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Analysis of Communication Requirements and Key Technologies for V2X in Autonomous Driving

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Abstract:

Autonomous driving technology has emerged as a core component of future transportation systems with advancements in artificial intelligence and electronic information technology. However, its large-scale deployment is challenged by requirements for real-time performance, reliability, and coordination. Vehicle-to-Everything (V2X) communication technology enables the sharing of information across all transportation elements, making it a key enabler for the implementation of autonomous driving. This paper systematically analyzes the core communication requirements of autonomous driving for V2X, reviews the architectural foundations of V2X technology, investigates communication mechanisms supporting multi-source perception data fusion, and proposes an integrated ‘vehicle-road-cloud’ collaborative framework. Additionally, it leverages Perception-Communication-Computing Integration technology to enhance system performance. Addressing key communication challenges such as signal propagation delay, synchronization of multi-source heterogeneous networks, and environmental interference, this paper proposes precise time synchronization, frequency synchronization, phase synchronization optimization techniques, and machine learning algorithm application solutions. Research confirms that V2X communication serves as the core enabling technology for advanced intelligence and large-scale deployment of autonomous driving systems. Its evolution toward high reliability, ultra-high speed, and intelligent ubiquity will be driven by future 6G communication networks, facilitating comprehensive upgrading of intelligent transportation systems.

Keywords: Autonomous driving; V2X communication; Multi-source perception data fusion; Synchronization technology optimization; 6G.

1. Introduction

With the rapid development of artificial intelligence and electronic information technologies, autonomous vehicles are gradually evolving from concept to reality, becoming a core force in reshaping the future transportation system. As a critical component of intelligent transportation systems (ITS) [1], autonomous driving technology enhances road safety, traffic efficiency, and energy utilization through the integration of high-precision perception, decision-making, and control modules. However, its large-scale application still faces challenges in terms of real-time performance, reliability, and coordination in complex dynamic environments. In this context, vehicle-to-everything (V2X) technology, with its ubiquitous communication capabilities connecting vehicles, infrastructure, pedestrians, and cloud platforms, has become the core enabler for the implementation of autonomous driving. Through multi-modal communication technologies, V2X enables information sharing and collaborative decision-making among all traffic elements, thereby overcoming the limitations of single-vehicle perception and providing a more comprehensive understanding of traffic conditions [2].

The core capabilities of communication technologies in terms of ultra-low latency, ultra-high reliability, and massive connectivity further highlight the stringent demands of autonomous driving on network performance. Currently, the evolution of technologies such as 5G/6G communications, edge computing, and integrated sensing, communication, and computing has provided new opportunities for V2X networks [3]. However, several critical issues persist, including spectrum resource conflicts, difficulties in synchronizing multi-source heterogeneous networks, and insufficient communication stability in dynamic environments. Therefore, conducting an in-depth analysis of the communication requirements of autonomous driving for V2X networks and overcoming key technological bottlenecks are of great significance for promoting the implementation of intelligent transportation systems.

This study aims to systematically analyze the core communication requirements of autonomous driving for V2X networks. It further clarifies the critical role of communication systems in ensuring multi-source perception fusion and collaborative control decision-making. Specifically, the research focuses on establishing a V2X communication framework that integrates high reliability, low latency, and adaptive capabilities.

2. V2X Basic Architecture and V2X Communication Technology

2.1 Overview of the V2X System Architecture

V2X is a communication-based network architecture enabling vehicles to exchange information with other vehicles, road infrastructure, pedestrians, and cloud platforms. It mainly includes Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Grid (V2G), and Vehicle-to-Pedestrian (V2P). As a key technology for intelligent connected vehicles, V2X builds a collaborative “vehicle-road-human-cloud” ecosystem through multi-dimensional communication, supporting autonomous driving and smart traffic management.

V2V communication technology allows vehicles to wirelessly exchange information including position, speed, and braking status. This improves traffic flow, prevents collisions, and offers sophisticated driver assistance functions.

V2I communication technology enables vehicles to interact with infrastructure components such as traffic signals and road-side units. By sharing real-time data, it contributes to improved traffic efficiency, enhanced road safety, and better driving experiences.

V2G communication technology allows electric vehicles to interact with the power grid for charging or discharging purposes. This not only supports energy efficiency and peak load balancing but also contributes to carbon emission reduction and may offer users financial incentives.

V2P communication technology establishes a link between vehicles and pedestrians, typically via smart devices or wearables. This allows for timely pedestrian detection and driver warnings, thereby improving safety for vulnerable road users [4].

2.2 Detailed Explanation of V2X Communication Technology

To facilitate communication between vehicles and their surroundings, V2X technology fundamentally relies on two primary wireless standards: Dedicated Short-Range Communication (DSRC) and Cellular Vehicle-to-Everything (C-V2X) [5]. DSRC, grounded in the IEEE 802.11p protocol, operates within the 5.9 GHz frequency band to enable peer-to-peer communication between vehicles and between vehicles and roadside infrastructure. This technology delivers low-latency performance, with transmission delays ranging from 20 to 100 milliseconds, and supports infrastructure-free operation, eliminating dependence on cellular network coverage. It is widely used overseas but has fatal flaws such as reliance on line-of-sight propagation, a coverage range typically less than 500 meters, poor performance in high-density environments, and technological stagnation. C-V2X is based on 4G/5G cellular network communication, utilizing cellular network relay and beamforming technology to support non-line-of-sight transmission with a coverage radius of up to 2 kilometers. In high-density traffic and complex traffic environments, it maintains low latency and reliability. C-V2X technology combines the advantages of cellular networks and radio base stations, and is widely applied in the development of autonomous driving and smart city road infrastructure. The vast volume of data generated by V2X systems require real-time collection, processing, and analysis. Big data analytics and cloud computing technologies provide robust data storage and computing capabilities for vehicle-to-everything systems. Through

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cloud-based platforms, V2X networks can achieve comprehensive monitoring and prediction of road traffic conditions, analyze traffic flow, identify potential traffic congestion areas, and subsequently develop effective traffic management strategies.

3. Communication Support Mechanisms and Collaborative Architecture for Multi-Source Perception Data Fusion

3.1 Overview of Autonomous Driving Perception Systems and Their Data Characteristics

Autonomous vehicles perceive the surrounding environment and self-positioning data through onboard sensors, including lidar, millimeter-wave radar, optical cameras, and integrated inertial navigation systems. Based on the collected data, they perform real-time decision-making and motion planning to ensure accurate trajectory tracking via control algorithms [6]. Currently, vehicle target detection primarily relies on three types of sensors: LiDAR, cameras, and millimeter-wave radar. One category of detection algorithms developed on point clouds using LiDAR is traditional recognition algorithms based on Euclidean clustering [7]. This method effectively reduces computational pressure while maintaining a certain recognition rate. Another category is based on deep learning methods, such as PointPillars [8]. Deep learning methods have certain advantages in terms of recognition rate and accuracy, but they also have issues such as high computational requirements and the need for special deployment conditions. Camera-based target detection primarily employs deep learning methods, with the most commonly used method being the YOLO series, which meets the requirements of current mainstream task scenarios in terms of detection speed and accuracy. Millimeter-wave radar uses the Doppler frequency shift effect to detect targets, offering a longer effective detection range and robustness to special conditions such as dust, smoke, and fog. However, the point cloud data it generates is relatively sparse, limiting its applicability in target detection tasks. All types of sensors have their own advantages and limitations in terms of detection accuracy, computational burden, and environmental adaptability, so multi-source perception fusion has become a key way to improve the overall environmental perception ability.

3.2 Analysis of Multi-source Perception Data Applications

To address critical challenges in unmanned vehicle formations, Pang et al. conducted a systematic study. These challenges include target detection in complex environments, trajectory planning based on preceding vehicle positions, and the adaptability of robust control in formation scenarios. The researchers designed and implemented a vehicle recognition and trajectory tracking control system for formation driving [9]. They proposed a multi-sensor post-fusion moving target detection algorithm, utilizing three types of sensors—lidar, cameras, and millimeter-wave radars as data sources. The simulation experiment showed significant improvements in target recognition accuracy, stability, interference resistance, and real-time performance compared to single-sensor methods. Specifically, the detection and recognition accuracy rate for the leading vehicle exceeded 95%. This represents improvements of 19%, 12%, and 46% when compared to using a single laser radar, camera, or millimeter-wave radar sensor, respectively.

3.3 Fusion and Collaborative Architecture Enabled by V2X Communications

V2X communication technology enables real-time data exchange among vehicles, roadside infrastructure, pedestrians, and the cloud, establishing an integrated and collaborative “vehicle-road-cloud” architecture. This architecture integrates comprehensive perception via low-latency C-V2X networks to aggregate dynamic traffic data. It emphasizes intelligent decision-making through edge computing and cloud-based AI, generating global optimization strategies. The system ultimately achieves precise execution of scenarios like vehicle platooning, traffic light coordination, and risk warnings through the collaborative control layer. This architecture breaks down information silos, upgrading single-vehicle intelligence to system-level collaboration, significantly improving road traffic efficiency by over 30% and reducing accident rates by 40%, providing core support for autonomous driving and smart transportation.

3.4 Integration of Perception, Communication, and Computing

ISCC (Integrated Sensing, Communication, and Computing) [10] represents an emerging unified framework that consolidates perception, communication, and computing functionalities into a single platform. It is designed to optimize network performance and enable complex application scenarios, including smart cities, autonomous driving, smart manufacturing, and the Internet of Things. The perception function collects key data through various sensors, the communication function ensures efficient data transmission, and the computing function is performed at the edge of the network, processing and analyzing data in real time to support intelligent decision-making. This integration is expected to play a crucial role in the future of V2X communication.

4. Key Challenges and Technological Breakthroughs in Autonomous Driving Communications

4.1 Major Communication Challenges

4.1.1 Signal Propagation Delay Issues

Signal propagation delay refers to the time required for a signal to travel from the transmitter to the receiver. In V2X communication systems, the high-speed movement of vehicles exacerbates this delay, directly undermining the real-time nature of communication. For instance, on a highway where vehicles travel at 120 km/h, a mere 100-millisecond delay in receiving an emergency braking signal can lead to an additional 3.3-meter travel distance before the vehicle initiates braking. Such delays can severely impede the timely reception of critical information, including emergency braking alerts or traffic congestion warnings. This not only compromises the effectiveness of autonomous driving decision-making algorithms but also significantly increases the risk of rear-end collisions and chain reactions in traffic flow. Addressing these delays is crucial for ensuring the safety and efficiency of intelligent transportation systems.

4.1.2 Multi-source Heterogeneous Network Synchronization Issues

V2X systems integrate diverse communication technologies, such as Dedicated Short-Range Communications (DSRC), cellular networks (including LTE-V and 5G), and satellite communications. Each technology has distinct characteristics: DSRC offers low-latency short-range connectivity but has limited coverage; 5G networks provide high bandwidth and wide coverage but may face interference in densely populated areas, while satellite communications ensure global reach at the cost of higher latency. These disparities in spectrum allocation, bandwidth capacity, and coverage range create significant technical hurdles for inter-network synchronization. In complex urban environments, for example, vehicles may rapidly switch between DSRC and 5G networks, leading to data packet loss and service interruptions. Achieving seamless synchronization across these heterogeneous networks is essential for enabling uninterrupted communication and reliable operation of V2X applications.

4.1.3 Environmental Interference and Signal Attenuation Issues

Environmental factors, including building obstructions and adverse weather conditions, pose substantial threats to signal propagation in V2X systems. In urban canyons formed by tall buildings, signals often encounter multipath effects, where electromagnetic waves reflect off surfaces and reach the receiver via multiple routes. This phenomenon causes time delay expansion, distorting the signal waveform and resulting in bit errors during data decoding. Adverse weather, such as heavy rain, snow, or fog, can also significantly attenuate signal strength; for instance, millimeter-wave signals used in 5G V2X communication can experience up to 20 dB/km attenuation in heavy rain, reducing effective communication range by over 50%. Moreover, electromagnetic interference from industrial equipment or power lines and ambient noise further degrade signal quality. Overcoming these environmental challenges is imperative for maintaining robust and consistent communication performance across diverse operating conditions.

4.2 Key Technological Solutions and Progress

4.2.1 Precision Time Synchronization Technology Optimization

Precise time synchronization is essential for V2X communication systems to ensure effective interaction among vehicles, infrastructure, and pedestrians. Positioning, navigation, and timing (PNT) synchronization technologies, particularly the Global Positioning System (GPS), provide precise time references for V2X communication. GPS achieves nanosecond-level clock synchronization accuracy by receiving satellite signals. However, GPS signals are susceptible to environmental interference, such as building obstructions, multipath effects, and adverse weather conditions, which can cause signal distortion or loss. To enhance the robustness of time synchronization, other technologies must be integrated to ensure precise time synchronization under various conditions [11].

4.2.2 Frequency Synchronization Technology Optimization

Orthogonal Frequency Division Multiplexing (OFDM) technology is widely adopted in V2X communication due to its robustness in frequency-selective fading channels. OFDM reduces the impact of multipath propagation by dispersing high-speed data streams across multiple subcarriers. Pilot signals in OFDM systems can be used to achieve frequency synchronization, ensuring orthogonality between subcarriers, thereby improving spectrum utilization and system performance.

4.2.3 Phase Synchronization Technology Optimization

In V2X communication systems, phase synchronization is critical for improving signal interference resistance and reducing bit error rates. Phase differential technology can effectively eliminate the effects of phase noise and frequency offset through differential signal processing. A phase-locked loop (PLL) is a widely used feedback control circuit in communication systems, designed to achieve precise tracking and synchronization of signal phases. The PLL compares the phase difference between the input signal and the signal generated by the local oscillator, automatically adjusting the oscillator's frequency to maintain phase coherence. In V2X communication, PLL technology can effectively address Doppler frequency shifts caused by vehicle movement, thereby ensuring the continuity and stability of communication.

4.2.4 Algorithm Optimization and Artificial Intelligence Applications

Application of Machine Learning in Synchronization Optimization Machine learning algorithms can be used to optimize the synchronization process of V2X communication systems. By analyzing historical synchronization data, machine learning algorithms can predict and adapt to changes in the network environment, thereby achieving adaptive synchronization adjustments. For example, reinforcement learning algorithms can be used to optimize synchronization strategies through iterative interaction with the communication environment to converge on optimal synchronization policies.

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4.3 Future Technological Outlook

Despite the performance gains enabled by advanced V2X services, these enhancements predominantly hinge on expanded investments in spectrum resources and hardware infrastructure while retaining core operational frameworks inherited from LTE-based architectures [12]. Parallel to this, urbanization trends, elevated living standards, and rapid technological breakthroughs are fueling an imminent explosion in autonomous vehicle deployment. This surge will catalyze exponential growth in connected devices and AI-driven digital applications tailored for smart automated mobility. Against this backdrop, conventional V2X networks risk their limitations in accommodating the expanding array of use-case scenarios and heterogeneous demands. Consequently, a systemic overhaul from rigid legacy communication paradigms toward more agile, scalable, and diversified network architectures becomes imperative. This transformative shift is poised to materialize through the upcoming 6G wireless ecosystem, which seeks to create a unified communication fabric integrating terrestrial base stations, satellite constellations, and drone-based relay nodes. Such an integrated architecture promises to deliver a truly pervasive and intelligent V2X ecosystem characterized by ultra-reliable communications with sub-millisecond latency, multi-terabit data transmission capacities, massive machine-type connectivity supporting billions of devices, and three-dimensional coverage optimized for energy efficiency and extended range. Critically, this next-generation framework will incorporate enhanced cryptographic protocols and adaptive resource management to ensure robust security and sustainability amidst escalating network complexity [13].

5. Conclusion

This article takes V2X communication technology as the foundational enabler for safe, efficient, and reliable autonomous driving, systematically analyzing its role as the critical infrastructure and core enabling technology for advancing intelligent and large-scale deployment of autonomous driving systems. The research delves into the nuanced analysis of communication demands, unpacking the real-time, high-reliability requirements such as sub-millisecond latency and robust connectivity in dynamic traffic environments. It also explores key technological challenges—including signal propagation delay, multi-source heterogeneous network synchronization, and environmental interference—by discussing adaptive modulation schemes and cross-layer optimization strategies. Furthermore, the study investigates the coordinated optimization of communication, perception, and decision-making processes, exploring a collaborative framework where V2X integrates with sensor technologies like LiDAR and camera systems to enhance multi-vehicle coordination accuracy. Looking ahead, the research highlights that V2X will become increasingly pivotal with the advancement of 6G, enabling ultra-wideband terabit-per-second data rates, global seamless coverage, and energy-efficient 3D networking to drive the transportation sector toward fully autonomous, smart, and sustainable mobility ecosystems.

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