XXXV Cycle

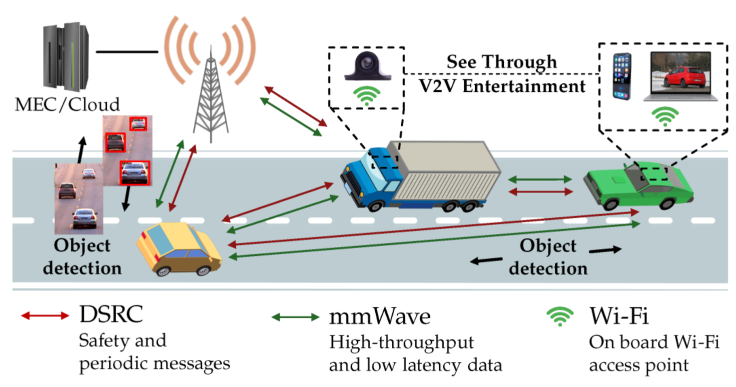
Edge-V
Enabling Vehicular Edge Intelligence in Unlicensed Spectrum Bands

Francesco Raviglione

Supervisor: Prof. Claudio Ettore Casetti

Research context and motivation

- **Vehicular networks**, usually referred to as V2X (Vehicle-to-Everything) communications, represent a fundamental enabler for the future **highly automated and connected vehicles**.
- They face several challenges, due to the **high mobility of nodes** and strict **latency and throughput** requirements.
- Several use cases have been developed, including **platooning**, **See Through**, **collision avoidance** and **Green Light Optimal Speed Advisory** (GLOSA).
- These applications require the exchange of data between vehicles (**V2V** communication) and infrastructure nodes, i.e., Road Side Units (RSUs, **V2I** and **V2N** communication).
- Communication can happen by means of **protocols** specifically targeted at V2X, i.e., **IEEE 802.11p**, the automotive version of "Wi-Fi", and **Cellular-V2X**, i.e., the application of cellular networks to V2X communications. Both IEEE 802.11p and C-V2X leverage a dedicated spectrum at **5.8-5.9 GHz** for V2V and direct vehicle-to-RSU communications.
- Innovative **use cases** based on **task offloading** and **Deep Learning (DL)** are emerging, with the need of **exchanging a large amount of data** between vehicles, with **very low latency** → *(i)* offloading AI/ML processing to other vehicles/RSUs, *(ii)* See Through with HQ video feedback, *(iii)* interactive entertainment systems, *(iv)* advanced object detection from cameras → **Vehicular Edge Intelligence (VEI)** is needed.
- To enable VEI, a **combination of different technologies with mmWave** is required, as IEEE 802.11p and C-V2X alone cannot satisfy its strict requirements.



Addressed research questions/problems

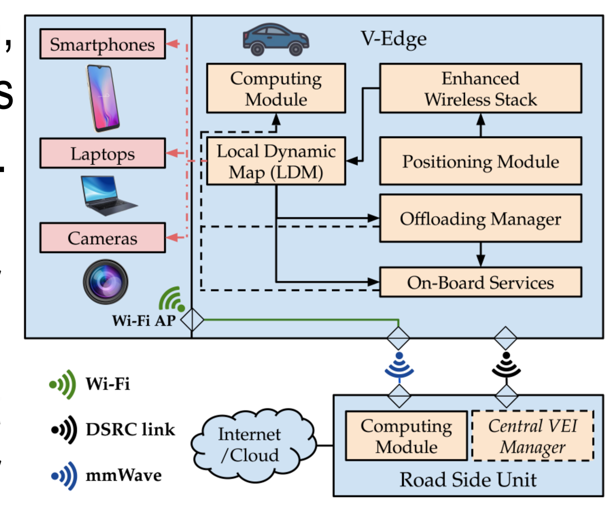
- Sharing sensor data can cause a **significant load on the network**. Sensors such as LIDARs can generate up to **TBs of data each hour**.
- **5G** is often considered a solution to the challenges posed by VEI. However, its **licensed spectrum** is expected to support up to 64 billion subscriptions by 2025, and it is quite **expensive** and already **congested**.
- **VEI on unlicensed spectrum** can enable several innovative use cases, by providing three main **advantages**: *(i)* reducing the usage of expensive 5G spectrum, *(ii)* reducing task offloading latency through direct V2V task offloading, *(iii)* enable VEI where cellular connectivity is limited or absent.
- An integrated **open framework for VEI on unlicensed spectrum**, based on **open-source software**, is still missing in literature and in the automotive field.
- To practically enable VEI, **optimized task offloading** to other vehicles and infrastructure nodes with free resources should be fully supported and integrated with DL-based and other innovative use cases.

Novel contributions

- We present the open **Edge-V framework**, practically enabling VEI thanks to a combination of 60 GHz mmWave, IEEE 802.11p and standard 5 GHz Wi-Fi (on **unlicensed spectrum**).
- We formulate the **Vehicular Edge Intelligence Problem** (VEIP) for optimized task offloading to other nodes, demonstrate that it is **NP-Hard** and provide a Greedy Heuristic.
- We develop a low-cost, fully working **proof-of-concept** based on off-the-shelf hardware and open-source software and **evaluate** Edge-V with simulations, in-lab and **in the field**.

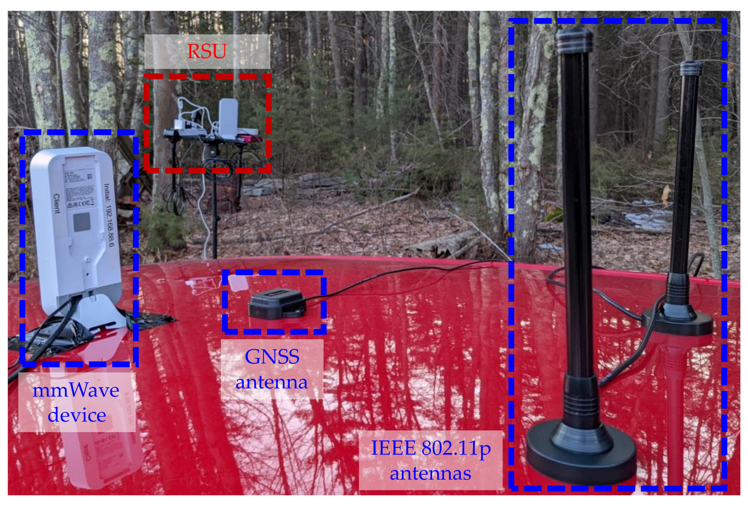
Edge-V

- Open framework enabling VEI use cases such as **high-speed multimedia streaming** between vehicles and **DL task offloading** (e.g., for object detection from camera frames).
- Designed to run, with different modules, on both **vehicles** and **RSUs**.
- Three wireless interfaces: *(i)* **directional mmWave**, for high throughput and low latency task offloading and high-speed data transfer, *(ii)* **IEEE 802.11p (DSRC)** for the exchange of standard-compliant messages and VEI-specific information, *(iii)* **5 GHz Wi-Fi** to enable connectivity of on-board devices to Edge-V and to the Internet through bridge with mmWave.
- **Enhanced Local Dynamic Map (LDM)** with data on nearby vehicles and infrastructure nodes, including their available resources (populated through the DSRC link).
- **Offloading Manager** running the logic defining the best vehicles to perform task offloading (AI/ML-based or mathematical optimization) → leverages **data from LDM**.



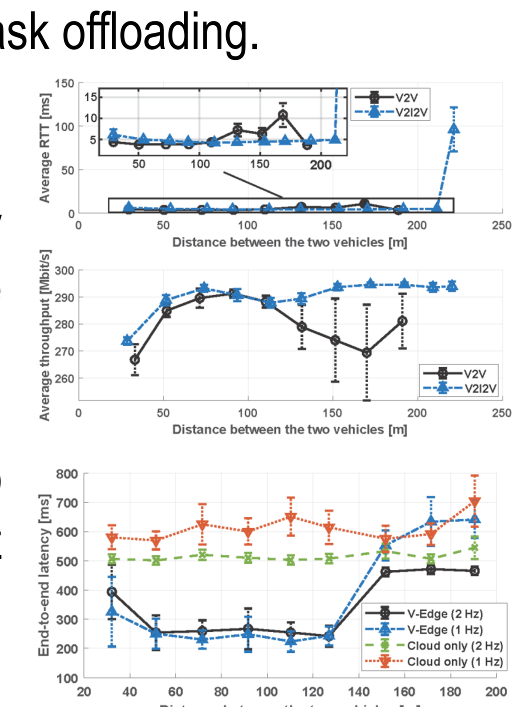
System model and Proof-Of-Concept

- We formulate the **VEIP problem** for the Offloading Manager (OM), modelling the system from a task offloading point of view, and demonstrate that it is **NP-Hard** through reduction to a Multiple Knapsacks Problem.
- We propose a **Greedy Heuristic** which can be employed by the OM to select the best nodes → give **priority** to nearby **vehicles** than to infrastructure (i.e., cloud/MEC via RSU).
- We develop a fully working **Proof-of-Concept** based on **off-the-shelf hardware** → open platform for *IEEE 802.11p* integrated with *IEEE 802.11ac* and interfaced with *IEEE 802.11ad* (mmWave @ 60 GHz) devices, together with **open-source software** implementing *(i)* a special version of ETSI **Cooperative Awareness Messages** (CAMs), exchanged via IEEE 802.11p to populate the LDM, *(ii)* the **LDM** itself, and *(iii)* a sample **OM**.



Adopted methodologies

- Evaluation with MATLAB simulations (OM greedy algorithm), **in-lab** and **on the field** with two real vehicles and one RSU → focus on **two use cases**: *(i)* Direct data exchange between vehicles with high throughput and low latency, *(ii)* DL task offloading.
- **Larger** DL tasks benefit more from local **distributed** computing than smaller tasks, when leveraging heuristics to solve VEIP.
- Latency is up to **65% lower** than the usage of cloud-only approaches when offloading DL tasks with Edge-V, while decreasing the mean average precision by only 18%.
- The combination of mmWave and sub-6 GHz connectivity can provide very good **end-to-end latency** of less than **5 ms** up to 110 m, with the LDM seamlessly updated thanks to the 5.9 GHz DSRC link (no interference with IEEE 802.11ac or mmWave).
- **Average** IEEE 802.11ac + mmWave **throughput**: **~280 Mbit/s**.



Future work

- Development and evaluation of **additional heuristics** for the Offloading Manager.
- Additional, **extensive field tests**, with increasing numbers of vehicles.

Submitted and published works

- F. Raviglione, M. Malinverno and C. Casetti, "*Demo: Open Source Platform for IEEE 802.11p NICs Evaluation*", IEEE WoWMoM 2019, Washington DC, USA, June 2019, pp. 1-3
- F. Raviglione, M. Malinverno and C. Casetti, "*Demo: Open source testbed for vehicular communication*", ACM MobiHoc 2019, Catania, Italy, July 2019, pp. 405-406
- F. Raviglione, M. Malinverno and C. Casetti, "*Characterization and Performance Evaluation of IEEE 802.11p NICs*", 1st ACM Workshop on Technologies, mOdels, and Protocols for Cooperative Connected Cars (TOP-Cars), Catania, Italy, July 2019, pp.13-18
- F. Raviglione, M. Malinverno and C. Casetti, "*A Flexible, Protocol-Agnostic Latency Measurement Platform*", IEEE VTC2019-Fall, Honolulu, Hawaii, USA, September 2019, pp. 1-5
- M. Malinverno, F. Raviglione, C. Casetti, C. F. Chiasserini, J. Mangues-Bafalluy and M. Requena-Esteso, "*A Multi-Stack Simulation Framework for Vehicular Applications Testing*", ACM DIVANet 2020, Alicante, Spain (held remotely), November 2020, pp. 17-24
- E. Coronado, F. Raviglione, M. Malinverno, C. Casetti, A. Cantarero, G. Cebrián-Márquez and R. Riggio, "*ONIX: Open Radio Network Information eXchange*", IEEE Communications Magazine, vol. 59, no. 10, November 2021, pp. 14-20
- F. Raviglione, M. Malinverno, S. Feraco, G. Avino, C. Casetti, C. F. Chiasserini, N. Amati and J. Widmer, "*Experimental assessment of IEEE 802.11-based V2I communications*", ACM PE-WASUN 2021, Alicante, Spain (held remotely), November 2021, pp. 33-40
- A. Minetto, S. Zocca, F. Raviglione, M. Malinverno, C. Casetti, C. F. Chiasserini and F. Dovis, "*Cooperative Localization Enhancement through GNSS Raw Data in Vehicular Networks*", 2021 IEEE Globecom Workshops, Madrid, Spain (held remotely), December 2021, pp. 1-6
- F. Raviglione, S. Zocca, A. Minetto, M. Malinverno, C. Casetti, C. F. Chiasserini and F. Dovis, "*From Collaborative Awareness to Collaborative Information Enhancement in Vehicular Networks*", Elsevier Vehicular Communications, vol. 36, June 2022
- F. Raviglione, C. M. Risma Carletti, C. Casetti, F. Stoffella, G. M. Yilma and F. Visintainer, "*S-LDM: Server Local Dynamic Map for Vehicular Enhanced Collective Perception*", IEEE VTC2022-Spring, Helsinki, Finland, June 2022, pp. 1-5
- F. Raviglione, C. Casetti and F. Restuccia, "*Edge-V: Enabling Vehicular Edge Intelligence in Unlicensed Spectrum Bands*", IEEE INFOCOM 2023, *submitted work*.

List of attended classes

- 01DTPRV – Connected Vehicles (didattica di eccellenza) (23/06/2022, 4 CFU)
- Lipari School on Advanced Networking Systems - Programmability, Security, and Algorithmic Challenges in Future Networks (10/07/2022, 6 CFU)

POLITECNICO DI TORINO

PhD program in
Electrical, Electronics and Communications Engineering