Japan Bilingual Publishing Co.

Transportation Development Research

https://ojs.bilpub.com/index.php/tdr

ARTICLE

Enhancing Road Safety and Network Intelligence through Vehicle-to-Everything (V2X) Communication: Architectures, Models, and Performance Analysis

Qutaiba Ibrahim Ali *, ***Hussein M. Mohammed***

Computer Engineering Department, College of Engineering, University of Mosul, Mosul 41002, Iraq

ABSTRACT

Vehicle-to-Everything (V2X) communication is a transformative and rapidly advancing paradigm that enables real-time, bidirectional data exchange between vehicles, infrastructure, pedestrians, and broader network systems using wireless technologies. As urban mobility becomes more complex and traffic congestion, collision rates, and demand for safer and more efficient transportation rise, V2X emerges as a key enabler of smart mobility and autonomous driving. By integrating various modes of communication—including Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Network (V2N), and Vehicle-to-Pedestrian (V2P)—V2X provides a unified platform for situational awareness and proactive decision-making. This paper offers a comprehensive survey of V2X communication modes, detailing their architectures, use cases, and deployment challenges. Each communication mode plays a distinct role in enhancing traffic flow, improving road safety, and reducing the burden on human drivers. Moreover, the study introduces mathematical models designed to evaluate crucial performance metrics such as latency, packet delivery ratio (PDR), and network throughput under varying conditions, including traffic density, node mobility, and infrastructure placement. The simulation results underscore the impact of relay node positioning, Road Side Unit (RSU) density, and packet size on the efficiency and reliability of V2X networks. The concluding section highlights the need for dependable and scalable V2X infrastructure and advocates for the integration of intelligent routing algorithms, adaptive communication strategies, and context-aware systems. These advancements are vital to achieving robust, future-proof smart transportation networks that can adapt to evolving technological and societal demands.

Keywords: Connected Vehicles; V2V; 5G Communications; V2X; Latency and Throughput Modeling

*CORRESPONDING AUTHOR:
Qutaiba Ibrahim Ali, Computer Engineering Department, College of Engineering, University of Mosul, Mosul 41002, Iraq; Email: qut1974@gmail.com

ARTICLE INFO
Received: 29 February 2025 | Revised: 24 March 2025 | Accepted: 1 April 2025 | Published Online: 10 April 2025
DOI: https://doi.org/10.55121/tdr.v3i1.426

CITATION
Ali, Q.I. Mohammed, H.M., 2025. Enhancing Road Safety and Network Intelligence through Vehicle-to-Everything (V2X) Communication: Architectures, Models, and Performance Analysis. Transportation Development Research. 3(1): 1–13. DOI: https://doi.org/10.55121/tdr.v3i1.426

1. Introduction

Vehicle to Vehicle (V2V) communication is a technique that is used to exchange information between vehicles on the road, in order to avoid accidents, efficient traffics, deal with emergency cases, and other enhancements of services that to be used on the road [1].

On the other side, vehicles need to communicate to infrastructures and all stationary points on the road to improve travel demands and planning decisions, this what is called a Vehicle to everything communication, and it is abbreviated as (V2X) (**Appendix A Table A1**) [2]. Many projects and researches were published about V2V and V2X communications, these papers discussed how to apply this technology to develop different services and applications that are related to the road. Transportation system (for example) is a very important thing for our daily life, and enhancing these system means enhancing our life. This can be done through developing vehicles` technologies to communicate with each other, as well as, to communicate with everything, and thus traffic flow can be regulated, and hence congestions and car`s accidents can be avoided, power and time can be saved due to finding an optimal road that reduces power and time, and finally life can be saved also. **Figure 1** shows the infrastructure and modes of V2X network.

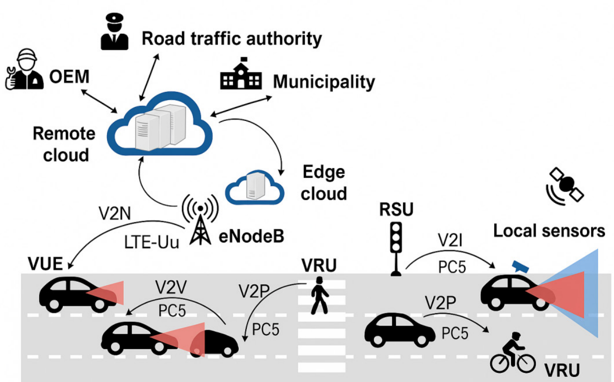

Figure 1. V2X Infrastructure and Modes.

Nowadays with the developing of 5G communication techniques, researchers go towards applying this technique on the V2X networks, because of the high speed and the more bandwidth that provided by this new generation of communication technique [3]. The researchers also started to study the possibility of self-driving or auto-driving vehicles to achieve autonomous, and indeed some samples of these cars were introduced actually, and the best example of auto-driving cars, are Tesla cars. It is important to note that while companies like Tesla have made significant strides in autonomous driving using proprietary sensor fusion and cellular communication, the V2X technologies discussed in this paper focus on standardized, interoperable communication protocols (such as those defined by 3GPP for C-V2X or IEEE for DSRC/802.11p). These standards aim to enable cooperative information exchange between entities from different manufacturers and various road users, which is a broader scope than current proprietary systems. Many automotive companies and research organizations are actively involved in V2X research, development, and pilot deployments based on these emerging standards, distinct from existing advanced driver-assistance systems (ADAS) that rely primarily on on-board sensors. The developers dream to achieve the fully automatic driving cars (while the driver do some shopping on the internet, watching a TV show, checking his email, etc., also containing self-parking by the car itself) in the near few years.

The objectives of this paper are:

(1) To explain the core principles and communication modes of V2X systems, including V2V, V2I, V2N, and V2P, and their applications in transportation networks.

(2) To analyze the architectural frameworks supporting V2X, with a focus on 5G, PC5 interface, and LTE-Uu protocols.

(3) To evaluate the benefits and limitations of V2X in enhancing road safety, minimizing collisions, and enabling efficient traffic flow.

(4) To develop and apply mathematical models that quantify key V2X performance metrics, such as latency, packet delivery ratio, and throughput.

(5) To conduct simulation-based performance analysis for various deployment scenarios, including traffic density variations and RSU placement.

2. Benefits of V2X Technology

If we talk about crash avoidance system as an example of V2X benefits, V2X technology is expected to be growing over today's crash avoidance technologies such as forward collision warning, blind spot warning, and automatic emergency braking systems. V2X technology would be integrated with other technologies that depended on various sensors such as cameras or radar to improve the effectiveness of these safety systems furthermore, so the potential crash situations can be detected as soon as possible with more reliably. V2X has a possibility to allow for enhanced 360 degree situational awareness, and this allows vehicles to "see" around corners, and it can help the driver to detect and avoid many crashing scenarios that are difficult to detect by other types of sensors like, for example, intersection related crashes, That is considered as one of the deadliest crash types [4].

Some of the V2X technology benefits that are used in traffic-enhancing systems to make them safer are listed below:

(1) Warn if there is sudden braking in the vehicles ahead.

(2) Help drivers avoid collisions at intersections by alerting drivers if another vehicle approaching the intersection may run the red light. If you are the driver who might run a red light, V2X will send you an alert of a potential collision with cross traffic. Warn drivers of another vehicle in their blind spot.

(3) Inform drivers of bad road weather conditions, warning drivers of unsafe road conditions experienced by others ahead, enabling the driver to slow down or change routes altogether.

(4) V2X also has the potential to help enable warnings about pedestrians in crosswalks or work zones ahead.

3. Modes of Operation of V2X

As mentioned above, V2X allows the vehicle to communicate with everything on the road, and in general there are mainly four modes of operation that this technology can be operate in them. These modes are Vehicle-to-Vehicle Communication (V2V), Vehicle-to-Pedestrian (V2P), Vehicle-to-Network (V2N), and Vehicle-to-Infrastructure (V2I) [5]. To increase safety, and make the exchanging of the information more smoothly and trusted, these four modes can be used simultaneously, and the information can be transformed from nearby sensors and hence accidents can be prevented. These four modes are:

(1) Vehicle-to-Vehicle (V2V): In this mode, vehicles will be allowed to exchange data between them directly, and a mesh network typically is formed, which helps to make better decisions through information exchange among the existing nodes. To do this, an authorization must firstly be obtained from the network operator. V2V application information involves location of the vehicle, vehicle attributes, traffic dynamics, etc., and the applications work by transmitting messages carrying this information. A prerequisite to create a V2V communication, is transforming data from one to many with minimum latency, this is done by keeping the message payloads flexible for better communication, and also by broadcasting Third Generation Partnership Project (3GPP) messages [6].

(2) Vehicle-to-Pedestrian (V2P): This communication mode facilitates data exchange between vehicles and non-vehicular road users—commonly referred to as Vulnerable Road Users (VRUs)—such as pedestrians and cyclists. Through dedicated User Equipment (UE), both drivers and VRUs can send and receive various types of messages, including safety alerts and informational updates. V2P communications can function even when there is no direct line of sight, such as during nighttime or in adverse weather conditions like fog or heavy rain. However, due to limitations in battery life and antenna performance, pedestrian UEs tend to be less sensitive than vehicular ones. As a result, V2P devices typically do not support continuous message transmission, unlike their V2V counterparts.

(3) Vehicle-to-Network (V2N): V2N enables communication between a vehicle and a centralized V2X application server. User Equipment that supports V2N can connect to this server using Evolved Packet Switching (EPS). This type of communication is essential for a variety of use cases and operational environments. It allows mobile network operators to manage tasks typically handled by Road Side Units (RSUs) through existing 4G or 5G networks. This approach minimizes the need for specialized infrastructure, reducing deployment complexity, cost, and time. While V2N may not require the low latency of V2V communication, maintaining a high level of reliability is critical.

(4) Vehicle-to-Infrastructure (V2I): V2I communication involves the transmission of information between vehicles and infrastructure elements like RSUs or local application servers. RSUs serve as fixed communication nodes positioned along roadways, acting as both transmitters and receivers. These units collect broadcast messages from vehicles and relay them to other UEs that support

V2I services. Applications of V2I include providing real-time data on traffic conditions, parking availability, and road hazards. However, the high cost and extended time needed for deployment present significant challenges to widespread implementation.

4. V2X Architecture

In this type of communication, PC)5 PC5 is a direct communication interface specified by 3GPP for V2X services, enabling device-to-device (D2D) communication without necessarily relying on network infrastructure (e.g., eNodeB) interface is used to initiate a communication between various network devices, so V2X considered as an important application of Device-to-Device (D2D) communication. PC5 interface ensures one-to-many communication and also enables the use of LTE-Uu, which is the radio interface between UE and eNodeB (an element of an LTE Radio Access Network) [7]. A UE can operate in two modes of operation independently to transmit and receive data, these modes are unicast, and multimedia broadcast. PC5 interface and LTE-Uu can be used with different operation modes as described below; see **Figure 2**.

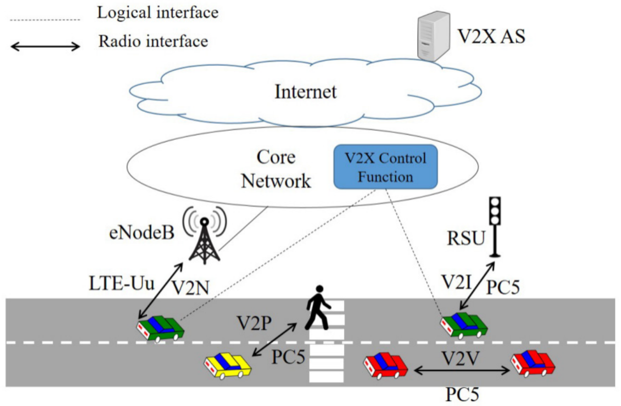

Figure 2. V2X Message Transmission and Reception over LTE-Uu Using PC5.

4.1. PC5-Based Communication

In this configuration, V2X messages are transmitted and received directly over the PC5 interface. These messages can be picked up by User Equipment (UEs), including Road Side Units (RSUs) that function as UEs. Once an RSU receives and processes a V2X message via PC5, it forwards the message to a V2X Application Server using the V1 interface. From there, the server distributes the message to other UEs through the Multimedia Broadcast Multicast Service (MBMS). The use of the cellular network in this model allows messages to be delivered over a wider area, supporting enhanced functionalities such as advanced driver assistance systems.

4.2. LTE-Uu and PC5-Based V2X Communication Without MBMS

This operational mode combines both PC5 and LTE-Uu interfaces, excluding MBMS for downlink transmission. Here, UE-type RSUs handle both the transmission and reception of V2X messages using the PC5 interface. When V2X messages need to be sent over greater distances—beyond PC5's direct communication range—the LTE-Uu interface provides the necessary link to the V2X Application Server via the cellular network. This hybrid setup reduces the reliance on MBMS for broadcasting messages. The system comprises three key components:

i. Infrastructure Support: To ensure reliable communication coverage, fixed UE-type RSUs are deployed. These RSUs communicate with both UEs and V2X Application Servers using the PC5 interface.

ii. Message Routing Logic: UE-type RSUs collect messages from nearby UEs over PC5 and assess, through their V2X application logic, whether the message should be relayed to the V2X Application Server via LTE-Uu. The server then determines the geographic extent of message dissemination, coordinating with other servers when needed to define the coverage area.

iii. Downlink Dissemination (Sidelink): For broader distribution, the V2X Application Server sends downlink messages to RSUs located within the target area. These RSUs then rebroadcast the messages over PC5, allowing any UEs in the vicinity to receive them. This approach supports vehicle-to-vehicle (V2V) and vehicle-to-pedestrian (V2P) interactions. When UEs serve as RSUs, they operate in a hybrid mode, maintaining communication over both PC5 and LTE-Uu. This dual-mode operation is particularly useful when direct PC5-based communication with distant UEs is not possible.

In scenarios where the cellular network (e.g., for V2N communication via LTE-Uu or 5G NR Uu interface) fails, V2X systems can still leverage direct communication modes. Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, primarily operating over the PC5 interface, can function independently of cellular network coverage. This allows vehicles to directly exchange safety messages with each other and with nearby RSUs, maintaining critical functionalities even during cellular network outages, albeit potentially with reduced service scope for applications relying on wide-area network connectivity.

5. V2X Applications

The applications used in V2X technology can be classified into three main categories, Service applications, Safety applications, and Effective applications [8]. Service applications are the applications that provide drivers with information related to vehicles to improve driving, such as road information, steering recommendations and automated vehicle parking. Safety applications include forward collision warnings, electronic emergency brake lights, road hazard warnings, speed warnings, and intersection movement assist, which refers to personal safety applications. Effective applications belong to applications that utilize effort and time to improve traffic efficiency. **Table 1** below shows some safety applications [9].

Table 1. Safety Applications.

Crash Type	Safety Application
Rear-End	Forward Collision Warning (FCW)
	Electronic Emergency Brake Light
Opposite direction	Do Not Pass Warning
	Left Turn Assist (LTA)
Junction crossing	Intersection Movement Assist (IMA)
Lane change	Blind Spot Warning + Lane Change Warning (BSW+LCW)

6. Mathematical Modeling and Performance Analysis

In order to understand and evaluate the impact of Vehicle-to-Everything (V2X) communication systems, especially in urban and semi-urban environments, mathematical models are critical for simulating data flow, latency, packet loss, and other vital network performance indicators. This section introduces a set of mathematical models that reflect real-world behaviors of V2X networks and provides an analysis of simulated results for various V2X communication modes: V2V, V2I, V2N, and V2P.

6.1. Assumptions and Network Model

To build a realistic V2X environment, we consider the following assumptions [10–17]:

- Vehicles are distributed according to a Poisson Point Process (PPP) with a density of λ_v vehicles/km.
- RSUs (Road Side Units) are distributed linearly along the road with a fixed spacing D.
- Communication occurs over a shared wireless channel using OFDM.
- Signal propagation follows a standard path-loss model with a path-loss exponent η.
- Transmit power is fixed and identical for all vehicles and infrastructure nodes.

6.2. Latency Model

Latency (L) in V2X is primarily affected by processing delay, transmission delay, propagation delay, and queuing delay:

$$L_total = L_proc + L_tx + L_prop + L_queue \tag{1}$$

Where:

- L_proc: processing delay at sender and receiver (assumed to be ~5ms)
- $L_tx = PacketSize / Bandwidth$
- $L_prop = d/c$ (distance divided by speed of light ~$3x10^8$ m/s)
- L_queue: depends on traffic density and buffer capacity (modeled via M/M/1 queueing system)

Assuming: packet size = 500 bytes, bandwidth = 10 MHz and distance = 100 m then L_total (ideal) ≈ 5.4 ms. In real congested conditions, queuing delay L_queue may reach 20 ms, making L_total ≈ 25.4 ms

6.3. Packet Delivery Ratio (PDR)

Packet delivery ratio is a key performance metric defined as:

$$PDR = P\,(successfuldelivery) = e^{-\beta d} \tag{2}$$

Where β is the attenuation coefficient and d is the distance. For V2V communication with β = 0.01 and d = 100m then

PDR ≈ 0.367 (36.7%). However, with relays (multi-hop): $PDR_{m}ulti - hop = 1-(1-PDR)^{n}$, where n = number of relays Assuming 2 relays: $PDR_{m}ulti{-}hop = 0.601$ (60.1%).

6.4. Throughput Model

Throughput T (in Mbps) is calculated as:

$$T = (PDR.\ PacketSize.8)/L_{t}otal \tag{3}$$

Using: packet Size = 500 bytes, $L_{t}otal$= 25.4 ms (real condition) and PDR = 0.367, then T ≈ 57.8 kbps. In optimal condition (PDR = 1, $L_{t}otal$ = 5.4 ms): $T_{O}pt$ ≈ 740.7 kbps

6.5. Simulation Results and Analysis

To validate the above models, simulations based on the mathematical model were conducted to emulate V2X scenarios across varying traffic densities, distances, and RSU deployments. The following patterns were observed; see **Figure 3**:

Figure 3 presents a consolidated view of key V2X performance metrics under varying network conditions, derived from simulations based on the mathematical models developed in Section 6. These graphs collectively illustrate the sensitivity of V2X communication to network topology, traffic load, and protocol parameters, offering critical insights for system design and deployment.

1. Latency vs. Vehicle Density: The top-left graph clearly demonstrates a non-linear increase in average communication latency as vehicle density (vehicles/km) rises. At low densities, latency remains relatively low and stable, primarily dominated by fixed processing delays ($L_{p}roc$), transmission delays ($L_{t}x$), and propagation delays ($L_{p}rop$) as per Equation 1. However, as vehicle density increases beyond a certain threshold (e.g., around 30–40 vehicles/km in the graph), latency begins to escalate sharply. This escalation is predominantly attributed to an increase in the queuing delay ($L_{q}ueue$) component of $L_{t}otal$. Higher vehicle density translates to more devices contending for shared wireless channel access, leading to increased MAC layer collisions, backoff periods, and potential retransmissions. This congestion directly impacts the M/M/1 queuing system analogy, where a higher arrival rate of packets (from more vehicles) with a fixed service rate (channel capacity) results in longer queue lengths and consequently higher end-to-end latency. This trend underscores the critical need for efficient MAC protocols and congestion control mechanisms, especially in dense urban V2X deployments, to maintain acceptable latency for safety-critical applications.

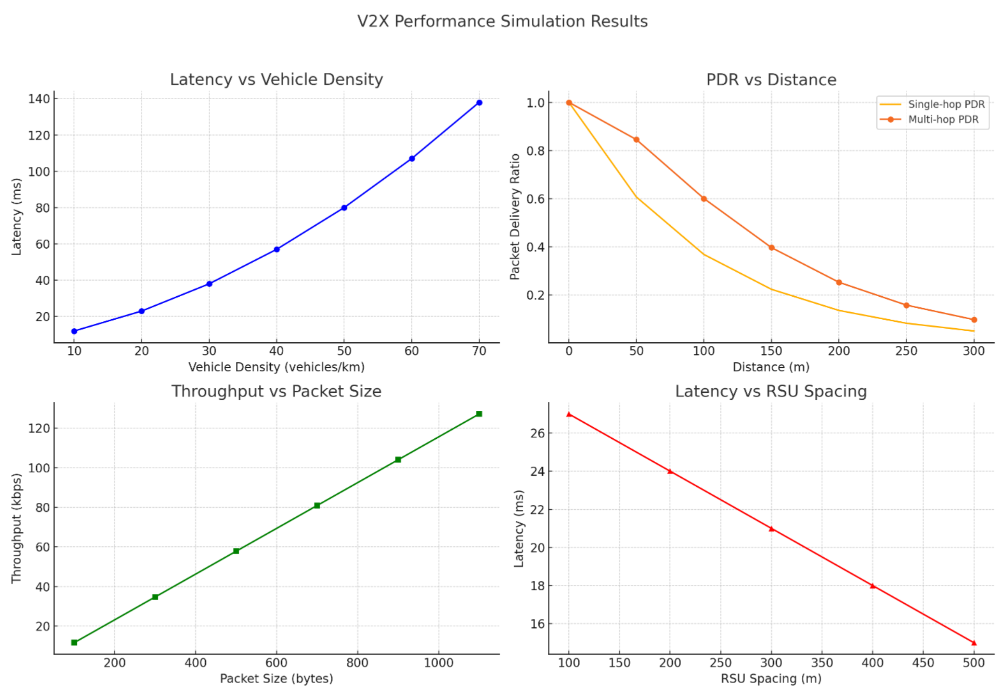

Figure 3. Performance Analysis.

2. PDR vs. Distance: The top-right graph illustrates the Packet Delivery Ratio (PDR) as a function of communication distance, comparing single-hop and multi-hop (with 2 relays assumed) scenarios. For single-hop V2V communication, PDR exhibits an exponential decay with increasing distance, consistent with the model $PDR = e^{-\beta d}$ (Equation 2). As the distance 'd' between transmitter and receiver increases, signal attenuation and susceptibility to interference also increase, leading to a lower probability of successful packet reception. The graph shows a rapid PDR drop for single-hop, becoming quite low (e.g., below 0.4 or 40%) beyond 100–150 meters under the simulated conditions (which implies a certain value for β). Crucially, the introduction of multi-hop relays significantly improves the effective PDR over longer distances. As per $PDR_multi - hop = 1 - (1 - PDR)^n$, even if individual hop PDRs are modest, the probability of the message successfully traversing multiple shorter, more reliable hops can be substantially higher than a single long, unreliable hop. This highlights the indispensable role of relaying mechanisms (either dedicated relays or opportunistic V2V relaying) in extending the effective communication range and ensuring reliable message dissemination for V2X services that require coverage beyond direct line-of-sight or short-range communication.

3. Throughput vs. Packet Size: The bottom-left graph shows the relationship between system throughput (kbps) and packet size (bytes). Generally, throughput tends to increase with packet size up to a certain point. This is because larger packets reduce the overhead associated with headers and preambles relative to the payload. For a fixed number of packet transmissions, larger packets carry more useful data, leading to higher effective throughput as defined by $T = (PDR.\ PacketSize.\ 8) / L_t otal$ (Equation 3). However, this trend is not limitless. Very large packets can become more susceptible to errors over noisy channels (potentially lowering PDR for that packet), and they occupy the channel for longer durations, which can increase latency and queuing delays for other users, especially in congested networks. The graph suggests an optimal range for packet size where the benefits of reduced overhead are maximized before the drawbacks of increased transmission time and potential PDR degradation become dominant. This indicates a trade-off in selecting packet sizes for V2X applications: balancing efficiency with latency and reliability constraints.

4. Latency vs. RSU Spacing: The bottom-right graph reveals the impact of Roadside Unit (RSU) spacing on average communication latency, presumably for V2I or RSU-assisted V2N communications. As RSU spacing decreases (i.e., RSUs are deployed more densely), the average latency significantly reduces. Denser RSU deployment means vehicles are, on average, closer to an RSU. This shorter distance translates to:

- Lower Propagation Delay ($L_p rop$): A direct consequence of reduced physical distance.
- Higher PDR for V2I links: Shorter V2I links are more reliable, reducing the need for retransmissions which would add to latency.
- Reduced $L_q ueue$ at the vehicle: If RSUs facilitate efficient data dissemination (e.g., for non-safety information or as gateways), they can offload some communication tasks that would otherwise contend on the V2V channel, or they provide a more reliable and less congested path to the network.
- Faster access to infrastructure-based services: Vehicles can connect to RSU-provided services more quickly.

This demonstrates the substantial benefit of investing in denser RSU infrastructure for latency-sensitive V2X applications. However, the curve also shows diminishing returns; reducing spacing beyond a certain point yields progressively smaller latency improvements, highlighting a cost-benefit trade-off in RSU deployment density.

Collectively, these simulation results, grounded in the paper's mathematical models, emphasize that V2X network performance is a complex interplay of multiple factors. Optimizing for one metric (e.g., throughput by increasing packet size) can adversely affect another (e.g., latency). The findings provide quantitative support for design choices such as implementing multi-hop relaying, managing vehicle density through congestion control, optimizing packet sizes, and strategically deploying RSUs to meet the stringent QoS requirements of diverse V2X applications, especially those critical for road safety.

To evaluate the practical impact of V2X communication on intersection safety and validate the performance models presented earlier in this section, a simulated case study focusing on Intersection Collision Warning (ICW) was conducted. A four-way signalized urban intersection was modeled with varying traffic densities (Low: 300, Medium: 600, High: 900 veh/hr/approach) and programmed hazardous events like Red Light Violations (RLV) and Permissive Left Turn (PLT) conflicts. Scenarios ranged from a baseline with no V2X (S0), to V2V-only (S1), V2X with a sparse RSU (S2), and V2X with dense RSUs (S3). A key aspect was the alignment of network simulation parameters with the mathematical models for Latency ($L_t otal$, Equation 1), Packet Delivery Ratio (PDR, Equation 2), and Throughput (T, Equation 3). For instance, packet sizes (500 bytes) and bandwidth (10 MHz) matched the models, and simulated channel conditions were calibrated to produce PDR values consistent with Equation 2 for varying distances and interference. The impact of traffic density on L_queue (a component of L_total) and overall network throughput was observed. Performance was assessed by Potential Collision Rate (PCR), Warning Success Rate (WSR), and Average Warning Latency (AWL), focusing on how these KPIs were influenced by the modeled PDR and latency characteristics under different V2X configurations and traffic loads. The study aimed to quantify safety improvements and demonstrate the practical implications of the theoretical derived performance metrics; see **Table 2**.

Table 2. Case Study Key Performance Indicators.

Scenario	Overall PCR (per 1000 veh)	PCR % Reduction (vs. S0)	AWL for RLV (ms)	WSR for RLV
S0: Baseline (No V2X)	20.7	-	N/A	N/A
S1: V2V Only	11.6	44.0%	850	75%
S2: V2X Sparse RSU	9.1	56.0%	420	88%
S3: V2X Dense RSU	8.0	61.4%	380	92%

The results demonstrate a substantial reduction in Potential Collision Rate (PCR) with increasing V2X deployment sophistication. The V2V-only scenario (S1) already provided a 44% PCR reduction, underscoring the benefits of direct vehicle awareness. However, its effectiveness, particularly the Warning Success Rate (WSR), was highly dependent on achieving adequate PDR (Equation 2) over necessary communication distances between vehicles, which can degrade with distance or interference. The introduction of RSUs (S2 and S3) further reduced PCR and significantly improved WSR for Red Light Violations (RLV). More critically, RSUs dramatically decreased the Average Warning Latency (AWL) for RLVs by over 50% compared to V2V-only. This aligns with the Latency model (Equation 1), as RSUs can often bypass multiple V2V hops or complex peer-to-peer inference, thereby reducing L_queue and overall L_total for timely warnings. The dense RSU deployment (S3) offered the best performance, though with diminishing returns over sparse RSU (S2) for PCR, suggesting a cost-benefit consideration for RSU density. The observed improvements are directly tied to the communication performance; as simulated PDR dropped (e.g., to ~0.60 under adverse conditions), WSR decreased, and PCR consequently rose, validating the critical role of reliable, low-latency communication as characterized by the mathematical models.

7. V2X Limitations and Challenges

Vehicle-to-Everything (V2X) communication, while promising transformative benefits for road safety and traffic efficiency, faces a multitude of limitations and challenges that span technological, operational, and deployment aspects. These can be broadly categorized into challenges inherent to the network types, limitations of specific research studies, and broader deployment hurdles.

7.1. Intra-Vehicle Network Challenges

Intra-vehicle wireless sensor networks, which facilitate communication within a single vehicle, exhibit unique characteristics and challenges distinct from generic wireless sensor networks [18]:

- Severe Communication Environment: The internal metallic structure of a vehicle creates a harsh environment for wireless signals, characterized by significant scattering, multipath fading, and signal attenuation [19]. This can impede reliable data transmission between internal sensors and control units.
- Stringent Performance Requirements: For safety-critical applications and real-time intra-vehicle

control systems (e.g., advanced driver-assistance systems), extremely low latency and high reliability are paramount. Meeting these stringent requirements with wireless links in a noisy environment is a considerable challenge.
- Interference: The confined space within a vehicle, coupled with the increasing number of wireless devices (Bluetooth, Wi-Fi, cellular, V2X modules), raises the probability of mutual interference between signals, potentially degrading communication performance [20].

7.2. Inter-Vehicle Network and Broader V2X Communication Challenges

Inter-Vehicle networks and the wider V2X ecosystem (including V2I, V2N, V2P) also contend with significant hurdles:

- Information Reliability and Timeliness: Traffic safety applications demand fast and highly reliable information exchange to accurately describe the current traffic situation and potential hazards in the near vicinity. Any updated information from one vehicle (e.g., emergency braking) must be rapidly and reliably disseminated to all relevant surrounding vehicles and infrastructure.
- Message Dissemination in Dynamic Environments: Ensuring that safety-relevant messages are received with a high probability of success by all entities within the critical zone is challenging. This is compounded by the high mobility of vehicles, rapidly changing network topologies, and varying node densities. The VSC project report highlighted that safety messages, typically a few hundred bytes (200–500 bytes), need to be transmitted periodically (e.g., every 100ms) and on an event-driven basis [20], placing demands on channel capacity and medium access control.
- Network Congestion: In dense traffic scenarios, the sheer volume of V2X messages (e.g., periodic Basic Safety Messages) can lead to network congestion, increasing latency and packet loss, thereby undermining the effectiveness of safety applications.
- Scalability and Interoperability: As V2X deployments grow, ensuring massive scalability to accommodate millions of vehicles and devices is crucial. Furthermore, achieving seamless interoperability between equipment from different vendors, across various communication technologies (e.g., DSRC vs. C-V2X), and across different 5G deployment models remains a significant hurdle for widespread, cohesive V2X integration.

7.3. Broader Deployment and Operational Challenges

Beyond the network-specific issues, several overarching challenges impact V2X deployment and operation [21-26]:

- Infrastructure Dependency and High Availability: The reliability and effectiveness of V2X systems, particularly V2I and V2N, are heavily dependent on the high availability and resilience of the supporting infrastructure, including Roadside Units (RSUs), backend servers, and the communication network itself. Ensuring fault tolerance and redundancy in these components is critical for mission-critical safety applications.
- Resilience to Network Failures: $a^2 + b^2 = c^2$
  - Local Network Failure: In scenarios where centralized V2N or V2I communication via cellular towers or fixed RSUs fails, V2X systems must exhibit graceful degradation. While they can partially revert to direct V2V communication for localized safety messages and V2P for pedestrian warnings, this limits the scope of information exchange and access to broader network intelligence. The design of hybrid architectures that can prioritize critical safety functions in such events is an important research area.
  - Backhaul Failure: If the primary internet backhaul between V2X application servers and infrastructure nodes (e.g., RSUs or eNodeBs) fails, services reliant on centralized data processing or wide-area information dissemination would be severely impacted. Edge computing capabilities at RSUs could mitigate this for some localized applications, but overall network intelligence would be reduced until connectivity is restored.
- Cybersecurity and Privacy: Cybersecurity remains

a paramount concern. V2X systems must be resilient against a range of threats including message spoofing, data tampering, denial-of-service attacks, Sybil attacks, and privacy violations (e.g., tracking). Ensuring robust authentication (e.g., via Public Key Infrastructure (PKI)), message integrity, confidentiality where needed, and availability requires sophisticated security architectures, potentially incorporating intrusion detection systems, and privacy-enhancing technologies. The highly dynamic nature of vehicular networks adds complexity to managing security credentials and revoking malicious actors.

- Cost and Investment: The deployment of V2X infrastructure, especially dense RSU networks, requires significant financial investment. The cost of equipping vehicles with V2X On-Board Units (OBUs), maintaining the infrastructure, and ensuring continuous software/security updates presents economic challenges for widespread adoption.

7.4. Limitations of This Study

While this paper provides a comprehensive survey and performance analysis, certain limitations inherent to the scope and methodology should be acknowledged:

- Simulation Scope and Assumptions: The mathematical models and simulations, while designed to reflect real-world behaviors, are based on specific assumptions (e.g., Poisson Point Process for vehicle distribution, standard path-loss models, idealized channel conditions for baseline calculations). Real-world scenarios may involve more complex factors such as urban canyon effects, diverse weather impacts, and non-ideal antenna placements not fully captured.
- Depth of Specific Areas: Certain aspects, such as the detailed design of MAC layer contention resolution mechanisms, the intricate performance of specific cybersecurity protocols, or the socio-economic factors influencing V2X adoption, were not the primary focus of this analysis.
- Cost-Performance Trade-off: While our analysis highlights performance benefits, such as those from dense RSU deployment, it does not delve into a detailed economic analysis. The performance benefits of dense RSU deployment, as shown in our models, come with significant infrastructure investment and maintenance costs. A key practical limitation for deployment is thus the economic feasibility and strategic planning required to optimize the cost-performance trade-off in diverse urban and rural environments.

Addressing these multifaceted limitations and challenges is crucial for the successful, widespread, and trustworthy deployment of V2X communication systems, unlocking their full potential to enhance road safety and network intelligence.

8. Conclusions and Future Work

This paper has comprehensively investigated the transformative role of Vehicle-to-Everything (V2X) communication in enhancing road safety and network intelligence. Through a detailed survey of V2X modes, architectures, and operational challenges, complemented by mathematical modeling and simulation-based performance analysis, we have quantified the critical influence of network parameters like RSU density, multi-hop relay support, and traffic volume on V2X efficacy. Our findings consistently demonstrate that robust infrastructure, such as a dense RSU network, and efficient communication protocols are paramount for achieving low latency and high packet delivery ratios (PDR)—metrics vital for the success of time-sensitive safety applications. The developed mathematical models for latency, PDR, and throughput offer a foundational understanding of these dynamics, while the intersection collision avoidance case study practically illustrated how improvements in these core communication metrics translate directly into tangible safety benefits, such as reduced potential collisions and faster hazard warnings. Despite these promising advancements, the path to widespread V2X adoption is still lined with challenges, including network congestion, real-time reliability, cybersecurity threats, and the economic considerations of deployment, all of which necessitate ongoing research and strategic planning.

The successful realization of V2X's potential hinges not only on continued technological innovation but also on supportive policy frameworks, strategic infrastructure investments, and robust standardization to ensure interoperability. Our analysis underscores that V2X is more than just a communication technology; it is a cornerstone for next-generation Intelligent Transportation Systems (ITS), poised to revolutionize how vehicles interact with their environment and each other. The insights gained from modeling and simulation highlight the delicate balance required between performance, cost, and complexity in designing and deploying effective V2X systems. As V2X technology matures, its integration into urban and highway infrastructure will be instrumental in mitigating accidents, optimizing traffic flow, and enabling a new era of cooperative mobility, ultimately shaping a safer and more efficient future for transportation worldwide.

Looking ahead, future research should focus on several key areas to propel V2X capabilities further. A primary direction involves leveraging Artificial Intelligence (AI) and Machine Learning (ML) for adaptive routing, dynamic resource management, and predictive network performance optimization. Concurrently, enhancing cybersecurity and privacy is crucial; this includes developing lightweight yet robust security protocols, advanced intrusion detection systems, and privacy-preserving data-sharing mechanisms specifically for the V2X domain. The integration of V2X with emerging 5G and beyond-5G (B5G) network features, such as network slicing and ultra-reliable low-latency communication (URLLC), alongside the exploration of fog and edge computing architectures, will be vital for supporting advanced applications like cooperative perception and real-time localized services. Furthermore, expanding real-world testbeds for large-scale deployment studies will be essential to validate simulation findings, assess human-factor interactions, and refine deployment strategies. Addressing these research avenues will be pivotal in overcoming current limitations and fully unlocking the transformative potential of V2X for intelligent, safe, and efficient global transportation ecosystems.

Author Contributions

“Conceptualization, Q.I.A. and H.M.M.; methodology, Q. I. A. and H.M.M.; software, Q.I.A.; validation,Q. I.A.; formal analysis, H.M.M.; investigation, H.M.M.; writing—original draft preparation, H.M.M.; writing—review and editing,Q.I.A. and H.M.M.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data of this paper is available via Email of the authors.

Acknowledgments

We thank University of Mosul for supporting this work.

Conflicts of Interest

The authors declare no conflict of interest.

Appendix A

Table A1. List of Key Terminology.

Terminology	Full Name / Description
V2X	Vehicle-to-Everything
V2V	Vehicle-to-Vehicle Communication
V2I	Vehicle-to-Infrastructure Communication
V2N	Vehicle-to-Network Communication
V2P	Vehicle-to-Pedestrian Communication
RSU	Roadside Unit
UE	User Equipment (often refers to devices in vehicles or carried by pedestrians)
OBU	On-Board Unit (V2X communication device installed in a vehicle)
VRU	Vulnerable Road User (e.g., pedestrians, cyclists)
PC5 Interface	A direct communication interface specified by 3GPP for V2X services, operating in the 5.9 GHz ITS band.
LTE-Uu	The radio interface between User Equipment (UE) and an eNodeB (evolved Node B) in an LTE cellular network.
eNodeB	Evolved Node B (Base station in LTE cellular networks)

Table A1. *Cont.*

Terminology	Full Name / Description
3GPP	3rd Generation Partnership Project (Standards organization for mobile telecommunications)
5G	Fifth-Generation mobile network technology
DSRC	Dedicated Short-Range Communications (A U.S. standard for V2X, often contrasted with C-V2X)
C-V2X	Cellular V2X (V2X communication based on cellular technology, e.g., LTE or 5G)
EPS	Evolved Packet System (The core network of an LTE system)
MBMS	Multimedia Broadcast Multicast Service (A service for broadcasting data to multiple UEs in a cellular network)
D2D	Device-to-Device Communication
PDR	Packet Delivery Ratio
ITS	Intelligent Transportation Systems
PPP	Poisson Point Process (A mathematical model for random point distribution, used for vehicle density)
OFDM	Orthogonal Frequency-Division Multiplexing (A digital transmission modulation scheme)
MAC Layer	Medium Access Control Layer (A sublayer of the data link layer responsible for channel access control)
PKI	Public Key Infrastructure (A system for creating, managing, distributing, using, storing, and revoking digital certificates)
BSM	Basic Safety Message (A core V2X message type, typically broadcast periodically by vehicles)
FCW	Forward Collision Warning
IMA	Intersection Movement Assist
BSW+LCW	Blind Spot Warning + Lane Change Warning

References

[1] Shi, Y., Peng, X.H., Bai, G., 2018. Efficient V2X Data Dissemination in Cluster-Based Vehicular Networks. Proceedings of the 17th International Conference on Advances in Vehicular Systems, Technologies and Applications (VEHICULAR 2018); 24–28 June 2018; Venice, Italy. pp. 1–6.

[2] Wikipedia, 2025. Vehicle-to-everything. Available from: https://en.wikipedia.org/wiki/Vehicle-to-everything (cited 15-1-2025).

[3] Molinaro, A., Campolo, C., 2018. 5G for V2X Communications. 5G Italy White eBook: from Research to Market. In: Marsan, M.A., Melazzi, N.B., Buzzi, S. (eds.). Consorzio Nazionale Interuniversitario per le TelecomunicazioniViale: Parma (PR), Italy. pp. 209–236.

[4] U.S. Department of Transportation, 2015. Driving a Safer Tomorrow: Vehicle-to-Vehicle Communications and Connected Roadways of the Future. Available from: https://www.transportation.gov/testimony/driving-safer-tomorrow-vehicle-vehicle-communications-and-connected-roadways-future (cited 15-1-2025).

[5] ETSI TS 122 185. 2018. Service requirements for V2X services. Release 15.

[6] ITU-R M.2084-0. 2015. Radio Interface Standards of Vehicle-to-Vehicle and Vehicle-to-Infrastructure Communications for Intelligent Transport System Applications.

[7] 3GPP TS 23.285. 2018. Architecture enhancements for V2X services. Release 15.

[8] CSAE T/CSAE 0053-2017. 2017. Cooperative Intelligent Transportation System, Vehicular Communication, Application Layer Specification and Data Exchange Standard. CSAE: Beijing, China.

[9] Wang, J., Shao, Y., Ge, Y., et al., 2019. A Survey of Vehicle to Everything (V2X) Testing. Sensors. 19(2), 334.

[10] Ali, Q.I., 2014. Design, implementation & optimization of an energy harvesting system for VANETs' road side units (RSU). IET Intelligent Transport Systems. 8(3), 298–307.

[11] Ali, Q.I., 2008. An efficient simulation methodology of networked industrial devices. Proceedings of 5th International Multi-Conference on Systems, Signals and Devices; 20–22 July 2008; Amman, Jordan. pp. 1–6.

[12] Ali, Q.I., 2015. Security issues of solar energy harvesting road side unit (RSU). Iraqi Journal for Electrical & Electronic Engineering. 11(1), 18. DOI: https://doi.org/10.33762/eeej.2015.102711

[13] Ali, Q.I., 2016. Securing solar energy-harvesting road-side unit using an embedded cooperative-hybrid intrusion detection system. IET Information Security. 10(6), 386–402.

[14] Ali, Q.I., 2011. Design & Implementation of High-Speed Network Devices Using SRL16 Reconfigurable Content Addressable Memory (RCAM). International Arab Journal of e-Technology. 2(2), 72–81.

[15] Alhabib, M.H., Ali, Q.I., 2023. Internet of autonomous vehicles communication infrastructure: a short review. Diagnostyka. 24(3). DOI: https://doi.org/10.29354/diag/168310

[16] Ali, Q.I., 2022. Realization of a robust fog-based green VANET infrastructure. IEEE Systems Journal. 17(2), 2465–2476.

[17] Ali, Q.I., Jalal, J.K., 2014. Practical design of solar-powered IEEE 802.11 backhaul wireless repeater. Proceedings of the 6th International Conference on Multimedia, Computer Graphics and Broadcasting; 20–23 December 2014; Hainan, China. pp. 9–12.

[18] Lu, N., Cheng, N., Zhang, N., et al., 2014. Connected Vehicles: Solutions and Challenges. IEEE Internet of Things Journal. 1(4), 289–299.

[19] Tsai, H.M., Viriyasitavat, W., Tonguz, O.K., et al., 2007. Feasibility of in-car wireless sensor networks: A statistical evaluation. Proceedings of the 2007 4th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks; 18–21 June 2007; San Diego, CA, USA. pp. 101–111.

[20] Eisenlohr, F.S., 2010. Interference in Vehicle-to-Vehicle Communication Networks Analysis, Modeling, Simulation and Assessment. KIT Scientific Publishing: Karlsruhe, Germany.

[21] Vanderveen, M., Shukla, K., 2018. Cellular V2X Communications Towards 5G. 5G Americas: Washington, DC, USA.

[22] Kawser, M.T., Fahad, M.S., Ahmed, S., et al., 2019. The Perspective of Vehicle-to-Everything (V2X) Communication towards 5G. International Journal of Computer Science and Network Security. 19(4), 146.

[23] Dahlman, E., Parkvall, S., Sköld, J., 2016. 4G LTE - Advanced Pro and The Road to 5G. Academic Press: New York, NY, USA. pp. 461–486.

[24] Amadeo, M., Campolo, C., Molinaro, A., et al., 2019. Enhancing the 3GPP V2X Architecture with Information-Centric Networking. Future Internet. 11(9), 199.

[25] Liu, Z., Liu, Z., Meng, Z., et al., 2016. Implementation and performance measurement of a V2X communication system for vehicle and pedestrian safety. International Journal of Distributed Sensor Networks. 12(9), 1550147716671267.

[26] Harding, J., Powell, G.R., Yoon, R., et al., 2014. Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application. National Highway Traffic Safety Administration: Washington, DC, USA.