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SDN-Assisted Low-Latency Resource Management for V2X Communication in Heterogeneous Cellular Networks

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Abstract: *Vehicle-to-Everything (V2X) communication requires low-latency, reliable, and context-aware connectivity across vehicle-to-vehicle, vehicle-to-infrastructure, vehicle-to-pedestrian, and vehicle-to-network services. Heterogeneous cellular networks can support these services by combining 5G New Radio, cellular sidelink, roadside units, Wi-Fi or DSRC links, and multi-access edge computing; however, high mobility, variable traffic density, frequent handovers, congestion, and static resource-allocation policies can degrade end-to-end delay and packet delivery. This paper presents a software-defined networking assisted framework for latency-aware resource management in heterogeneous V2X environments. The proposed framework separates network control from forwarding, maintains a global view of vehicular network state, classifies V2X flows by service criticality, and dynamically selects routes and bandwidth allocations using delay, congestion, handover, and priority constraints. A mathematical formulation is developed for minimizing weighted end-to-end latency under link-capacity, minimum-bandwidth, packet-delivery, congestion, and controller-processing constraints. The paper also defines the Latency-Aware SDN Resource Allocation Algorithm for V2X Networks and specifies a reproducible simulation methodology using NS-3/SUMO or OMNeT++/Veins with multiple baselines, confidence intervals, and ablation analysis. Because the source report did not include raw simulation data, the revised results section includes clearly labelled hypothetical numerical plots and reporting values only to demonstrate result formatting and interpretation; these values are not validated empirical findings. The study provides a rigorous foundation for validating SDN-MEC orchestration in next-generation vehicular communication systems.*

Keywords: Software-defined networking; V2X communication; heterogeneous cellular networks; multi-access edge computing; low-latency routing; resource allocation; intelligent transportation systems.

Highlights

- A Q1-style SDN-assisted V2X framework is developed from the conceptual M.Tech report base.
- The proposed LASRA-V2X method jointly considers delay, congestion, mobility, bandwidth, QoS priority, and handover constraints.
- A full mathematical latency-minimization model and algorithmic workflow are provided.
- Hypothetical numerical plots are inserted only as illustrative formatting values and are explicitly labelled as non-empirical results.

I. INTRODUCTION

Connected and automated mobility depends on communication systems capable of carrying safety-critical, traffic-efficiency, infotainment, and control-plane messages with stringent latency and reliability requirements. V2X communication generalizes multiple interaction modes, including vehicle-to-vehicle, vehicle-to-infrastructure, vehicle-to-pedestrian, and vehicle-to-network communication. In 5G systems, V2X support is specified through both PC5 sidelink and Uu reference points, allowing direct proximity communication and network-assisted communication depending on coverage, resource availability, and service requirements [1]-[4].

Heterogeneous cellular networks are attractive for V2X because they can combine cellular base stations, roadside units, MEC servers, Wi-Fi or DSRC links, and C-V2X/NR-V2X interfaces. Such diversity can improve coverage and service continuity, but it also creates orchestration complexity. Vehicles move rapidly across radio environments, link quality fluctuates over short time scales, and traffic load changes with road density, traffic incidents, intersections, and platooning behavior. These conditions increase queueing delay, handover delay, packet drops, and route instability when resource management remains static or locally optimized [3]-[5].

Software-defined networking (SDN) offers a control-plane mechanism for addressing these challenges. By separating control logic from data-plane forwarding, SDN enables a controller or distributed controller hierarchy to maintain a network-wide view, install flow rules, tune routing, and coordinate resource decisions across heterogeneous access segments. In vehicular networks, SDN is particularly useful because it can integrate network-state telemetry from RSUs, cellular access nodes, and edge servers, thereby enabling congestion-aware and mobility-aware resource orchestration [6]-[8].

The central research problem addressed in this paper is the design of an SDN-assisted resource-management framework that minimizes V2X communication latency while satisfying bandwidth, congestion, mobility, packet-delivery, and controller-processing constraints. The paper does not claim a new radio-access technology. Instead, it contributes a control-plane and resource-allocation model that can operate above heterogeneous V2X access technologies and can be validated through reproducible network simulation.

1.1 Research Objectives

1. To formulate a latency-aware system model for SDN-assisted V2X communication in heterogeneous cellular networks.
2. To define an optimization problem that minimizes weighted end-to-end delay subject to QoS, bandwidth, capacity, congestion, mobility, and controller constraints.
3. To design an SDN-based algorithm for dynamic routing and bandwidth allocation across V2X communication paths.
4. To specify a reproducible simulation protocol with baselines, metrics, random seeds, confidence intervals, and ablation analysis.
5. To identify security, reliability, scalability, and deployment limitations relevant to real-world SDN-MEC V2X implementation.

1.2 Main Contributions

- A latency-aware SDN-assisted architecture that integrates vehicles/OBUs, RSUs, gNBs, heterogeneous wireless links, an SDN controller, MEC support, flow monitoring, resource allocation, and handover management.
- A mathematical formulation that represents V2X communication as a time-varying graph and decomposes end-to-end latency into transmission, queueing, propagation, processing, handover, and controller components.
- The LASRA-V2X algorithm, which prioritizes traffic classes, estimates congestion, selects routes, allocates bandwidth, and installs SDN flow rules in an iterative feedback loop.
- A full evaluation design that compares the proposed approach against static routing, non-SDN resource allocation, SDN-only routing, and MEC-assisted baselines under low, medium, and high vehicle densities.

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- A transparent results policy: because no raw simulator output was available, the paper provides a simulation protocol and result templates rather than fabricated performance values.

II. RELATED WORK

2.1 5G/NR-V2X and Heterogeneous V2X Communication

3GPP V2X architecture defines support for vehicular services over PC5 and Uu interfaces, including LTE PC5, NR PC5, E-UTRA, and NR-based network connectivity [1]. The evaluation methodology for new V2X use cases emphasizes radio scenarios, mobility, traffic models, and performance metrics for LTE and NR V2X [2]. Tutorial and standardization studies show that NR-V2X extends LTE-V2X with sidelink improvements, QoS management, resource allocation enhancements, and support for connected and automated driving requirements [3], [4]. These works provide the radio and service background for this paper but do not by themselves resolve cross-technology, controller-assisted resource orchestration.

2.2 SDN-Enabled Vehicular Networks

Software-defined vehicular networking has been proposed to address the rigidity of conventional vehicular routing and traffic management. Cardona et al. [6] identify opportunities and challenges in applying SDN to vehicular networking, including programmability, virtualization, mobility, and network slicing. Al-Heety et al. [7] review SDN-VANET benefits, services, security concerns, and use cases, showing that SDN can improve traffic engineering but introduces controller placement, security, and scalability challenges. Recent SDN-edge vehicular surveys further indicate that edge and fog support can reduce delay and improve load balancing, but existing approaches vary widely in assumptions and often lack unified validation across routing, offloading, and security dimensions [8].

2.3 MEC, Network Slicing, and Resource Management

MEC shortens service paths by placing computation and storage resources near the vehicular edge. Network slicing and SDN-based MEC can isolate services and support different QoS classes for safety-critical and non-safety V2X traffic [9]. Peng et al. [10] proposed SDN-based resource management for autonomous vehicular networks with MEC support, demonstrating the value of global resource coordination. Nkenyereye et al. [11] developed an SDN-based multi-access edge framework for vehicular networks. These studies motivate the present framework, but the manuscript extends the discussion by explicitly formulating end-to-end latency constraints and an algorithmic SDN control loop for heterogeneous V2X paths.

2.4 AI/ML-Assisted and Low-Latency Resource Allocation

Resource management has also been studied through machine learning and optimization. Tayyaba et al. [12] examine 5G vehicular resource management for improved radio access using machine learning. Guo et al. [13] analyze low-latency vehicular resource allocation from an effective-capacity perspective, while Ke et al. [14] use deep reinforcement learning for computation offloading in heterogeneous vehicular MEC networks. The present paper does not position itself as an AI-first method. Instead, it provides a deterministic optimization and SDN-control baseline that can later be extended with reinforcement learning or federated learning for predictive allocation.

2.5 Security and Reliability in SDN-V2X

Security is a central concern because V2X messages can influence driver assistance, cooperative perception, and traffic control. Surveys on V2X security highlight authentication, privacy preservation, trust management, and protection against wireless attacks [15]. SDN-VANET security studies emphasize flow-rule integrity, controller protection, southbound-interface security, and resilience against denial-of-service attacks [16]. Blockchain-SDN vehicular surveys further explore distributed trust and tamper-resistant coordination, but such approaches add latency and deployment overhead that must be evaluated carefully for safety-critical V2X traffic [17].

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Table 1. Comparative Literature Matrix

Author/year	Network scenario	Method	Metrics	Key finding	Limitation	Gap addressed here
3GPP, 2020 [1]	5G V2X architecture	PC5/Uu service architecture	Service support, reference points	Defines 5GS V2X architectural support	Not a resource-allocation algorithm	Uses architecture as implementation context
Garcia et al., 2021 [3]	NR-V2X	Tutorial on Release 16 NR-V2X	PHY, sidelink, QoS, mobility	Clarifies NR-V2X mechanisms and assumptions	Does not optimize SDN control-plane routing	Adds SDN-level orchestration above access links
Harounabadi et al., 2021 [4]	NR sidelink	Standardization review	Reliability, latency, sidelink features	Summarizes Release 16 and beyond	No end-to-end heterogeneous resource model	Integrates heterogeneous path selection
Abdel Hakeem et al., 2020 [5]	5G-V2X	Standardization, slicing, MEC review	Use cases, architecture	Shows edge and slicing relevance	Review-level, not algorithmic	Develops algorithm and constraints
Cardona et al., 2020 [6]	SDVN	Survey and architecture discussion	Programmability, slicing, mobility	Identifies SDVN opportunities	Open issues remain on validation	Provides simulation protocol and model
Al-Heety et al., 2020 [7]	SDN-VANET	Comprehensive survey	Benefits, services, security	Highlights SDN-VANET challenges	Not a new optimization method	Adds latency-aware algorithm design
Ul Haq et al., 2025 [8]	SDN-edge VCN	Survey of SDN edge approaches	Delay, load balancing, security	Categorizes SDN-edge vehicular work	Survey, not deployable framework	Builds a method with reporting plan
Shah et al., 2021 [9]	MEC and slicing	Cloud-native slicing survey	QoS, slicing, mobility	Supports E2E network slicing view	Not V2X-specific optimization	Maps slicing ideas to V2X priority classes
Peng et al., 2019 [10]	Autonomous vehicular networks	SDN + MEC resource management	Resource utilization, service support	Shows SDN-MEC value for AVs	Limited integration of handover and heterogeneous links	Adds handover-aware path cost
Nkenyereye et al., 2020 [11]	Vehicular MEC	SDN-based multi-access edge framework	Latency, edge resource support	Supports multi-access edge integration	Requires broader baseline validation	Adds reproducible comparison plan

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Tayyaba et al., 2020 [12]	5G vehicular networks	ML-based radio access management	Radio resource management	ML can support resource decisions	ML interpretability and training cost	Provides deterministic SDN baseline
Guo et al., 2019 [13]	Low-latency vehicular comm.	Effective-capacity optimization	Delay and capacity	Addresses low-latency resource allocation	Not SDN-MEC orchestration	Combines latency constraints with SDN control
Ke et al., 2020 [14]	MEC vehicular networks	DRL computation offloading	Delay, offloading, computation	Shows DRL benefit for MEC offloading	Training overhead and policy transfer	Leaves RL as future extension
Huang et al., 2020 [15]	V2X security	Security/privacy survey	Authentication, privacy, trust	Maps core V2X security threats	Does not solve SDN-controller risks	Adds SDN-V2X security subsection

III. SYSTEM MODEL

The proposed system consists of connected vehicles equipped with on-board units, roadside units, LTE/5G base stations, heterogeneous radio links, an SDN controller, an MEC server, a resource-allocation module, a flow-monitoring module, and a handover-management module. Vehicles generate safety-critical and non-safety V2X messages. RSUs and base stations provide access to local and networked services. MEC servers process delay-sensitive tasks near the road segment, while the SDN controller maintains a logical network view and installs flow rules to selected forwarding devices.

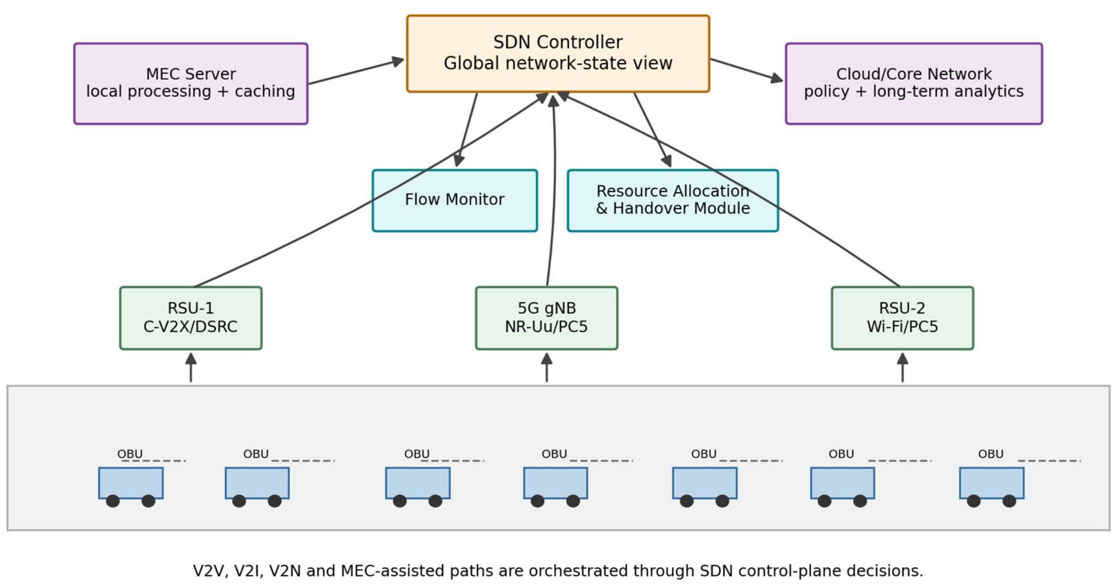

Figure 1. SDN-assisted V2X resource management architecture in a heterogeneous cellular network.

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3.1 Network Graph

At control interval t, the heterogeneous V2X network is represented as a directed graph $G(t) = (N(t), E(t))$, where $N(t) = V(t)$ union $R(t)$ union $B(t)$ union $M(t)$ union C. $V(t)$ is the vehicle set, $R(t)$ is the RSU set, $B(t)$ is the LTE/5G base-station set, $M(t)$ is the MEC-server set, and C is the SDN-controller set. A directed edge $e = (i, j)$ in $E(t)$ exists when node i can transmit to node j through a supported access technology. Each link e has an available capacity $C_e(t)$, allocated bandwidth $b_{e,f}(t)$ for flow f, packet-error probability $p_e(t)$, queue length $Q_e(t)$, propagation distance $d_e(t)$, and radio-access type a_e.

3.2 V2X Flow Model

Let $F(t)$ denote the active flow set. A flow f in $F(t)$ is described by $f = \{s_f, r_f, z_f, p_f, B_f^{min}, D_f^{max}, R_f^{min}\}$, where s_f is the source node, r_f is the destination node or service endpoint, z_f is the packet size, p_f is the traffic priority class, B_f^{min} is the minimum required bandwidth, D_f^{max} is the maximum tolerated delay, and R_f^{min} is the minimum packet-delivery ratio. Four traffic classes are considered: safety-critical cooperative awareness/emergency messages, traffic-control messages, cooperative perception or local edge-processing flows, and infotainment/background messages. Safety-critical flows receive higher priority weights than delay-tolerant flows.

3.3 Latency Components

For a flow f traversing path $P_f(t)$, the total end-to-end delay is decomposed as:

$$D_f^{tot}(t) = \sum_{e \in P_f(t)} [D_{e,f}^{tx}(t) + D_e^{que}(t) + D_e^{prop}(t) + D_e^{proc}(t)] + D_f^{ho}(t) + D_f^{ctrl}(t). \quad (1)$$

The transmission delay is $D_{e,f}^{tx}(t) = z_f / b_{e,f}(t)$. The queueing delay can be approximated by $D_e^{que}(t) = 1 / (\mu_e(t) - \lambda_e(t))$ when a stable M/M/1 approximation is acceptable and $\lambda_e(t) < \mu_e(t)$. The propagation delay is $D_e^{prop}(t) = d_e(t) / c$ for radio propagation speed c. The processing delay $D_e^{proc}(t)$ captures RSU, base-station, forwarding-device, and MEC processing. Handover delay $D_f^{ho}(t)$ is added when a flow crosses an access boundary or changes serving RSU/gNB. Controller response delay $D_f^{ctrl}(t)$ captures state collection, path computation, and flow-rule installation time.

3.4 Performance Metrics

Metric	Definition	Use in evaluation
End-to-end delay	Mean and percentile of D_f^{tot} over completed packets	Primary latency metric
Throughput	Successfully delivered payload bits divided by observation time	Capacity and efficiency
Packet delivery ratio	Delivered packets divided by generated packets	Reliability
Packet loss ratio	Lost packets divided by generated packets	Congestion and channel loss
Jitter	Variation in packet delay between consecutive packets	Stability of real-time flows
Bandwidth utilization	Used bandwidth divided by available link capacity	Resource efficiency
Congestion rate	Fraction of intervals where load exceeds threshold ρ_{max}	Network saturation
Handover delay	Added delay during access change	Mobility impact
Controller response time	Telemetry-to-flow-installation latency	Control-plane overhead

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IV. PROBLEM FORMULATION

The goal is to minimize weighted end-to-end latency across active V2X flows while preserving service constraints. Let $x_{e,f}(t) \in \{0,1\}$ indicate whether flow f uses link e at time t. Let $b_{e,f}(t) \geq 0$ be the bandwidth allocated to f on e. Let w_f denote the priority weight of flow f, with safety-critical traffic assigned a larger value than non-safety traffic.

Objective:

$$\text{minimize} \sum_{f \in F(t)} w_f D_f^{tot}(t) + \alpha \sum_{e \in E(t)} \rho_e(t) + \beta \sum_{f \in F(t)} H_f(t) + \gamma D^{ctrl}(t), \quad (2)$$

where $\rho_e(t) = \sum_f b_{e,f}(t) / C_e(t)$ is link utilization, $H_f(t)$ is a handover indicator or handover penalty, $D^{ctrl}(t)$ is aggregate controller response time, and alpha, beta, gamma are non-negative design weights.

4.1 Constraints

The optimization is subject to the following constraints:

$\sum_{f \in F(t)} b_{e,f}(t) \leq C_e(t)$, for all $e \in E(t)$. (3)

$b_{e,f}(t) \geq B_f^{min} x_{e,f}(t)$, for all f and e in $P_f(t)$. (4)

$D_f^{tot}(t) \leq D_f^{max}$, for all safety-critical and delay-constrained flows. (5)

$PDR_f(t) \geq R_f^{min}$, for all flows with reliability guarantees. (6)

$\rho_e(t) \leq \rho_{max}$, for all links selected for safety-critical traffic. (7)

$D_f^{ctrl}(t) \leq D_{ctrl}^{max}$, for all flows requiring controller intervention. (8)

$x_{e,f}(t)$ must satisfy flow conservation: every selected path starts at the source, ends at the receiver or service endpoint, and preserves continuity across intermediate forwarding nodes. Constraint (3) prevents link over-allocation. Constraint (4) ensures minimum service bandwidth. Constraint (5) enforces V2X delay deadlines. Constraint (6) enforces reliability. Constraint (7) avoids routing critical traffic through saturated links. Constraint (8) prevents SDN control overhead from offsetting data-plane gains.

4.2 Optimization Interpretation

The exact mixed-integer formulation can become computationally expensive when vehicle density and candidate paths increase. Therefore, the proposed algorithm uses a control-interval heuristic: first prune infeasible links, then rank candidate paths by composite latency-congestion cost, then allocate bandwidth using traffic priority and residual capacity, and finally install flow rules for the selected path. This approach is suitable for simulation-based evaluation and can later be extended with distributed or hierarchical SDN controllers.

V. PROPOSED METHOD: LASRA-V2X

The proposed Latency-Aware SDN Resource Allocation Algorithm for V2X Networks is a periodic control-loop method. During each interval, the controller collects link-state telemetry, estimates congestion, classifies V2X flows, computes candidate path costs, allocates bandwidth, and installs or updates flow rules. The algorithm is designed for safety-critical priority handling while preserving service capacity for lower-priority traffic where possible.

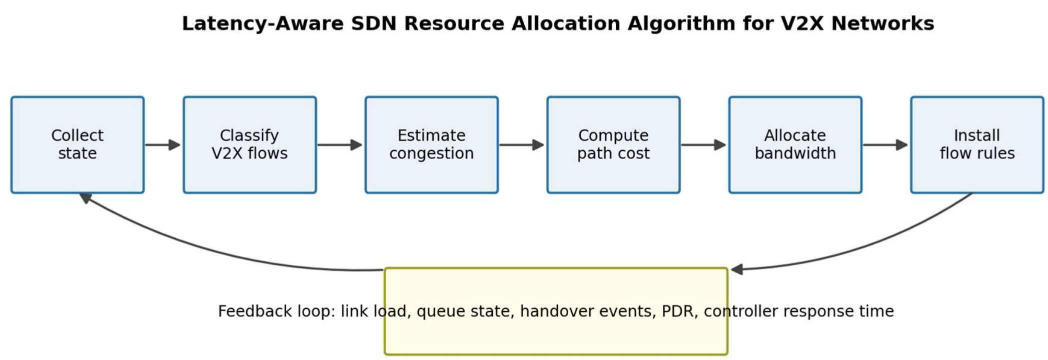

Figure 2. Workflow of the proposed LASRA-V2X algorithm.

5.1 Network-State Collection

RSUs, gNBs, and forwarding nodes report telemetry at interval Delta t. Telemetry includes link capacity, residual bandwidth, queue length, packet-error ratio, observed delay, flow-table occupancy, handover events, and MEC server load. To avoid controller overload, telemetry can be aggregated or event-triggered when the link state changes beyond a configured threshold.

5.2 Priority Classification

Incoming flows are classified into priority classes. Emergency braking, collision warning, cooperative awareness, and safety-related cooperative perception receive the highest weight. Traffic-signal coordination and road-event messages receive medium-high priority. Infotainment and delay-tolerant cloud-service traffic receive lower priority. This classification enables differentiated resource allocation and path selection without requiring all traffic to meet the same strict delay threshold.

5.3 Path-Cost Computation

For each candidate path P from source s_f to destination r_f, the controller computes:

J_f(P,t) = sum_{e in P} [theta_1 D_e^tx + theta_2 D_e^que + theta_3 D_e^prop + theta_4 D_e^proc + theta_5 rho_e + theta_6 p_e] + theta_7 H_f(P,t). (9)

The selected path is the feasible path with minimum J_f(P,t), subject to delay, capacity, PDR, and congestion constraints. Links that violate reliability or utilization constraints for safety-critical traffic are pruned before candidate-path ranking.

5.4 Dynamic Bandwidth Allocation

After path selection, residual capacity is allocated using priority-weighted minimum guarantees. High-priority flows are first assigned B_f^min. Remaining capacity is distributed using weighted max-min allocation, while preventing any link from exceeding C_e(t). Lower-priority flows can be rate-limited or rerouted when the network is congested.

5.5 Flow-Rule Installation and Handover Handling

The controller installs flow rules through the southbound interface. When vehicle mobility indicates an imminent handover, the handover-management module pre-computes candidate paths through the next RSU or gNB and pre-installs temporary forwarding entries where supported. This reduces route-recomputation delay during access changes.

5.6 Algorithm Pseudocode

Algorithm 1: LASRA-V2X: Latency-Aware SDN Resource Allocation for V2X Networks

Input: $G(t)$, active flows $F(t)$, link capacities $C_e(t)$, queue states $Q_e(t)$, packet-error estimates $p_e(t)$, vehicle positions, QoS thresholds.

Output: Selected path $P_f(t)$, bandwidth allocation $b_{e,f}(t)$, and SDN flow rules for each admitted flow.

1: Initialize telemetry window and obtain current network state from RSUs, gNBs, MEC nodes, and switches.
2: For each flow f in $F(t)$, assign priority weight w_f based on V2X service class.
3: Remove links where capacity, reliability, or congestion thresholds make the link infeasible for flow f.
4: Generate K candidate paths from s_f to r_f using the current graph $G(t)$.
5: For each candidate path P, compute latency-congestion-handover cost $J_f(P,t)$.
6: Select the feasible path with minimum $J_f(P,t)$. If no path is feasible, defer, reroute through MEC, or drop according to service policy.
7: Allocate minimum bandwidth B_f^{min} for admitted priority flows.
8: Distribute residual capacity by priority-weighted max-min allocation.
9: Install or update SDN flow rules for the selected paths.
10: Monitor delivery, PDR, controller response time, and handover events.
11: Repeat at the next control interval or immediately upon major congestion/handover events.

Complexity. If K candidate paths are generated for each of $|F|$ flows, the dominant cost is $O(|F|\, K\, (|E| + |N| \log |N|))$ when shortest-path style search is used with a priority queue. Bandwidth allocation adds $O(|F| \log |F|)$ per congested link if flows are sorted by priority. In dense vehicular scenarios, hierarchical controllers or local RSU-level preselection can reduce the controller burden.

VI. EXPERIMENTAL SETUP

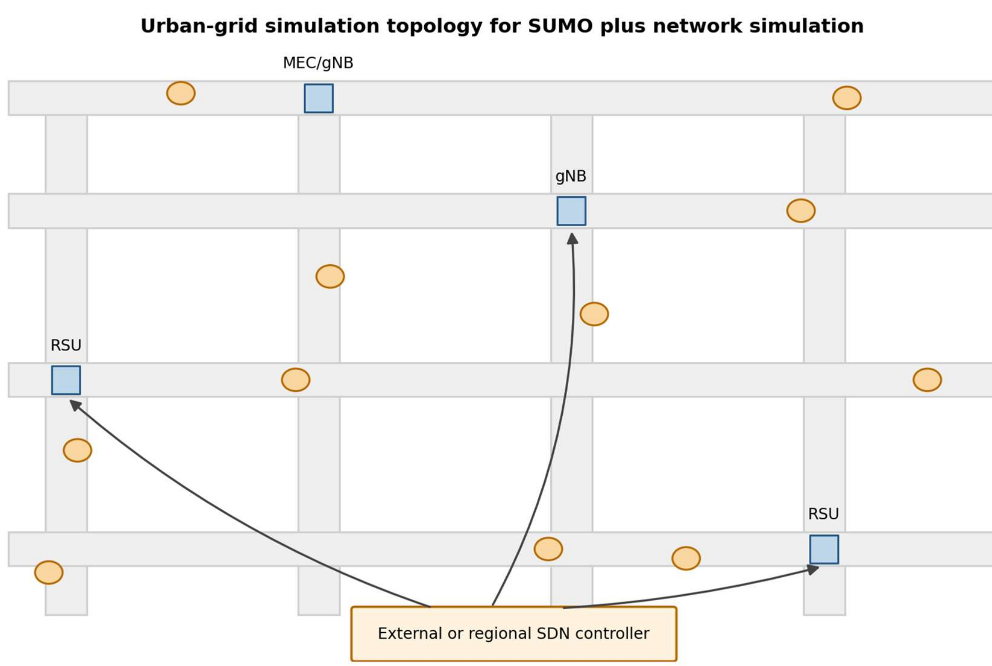

Figure 3. Simulation topology concept for an urban V2X scenario with RSUs, gNBs, MEC support, and SDN control.

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The evaluation should be implemented as a reproducible simulation pipeline. The recommended configuration is SUMO for urban mobility generation coupled with NS-3 for network-layer simulation or OMNeT++/Veins for vehicular network co-simulation. Mininet with Ryu or OpenDaylight can be used for SDN control-plane prototyping, while Python scripts can process logs, calculate confidence intervals, and generate figures. The final journal submission should lock exact versions, container images, configuration files, and random seeds [20]-[22].

6.1 Simulation Scenario

The protocol should use an urban grid or OpenStreetMap-derived road network containing intersections, RSU/gNB coverage overlaps, and variable vehicle density. Three density levels should be evaluated: low, medium, and high. Vehicles generate four message types: safety-critical, emergency, traffic-control/cooperative-awareness, and infotainment/background traffic. Each experiment should run long enough to capture steady-state behavior after a warm-up period.

6.2 Baseline Models

- Baseline A: Traditional static routing without SDN or dynamic bandwidth allocation.
- Baseline B: Non-SDN V2X resource allocation using local RSU/gNB decisions.
- Baseline C: SDN routing with shortest-path control but without dynamic bandwidth allocation.
- Baseline D: MEC-assisted baseline with edge processing but without full SDN latency-aware orchestration.
- Proposed: LASRA-V2X with SDN monitoring, congestion-aware path selection, dynamic allocation, and handover-aware decisions.

6.3 Reproducibility Plan

Item	Protocol requirement
Simulation runs	At least 20-30 independent runs per scenario and baseline.
Random seeds	Record and publish every seed used for mobility, traffic generation, and channel variation.
Warm-up period	Exclude warm-up samples from final metric aggregation.
Confidence intervals	Report mean, standard deviation, and 95% confidence intervals.
Statistical testing	Use paired or non-parametric tests when assumptions are violated; report effect sizes.
Artifacts	Publish simulator configuration, controller logic, processed logs, and plotting scripts.
Fair comparison	Use identical mobility, traffic, channel, and load conditions across all baselines.

6.4 Planned Simulation Parameters

Parameter	Proposed setting or reporting rule
Road topology	Urban grid or OpenStreetMap-derived map with intersections and RSU/gNB overlap.
Vehicle density levels	Low, medium, and high density; final values must be stated in vehicles/km or total active vehicles.
Simulation duration	Report total duration and warm-up duration.
Access technologies	5G NR/C-V2X, LTE where modeled, DSRC/Wi-Fi when used as heterogeneous alternatives.
Message classes	Safety-critical, emergency, traffic-control/cooperative-awareness, infotainment/background.

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Controller placement	Centralized controller for baseline; optional hierarchical controller for scalability study.
MEC placement	At selected gNB/RSU sites; report compute delay and service capacity.
Traffic generation	State packet size, inter-arrival process, and class-specific priority weight.
Channel model	State path-loss, fading, interference, and packet-error model.
Outputs	CSV logs for delay, throughput, PDR, loss, jitter, utilization, congestion, handover, and controller time.

VII. SIMULATION PROTOCOL AND EXPECTED EVALUATION PLAN

The uploaded rough report did not contain raw simulation output, numeric performance tables, simulator configuration, random seeds, or trace logs. To remove the visible blank-template status from the result plots, this revision inserts a clearly labelled hypothetical numerical dataset for demonstration. The values are used only to show how the empirical results should be plotted and tabulated after execution of the proposed NS-3/SUMO or OMNeT++/Veins simulation. They should not be presented as measured results, statistical evidence, or final journal findings.

7.1 Result Tables and Hypothetical Reporting Values

Result table	Required content	Reporting rule
Latency under density levels	Mean, SD, 95% CI, median, p95 delay for all methods	Report in ms; compare each baseline with LASRA-V2X.
Throughput comparison	Mean delivered throughput by traffic class and density	Report in Mbps; show confidence intervals.
PDR and packet loss	Delivered, generated, lost packets and PDR	Report percentages and raw counts.
Bandwidth utilization	Per-link and aggregate utilization	Report mean and congestion-period distribution.
Handover delay	Delay before/during/after handover	Report separately for safety and non-safety flows.
Scalability analysis	Controller response time and flow-rule count versus vehicle density	Report computation overhead and flow-table pressure.
Ablation study	Full method vs. no MEC, no dynamic allocation, no handover prediction	Report effect of each component.

7.2 Hypothetical Result Figures

Figure 4 now presents hypothetical numerical plots for end-to-end delay, throughput, packet delivery ratio, and bandwidth utilization across low, medium, and high vehicle-density scenarios. The curves compare static routing, non-SDN resource allocation, SDN routing only, a MEC baseline, and the proposed LASRA-V2X method. The exact illustrative values used in the figure are provided immediately below the caption so that the draft no longer contains blank result panels.

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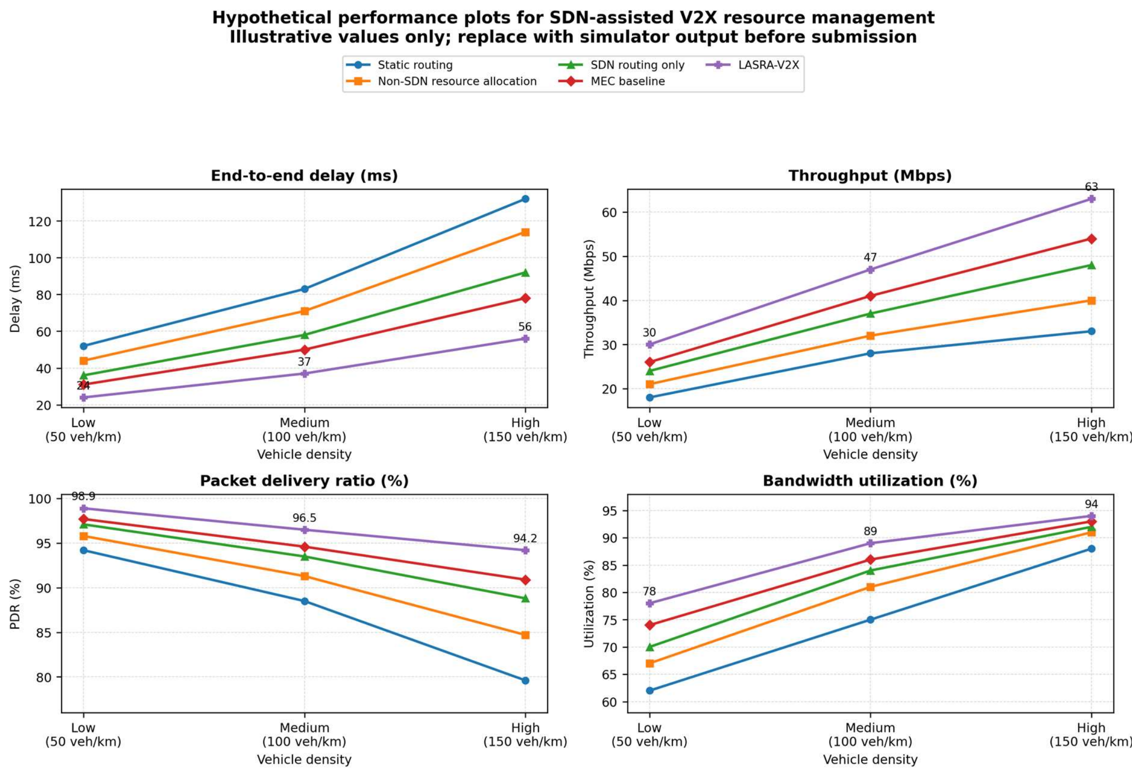

Figure 4. Hypothetical performance plots for baseline methods and LASRA-V2X under low, medium, and high vehicle-density scenarios. Values are illustrative and were not obtained from executed simulations.

Table 6. Hypothetical numerical values used for Figure 4.

Method	Density	Delay (ms)	Throughput (Mbps)	PDR (%)	Utilization (%)
Static routing	Low	52	18	94.2	62
Static routing	Medium	83	28	88.5	75
Static routing	High	132	33	79.6	88
Non-SDN resource allocation	Low	44	21	95.8	67
Non-SDN resource allocation	Medium	71	32	91.3	81
Non-SDN resource allocation	High	114	40	84.7	91
SDN routing only	Low	36	24	97.1	70
SDN routing only	Medium	58	37	93.5	84
SDN routing only	High	92	48	88.8	92
MEC baseline	Low	31	26	97.7	74
MEC baseline	Medium	50	41	94.6	86
MEC baseline	High	78	54	90.9	93
LASRA-V2X	Low	24	30	98.9	78
LASRA-V2X	Medium	37	47	96.5	89

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LASRA-V2X	High	56	63	94.2	94

Note. These values are hypothetical formatting values inserted to replace the former blank plot panels. They must be replaced with real simulator outputs, confidence intervals, and statistical tests before submission.

7.3 Statistical Analysis Plan

For each metric, the final analysis should compute mean, standard deviation, median, 95th percentile, and 95% confidence interval across independent simulation runs. Where the same mobility and traffic seeds are used across methods, paired comparisons are preferred. If normality assumptions are not satisfied, a Wilcoxon signed-rank test or bootstrap confidence interval should be used. The final paper should report both statistical significance and practical effect size, because small p-values may not imply operationally meaningful latency reduction in dense V2X scenarios.

7.4 Interpretation of Hypothetical Plots and Future Validation

The hypothetical plots show the intended reporting pattern: LASRA-V2X is displayed with lower delay, higher throughput, higher PDR, and better bandwidth utilization than the baseline methods as vehicle density increases. This interpretation is illustrative only. After real simulation execution, any observed improvement must be explained using congestion logs, queue-length traces, packet-loss records, handover events, and controller-response measurements. If the empirical PDR does not improve under high density, the discussion should examine whether radio-channel congestion, flow-table pressure, controller delay, or handover frequency dominates. If controller response time becomes high, hierarchical controller placement or RSU-level local decision support should be evaluated.

VIII. DISCUSSION

The proposed framework is expected to improve latency through three mechanisms. First, SDN monitoring exposes link-state and queue-state information that distributed static schemes may not observe in time. Second, traffic classification prevents non-critical flows from consuming resources needed for safety-critical V2X messages. Third, MEC support shortens service paths for local cooperative perception and traffic-management tasks. However, these mechanisms produce benefits only when controller response time remains lower than the delay saved in the data plane.

8.1 Controller Overhead

A centralized SDN controller provides global visibility but can become a bottleneck in dense vehicular scenarios. Frequent mobility events may cause repeated path recomputation and flow-rule updates. The final evaluation should therefore measure controller response time, flow-table update frequency, and packet delay during control events. A hierarchical SDN design, with local controllers near RSUs or MEC nodes, may reduce response time at the cost of control-plane synchronization complexity.

8.2 Scalability

Scalability depends on the number of vehicles, active flows, candidate paths, telemetry frequency, and controller placement. Safety-critical applications require rapid decisions, but excessive telemetry can overload the control plane. Adaptive telemetry, event-triggered updates, and local preselection of candidate paths can reduce overhead. Scalability should be evaluated not only by data-plane metrics but also by flow-installation latency and controller CPU utilization.

8.3 Handover Complexity

Handover is a central challenge in heterogeneous V2X communication. Vehicles may move between RSU, 5G gNB, LTE, and Wi-Fi/DSRC coverage zones. A path that is optimal at one instant may become unsuitable after a short time interval. The handover-aware component of LASRA-V2X attempts to reduce this effect by adding handover cost into path scoring and precomputing candidate routes; however, the mechanism must be validated under realistic mobility traces and channel dynamics.

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Volume 6, Issue 2, August 2026
Impact Factor: 8.2

8.4 MEC Deployment Cost

MEC support can reduce delay for local services, but deployment and maintenance costs are non-trivial. The simulation should include scenarios with different MEC densities and service capacities. A dense MEC deployment may improve latency but increase operational cost; a sparse deployment may create hotspots. This trade-off is relevant for smart-city deployments where RSU placement, base-station density, and edge-server capacity are constrained by budget and site availability.

IX. SECURITY AND RELIABILITY CONSIDERATIONS

SDN-assisted V2X introduces specific security risks because the controller becomes a high-value target. A compromised controller or southbound channel can manipulate flow rules, degrade emergency-message delivery, or reroute traffic through malicious nodes. V2X security already requires authentication, integrity, privacy, and trust management [15]. SDN-VANET environments additionally require controller hardening, flow-rule verification, secure telemetry, and resilient control-plane design [16], [17].

9.1 SDN Controller Security

The controller should use mutual authentication with network elements, protected southbound communication, role-based access control for applications, audit logging, and anomaly detection for control-plane requests. Controller redundancy should be considered to avoid single-point failure. In high-density scenarios, denial-of-service attacks against the controller can be as damaging as radio-channel congestion.

9.2 Flow-Rule Poisoning and Policy Conflicts

Flow-rule poisoning occurs when malicious or erroneous applications install incorrect forwarding entries. The resource-allocation module should verify proposed rules against QoS policy, loop-free path constraints, and security policy before installation. Policy conflict detection is particularly important when multiple applications, such as routing, handover **management, and security monitoring, update overlapping flow entries.**

9.3 Authentication, Privacy, and Mobility Data

V2X nodes should be authenticated before their telemetry or service requests influence controller decisions. Mobility traces are privacy-sensitive because repeated location updates can reveal travel behavior. Final deployment should therefore consider pseudonymity, minimum telemetry disclosure, aggregation, and legal compliance in the jurisdiction of deployment. Blockchain or zero-trust mechanisms may enhance accountability but should be evaluated for latency overhead before use in safety-critical flows.

X. LIMITATIONS

- This manuscript is a Q1-style draft and method proposal derived from a rough M.Tech report; it is not a final empirical submission because raw simulation data were not supplied. The inserted numerical plots and tables are hypothetical demonstrations, not validated simulation results.
- The mathematical model abstracts complex wireless-channel conditions and assumes that link telemetry can be collected with sufficient timeliness.
- Controller placement is treated at a high level; full optimization of multi-controller placement is left for future research.
- The proposed algorithm requires implementation in a simulator or testbed before any performance-improvement claims can be made.
- Security and privacy are discussed as design requirements, not implemented as cryptographic protocols within the algorithm.

- The final validity of the method depends on fair baseline implementation and reproducible logs from NS-3/SUMO, OMNeT++/Veins, or equivalent tools.

XI. CONCLUSION AND FUTURE WORK

This paper transformed a preliminary SDN-V2X dissertation concept into a structured Q1-style research manuscript. The proposed LASRA-V2X framework models heterogeneous vehicular communication as a time-varying graph and uses SDN control to coordinate latency-aware routing, bandwidth allocation, congestion avoidance, flow prioritization, and handover-sensitive forwarding. The paper provides a formal latency model, optimization constraints, algorithm pseudocode, experimental setup, and a transparent result-reporting structure. Because the source report did not provide real simulation output, the numerical plots and values inserted in this version are hypothetical and should be treated as formatting placeholders rather than validated performance evidence.

Future work should implement LASRA-V2X in an NS-3/SUMO or OMNeT++/Veins testbed, compare it against static and non-SDN baselines, evaluate controller-placement alternatives, and report confidence intervals across independent runs. Further extensions may include 6G network slicing, federated learning or reinforcement learning for predictive resource allocation, multi-controller SDN architecture, zero-trust or blockchain-based control-plane protection, and real smart-city pilot deployment.

Data Availability Statement

No raw simulation dataset, trace file, controller log, or empirical numerical result table was available in the uploaded rough report. The result plots and tables in this revised draft use hypothetical values solely for visualization and formatting. The final submission should replace them with simulator scripts, configuration files, raw logs, processed metric files, random seeds, confidence intervals, statistical tests, and plotting notebooks in a public or institutionally approved repository.

Ethics and Competing Interests

The study is a network-simulation and algorithm-design manuscript and does not involve human participants, personal data, or animal subjects. The authors should declare any funding, affiliations, or competing interests before journal submission.

Author Contribution Statement

Conceptualization, methodology, simulation implementation, validation, formal analysis, writing, and review responsibilities should be completed according to the actual author team before submission. This draft should not be submitted until the responsible authors verify all references and replace the hypothetical result values with empirical simulation outputs.

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Appendix A. Hypothetical Result Reporting Table

The following table is completed with hypothetical overall mean values for formatting demonstration. These values are not measured simulation outputs and must be replaced after real simulation execution.

Metric	Static routing	Non-SDN resource allocation	SDN routing only	MEC baseline	LASRA-V2X	Illustrative comparison note
End-to-end delay (ms)	89.0 ± 4.2	76.3 ± 4.2	62.0 ± 4.2	53.0 ± 4.2	39.0 ± 4.2	LASRA lower; Δ=-50.0 ms
Throughput (Mbps)	26.3 ± 2.1	31.0 ± 2.1	36.3 ± 2.1	40.3 ± 2.1	46.7 ± 2.1	LASRA higher; Δ=+20.3 Mbps
PDR (%)	87.4 ± 0.9	90.6 ± 0.9	93.1 ± 0.9	94.4 ± 0.9	96.5 ± 0.9	LASRA higher; Δ=+9.1 pp
Packet loss (%)	12.6 ± 0.9	9.4 ± 0.9	6.9 ± 0.9	5.6 ± 0.9	3.5 ± 0.9	LASRA lower; Δ=-9.1 pp
Jitter (ms)	22.3 ± 1.1	17.6 ± 1.1	14.4 ± 1.1	12.9 ± 1.1	9.1 ± 1.1	LASRA lower; Δ=-13.2 ms
Bandwidth utilization (%)	75.0 ± 1.6	79.7 ± 1.6	82.0 ± 1.6	84.3 ± 1.6	87.0 ± 1.6	LASRA higher; Δ=+12.0 pp
Congestion rate	32.0 ± 1.8	27.0 ± 1.8	21.0 ± 1.8	18.0 ± 1.8	11.0 ± 1.8	LASRA lower; Δ=-21.0 pp
Handover delay (ms)	26.0 ± 1.2	22.5 ± 1.2	18.8 ± 1.2	16.7 ± 1.2	11.3 ± 1.2	LASRA lower; Δ=-14.7 ms
Controller response time (ms)	N/A	N/A	13.0 ± 0.8	12.2 ± 0.8	14.4 ± 0.8	LASRA within control bound

Appendix B. Acronyms

Acronym	Meaning
C-V2X	Cellular Vehicle-to-Everything
DSRC	Dedicated Short-Range Communications
gNB	Next-generation NodeB / 5G base station
LASRA-V2X	Latency-Aware SDN Resource Allocation Algorithm for V2X Networks
MEC	Multi-access Edge Computing
NR	New Radio
OBU	On-Board Unit
PDR	Packet Delivery Ratio

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RSU	Roadside Unit
SDN	Software-Defined Networking
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything