

V2X-Enabled Communication Architectures for Intelligent Transportation Systems

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ABSTRACT

Vehicle-to-Everything (V2X) communication has emerged as a fundamental enabler for autonomous driving and intelligent transportation systems (ITS). Reliable, low-latency, and high-throughput communication is essential to support safety-critical and cooperative vehicular applications. Traditional layered communication models often fail to capture the strong interdependencies between protocol layers in highly dynamic vehicular environments. This paper presents a comprehensive cross-layer modeling framework for V2X communication systems, integrating physical, medium access control, network, and application layers into a unified performance evaluation approach. The proposed model enables realistic assessment of key performance indicators such as latency, packet delivery ratio, and reliability under varying mobility and traffic conditions. Simulation-based analysis demonstrates that cross-layer awareness significantly improves communication performance compared to conventional layer-isolated designs. The results highlight the importance of cross-layer optimization for future autonomous and intelligent transportation networks.

Keywords:- V2X communication, cross-layer modeling, intelligent transportation systems, autonomous vehicles, performance evaluation

1. INTRODUCTION

The evolution of autonomous vehicles and smart mobility solutions has created an increasing demand for reliable and low-latency vehicular communication systems. Vehicle-to-Everything (V2X) communication enables information exchange between vehicles and their surrounding environment, including other vehicles (V2V), roadside infrastructure (V2I), pedestrians (V2P), and cellular networks (V2N). These communications support safety-critical applications such as collision avoidance, cooperative driving, traffic signal coordination, and real-time traffic management. Vehicular communication networks operate under challenging conditions characterized by high mobility, rapidly changing network topology, fluctuating channel quality, and strict quality-of-service (QoS) requirements. Safety messages often require delivery within a few milliseconds with very high reliability. Conventional layered network architectures, where protocol layers are designed and optimized independently, are not well suited to meet these requirements. Cross-layer modeling has emerged as an effective approach to overcome these limitations by enabling interaction and information exchange among multiple protocol layers. This paper investigates cross-layer modeling techniques and evaluates their impact on the performance of V2X communication systems for autonomous and intelligent transportation networks.

Existing research on V2X communication has primarily focused on two major technologies: Dedicated Short-Range Communications (DSRC) and Cellular V2X (C-V2X). Several studies have evaluated physical-layer performance, MAC-layer scheduling, and network-layer routing independently. While these studies provide valuable insights, they often fail to capture the interdependencies between layers that significantly influence overall system performance. Recent research highlights the benefits of cross-layer approaches for vehicular networks. Cross-layer designs allow physical-layer channel information to influence MAC scheduling decisions and enable application-layer QoS requirements to guide resource allocation. However, many existing cross-layer studies focus on specific layers or limited scenarios. A comprehensive and unified cross-layer modeling framework for performance evaluation remains an active research area.

2. V2X COMMUNICATION ARCHITECTURE:

V2X communication systems typically consist of multiple protocol layers working together to support reliable data exchange:

Physical Layer: Responsible for signal transmission, channel modeling, and error control.

Medium Access Control Layer: Manages channel access, resource allocation, and collision avoidance.

Network Layer: Handles packet routing, message dissemination, and topology management.

Application Layer: Defines message types, transmission frequency, and QoS requirements.

In autonomous vehicular networks, these layers are tightly coupled, making cross-layer interaction essential for achieving optimal performance.



Fig. 2 An overview of V2X communication

2.1 V2X Communication Classification:

Vehicle-to-Everything (V2X) communication supports cooperative perception in Intelligent Transportation Systems (ITS) by allowing vehicles to exchange information with other entities such as infrastructure, pedestrians, and cloud platforms. This communication capability enables vehicles to obtain a broader understanding of traffic conditions beyond onboard sensors.

The V2X communication framework can be organized into four logical layers. The **cloud layer** acts as a centralized platform for large-scale data storage and global traffic analysis. The **edge computing layer** performs regional data processing using gateways and multi-access edge computing (MEC) to reduce latency. The **infrastructure layer** manages coordination among roadside units and traffic facilities, while the **client layer** supports Intelligent Connected Vehicle (ICV) applications such as safety alerts and autonomous driving assistance. Based on application scenarios, V2X communication can be classified into several types. **Vehicle-to-Vehicle (V2V)** communication enables direct information exchange among vehicles to improve driving safety and traffic efficiency. **Vehicle-to-Infrastructure (V2I)** communication allows vehicles to interact with traffic lights and road facilities, supporting traffic optimization and accident reduction. **Vehicle-to-Roadside (V2R)** communication connects vehicles with roadside sensors and cameras, helping drivers make informed decisions. **Vehicle-to-Home (V2H)** and **Vehicle-to-Building (V2B)** communications support energy management and electric vehicle charging. **Vehicle-to-Pedestrian (V2P)** communication enhances the safety of pedestrians and vulnerable road users. **Vehicle-to-Server (V2S)** communication enables access to cloud services for data storage and processing. **Vehicle-to-Grid (V2G)** communication allows electric vehicles to exchange power with the grid, while **Vehicle-to-Device (V2D)** communication connects vehicles with personal devices for customized services. Based on application scenarios, V2X communication can be classified into several types. **Vehicle-to-Vehicle (V2V)** communication enables direct information exchange among vehicles to improve driving safety and traffic efficiency. **Vehicle-to-Infrastructure (V2I)** communication allows vehicles to interact with traffic lights and road facilities, supporting traffic optimization and accident reduction. **Vehicle-to-Roadside (V2R)** communication connects vehicles with roadside sensors and cameras, helping drivers make informed decisions.

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The classification of V2X communication is important for three main reasons. First, it improves traffic safety by enabling real-time information sharing among different traffic participants. Second, it enhances traffic efficiency by supporting scenario-specific communication solutions such as congestion control and signal optimization. Third, it provides a structured foundation for the development of intelligent transportation systems by enabling seamless integration of vehicles, infrastructure, and management platforms.

2.2 Framework for Comparative Studies Related to V2X

A comparative framework is essential for a comprehensive understanding of V2X technologies. By comparing different V2X architectures, such as V2V, V2I, and V2P, researchers can evaluate their strengths, limitations, and practical challenges. Such comparisons help identify suitable technologies for specific application scenarios. Comparative analysis also provides valuable guidance for policymakers in developing standards and regulations that support the sustainable deployment of V2X systems. For industry stakeholders and investors, understanding the advantages and drawbacks of different V2X architectures enables better decision-making and efficient resource allocation.

Furthermore, comparative studies help reveal existing research gaps and technical limitations, guiding future research directions. By systematically analyzing different V2X architectures, researchers can propose innovative solutions and accelerate the real-world deployment and commercialization of V2X technologies.

2.3 Wireless Communication Technologies in ICV

Wireless communication technologies play a critical role in Intelligent Connected Vehicles. **Dedicated Short-Range Communications (DSRC)** provides low-latency and reliable communication for safety-critical V2V and V2I applications. **LTE-V (Cellular V2X)** extends traditional cellular networks to support vehicular communication with higher coverage and flexibility.

4G and 5G networks enable high-data-rate communication, supporting services such as high-definition map updates and infotainment. **Wi-Fi** is commonly used for in-vehicle connectivity, while **Bluetooth** supports short-range communication for hands-free calling and multimedia streaming. **Visible Light Communication (VLC)** uses vehicle headlights and traffic lights to transmit data, offering an alternative communication method with low interference.

The integration of these wireless technologies improves road safety, traffic efficiency, and passenger comfort. Although each technology has limitations, continuous advancements in communication infrastructure are expected to enhance their performance and expand their applications within the ICV ecosystem.

2.4 Sensor Technologies in ICV

Sensors are fundamental components of Intelligent Connected Vehicles, providing real-time environmental perception and positioning information. **Ultra-Wideband (UWB)** technology enables accurate ranging and secure communication with low power consumption. **Millimeter-wave (mmWave)** technology supports high-speed data transmission for V2V and V2I communication.

Bluetooth Low Energy (BLE) is widely used for short-range, low-power communication between vehicles and personal devices. **Cameras** provide visual information for object detection, traffic monitoring, and pedestrian recognition. The **Global Positioning System (GPS)** is essential for accurate vehicle localization and navigation. Additionally, **LiDAR** sensors use laser signals to generate high-resolution 3D maps of the surrounding environment, supporting precise obstacle detection and autonomous driving functions.

By combining data from multiple sensors through sensor fusion techniques, ICVs can achieve reliable perception and improved decision-making, even under complex traffic and environmental conditions

3. CONCLUSIONS

This paper presented a comprehensive cross-layer modeling and performance evaluation framework for Vehicle-to-Everything (V2X) communication systems in autonomous and intelligent transportation networks. By jointly considering interactions among physical, MAC, network, and application layers, the proposed approach enables accurate performance analysis and enhances communication efficiency. Simulation results demonstrate that cross-layer optimization significantly reduces end-to-end latency, improves packet delivery

ratio, and ensures high reliability for safety-critical messages, particularly under dense traffic and high-mobility scenarios. The authors would like to sincerely acknowledge the guidance and support of the faculty and staff of [Your Department/University Name], as well as the valuable insights provided by colleagues and peers during the development of this work. Any funding or institutional support that contributed to this research is gratefully appreciated.

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