UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

Università degli Studi di Modena e Reggio Emilia

Dipartimento di Ingegneria "Enzo Ferrari"

International Doctorate in Information and Communication Technologies

XXXV Cycle

Vehicular Connectivity in 5G and Beyond

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Outline

1. Introduction to Cellular Vehicle-to-Everything (C-V2X) Sidelink
2. The MoReV2X Simulator *(Simulation)*
3. C-V2X Sidelink: Assessing the Achievable Performance *(Simulation)*
4. Machine Learning for Disseminating Awareness Messages *(Simulation)*
5. Awareness Messages by VRUs and Vehicles: Field Tests *(Experiments)*
6. Fundamental Limits on the Performance of PD-NOMA *(Analysis)*
7. Final Remarks

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1. **Introduction to Cellular Vehicle-to-Everything (C-V2X) Sidelink**
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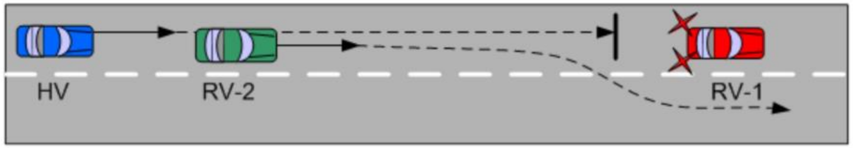
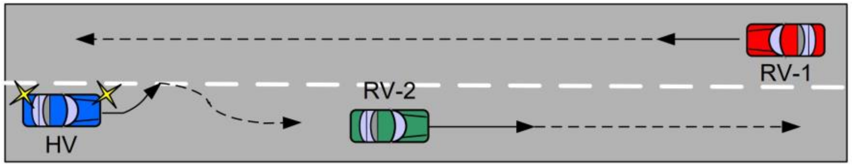
Vehicular Communications

- Current autonomous driving systems rely on local sensors such as LIDARs, RADARs, and cameras
- Vehicle-to-Everything (V2X) communications have two main advantages over local sensors:
  - Longer range
  - Work also in Non-Line-Of-Sight (NLOS) conditions
- The ultimate goal is to increase road safety and improve transportation efficiency



Forward Collision Warning (FCW)

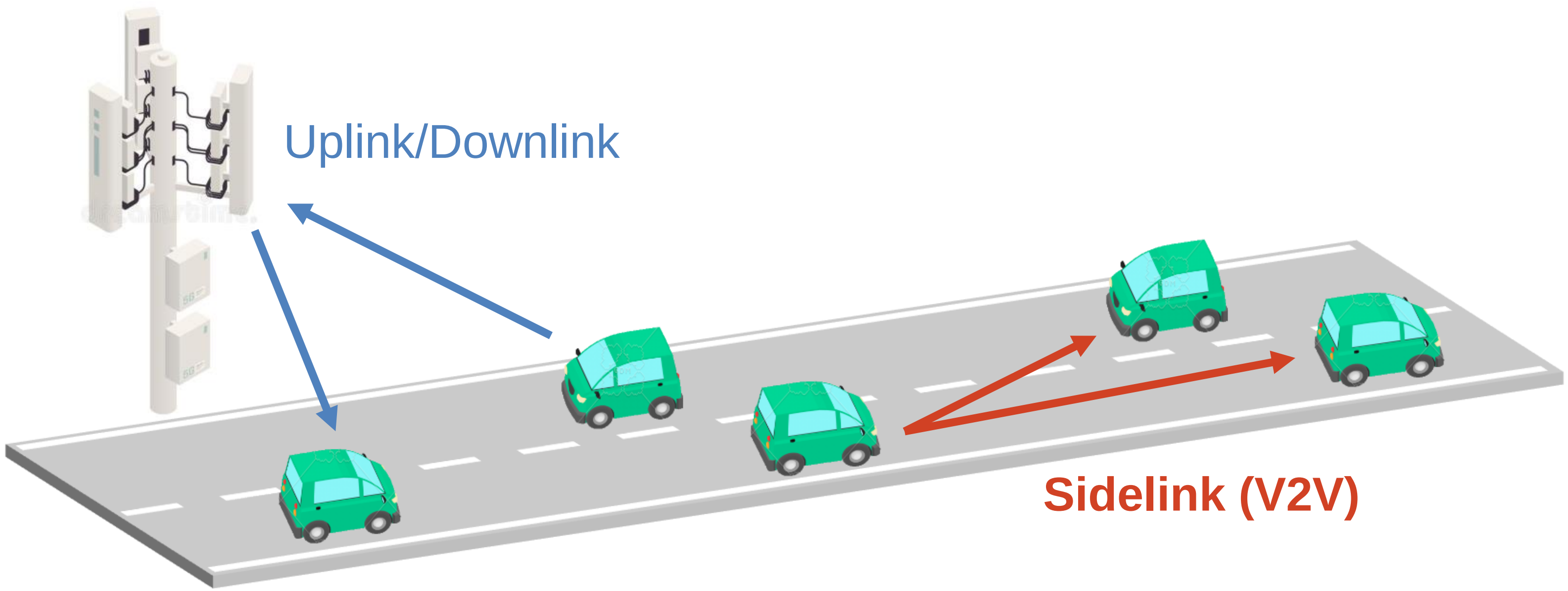


Do Not Pass Warning (DNPW)

Vulnerable Road User (VRU) Protection

C-V2X Sidelink

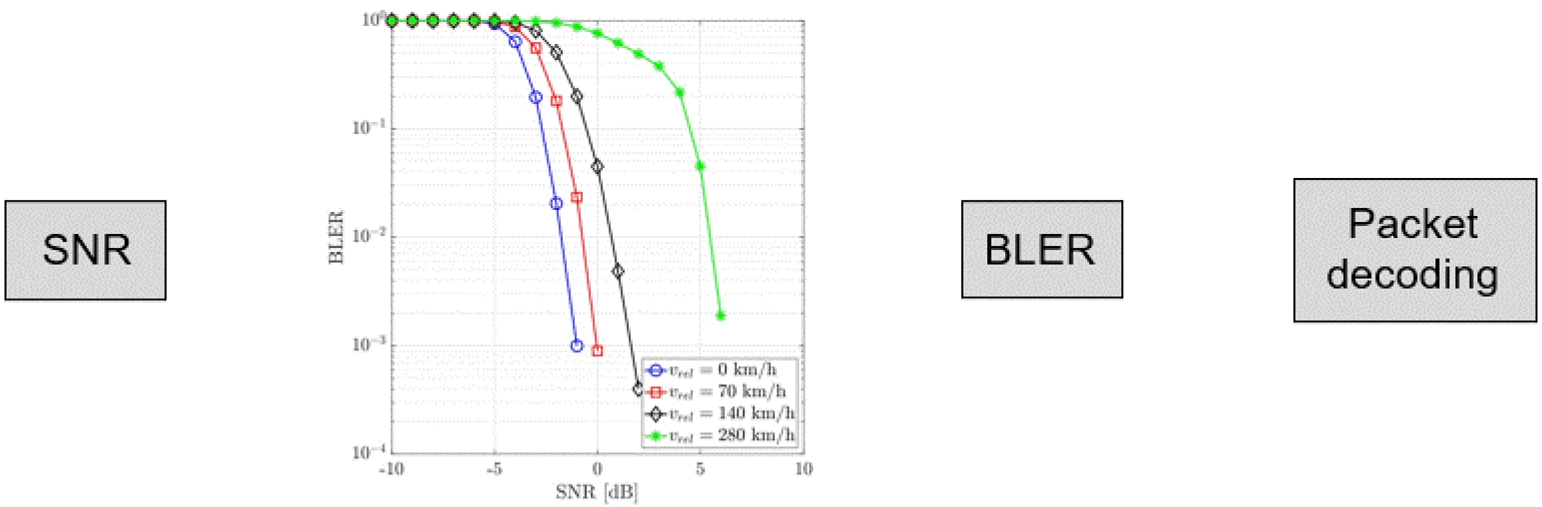
- Cellular Vehicle-to-Everything (C-V2X) technology
  - Uplink/Downlink communications: legacy radio links, operating in licensed bands
  - Sidelink (SL) communications: designed for V2V, operating in the 5.9 GHz ITS band
- C-V2X SL communications
  - LTE-V2X SL: support of basic safety-related applications
  - New Radio (NR)-V2X SL: support of more sophisticated enhanced V2X (eV2X) use cases in 5G



Outline

The MoReV2X Simulator

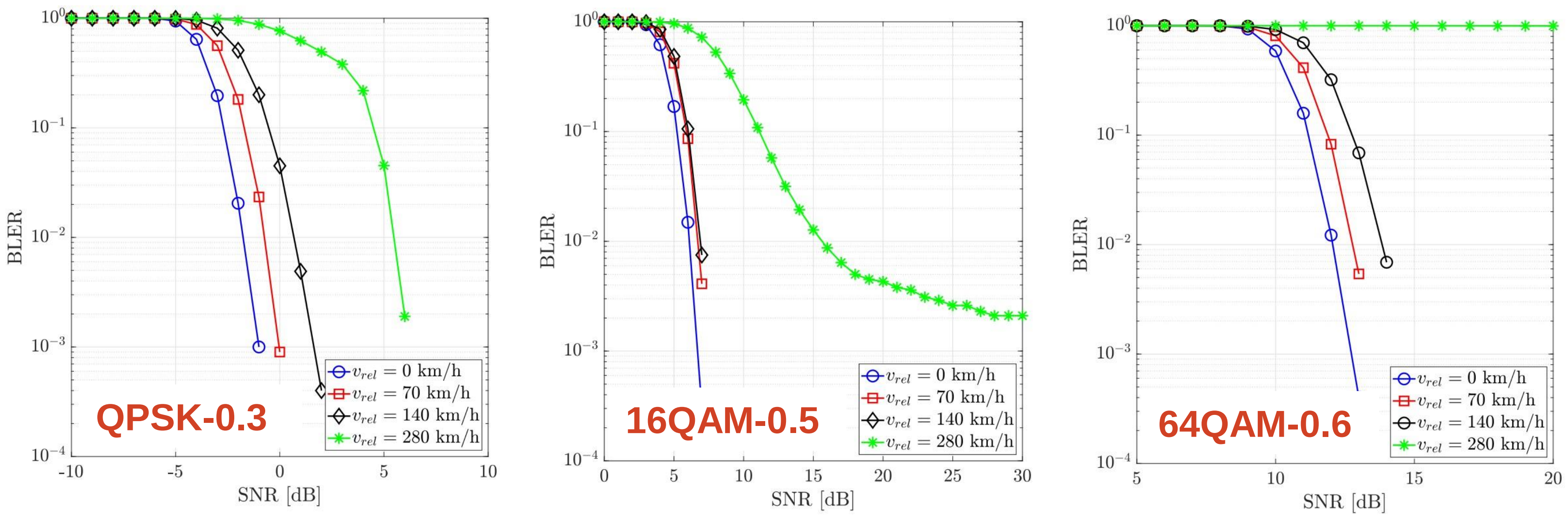
- Features a standard-compliant LTE-V2X SL and NR-V2X SL implementation
- Includes the traffic and channel models defined by 3GPP
- Evaluates a complete set of performance metrics
- Leverages pre-built error models to capture the PHY layer performance
    - Based on BLock Error Rate (BLER) vs Signal-to-Noise Ratio (SNR) curves
    - However, only a limited number of BLER curves is available for NR-V2X SL



- MoReV2X is openly available at: https://github.com/LLusvarghi/MoReV2X

The PHY Layer Simulator: BLER Curves

- Obtained developing a custom simulator based on MATLAB's 5G toolbox
  - Following the recommended NR-V2X SL configurations (1904 curves)
- Represent the first complete set of BLER vs SNR curves (openly available)
  - Foster the development of a common NR-V2X SL evaluation framework
- Provide an exhaustive evaluation of the PHY layer performance
  - Transmitter-receiver relative speed
  - Modulation and Coding Scheme (MCS)
  - Channel model
  - Number of subchannels



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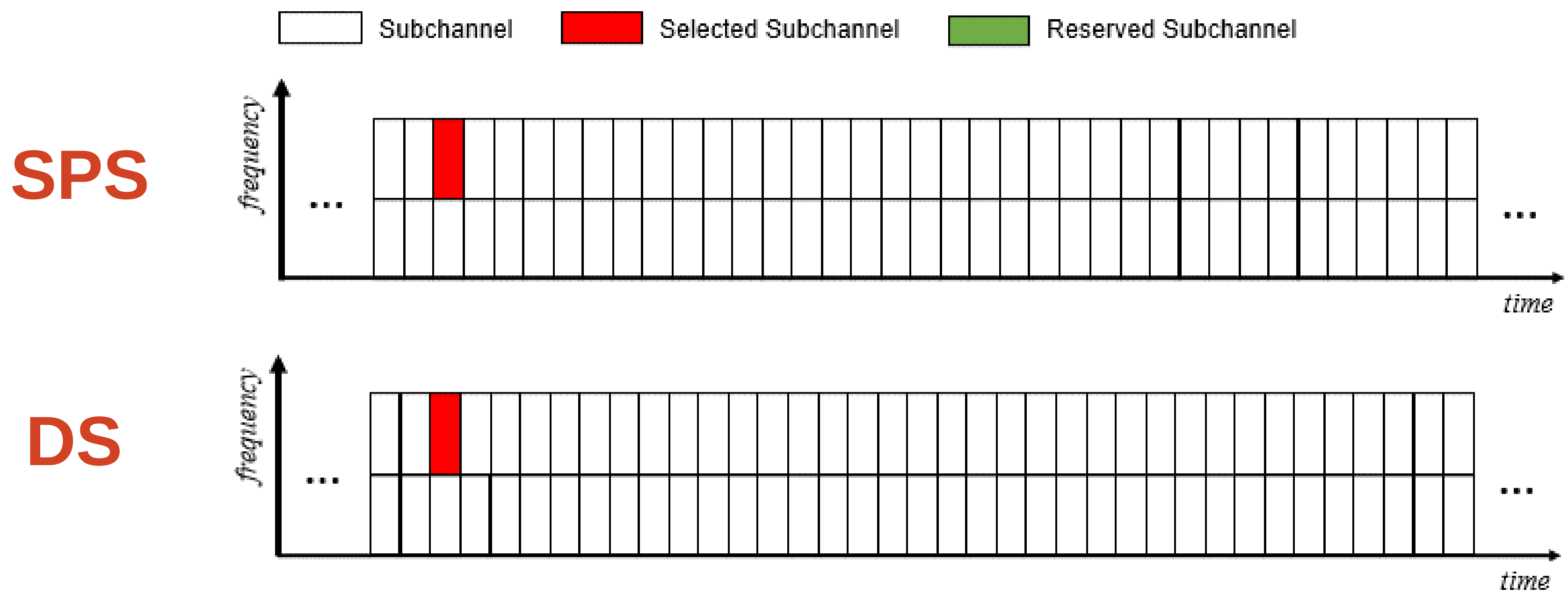
MAC Sublayer: the SPS and DS Algorithms

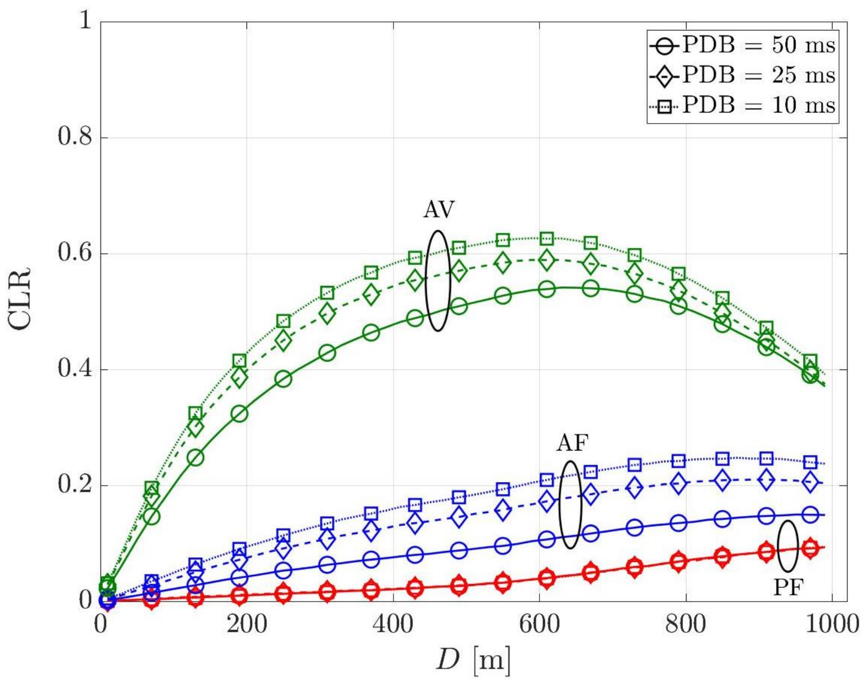
- The Semi-Persistent Scheduling (SPS) algorithm is based on the periodic reservation of resources
  - Reselection counter (C_{resel})
  - Resource Reservation Interval (RRI)
- The Dynamic Scheduling (DS) algorithm is a reservation-less variant of the SPS scheme
  - $C_{resel} = 1$



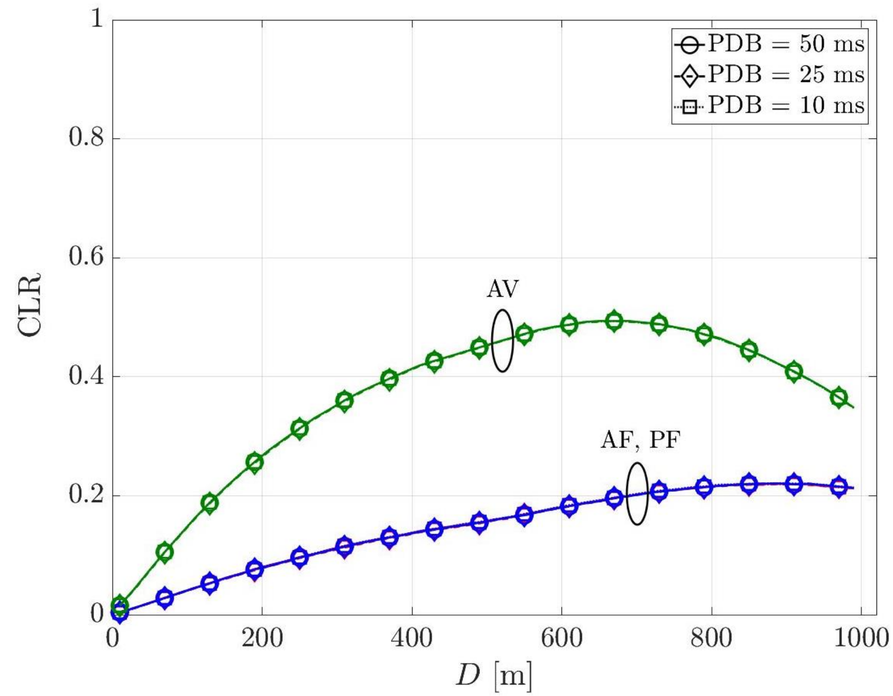
SPS and DS Comparison: Impact of the PDB

- The CLR measures the fraction of packets lost in a collision
- The SPS collision probability increases for more stringent PDB requirements
  - When aperiodic traffic is considered
- DS is not affected by the PDB
  - Regardless of the traffic type

Semi-Persistent Scheduling (SPS)



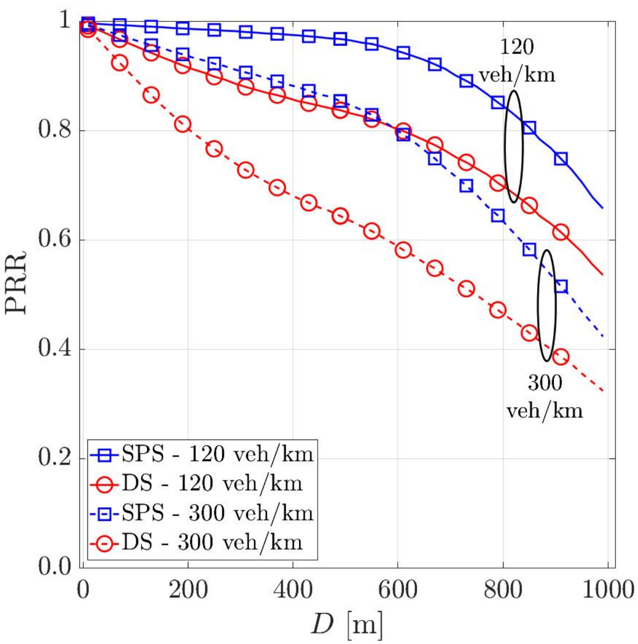
Dynamic Scheduling (DS)



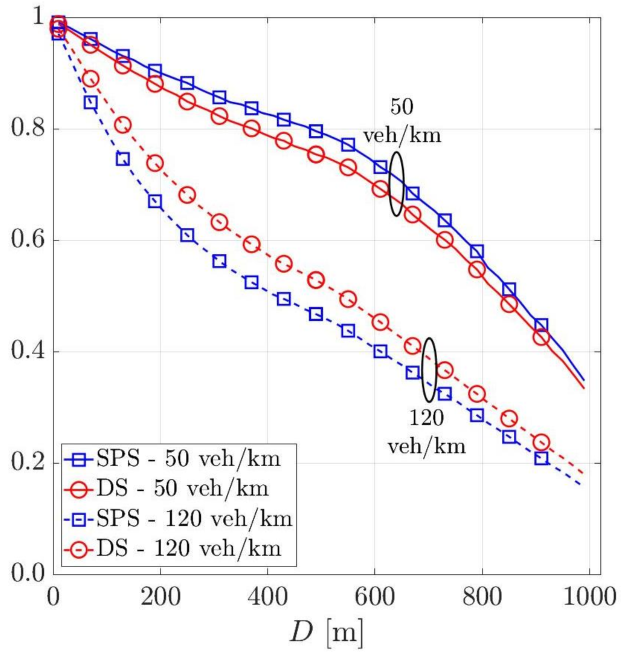
SPS and DS Comparison

- The PRR measures the fraction of correctly received packets
- Periodic traffic: SPS achieves the best performance
- Aperiodic traffic
    - The SPS performance is deteriorated
        - Due to the mismatch between the aperiodic generation of packets and the periodic reservation of resources
    - DS outperforms SPS

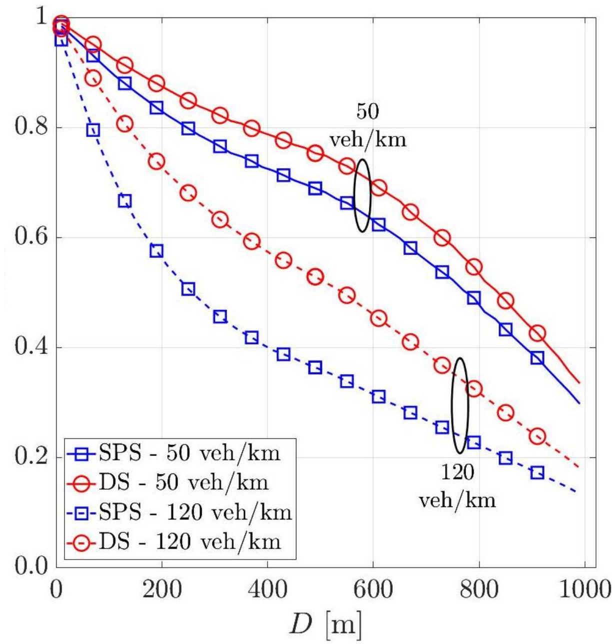
Periodic



Aperiodic, PDB = 50 ms



Aperiodic, PDB = 10 ms



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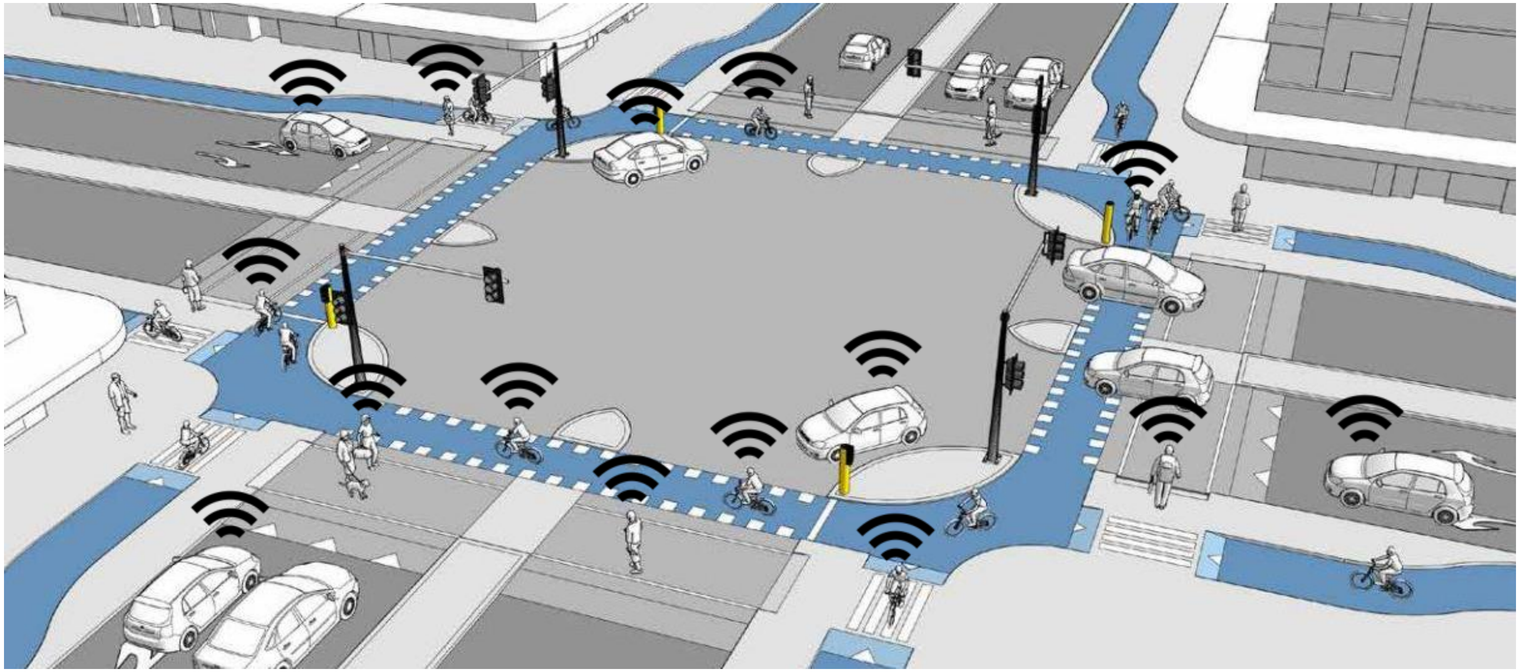
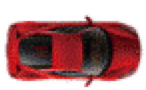
Awareness Messages

- Broadcasted by road users to inform other road occupants
  - About their position, dynamic, and attributes
- Cooperative Awareness Messages (CAMs)
  - Broadcasted by cars and motorcycles
- VRU Awareness Messages (VAMs)
  - Disseminated by VRUs: pedestrians, bicycles, e-scooters



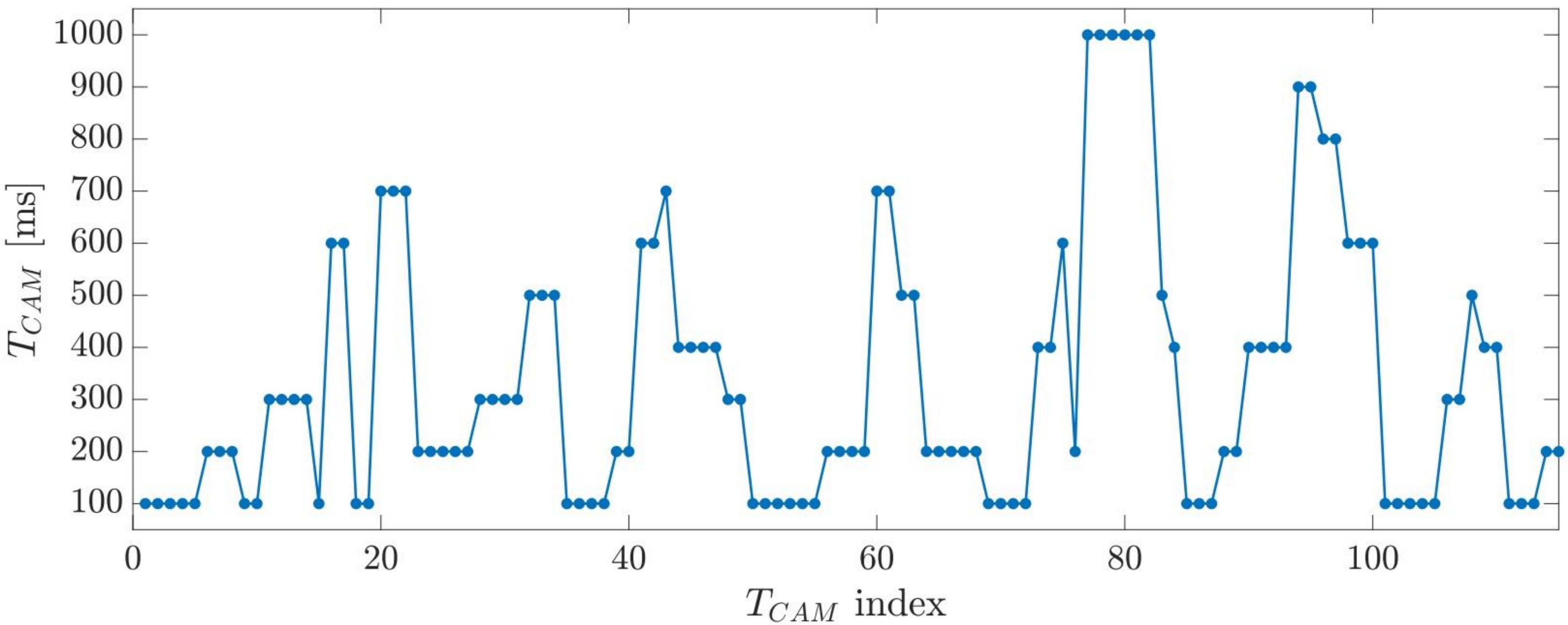
CAM Dissemination Rules

- A new CAM is generated when one of the following conditions is satisfied:
    1. The difference between the current heading and the heading included in the previous CAM is larger than $\Delta H = 4°$
    2. The distance between the current position and the position included in the previous CAM is larger than $\Delta D = 4\ m$
    3. The difference between the current speed and the speed included in the previous CAM is larger than $\Delta S = 0.5\ m/s$
    4. The time elapsed since the last CAM generation is larger than $T_{CAMMax} = 1000\ ms$
- The inter-arrival time between CAMs, T_{CAM}, depends on the vehicle dynamics



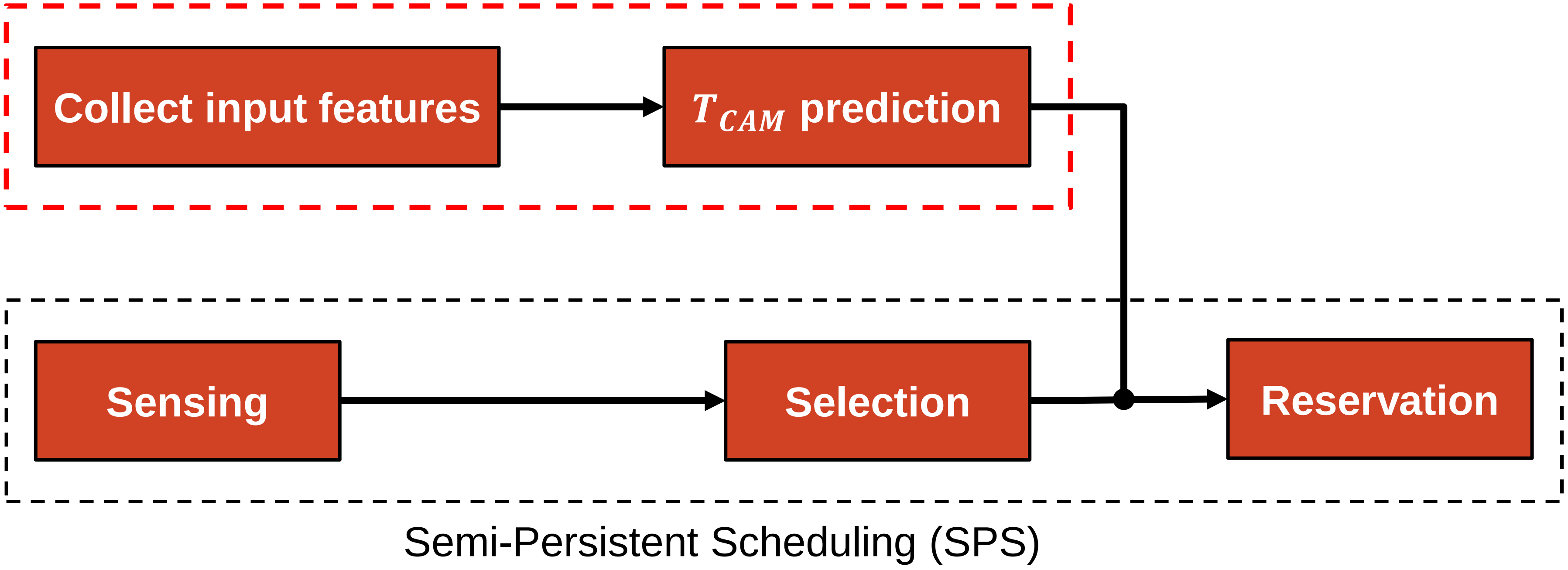
CAM Dissemination

- The inter-arrival time between CAMs, T_{CAM}, depends on the vehicle dynamics
  - The generated traffic is aperiodic
- **Q:** *How to serve CAM traffic using the SPS algorithm?*
  - *How to properly configure RRI and C_{resel}?*



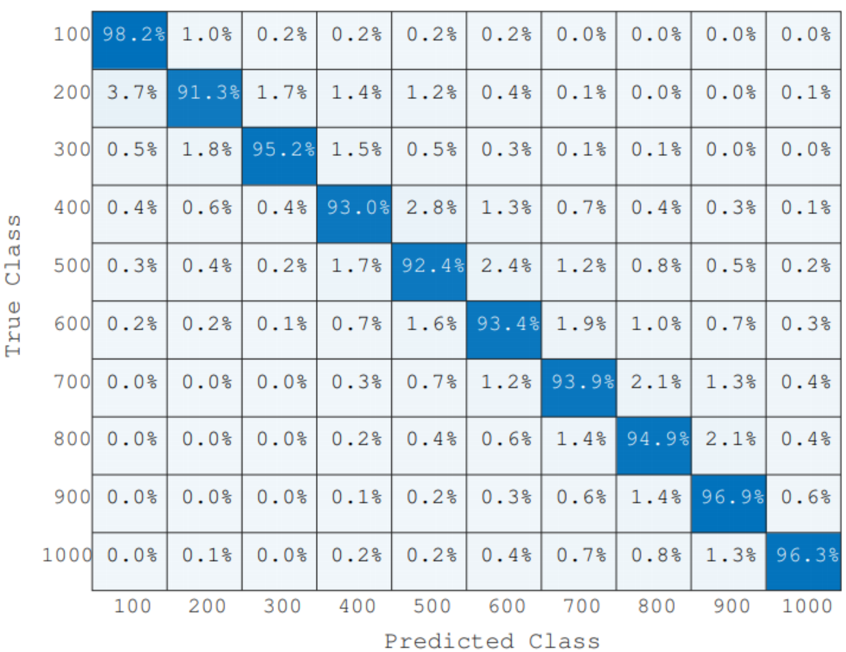
CAM Dissemination: Machine Learning

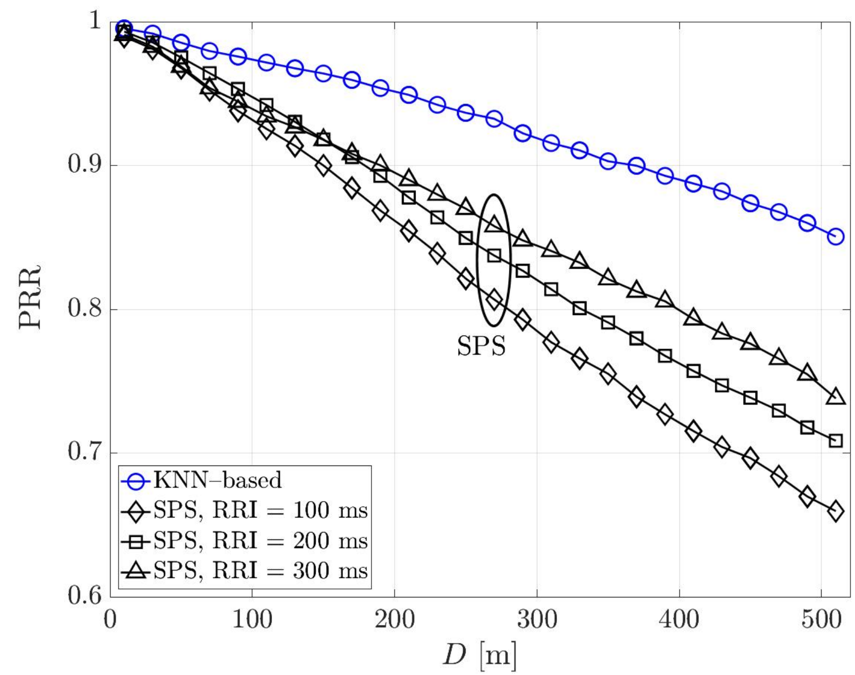
- **A:** *Leverage Machine Learning to predict future T_{CAM} values*
  - Accordingly configure the RRI and C_{resel} parameters
  - Using the K-Nearest Neighbors (KNN) algorithm
  - Input features:
    - trajectory, speed and position of the generating vehicle
    - position and speed of the preceding vehicle



CAM Dissemination: Numerical Results

- KNN is able to correctly predict future T_{CAM} values
  - Prediction accuracy is larger than 90%
- The proposed ML-based approach outperforms legacy SPS for three different RRI static configurations
  - $RRI = 100, 200, 300\ ms$





CAM Dissemination: Numerical Results

- The proposed ML-based solution is very close to the Ground-Truth (GT) benchmark
- ML-based resource allocation can be a solution to disseminate aperiodic traffic
- Its gain with respect to legacy SPS increases for larger packet size values

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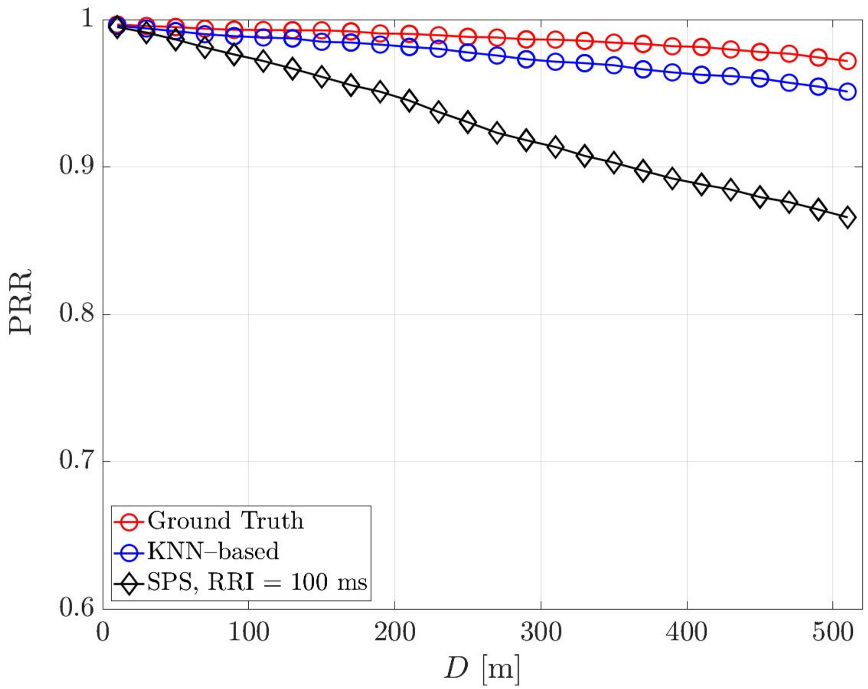

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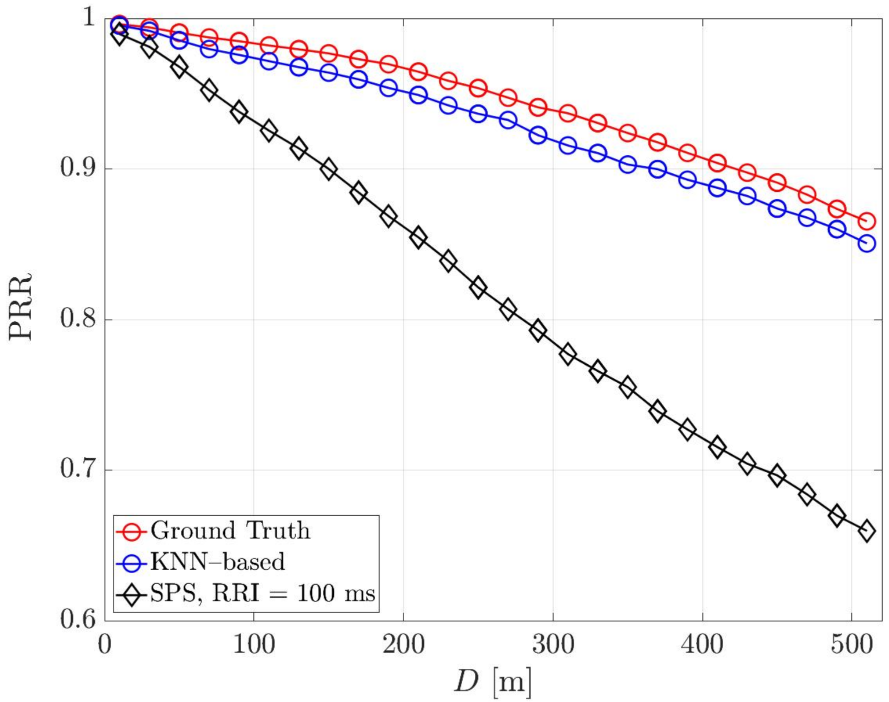

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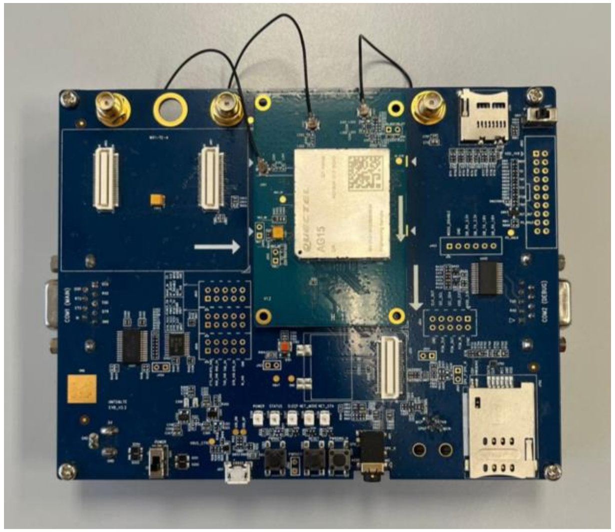
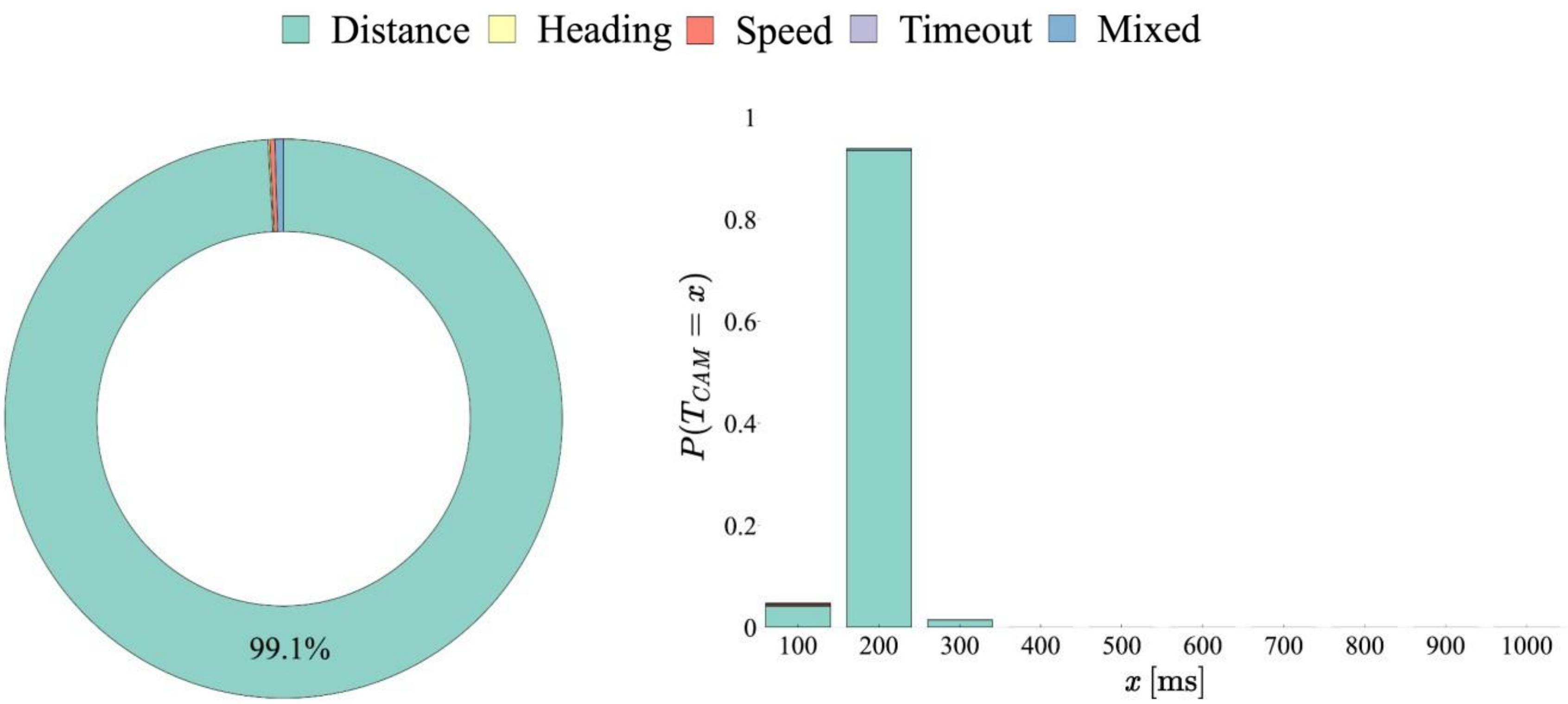
Field Tests

- Awareness messages have been studied only with simulations
  - Lack of real-world measurements
- Simulations cannot perfectly capture the road user (vehicle, VRU) dynamics
- The goal of the field tests was to:
  - Implement the algorithms that rule CAMs and VAMs generation on the Quectel AG15 LTE-V2X SL boards
    - Analyze the generated CAMs and VAMs



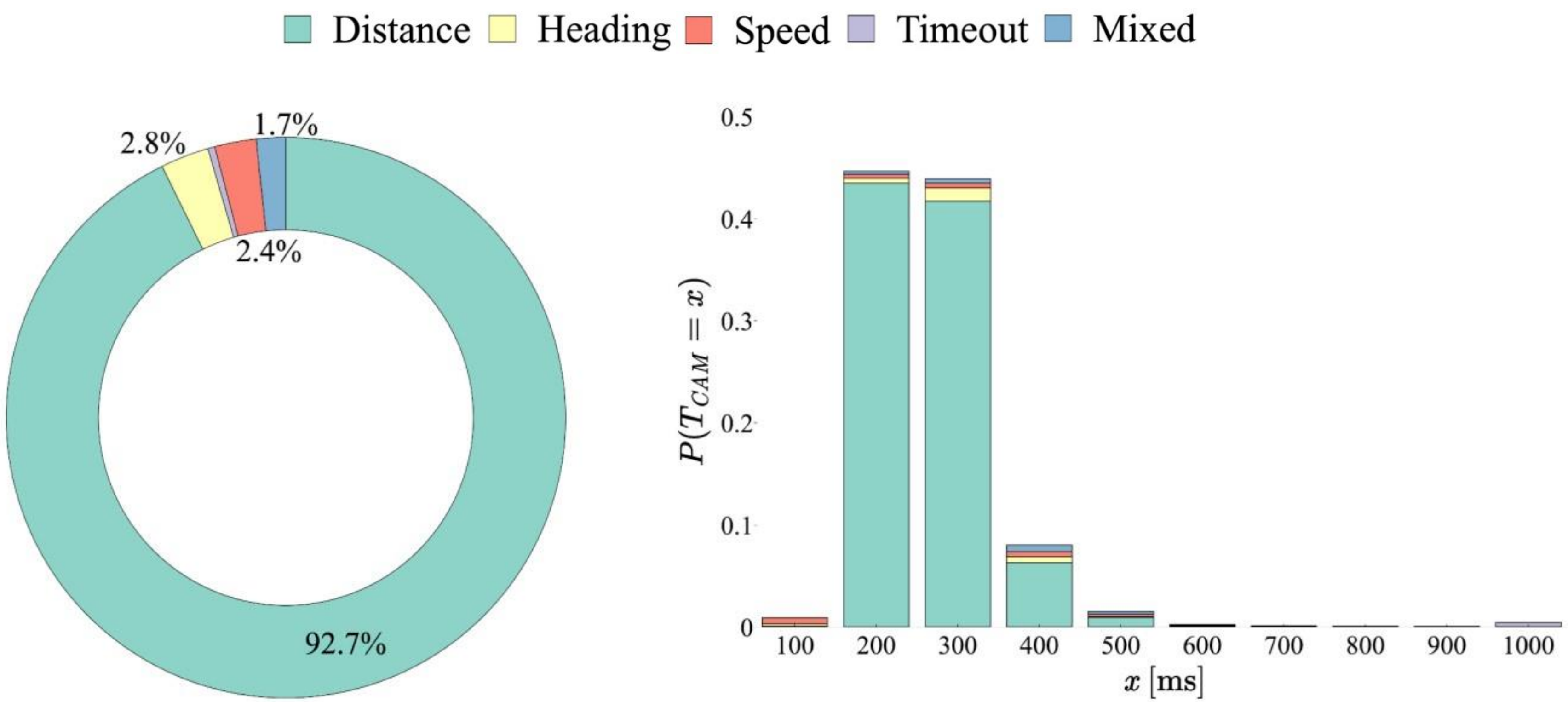
CAM Dissemination, Highway: Results

- 99.1% of the transmitted CAMs is triggered by the distance condition
    - Due to the straight trajectory and the approximately constant speed
- The generated traffic is almost periodic: $\mathrm{P}(T_{CAM} = 200\ ms) = 0.93$



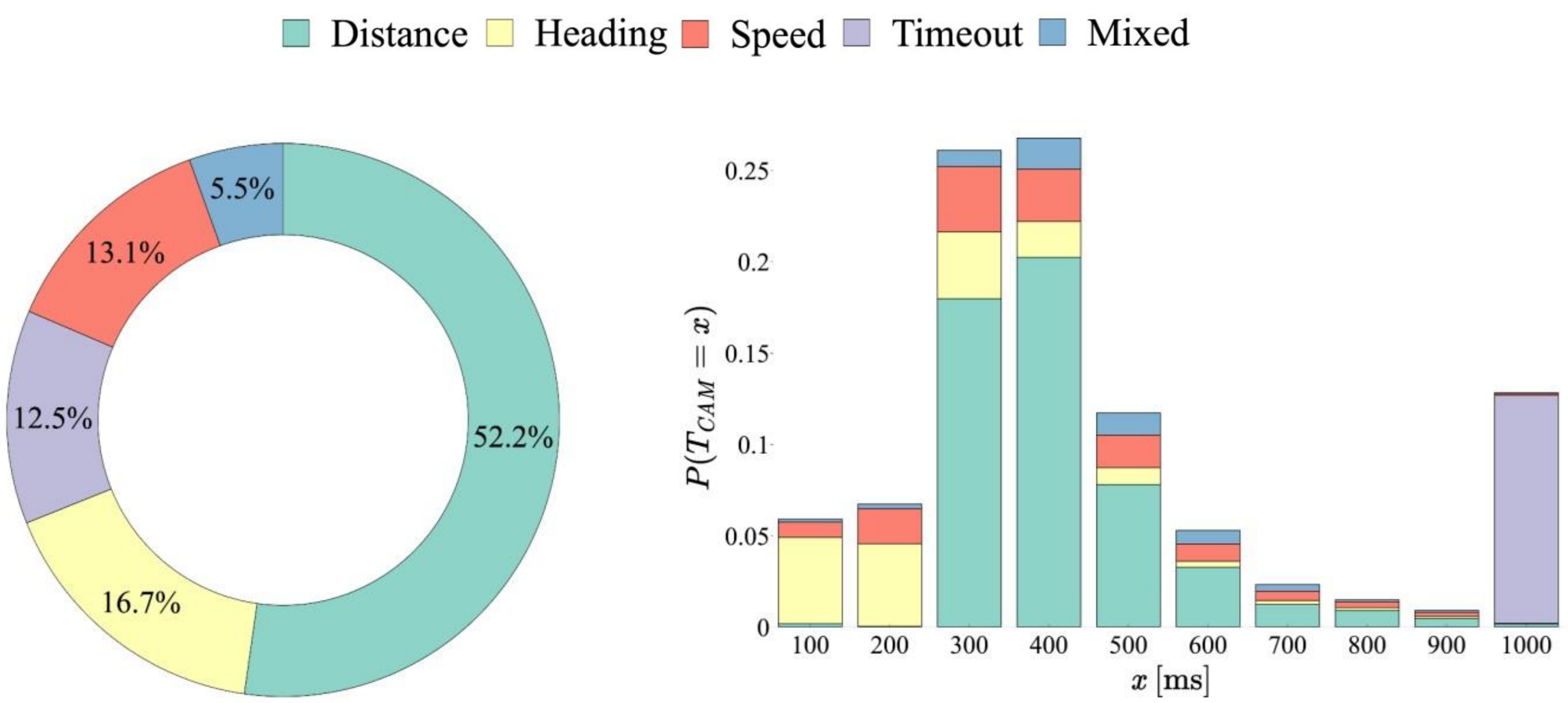
CAM Dissemination, Suburban: Results

- CAMs generated by the distance condition are still the most frequent
- T_{CAM} values at $100\ ms$ are no longer present
- T_{CAM} values are concentrated at $200\ ms$ and $300\ ms$



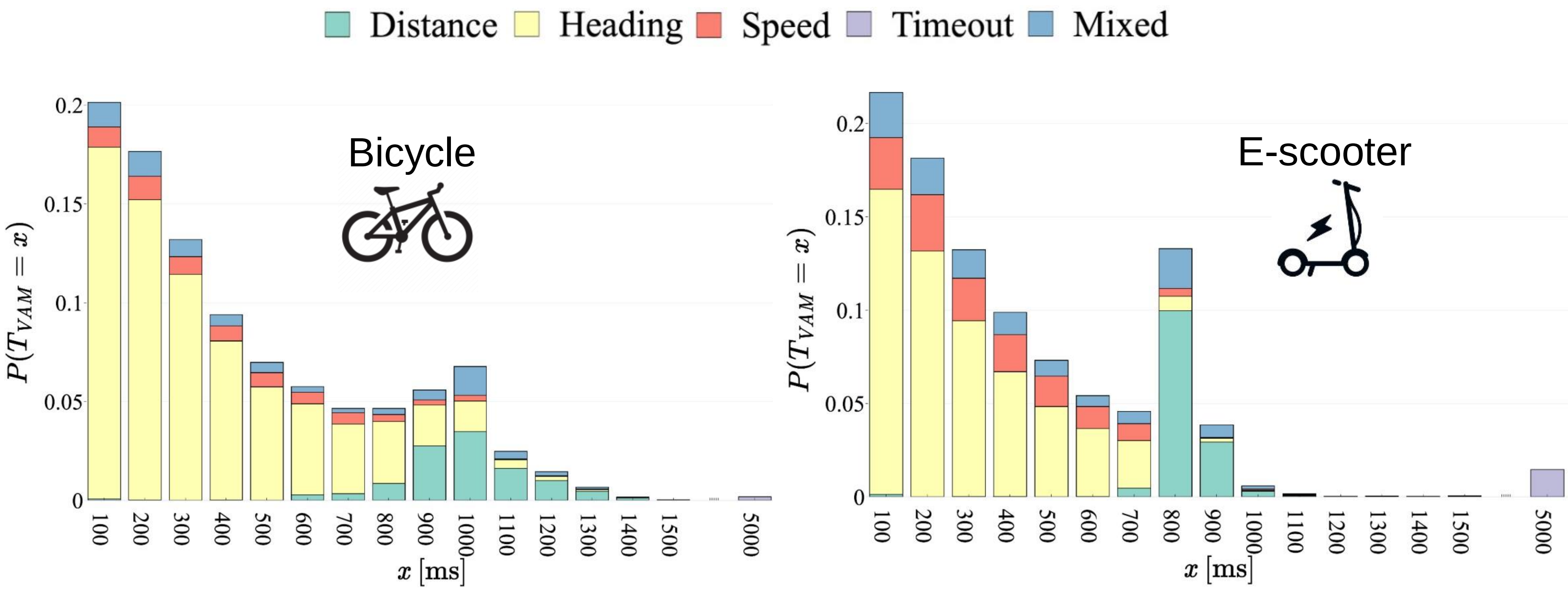
CAM Dissemination, Urban: Results

- The percentage of CAMs triggered by the distance condition decreases
- More even distribution of the trigger types
  - Non-negligible fraction of timeout triggers: traffic light type of situations



VAM Dissemination: Results

- The majority of VAMs is triggered by a heading variation
  - $\Delta H = 4°$, $\Delta D = 4\ m$, and $\Delta S = 0.5\ m/s$
- Heading-triggered VAMs are particularly concentrated at small T_{VAM} values

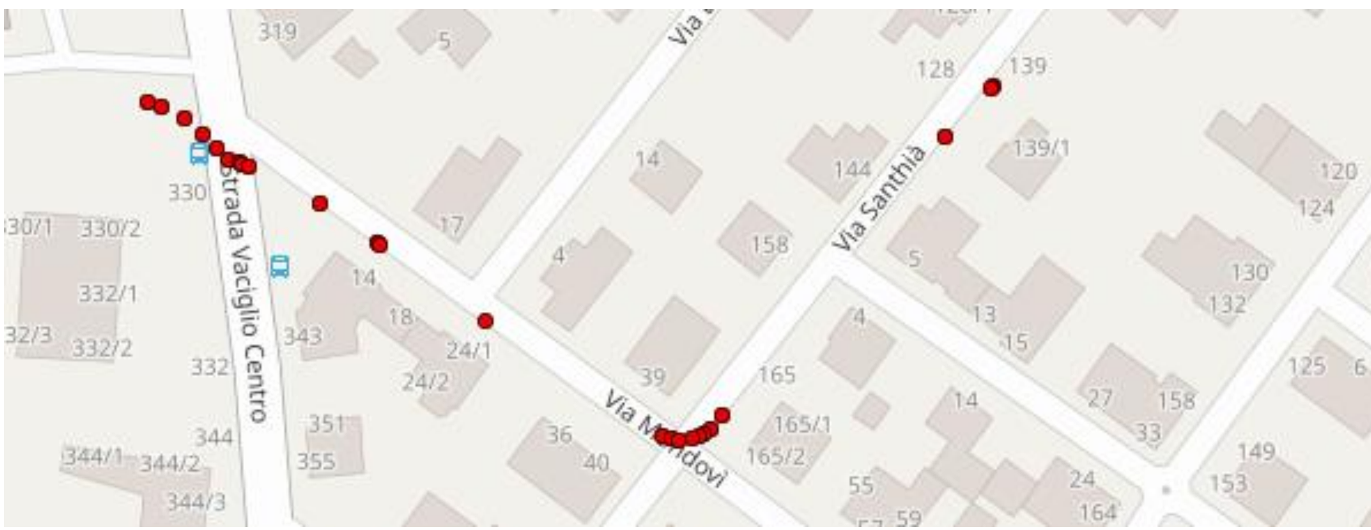


VAM Dissemination: Heading Threshold

- VAMs caused by heading variations should be triggered by potentially dangerous steering or lane-changing movements
  - However, a large number of heading-triggered VAMs is generated under non-relevant circumstances
- Eventually, waste of radio resources for too frequent VAM broadcasting
  - Identify a more suitable heading threshold for VAM dissemination
  - Without losing relevant information about the VRU movements

$$\Delta H = 40^\circ$$

$$\Delta H = 10^\circ$$

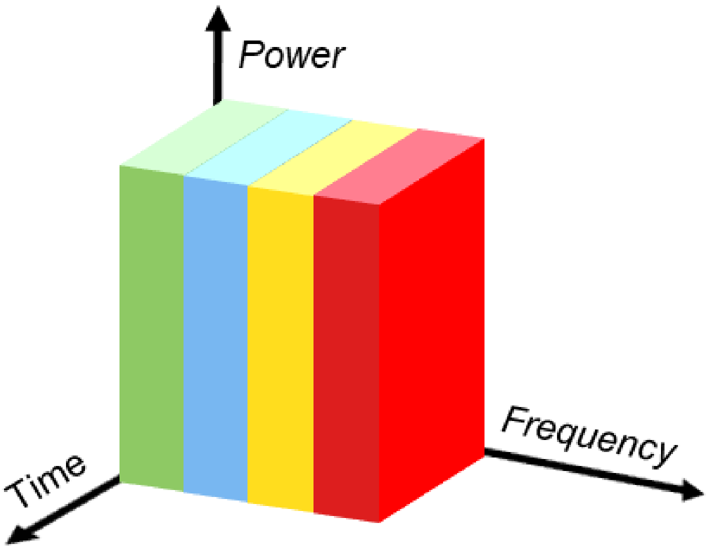


Outline

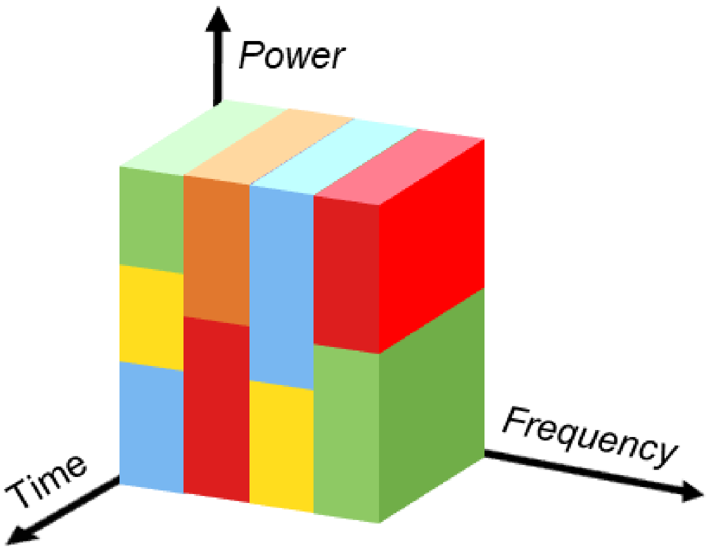
Power-Domain NOMA

- Traditional Orthogonal Multiple Access (OMA) techniques support a limited number of simultaneously active users
- Power-Domain Non-Orthogonal Multiple Access (PD-NOMA) is able to accommodate multiple users on the same resources
    - By carefully assigning different power levels

OMA



PD-NOMA



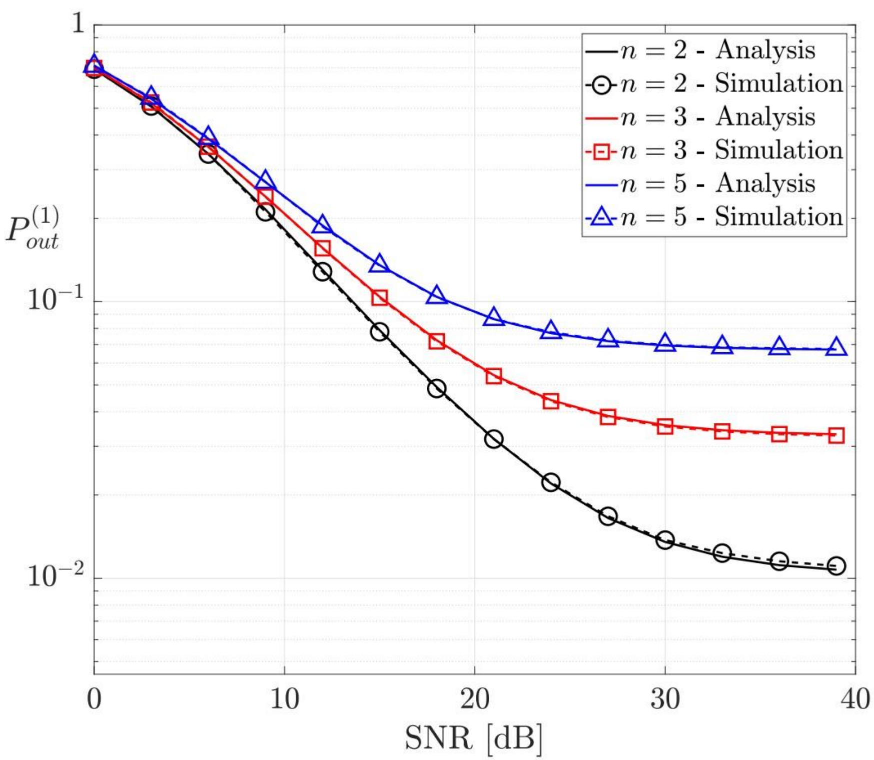
The Analytical Approach

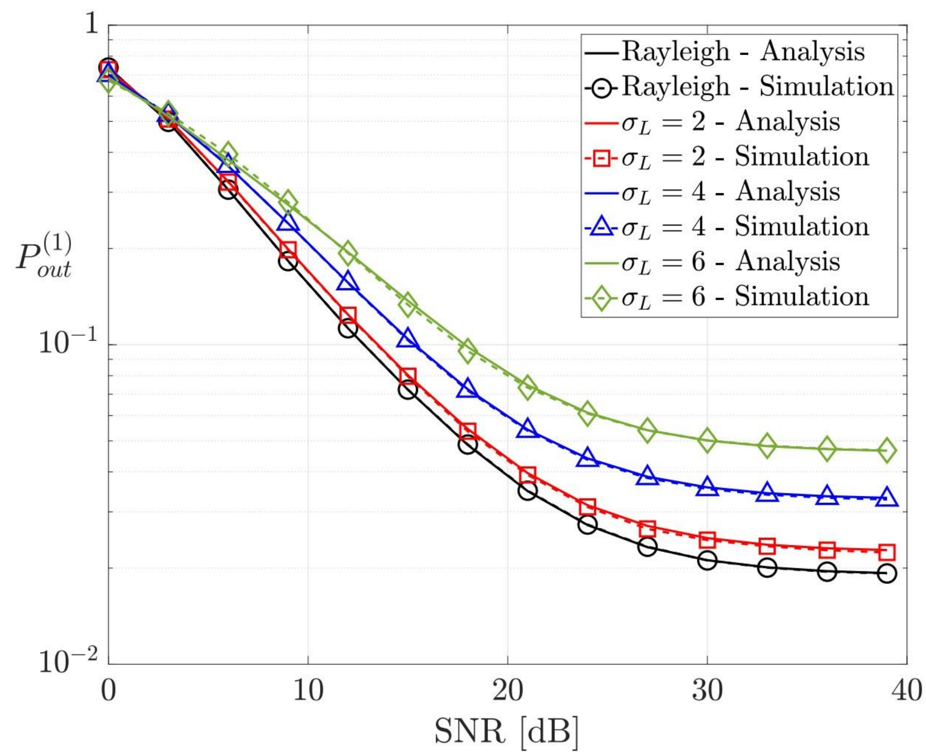
- Outage probability $P_{out}^{(j)}$
  - Probability that the receiver fails to decode the j-th strongest signal
- Limitations of existing studies
  - Maximum number of simultaneously active users is 3, $n < 3$
  - Consider only Rayleigh fading
- The proposed approach
  - Works for an arbitrary number of simultaneously active users (n)
  - Considers both Rayleigh fading and log-normal shadowing

$$P_{out}^{(1)} \approx 1 - \sum_{k_1=1}^{3} a_{k_1} \cdot \ldots \cdot \sum_{k_{n-1}=1}^{3} a_{k_{n-1}} \sum_{k_n=1}^{3} a_{k_n} \times \left[\sum_{i=1}^{n} \frac{\exp\left(\frac{-\hat{\gamma}_1 \sigma^2}{b_{i,k_i}}\right)}{\prod_{\substack{j=1 \\ j \neq i}}^{n} \left(1 + \frac{b_{j,k_j}}{b_{i,k_i}} \hat{\gamma}_1\right)} \right]$$

Numerical Results

- Regarding $P_{out}^{(j)}$, the obtained results disclose
  - The impact of the number of simultaneously active users (n)
  - The impact of log-normal shadowing
- Monte Carlo simulations validate the accuracy of the proposed approach





Outline

Final Remarks

- Investigated the C-V2X Sidelink technology from three different perspectives
  - **Simulation**
    - Developed MoReV2X and a PHY layer simulator
    - Assessed the LTE-V2X SL and NR-V2X SL achievable performance
    - Proposed and evaluated a novel ML-based scheduling algorithm
  - **Experiments**
    - Obtained the first set of openly-available CAMs and VAMs
    - Identified the limitations of the VAM dissemination algorithm
      - Proposed an adjustment for the heading threshold
  - **Analysis**
    - Proposed a novel analytical approach for PD-NOMA
    - Disclosed the impact of an arbitrary number of active users and log-normal shadowing on the outage probability

List of publications

[1] **L. Lusvarghi** and M. L. Merani, "On the Coexistence of Aperiodic and Periodic Traffic in Cellular Vehicle-to-Everything," *IEEE Access*, vol. 8, pp. 207076-207088, 2020.

[2] **L. Lusvarghi** and M. L. Merani, "MoReV2X - A New Radio Vehicular Communication Module for ns-3," *2021 IEEE 94th Veh. Technol. Conf. (VTC2021-Fall)*, 2021, pp. 1-7.

[3] **L. Lusvarghi** and M. L. Merani, "Machine Learning for Disseminating Cooperative Awareness Messages in Cellular V2V Communications," *IEEE Transactions on Vehicular Technology*, vol. 71, no. 7, pp. 7890-7903, July 2022.

[4] A. Molina-Galan, B. Coll-Perales, **L. Lusvarghi**, J. Gozalvez and M. L. Merani, "How does 5G NR V2X Mode 2 Handle Aperiodic Packets and Variable Packet Sizes?," *2022 IEEE 23rd Int. Conf. on High Performance Switching and Routing (HPSR)*, 2022, pp. 183-188.

[5] **L. Lusvarghi** and M. L. Merani, "Fundamental Limits on the Uplink Performance of the Dynamic-Ordered SIC Receiver," *IEEE Access*, vol. 10, pp. 73178-73189, 2022.

List of publications

[6] **L. Lusvarghi**, C. A. Grazia, M. Klapez, M. Casoni and M. L. Merani, "Awareness Messages by Vulnerable Road Users and Vehicles: Field Tests via LTE-V2X," in *IEEE Transactions on Intelligent Vehicles*.

[7] **L. Lusvarghi**, A. Molina-Galan, B. Coll-Perales, J. Gozalvez and M. L. Merani, "A Comparative Analysis of the Semi-Persistent and Dynamic Scheduling Schemes in NR-V2X Mode 2," in *Elsevier Vehicular Communications,* 2023.

[8] **L. Lusvarghi**, B. Coll-Perales, J. Gozalvez and M. L. Merani, "Link Level Evaluation of NR V2X Sidelink Communication," submitted to *IEEE Transactions on Vehicular Technology*.

[9] A. Molina-Galan, **L. Lusvarghi**, B. Coll-Perales, J. Gozalvez and M. L. Merani, "On the Impact of Re-evaluation in 5G NR V2X Mode 2," submitted to *IEEE Transactions on Vehicular Technology.*

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Thank you for your attention!