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Proceedings Paper:

Cinque, E., Di Marco, P., Mihaylova, L. et al. (2026) Open challenges in communications and positioning for connected and automated vehicles. In: Proceedings of the XXXVIth URSI General Assembly and Scientific Symposium. XXXVIth URSI General Assembly and Scientific Symposium, 15-22 Aug 2026, Krakow, Poland. Union Radio-Scientifique Internationale (URSI).

<https://doi.org/10.46620/URSIGASS26/SSSY5824>

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Open Challenges in Communications and Positioning for Connected and Automated Vehicles

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Abstract

While Global Navigation Satellite Systems (GNSSs) have been retained as the fundamental global coverage component for navigation and have been continuously improving their performance, it is now recognized that accurate positioning for intelligent mobility is a multi-sensor fusion problem. In this vision, wireless communications technologies may inherently contribute through signals of opportunity, while also providing the pervasive connectivity that enables cooperative strategies for positioning and navigation. The present paper moves from the analysis of latest requirements for Cooperative Connected and Automated Mobility (CCAM) services and applications, then outlines the main challenges to be addressed for communications and positioning; connections to research activities in relevant ongoing projects are finally mentioned.

1. Introduction

The transition toward Cooperative Connected and Automated Mobility (CCAM) represents one of the most significant shifts in modern transportation, promising to enhance road safety, optimize traffic efficiency, and reduce environmental impact. However, achieving the highest levels of automation, where the vehicle performs all driving functions under specific or under all conditions without any human interventions, requires a fundamental shift from autonomous systems, which typically rely only on on-board sensors, to a cooperative paradigm, that relies on communications among vehicle or between vehicles and infrastructure (V2X, Vehicle-To-Everything). In this vision, integration of advanced communication technologies and high-precision positioning emerges as the fundamental enabler for collective situational awareness and safe cooperative automated maneuvers.

Global Navigation Satellite Systems (GNSSs) have provided for a quite long time the essential worldwide coverage for positioning services, that have in turn been integrated into maps to finally provide appreciated navigation services to the drivers in road mobility. On the other side, the localization accuracy and integrity have not been satisfactory for automated operations, and current driving assistance systems basically rely on local sensors, such as LiDAR, radar, and cameras: nevertheless, while they provide essential line-of-sight perception, they are

inherently limited by physical obstructions, adverse weather, and the electronic horizon of a vehicle.

Communication technologies overcome the limitation of “local” operations by allowing vehicles to see around corners and negotiate maneuvers with other road users and infrastructure. We may consider the potential of latest generation and upcoming cellular communications with their emerging non-terrestrial network (NTN) component, along with specific cellular V2X (C-V2X) technologies, as the fundamental enabler for larger scale cooperative operations. Beyond the native scope of extending the “local horizon” toward an “electronic horizon”, communication systems can inherently provide a large set of signals of opportunity, that can be fused with those produced by GNSS and other sensors in order to support the high-precision and high integrity positioning that is required for the most advanced levels of CCAM.

Moving from years long investigation and experimental validation in a set of collaborative projects that the authors are involved in, the purpose of this paper is to organize and share latest advances in definition of classes of application and services, along with communication standards and localization techniques. Open challenges are then outlined, along with the mention of problems and solutions currently addressed in related research projects.

2. Operation domains, service requirements and related use cases

CCAM is a complex ecosystem, covering a wide variety of operating conditions and use cases. According to the European Road Transport Research Advisory Council (ERTRAC) roadmap, operational research, standardization, and investments are structured around four main domains: highways and corridors, urban mixed traffic, rural roads and confined areas [1]. Each CCAM use case is mapped to at least one domain, defined by specific traffic conditions. Highways and corridors are characterized by high speeds and relatively predictable traffic, facilitating automation and V2X-supported assistance functions. These conditions also enable the deployment of cooperative and partially/highly automated functions. From a V2X perspective, highways and corridors typically require long communication ranges, high reliability and low latencies to support cooperative driving at high speeds, despite moderate vehicle densities. By referring to ETSI TR 102 638 standard classification, typical use cases include Cooperative Adaptive Cruise

Control (C-ACC), Cooperative Intelligent Speed Adaptation (C-ISA), Cooperative Active Lane Keeping (C-ALK), and Cooperative Lane Change (CLC). Urban mixed traffic is characterized by complex interactions between road users and infrastructure with high vehicle densities (up to several hundred vehicles per km²), frequent non-line-of-sight conditions, and rapidly changing traffic dynamics, resulting in strict V2X latency (max 50 ms) and reliability requirements. In such heterogeneous environments, cooperative and connected functions are essential to improve safety and traffic efficiency. CCAM use cases of augmented perception and intersection crossing assistance defined in ETSI TR 102 638, are of particular interest. In contrast, rural roads have low vehicle density and sparse infrastructure deployment. Here V2X communication can significantly enhance accessibility and safety through extended awareness services, even under less strict latency requirements. Use cases of particular interest include advanced pre-crash sensing, advanced non-connected slow vehicles, and cooperative vehicle energy-critical situations. Finally, confined areas represent controlled environments with limited access, predictable traffic, and moderate vehicle densities, allowing greater operational flexibility. Relevant use cases in this domain may include Urban Mapping/HD Map localization for testing and data collection, and Infrastructure-to-Vehicle signalling, where V2X communication can be implemented with minimal safety or legal risks.

3. Role of communication technologies

In this section, we review the reference standards for terrestrial and satellite communications, looking at the open challenges and opportunities in the integration of the two domains.

3.1 Reference standards and regulations for terrestrial communications

Current terrestrial communication strategies increasingly favor a hybrid model, integrating immediate situational awareness through direct V2X links, while leveraging long-range wide-area networks to fulfill the high-throughput demands of cooperative perception. Accordingly, the state-of-the-art for terrestrial vehicle connectivity is currently dominated by two main paradigms: dedicated short-range communications (DSRC) based on IEEE 802.11, and 5G C-V2X.

While the foundational IEEE 802.11p (ITS-G5 in Europe) provided the first ad-hoc broadcast capabilities for vehicular scenarios, the current focus of DSRC has shifted toward IEEE 802.11bd. This evolution introduces advanced physical layer enhancements for better channel estimation in high-mobility scenarios with fast-fading channels and support for mmWave frequencies to achieve very high throughput.

Regarding 5G C-V2X (or 5G-NR V2X), the industry is rapidly adopting 3GPP Release 16 and 17 specifications.

Unlike early C-V2X, that is based on LTE Rel-14 and was limited to broadcast, NR-V2X supports unicast and groupcast communications via an enhanced Sidelink interface. Key advancements include a network-managed and autonomous resource allocation schemes.

For unlicensed operations, deployment of V2X and C-V2X is governed by global spectrum harmonization in the 5.9 GHz band (5855–5925 MHz), managed by ITU-R and ETSI. For European markets, compliance with the Radio Equipment Directive (RED) is ensured through standards like ETSI EN 302 571 (for DSRC) and ETSI TS 103 613 (for 5G-V2X).

3.2 Satellite communications and non-terrestrial networks

Connected and autonomous vehicles (CAVs) are constrained by service continuity, not merely onboard intelligence. Terrestrial V2X is indispensable for local safety loops, yet it cannot guarantee ubiquitous coverage or resilience across the road network. 5GAA therefore treats NTN as a complementary layer to close terrestrial coverage gaps and sustain services during outages, with a focus on narrowband/wideband services and a path to broadband [2, 3]. In parallel, 3GPP's NTN programme integrates satellites into the 5G system to deliver service ubiquity, continuity and scalability, while accounting for Low/Medium Earth Orbit (LEO/MEO) dynamics (moving cells, Doppler and delay variation) that require beam and mobility management. These constraints motivate dedicated satellite-access UE RF/performance requirements as defined in ETSI TS 138 101-5. Road classes expose the partitioning. On motorways, cooperative manoeuvres and platooning require low-latency short range connectivity as the primary bearer, with NTN providing a network backstop across network coverage discontinuities [3]. On A-roads and rural single carriageways, availability dominates: NTN becomes the default bearer for telemetry, incident reporting and map/operations data when terrestrial networks are absent [2]. In dense urban arterials, NTN is best treated as opportunistic augmentation because line-of-sight intermittency and spectrum coexistence constraints in the ITS band, as addressed in ETSI TR 103 667; safety-critical interactions remain terrestrial-first [2].

3.3 An integrated vision toward 6G

Autonomous vehicle deployment will require Ultra Reliable Low Latency Communications (URLLC) and distributed sensing beyond current 5G capabilities. 6G is envisioned to provide integrated communication and sensing with peak data rates of 1 Tb/s, sub-millisecond latency, cm-level localisation, and 99.9999% reliability. Key enabling technologies include THz signals, Intelligent Reflective Surfaces (IRSs), fingerprinting-based localisation, cell-free architectures, integration of NTN, and Artificial Intelligence (AI). The latter will complement traditional estimators by learning patterns

from Channel State Information (CSI), supporting sensing applications such as object detection, mapping, localisation, and tracking in complex environments. Cell-free architectures with distributed access points coordinated through backhaul networks that provide seamless coverage and cooperative communication, will help cope with higher attenuation and blockage of THz frequency signals. Challenges remain, including high path loss, atmospheric sensitivity, poor penetration, waveform design limitations, and power and thermal constraints of high-frequency antenna systems. Despite the challenges, 6G represents a promising foundation for scalable sensing, localisation, and communication for CAVs.

4. Positioning methods and technologies

This section reviews the main positioning methods and technologies relevant to CCAM.

4.1 GNSS and correction methods for positioning

GNSS systems such as GPS, Galileo, and BeiDou are affected by dilution of precision, atmospheric delays, ionospheric effects, and clock and propagation errors. These are mitigated using established correction techniques [4, 5], primarily Real-Time Kinematic (RTK), Precise Point Positioning (PPP), and hybrid PPP-RTK.

RTK achieves decimeter-level accuracy with >95% availability in automotive applications using corrections from reference stations. PPP provides globally scalable corrections using precise satellite products but has slower convergence. PPP-RTK combines RTK fast convergence with PPP scalability, enabling wider coverage while maintaining high accuracy. Current developments integrate GNSS with complementary sensors such as IMUs, cameras, prior maps, and 5G positioning, supporting signal correction, drift mitigation, and multi-sensor localisation.

4.2 5G Positioning systems

5G positioning is entering deployment under 5G-Advanced (3GPP Release 18 and 19). Key techniques include: Multi-Round Trip Time ranging, Time Difference of Arrival (TDOA) using downlink positioning reference signals and uplink transmissions, mmWave ranging (≥ 24 GHz), improving timing resolution and distance precision. Urban positioning is limited by non-line-of-sight (NLOS) propagation caused by signal reflections. NLOS mitigation uses high-definition maps, signal consistency checks, and statistical or machine learning methods to identify and down-weight indirect paths. Standardisation continues to evolve, requiring integration of positioning with sensing, autonomy requirements, environmental conditions, and navigation system architectures.

4.3 Multi-sensor localisation systems

Multi-sensor localisation provides high-integrity positioning by avoiding single-sensor failure modes. Typical systems combine GNSS (RTK/PPP-aided), IMU, and wheel odometry, where inertial and odometric sensors provide high-rate motion continuity, and GNSS provides absolute global reference [4, 5]. Additional robustness is achieved using camera and LiDAR odometry and map-based localisation, which constrain drift during GNSS outages or degradation [4]. These systems fuse asynchronous, heterogeneous measurements with varying uncertainty and intermittent availability. Modern pipelines maintain continuous ego-motion using high-rate proprioceptive sensing, with intermittent absolute corrections from GNSS, maps, exteroceptive sensors, and emerging radio-based positioning such as 5G/NR. This introduces architectural challenges including GNSS/INS coupling, heterogeneous measurement integration, and estimator design to ensure bounded-error performance under CCAM operating conditions.

4.4 Sensor fusion architectures and techniques

CAV positioning requires multi-sensor fusion, as standalone GNSS or dead reckoning cannot meet continuity, accuracy, and reliability requirements [4, 5]. Modern architectures use IMU-centric propagation with wheel odometry and vehicle kinematics, while absolute updates from GNSS, maps, LiDAR, and cameras limit drift under degraded GNSS conditions [4]. A key design choice is GNSS/INS coupling. Loosely coupled integration combines GNSS outputs with inertial states, while tightly coupled integration incorporates raw GNSS observables, improving robustness under limited satellite visibility and measurement bias [6, 7]. LiDAR and camera constraints increasingly provide drift-limiting geometric priors in GNSS-denied environments. Extended and Error-State Kalman filters (EKF and ESKF, respectively) remain widely used, while factor graph optimisation (FGO) supports asynchronous measurements and sliding-window optimisation, improving performance with intermittent GNSS. 5G/NR-V2X introduces an additional positioning modality, enabling metre-to-sub-meter accuracy using wide bandwidth signals and antenna arrays. Cooperative localisation using shared infrastructure and vehicle measurements can be fused with onboard sensor constraints.

4.5 AI driven methodologies

AI-driven positioning enhances multi-sensor fusion by learning adaptive uncertainty models and measurement reliability under non-stationary and non-Gaussian errors. Convolutional Neural Network - Gated Recurrent Unit (CNN-GRU) motion state recognition adapts process and measurement noise in Kalman filters, improving consistency [8], while GRU-based approaches generate

pseudo-measurements during GNSS outages to support INS through adaptive filtering. Long Short-Term Memory based methods fuse GNSS, laser-SLAM (Simultaneous Localization and Mapping), and odometry using learned temporal dependencies to improve localisation stability [9]. AI is also applied to GNSS measurement validation, where denoising autoencoders extract robust features and detect NLOS conditions, enabling filters to down-weight biased observations. These approaches retain physics-based fusion while improving uncertainty estimation and measurement selection.

5. Open challenges and on-going projects

In recent years, the automotive industry has faced significant changes driven by sustainability, software integration, and the rise of AI. Manufacturers have shifted from traditional electro-mechanical designs to Software Defined Vehicles (SDVs), leveraging software and virtualization to enhance functionality, connectivity, and autonomy. The new challenges introduced by the growing prevalence of software in vehicles include regulations focused on automotive software integrity and the need for cybersecurity, guarantees and protections for customer privacy. To advance connected and autonomous driving, a long-term, backward-compatible development vision is essential, encompassing V2X connectivity, service availability, and infrastructure sensing.

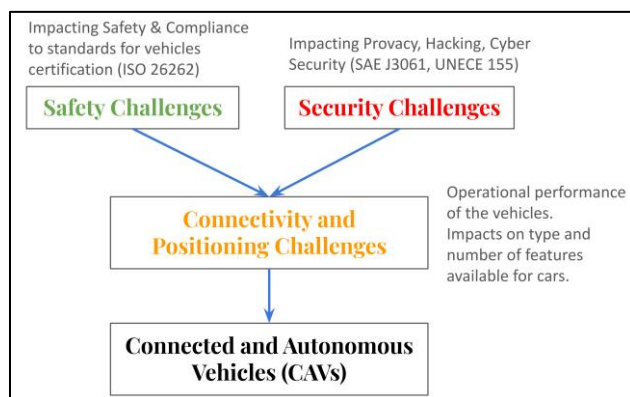


Figure 1. Challenge groups for CAVs.

The enablers and the challenge groups for autonomous driving are captured in Figure 1. In response, initiatives like I-PoCARS¹ (Integrated Proof of Concept for real-time Automotive useR case with STEP) have emerged. I-PoCARS develops a cross-industry framework for advanced vehicle localization, combining space, ground, and vehicle segments and benchmarking signal/data fusion algorithms (GNSS, 5G, and on-board sensors). Its innovation lies in augmenting in-vehicle GNSS with 5G corrections and testing solutions in both simulated and real vehicles. Supporting this approach is the P-CAR (PNT Center for Automated Road-Transport) laboratory, designed to validate and certify CAV functionalities.

¹ We are grateful to the ESA support via the I-PoCARS project, grant number NAVISP-EL2-235

P-CAR uses a hybrid testing method focused on safety, integrity, and performance across multi-sensor environments and operational scenarios. I-PoCARS and P-CAR are coordinated by Vodafone and Radiolabs, respectively, and funded by the European Space Agency (ESA) under the NAVISP Programme.

6. Conclusions

Reliable autonomous driving requires a shift from sensor-only systems to cooperative approaches based on V2X communications and accurate, reliable positioning. Autonomous driving demands URLLC capabilities beyond 5G, with 6G enabling integrated communication and sensing. While GNSS suffers from errors and signal impairments, its performance can be improved through PPP/RTK techniques and complemented by multi-sensor fusion, 5G positioning, and AI-based methods. This paper addresses key challenges in communication and positioning, highlighting the role of international research initiatives such as I-PoCARS and P-CAR in advancing safe and reliable CCAM systems.

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