

Open Platforms for Connected Vehicles

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Vehicular technologies are being recently invested by astonishing innovations, aimed at making the future vehicles safer, smarter and greener. Future transportation systems are indeed expected to heavily leverage connected and autonomous vehicles, which have emerged into the market in the past decade.

In the past, since the introduction of the Anti-lock Braking Systems (ABS), almost 50 years ago, driving assistance and automation systems leveraged only on-board sensors. However, these sensors are characterized by a limited range, and cannot enable the most advanced use cases, such as collision avoidance to increase road safety. This led to the birth of vehicular communication, represented by the data exchange between road users through dedicated wireless networks. Vehicle-to-Everything (V2X) communication thus become the fundamental enabler for all the next-generation of automotive services, towards the sought-after very high and full automation levels defined by the Society of Automotive Engineering. Vehicular networks are, however, characterized by several challenges due to the high mobility of nodes and the frequent topology changes. Furthermore, as most V2X applications are safety critical, they should be able to guarantee a very low latency and high network reliability.

This thesis starts by presenting an overview on the main use cases for connected and autonomous vehicles and on the different types of V2X communications. Then, it provides an analysis of the technologies specifically designed for vehicular networks. These wireless technologies have been standardized with the aim of overcoming the challenges of V2X and include IEEE 802.11p, LTE-V2X and NR-V2X, concerning the lower layers, and the ETSI ITS-G5 and IEEE WAVE protocol stacks for the higher layers.

A fundamental role in the development, deployment and testing of innovative V2X systems is played by open and customizable platforms. Indeed, the open source paradigm provides several advantages and enables knowledge sharing between researchers, and between academia and industry. Open platforms enable the reproducibility of results, foster further research, provide an unprecedented flexibility for experimental purposes, represent a low-cost way of analyzing and testing new protocols and applications and provide transparency and reliability, thanks to the code being open to contributions.

This thesis thus focuses on open platforms and frameworks for connected vehicles, including the presentation of a fully-open Dedicated Short-Range Communications (DSRC) platform based on customizable hardware and a special version of the OpenWrt Linux distribution, effectively enabling V2X communication in the 5.8-5.9 GHz Intelligent Transport Systems (ITS) frequency range. Then, it presents a novel latency measurement protocol (LaMP) for automotive scenarios and the first tool relying on this protocol, called LaTe. The combination of LaTe and our open DSRC framework

allowed us to perform several measurements to provide interesting insights on the behaviour of IEEE 802.11p, both concerning throughput and latency. Our platform has also been leveraged as a starting point for the development of an open, plug and play and low cost On-Board Unit (OBU), with open source software implementing the ETSI ITS-G5 stack. Furthermore, thanks to LaTe, it was possible to develop a long term network testing framework (LTNT), leveraged to assess the performance of an innovative automotive edge system, showing how it can provide low latency and high throughput.

The presentation of open platforms for V2X is complemented with the design, development and evaluation of both Edge-V, the first open framework enabling Vehicular Edge Intelligence thanks to the combination of unlicensed spectrum technologies, and Open Radio Network Information eXchange (ONIX), a flexible Radio Network Information Service designed to support 4G/5G networks and vehicular applications such as Collision Avoidance.

The evaluation of different technologies for V2X also plays a crucial role in development and deployment of an open platform for connected vehicles. Indeed, these technologies represent fundamental enablers for the overlying applications and use cases.

Therefore, this thesis presents a new open source framework for simulating and emulating V2X scenarios, called ms-van3t, which is compared with other existing solutions in literature, highlighting several novel features enabling advanced testing of vehicular applications. It is then exploited to provide a comparison study, thanks to realistic simulations, between IEEE 802.11p and C-V2X. The simulation studies are further complemented by several measurements in the field, both in a static laboratory context and on the road. These field tests provide several insights on the performance of IEEE 802.11p, which is also compared with millimeter Wave (mmWave) and IEEE 802.11ac in a Vehicle-to-Infrastructure scenario.

Finally, a novel open protocol for the exchange of raw Global Navigation Satellite System (GNSS) data between vehicles is proposed and evaluated. Thanks to this protocol, which is proved to reliably support both IEEE 802.11p and C-V2X, it becomes possible to enable a plethora of collaborative positioning approaches. We also present an innovative, 5G-enabled MEC service storing a centralized local dynamic map of the road, aimed at providing data to other MEC services, when needed, to manage highly automated maneuvers in a centralized way. This service is evaluated, both in-lab and in the field, after being deployed to multiple MEC platforms managed by different Mobile Network Operators. Two Stellantis vehicles equipped with V2X OBUs have been used to test our service in the field.

The design and development of open platforms, the evaluation of different technologies (by simulations and in the field) and the deployment of novel protocols and services all represent fundamental steps in the deployment and testing of complete open V2X environments. As discussed in this thesis, this enables researchers to gather insights on different technologies for V2X and on their combination and test innovative applications for future road deployment, towards a new generation of safer, smarter and greener vehicles.