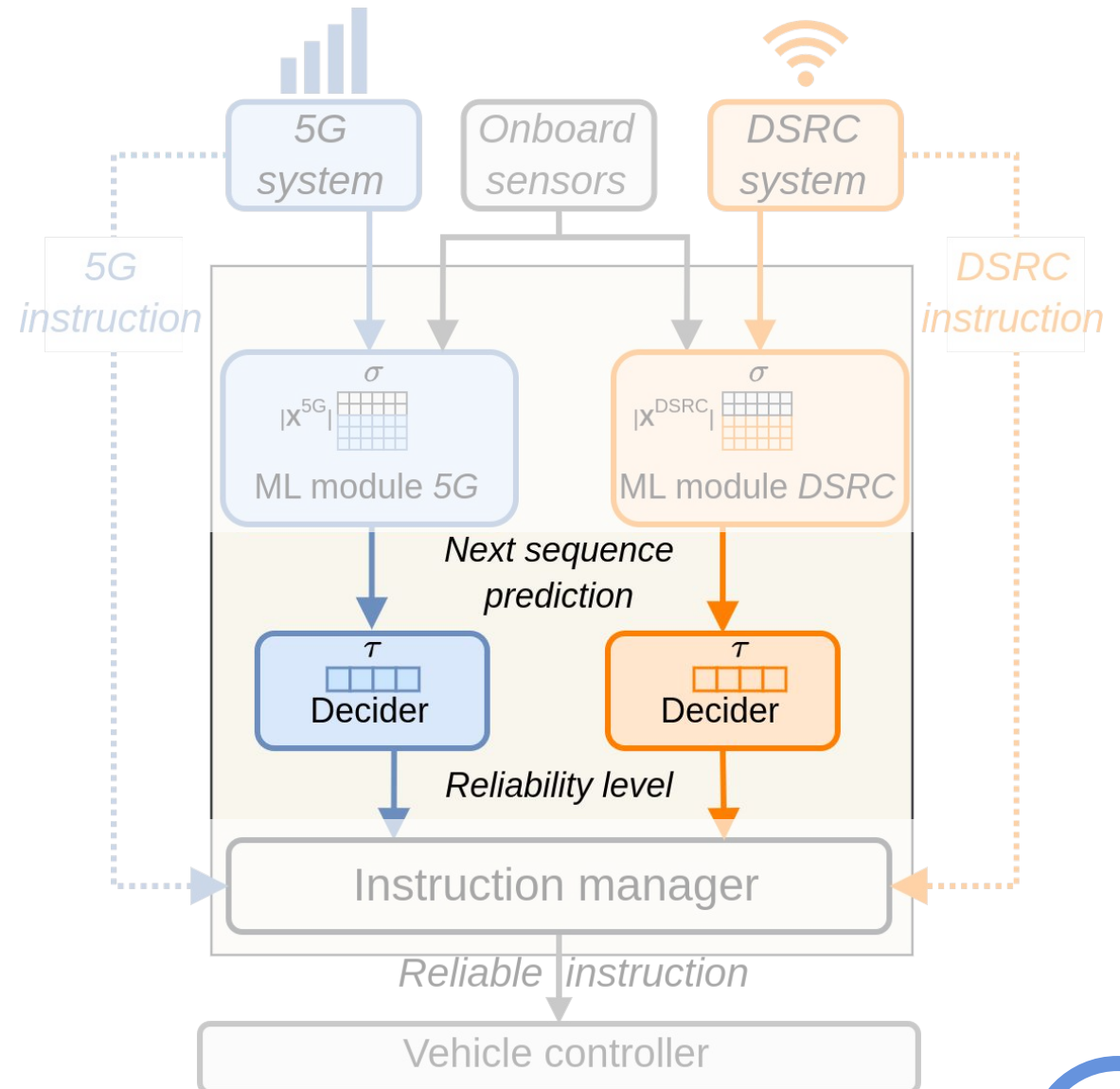
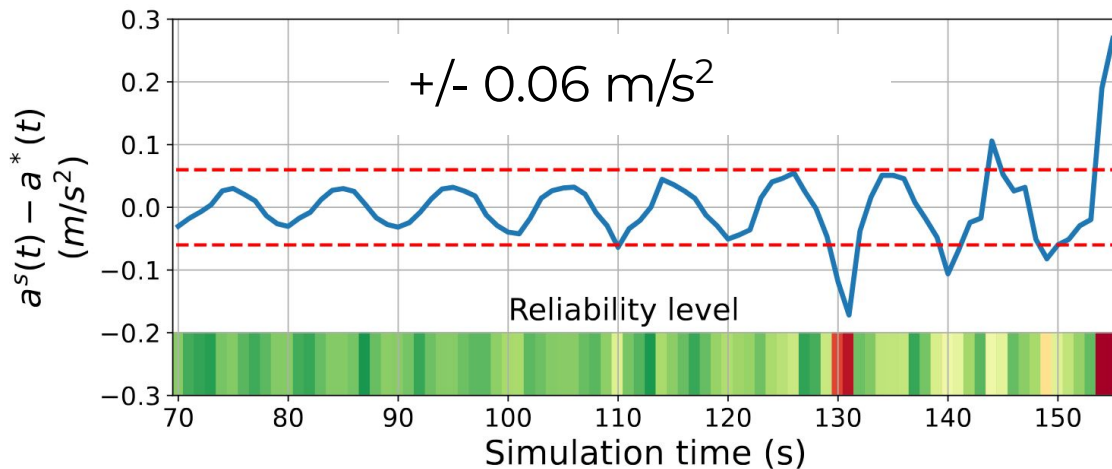


# ML Onboard system

Is the platoon system reliable?

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

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



# ML Onboard system

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

**5G reliable**

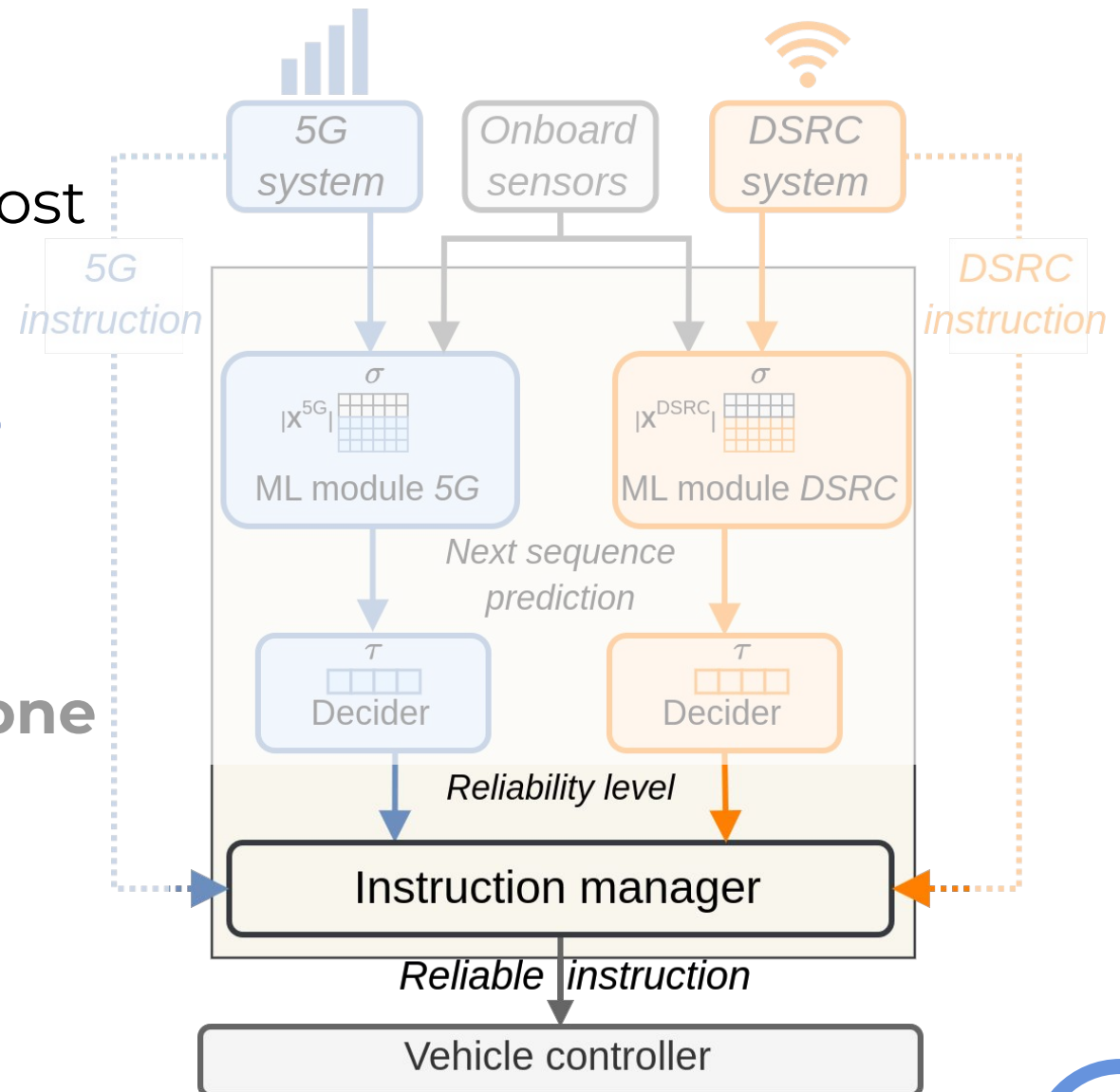
→ **5G-Edge**

**5G unreliable & DSRC reliable**

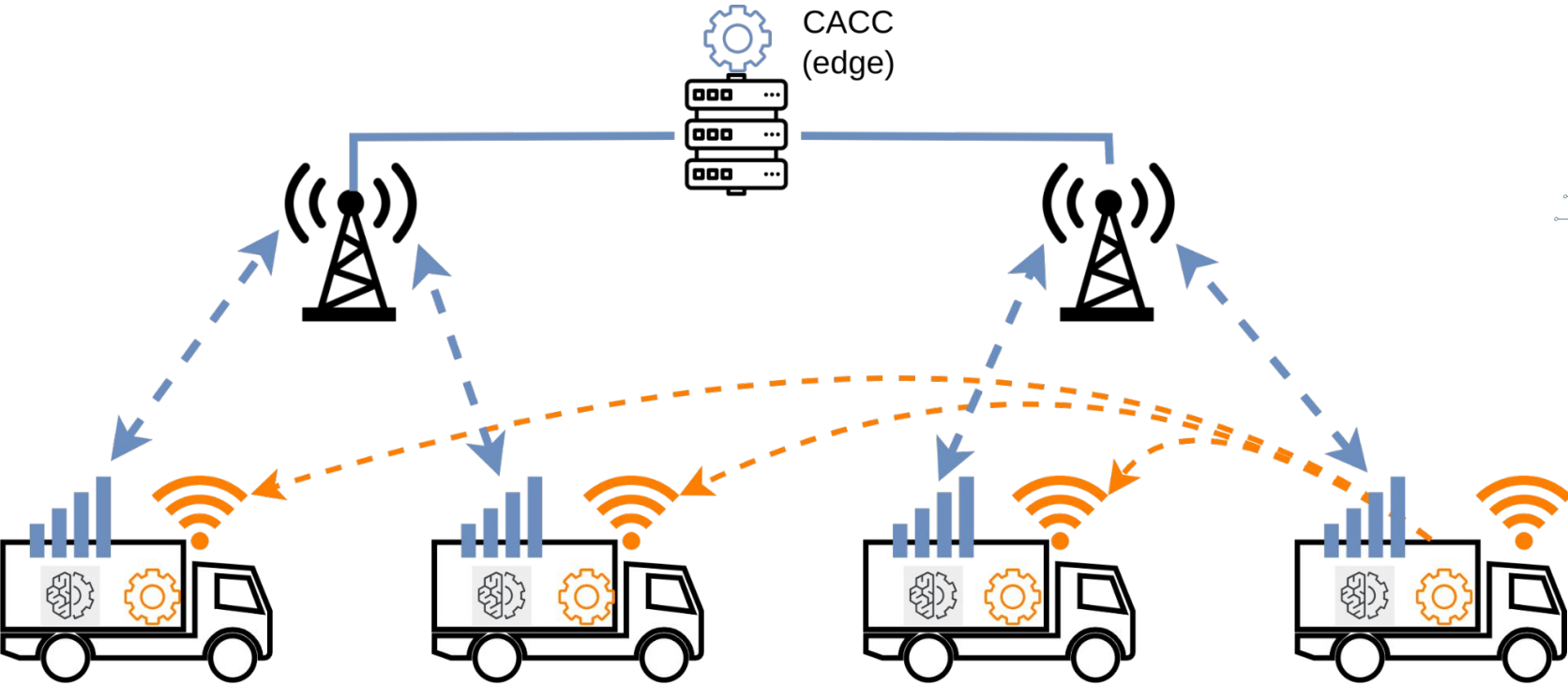
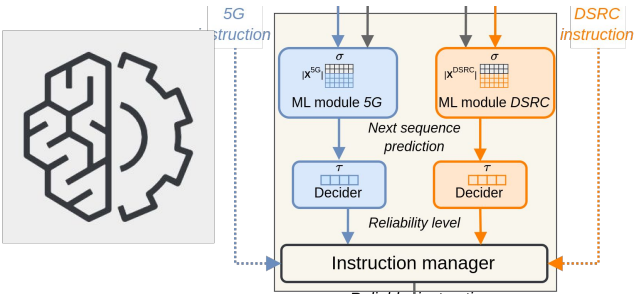
→ **DSRC**

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

**Hysteresis** parameter to prevent continuous switches



# Simulation framework



Simulation of Urban MObility

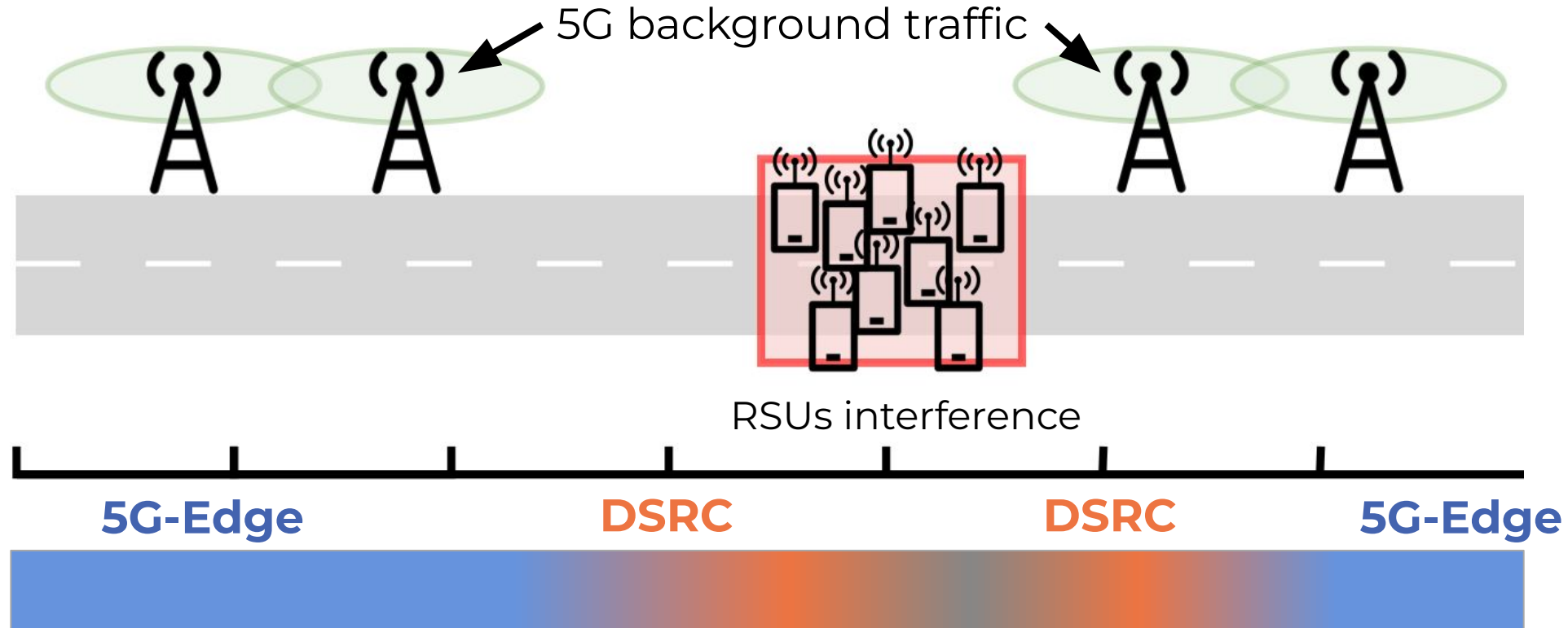
# Evaluation setting

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**

# 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 ( $\pm 5$ 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 ( $\sigma$ )	5 s (20 time steps)
Prediction time steps ( $\tau$ )	5 s (20 time steps)
Decider thresholds ( $\delta, \Delta$ )	$\delta = 0.06m/s^2, \Delta = 0.07m/s^2$
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	<i>ITU-Urban &amp; ITU-Rural</i> 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	$20 \pm 5$ ms

# Baselines

**PDR-Based:** packet delivery ratio based baseline

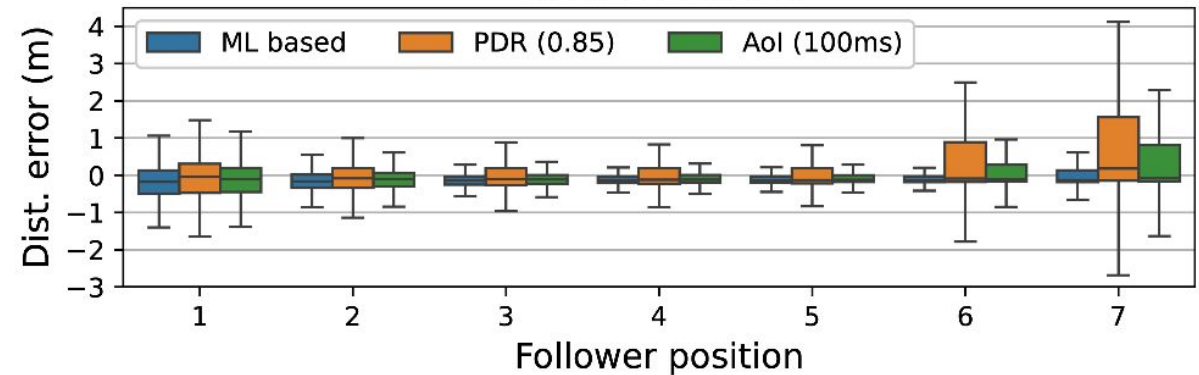
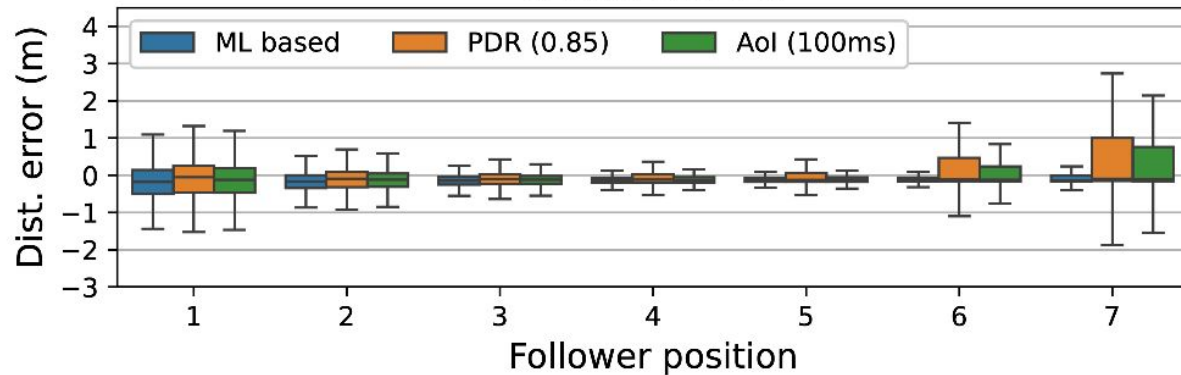
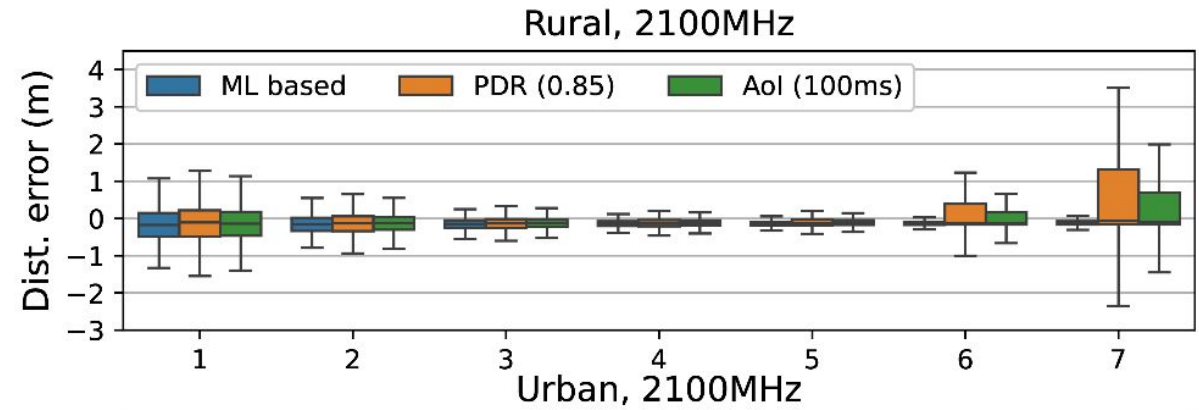
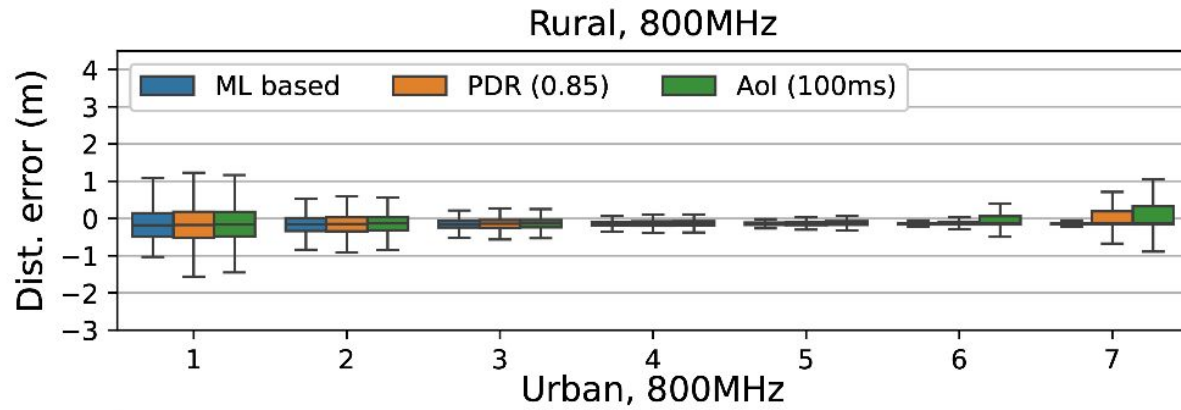
- Exponential smoothing of PDR
- $\text{PDR} < 85\% \rightarrow$  Platoon system unreliable
- Approach based on [1]

**Aol-Based:** age of information based baseline

- Avg. of Aol of CAMs
- Exponential smoothing of avg. of Aol
- $\text{Avg. Aol} > 100 \text{ ms} \rightarrow$  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,

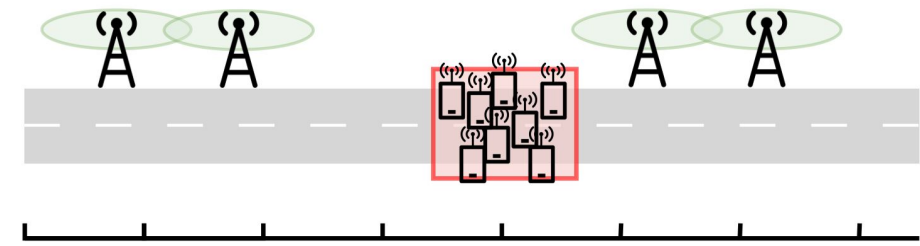
# Results - Platoon stability



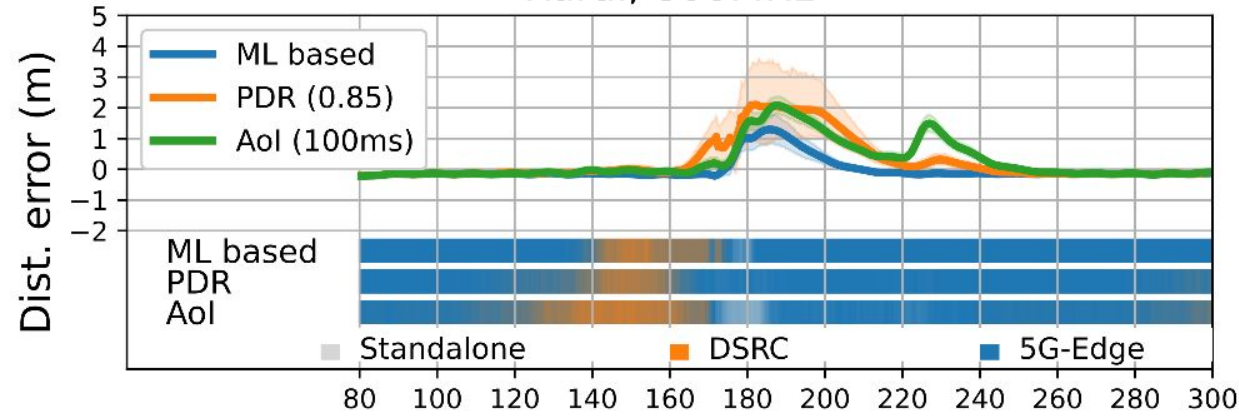
ML based guarantees more strong platoon string stability than the baselines

# Results - Error distance over time

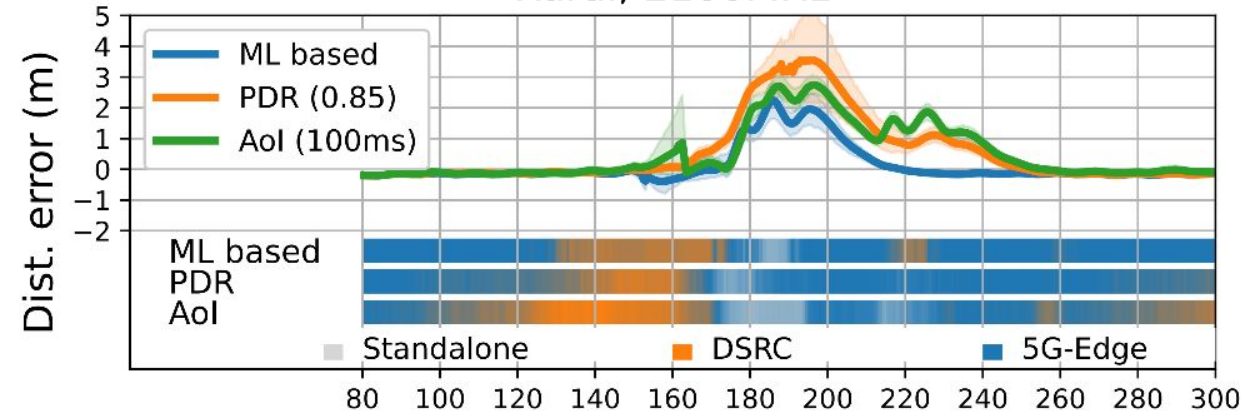
## 6th follower



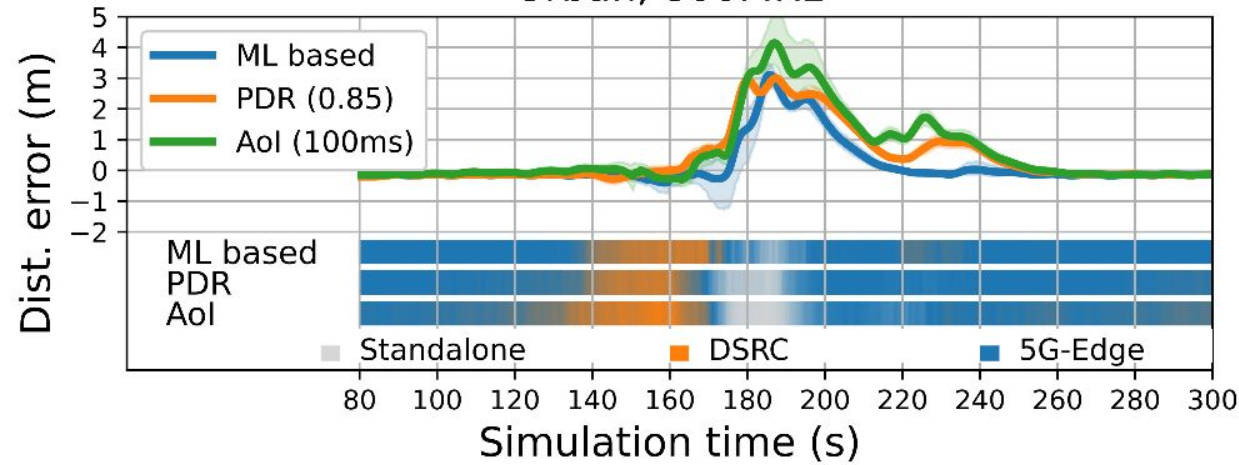
Rural, 800MHz



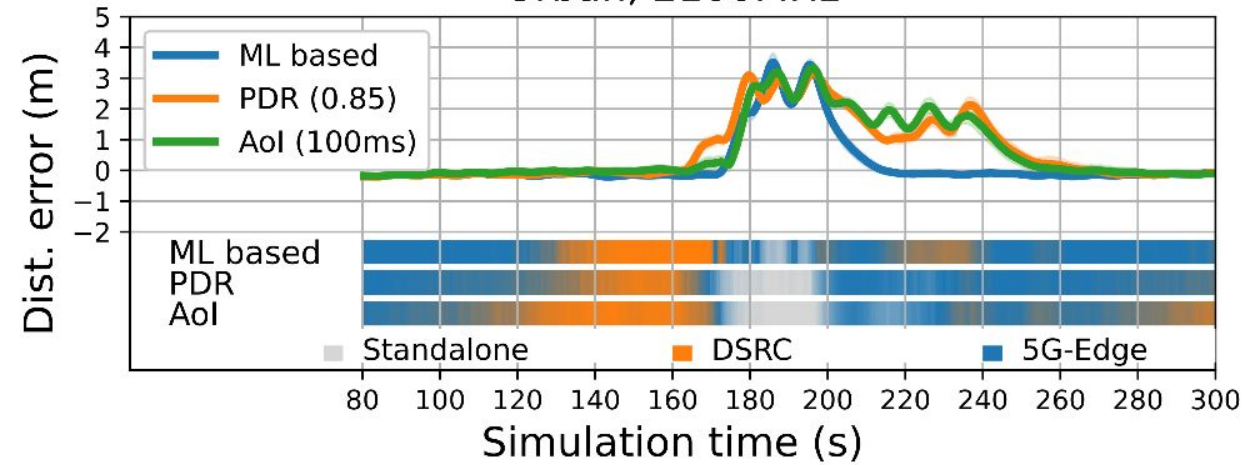
Rural, 2100MHz



Urban, 800MHz

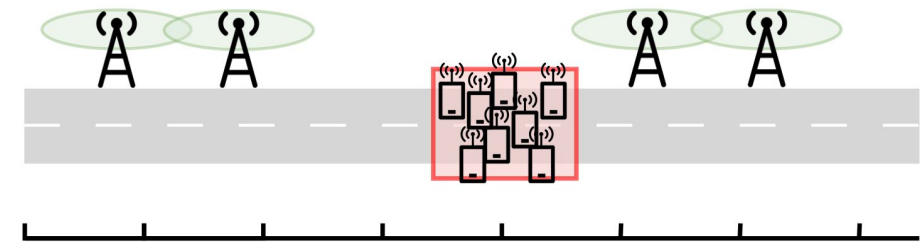


Urban, 2100MHz

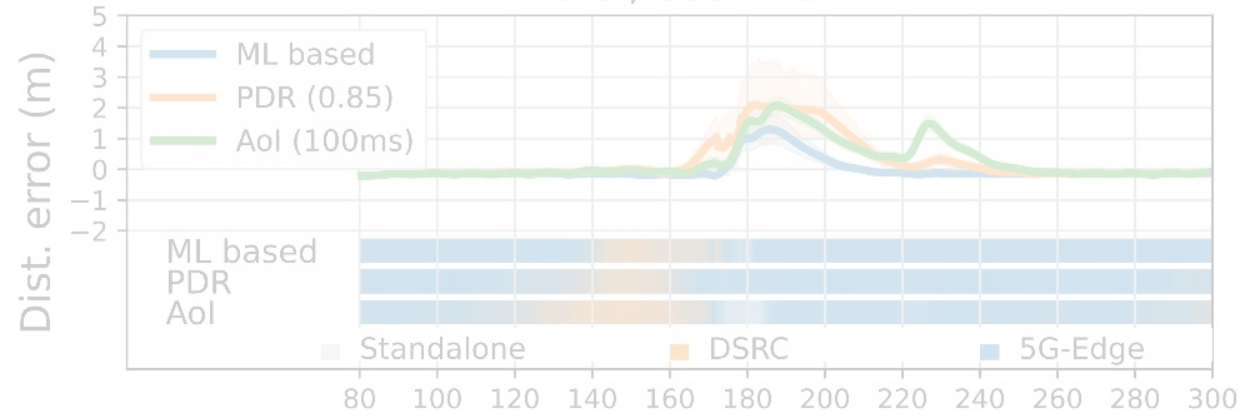


# Results - Error distance over time

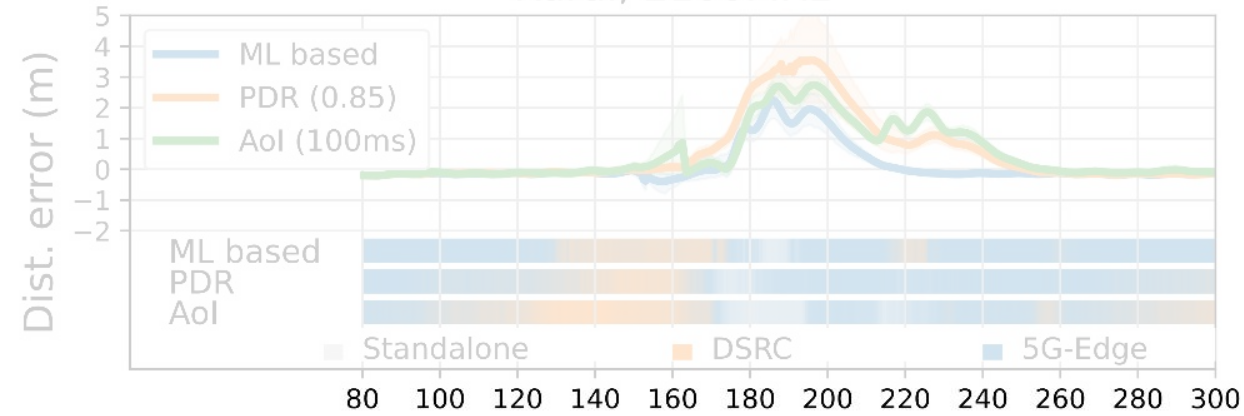
## 6th follower



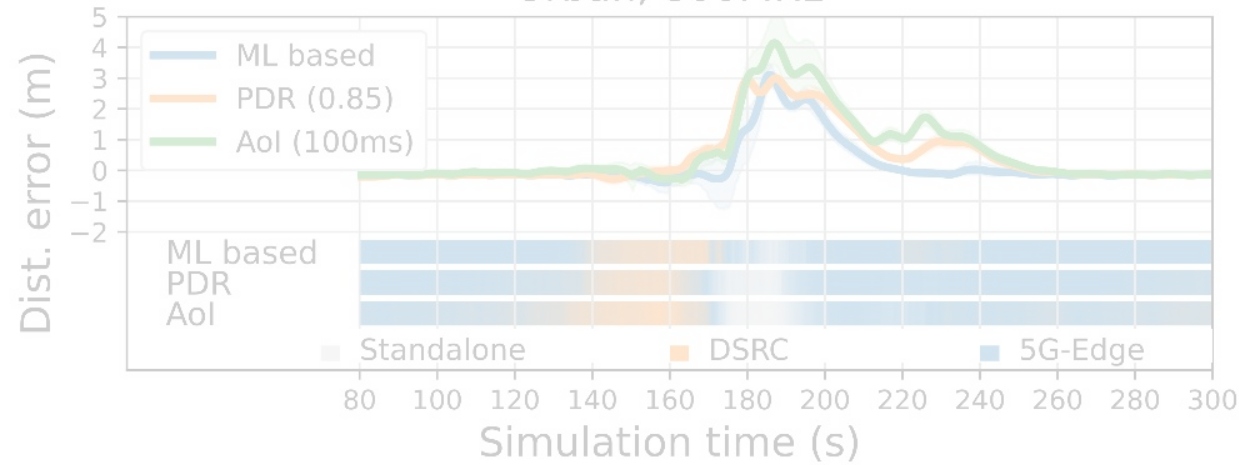
Rural, 800MHz



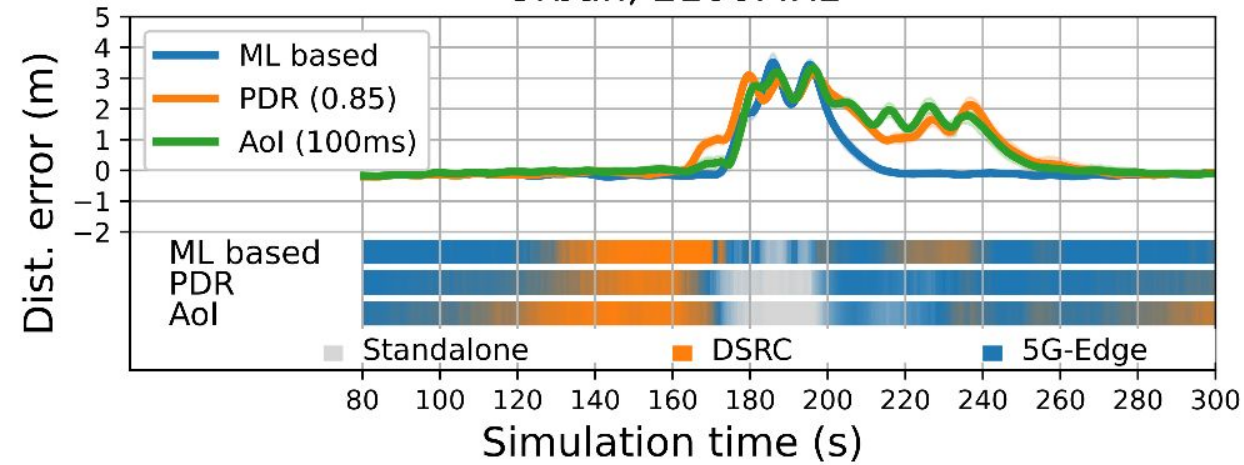
Rural, 2100MHz



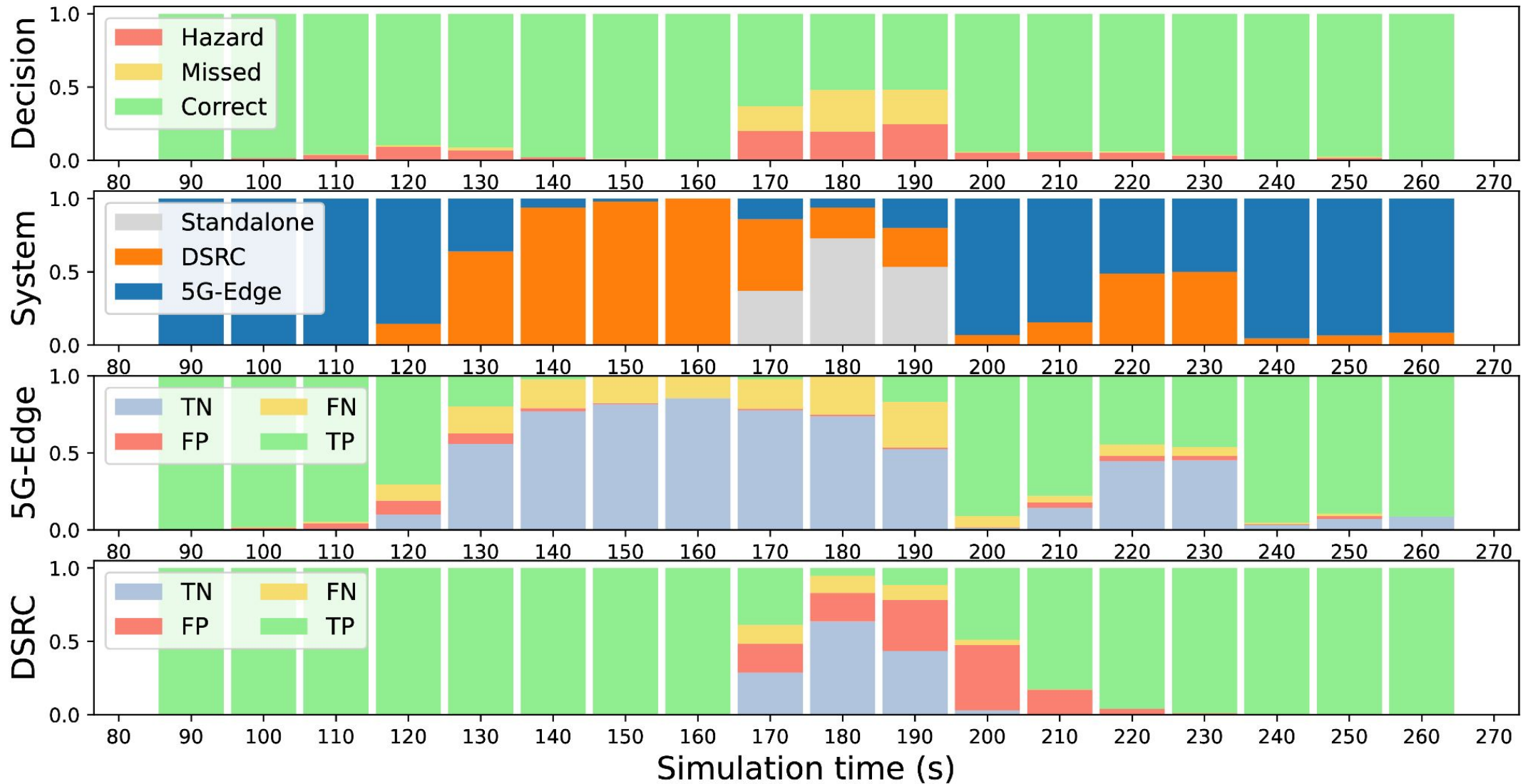
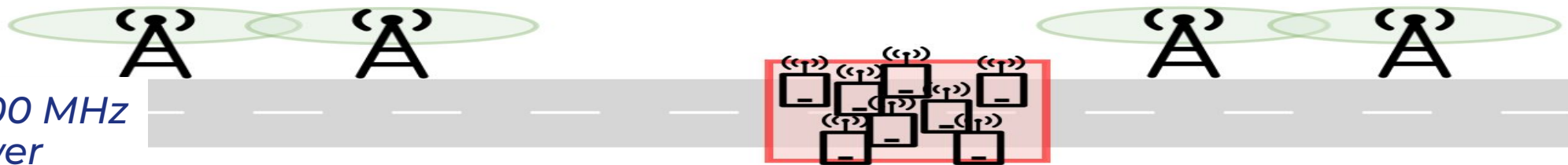
Urban, 800MHz



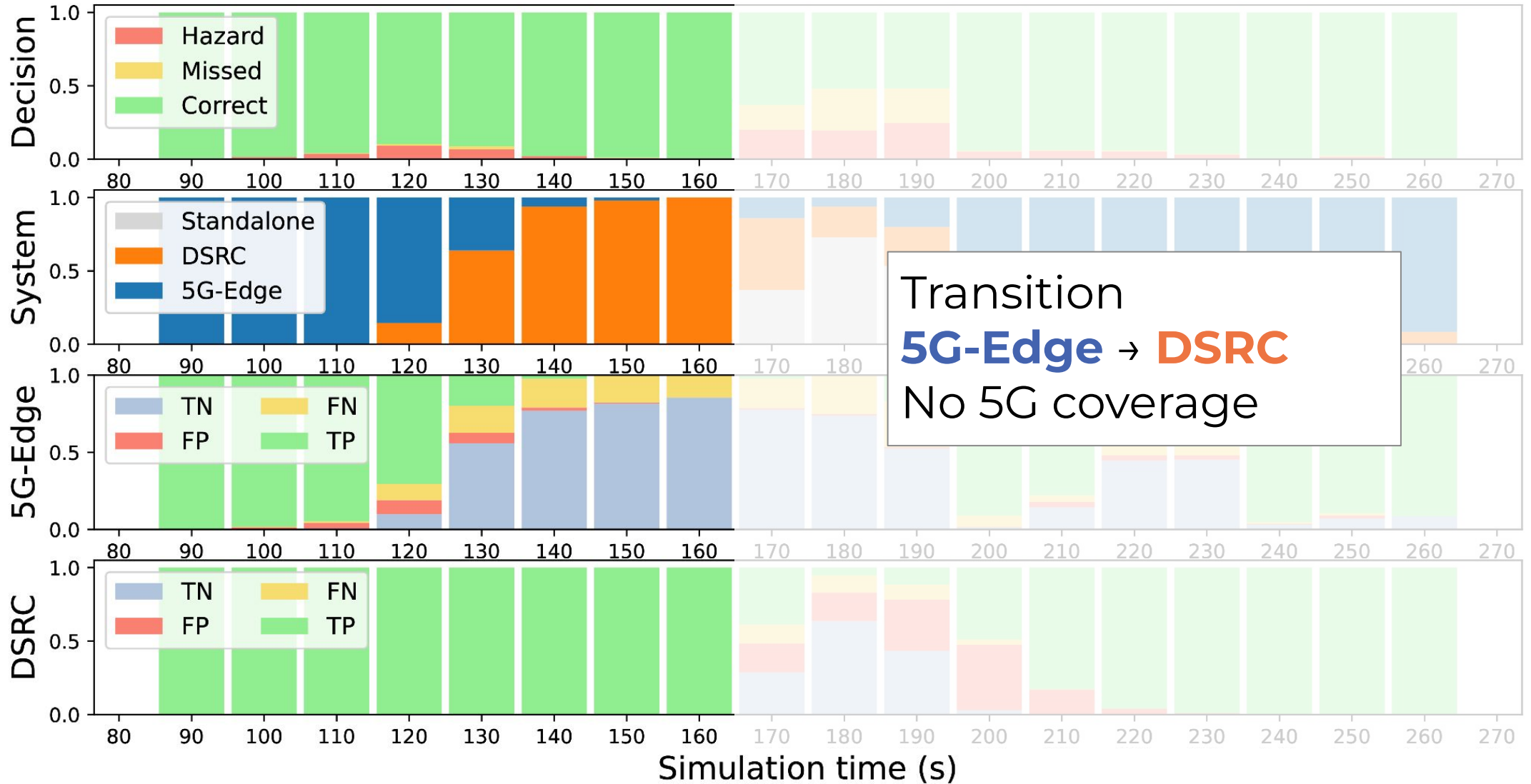
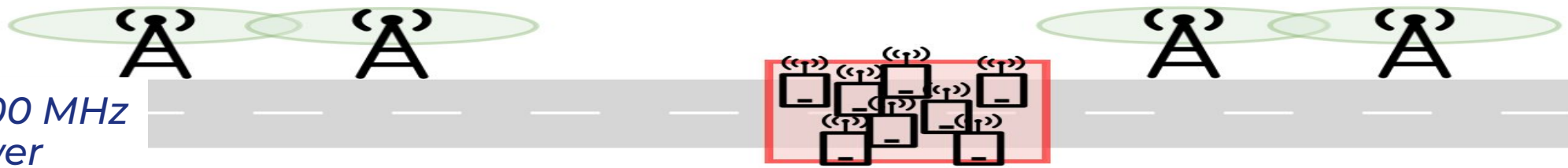
Urban, 2100MHz



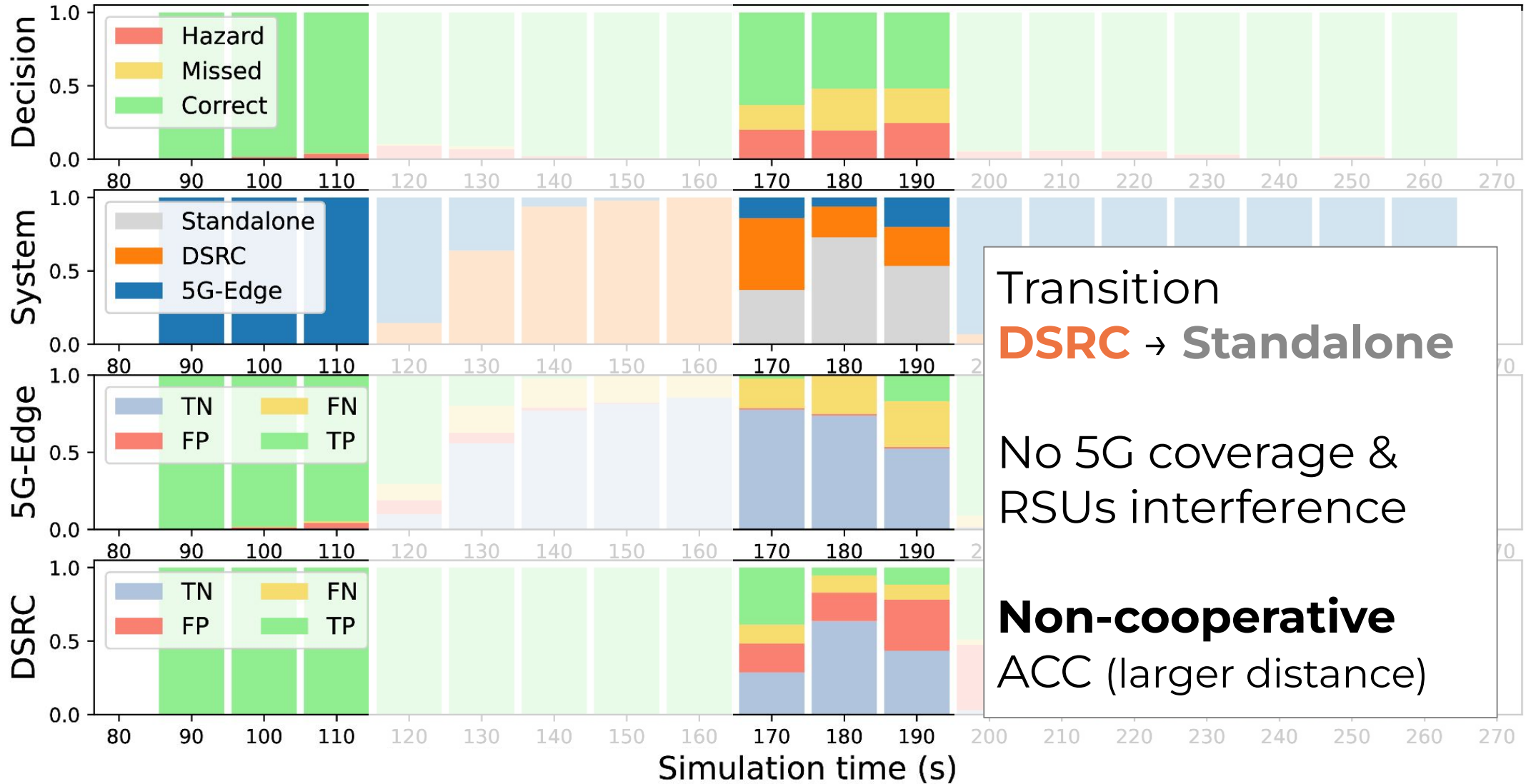
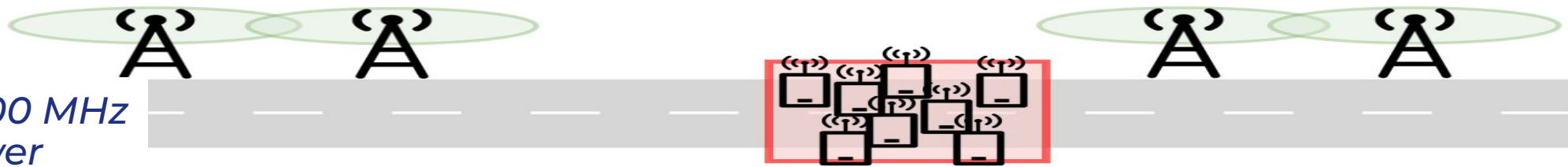
Urban 2100 MHz  
6th follower



Urban 2100 MHz  
6th follower



Urban 2100 MHz  
6th follower

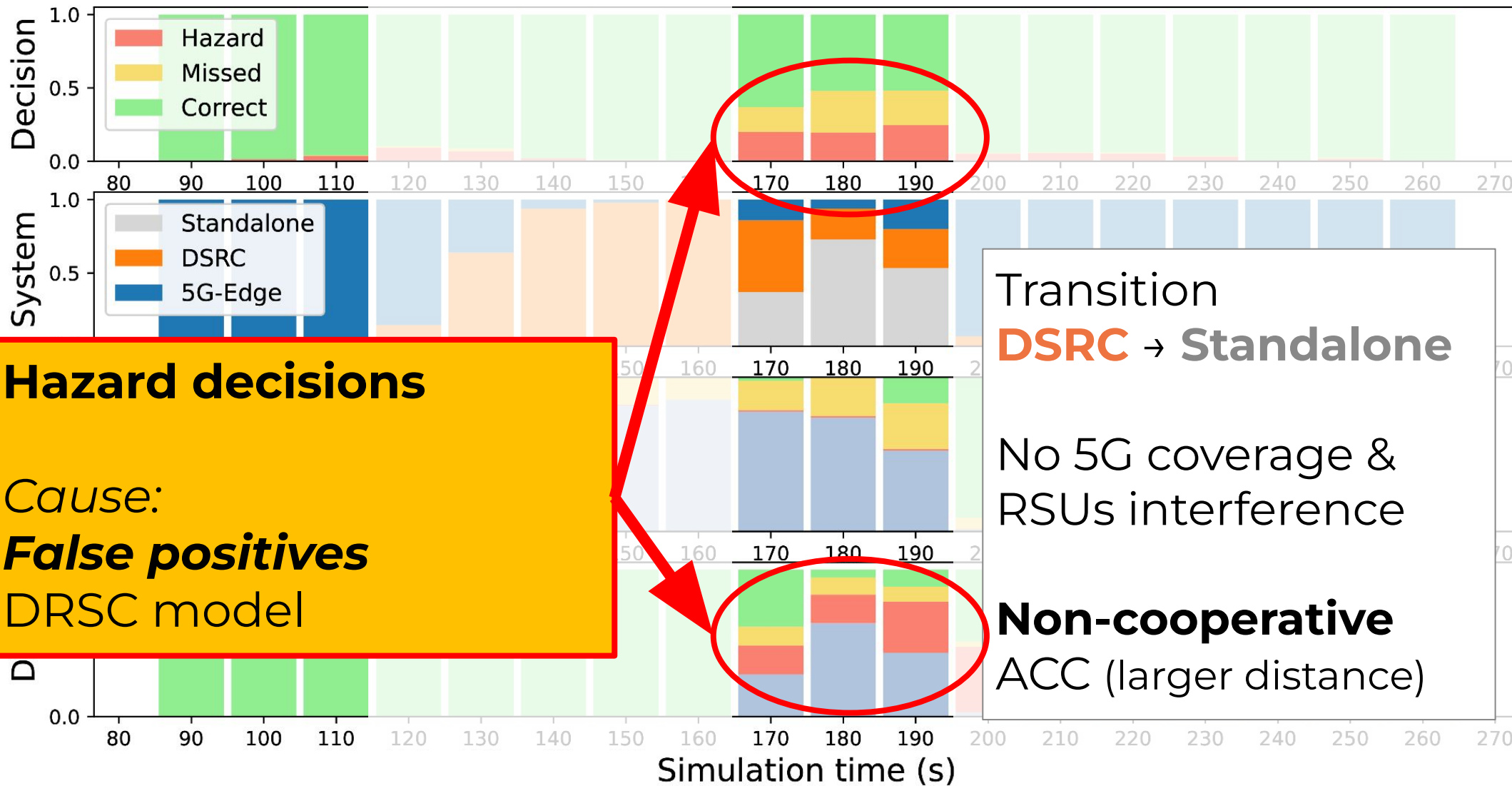
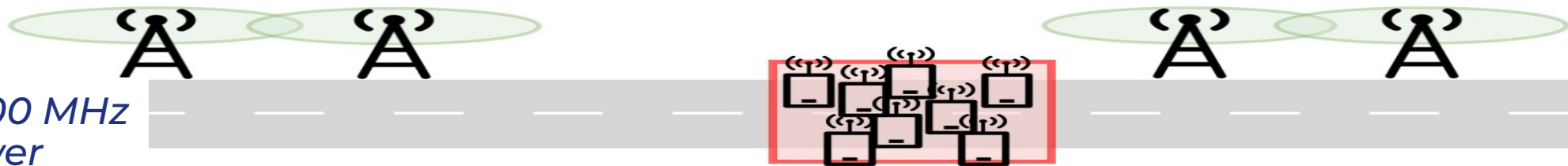


Transition  
**DSRC** → **Standalone**

No 5G coverage &  
 RSUs interference

**Non-cooperative**  
 ACC (larger distance)

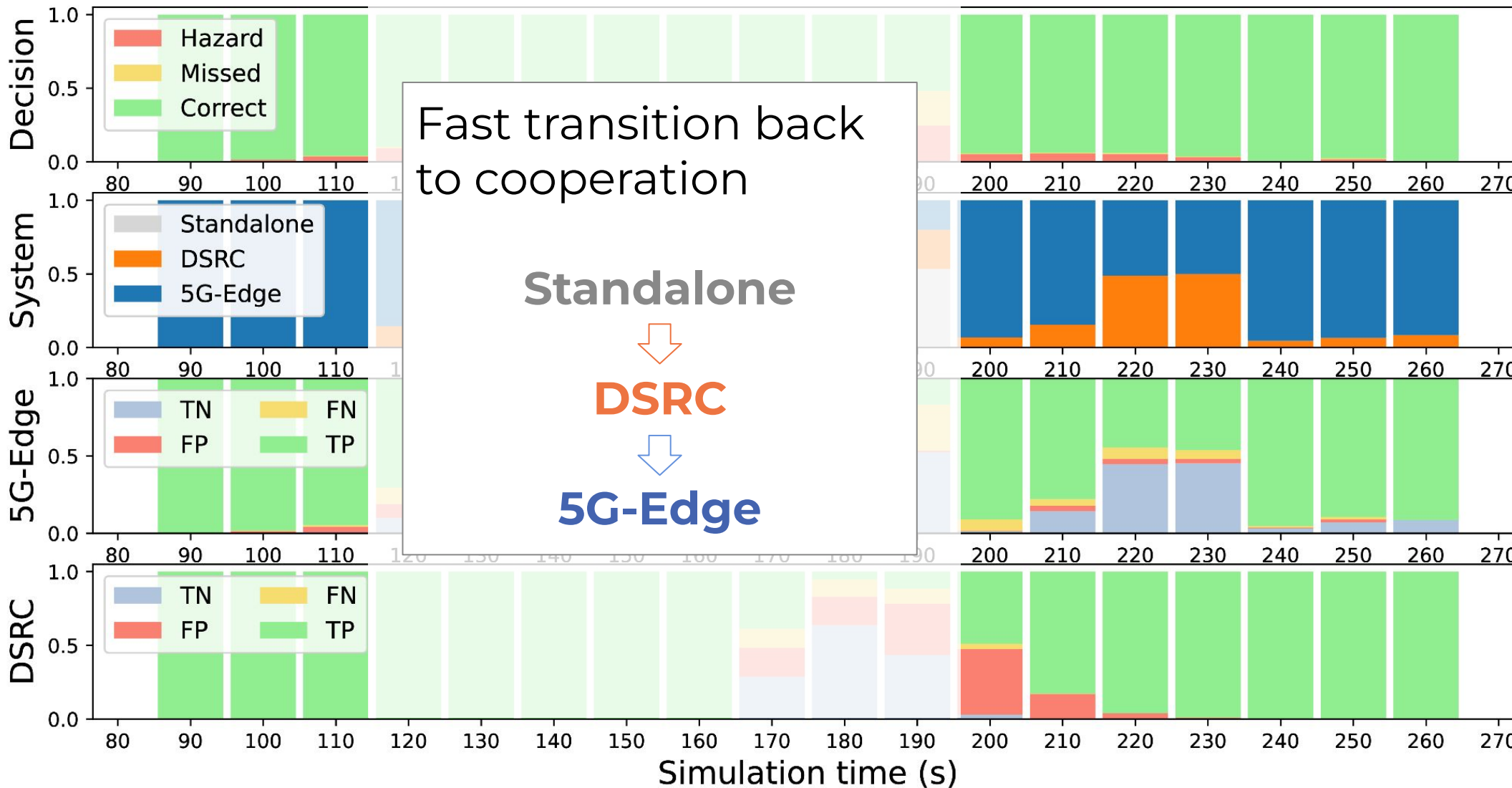
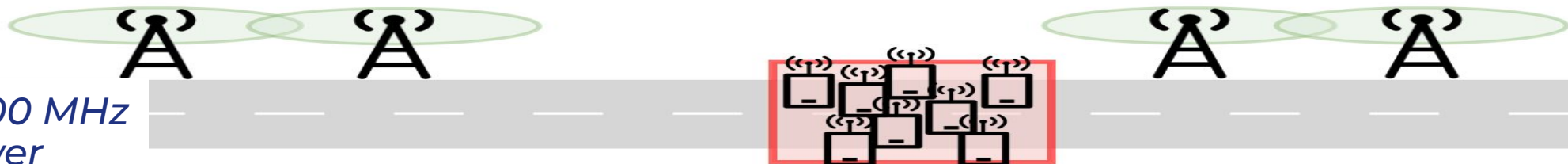
Urban 2100 MHz  
6th follower



**Hazard decisions**  
Cause:  
**False positives**  
DRSC model

Transition  
**DSRC** → **Standalone**  
  
No 5G coverage & RSUs interference  
  
**Non-cooperative**  
ACC (larger distance)

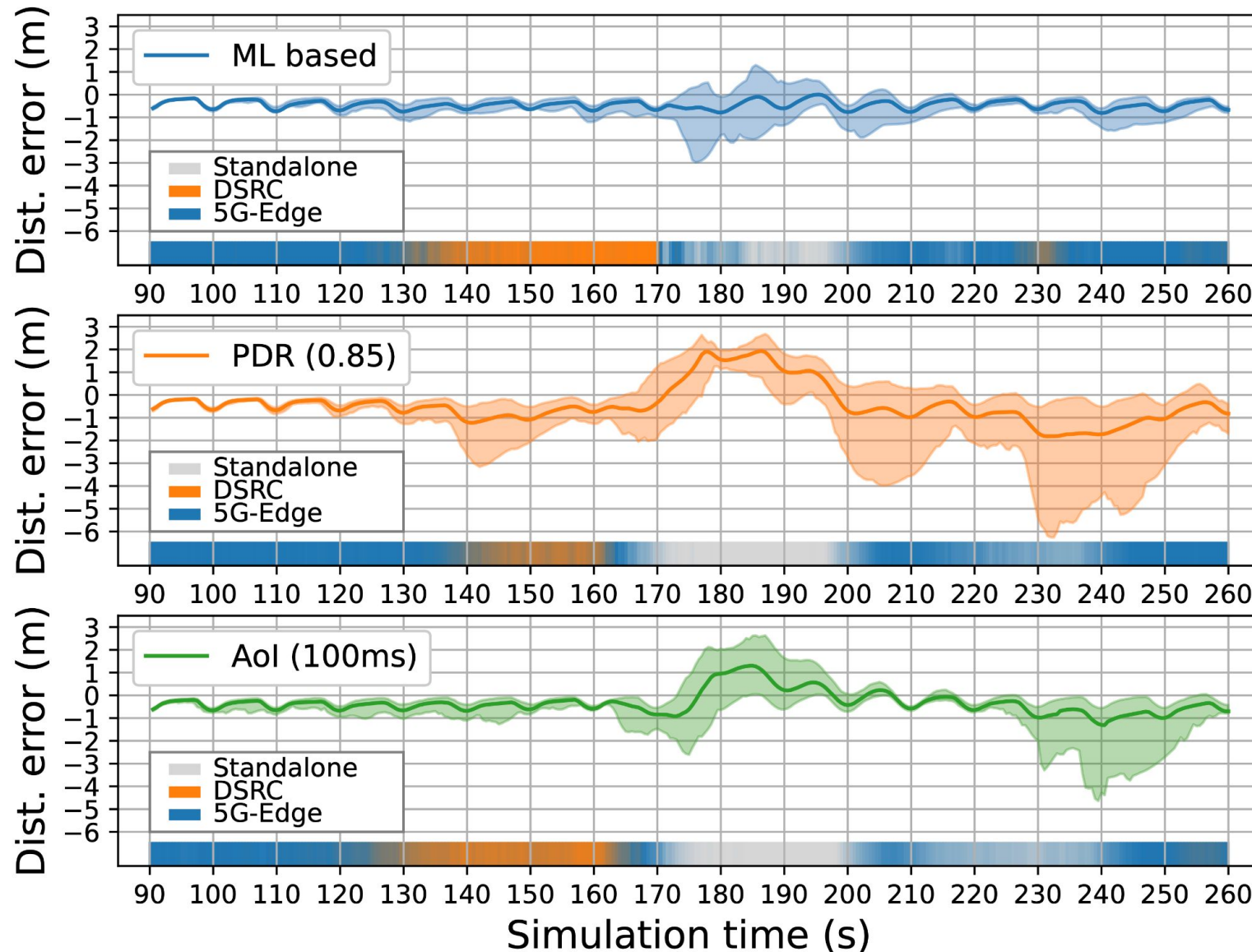
Urban 2100 MHz  
6th follower



# Decision system accuracy

<i>Rural</i>	800 MHz			2100 MHz		
	<i>Correct</i>	<i>Missed</i>	<i>Hazard</i>	<i>Correct</i>	<i>Missed</i>	<i>Hazard</i>
<b>ML based</b>	97.4	0.5	2.1	95.1	1.1	3.8
<b>PDR (0.85)</b>	91.0	2.1	6.9	87.2	4.5	8.3
<b>AoI (100ms)</b>	95.0	3.7	1.3	93.2	5.5	1.3
<i>Urban</i>	800 MHz			2100 MHz		
	<i>Correct</i>	<i>Missed</i>	<i>Hazard</i>	<i>Correct</i>	<i>Missed</i>	<i>Hazard</i>
<b>ML based</b>	94.4	1.4	4.2	92.7	2.2	5.1
<b>PDR (0.85)</b>	88.6	6.3	5.1	82.0	9.2	8.8
<b>AoI (100ms)</b>	91.7	6.7	1.6	90.1	8.2	1.7

# 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

# 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

## **What's next**

- DSRC model needs *fine tuning* to prevent false positives
- Testing other leader speed patterns
- More sophisticated and precise decision function
- Explainability



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# Thanks for your attention

*Publication reference*

C. Quadri, M. Dileo, V. Mancuso and M. A. Marsan,  
"DNN-Controlled Multi-Technology Platooning,"  
2025 IEEE Vehicular Networking Conference (VNC), Porto, Portugal, 2025