International Journal of Computer Networks and Applications (IJCNA)
DOI: 10.22247/ijcna/2024/28 Volume 11, Issue 4, July – August (2024)

RESEARCH ARTICLE

Impact of Network Complexity, Mobility Models, and Wireless Technologies on SDN-DTN Performance in Internet of Vehicles (IoV) Environments

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Received: 23 April 2024 / Revised: 06 August 2024 / Accepted: 14 August 2024 / Published: 31 August 2024

Abstract – The Internet of Vehicles (IoV) is a rapidly advancing field that necessitates highly efficient data transmission, particularly for services like video streaming, which require seamless delivery of audio and video content. However, the dynamic nature and high mobility inherent in IoV present significant challenges, impacting key metrics such as initial start time, stall count, and stall length. Existing research has addressed some optimization factors, yet comprehensive solutions that consider network complexities, node mobility patterns, and varying wireless technologies are still needed. This study proposes a model combining Software-Defined Networking (SDN) and Delay-Tolerant Networking (DTN) concepts to address these challenges. By exploring the impact of network complexities, node mobility patterns, and wireless technologies (including 802.11g and 802.11ax) on video streaming performance in both intra and inter-IoV networks, the study identifies critical factors contributing to optimal performance. The proposed SDN-DTN based model dynamically adapts to changing network conditions, thereby minimizing initial start times, reducing stall counts, and shortening stall lengths compared to existing methods. This approach offers valuable insights into designing robust and adaptive IoV infrastructure, emphasizing the importance of addressing complex network dynamics for seamless video streaming. The findings highlight the necessity of integrating advanced networking technologies to overcome the inherent challenges of IoV, ensuring a more resilient and efficient data transmission framework.

Index Terms – Delay-Tolerant Networking, Internet of Vehicles, Metrics, Performance Analysis, Simulator, Software-Defined Networking, Video Streaming, Wireless Technologies.

1. INTRODUCTION

The Internet of Vehicles (IoV) revolutionizes transportation by integrating vehicles with the Internet and other communication technologies, creating an intelligent and interconnected system. This innovation consists of an array of sensors, communication devices, and onboard computers embedded within vehicles to transform them into active data sources. This interconnectedness facilitates real-time data exchange between vehicles, infrastructure, and other road users, leading to significant advancements in connectivity and efficiency within the transportation sector. Vehicles equipped with numerous sensors collect data on various parameters such as speed, location, fuel consumption, and environmental conditions[1][2].

The IoV networks involve extensive information transmission, including voice, video and messages, from vehicular equipment to various infrastructures. These infrastructures can include other vehicles for Vehicle-to-Vehicle (V2V) communication, which allows vehicles to share real-time data about traffic conditions, road hazards, and other critical information. Vehicle-to-Infrastructure (V2I) communication, which involves interaction with traffic lights, road signs, and other elements of the transportation infrastructure to optimize traffic flow and improve safety. Vehicle-to-Sensor (V2S) communication, which involves environmental sensors that monitor weather conditions, air quality, and other environmental factors that can affect driving conditions. Vehicle-to-Passenger (V2P) communication, which enhances passenger engagement by providing real-time updates, entertainment options, and connectivity services within the vehicle. Vehicle-to-Cloud (V2C) communication, which integrates cloud services allowing vehicles to access powerful computing resources, data storage, and advanced analytics. This integration supports services such as navigation, predictive maintenance, and personalized driving experiences. Vehicle-to-Home (V2H) communication, which connects vehicles with smart home systems, enabling seamless integration and control of home automation devices from within the vehicle. Vehicle-to-Building (V2B) communication which links vehicles with building systems, facilitating functions such as automated parking, security access, and energy management. Vehicle-to-Grid (V2G) communication which interacts with the electrical grid, allowing vehicles to exchange energy with the grid, hence supporting renewable energy integration and grid stability. Finally, Vehicle-to-Roadside (V2R) communication which provides updates and information from roadside units, enhancing navigation and situational awareness for drivers [3].

This interconnected IoV ecosystem significantly enhances intelligence and efficiency in transportation. By enabling seamless communication between vehicles, infrastructure, and various other systems, IoV fosters a more responsive and adaptive transportation network. This leads to improved traffic management, increased safety, reduced environmental impact, and a more convenient and engaging driving experience for passengers. The comprehensive integration of IoV components creates a robust framework that supports the future of smart, connected transportation. Given the dynamic nature of IoV environment, network characteristics can be unpredictable, particularly during periods of high traffic that may surpass available infrastructures, leading to a resource-constrained scenario[4].

Delay-Tolerant Networks (DTNs) have been recognized as suitable technologies for operating in resource-constrained scenarios due to their inherent store and forward mechanism. This mechanism allows DTNs to store data packets temporarily at intermediate nodes when a direct end to end connection is not available, and then forward them when the connection is restored. This approach makes DTNs particularly effective in environments where network connectivity is intermittent or unreliable, such as remote areas, disaster-stricken regions, and space communications.

Despite their advantages, DTNs exhibit limited flexibility in certain aspects. One major limitation is their static routing protocols, which are not well-suited to dynamic and rapidly changing network topologies[5]. In traditional DTNs, the routing decisions are often made based on predefined rules or historical data, which can result in suboptimal performance when network conditions change unexpectedly. This inflexibility can lead to increased latency and reduced reliability in data delivery, especially in highly mobile environments like the Internet of Vehicles (IoV).

Additionally, DTNs rely heavily on the availability of intermediate nodes with sufficient storage capacity to hold data packets until they can be forwarded. In scenarios where such nodes are scarce or their storage resources are limited, the performance of DTNs can degrade significantly. This constraint poses a challenge in ensuring efficient data transmission and timely delivery, particularly in networks with high data volume and limited storage infrastructure[6].

Moreover, the store and forward mechanism of DTNs can introduce delays, as data packets may need to wait at intermediate nodes for extended periods before being forwarded. This can be problematic for applications requiring low latency, such as real-time video streaming or critical communication services. The delay tolerance inherent in DTNs, while beneficial for some applications, may not meet the stringent requirements of others like limited flexibility[7].

Software-Defined Networks (SDNs) on the other hand, can provide the needed flexibility by allowing dynamic and programmable control over the network, enabling real-time adjustments to routing and resource allocation based on current network conditions[8]. By integrating SDN with DTNs, it is possible to enhance the adaptability and performance of the network, making it more suitable for complex and dynamic environments like IoV [9]. However, the performance of SDN is influenced by various factors such as network size, complexity, the capabilities of hardware and software devices, and the specific applications being deployed. In large and complex networks, the centralized control approach of SDN can lead to bottlenecks and scalability issues, as the SDN controller must manage and process a vast amount of network data and control messages[10]. The efficiency of SDN also heavily relies on the performance and compatibility of the underlying hardware and software devices, which must support SDN protocols and features to fully leverage its advantages[11].

When considering video streaming in IoV scenarios, such as vehicle surveillance, optimizing performance metrics becomes crucial to ensure a seamless and effective monitoring experience for users. Key performance metrics that need to be optimized include stall count, initial start time, and stall length. In addressing these limitations, an integrated infrastructure of SDN and DTNs is used.

The combined architecture of SDN and DTNs has proven to be effective in optimizing data transmission in areas with intermittent connectivity, such as Tactical Edge Networks (TENs)[5], Vehicular Ad-hoc Networks (VANETs)[12], and post-disaster scenarios[13]. In TENs, for example, where reliable communication is critical for military operations, the integration of SDN and DTNs enhances the network's ability to adapt to changing conditions and maintain communication despite disruptions. Similarly, in VANETs, the combined architecture supports efficient data exchange between vehicles, improving safety and traffic management. In post-disaster scenarios, where traditional communication infrastructure may be compromised, the SDN-DTN architecture enables resilient data transmission by dynamically rerouting data through available nodes and using store and forward techniques to overcome connectivity gaps. These applications demonstrate the robustness and flexibility of the combined architecture in challenging environments. However, existing studies have predominantly focused on information transmission within intranets[5], addressing the internal communication within specific, controlled environments. While these studies have provided valuable insights into the benefits of the SDN-DTN combination for data transmission in such scenarios, they have often neglected the opportunity to delve into the broader technological effects on data transmission within IoV networks.

IoV networks introduce additional layers of complexity due to factors such as wireless communication technologies, mobility patterns of vehicles, and the overall complexity of the network environment. Wireless communication technologies like 802.11g and 802.11ax have different capabilities and performance characteristics, which can significantly impact data transmission quality in IoV scenarios. Mobility patterns, which are highly dynamic and unpredictable in vehicular networks, further complicate the reliable delivery of data. Vehicles constantly change their position and speed, leading to frequent disconnections and reconnections that must be managed effectively[14][15].

Additionally, the complexity of IoV networks, characterized by a high density of nodes (vehicles, sensors, infrastructure elements) and the variety of communication links (V2V, V2I, V2S, V2P, V2C, V2H, V2B, V2G, V2R), presents unique challenges for ensuring efficient and reliable data transmission. Each type of communication link has distinct requirements and constraints, necessitating a comprehensive approach to network management.

By exploring these technological effects, researchers can identify critical factors that influence data transmission performance in IoV networks and develop targeted strategies to optimize these factors. For instance, understanding how different wireless technologies perform under various traffic conditions and mobility scenarios can inform the design of adaptive communication protocols that adjust in real-time to maintain optimal data flow. Investigating the impact of vehicle mobility patterns can lead to the development of predictive algorithms that anticipate disconnections and proactively reroute data to minimize disruptions.

This study therefore

- Examines the influence of network complexity on the operational performance of SDN-DTN in dynamic IoV environments,
- Analyzes how different mobility models of vehicles impact the stability and performance of the network,
- Evaluates the suitability and performance of various wireless technologies, such as 802.11g and 802.11ax, in IoV scenarios,
- Optimizes streaming processes within both intranets and internetworks,
- Identifies critical factors that enhance streaming performance and overall efficiency in SDN-DTN architectures for IoV networks, and
- Develops strategies to improve the robustness and adaptability of SDN-DTN systems in complex and dynamic IoV environments.

The goal is to deploy SDN-DTN for reliable data delivery in a bustling IoV context, providing valuable insights into traffic data and video information transmission by addressing gaps in understanding IoV systems, this research contributes to enhancing the performance of dynamic vehicular networks.

The rest of the paper is structured as follows: Section 2 discusses all the involved technologies highlighting all their utilization. Section 3 delves into the methodology undertaken to perform all the analysis. Section 4 discusses all the findings obtained from the simulations and Section 5 summarizes all the findings obtained while highlighting all the necessities unveiled.

2. BACKGROUND

IoV revolutionizes transportation by integrating vehicles with sensors, communication devices, and onboard computers,

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thereby enabling vehicles to communicate with each other and with the surrounding infrastructures [16]. This in turn enables real-time data exchange on vehicle speed, location, road conditions and more, leading to enhanced intelligence and efficiency in transportation[3]. All this is done to enhance vehicular safety, traffic efficiency, passenger experience, enable autonomous driving and preserve the environment. IoV infrastructures, encompassing V2S, V2P, V2C, V2H, V2B, V2G and V2R, revolutionize vehicular dynamics.

With all these categories involved in IoV, a lot of work has been done to improve on the communication efficiency, for example, technologies like Video streaming approaches [17], computing techniques like fog communications[18], as well as machine learning concepts like Reinforcement learning in [19].

Due to the dynamic nature exhibited by the IoV categories, a better technology is required to substantially boost communication through tackling the ground mechanics and this happens to be DTN. DTN, whose capability is majorly focused on store and forward is deemed to be a necessary technology to counteract the poor performance exhibited by the alternative driven IoV technologies.

DTN strategically addresses the technical challenges inherent in heterogeneous networks, where communication flows contend with consistent disruptions attributed to factors such as link unreliability and latency [20]. To triumph over these hurdles, DTN adopts a store, carry and forward message routing approach, thereby ensuring the resilience and reliability of data transmission. DTN technology encompasses a diverse range of communication protocols designed to facilitate data forwarding in environments where network connectivity is intermittent. These protocols, including Epidemic[21], Probability Routing Protocol using History of Encounters and Transitivity (PRoPHET)[22], PRoPHETv2, MaxProp, Resource Allocation Protocol for Intentional DTN routing (RAPID), Spray and Wait[23], and Spray and Focus[24], each offers unique mechanisms to improve the efficiency and effectiveness of data transfer under challenging network conditions. Epidemic routing, inspired by the spread of diseases, replicates and disseminates data packets to all nodes in the network, ensuring high delivery rates but consuming significant resources. PRoPHET uses historical data of node encounters to predict delivery probabilities, making more informed forwarding decisions and reducing resource usage. PRoPHETv2 enhances these calculations for more complex scenarios. MaxProp[25], [26] prioritizes data packets based on their likelihood of successful delivery, using a ranking system to manage transmission and storage effectively. RAPID focuses on optimizing specific performance metrics by dynamically allocating resources, balancing trade-offs between delivery delay and success probability. Spray and Wait initially sprays a limited number of packet copies to a few nodes, which then wait to encounter the destination or a closer node, reducing resource consumption while maintaining reasonable delivery rates. Spray and Focus adds a focus phase, where nodes switch to a more directed forwarding approach after the initial spray, combining controlled replication with intelligent forwarding. Each protocol contributes uniquely to DTN efficiency by addressing specific challenges of intermittent connectivity. Resource optimization is emphasized by MaxProp and RAPID, while PRoPHET and PRoPHETv2 improve delivery probabilities through predictive models. Spray and Wait and Spray and Focus balance redundancy and resource constraints with strategic forwarding.

Recent research on DTNs has focused on enhancing data delivery efficiency and managing network congestion through advanced protocols and frameworks. Olivia et al. introduced a dynamic approach, employing multiple DTN routing protocols concurrently, with each node adapting based on network conditions. Simulations using the Opportunistic Network Environment(ONE) simulator show this multi-protocol strategy improves delivery ratio and overall performance compared to single-protocol MANETs, enhancing adaptability and robustness[27] however, there was challenge of exploring other metrics other than delivery ratio which can be beneficial when it comes to video streaming efficiencies. Wiliam developed and tested DTN routing protocol (MK-DTN) on Android devices which could be used for streaming using a demo app. The study found that combining forwarding and flooding-based protocols improved performance, with the new MKP protocol showing lower CPU, memory, and battery usage however the long-term energy efficiency implications, especially in continuous data transmission scenarios, were not fully explored[28]. Min Wook Kang et al. introduced a new DTN routing protocol for Information-Centric Networking (ICN), which improved data delivery by using requester information to compare average delivery predictability among nodes[29]. The effectiveness of the protocol in larger, more complex networks was not thoroughly tested, raising concerns about its scalability. The Smart-DTN-CC framework, developed by researchers in 2021, employed Reinforcement Learning(RL) to dynamically manage congestion in high-latency, intermittently connected networks [30]. The energy consumption associated with continuous learning and adaptation processes was not thoroughly explored. An improved routing algorithm, proposed by researchers in 2021, prioritized data packets in double-layered DTNs to reduce delays and increase delivery success rates. Unfortunately The algorithm's performance under diverse and unpredictable network conditions, such as varying mobility patterns and environmental factors, needed thorough validation to ensure robustness[31]. Additionally, a 2022 study introduced a congestion control framework

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specifically designed for DTNs, employing advanced techniques to manage resources and ensure data delivery despite frequent disruptions. The framework's effectiveness in highly dynamic and large scale DTN environments remained uncertain, as the study may not have comprehensively tested scalability under varied network conditions [32].

SDN enhances network architecture by centralizing control functions through software-based controllers and Application Programming Interfaces (APIs), separating the management and forwarding planes to improve network responsiveness and flexibility. Key components of SDN include applications that manage network functions, controllers such as POX, RYU, and Floodlight, and networking devices that handle data forwarding based on controller instructions. SDN employs diverse models like Open SDN, SDN by APIs, Overlay SDN, and Hybrid SDN, ensuring adaptability in network design[32].

Recent research on SDN in the context of IoV video streaming has focused on enhancing network performance and Quality of Service (QoS) through various innovative approaches. One notable study proposed SDN-enabled routing for IoV that integrated fog computing to provide agile message forwarding with minimized routing overhead, crucial for applications like video streaming where low latency and high reliability were essential. This approach utilized road-aware routing protocols that segmented roads and used gateway vehicles to efficiently manage data packets, reducing control overhead and ensuring stable communication paths[33]**.** the study may not have fully explored the scalability of the proposed solution in large-scale IoV deployments.

Another significant contribution was the QoCoVi framework, which introduced a Quality of Experience (QoE) and cost-aware adaptive video streaming solution for IoV. This approach dynamically adjusted video quality based on network conditions and user requirements, ensuring timely delivery of video segments with optimal quality and minimal cost. By leveraging SDN, the framework prioritized video streaming traffic, thereby improving the overall user experience in vehicular networks[17]. The energy consumption associated with continuous monitoring and adaptation processes was not thoroughly explored, raising concerns for battery-operated devices within the IoV ecosystem.

The integration of SDN with Network Function Virtualization (NFV) in IoV, as explored in the Fog Enabled Networks (FENS) framework, highlighted the potential of FEN slicing to cater for the diverse QoS requirements of vehicular applications. This approach allowed for dynamic resource allocation and management, facilitating efficient handling of video streaming alongside other critical services [34]. While the framework showed promise in simulations, extensive real-world testing is essential to validate its practicality and effectiveness under diverse and unpredictable conditions.

Research on SDN and DTNs has highlighted several challenges in their individual applications, particularly in the context of IoV video streaming. SDN enhances network architecture by centralizing control functions and separating the management and forwarding planes, which improves network responsiveness and flexibility. However, it faces challenges in maintaining low latency and real-time adaptation in dynamic vehicular environments. Scalability issues arise as the number of connected vehicles increases, making it difficult for SDN controllers to manage many flows efficiently.

DTNs, on the other hand, are designed to handle intermittent connectivity through their store and forward mechanism, which ensures data delivery despite disruptions. However, their limited flexibility due to static routing protocols may not adapt well to rapidly changing network topologies. DTNs also rely heavily on the availability of intermediate nodes with sufficient storage capacity, and the store and forward mechanism can introduce significant delays, which is problematic for applications requiring low latency, such as real-time video streaming. To address the above challenges, researchers take advantage of integrated architecture. The integrated architecture combining SDN and DTNs leverages the strengths of both technologies to enhance network performance in the IoV.

The combined SDN-DTN architecture synergizes these technologies, allowing SDN's centralized control to dynamically manage network resources while DTNs ensure data delivery through their resilient store and forward approach. This integration enables adaptive routing and resource allocation based on real-time network conditions, improves scalability by distributing control functions, and enhances security through a decentralized operational model [35], [36].

Recent research has explored the integration of SDN and DTNs to enhance network performance in various scenarios. Olivia et al. proposed a Centralized Controller Multi-Agent (CCMA) algorithm that integrated SDN and DTN principles, enhanced with RL, to improve VANET performance. Validated in a simulated environment, the algorithm optimized DTN routing protocols and buffer schedules based on network state information. Implemented in various environments, the study showed improved TTL, buffer management, link quality, delivery ratio, latency, and overhead scores compared to single-protocol VANETs[12]. The centralization of the controller also posed a single point of failure risk, undermining the network's robustness and reliability. The research study [13], proposed a new architecture combining SDN and DTN to enhance network management and automation. This architecture consisted of four layers: Victim nodes (DTN-enabled devices like PDAs and smartphones), the DTN Layer (comprising bundle storage and convergence layer), DTN Tend (a monitoring application providing feedback for performance optimization), and the Control station. The simulation, conducted using Mininet-WiFi, demonstrated a high message delivery rate of 99.540% and a low packet loss of 0.460% in the best-case scenario. However, the proposed architecture faced challenges, such as the lack of priority settings between defined services, resulting in a First Come First Serve (FCFS) approach when multiple service requests occurred simultaneously. Addressing these limitations in future research could further enhance the architecture's efficiency and effectiveness.

Another study in [37], proposed Software-Defined Delay Tolerant Networking (SDDTN) for managing large DTN networks, especially in space missions, leveraging data plane programming to handle dynamic conditions. Ensuring seamless integration and interoperability with existing space communication protocols and infrastructure was another challenge. Finally researchers in [5], proposed combining SDDTN approaches to meet the stringent requirements of last-mile TEN applications like video streaming where they didn't validate their effect on the internetwork case scenarios.

Having witnessed the performance exhibited by the integrated architecture, authors thought it best to apply the same approach to further analyze the impact of the other parameters like network complexities.

The integration of SDN and DTN in IoV as fully summarized in Table 1 yields a range of solutions like enhanced Inter-Vehicle communication for traffic updates, dynamically connected traffic management for efficient flow, emergency services for disaster communication, rural connectivity for remote areas, logistics management for supply chains, smart parking for congestion reduction and traffic flow management for environmental monitoring. These applications collectively tackle various challenges in IoV, promoting efficiency and connectivity in the vehicular environment [38].

Assessing SDN-DTN performance in live video streaming involves critical metrics: Stall Count (indicating buffering events), Initial Start Time (from user request to the first frame, influencing waiting times), and Stall Length (duration of interruptions during buffering, affecting overall experience). Achieving lower stall count, shorter initial start time, and minimized stall lengths are crucial for delivering a seamless and responsive video streaming service over IoV infrastructure.

Existing research on SDN, DTN and IoV has predominantly focused on isolated aspects of SDN or DTN, revealing a notable void in comprehensive analysis of the integrated performance of SDN-DTN architecture. Previous studies have inadequately addressed the influence of network complexity, mobility models, and wireless technologies on SDN-DTN, particularly within the IoV context [5].

Table 1 Summary of the Related Research Works

DTN			
REF	Title	Contribution	Challenge
[27]	Enhancing Bundle Delivery Efficiency in Mobile Ad-hoc Networks with a Multi-protocol Delay-Tolerant Network	Multiprotocol DTN using a novel simulator [39] to improve delivery	Scalability issue, Need to consider other metrics
[28]	The development of Delay Tolerant Routing Protocols for Android based devices	Developed MK-DTN protocol to enhance DTN communication using Android devices	Proper utilization of resources like CPU, memory and storage
[29]	An Efficient Delay-Tolerant Networks routing protocol for information-Centric Networking	New DTN routing protocol for Information -Centric Networking (ICN)	Protocol was not tested against scalability
[30]	Smart congestion control for delay and disruption tolerant networks	Smart-DTN-CC framework, to dynamically manage congestion in high-latency environments	Energy consumption due to continuous learning not explored
[31]	An Improved Earliest-Delivery Routing Algorithm in Double-layered DTNs	Improved earliest-delivery routing algorithm specifically designed for	Performance under diverse and unpredictable network

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		double-layered DTNs	conditions
[32]	An Improved Probabilistic Routing Algorithm Based on Moving Direction Prediction in DTNs	Congestion control framework specifically designed for DTNs	Scalability under varying network conditions was not studied
SDN			
[33]	SD-IoV: SDN enabled routing for internet of vehicles in road-aware approach	Integrated fog computing to provide agile message forwarding	Scalability of the proposed solution in large-scale IoV deployments
[17]	QoCoVi: QoE- and cost-aware adaptive video streaming for the Internet of Vehicles	Leveraged SDN to prioritize video streaming traffic and improve the overall user experience in vehicular networks	Energy consumption associated with continuous monitoring and adaptation processes was not thoroughly explored
[34]	FENS: Fog-Enabled Network Slicing in SDN/NFV-Based IoV	Fog-enabled network slicing to meet the diverse QoS requirements of vehicular applications	Extensive real-world testing to validate practicality and effectiveness under diverse and unpredictable conditions
Combined SDN-DTN			
[13]	SDN-DTN Combined Architecture in Post Disaster Scenario — A new way to start	Framework for agile message forwarding, minimizing routing overhead and ensuring stable communication paths even when traditional networks fail	Lack of priority settings between defined services, resulting in a FCFS approach
[12]	Combining Software-Defined and Delay-Tolerant Networking Concepts with Deep Reinforcement Learning Technology to Enhance Vehicular Networks	Algorithm that optimized DTN routing protocols and buffer schedules based on network state information.	Single point of failure
[37]	Towards Software-Defined Delay Tolerant Networks	SDDTN for managing large DTN networks	Seamless integration with existing space communication protocols
[5]	Combining Software-Defined and Delay-Tolerant Approaches in Last-Mile Tactical Edge Networking	Addressed last-mile TEN applications like video streaming in TENs	Effects on internetwork case scenarios were not validated

3. METHODOLOGY

A realistic IoV scenario is constructed using simulation tool (Mininet), which allows for the creation of diverse network complexities through dynamic node configuration and connectivity. This setup integrates real world mobility models derived from actual vehicular traces to emulate vehicular movements within a smart city environment. The constructed IoV scenario serves as a crucial foundation for analyzing video streaming across various network configurations. The primary objective of this research is to examine the impact of different factors specifically node characteristics, wireless technologies, and mobility models on the overall performance of IoV streaming. The study aims to identify how these independent variables affect key performance metrics for video streaming in a dynamic vehicular network.

The independent variables in this study are mobility models, wireless technologies, and the number of clients, while the dependent variables are video playback start time, the average number of video stalls, and the average video stall length. Different mobility models simulate various patterns of vehicular movement, influencing how nodes interact and communicate within the network. Real world data is used to create accurate mobility models that reflect actual vehicular behavior in smart cities. Various wireless communication standards, such as 802.11g, and 802.11ax, are tested to evaluate their efficiency in handling video streaming data, assessing their capacity to maintain stable and high-quality connections between moving vehicles. Additionally, the number of clients (vehicles) in the network is varied to understand how network load affects performance, determining the scalability of the network and its ability to handle increasing numbers of connected devices.

Through rigorous experimentation within the constructed IoV environment, this research meticulously measures the effects of the independent variables on the dependent variables. The study employs extensive simulations to replicate various network conditions and vehicular movements, providing a comprehensive analysis of video streaming performance. The insights gained from these experiments are invaluable for understanding the factors that influence video streaming in dynamic vehicular networks. This research highlights the importance of choosing appropriate mobility models, wireless technologies, and optimizing the number of clients to enhance video streaming performance. The findings contribute to the development of more efficient and effective communication solutions for future smart transportation systems, ensuring better QoS for applications such as real-time video streaming in IoV scenarios. By addressing these critical aspects, the research paves way for advancements in smart transportation technologies, aiming to achieve seamless and reliable inter-vehicular communication in increasingly complex and demanding urban environments.

3.1. Proposed IoV Framework

In this integrated architecture, the fusion of SDN, DTN, and IoV paradigms forms a sophisticated network environment specifically designed to address the complexities of dynamic vehicular communication. In Figure 1, the entities within the IoV, represented by On-Board Units (OBUs) and Road-Side Units (RSUs), are seamlessly integrated into the SDN-DTN framework, creating a cohesive system governed by an active-master-passive-slave redundancy architecture.

Both RSUs and OBUs are equipped with SDN controllers and DTN instances. The SDN controllers are responsible for optimizing traffic flow to ensure high QoS. The DTN instances handle hop-by-hop data transmission using underlying routing protocols within and between IoV mesh network segments via V2I and V2V connectivity. RSUs act as active-master SDN controllers within their designated network segments and serve as active stationary DTN instances, routing data through the established back-haul infrastructure. This infrastructure supports the streaming of live video feeds from a central data center. Within each network segment, OBUs operate as passive-slave SDN controllers with active DTN instances. In the event of an active-master SDN controller (RSU) failure or unreachability, a passive-slave SDN controller (OBU) transitions to an active-slave SDN controller through a leader election process. This process continues until the designated master SDN controller (RSU) recovers and becomes active again.

The architecture ensures redundancy by allowing OBUs to seamlessly transition into active-slave roles during RSU failures, thereby maintaining network stability and performance. This approach contrasts with the research conducted by Olivia et al.[12], which utilized a centralized controller architecture that created a single point of failure. By distributing control functions across multiple OBUs, our architecture avoids this vulnerability, ensuring continuous operation even if the primary RSU becomes unavailable. This decentralized approach enhances the network's resilience and reliability, providing a robust solution for managing dynamic and potentially unstable vehicular environments.

Inter-network communication is facilitated by RSUs acting as DTN gateways via V2I communication, relaying live video feeds to the data center and data between networks through the back-haul infrastructure. In addition to V2I communication, inter-network communication is also supported by DTN connectivity between network segments via V2V communication. This is crucial when an RSU within a network is faulty or unreachable, ensuring continuous data transmission and network reliability.

The integrated SDN-DTN architecture effectively manages the mobility dynamics of vehicular networks by allowing seamless transitions between active and passive roles,

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ensuring continuous communication and data flow even in highly dynamic environments. By distributing control functions and using DTN's store and forward mechanism, the architecture optimizes resource usage, reducing the load on individual network components and enhancing overall efficiency. The integrated SDN-DTN framework can dynamically adapt to changing network conditions, providing robust and resilient communication solutions. The use of multiple communication protocols and redundancy mechanisms ensures high reliability and performance.

This integration of SDN, DTN, and IoV technologies addresses the key challenges of mobility, resource constraints, and network variability, fostering the deployment of efficient and resilient IoV systems. The integrated approach supports advanced applications such as real-time video streaming, emergency response, and smart city infrastructure management. This architecture represents a significant advancement in managing IoV communication challenges, ensuring high QoS, reliability, and efficiency, which are essential for the future of smart transportation systems.

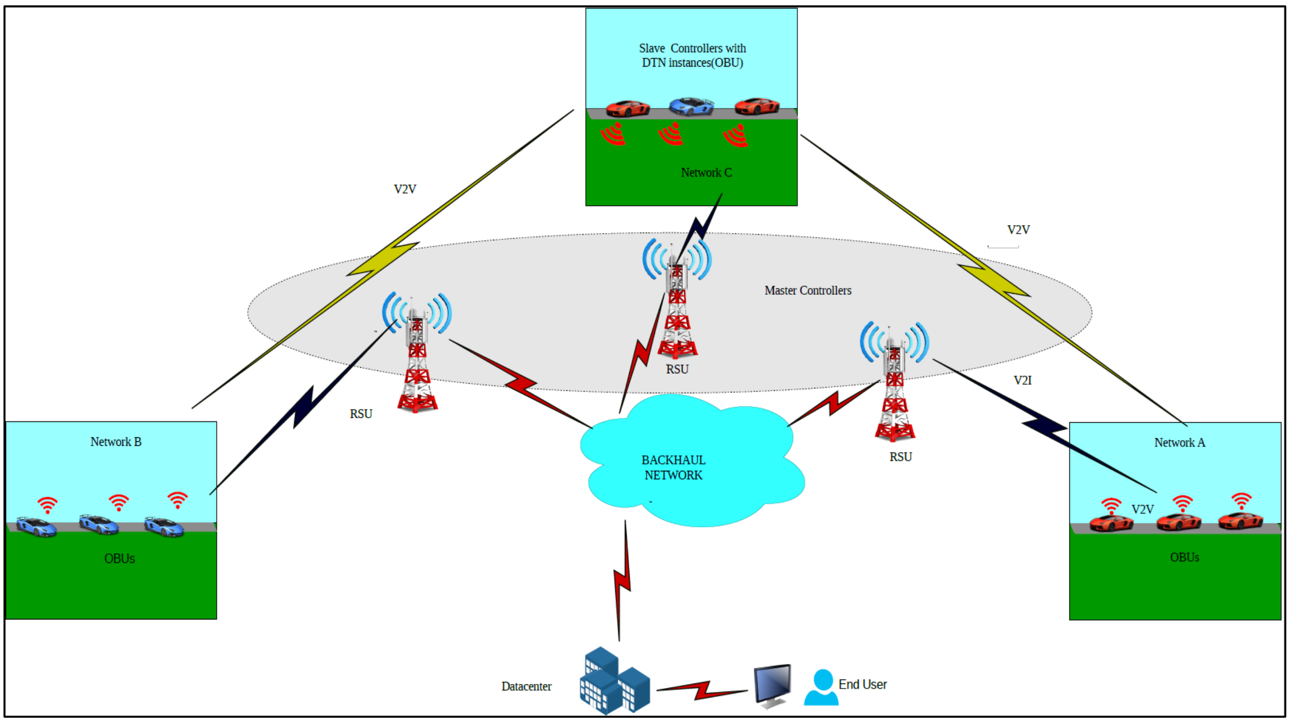

Figure 1 Proposed Framework of a Data Communication in a Typical IoV Setup

3.2. Simulation Setup

A comprehensive network simulation environment is established using two Virtual Machines (VMs) to facilitate the cost-effective study of SDN. One VM emulates Mininet, while the other emulates Mininet-WiFi. These tools are chosen because they are well-suited for studying SDNs, providing a robust platform for simulation. The Mininet VM is configured to host a remote SDN controller, RYU, replicating a realistic scenario where the SDN controller is remote from the network it manages. The RYU controller is selected due to its compatibility with Mininet, both being built in Python, which ensures seamless integration and ease of configuration.

The Mininet-WiFi VM hosts the Mininet-WiFi software, used to run SDN simulation scenarios for wireless technologies. Mininet-WiFi, derived from Mininet, is an appropriate platform for these simulations due to its capability to handle wireless network configurations and SDN functionalities. The simulation setup, depicted in Figure 2, is based on a similar but independent investigation detailed in a state-of-the-art study[5]. This research aims to validate and expand upon the findings of that study. To ensure the setup matches the description in the previous study, the source code was patched to use the specific version of the API provided by the Mininet-WiFi installation.

The primary goal of this simulation environment is to create a realistic IoV scenario using relevant simulation tools and methodologies. The integration of Mininet and Mininet-WiFi allows for the creation of a diverse network environment, incorporating dynamic node configuration and connectivity. This setup also includes real-world mobility models derived from actual vehicular traces to emulate authentic vehicular movements within a smart city environment. The IoV scenario serves as a crucial foundation for analyzing video

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streaming across various network configurations, examining the effects of node characteristics, wireless technologies, and mobility models on the overall performance of inter-vehicular DTN streaming.

To enable the simulation of video streaming within this setup, FFmpeg binaries, specifically ffplay and ffserver, are utilized. The ffplay source code was patched and recompiled to enable detailed logging of performance parameters, allowing for an in-depth analysis of video streaming performance within the simulated network. This modification is crucial for capturing all necessary performance metrics, providing valuable insights into the effectiveness of the SDN-DTN integrated architecture for IoV scenarios.

Through rigorous experimentation within this constructed IoV environment, the research meticulously measures the effects of independent variables; mobility models, wireless technologies, and the number of clients on dependent variables such as video playback start time, average number of video stalls, and average video stall length. The findings highlight the importance of selecting appropriate mobility models and wireless technologies, as well as optimizing the number of clients to enhance video streaming performance. This comprehensive setup and methodology aim to offer a detailed understanding of how SDN and DTN can be integrated to optimize network performance in dynamic vehicular environments. The insights gained will contribute to developing more efficient and resilient IoV systems, addressing key challenges such as mobility, resource constraints, and fluctuating network conditions, thereby fostering the deployment of effective communication solutions for future smart transportation systems.

The model developed in this research introduces several key advancements over previous models, particularly in network simulation, integration of technologies, and real-world applicability within the IoV framework. Unlike earlier models that often utilized a single virtual machine and a single simulation environment[27][39], this research employs a dual virtual machine setup: one emulating Mininet and the other Mininet-WiFi. This configuration allows for sophisticated simulations of both wired and wireless network configurations. Additionally, the Mininet VM hosts a remote RYU SDN controller, replicating a realistic scenario where the SDN controller was separate from the network it managed, enhancing realism and applicability. Both Mininet and RYU are built in Python, ensuring seamless integration and ease of configuration.

Furthermore, this research incorporates wireless technologies through Mininet-WiFi, which is specifically designed to handle mobile and wireless nodes, providing a more comprehensive analysis than models focusing solely on wired or wireless configurations. Real-world mobility models derived from actual vehicular traces are used to emulate authentic vehicular movements within a smart city environment, enhancing the validity of the simulations.

Overall, the model offers significant improvements in realism and applicability, contributing valuable insights into the development of more efficient and resilient IoV systems. This research addresses key challenges such as mobility, resource constraints, and fluctuating network conditions, fostering the deployment of effective communication solutions for future smart transportation systems.

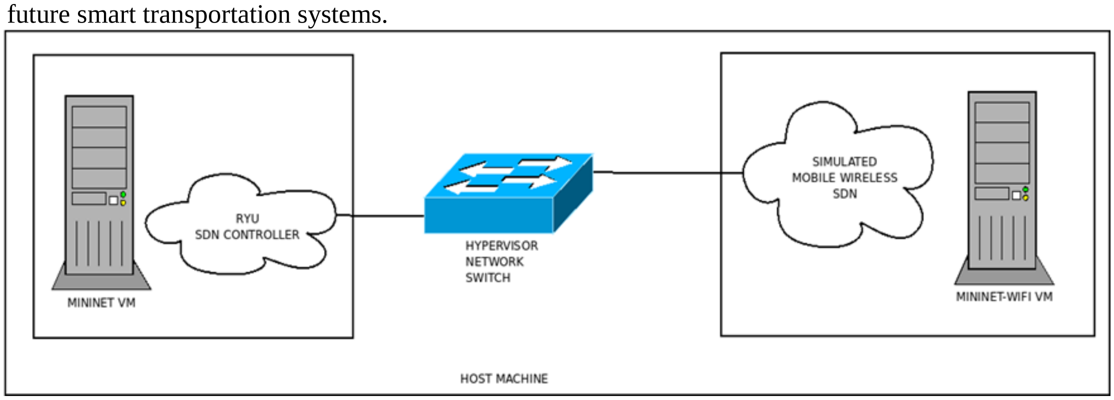

Figure 2 Simulation Environment Topology

3.2.1. Node Deployment

Thirty (30) nodes are deployed in each network, with specific configurations representing the number of simultaneous video streams in those networks, as shown in Table 2.

3.2.2. Interface Configuration

All interfaces in the network environment are configured to operate at a maximum-possible capacity of about 1 Gbps for both wired and wireless connections. This is done to ensure consistent data transfer rates in all the networks. However, the actual throughput on these links is far less than this limit.

3.2.3. Network Scenario

Intra-Network: The Intra-Network scenario, as depicted in Figure 3, is designed to simulate an isolated network environment within the IoV framework. In this setup, a maximum of 30 OBUs are connected to each other through wireless mesh connectivity, creating a robust and dynamic network of mobile nodes. The OBUs represent vehicles equipped with wireless communication capabilities, capable of forming ad-hoc networks on the go.

For the streaming of video content, the scenario includes a dedicated station equipped with streaming servers (ffserver). These servers are responsible for providing the video content that needs to be streamed across the network. The video streaming client (ffplay) is implemented on one of the host computers (h1), which is connected to the RSU via a wired link. The RSU serves as a stationary point of communication within the network, managing traffic and facilitating data exchange between the OBUs.

This scenario effectively simulates intra-network communication within an IoV setup, where vehicles (OBUs) are in constant motion but need to maintain reliable communication for applications such as video streaming. The RSU acts as the central hub, ensuring that data packets, including video streams, are efficiently routed between the mobile OBUs. By connecting the video streaming client (h1) to the RSU over a wired link, the setup ensures stable video streaming from the ffserver, despite the wireless nature of the OBUs' connections.

The primary objective of this scenario is to evaluate the performance of intra-network communication within a vehicular network, focusing on the quality of video streaming. This includes assessing metrics such as video playback start time, the number of video stalls, and the length of these stalls. The wireless mesh connectivity among OBUs allows for a highly dynamic and realistic simulation of vehicular communication, where each vehicle adapted to changes in network topology and maintained seamless data transmission.

This setup is crucial for understanding the behavior of video streaming applications in IoV environments. It provides insights into how effectively data could be transmitted within a network of moving vehicles, managed by a stationary RSU. The findings from this scenario contribute to the development of more robust and efficient communication protocols and architectures for future smart transportation systems, ensuring high-quality service even in highly dynamic and mobile environments.

Table 2 Network Parameters Considered

Number of streaming clients (Intranet)	3, 6, 9, 12, 24, 30
Number of streaming clients (Internet)	3, 6, 9, 12, 24, 29
Wireless technologies	802.11g (g), 802.11ax (ax)
Mobility models	Random Waypoint (rwp), Random Direction (rd)
Experiment run	3
Video length	60 sec
Video codec	h264
Maximum-possible Link capacity	1 Gbps (approx)
Routing mechanism	Default and static routes

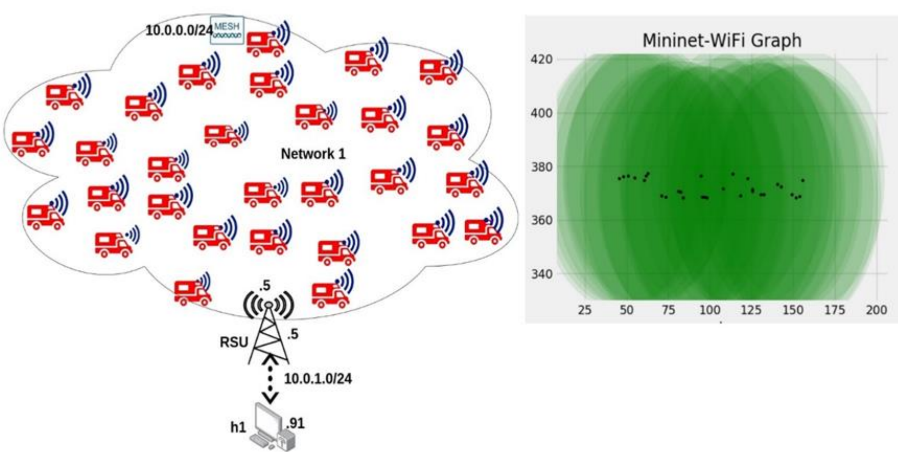

Figure 3 Intranet of 30 Stations and its Mobility

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Internetwork: In this expanded network scenario, illustrated in Figure 4, two separate wireless mesh networks, referred to as Network 1 and Network 2, are interconnected using a third mesh network, designated as Network 3. This configuration establishes a complex and dynamic communication environment within the IoV framework. Network 3 acts as a bridge between OBUs 2 and 3 from the respective networks, enabling seamless data transmission across the isolated networks.

Network 1 comprises 9 nodes, with an RSU (RSU1) connected via a wired link to the video streaming client (ffplay) on host computer h1. This network is responsible for receiving video streams from Network 2. Network 2 consists of 20 streaming servers (ffserver) that generate video content, which is intended to be streamed to the client in Network 1. However, in this scenario, Network 2 does not have an available RSU to manage the data traffic, simulating a situation where the RSU is either unavailable or non-functional.

The absence of an RSU in Network 2 necessitates the routing of video streams through Network 1 to reach the video streaming client (ffplay). The interconnection provided by Network 3 allows OBUs in Network 2 to communicate with OBUs in Network 1, leveraging the stability and management capabilities of RSU1 in Network 1. This setup creates a layered and interconnected mesh network system where video streaming data from Network 2 is routed through Network 1, ensuring continuous and reliable data transmission despite the unavailability of a dedicated RSU in Network 2.

This scenario effectively simulates communication across multiple IoV networks with varying infrastructure availability. It emphasizes the importance of robust inter-network connectivity and the role of mesh networks in maintaining seamless communication. By routing video streams from Network 2 through Network 1, the scenario tests the resilience and adaptability of the network in handling dynamic and unpredictable conditions, such as the failure or absence of an RSU.

The primary objective of this scenario is to assess the performance of inter-network communication within the IoV framework, focusing on the quality and reliability of video streaming. Key performance metrics include video playback start time, the frequency and duration of video stalls. The scenario provides valuable insights into how inter-network connectivity and mesh networking can be leveraged to overcome infrastructure limitations and ensure continuous data flow in vehicular networks.

This setup is crucial for developing strategies to enhance the robustness and efficiency of IoV systems. It demonstrates how interconnected mesh networks can compensate for infrastructure shortcomings and highlights the importance of flexible and adaptive network designs. The findings from this scenario contribute to the advancement of smart transportation systems, ensuring that high-quality services such as real-time video streaming remain reliable even in complex and dynamic environments where network infrastructure may be compromised**.**

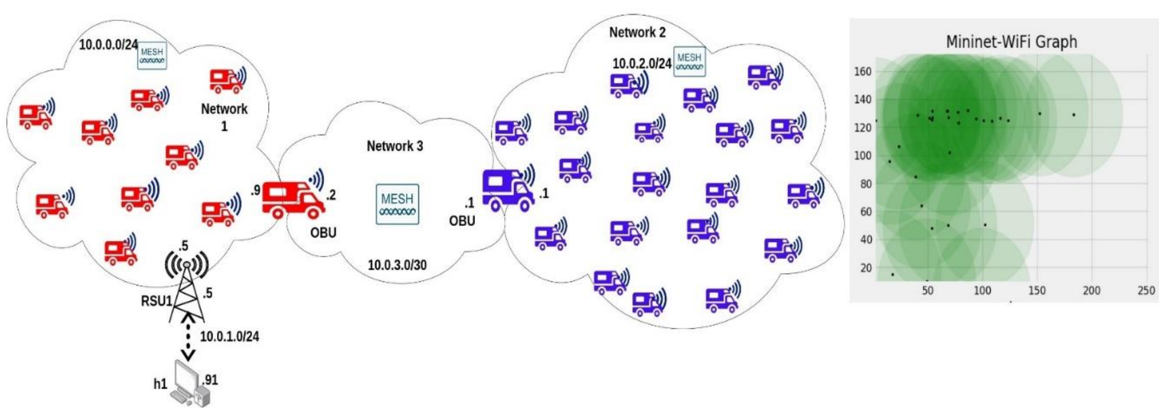

Figure 4 Inter-Network of 29 Stations and its Mobility

Video Streaming Setup: Videos are hosted across all station stream servers (using the ffserver software) in the various networks to assess the network performance concerning the specified network scenarios outlined in Table *2*.

Network Scenarios: Different network scenarios are tested by varying the following factors: Node Density: Used subsets of stations (3, 6, 9, 12, 24 and 30 in number) to evaluate the influence of node complexity on the streaming performance, Wireless Technologies: Compared the performance of 802.11g and 802.11ax in the networks, Mobility Models: Implemented different mobility models (random waypoint and random direction) to analyze the effect of station mobility on streaming performance.

4. RESULTS

Extensive simulations are conducted to analyze the influence of network complexity, mobility models and wireless technologies on SDN-DTN performance. The research uncovers unexpected findings across different IoV scenarios.

4.1. Intranetwork Simulation

The outcomes illustrated in Figures 5, 6, and 7 closely align with the findings of a prior study [5], which explored similar variables depicted in Figures 5a, 6a, and 7a. Both studies converge on the observation that diverse wireless technologies and mobility models exert minimal influence on the network's overarching performance. However, this study reveals notable improvements in video streaming performance when using the group setup, particularly in video playback stall times, stall counts, and stall lengths. Specifically, the video playback stall time improved significantly, achieving a minimum of 900ms when three clients were utilized, compared to the results shown in Figure 5a of the previous study. Additionally, there was a significant reduction in the stall count, with this approach experiencing as low as 0.5 stalls on average, as opposed to the baseline depicted in Figure 6a. The stall length also saw a substantial decrease, with values as low as 20ms observed, highlighting the effectiveness of the group setup in minimizing playback interruptions, compared to Figure 7a. These improvements were consistently observed across a nine-client setup.

An extended examination encompassing a range of nodes, considering varying wireless technologies and mobility models such as ax-rwp and ax-rd, is depicted in Figures 5b, 6b, and 7b. While the overall performance is better in this study, the extended analysis further solidifies the perspective that network scalability and complexity, especially the increased node count, are pivotal factors influencing its performance dynamics. This observation outweighs the impact of specific mobility models or wireless technologies, underscoring the importance of designing scalable and complex network infrastructures. The consistent improvements across different client setups highlight the robustness of the group setup in enhancing video streaming performance, providing valuable insights for developing resilient and efficient communication solutions for future smart transportation systems. These findings are crucial for advancing the design and deployment of IoV systems that maintain high-quality service levels in complex and rapidly changing network conditions.

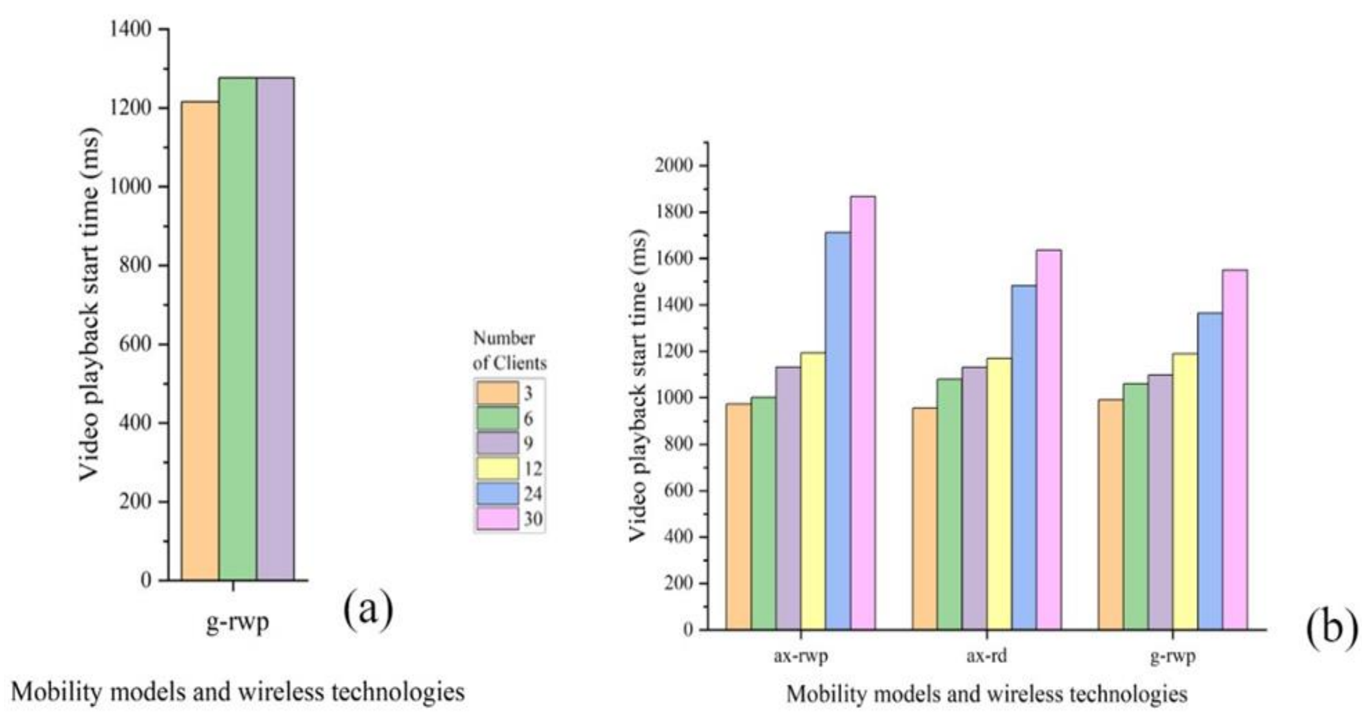

Figure 5 Video Playback Start Time Performance with Change in Mobility Models and Wireless Technologies for Both the Prior [5] and Current Studies ((a) and (b)) Respectively (Network Scenario: Intranet, Number of Stations: 30)

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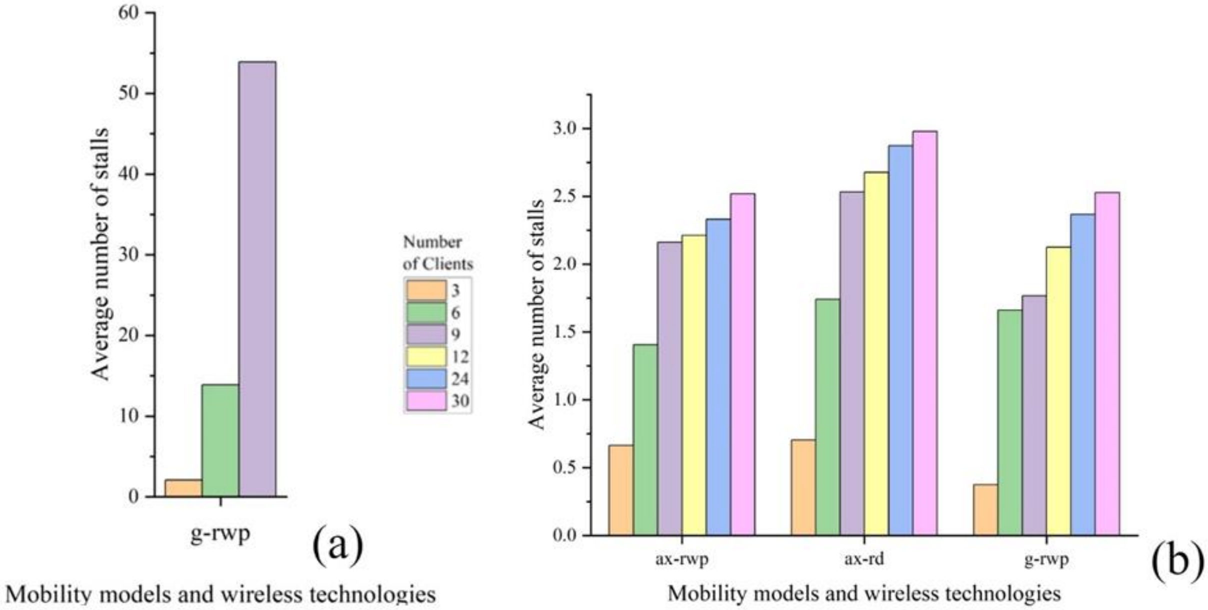

Figure 6 Video Stall Count Performance with Change in Mobility Models and Wireless Technologies for Both the Prior [5] and Current Studies ((a) and (b)) Respectively (Network Scenario: Intranet, Number of Stations: 30)

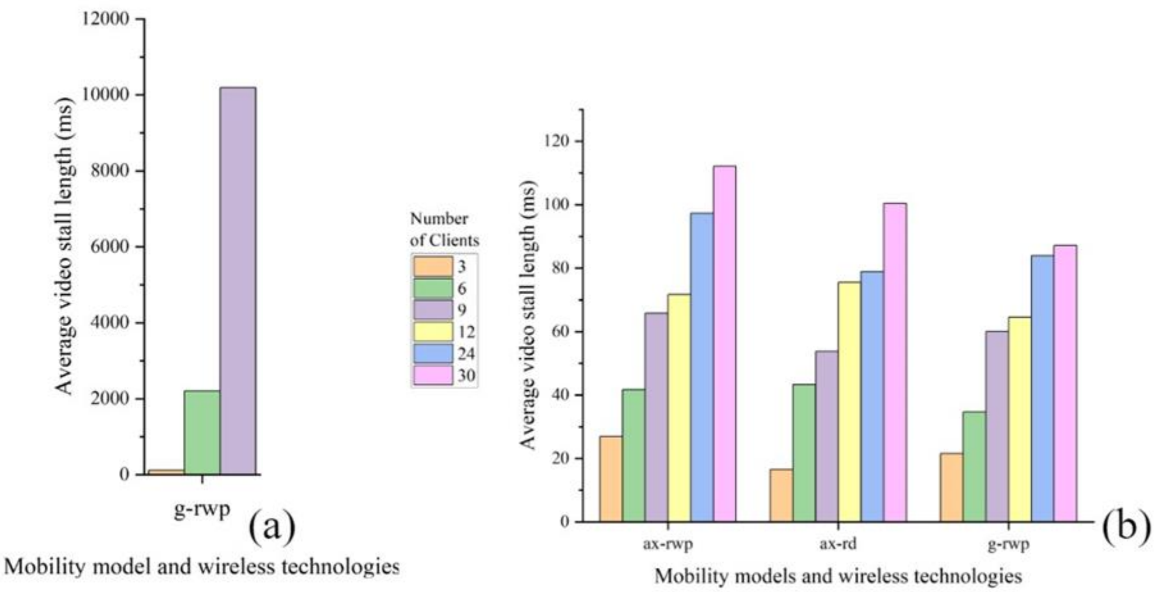

Figure 7 Video Stall Length Performance with Change in Mobility Models and Wireless Technologies for Both the Prior [5] and Current Studies ((a) and (b)) Respectively (Network Scenario: Intranet, Number of Stations: 30)

4.2. Internetwork Simulation

An investigation of an external network scenario, depicted in Figure 4, is designed to emulate real-world IoV conditions, aiming to validate and reinforce the consistent trends observed in the original study by subjecting the external network to similar parameters and variables. This assessment focuses on determining whether the scalability and complexity of the network, particularly node increments, remain the dominant factors influencing performance. The stall time in the external network scenario, shown in Figure 8,

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exhibits a trend similar to that observed in the intranet setup, with a minimum stall time of 1100ms, slightly higher than in the intranet scenario. The stall length values significantly increase due to the greater distances between the host device and the sparsely located streaming devices, consistently growing with the number of IoV nodes, as illustrated in Figure 10. The stall count, depicted in Figure 9, also increases with the number of nodes, with a minimum count of 1.9, higher than in the intranet setup.

For consistency with the original study [3], the g-rwp results are chosen for comparison. The results for 3, 6, and 9 clients from the external network scenario are compared with the intranet findings in Figures 5b, 6b, and 7b, summarized in Table *3*. Interestingly, there is no significant difference in average scores across different WiFi technologies and mobility models, attributed to the SDN-DTN architectural design's ability to maintain stable performance despite these changes. However, the consistently increasing trends in performance parameters with more clients indicate that network complexity significantly impacts performance, irrespective of network technologies.

This finding highlights that network complexity and node count are critical factors affecting performance, reinforcing the initial conclusion's significance and broader applicability within the IoV domain. Despite the stability provided by the SDN-DTN architecture, increased node count and physical separation introduce challenges that need to be managed to maintain optimal performance. These findings demonstrate the value of the SDN-DTN integrated approach, providing consistent and reliable performance across varying network conditions and configurations, contributing to the development of efficient and resilient communication solutions for future smart transportation systems, ensuring high-quality service even in complex and dynamically changing vehicular environments.

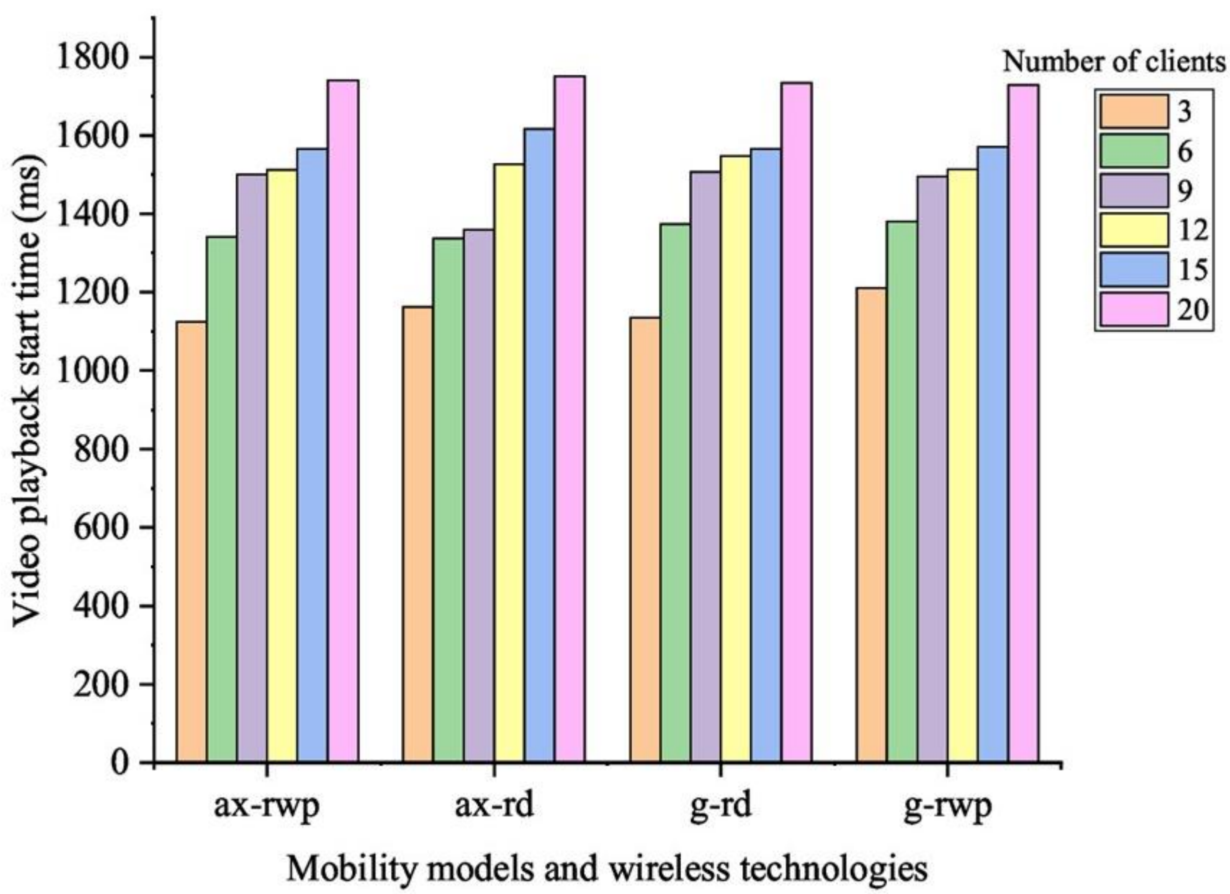

Figure 8: Video Playback Start Time Performance with Change in Mobility Models and Wireless Technologies (Network Scenario: Internetwork, Number of Stations: 20)

International Journal of Computer Networks and Applications (IJCNA)
DOI: 10.22247/ijcna/2024/28 Volume 11, Issue 4, July – August (2024)

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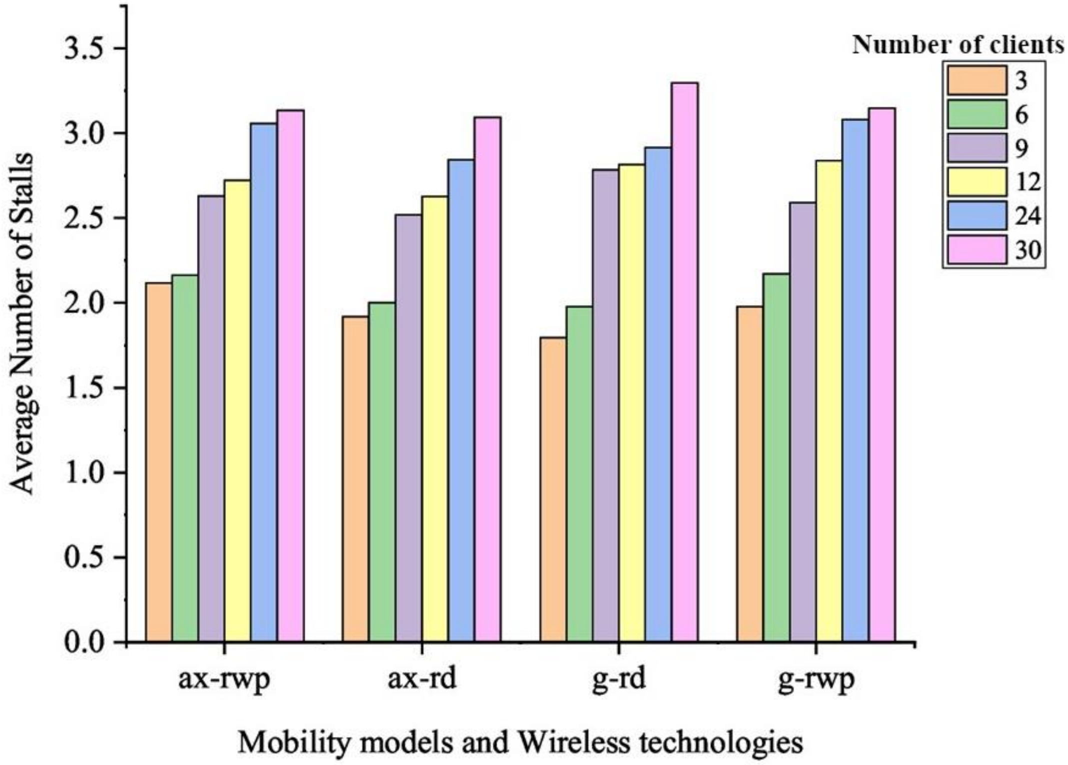

Figure 9 Video Stall Count Performance with Change in Mobility Models and Wireless Technologies (Network Scenario: Internetwork, Number of Stations:20)

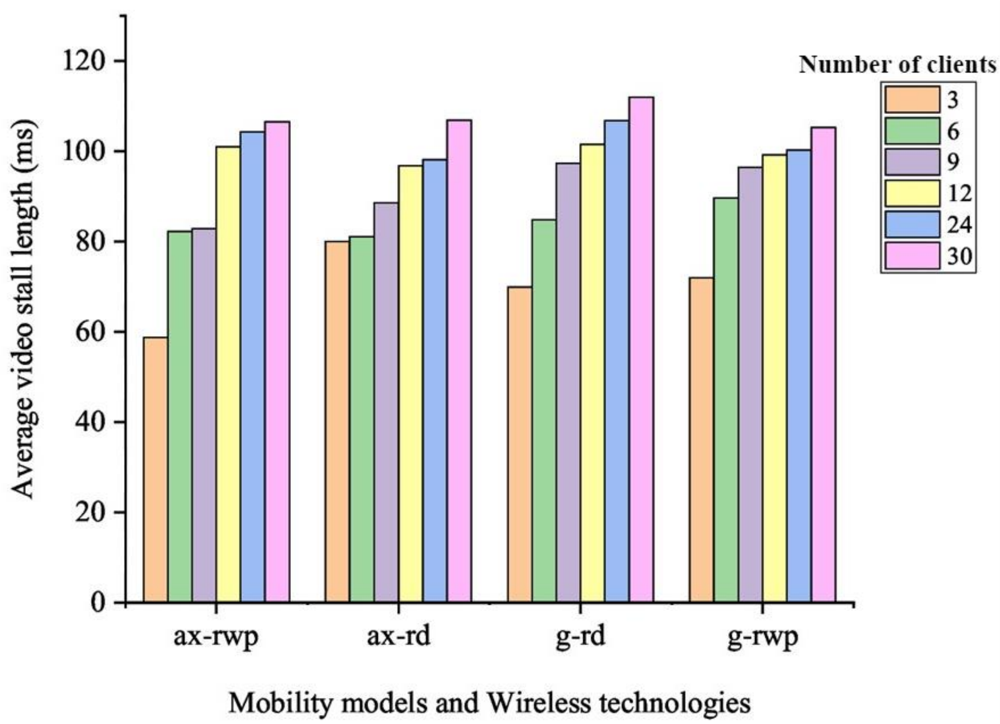

Figure 10 Video Stall Length Performance with Change in Mobility Models and Wireless Technologies (Network Scenario: Internetwork, Number of Stations: 20)

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Table 3 Comparison of the g-rwp Performance Between Intranetwork and Internetwork Setups

	Intranet Metrics			Internetwork Metrics		
Node count	Playback (ms)	Stall count	Stall length	Playback (ms)	Stall count	Stall length
3	1000	0.25	20	1200	2.0	70
6	1100	1.75	30	1400	2.25	90
9	1200	1.87	60	1500	2.5	1500

From the results shown above, increased node count in both intra-network and internetwork scenarios causes congestion, impacting streaming performance. Internetwork performance is notably influenced by node-server proximity, potentially due to signal interference. Parameters like playback start time, stall count, and stall length increase, indicating data loss. Similar interference issues are observed in Bluetooth communication in proximity to other wireless devices [40].

Overall, the proposed model achieves better results due to several key enhancements over previous models. It uses two virtual machines (Mininet and Mininet-WiFi) to accurately simulate both wired and wireless network configurations, enhancing realism. The model incorporates a remote RYU SDN controller, reflecting real-world conditions, and uses real-world mobility models for authenticity. Enhanced video streaming simulations using FFmpeg binaries allow for detailed performance analysis, measuring metrics such as playback stall times, stall counts, and stall lengths. The model effectively handles increased node count and network complexity, maintaining robust performance. Integrating SDN and DTN technologies optimizes network performance, combining centralized control with resilient data transmission. Validation against similar studies ensures the findings are robust and reliable. These factors contribute to superior network performance, especially in dynamic IoV environments, and provide valuable insights for developing resilient and efficient communication solutions for future smart transportation systems.

5. CONCLUSION AND FUTURE DIRECTION

This study analyses the impact of node complexity, mobility models, wireless technologies on the SDN-DTN architecture and its application in IoV where it is duly noted that network complexity is a key factor in designing SDN-DTN based IoV architectures. Based on this analysis, this research suggests implementing advanced network optimization techniques, machine learning for congestion prediction, leveraging 5G capabilities, and intelligent data caching. These strategies aim to significantly enhance network performance, offering a seamless streaming experience. The research emphasizes the importance of integrated SDN-DTN architecture in IoV, providing valuable insights for resilient vehicular communication infrastructure. As IoV adoption grows, the study contributes to advancing intelligent transportation systems and fostering innovation in vehicular communication networks.

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RESEARCH ARTICLE

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How to cite this article:

Olivia Nakayima, Mostafa I. Soliman, Kazunori Ueda, Samir A. Elsagheer, "Impact of Network Complexity, Mobility Models, and Wireless Technologies on SDN-DTN Performance in Internet of Vehicles (IoV) Environments", International Journal of Computer Networks and Applications (IJCNA), 11(4), PP: 449-467, 2024, DOI: 10.22247/ijcna/2024/28.