1

Introduction

Every day on our roads, a silent crisis unfolds. Globally, road traffic accidents result in approximately 1.19 million fatalities and 20-50 million injuries annually [1], representing both a public health crisis and a significant socioeconomic burden. These statistics underscore the fundamental limitations of conventional transportation infrastructures that rely primarily on human judgment and static traffic management systems. The economic impact is equally concerning, traffic congestion alone costs major economies between 1-2% of their GDP annually through lost productivity, excess fuel consumption, and environmental degradation [2]. So, what if our car could "see" around corners or warn us about a crash before it happens? Real-world pilot projects, such as the Tampa Hillsborough Expressway Authority Connected Vehicle Pilot [3], Ann Arbor Connected Environment [4], and large-scale deployments in China [5], have demonstrated that 60-80% of unimpaired collisions could be prevented through real-time hazard warnings and cooperative maneuvers enabled by Vehicle-to-Vehicle (V2V) communications. When it comes to avoiding crashes, every millisecond matters. Studies show that reducing communication delay from 100ms to 50ms significantly improves collision avoidance systems, potentially saving thousands of lives annually [6]. Think of it as the difference between a near-miss and a tragic accident.

Vehicular Ad-hoc Network (VANET) represents the technological framework enabling safety-critical/non-safety critical communications [7]. Unlike conventional wireless networks, VANETs are specifically engineered to operate in highly dynamic vehicular environments characterized by rapid topology changes, variable node density, and stringent Quality-of-Service (QoS) requirements. By facilitating real-time information exchange between vehicles (V2V), infrastructure elements (Vehicle-to-Infrastructure (V2I)), and broader network services (V2N), VANETs create a cooperative awareness environment that extends drivers' perceptual horizons beyond line-of-sight limitations. This thesis explores intelligent ways for vehicles to communicate with each other (faster message dissemination), by creating clusters based on where vehicles are actually heading rather than just how close they are, using nature-inspired problem-solving techniques to handle complex routing decisions, and bringing computing power closer to vehicles for faster responses in critical situations.

1.1 EVOLUTION AND ARCHITECTURAL FOUNDATIONS OF VANETS

VANETs represent a specialized evolution of Mobile Ad-hoc Networks (MANETs), optimized specifically for high-mobility vehicular environments. The conceptual foundations of VANETs can be traced to early

2000s military-academic collaborations such as the FleetNet project [1], which established the feasibility of decentralized inter-vehicle communications. This initial research demonstrated that vehicles could form self-organizing networks capable of disseminating safety-critical information without relying on fixed infrastructure. The subsequent development trajectory has been shaped by three parallel forces: academic research advancing theoretical frameworks, industry standardization efforts establishing interoperability protocols, and governmental initiatives allocating spectrum resources and regulatory frameworks.

Figure 1.1 illustrates the core architecture of European Telecommunications Standards Institute (ETSI) Intelligent Transportation System (ITS)-G5 protocol stack [8] (detailed in Chapter 2), which is structured into distinct functional layers to enable cooperative vehicular communication. The Access layer specifies

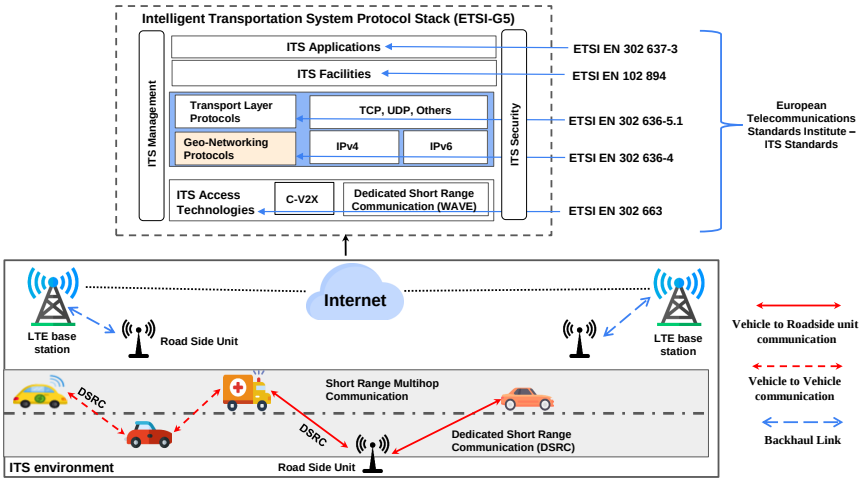

Figure 1.1: Intelligent Transportation System framework: Vehicles exchange data via vehicle-to-vehicle and vehicle-to-roadside units links, with roadside units bridging local networks to find efficient routes.

variants of IEEE 802.11p [9] operating in the 5.9 GHz band to provide low-latency wireless links. The Network & Transport layer, implements GeoNetworking and Basic Transport Protocol (BTP) for location-based routing and packet forwarding, supporting high-mobility communication. Above this, the Facilities layer encapsulates application services such as Cooperative Awareness Message (CAM) and Decentralized Environmental Notification Message (DENM), effectively abstracting the Application layer from the underlying network details. Finally, the Application layer hosts user-centric functionalities, ranging from safety alerts to traffic optimization and remains protocol-agnostic to the lower layers' specifics. In parallel, the United States adopts the IEEE 1609.x (Wireless Access in Vehicular Environments (WAVE)) suite [10] for similar vehicular communication needs. In our research, we emphasize the Network & Transport layer, aiming to optimize routing and data dissemination without constraining or modifying the Applications layer. ITS operate through two foundational communication paradigms:

1. **V2V Communications**: V2V messages enable cooperative awareness through continuous broadcasting of kinematic data (position, velocity, acceleration) using On-board Unit (OBU) integrated within vehicles. This real-time status information significantly enhances driver awareness by providing early alerts about imminent hazards such as sudden braking or lane changes ahead [11].

[1] https://uk.nec.com/en_GB/en/documents/Fleetnet_flyer.pdf

2. **Vehicle-to-Infrastructure (V2I) Communications**: Interactions between vehicles and roadside infrastructure facilitate broader situational awareness and enable applications such as electronic toll collection, traffic signal prioritization, and infrastructure-based hazard warnings [11].

1.2 COMMUNICATION TECHNOLOGIES AND PROTOCOL STACKS

The effectiveness of VANETs fundamentally depends on the underlying wireless communication technologies and their associated protocol stacks. Currently, two primary communication paradigms dominate VANET deployments: IEEE 802.11p/WAVE [9] and Cellular Vehicle-to-Everything (C-V2X) [12].

IEEE 802.11p and WAVE Protocol Stack: IEEE 802.11p represents a specialized amendment to the IEEE 802.11 Wi-Fi standard for vehicular environments. Operating within the dedicated 5.9 GHz ITS frequency band, IEEE 802.11p serves as the foundation for Dedicated Short-Range Communication (DSRC) [13], enabling low-latency direct V2V and V2I communications over distances up to 300 meters under typical conditions [14]. To accommodate the unique challenges of vehicular environments (particularly high node mobility and frequent topology changes) IEEE 802.11p implements several critical modifications to conventional Wi-Fi protocols:

1. **Simplified Association Process**: IEEE 802.11p omits traditional Wi-Fi association handshakes, enabling immediate data exchange without connection establishment delays.
2. **Enhanced QoS Mechanisms**: The Enhanced Distributed Channel Access (EDCA) mechanism, an integral component of IEEE 802.11p, implements multiple priority queues to ensure that time-critical safety messages receive transmission precedence over non-safety data.
3. **Optimized Frame Structure**: Shorter frame intervals and robust modulation schemes enhance reliability under challenging propagation conditions characteristic of vehicular environments.

Building upon IEEE 802.11p at higher networking layers, the IEEE 1609 WAVE standards [15] define a comprehensive networking and security framework specifically designed for vehicular applications. This framework encompasses:

- **Resource Management Protocols** (IEEE 1609.1): Manages resource allocation and service advertisement, enabling vehicles to dynamically discover Road Side Units (RSUs) and Cluster Heads (CHs). This supports adaptive routing in dense environments.
- **Security Services** (IEEE 1609.2): Ensures secure communication through cryptographic authentication, message integrity, and encryption, enhancing trust and resilience against attacks.
- **Networking Services** (IEEE 1609.3): Supports WAVE Short Messages (WSMs) and IPv6 routing, enabling scalable, efficient delivery of both safety-critical and infotainment data.
- **Multi-Channel Operations** (IEEE 1609.4): Enables multi-channel operations, ensuring safety and non-safety traffic coexist without interference. Control and service channels are separated to preserve reliability for high-priority messages.

These standards collectively establish the interoperability framework essential for vehicles from diverse manufacturers to communicate effectively Cooperative-Intelligent Transport Systems (C-ITS) [16].

C-V2X: In parallel with IEEE 802.11p-based solutions, the telecommunications industry has developed C-V2X technology as both an alternative and complementary paradigm for vehicular communications. Standardized initially in Release 14 [17] by the Generation Partnership Project (3GPP) and subsequently enhanced in Releases 15 and 16 [18, 19], C-V2X leverages cellular radio interfaces to support both direct device-to-device connections and infrastructure-mediated communications. C-V2X defines two operational modes that provide complementary capabilities:

1. **Direct Sidelink Mode (PC5 Interface)**: Enables direct V2V/V2I communications independent of cellular base station scheduling, functionally similar to DSRC but with enhanced reliability through advanced resource allocation mechanisms.
2. **Network Mode (Uu Interface)**: Utilizes existing cellular infrastructure for broader information dissemination, particularly beneficial for non-time-critical applications requiring extended geographical coverage.

This dual-mode architecture offers greater flexibility compared to DSRC alone, urgent safety messages can be transmitted directly with ultra-low latency, while less time-sensitive information can leverage existing cellular networks for broader dissemination. The evolution of C-V2X has accelerated with fifth-generation cellular technology (5G New Radio), which delivers significant performance enhancements critical for advanced vehicular applications having ultra-low latencies below 10ms enable time-critical applications such as cooperative collision avoidance [20]. Further, C-V2X provide advanced channel coding and resource allocation mechanisms to achieve high packet delivery ratios and data rates to support bandwidth-intensive applications including sensor data sharing for cooperative perception. The industry momentum behind C-V2X is evidenced by the formation of the 5G Automotive Association (5GAA)[2], a cross-industry consortium comprising over 110 automobile manufacturers[3], telecommunications providers, and technology companies. This consortium has driven interoperability testing, standardization efforts, and regulatory advocacy to significantly accelerate C-V2X adoption worldwide. Consequently, leading automobile manufacturers such as Audi, Ford, BMW, Qualcomm have begun integrating dual-mode DSRC/C-V2X capabilities into their product roadmaps to ensure robust vehicle communications [12].

1.3 RESEARCH MOTIVATIONS AND CHALLENGES

The motivation for advancing VANET technologies comes from their demonstrated potential to address critical real-world transportation challenges. Empirical evidence from pilot deployments and controlled studies consistently demonstrates that effective vehicular communications can significantly mitigate three primary challenges:

1. **Road Safety**: Rapid V2V communication has been shown to prevent 60-80% of traffic accidents through timely hazard notifications [21]. Field trials also have demonstrated that reducing commu-

[2]https://5gaa.org/
[3]https://5gaa.org/members/

nication latency from 100ms to 50ms markedly enhances the effectiveness of collision avoidance systems, potentially saving thousands of lives annually [22].

2. **Traffic Efficiency**: Imagine a vehicle knowing when traffic signals will change or receiving live updates about congestion ahead. Coordinated driving enabled by VANETs can reduce congestion-related costs by 20-30% through smoother traffic flow, optimized routing, and reduced stop-and-go patterns [16]. These efficiency gains translate directly into economic benefits through reduced fuel consumption, lower emissions, and increased productivity.

3. **Emergency Response**: When seconds count, instant notification can save lives. Emergency alerts can substantially reduce emergency response times by instantly notifying authorities and nearby vehicles when incidents occur. Field trials have demonstrated approximately 30% reduction in response times through automated crash notification systems [23, 24].

The economic implications of these benefits are substantial, the U.S. Department of Transportation estimates that fully deployed Vehicle-to-Everything (V2X) systems could prevent 439,000 crashes, save 987 lives, and generate $71 billion in economic benefits annually in the United States alone [25]. Similar analyses in Europe and Asia project comparable benefits, underscoring the global significance of VANETs technologies. The theoretical benefits of VANETs have been increasingly validated through real-world implementations across diverse geographical and operational contexts. In the United States, the Department of Transportation's Connected Vehicle Pilot program implemented DSRC-based V2V communication in Tampa, Florida, broadcasting bus collision warnings in live traffic conditions [3]. This deployment achieved median communication latencies around 60ms even under congested downtown conditions, demonstrating that safety-critical messages can be delivered rapidly enough for effective hazard prevention. Similarly, a New York City pilot employed IEEE 802.11p/WAVE with QoS prioritization via EDCA mechanisms, maintaining reliable delivery of critical safety messages despite significant radio interference typical in dense urban environments [23]. Beyond DSRC implementations, the Virginia Department of Transportation, in collaboration with Audi, deployed traffic signals and work-zone markers equipped with C-V2X RSUs to provide real-time alerts to drivers. This deployment demonstrated the feasibility of C-V2X technology in operational traffic environments, achieving consistent sub-100ms latencies for safety-critical messages [26].

International deployments have further validated VANET technologies across diverse operational contexts. In Wuxi, China, a citywide pilot involving hundreds of connected vehicles adhering to 3GPP Release 14/15 standards successfully sustained sub-50ms end-to-end latency for high-priority emergency messages through advanced sidelink scheduling techniques [5]. Similarly, industry-led demonstrations by companies such as Qualcomm and Huawei showcased 5G-based C-V2X systems achieving latencies below 30ms in field tests [11]. European cross-border trials, including ConVeX [27], CONCORDA [28], 5G CARMEN [29], and 5G MOBIX [30], evaluated C-V2X performance along highways and at blind intersections. These projects consistently reported robust connectivity with sub-100ms latencies even under challenging non-line-of-sight conditions, validating the technology's practicality across complex international scenarios [31]. These successful deployments have catalyzed governmental and industrial initiatives worldwide to accelerate VANET adoption. Countries including the United States, Germany, Japan, and South Korea have established national programs with dedicated spectrum allocations specifically reserved for V2X communications. Developing nations, including India, Brazil, and several African countries, have also initiated groundwork to explore VANET implementations despite challenging local conditions characterized by heterogeneous vehicle types and limited infrastructure support [32].

India's initiatives are also noteworthy, the National Highways Authority (NHAI) recently updated its traffic management standards (AIS140 [33]) to incorporate provisions supporting V2X systems within national highway operations. The Indian government further recommended including V2X communication capabilities as criteria within the Bharat New Car Assessment Program (Bharat NCAP) for enhanced vehicle safety ratings [34]. Such policy-level endorsements reflect clear recognition that connected vehicle technologies will be integral components of India's future transportation ecosystem. The Telecommunications Standards Development Society of India (TSDSI) has actively engaged industry stakeholders, academia, and policymakers to assess national readiness for connected and autonomous driving technologies. TSDSI is specifically addressing use-cases unique to India's mixed traffic environments (cars, motorcycles, auto-rickshaws), intermittent connectivity issues, cost constraints, and identifying necessary adaptations required for successful local VANETs deployments [35]. Concurrently, Indian automobile manufacturers (e.g., Kia Motors with Kia Connect 2.0[4]) and telecom operators (e.g., MG Motors collaborating with Jio on Connected Car Solutions [36]) have initiated preliminary projects exploring V2V communication features within electric vehicles on Indian roads [37]. Although these initiatives remain at early stages without large-scale deployment yet achieved, they clearly indicate growing industry interest within India toward aligning with global advancements in connected vehicle technologies.

Real-world pilot deployments of VANET technologies have underscored a set of concrete networking challenges that motivate this research. In essence, the central challenge is that vehicular networks must operate under extreme mobility, variable density, and limited infrastructure, conditions which conspire to disrupt data delivery. Figure 1.2 illustrates this "big picture" problem context, showing how rapidly moving vehicles, uneven node distribution, and limited connectivity complicate communication. The following real-world observations highlight the key issues and define the problem this thesis tackles.

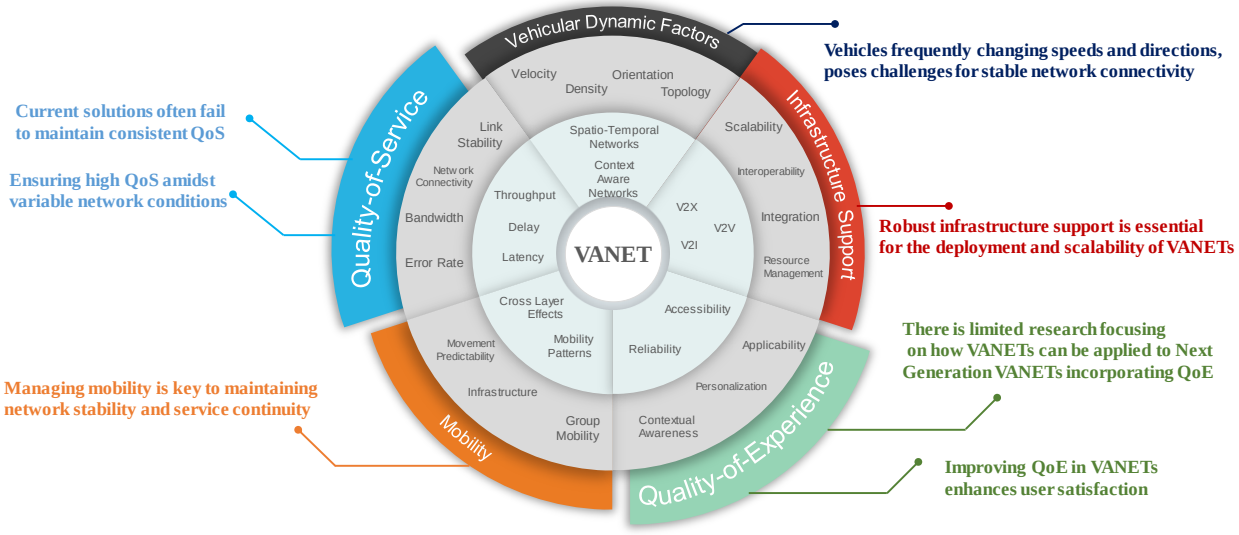

Figure 1.2: The problem – motivation - a big picture

- **Mobility-Driven Topology Churn:** Vehicles in a VANET form a constantly changing ad-hoc network. Links between cars can form and break within seconds as relative positions change [38]. For example, two cars driving in opposite directions at highway speed ($\tilde{1}$00 km/h) remain within wireless

[4]https://www.kia.com/content/dam/kia2/in/en/images/kia-connect/Kia_Connect_2.0.pdf

range for only ~10–15 seconds. Even cars moving in the same direction may abruptly lose contact due to lane changes, highway exits, or obstacles blocking line-of-sight. This fleeting connectivity was evident in cross-border highway pilots like 5G-CARMEN, where maintaining service continuity as vehicles passed between different network domains required seamless handovers and fast route re-establishment. The topology churn induced by high mobility means any routing or dissemination scheme must rapidly adapt to frequent link breakages and reconnections.

- **Unreliable Wireless Links (Non-Line-of-Sight and Interference):** Real urban environments introduce signal blockers (buildings, trucks) and interference, making V2V/V2I links intermittent and unreliable. Pilot deployments reported that even with advanced radios, non-line-of-sight (NLOS) conditions can degrade communication quality. For instance, the New York City pilot noted challenges using DSRC in "urban environments" streets, requiring careful channel management and placement of roadside units. European field tests have similarly demonstrated that maintaining sub-100ms latency under NLOS conditions is difficult without leveraging robust 5G networks and edge assistance. These findings reinforce that VANET protocols must be fault-tolerant, expecting periodic packet loss and sudden drops in link quality.

- **Sparse Infrastructure and Coverage Gaps:** Unlike cellular networks, VANETs cannot assume ubiquitous infrastructure. Many real deployments are confined to pilot zones with a limited number of RSUs. For example, the Tampa Connected Vehicle (CV) Pilot installed only 47 RSUs to cover downtown corridors, and the Wyoming CV pilot spaced RSUs along a rural highway with large gaps in between. Sparse deployment means vehicles often have no fixed relays nearby, especially in developing regions where ITS infrastructure is nascent. In India's early smart highway initiatives, for instance, vehicles must frequently rely on direct V2V communication in the absence of roadside coverage, as nationwide V2X infrastructure is still in its infancy. This poses a dual challenge: maintaining connectivity over potentially multi-hop V2V chains when no infrastructure is present, and handling network partitions in very low vehicle-density scenarios (e.g. late-night highways). A key motivation for this thesis is to enable data dissemination that remains effective even with minimal infrastructure support.

- **Variable Traffic Density and Broadcast Storms:** Network density in VANETs can range from extremely sparse to extremely dense, and both extremes are problematic. In sparse traffic, there may be too few neighboring vehicles to forward a message, causing frequent disconnections. Conversely, in traffic-dense areas (urban downtowns or jammed highways), the wireless channel can be overwhelmed by the sheer number of broadcast messages. This broadcast storm problem is well-documented: when hundreds of vehicles are within radio range, simultaneous transmissions lead to radio collisions and congestion, crippling the network. For example, an urban VANET may see vehicle densities >150 vehicles/km^2, which without controlled dissemination can saturate the 5.9GHz DSRC channel. The Wuxi city-scale C-V2X deployment (with a few hundred equipped cars) had to carefully schedule safety message broadcasts to avoid channel overload, ensuring critical warnings still got through. Likewise, the NYC pilot (over 8,000 vehicles) expended significant effort in tuning broadcast rates and message priorities to mitigate congestion. These real-world lessons motivate our focus on density-aware routing/dissemination techniques that prevent overload while still reaching all relevant receivers.

- **Stringent QoS Requirements:** Many VANET applications are safety-critical, demanding ultra-low latency and high reliability. Collision warnings, for example, need to reach affected vehicles within a hundred milliseconds or less. Achieving such QoS consistently in a volatile network is a core

challenge. The Tampa CV pilot demonstrated that under ideal conditions a well-designed DSRC system can attain $\tilde{6}$0ms end-to-end latencies for safety messages, and a large C-V2X pilot in Wuxi, China achieved even sub-50ms latency for emergency alerts. These are encouraging results, but they were obtained with careful engineering, ample infrastructure, and controlled scenarios. In broader deployments, maintaining <100ms delivery as vehicles rapidly enter/leave communication range and contend for the channel remains an open problem [39, 40]. This thesis is motivated by the need to meet such QoS demands in realistic conditions – ensuring that critical data is delivered on time despite network dynamics and contention.

- **Spatial Dependency of Mobility Patterns**: Vehicle movements exhibit strong spatial dependencies, vehicles follow roads, obey traffic signals, and maintain consistent trajectories within lane boundaries. Unlike random mobility models used in conventional MANETs, vehicular movements are constrained by road infrastructure and traffic regulations. This spatial dependency creates predictable movement patterns that can be leveraged for routing optimization but also introduces challenges when vehicles encounter intersections, merges, or exits where movement patterns suddenly change. Experimental studies using real-world GPS traces [41] have shown that vehicles maintain consistent trajectories approximately 70-80% of the time, with deviations primarily occurring at decision points such as intersections or lane changes.

- **Integration and Interoperability Challenges:** Finally, practical deployment experiences have revealed that even when the networking theory holds, system integration can falter. The Tampa pilot found that several "deployment-ready" devices and applications were not as mature as expected, requiring extensive on-site troubleshooting and iterative testing. Similarly, early pilots uncovered issues with interoperability across vendors and technologies – for example, Europe's shift from IEEE 802.11p to C-V2X raised questions on how legacy and new systems coexist. Ensuring security and privacy (as the NYC pilot did with a full credential management system) also adds overhead that can affect performance. These challenges strengthen the case for research that anticipates real-world complexities. In short, bridging the gap from lab prototypes to deployable solutions motivates us to focus on robustness, standards compliance, and adaptability in our VANET protocols.

In summary, the problem addressed by this thesis is how to achieve reliable, low-latency routing and data dissemination in VANETs under real-world conditions. The work is driven by the issues observed in pilot deployments worldwide: highly dynamic topology and link instability, broadcast storms in dense traffic, long connectivity gaps in sparse networks, and other deployment constraints as outlined above. Figure 1.2 encapsulates this problem space, illustrating the interplay of mobility, density, and infrastructure factors that degrade network performance. By tackling these intertwined challenges, the thesis aims to develop next-generation VANET communication techniques that remain effective where naive approaches break down, thereby enabling vehicular networks to fulfill their promise of safer and more efficient transportation in large-scale, real-life deployments.

1.4 RESEARCH OBJECTIVES AND APPROACH

The primary goal of this thesis is to develop and evaluate next-generation routing and data dissemination techniques that significantly enhance VANET performance across multiple dimensions. We aim to develop solutions that adapt to constantly changing traffic patterns, ensure stable connections (communication links)

for both safety messages (like crash warnings) and convenience features (like traffic updates), work well in both light and heavy traffic, and maintain the QoS levels needed for both safety and non-safety applications. The key research objectives are outlined as follows:

1. **Directional-Awareness in Vehicular Routing**: Imagine you are a driver receiving a road hazard alert. *Would you rather get this message from a car traveling behind you (which hasn't encountered the hazard yet) or from one ahead of you (which has passed the danger)?* Intuitively, a car ahead provides more timely information. Current vehicular communication systems often don't consider this simple logic, they broadcast messages in all directions, creating unnecessary network traffic.

   This objective aims to develop communication techniques that use vehicle direction as a key factor in deciding who should relay messages. By incorporating vehicle orientation, trajectory vectors, and relative directional alignment into routing logic, directional aware protocols can significantly reduce redundant transmissions. Messages can be selectively forwarded primarily along beneficial directions aligned with traffic flow, thereby achieving lower end-to-end latency and higher packet delivery ratios.

2. **Dynamic Clustering for Network Stability (Communication Links)**: Similarly, *imagine how emergency vehicles create temporary order in traffic, other vehicles respond by moving aside in coordinated ways.* Similarly, in digital communication, temporary groups (clusters) of vehicles can work together to pass messages efficiently. This objective works towards creating more stable clusters on the road where certain vehicles take leadership roles in managing communication. Such clustering directly addresses scalability challenges (including broadcast storms) by limiting channel contention through controlled message propagation. CHs serve as temporary communication anchors even as individual vehicles frequently join or leave clusters due to mobility-induced factors. However, the clustering strategy must be lightweight in terms of overhead and rapidly reconfigurable to accommodate frequent topology changes characteristic of vehicular networks.

3. **Spatio-Temporal Aspect of Vehicular Network and Network Softwarization**: *The vehicular traffic behaves differently in a city during morning office time versus mid-afternoon versus evening.* Traditional communication systems use the same approach regardless of when and where vehicles are operating. This objective focuses on to design a framework that leverages spatio-temporal patterns and edge computing to handle dynamic VANET conditions. For example, during rush hour at busy intersections, the system should prioritize short-range, high-frequency messages about immediate traffic conditions. On highways, it should favor longer-range communication about upcoming exits or hazards. This awareness allows adaptive routing decisions that proactively account for short-term fluctuations in topology, minimizing packet delays and improving delivery reliability. Additionally, we aim to explore bringing computing power closer to vehicles through RSUs rather than relying on distant servers to reduce delays and improve responsiveness (addressing network variability) for time-critical warnings.

4. **Real-World Scenario Evaluation**: The final objective is to evaluate the effectiveness of the proposed VANET solutions through comprehensive validation methodologies involving both large-scale simulations and small-scale physical deployments (through testbed). Specifically, the developed routing protocols will be tested using realistic simulation environments designed to closely mimic actual urban road networks imported from OpenStreetMap, utilizing simulation tools such as Simulation of Urban Mobility (SUMO). Subsequently, the proposed approaches will also be validated through physical experimentation using scaled-down hardware testbeds designed to emulate realistic VANET environments.

These objectives collectively address the fundamental challenges in VANET routing and data dissemination, with particular emphasis on enhancing performance in the challenging traffic conditions characteristic of developing regions.

1.5 RESEARCH CONTRIBUTIONS

This thesis attempts to solve contemporary challenges as highlighted in Section 1.3, using directional awareness based protocols, nature based heuristics, and network softwarization. Novel solutions are proposed that assist in fast message dissemination along with satisfying QoS constraints as required by vehicular applications. Figure 1.3 provides a visual summary of the key proposed protocols.

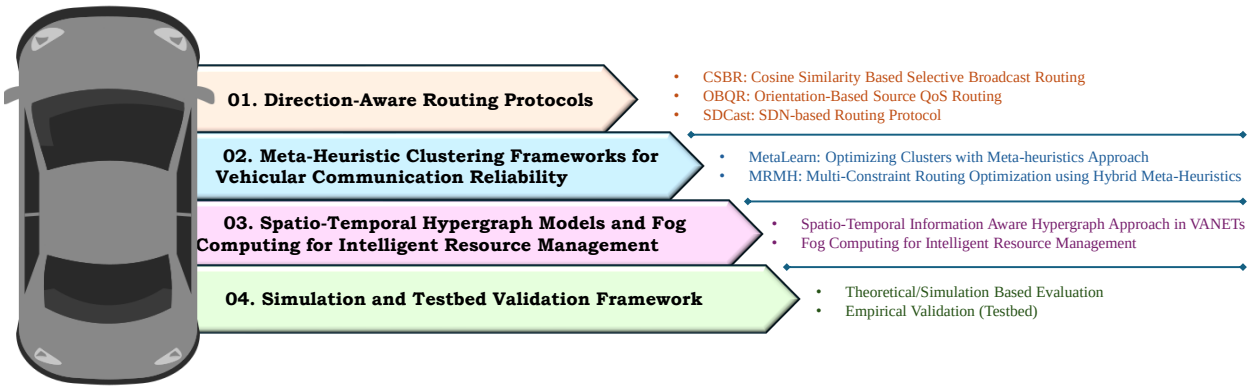

Figure 1.3: Summary of contributions

1.5.1 Direction-Aware Routing Protocols

The fundamental challenge of VANET routing protocols lies in their reliance on proximity-based grouping and scalar metrics (link availability, bandwidth, position), resulting in unstable clusters and frequent route recalculations. Addressing this challenge requires a shift from distance-based to direction-based network organization that aligns with actual vehicle movement patterns rather than just their momentary positions. We propose directional-aware approaches to VANET communication through angular similarity metrics and multi-constraint optimization, creating stable network structures that follow natural traffic patterns while efficiently managing network resources. Our comprehensive solution evolves through three protocols from directional clustering to QoS optimization to intelligent network control, each building upon its predecessor to overcome the limitations of traditional routing approaches in dynamic vehicular environments.

CSBR: Cosine Similarity Based Selective Broadcast Routing: Cosine Similarity Based Selective Broadcast Routing (CSBR) leverages non-linear cluster formation based on cosine similarity indexing to group vehicles with similar directional movements. The novelty of CSBR lies in its two-phase approach: first establishing stable clusters by calculating angular similarity between vehicles regardless of their linear proximity, then implementing a probability-based selective broadcast mechanism that significantly reduces network congestion. CHs are intelligently selected based on minimum cosine distance and maximum adjacency values, creating inherently more stable clusters in dynamic environments. For route discovery, CSBR

employs a distinctive probabilistic forwarding approach where cluster members make packet forwarding decisions based on a specialized probability function, balancing network load while maintaining connectivity. CSBR demonstrated a higher packet delivery ratio, reduced communication overhead, and required fewer neighbor discovery messages.

OBQR: Orientation-Based Source QoS Routing: To address frequent link failures due to the limitations of using single scalar metrics (position, link availability, bandwidth), Orientation-Based Source QoS Routing (OBQR), leverages orientation-based clustering (CSBR) and source-based QoS routing. The novelty of OBQR lies in its use of directional awareness and integration of multiple QoS constraints, including link availability time, transmission cost, and path delays into a single objective using a scalarization technique, transforming the complex multi-constraint routing problem into a single optimization problem. Additionally, OBQR integrates real-time traffic awareness through car-following models and lane-changing models to refine clustering and routing decisions, resulting in more stable communication paths.

SDCast: Software-Defined Networking (SDN)-based Routing Protocol: SDCast integrates SDN with Reinforcement Learning (RL) (Q-learning) and builds upon its predecessor protocols CSBR and OBQR. The novelty of SDCast lies in its cosine similarity-based clustering approach (CSBR) in conjunction with a CH selection mechanism that calculates eligibility scores using multiple parameters including adjacency values, estimated route durations, velocity variations, and positional metrics. For optimal route discovery, SDCast implements a constraint-based Q-learning algorithm that transforms the multi-objective routing problem into a RL framework with a specialized reward function incorporating link availability duration, bandwidth, and delay parameters (following OBQR). The hybrid SDN architecture further enhances system efficiency by distributing computational load between centralized controllers, RSUs, and vehicle OBUs. SDCast provides higher packet delivery ratio, increased throughput, longer cluster head lifetime, lower cluster transition rate.

1.5.2 Meta-Heuristic Clustering Frameworks for Vehicular Communication Reliability

The other challenge in VANET routing is poor convergence issues when attempting to solve multi-constraint optimization problems across heterogeneous network zones with varying density patterns. Route optimization approaches either prioritize exploration (risking slow convergence) or exploitation (risking local optima convergence), resulting in sub-optimal cluster formations and inefficient routing paths in dynamic vehicular environments. Furthermore, single-algorithm techniques typically solve either the clustering problem or the routing problem independently. We propose nature-inspired solutions to address routing optimization challenges through algorithm hybridization, combining global population-based search techniques with powerful local refinement mechanisms to simultaneously optimize cluster stability and route discovery while dynamically adapting to network volatility through nonlinear convergence control.

MetaLearn: Optimizing Clusters with Meta-heuristics Approach: This framework (MetaLearn), proposes a hybrid approach that optimizes routing in VANET by combining meta-heuristics with RL. The novelty of MetaLearn lies in its two-phase architecture: first utilizing Grey Wolf Optimization (GWO) for stable cluster formation and optimal CH selection based on multiple QoS parameters, then employing Temporal Difference Learning (specifically Q(λ) learning) for intelligent route discovery between clusters. This combination balances global exploration through GWO with exploitation through Q(λ) learning, overcoming limitations of single-technique approaches. Another contribution is the parameterized method that removes future rewards uncertainty while enabling vehicular state exploration to optimize multilevel net-

work structures. The customized reward function further enhances cluster stability and routing efficiency by considering link availability, delay, distance, and queue occupancy.

MRMH: Multi-Constraint Routing Optimization using Hybrid Meta-Heuristics: To address reliance on absolute positional information and static clustering limitations, this framework introduces a novel Multi-constraint Routing Mechanism using Hybridization (MRMH), uniquely combining GWO and Sequential Quadratic Programming (SQP). MRMH leverages GWO's global exploration capabilities while effectively mitigating its premature convergence through SQP's refined local optimization abilities, specifically designed to handle nonlinear, multi-dimensional VANET constraints. Moreover, MRMH incorporates a novel nonlinear decay formulation for dynamically adjusting exploration and exploitation phases, significantly enhancing adaptive responsiveness (variations in network volatility) to real-time vehicular dynamics. A novel fitness function integrating critical vehicular parameters (inter-cluster distance, relative velocity, and orientation similarity) optimize CH selection, ensuring robust and stable routing paths.

1.5.3 Spatio-Temporal Information Aware Hypergraph Models and Fog Computing for Intelligent Resource Management

Another fundamental limitation addressed in this thesis is the use traditional graph based routing methods for multi-dimensional vehicle interactions and reliance on centralized processing for latency-sensitive applications. These constraints create critical bottlenecks in both routing decision quality and computational resource management across geographically dispersed networks. We propose novel hypergraph-based approach that accurately capture complex many-to-many communication patterns while integrating deep learning for spatio-temporal feature extraction, alongside a novel Software-Defined Fog Computing Framework (SDFC) framework that strategically distributes intelligence throughout the network hierarchy using parallel clustering and adaptive load balancing mechanisms. Together, these frameworks deliver improvements in routing optimization, latency reduction, and resource utilization.

Spatio-Temporal Information Aware Hypergraph Approach in VANETs: Efficient routing in Software Defined Vehicular Network (SDVN) remains a significant challenge due to their highly dynamic and multi-dimensional communication patterns, which traditional graph-based routing methods inadequately capture. To address these limitations, this framework introduces a novel hypergraph-based deep learning routing framework. The key novelty of this work lies in representing vehicular communication interactions through hypergraphs, effectively modeling multi-way, complex dependencies among multiple vehicles that conventional graphs fail to represent. Furthermore, the approach integrates Convolutional Neural Networks (CNN) for spatial feature extraction, Gated Recurrent Unit (GRU) for temporal dynamics modeling, and a Deep Deterministic Policy Gradient (DDPG)-based RL model for adaptive routing policy optimization. An integrated attention mechanism further refines spatio-temporal features by prioritizing critical routing decisions in real-time. Simulation and empirical (testbed) experiments demonstrate that this hypergraph-enhanced methodology substantially outperforms existing routing solutions, achieving explicit improvements in critical QoS metrics, lower latency, faster model convergence, reduced computational overhead, and significantly lower memory utilization.

Fog Computing for Intelligent Resource Management: To provide intelligent resource management, this work introduces a SDFC framework specifically for VANET environments. The novelty of this work lies in the integration of fog computing paradigms with SDN, enabling dynamic, decentralized decision-making at the network's edge. The proposed approach employs a Parallel Dynamic Clustering (PDC) algorithm, in-

spired by Hadoop's MapReduce model, facilitating rapid and scalable clustering of vehicular nodes based on geographical proximity and communication frequency. Additionally, the framework utilizes a flow-based load balancing mechanism, specifically integrating Traefik with a Proportional-Integral-Derivative (PID) controller, ensuring adaptive and precise traffic distribution among fog nodes. Another contribution is the intelligent controller placement strategy, employing integer linear programming combined with a greedy algorithm, which strategically positions network controllers to minimize communication overhead and latency. Empirical evaluations conducted via testbed experiments and OMNeT++ simulations demonstrate that the proposed SDFC framework achieves an improvement in response time, a reduction in network latency, and faster resource allocation.

1.6 RESEARCH METHODOLOGY AND VALIDATION APPROACH

This thesis employs a comprehensive research methodology that combines theoretical/simulation-based evaluation, and experimental validation to ensure both theoretical validation and practical relevance. The research process follows a systematic progression through several interconnected phases:

1.6.1 Theoretical/Simulation Based Evaluation

The initial phase involves utilizing simulation frameworks for the validation of the proposed techniques, enabling controlled experimentation across diverse scenarios. This includes:

- **Network Traffic Patterns:** Our experimental setup followed a realistic vehicle communication network where vehicles frequently share digital updates with each other. These vehicles send out regular beacon messages every 100 to 300 milliseconds containing essential information such as their position, speed, and vehicle ID. This follows established standards used in Europe (ETSI CAMs) [7] and the United States (Basic Safety Message (BSM) protocols) that typically update 10 times every second. Beyond these routine updates, vehicles also transmit urgent emergency alerts whenever they detect road hazards, which get priority treatment in the network using IEEE 1609 EDCA mechanisms and DENM messages [42]. Additionally, the simulation also includes everyday traffic like entertainment streaming and map updates, which travel over UDP connections and are managed by RSUs connected to a central SDN controller through LTE. We model a busy traffic scenario with 200 vehicles moving within a 5 $\times$ 5 kilometer area, comparable to the real-world U.S. Safety Pilot Model Deployment [14] that equipped 3,000 vehicles with DSRC technology across 73 square kilometers. Further, the simulation's wireless communication module strictly follows the IEEE 802.11p standard, operating in the 5.85-5.925 GHz frequency range with 10 MHz channels and data speeds ranging from 3 to 27 Mbps. Vehicles transmit at 20 dBm power, while RSUs can reach up to 33 dBm, matching the capabilities of commercial Cohda Wireless MK5[5] OBUs used in real deployments. To accurately represent how signals behave in the real world, we use a two-ray ground model combined with Nakagami fading, closely mimicking actual DSRC signal characteristics. At the MAC layer, the simulations setup implement IEEE 1609.4 and 802.11p EDCA default settings with transmit queues that can hold up to 50 packets, reflecting the typical hardware limitations found in production-grade OBUs.

[5] https://www.cohdawireless.com/solutions/hardware/mk5-obu/

- **Mobility Modeling**: Our simulations use real-world traffic patterns to create vehicular movements. We use the SUMO platform [43] to generate realistic traffic flows across city streets and highways. Further, we create a digital twin of actual roadways by importing real street maps from OpenStreetMap [44]. The maps were further carefully verified against high-resolution satellite images before converting them into simulation-ready formats using NETCONVERT tools, preserving important features like speed limits, lane merges, and traffic signals. The vehicles in our simulation behave like real drivers, following realistic speed patterns, 30–50 km/h in busy city areas and up to 120 km/h on highways [45]. We use car-following and lane-changing models that mimic how actual drivers behave in traffic. Figure 1.4 shows how we model these traffic flows with vehicle dynamics. Just like

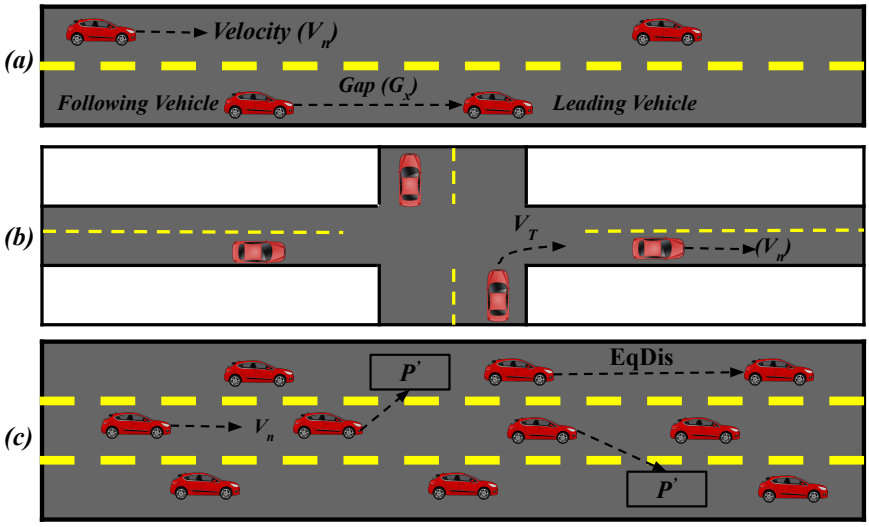

Figure 1.4: Traffic flow arrangement with vehicle dynamics. (a) Car-following model. (b) Turning decision model (c) Lane changing model.

real drivers maintain a safe distance from the car ahead, our model includes a safety gap calculation shown in equation (1.1):

$$SG_x = \ell_{x-1} - L_{\alpha-1} - \ell_x, \tag{1.1}$$

This equation calculates the space between vehicles, ℓ_{x-1} represents where the front vehicle is positioned, ℓ_x shows where the following vehicle is, and $L_{\alpha-1}$ is the length of the lead vehicle. The result, SG_x, tells us the actual gap between the back bumper of the front car and the front bumper of the following car. Just as you adjust this gap based on your speed in real driving (more space at higher speeds), our safety gap model [46] ensures vehicles maintain appropriate spacing to prevent collisions under various conditions [47]. Further, the simulation setup also captures how drivers adjust their speed in response to others like de-accelerating the car when approaching a slower vehicle. This dynamic car-following behavior is described by:

$$\frac{dvel_\alpha}{dt} = a_m(G_x(t), vel_\alpha(t), \Delta vel_\alpha(t)), \tag{1.2}$$

This equation shows how a driver changes speed ($\frac{dvel_\alpha}{dt}$) based on the gap to the next car ($G_x(t)$), their current speed ($vel_\alpha(t)$), and the speed difference between them and the car ahead ($\Delta vel_\alpha(t)$). The function a_m represents how these factors combine to determine acceleration or braking, similar to how one might react differently when following a slow truck versus another car. For turning or

changing lanes maneuvers that require special care in real driving, following safety equation has been formulated:

$$a_n(SG_n, vel_n, vel_{n-1}) > -b^a_{safe}, \tag{1.3}$$

This ensures that when a vehicle makes a turn or changes lanes, it won't need to brake too suddenly (staying above the safety threshold $-b^a_{safe}$) based on the available gap (SG_n) and the speeds of both the maneuvering vehicle (vel_n) and the vehicle ahead (vel_{n-1}). These detailed models work together to create a virtual traffic environment that behaves like real-world traffic. This allows us to test how different communication methods perform under various conditions, from smooth-flowing highway traffic to congested city intersections with vehicles constantly changing speed and direction [48].

- **Network Modeling**: In VANETs, graph theory gives a way to transform chaotic movements of vehicles into a structured graph. In our model, we represent each vehicle/RSUs as a vertex in a graph $G = (V, E)$, while the wireless connections between them become edges connecting vehicles and RSUs. Each vertex carries important information i.e., location, velocity, and orientation. The position of any vehicle v_i at a specific moment t is given by coordinates $\mathbf{p}_i(t) = (x_i(t), y_i(t))$, which change as the vehicle moves. Meanwhile, the communication links between vehicles have their own characteristics, i.e., signal strength, data capacity, and delay time.

  Two vehicles can communicate only when they're close enough to each other, within a maximum range of R (typically a few hundred meters). We create a connection matrix called an adjacency matrix $A(t)$ that shows which vehicles can send messages to each other at any moment, where $a_{ij}(t) = 1$ means vehicles i and j can communicate, and $a_{ij}(t) = 0$ means they can't. This matrix constantly updates as vehicles move around, providing a real-time snapshot of the network. Data flowing through this network follows a simple principle of balance:

$$\sum_{v_i \in V} f_{ij} = \sum_{v_j \in V} f_{ji}, \quad \forall v_i \in V$$

  where f_{ij} represents information flowing from vehicle i to vehicle j. We measure how densely connected our network is by calculating what percentage of all possible connections actually exist. This helps us understand where data congestion might occur. Using these graph-based models, we can calculate critical measurements like the average number of hops a message needs to travel, the maximum distance between any two vehicles in the network, and how tightly clustered vehicles are. These measurements help us identify which vehicles and connections are most critical, like finding the key intersections in a city whose closure would cause the most traffic problems. This knowledge guides us in developing intelligent routing algorithms that can quickly adapt when vehicles enter, leave, or change position in our network.

- **Network Simulation Tools**: The research employed three simulation platforms to validate the proposed VANET routing and data dissemination techniques:

  Network Simulator 2 (Network Simulator 2 (NS2)): NS2 is a discrete event simulator designed specifically for networking research, offering extensive support for simulating TCP, routing, and multicast protocols across both wired and wireless networks [49]. The simulator's dual-layer architecture combines a C++ core for event-driven simulations with an OTcl interpreter for configuration and scripting, enabling detailed protocol modeling alongside flexible scenario configuration. For VANET-specific simulations, NS2 provides essential mobility models including Random Waypoint, Manhattan Grid, and support for realistic vehicular traces. Its capabilities are significantly enhanced through integration with specialized modules like Mobility Model Generator for Vehicular Network

(MOVE) [50] and SUMO [51], which generate realistic vehicular mobility patterns that seamlessly integrate into NS2 simulations. This integration enables accurate representation of vehicle movements along road networks, including lane changes, varying speeds, and intersection behaviors critical for evaluating routing protocol performance under realistic conditions.

Network Simulator 3 (Network Simulator 3 (NS3)): NS3, the successor to NS2, addresses its predecessor's limitations through a more modular and flexible architecture implemented in C++ with Python bindings [52]. This modern design delivers enhanced performance and scalability for complex network simulations, particularly beneficial for large-scale VANET scenarios. The simulator includes sophisticated physical layer models that accurately represent propagation loss, interference, and fading effects characteristic of vehicular environments. A particularly valuable feature is NS3's support for real-time network emulation and integration with real-world network stacks, enabling hybrid simulations that combine simulated and physical network components. This capability proved essential for validating the proposed routing protocols under conditions closely approximating real-world deployments. NS3's extensive protocol libraries and seamless integration with SUMO for mobility modeling enabled comprehensive evaluation of the routing protocols and clustering mechanisms developed in this research.

Objective Modular Network Testbed (Objective Modular Network Testbed (OMNeT++)): OMNeT++ provides a comprehensive simulation framework built around a highly modular, component-based architecture [53]. Simulations are constructed from reusable components called modules that can be assembled and configured to model complex network behaviors, making it particularly well-suited for VANET research. The framework features a powerful Graphical User Interface (GUI) that supports the design, execution, and analysis of simulation scenarios, with visualization tools for network topology, traffic flows, and performance metrics. OMNeT++ integrates with external tools including SUMO for mobility modeling and the INET framework for detailed protocol simulation, facilitating the creation of realistic vehicular network scenarios. Advanced features such as hierarchical modeling, detailed parameter configuration, and comprehensive logging and analysis tools enabled in-depth study and optimization of the proposed VANET protocols, particularly for evaluating the spatio-temporal hypergraph models and fog computing frameworks developed in this research.

These three simulation platforms, each with complementary strengths, provided a strong foundation for validating the research contributions across diverse scenarios and network conditions.

- **Performance Metrics**: Comprehensive performance evaluation considers multiple metrics, including packet delivery ratio, end-to-end latency, network throughput, control overhead, cluster stability, and computational efficiency. These metrics are analyzed across different network conditions to provide a assessment of the proposed techniques.

1.6.2 Empirical Validation

To bridge the gap between simulation and real-world deployment, selected components of the proposed solutions are implemented and evaluated on physical testbeds:

- **Duckietown Platform**: Duckietown is an advanced educational and research platform designed for autonomous driving and ITS experiments [54]. It comprises a modular and scalable setup that includes miniature autonomous vehicles (Duckiebots) and a configurable road infrastructure, providing a comprehensive environment for developing and testing autonomous driving algorithms. Duckiebots

are equipped with sensors, cameras, and processing units, and operate within a modular road system featuring traffic signs, intersections, and other urban features. Duckietown supports the implementa-

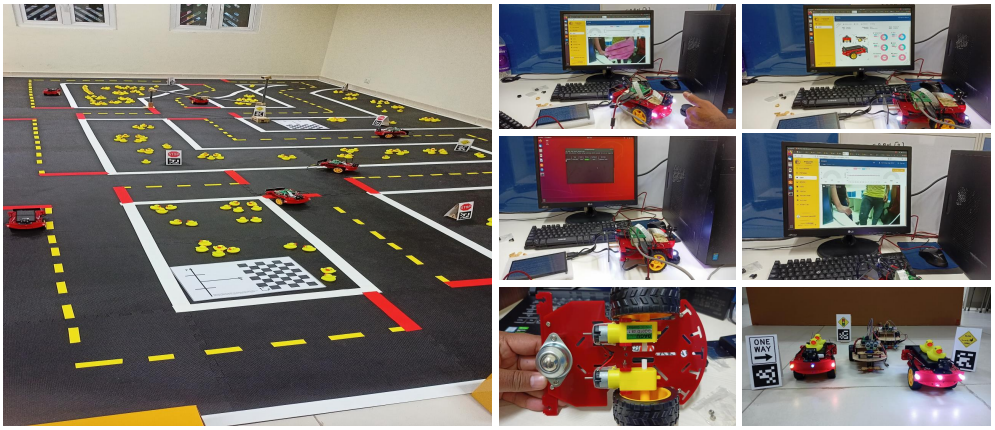

Figure 1.5: Duckietown testbed for vehicular communication

tion and testing of various algorithms related to perception, planning, and control in a controlled environment. It also facilitates experiments on V2V and V2I communication, making it highly suitable for VANET research. The platform's scalability and customizability enable researchers to replicate complex urban scenarios and assess the scalability of their solutions. Duckietown's modular design allows for the seamless addition of new components and features, enhancing its versatility for diverse research needs. Figure 1.5 illustrates the vehicular testbed developed for this research, showcasing a comprehensive setup designed to evaluate various aspects of VANET performance.

- **Edge Computing Testbed**: The Intel Xeon Server with NVIDIA Jetson constitutes a robust computational platform capable of handling intensive Machine Learning (ML) and Artificial Intelligence (AI) workloads essential for VANETs applications. The Intel Xeon Server, with its multiple cores and

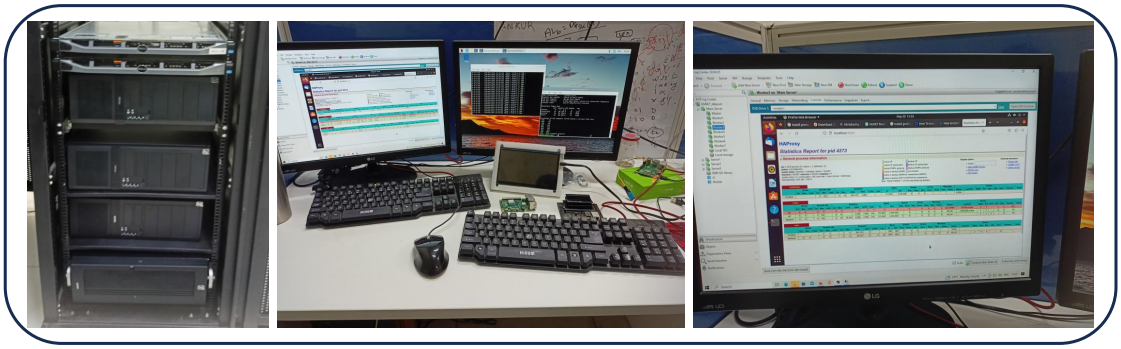

Figure 1.6: Server testbed for vehicular communication

substantial memory capacity, is ideal for executing complex simulations and data processing tasks inherent in HPC applications. This server provides the computational power required for large-scale VANET simulations. Integrated with the server, the NVIDIA Jetson module offers GPU acceleration, significantly enhancing real-time data analysis and ML capabilities. The integration of Intel Xeon and NVIDIA Jetson enables real-time processing of the vast amounts of data generated by VANETs. This

supports the deployment of advanced algorithms that demand high throughput and low latency, ensuring efficient handling of dynamic vehicular data. Figure 1.6 illustrates the server and edge device setup developed for this research, highlighting the infrastructure designed to support the experiments. It includes a central server responsible for managing data processing and storage, connected to multiple edge devices deployed at strategic locations.

- **Hardware Testing**: Raspberry Pi devices serve as edge computing nodes within VANETs, facilitating local data processing and communication. These devices provide an affordable and flexible platform for implementing edge computing in VANETs. Deployable in vehicles (OBU) or RSU, Raspberry Pi devices process data locally, reducing reliance on centralized cloud servers and minimizing latency. They support a wide array of sensors, including Global Positioning System (GPS), cameras, and environmental sensors, enabling the collection of diverse data types crucial for VANET applications such as vehicle tracking, environmental monitoring, and safety alerts.

1.7 THESIS ROADMAP

The remainder of this thesis is organized as follows:

Chapter 2: Background and Related Works provides a comprehensive literature review of existing VANET routing (field pilots and simulation both) and data dissemination techniques. It critically analyzes current approaches to mobility-aware routing, QoS optimization, clustering mechanisms, and software-defined networking in vehicular environments. The chapter identifies key research gaps and establishes the context for the contributions presented in subsequent chapters.

Chapter 3: Direction-Aware Routing Protocols introduces novel routing protocols that leverage directional information to enhance network performance. The chapter presents the CSBR, OBQR, and SDCast protocols, detailing their design principles, algorithmic implementations, and performance characteristics.

Chapter 4: Meta-Heuristic Clustering Frameworks for Vehicular Communication Reliability explores advanced clustering techniques that enhance network stability in highly dynamic vehicular environments. The chapter presents the MetaLearn and MRMH frameworks, which combine meta-heuristic optimization with reinforcement learning to establish stable cluster structures.

Chapter 5: Spatio-Temporal Hypergraph Models and Fog Computing for Intelligent Resource Management investigates the integration of fog computing and software-defined networking principles to enhance VANET adaptability. The chapter presents a spatio-temporal hypergraph model and a software-defined fog computing framework that enable efficient resource management and dynamic network reconfiguration. Experimental results validate the effectiveness of these approaches in improving network performance and computational efficiency.

Chapter 6: Conclusions and Future Directions synthesizes the key findings and contributions of the thesis, discussing their implications for future VANET deployments. The chapter also identifies promising directions for future research, highlighting emerging technologies and challenges that warrant further investigation.