



Finanziato  
dall'Unione europea  
NextGenerationEU



Ministero  
dell'Università  
e della Ricerca



Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA



UNIVERSITÀ  
DEGLI STUDI  
DI MILANO



**FORESEEN**

# Impact of Network Delays on Edge-Assisted Platooning Systems in 5G Networks: Addressing Latency Challenges

Christian Quadri

Università degli Studi di Milano

Salvatore Pedone

Università degli Studi di Palermo

Adriano Fagiolini

Università degli Studi di Palermo

PRIN-PNRR 2022 project (Grant P2022WYAEW)



Finanziato  
dall'Unione europea  
NextGenerationEU



Ministero  
dell'Università  
e della Ricerca



Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA

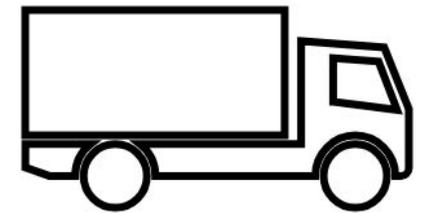
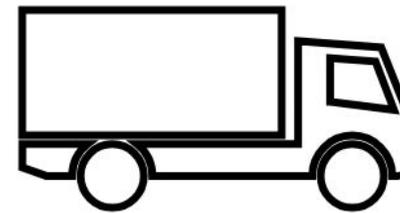
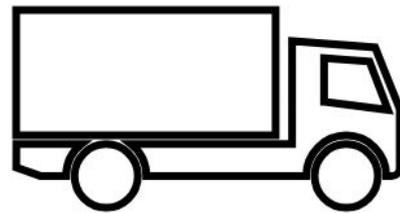
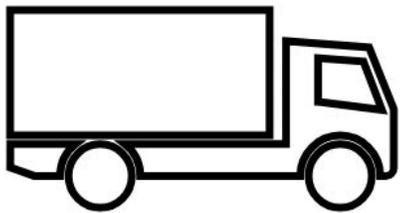


UNIVERSITÀ  
DEGLI STUDI  
DI MILANO

# Platooning

Better road utilization & comfort

Reduced fuel consumption & carbon footprint



**Automated coordination among vehicles**

**Control law**

**Efficient communication wireless channel**



Finanziato  
dall'Unione europea  
NextGenerationEU



Ministero  
dell'Università  
e della Ricerca



Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA

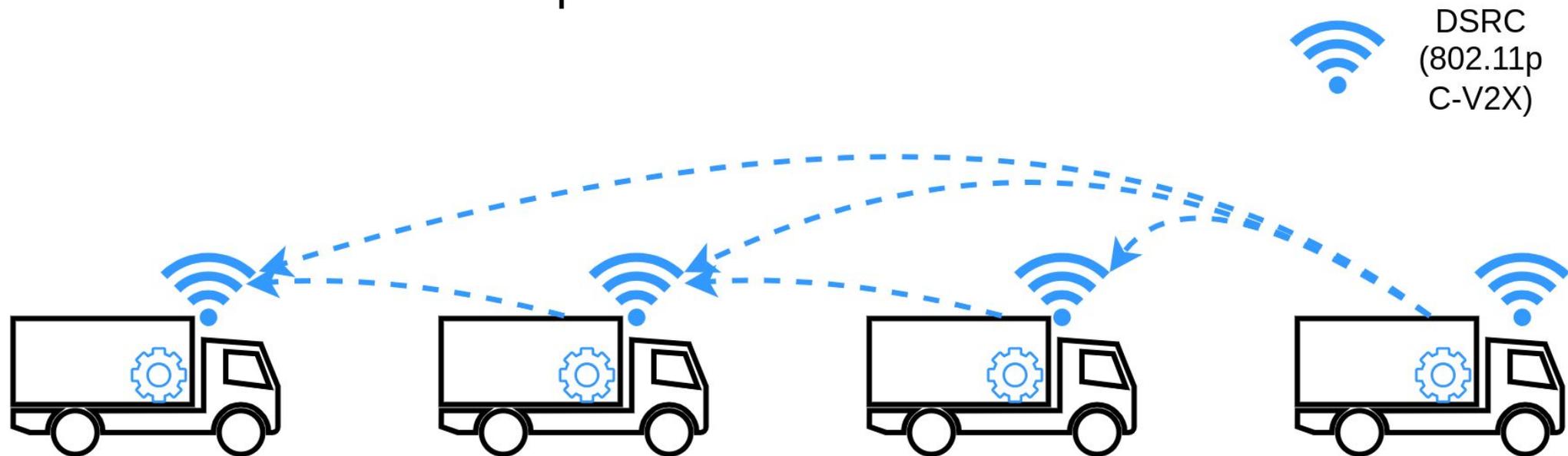


UNIVERSITÀ  
DEGLI STUDI  
DI MILANO

## Legacy platoon control

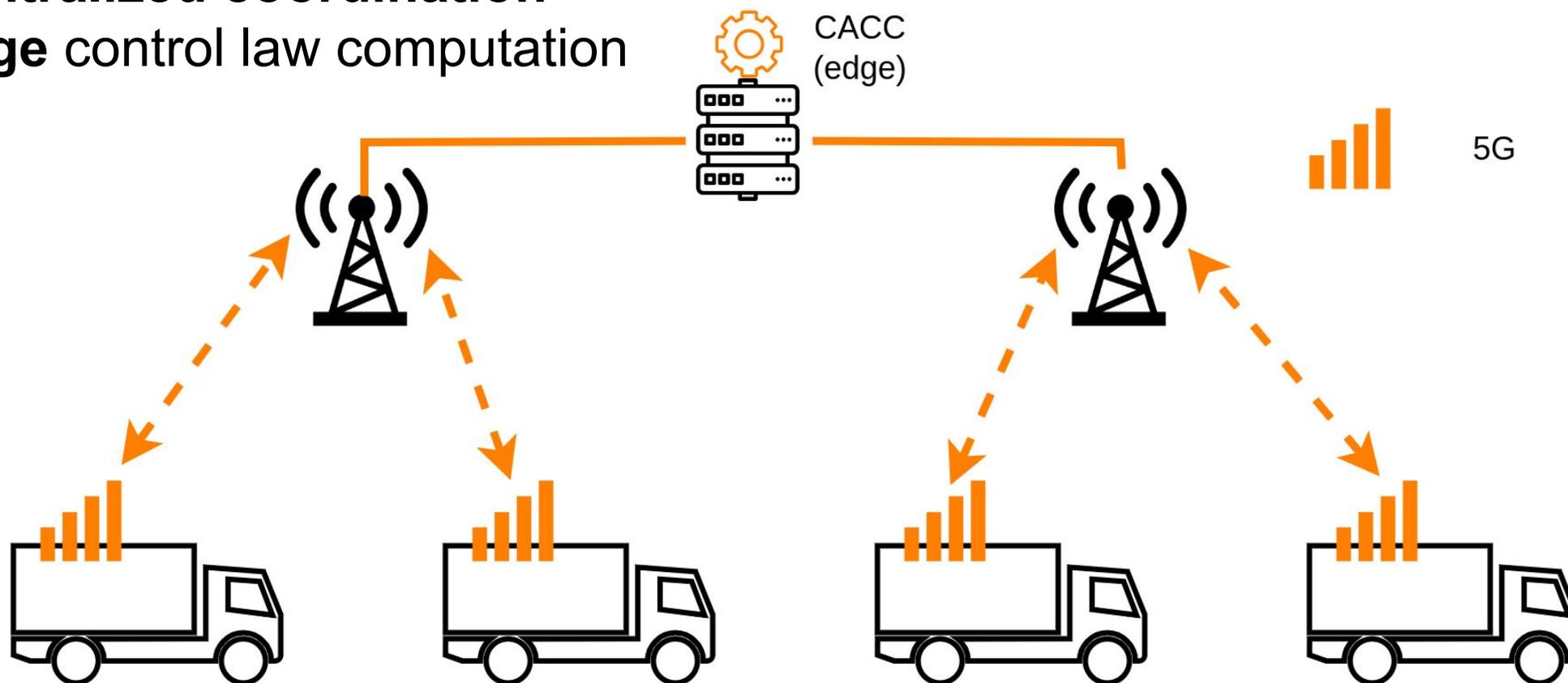
**Distributed coordination** through Dedicated Short Range  
Communication system

**On-board** control law computation



# Centralized 5G-Edge-based platoon control

**Centralized coordination**  
**Edge control law computation**





## DSRC vs 5G-Edge

	<b>DSRC</b>	<b>5G-Edge</b>
Infrastructure requirements	<b>None</b>	5G coverage + Edge capabilities
Radio channel contention	<b>High (Random Access)</b>	<b>Base station coordination</b>
Long platoons	<b>Difficult Limited radio range Multi-hop delays</b>	<b>Easy and scalable</b>
Network transmissions	Broadcast	Unicast Uplink Unicast Downlink





Finanziato  
dall'Unione europea  
NextGenerationEU



Ministero  
dell'Università  
e della Ricerca



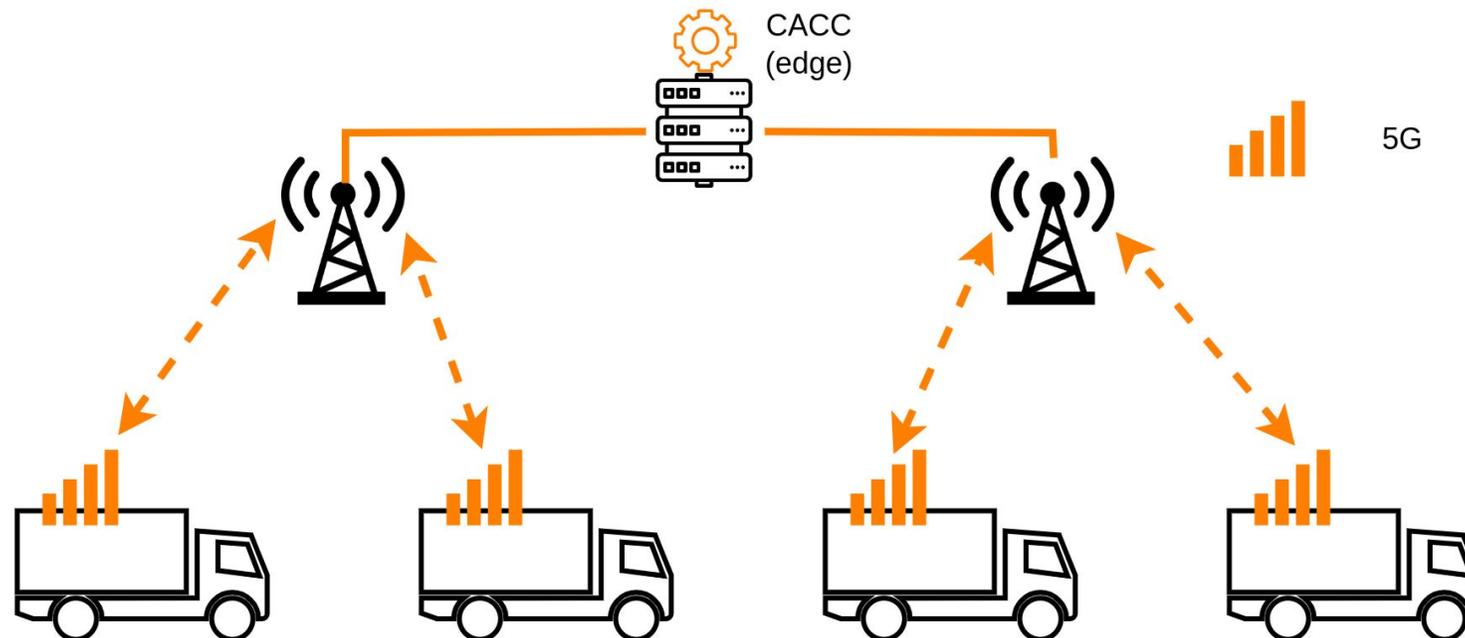
Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA



UNIVERSITÀ  
DEGLI STUDI  
DI MILANO

## Goal

**Investigate the influence of uplink and downlink network delays on an 5G-edge platooning system**





Finanziato  
dall'Unione europea  
NextGenerationEU



Ministero  
dell'Università  
e della Ricerca

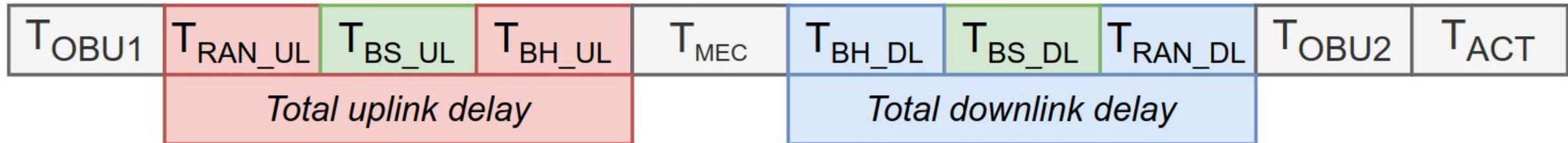


Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA



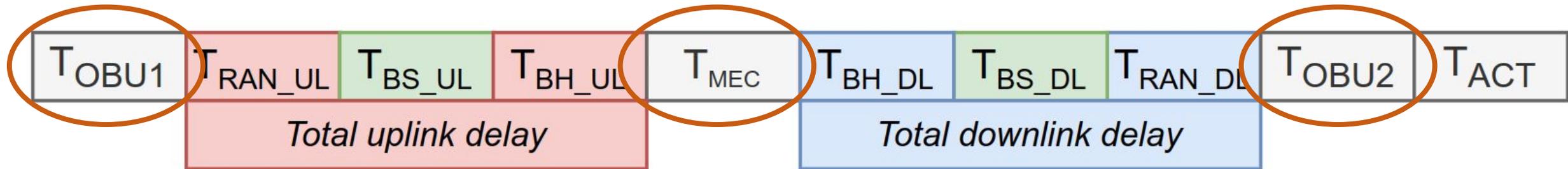
UNIVERSITÀ  
DEGLI STUDI  
DI MILANO

## Network delay schema 5G-Edge platooning





## Network delay schema 5G-Edge platooning



Negligible computation delay

On-Board Unit

Edge control law computation



## Network delay schema 5G-Edge platooning

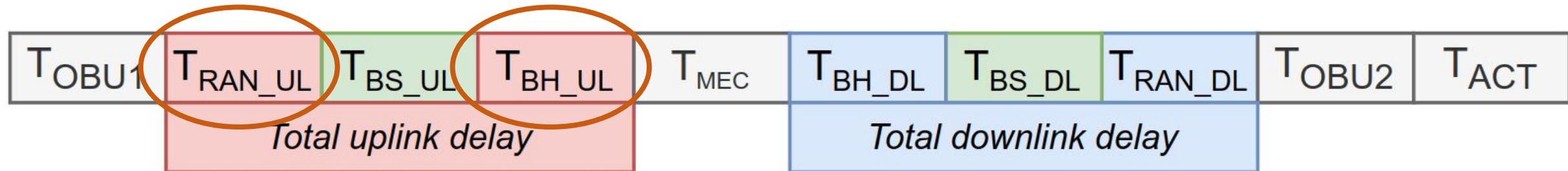


### Vehicle actuation lag

Independent of platooning system  
and specific for the type of vehicle



## Network delay schema 5G-Edge platooning



Uplink vehicle's data transmission

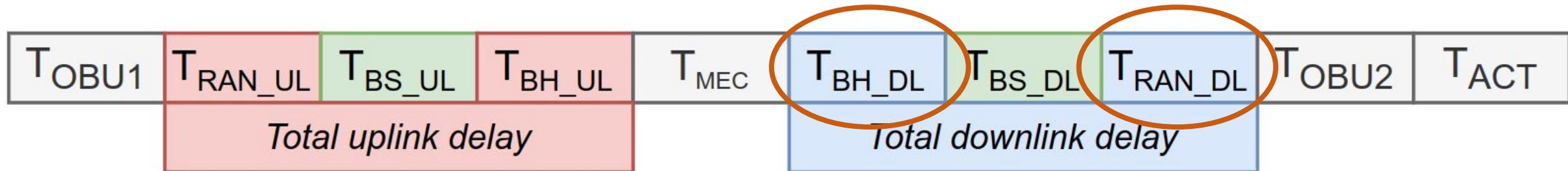
**RAN:** Vehicle to Base station (radio link quality dependency)

**Backhaul:** Base station to edge server (negligible)





## Network delay schema 5G-Edge platooning



Downlink instruction data transmission

**Backhaul:** Edge server to Base station (negligible)

**RAN:** Base station to Vehicle (radio link quality dependency, *less than uplink*)



## Network delay schema 5G-Edge platooning



Base station scheduling and queueing time

**Base stations control** the usage of the **network resources** (*no contention*)

**Uplink and downlink scheduling and queueing are independent** (*almost*)



## Network delay schema 5G-Edge platooning



Base station scheduling and queueing time

**Base stations control** the usage of the **network resources** (*no contention*)

**Uplink and downlink scheduling and queueing** are **independent** (*almost*)

**We investigate the impact of scheduling and queueing delay on platoon performance**



## Cooperative Adaptive Cruise Control (CACC)

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

$$\dot{\varepsilon}_i = \dot{x}_i - \dot{x}_{i-1}$$

$$\varepsilon_i = x_i - x_{i-1} + l_{i-1} + d_{des}$$

$$\alpha_1 = 1 - C_1$$

$$\alpha_2 = C_1$$

$$\alpha_3 = - \left( 2\xi - C_1 \left( \xi + \sqrt{\xi^2 - 1} \right) \right) \omega_n$$

$$\alpha_4 = -C_1 \left( \xi + \sqrt{\xi^2 - 1} \right) \omega_n$$

$$\alpha_5 = -\omega_n^2$$

Constant distance policy

Required data:

Self vehicle (i)

Front vehicle (i-1)

Leader vehicle (0)

Output:

Desired acceleration (i)

CACC from PATH project Rajesh Rajamani et al. "Demonstration of integrated longitudinal and lateral control for the operation of automated vehicles in platoons", IEEE Transactions on Control Systems Technology 8.4 (2000), pp. 695-708.



Finanziato  
dall'Unione europea  
NextGenerationEU



Ministero  
dell'Università  
e della Ricerca

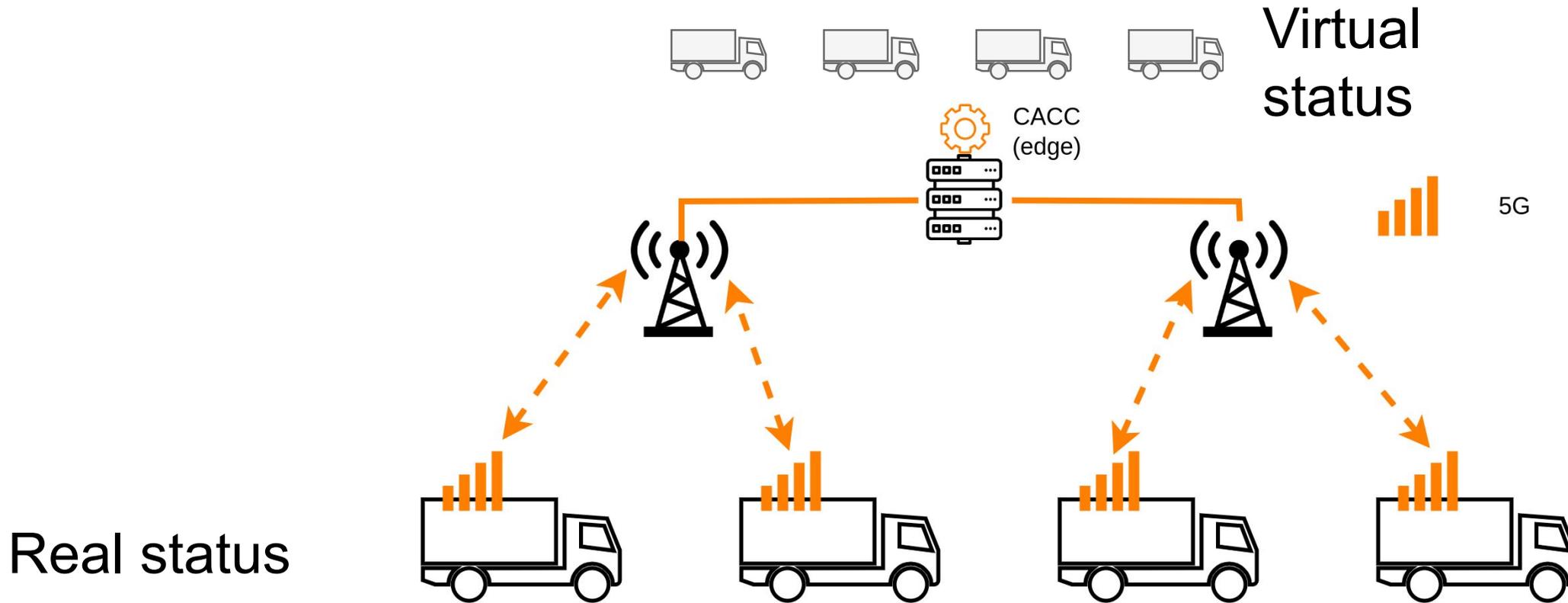


Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA



UNIVERSITÀ  
DEGLI STUDI  
DI MILANO

## Real vs Virtual platoon status

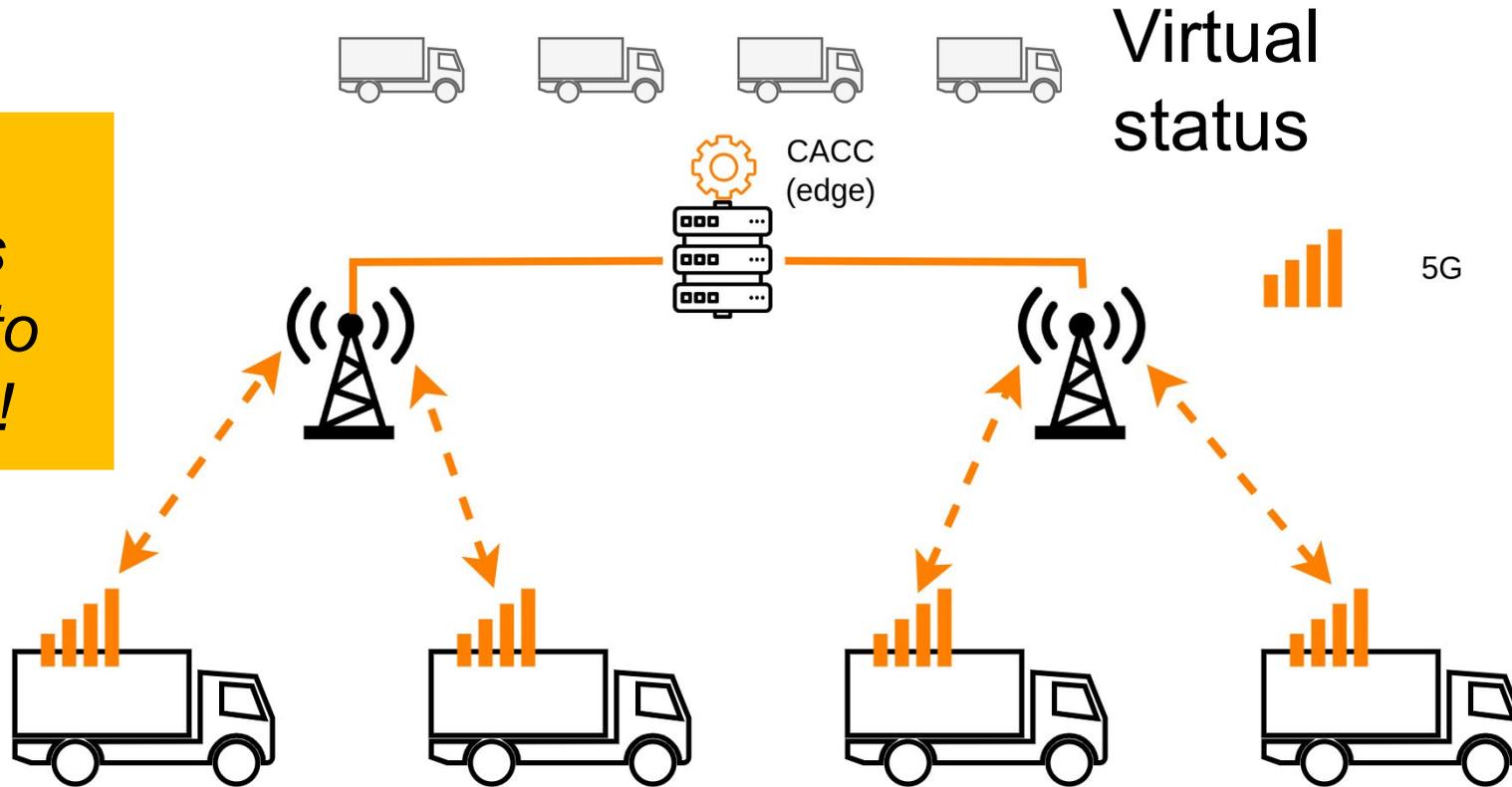




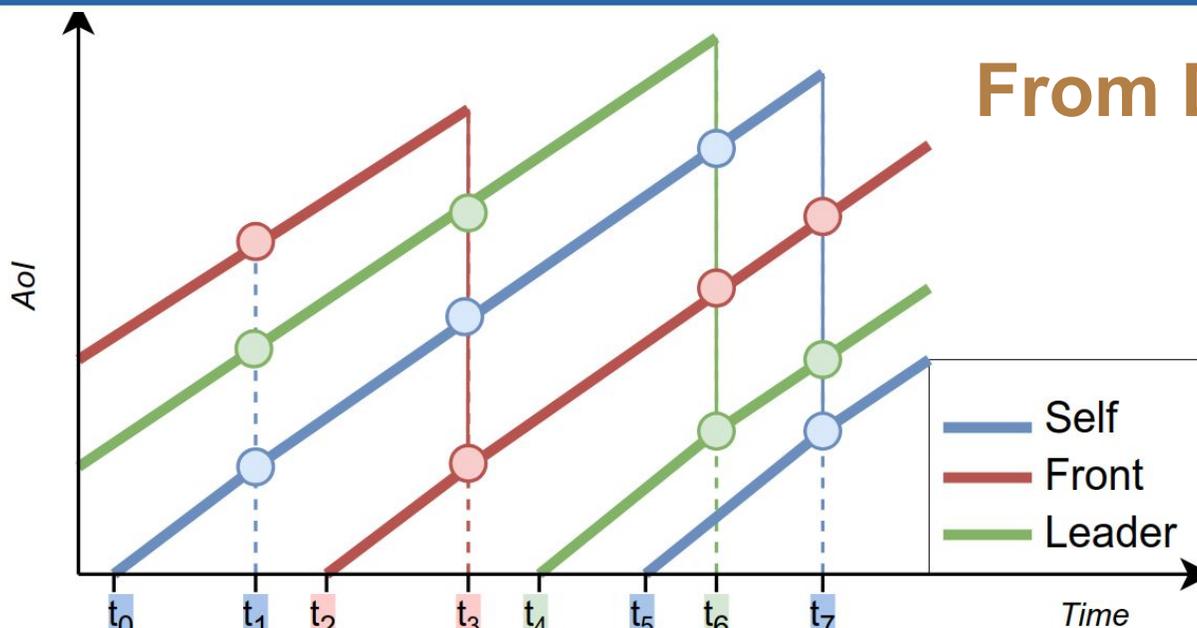
# Real vs Virtual platoon status

*Virtual platoon representation is highly sensitive to network delays!!!*

Real status



Vehicles Data Uplink



## From Delay to Age of Information

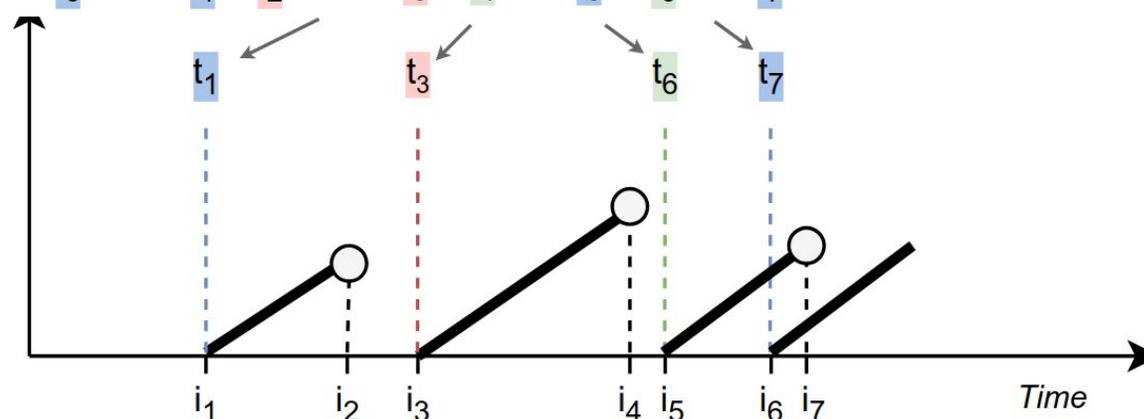
Vehicle data received by edge triggers control law computation

Data AoI depends on network delays – Uplink

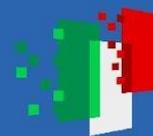
Instructions are sent to vehicles

Instruction AoI depends on network delays – Downlink

Vehicle Instruction Downlink



**5G only delay component**



## Evaluation

### General parameters

Simulated road	Straight 3-lane highway
Simulation duration	300 s (100 s of warm-up time)
Simulation scenario repetitions	20 random seeds

### Platoon parameters

Number of platoon members	8
Leader speed pattern	Sinusoidal 90 km/h ( $\pm 5$ km/h), 0.1 Hz

### *CACC parameters (see [12])*

Weighting factor ( $C_1$ )	0.5
Damping factor ( $\xi$ )	1
Controller bandwidth ( $\omega_n$ )	0.2 Hz
Target distance ( $d_{des}$ )	15 m

## Simulator frameworks



**Simulation of  
Urban MObility**



Finanziato  
dall'Unione europea  
NextGenerationEU



Ministero  
dell'Università  
e della Ricerca



Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA



UNIVERSITÀ  
DEGLI STUDI  
DI MILANO

## Evaluation

### Mobile network configuration

Number of base stations	8 (along the highway)
Inter-Base station distance	1000 m
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
Base station model	ITU-Urban macrocell
Pathloss model	Free Space with $\alpha = 3.5$
Base station scheduler	Max Channel Indicator

### Background network traffic

Number background device ( $N_{bg}$ )	0, 30, 60, 90 UEs
Application type	UDP Constant Bit Rate
Packet size (UL/DL)	10, 500 byte
Packet frequency (UL/DL)	20 pkt/s
Generation starting time	120 s – 140 s
Generation ending time	220 s – 240 s

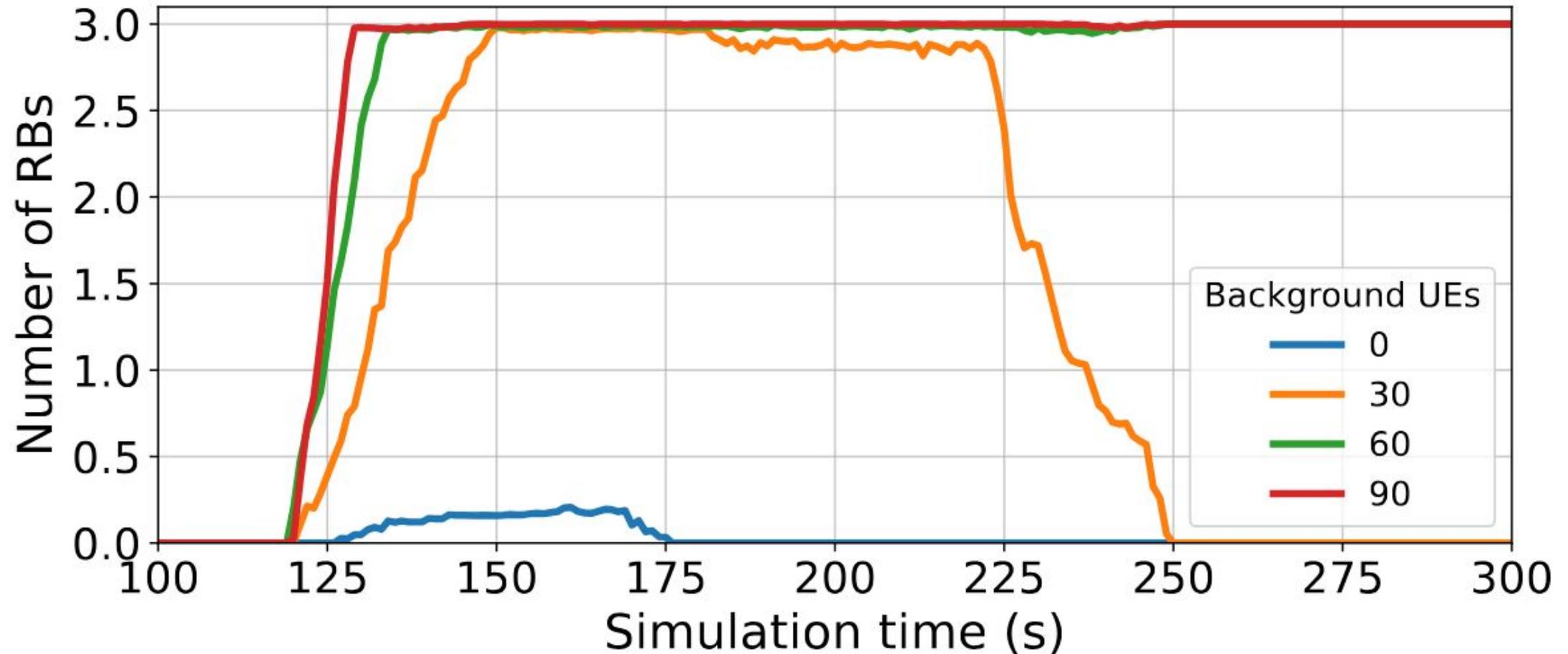
## Simulator frameworks



**Simulation of  
Urban MObility**

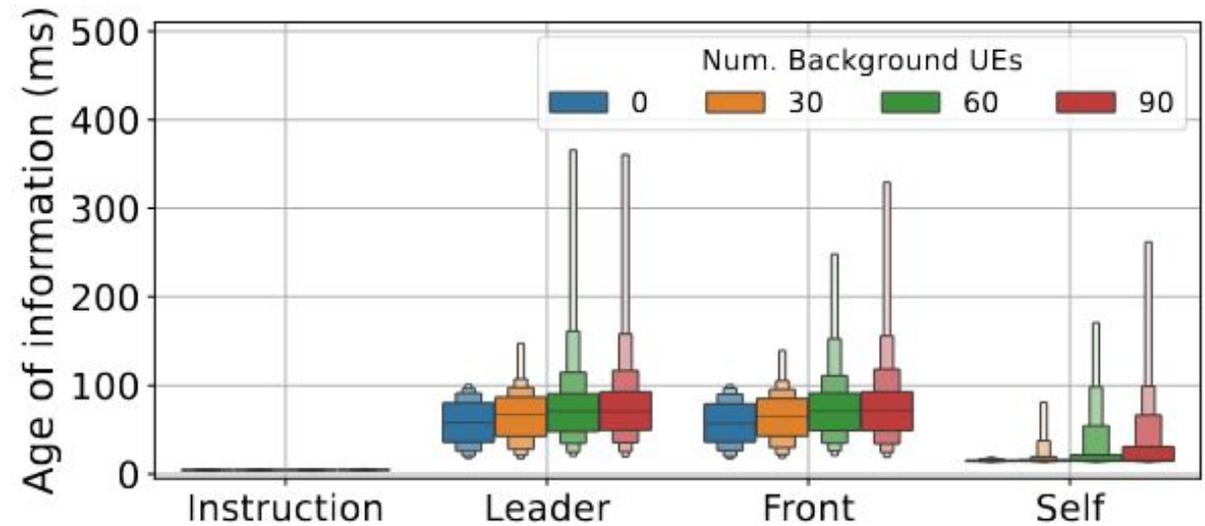
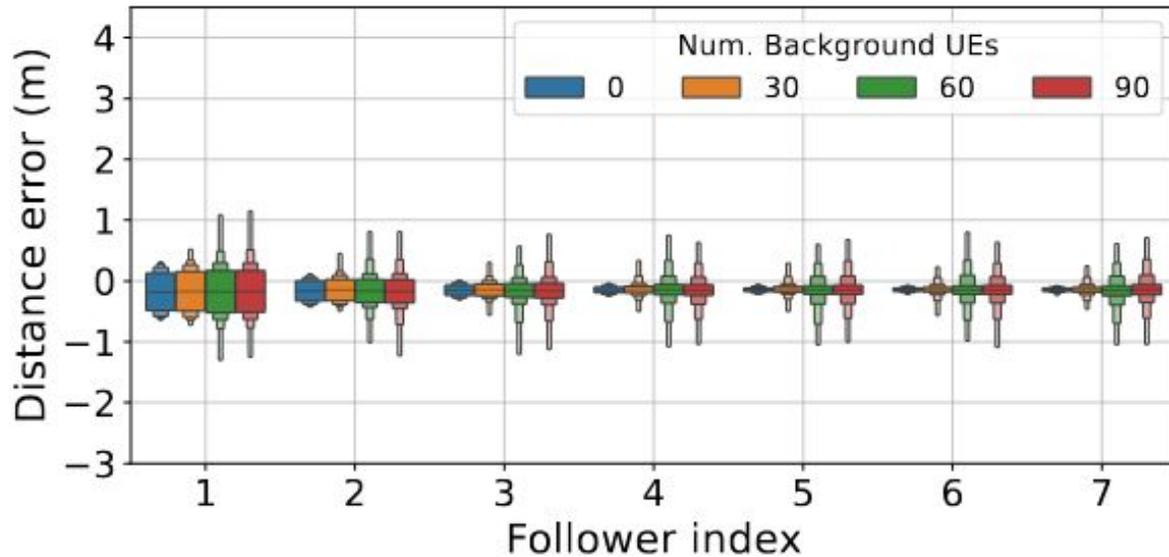


## Base station resource usage





## Uplink delay impact on distance policy and string stability

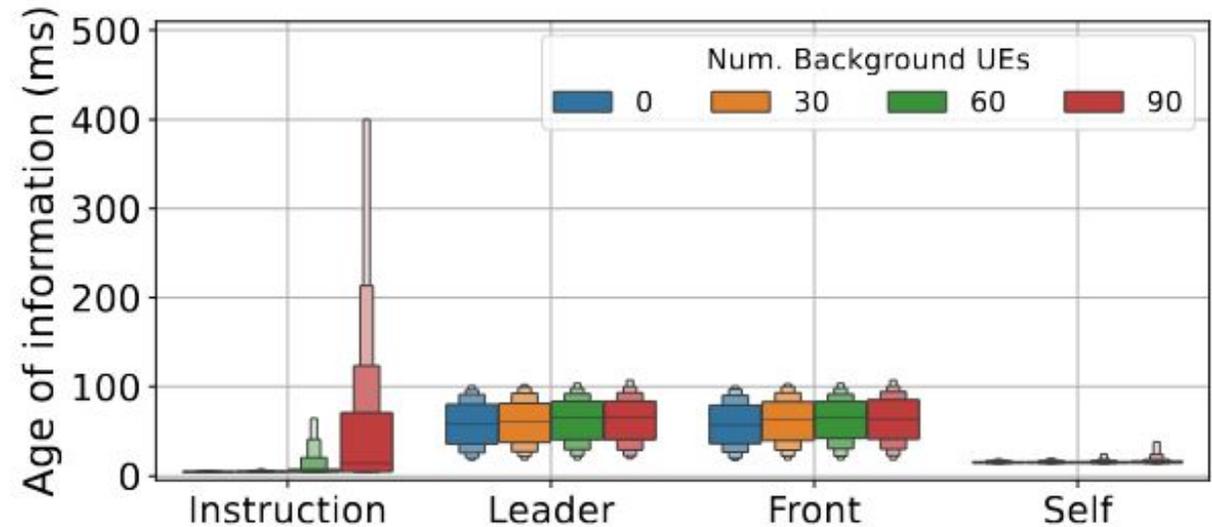
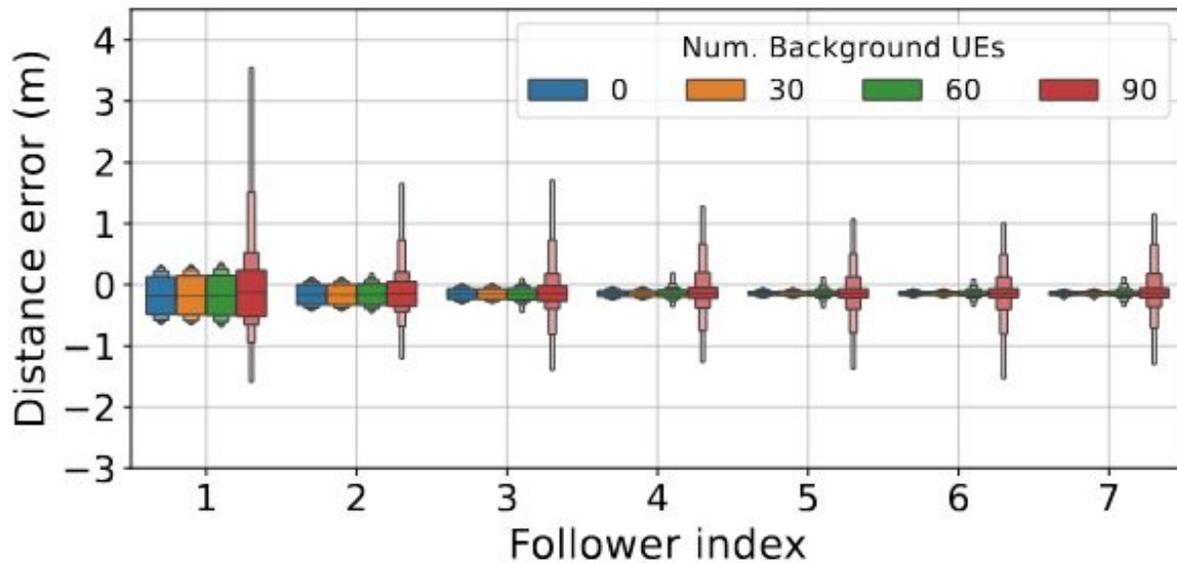


Distance error bounded (-1.5 m, +1.5 m)

String stability not completely preserved above 60 background devices

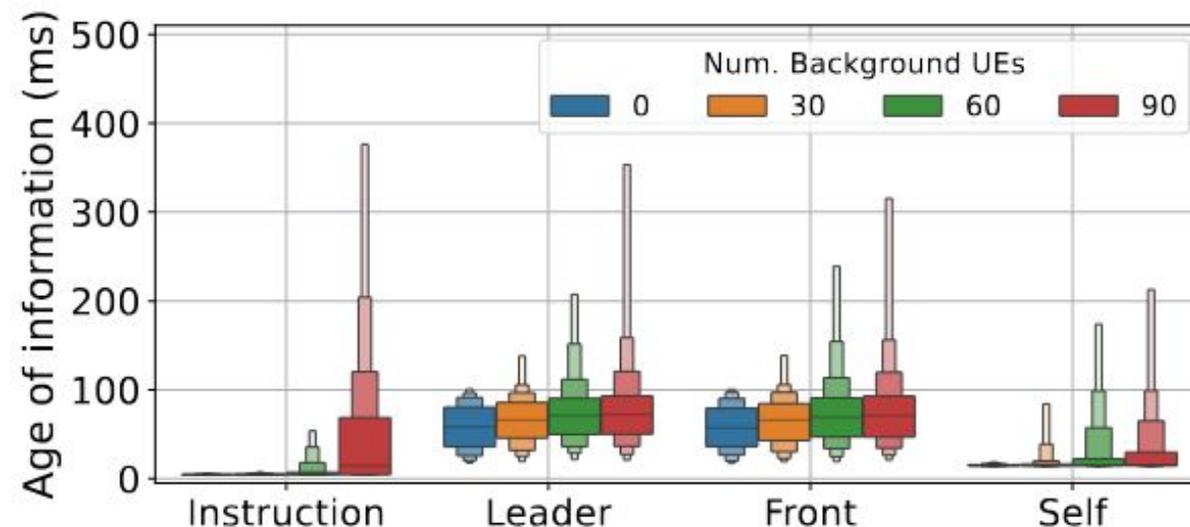
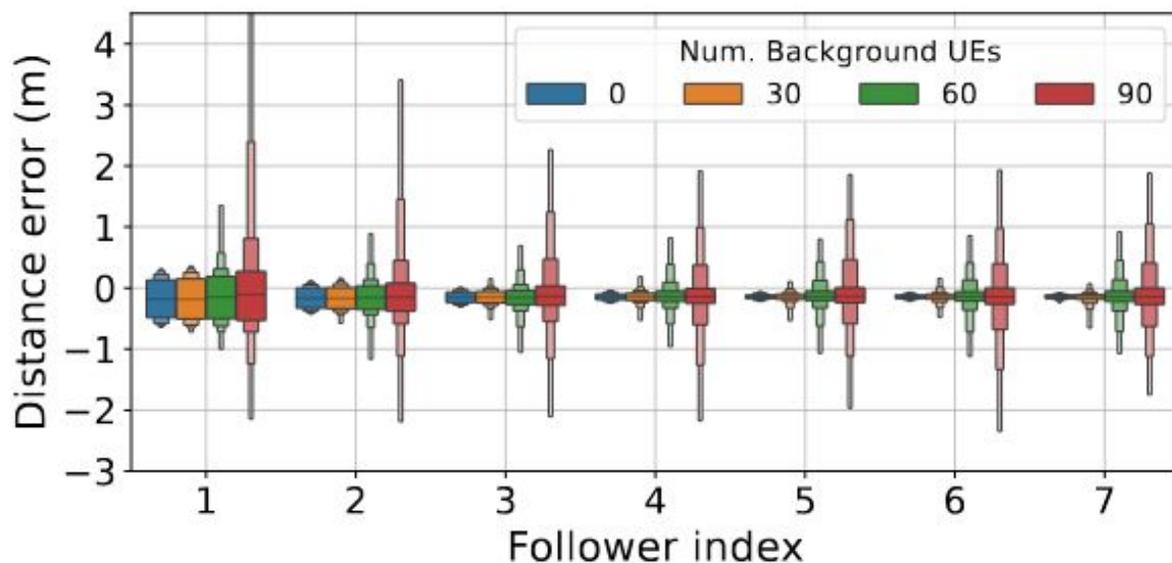


## Downlink delay impact on distance policy and string stability

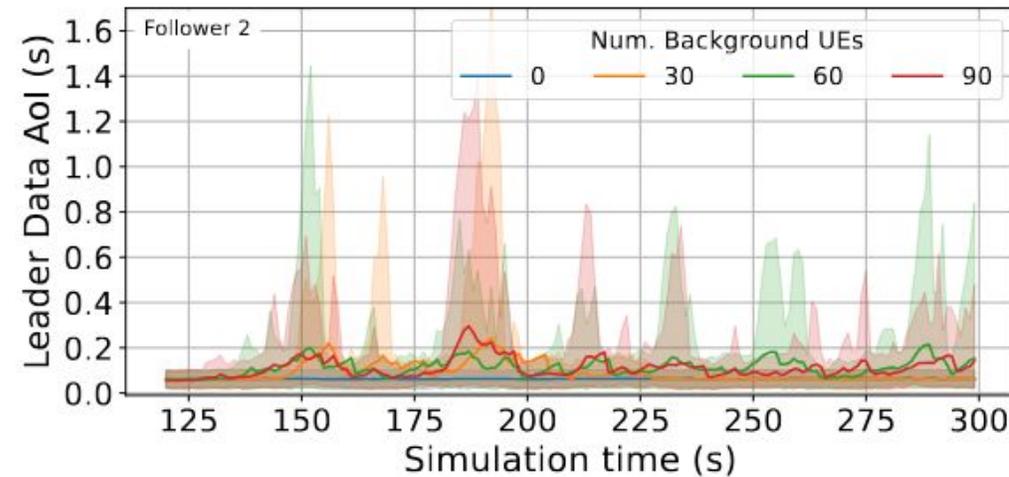
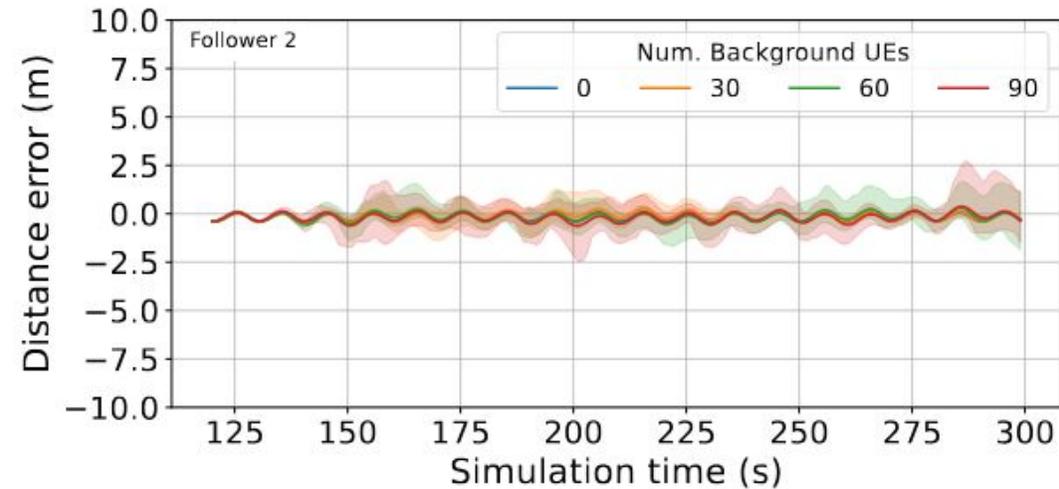
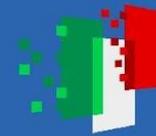


Larger error interval (-1.5 m, +3.5 m) with similar Aoi values  
String stability not preserved above 90 background devices

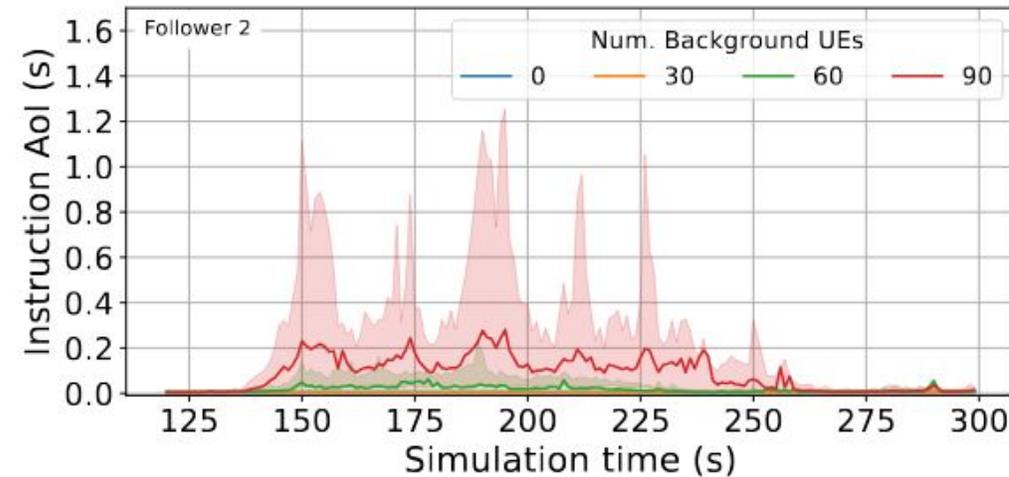
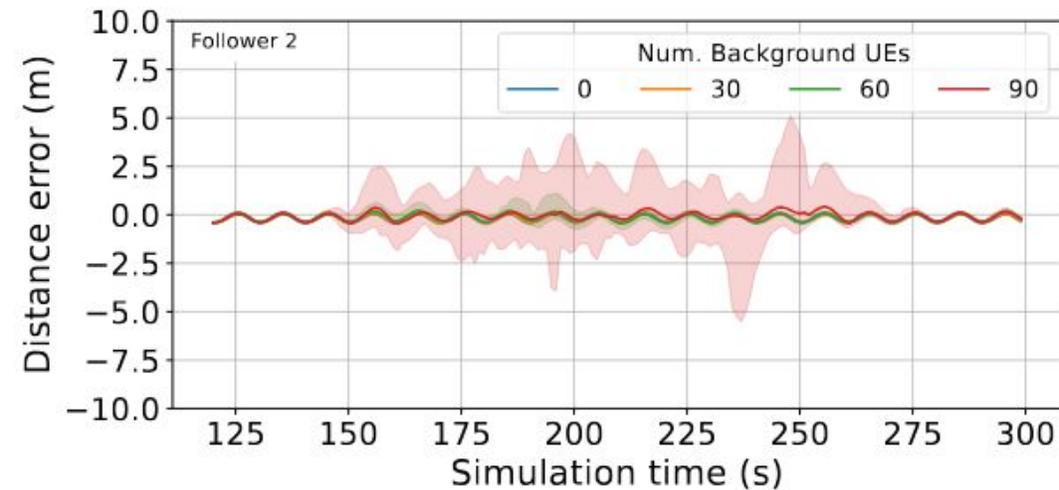
## Uplink and Downlink delay impact on distance policy and string stability



Critical error interval (-2 m, **+4.5 m**) → Combined effects  
String stability preserved above 60 background devices



Uplink background



Downlink background



## Conclusion

- **Platoons** using CACC control law **tolerates** moderately high and prolonged **uplink network delays**
- **Downlink** is more **critical** and must be kept low
- Mobile **network operators** should **prevent network congestion** designing **tailored scheduling policies**
- **Designing of specific control laws** accounting for asymmetric delays





Finanziato  
dall'Unione europea  
NextGenerationEU



Ministero  
dell'Università  
e della Ricerca



Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA



UNIVERSITÀ  
DEGLI STUDI  
DI MILANO



**FORESEEN**

Thank you

for your attention