

Article

Computer-Aided Efficient Routing and Reliable Protocol Optimization for Autonomous Vehicle Communication Networks

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Abstract: The rise of autonomous vehicles necessitates advanced communication networks for effective data exchange. The routing protocols Ad hoc On-Demand Distance Vector (AODV) and Greedy Perimeter Stateless Routing (GPSR) are vital in mobile networks (MANETs) and vehicular ad hoc networks (VANETs). However, their performance is affected by changing network conditions. This study examines key routing parameters—MaxJitter, Hello/Beacon Interval, and route validity time—and their impact on AODV and GPSR performance in urban and highway scenarios. The simulation results reveal that increasing MaxJitter enhances AODV throughput by 12% in cities but decreases it by 8% on highways, while GPSR throughput declines by 15% in cities and 10% on highways. Longer Hello intervals improve AODV performance by 10% in urban settings but reduce it by 6% on highways. Extending route validity time increases GPSR's Packet Delivery Ratio (PDR) by 10% in cities, underscoring the need to optimize routing parameters for enhanced VANET performance.

Keywords: routing protocols; AODV; GPSR; bio-inspired algorithms; autonomous vehicles; BACM (bio-inspired adaptive chameleon method)



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1. Introduction

In the rapidly evolving field of wireless communication, routing protocols are essential for establishing efficient data transmission pathways in networks [1]. These protocols facilitate the exchange of information among nodes in dynamic environments, such as mobile ad hoc networks (MANETs) and vehicular ad hoc networks (VANETs) [2]. Among the most widely utilized routing protocols are Ad hoc On-Demand Distance Vector (AODV) and Greedy Perimeter Stateless Routing (GPSR) [3]. AODV establishes routes on an as-needed basis, minimizing overhead while ensuring that data packets reach their destinations, while GPSR employs geographic information to route packets based on the relative positions of

nodes, which is particularly beneficial in environments with high mobility [4]. The effectiveness of these protocols, however, is challenged by the increasing complexity of modern networks, necessitating enhanced adaptability and resilience to fluctuating network conditions and varying node densities [5]. To address these challenges, bio-inspired algorithms have emerged as innovative solutions [6]. These algorithms draw inspiration from natural processes, allowing for adaptable strategies that can respond dynamically to environmental changes [7]. A notable example is the Bio-Inspired Adaptive Chameleon Method (BACM), which mimics the adaptive capabilities of the chameleon, an organism known for its ability to alter its behavior based on environmental stimuli [8]. BACM enhances AODV and GPSR by introducing a dynamic routing strategy that adjusts to changes in network topology, traffic conditions, and environmental constraints [9]. Existing research on VANET routing protocols like AODV and GPSR lacks a detailed analysis of how parameters and indicators, such as MaxJitter, Hello/Beacon Interval, and route validity time, affect performance in urban and highway scenarios, particularly for critical applications like autonomous vehicles [10]. VANET routing protocols can be broadly classified into two main categories based on the information used to calculate routing paths: geographical and topological protocols. Geographical routing utilizes vehicle positioning systems and location information to determine paths. In contrast, topological routing relies on the distribution of topology information among vehicles [11]. Topological protocols are further divided into reactive, proactive, and hybrid protocols. Geographical protocols, on the other hand, are categorized into greedy and stateless, street-aware, connectivity-aware, and infrastructure-assisted protocols. Additionally, a new paradigm based on bio-inspired algorithms has emerged and been classified into revolutionary and swarm intelligence protocols [12]. The following subsections provide further details on each category, emphasizing the principles, advantages, disadvantages, and research challenges associated with these routing protocols. Recent advances from past studies examine protocol performance, looking at the general perfective. They fall short of fully addressing and exploring how variation in these parameters affects low latency, high reliability, and adaptive communication [13]. Thus, the work closes this gap by exploring the impact of parameters like MaxJitter, Hello/Beacon Interval, and route validity time on VANET routing protocols like AODV and GPSR in urban and highway settings. This will provide practical applicability for maximizing network performance, highlighting the critical role VANETs play in facilitating autonomous navigation and dependable communication. These parameters enable optimized route discovery, improved packet delivery rates, and minimized energy consumption, making it particularly suitable for dynamic network applications, including those involving autonomous vehicles [14–16]. In this work, we propose integrating the BACM into AODV and GPSR protocols to significantly enhance their performance in terms of throughput, delay, and routing overhead. This paper presents a comprehensive evaluation of BACM's effectiveness, detailing its design principles, implementation in AODV and GPSR, and a comparative performance analysis. Through simulations and real-world testing, we demonstrate how BACM can provide a robust, adaptive solution for enhanced routing in dynamic wireless networks. Further, this work provides an important contribution by giving a detailed examination of how major routing parameters—MaxJitter, Hello/Beacon Interval, and route validity time—influence the performance of AODV and GPSR routing protocols in urban and highway settings within VANETs and MANETs, respectively. We show in simulation results that optimizing these parameters can significantly improve network performance, such as improving AODV throughput by 12% in urban environments with increased MaxJitter and increasing GPSR's Packet Delivery Ratio by 10% in cities with extended route validity time. Our findings fill a gap in the existing literature by providing practical insights into how these parameters can be fine-tuned to improve routing efficiency under dynamic and

diverse network conditions, which is especially important for the development of reliable communication systems for self-driving vehicles. Hence, this study provides the following:

- A detailed study on the routing parameters MaxJitter, Hello/Beacon Interval, and route validity time and their impact on performance in urban and highway in autonomous navigation;
- Accurately identified how the key parameters could significantly improve network performance with up to a 12% increase in AODV throughput in urban settings and 10% for GPSR's Packet Delivery Ratio in cities;
- The findings offer practical applications for enhancing routing efficiency in complex network conditions that allow reliable communication systems for autonomous vehicles.

2. Method

The selection of routing parameters was a crucial step in optimizing the performance of routing protocols in dynamic network environments. Both AODV (Ad hoc On-Demand Distance Vector) and GPSR (Greedy Perimeter Stateless Routing) protocols had several tunable parameters that impacted their performance, such as route discovery frequency, packet transmission rates, and link-layer characteristics [17]. The MaxJitter value is used by the protocol to introduce a random time interval between the sending of two consecutive periodic packets. The Hello/Beacon Interval refers to the time period between the transmission of Hello or Beacon messages by nodes in a network, and route validity time refers to the duration for which a route in a routing table is considered valid before it expires. In the context of routing protocols like AODV and GPSR, the route validity time is used to determine how long a route remains active and usable for packet forwarding before it needs to be refreshed or updated. These tunable parameters were derived from protocol draft documents (GPSR, Karp and Kung 2000 [18]; AODV, C. Perkins, Belding-Royer, and Das 2003 [19]), which provided detailed descriptions of each parameter and its role within the protocol [20]. The careful selection of these parameters ensured that the protocols were tailored to meet the specific needs of the network environment in which they were implemented, allowing for better adaptability and efficiency [21]. Once the appropriate routing parameters were selected, a performance analysis was conducted to evaluate how these parameters affected overall network performance. The simulation process involved running each protocol with the selected parameters in various network scenarios to assess critical performance metrics, such as throughput, delay, packet delivery ratio, and energy consumption. By subjecting the protocols to these simulations, it was possible to identify the influence that each parameter had on the network's behavior under different conditions, including varying node mobility, network density, and traffic load [22]. This analysis was essential for understanding which parameters contributed most to the efficiency and reliability of the routing protocol in a real-world setting. To measure the effects of a routing protocol's parameters on the VANET performance, the Taguchi Optimization Method (TOM) was used to perform the delta analysis of the control factors mechanism in TOM. The detailed process is presented in the Supplementary Materials. This method was particularly useful for determining the most significant parameters by analyzing how changes in each parameter affected the desired outcome, such as improved packet delivery or reduced latency. The Taguchi method helped systematically explore the interactions between parameters, ensuring that the optimization process focused on those that offered the most substantial impact on performance. By measuring the effect of each parameter, the analysis narrowed down the list of parameters to those that were most critical for fine-tuning during optimization. As a result of this analytical process, a shortlist of three inner parameters was identified for fine-tuning in the next stage of optimization. These parameters were those that had shown the greatest influence on the performance

metrics during the simulation and Taguchi SNR delta analysis. Fine-tuning these parameters was expected to yield significant improvements in network performance, as they had the most substantial effect on key factors such as route stability, data transmission efficiency, and overall network scalability. At this stage, it became clear which elements of the protocol's configuration were most sensitive to changes, allowing for a more focused and effective optimization effort. The optimization stage centered on refining these three inner parameters to achieve the best possible performance of the routing protocols. By iterating through different configurations and testing the impact of small adjustments, the fine-tuning process sought to balance the trade-offs between competing performance metrics, such as minimizing routing overhead while maximizing throughput, as shown in Figure 1. The outcome of this stage was a set of optimized parameter values that enhanced the adaptability, efficiency, and robustness of the AODV and GPSR protocols, ensuring they performed at their best in dynamic, real-world wireless networks. The study used the INET3.5 simulation framework and OMNET++ simulator. The network protocol stack in INET3.5 provides a reach library of network protocol implementation and architecture. The implementation of a specific set of protocols can be combined in a compound module. The combined module is used in this work to implement a VANET node based on a wireless node module (WN) in INET3.5, which shows a snapshot of the internal structure of a WN for CM-AODV protocol implementation. WN is the basic building structure of the protocol stack. It comprises wireless, mobility, network, routing, transport, and application sub-modules. Each sub-module implements a functionality of a specific layer in the network protocol stack. The design of the wireless communication link used in this research work is detailed in the Supplementary Materials.

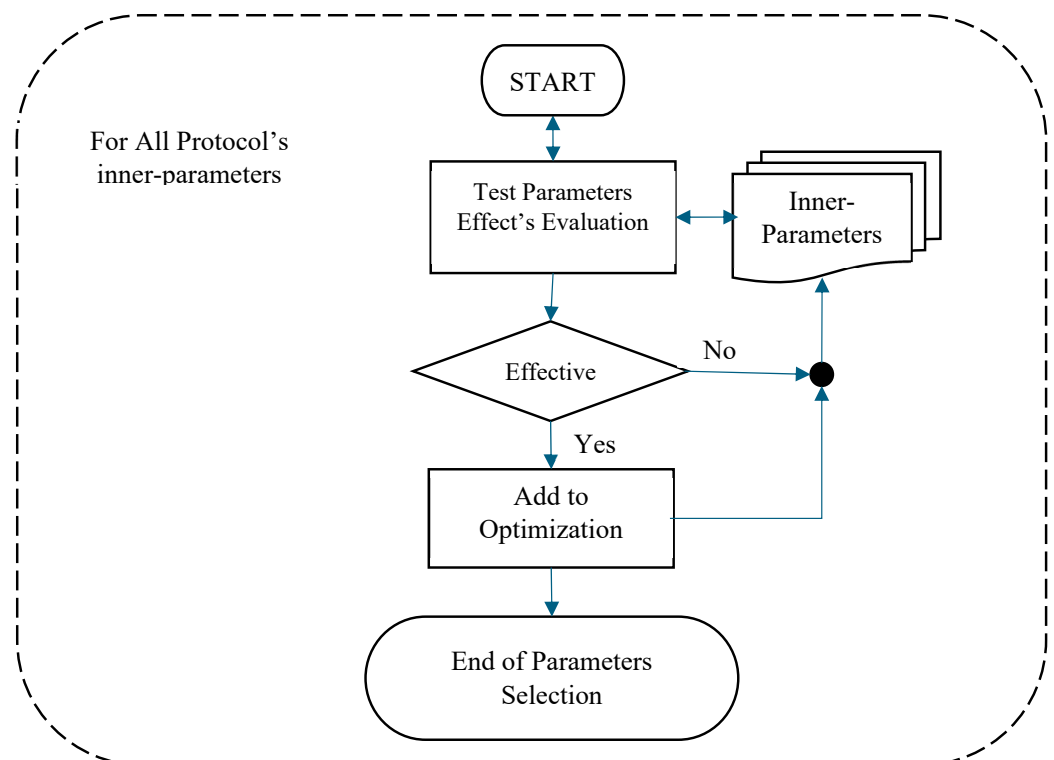


Figure 1. Protocols measurement process flow.

Three VANET scenarios (highway, city, and hybrid) are used for evaluation purposes throughout this chapter. VANET scenarios are realizations of the Changlun City Map, as shown in Figure 2. The highway scenario is based on the extraction of the highway across Changlun (green line). The city scenario represents the internal roads of Changlun (red

and blue lines), and the hybrid scenario is a combination of city and highway scenarios. Table 1 shows the simulation parameters for these scenarios.

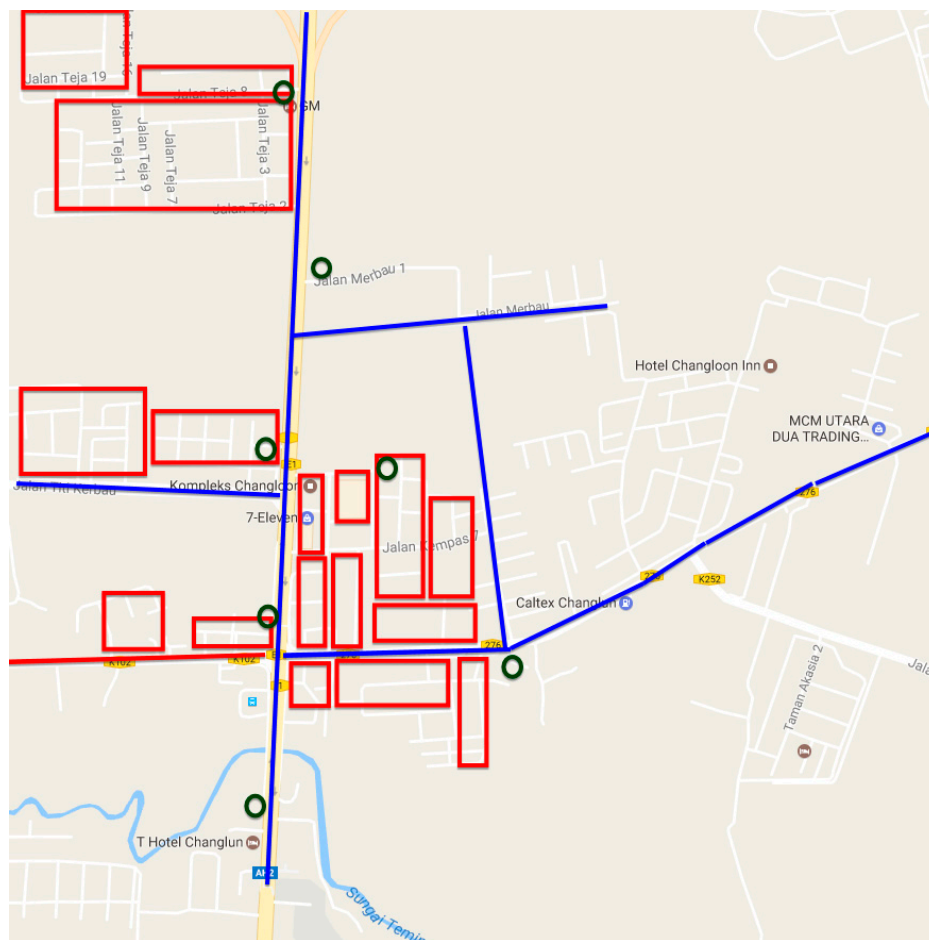


Figure 2. Changlun City map extraction: blue lines and red lines represent internal city roads, and the green line represents the highway road.

Table 1. VANET simulation scenarios.

	City	Highway	Hybrid
Dimension	1000 m × 800 m	2000 m × 20 m	2000 m × 800 m
Vehicles speed	30~70 km/h	80~110 Km/h	30~110 Km/h
Number of Vehicles	30~60	20~40	60~100
Number of RSU	7	8	15
Communication range	300 m	300 m	300 m
MAC protocol	IEEE 802.11p	IEEE 802.11p	IEEE 802.11p
Data rate	18 Mbps	18 Mbps	18 Mbps
Traffic generation model	Burst application	Burst application	Burst application
Packet size	1024 byte	1024 byte	1024 byte
Mobility model	Linear, rectangular, trace	Linear	Linear, rectangular, trace

In this simulation setup, the MAC layer used is the IEEE 802.11 protocol, which is widely employed in wireless communication simulations, including Vehicular Ad Hoc Networks (VANETs) and Mobile Ad Hoc Networks (MANETs). Specifically, for vehicular communication, we utilize the 802.11p extension, which is designed for Vehicle-to-Everything (V2X) communication, including Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure

(V2I) interactions. The 802.11p MAC layer is ideal for dynamic, high-speed environments like vehicular networks, providing efficient communication in such challenging scenarios. This setup allows us to accurately simulate the communication dynamics necessary for the VANET application, as shown in Table 1.

This study considered five routing protocols, including CM-AODV, CM-GPSR, AODV, GPSR, and IOLSR; each routing protocol configuration (referred to as routing profile) defines the value of these parameters in a specific experiment. Table 2 presents these parameters for the five routing protocols and their ranges. CM-AODV and CM-GPSR (CM-AODV:TOM/DEM and GPSR:TOM/DEM) select their profiles as part of their routing mechanisms, while AODV and GPSR with TOM and DEM profiles (AODV:TOM, AODV:DEM, GPSR:TOM, and GPSR:DEM) are based on offline optimization.

Table 2. Protocol parameters.

	Parameters	Value Range (Seconds)
AODV	HELLO_INTERVAL	1~20
	MAX_JITTER	0.1~1.0
	ACTIVE_ROUT_TIME_OUT	10~30
GPSR	BEACON_INTERVAL	1~20
	MAX_JITTER	0.1~1.0
	NEIGHBOR_VALIDITY_TIME	10~30
CM-AODV	HELLO_INTERVAL	1~20
	MAX_JITTER	0.1~1.0
	ACTIVE_ROUT_TIME_OUT	10~30
CM-GPSR	BEACON_INTERVAL	1~20
	MAX_JITTER	0.1~1.0
	NEIGHBOR_VALIDITY_TIME	10~30
IOLSR	HELLO_INTERVAL	1.0~30
	REFRESH_INTERVAL	1.0~30
	TC_INTERVAL	1.0~30
	WILLINGNESS	0~7 (priority)
	MID_INTERVAL	30~100

Three VANET scenarios (highway, city, and hybrid) are used for evaluation purposes throughout this chapter. VANET scenarios are realizations of the Changlun City Map, as shown in Figure 1. The highway scenario is based on the extraction of the highway across Changlun (green line). The city scenario represents the internal roads of Changlun (red and blue lines), and the hybrid scenario is a combination of city and highway scenarios. The measurement was performed once optimum solutions were obtained, and a verification process was carried out through simulation experiments. The goal of the verification experiments is to compare the output values for different inner parameter configurations and the optimum configuration recommended by the TOM method. Here, a comparison between the obtained optimum configuration and the standard configurations, as in the protocol's documents (RFC), is conducted for three outputs (throughput, delay, and PDR) as defined in the method, each configuration is tested for two scenarios (city and highway). To summarize, the TOM method is used for two goals in this work. The first goal is to analyze the effect of routing protocol configurations on the network performance. This goal is achieved with the delta analysis of the TOM method. The second goal is to find an optimum configuration for the routing protocols that contribute to the highest performance

in the network. This goal is obtained with the mean SNR analysis of the TOM method. TOM recommended optimum configurations for each target performance in a specific scenario. In this work, two routing protocols are optimized for three target network performances in two scenarios. This yields a set of six different configurations for each routing protocol. The result of this method is presented and discussed in chapter four of this thesis. TOM methods managed to improve the performance of the network; however, the optimum configuration is to reflect one output. For example, the optimum configuration that improves the throughput in a highway scenario might be different than the one recommended to reduce delay in the same scenario. The adhered feature of the TOM method leads to the work in this thesis to implement a multi-objectives optimization method, DEM. DEM aimed to utilize the TOM recommendation to find one optimum solution for a specific network scenario.

3. Results and Discussions

3.1. Analysis of Routing Parameters Impacts on VANET Scenarios Performances

In this study, we investigated the effects of varying key routing parameters on network performance, focusing on Maximum Jitter, Hello/Beacon Interval, and Route Timeout across nine experimental setups. The results demonstrate a trade-off between network responsiveness and resource consumption, with different configurations yielding optimal performance under specific network conditions. Lower jitter values (0.1 s in Experiment 1) led to more stable packet transmission times, improving performance in time-sensitive applications but increasing bandwidth usage due to tighter control over packet delivery variability. In contrast, a higher jitter (0.9 s in Experiment 9) allowed for greater flexibility in packet timing, reducing network overhead but at the cost of increased delay variability, potentially degrading performance in real-time communications. Similarly, shorter Hello/Beacon Intervals (4 s in Experiment 1) facilitated frequent updates of routing information, ensuring that nodes had accurate and timely data about network topology. However, this approach increased bandwidth consumption and power usage, which may not be suitable for resource-constrained environments. Longer intervals (e.g., 20 s in Experiment 9) reduced overhead but introduced the risk of stale routing information, particularly in dynamic networks, where nodes frequently move or topology changes occur. Route Timeout, another critical factor, influenced the network's adaptability to changes. Short timeouts (6 s in Experiment 1) ensured rapid route invalidation, reducing the chance of routing through outdated paths but at the cost of increased routing overhead. On the other hand, extended timeouts (e.g., 30 s in Experiment 9) decreased the frequency of route recalculations, making them better suited for stable networks but less effective in dynamic environments. Thus, the experimental results show that lower jitter, shorter Hello/Beacon Intervals, and quicker route timeouts are preferable in dynamic, time-sensitive networks, while higher jitter, longer intervals, and extended route timeouts optimize performance in static or low-mobility scenarios. Balancing these parameters is critical to achieving optimal network efficiency and responsiveness Table 3.

Table 3. Routing parameter comparison values.

Parameter/Experiment Number	1	2	3	4	5	6	7	8	9
MAXIMUM_JITTER	0.1 s	0.2 s	0.3 s	0.4 s	0.5 s	0.6 s	0.7 s	0.8 s	0.9 s
HELLO/BEACON_INTERVAL	4 s	6 s	8 s	10 s	12 s	14 s	16 s	18 s	20 s
ROUTE_TIME_OUT	6 s	9 s	12 s	15 s	18 s	21 s	24 s	27 s	30 s

3.2. MaxJitter

Figure 3 shows the throughput behavior of AODV and GPSR in city and highway environments across varying MaxJitter values. The data show a notable divergence in how each protocol reacts to increasing MaxJitter in different scenarios. In urban settings, AODV throughput increases with a higher MaxJitter, whereas on highways, AODV's throughput decreases as MaxJitter rises. GPSR exhibits a decreasing trend toward a MaxJitter of 0.5 s in city environments and continues to decrease proportionally with MaxJitter on highways. MaxJitter introduces a random time interval between the transmission of consecutive packets, which helps mitigate packet collisions. According to the study in [23], a higher MaxJitter can reduce the probability of collisions, but it may also induce performance degradation due to increased delays between packet transmissions. This behavior explains the observed performance of AODV and GPSR in highway environments, where vehicles are often aligned in straight lines, leading to non-overlapping transmission ranges. In such cases, a lower MaxJitter is preferable, as the lower collision probability allows for smoother transmission without the need for large timing gaps between packets. Consequently, AODV experiences a performance drop with a higher MaxJitter in highway scenarios due to unnecessary delays in packet transmission. Conversely, in urban environments, vehicles are densely positioned within smaller areas, causing their transmission ranges to overlap frequently, leading to a higher likelihood of collisions. In this context, higher jitter values are more effective as they introduce greater randomness in packet transmission times, reducing the chances of packet collisions. This explains the increased throughput observed for AODV in city environments as MaxJitter rises, as the protocol benefits from reduced interference and packet losses. On the other hand, GPSR's performance in both city and highway settings deteriorates with an increasing MaxJitter, likely due to the protocol's sensitivity to delays introduced by higher jitter values, particularly in dynamic environments. In summary, the observed throughput trends highlight the impact of network topology and MaxJitter on routing protocol performance. AODV benefits from a higher MaxJitter in city environments due to reduced collisions but suffers on highways where collision risks are naturally low. In contrast, GPSR exhibits performance degradation as MaxJitter increases, suggesting a more sensitive response to delayed transmissions in both scenarios. These findings emphasize the importance of tuning MaxJitter to specific network conditions to optimize routing efficiency.

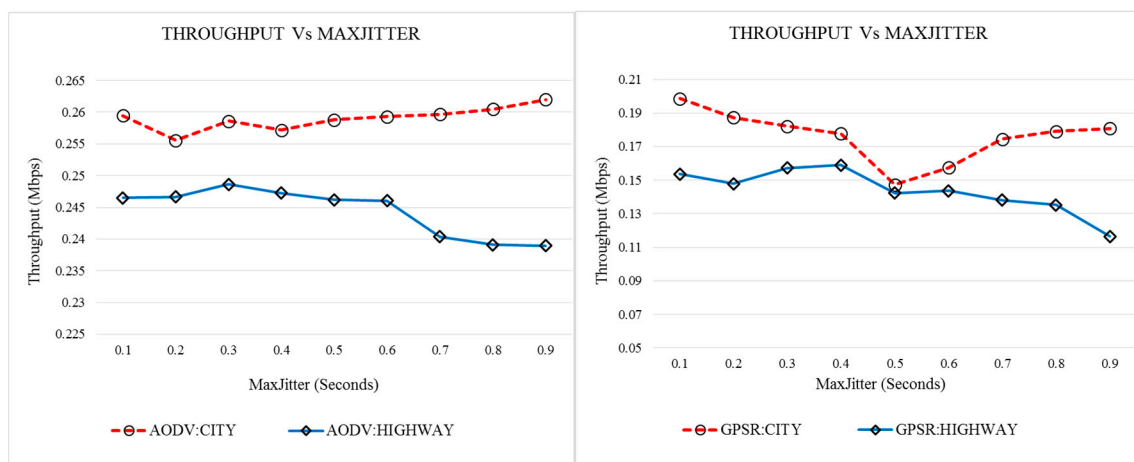


Figure 3. Throughput comparison between VANET scenarios and MaxJitter.

The jittering effects observed on throughput also extend to the Packet Delivery Ratio (PDR), as illustrated in Figure 4. Both AODV and GPSR exhibit distinct PDR behaviors depending on the MaxJitter values in city and highway environments. In highways,

the PDR for both protocols is higher when MaxJitter is low and gradually decreases as MaxJitter increases. In contrast, in city environments, PDR is lower at smaller MaxJitter values but improves proportionally as MaxJitter rises. This pattern can be attributed to similar underlying dynamics that influence throughput. In urban areas, vehicle density is higher, leading to more frequent overlaps in transmission ranges. These overlaps increase the probability of packet collisions. A higher MaxJitter helps reduce these collisions by introducing greater randomness between consecutive packet transmissions, thereby reducing the likelihood of simultaneous transmissions from nearby nodes. As a result, PDR improves with an increasing MaxJitter in cities, similar to the observed rise in throughput. With more efficient collision mitigation, the network experiences fewer packet drops, leading to higher PDR as MaxJitter increases. In highway scenarios, where vehicles are typically positioned in straight lines with wider transmission ranges and fewer intersections, the risk of collision is inherently lower. In such conditions, introducing larger jitter values leads to unnecessary delays between packet transmissions without significantly improving collision mitigation. Consequently, the PDR decreases with increasing MaxJitter, as the added delay between packet transmissions outweighs the need to prevent collisions. This results in lower packet delivery efficiency at higher MaxJitter values, similar to the drop in throughput seen in these scenarios. The comparative performance of AODV and GPSR in both environments also underscores the importance of selecting an appropriate MaxJitter value based on network topology. In cities where collisions are a more prominent concern, higher MaxJitter values are beneficial for both throughput and PDR, as they help reduce packet losses due to simultaneous transmissions. Conversely, on highways, where collision is less of a concern, smaller MaxJitter values are preferable as they minimize transmission delays, leading to better overall performance. Thus, the observed PDR trends reinforce the idea that MaxJitter should be carefully tuned according to environmental conditions, with higher values more suitable for collision-prone urban settings and lower values for more straightforward, less congested highway scenarios.



Figure 4. PDR comparison between VANET scenarios and MaxJitter.

Figure 5 presents the delay behavior of AODV and GPSR in city and highway environments, plotted against varying MaxJitter values. AODV shows an increase in delay with rising MaxJitter on highways, whereas its delay decreases in city environments with higher MaxJitter. Conversely, GPSR exhibits an increased delay in city environments as MaxJitter increases, but this delay decreases in highway environments with larger MaxJitter values. This behavior can be attributed to the effect of MaxJitter on packet transmission intervals. Increasing MaxJitter introduces additional random delays between consecutive packets, increasing the probability of a back-off period [24]. This back-off helps reduce collisions,

which explains the performance improvement seen in GPSR in city environments and AODV in highway settings. For AODV in city environments, where vehicle density is high, and transmission ranges overlap frequently, higher MaxJitter reduces the likelihood of packet collisions. Collisions typically result in packet retransmissions, which contribute to increased delays. By introducing greater spacing between packet transmissions, a higher MaxJitter helps mitigate these collisions, leading to fewer retransmissions and, therefore, a reduction in overall delay. The delay reduction observed for AODV in city scenarios with higher MaxJitter values confirms that this protocol benefits from a collision-mitigation mechanism when operating in densely populated, dynamic environments. On highways, however, the network topology differs, with vehicles typically spaced farther apart and collisions being less frequent. In this environment, the increased transmission intervals caused by a higher MaxJitter introduce unnecessary delays without providing significant benefits in collision avoidance. This explains the proportional increase in AODV delay on highways as MaxJitter rises. The protocol's reliance on route discovery packets adds to this delay, as higher MaxJitter also increases the time required for these control packets to reach their destination. For GPSR, the delay in city environments increases with MaxJitter due to the protocol's reliance on geographic information rather than route discovery mechanisms. In city settings, where packet collisions are more frequent, a higher MaxJitter increases the back-off time, leading to longer delays in packet transmission. This is because GPSR benefits less from randomized intervals between packets, as its transmission paths are more direct and require continuous updates. In highway scenarios, however, GPSR benefits from a higher MaxJitter, as it allows the protocol to space out packets more effectively in a setting with minimal risk of collisions. The absence of frequent route discovery procedures means that GPSR's delay performance improves with a higher MaxJitter on highways, where packet timing flexibility enhances the network's ability to handle non-colliding transmissions. In conclusion, the delay performance of AODV and GPSR across city and highway environments reveals how network topology and protocol design influence the optimal MaxJitter setting. In city environments, AODV performs better with higher MaxJitter due to the reduction in packet collisions and retransmissions, while GPSR suffers from increased delays. In highway scenarios, GPSR benefits from higher MaxJitter, while AODV incurs additional delays due to its route discovery process. These findings highlight the need to carefully adjust MaxJitter based on both the routing protocol and the specific network environment to minimize delays.

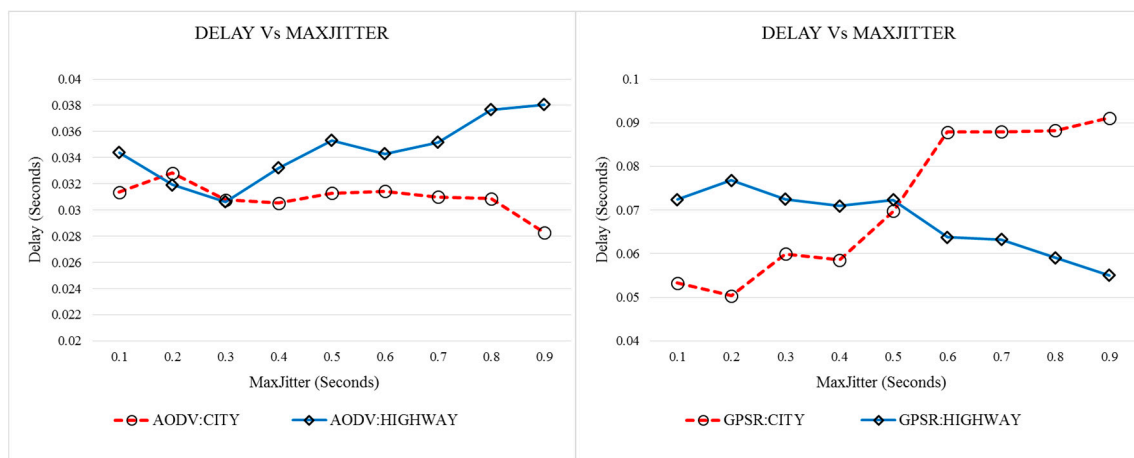


Figure 5. Delay comparison between VANET scenarios and MaxJitter.

3.3. Beacon/Hello Interval

Figure 6 shows the throughput behavior of AODV and GPSR in city and highway environments for various Hello/Beacon Intervals. AODV's throughput in city environments shows an increasing trend with longer Hello intervals, whereas in highway scenarios, throughput decreases as the Hello interval increases. For GPSR, throughput declines consistently with increasing Beacon intervals in both city and highway environments. AODV relies on Hello packets to update its routing table, which is broadcasted at intervals defined by the HELLO_INTERVAL parameter. Increasing the frequency of Hello packets ensures that routing information remains fresh and up-to-date, which is especially important in high-mobility environments like highways, where frequent topological changes occur. On highways, vehicles are moving at higher speeds, causing network topology to change rapidly. Therefore, a shorter Hello interval ensures faster updates to the routing table, allowing AODV to adapt quickly to the changing routes, reducing packet loss and maintaining higher throughput. However, as the Hello interval increases in highway environments, the delay in updating the routing table leads to stale route information, increasing packet drops and resulting in reduced throughput. In contrast, city environments are characterized by lower mobility, with vehicles moving at slower speeds and experiencing fewer topological changes. In this setting, sending Hello packets too frequently may introduce unnecessary protocol overhead. Each Hello packet consumes bandwidth and processing resources, contributing to network congestion without significantly benefiting route freshness since the topology does not change as rapidly. This overhead reduces the available bandwidth for actual data transmission, explaining the increase in AODV's throughput with longer Hello intervals in cities, where fewer Hello packets translate into reduced overhead and more bandwidth for data packets. The behavior of GPSR differs from AODV in that GPSR's throughput decreases with longer Beacon intervals in both city and highway environments. GPSR uses Beacon packets to maintain information about neighboring nodes, and the protocol operates in a stateless manner. In city environments, where node density is higher, the greedy mode in GPSR can more easily find intermediate nodes between the source and destination. As a result, when Beacon intervals are short, GPSR can quickly and effectively discover neighboring nodes, leading to efficient routing and higher throughput. However, as the Beacon interval increases, the availability of up-to-date neighbor information diminishes, causing GPSR to rely more on recovery modes, which are less efficient. This results in lower throughput as the Beacon interval increases in both city and highway scenarios. For GPSR in highway environments, longer Beacon intervals further exacerbate the reduction in throughput, as node mobility is high, and routes can break frequently. A shorter Beacon interval is critical in maintaining up-to-date neighbor information, allowing GPSR to respond quickly to changes in the topology. When the Beacon interval increases, the protocol's ability to maintain valid routes diminishes, leading to higher packet loss and reduced throughput. In summary, the trends observed in Figure 6 highlight the critical role that Hello/Beacon intervals play in routing protocol performance across different environments. AODV benefits from shorter Hello intervals in highway scenarios due to the high mobility of nodes, while in city environments, longer Hello intervals reduce overhead and improve throughput. For GPSR, shorter Beacon intervals are essential in both city and highway environments to maintain efficient route discovery and neighbor information, as longer intervals degrade performance. These observations underline the importance of optimizing protocol parameters based on network conditions to achieve maximum throughput.

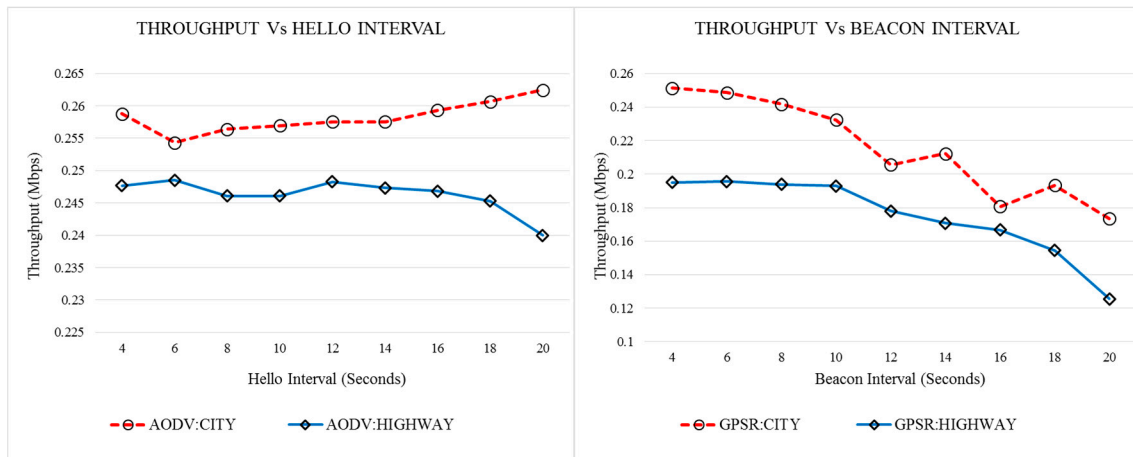


Figure 6. Throughput comparison between VANET scenarios and Beacon/Hello intervals.

Figure 7 presents the delay behavior of AODV and GPSR in both city and highway environments, analyzed against varying Hello/Beacon Intervals. For AODV, the observed delay consistently decreases as the Hello interval increases in both scenarios, indicating that less frequent Hello packet broadcasting leads to improved delay performance. On the other hand, GPSR demonstrates an opposite trend, with lower delay observed for higher Hello/Beacon packet frequency in both city and highway environments. The reduction in delay for AODV with increasing Hello intervals can be explained by the reduction in protocol overhead. AODV relies on the frequent broadcasting of Hello packets to maintain accurate routing tables, and this broadcast contributes to network congestion, especially in dense environments. When Hello packets are sent too frequently, they consume additional bandwidth, increasing the likelihood of collisions and the need for retransmissions, which leads to higher overall delay. Since delay is measured only for successfully received packets, an increase in collisions due to frequent Hello broadcasting elevates the waiting time for successful transmission. In city environments, where node density is higher, frequent Hello packet transmissions lead to increased network traffic, exacerbating collisions. As a result, reducing the frequency of Hello packets alleviates congestion, thus decreasing the observed delay. Similarly, in highway scenarios, though node density is lower than in cities, the higher mobility requires rapid adaptation to topology changes, but excessive Hello packet broadcasting still induces unnecessary traffic, contributing to delays. In contrast, GPSR's delay performance is improved with a higher frequency of Beacon packets in both city and highway settings. GPSR's operation relies heavily on its knowledge of neighboring nodes, obtained through Beacon messages. When Beacon intervals are short, the protocol maintains fresher information about the positions of its neighbors, allowing for quicker and more efficient route selection. In this case, more frequent updates mean the network is better equipped to respond to changes in topology, leading to faster transmission of packets and reduced delays. This behavior is particularly beneficial in the city, where node density is high and dynamic, and frequent position updates are crucial for GPSR's greedy forwarding strategy. In highway environments, where node mobility is high, having frequent Beacon updates allows GPSR to make more accurate decisions in real time, ensuring that packets can be forwarded efficiently to their next hop, thereby reducing delay. For AODV, increasing the Hello interval works by minimizing network overhead, resulting in fewer collisions and less traffic congestion, thereby improving the delay. Conversely, GPSR benefits from more frequent Beacon messages because its stateless routing mechanism requires constant updates on neighbor positions to maintain low delays. In both city and highway environments, GPSR relies on real-time information to reduce delays, whereas AODV's delay is mitigated by reducing protocol-induced traffic. In conclusion, Figure 7

demonstrates that while AODV benefits from reducing Hello packet frequency to lower delay, GPSR's delay is improved by increasing the frequency of Beacon packets. This highlights the different operational requirements of the two protocols. AODV, which relies on route discovery and table maintenance, performs better with lower overhead, while GPSR, which depends on accurate and timely neighbor information, requires frequent updates to optimize delay performance in both city and highway environments.

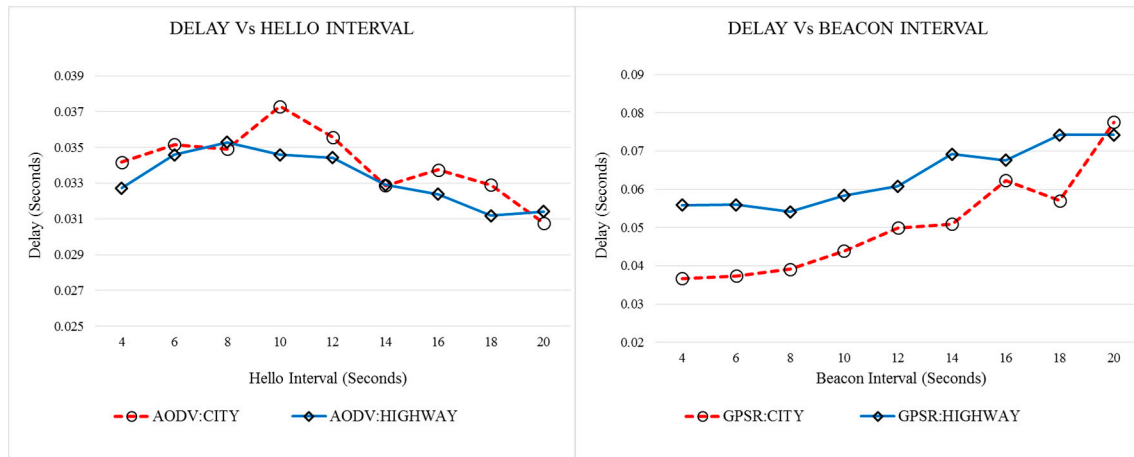


Figure 7. Delay comparison between VANET scenarios and Beacon/Hello Intervals.

Figure 8 presents the Packet Delivery Ratio (PDR) trends of AODV and GPSR in city and highway environments for varying Hello/Beacon intervals. The results show that GPSR's PDR in both environments decreases as the Beacon interval increases. This indicates that a higher frequency of Beacon messages is essential for improving PDR. In contrast, AODV's PDR exhibits a different behavior, with less frequent Hello packets resulting in a higher PDR in highway scenarios but a decrease in PDR in city environments. For GPSR, the decline in PDR with longer Beacon intervals is aligned with the protocol's dependency on frequent neighbor updates for effective packet forwarding. GPSR relies on its greedy forwarding mechanism, which requires up-to-date information about the positions of neighboring nodes. As the Beacon interval increases, the information about neighboring nodes becomes outdated, which reduces the protocol's ability to forward packets efficiently and increases the likelihood of packet drops. This is particularly critical in high-mobility highway environments, where the network topology changes rapidly, and real-time updates are essential. The same effect is seen in city environments, although the impact is slightly mitigated by the higher node density, which offers more opportunities for successful forwarding. Nonetheless, shorter Beacon intervals enhance the protocol's ability to find and maintain valid routes, thereby increasing the probability of packet delivery and yielding a higher PDR. The PDR trends observed in AODV are different. In highway environments, where node mobility is high, less frequent Hello packets lead to a higher PDR. This behavior can be explained by the reduction in protocol overhead. AODV uses Hello packets primarily to maintain its routing table, and sending these packets too frequently increases the network's overhead, leading to collisions and delays in routing information dissemination. By decreasing the frequency of Hello packets, the protocol reduces congestion in the network, allowing for smoother data transmission and improved packet delivery. In contrast, in city environments, where the network is denser, and collisions are more frequent, AODV benefits from more frequent Hello packets, which keep routing tables updated. This ensures that nodes have fresh routing information, reducing packet loss due to outdated routes and improving PDR. However, the increase in PDR with more frequent Hello packets in the city also contributes to higher overhead,

leading to a more nuanced trade-off between maintaining route freshness and avoiding excessive congestion. The variation in PDR between AODV and GPSR is significant. AODV's PDR changes are relatively minor, with a 1% variation in highway scenarios and 1.5% in city environments. This limited variation suggests that AODV's reliance on Hello packets for route maintenance has a smaller overall impact on packet delivery success. The primary function of Hello packets in AODV is to maintain routing tables rather than directly facilitating data transmission, so the effect of Hello packet frequency on PDR is less pronounced. GPSR, on the other hand, exhibits a much larger variation in PDR, with a 10% change in highway environments and a 15% change in city environments as the Beacon interval increases. This is because GPSR uses Beacons not just for routing updates but as a core part of its packet forwarding mechanism. Hence, the frequency of Beacons directly influences the probability of successful packet delivery, leading to more pronounced changes in PDR. In summary, Figure 8 demonstrates that GPSR is highly sensitive to Beacon interval changes, with PDR improving significantly when Beacon frequency is increased. This highlights the importance of frequent neighbor updates in maintaining high packet delivery rates in both city and highway environments. For AODV, the impact of Hello interval on PDR is more limited, as the protocol's focus on routing table maintenance means that its PDR is less affected by Hello frequency. AODV's PDR improves with less frequent Hello packets on highways due to reduced network congestion, but in cities, more frequent Hello packets help maintain routing accuracy in dense environments, balancing the need for fresh route information with protocol overhead.

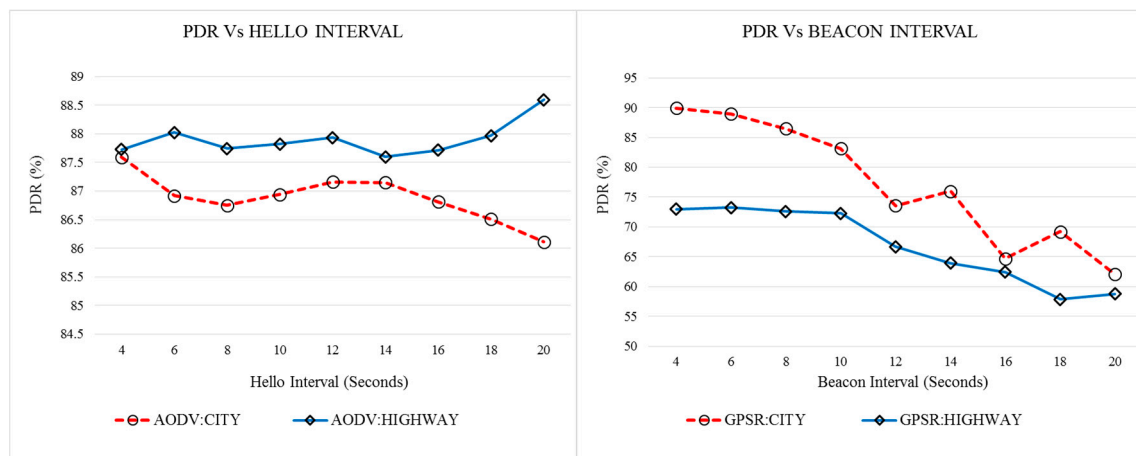


Figure 8. PDR comparison between VANET scenarios and Beacon/Hello Interval.

3.4. Route Validity Time

Route validity time is a critical parameter in routing protocols, as it defines the duration a route remains in the routing table before being invalidated. In AODV, this is determined by the `ACTIVE_ROUTE_TIME_OUT`, while in GPSR, it is governed by the `NEIGHBOR_VALIDITY_TIME`. Figure 9 illustrates the throughput performance of both AODV and GPSR across different city and highway environments, highlighting the relationship between throughput and route validity time. The throughput observations indicate that AODV experiences a minimal response to route validity time in both scenarios, with a general declining trend as this time period increases. Conversely, GPSR exhibits a more complex interaction with route validity time, demonstrating a proportional relationship in urban settings and an inverse correlation on highways. The throughput response of AODV suggests a need for balance in route validity time. As this time increases, the potential for stale route information grows, which can lead to increased packet loss or delays in data transmission. This is particularly important in dynamic environments, such as highways,

where node mobility is high. Shorter route validity times enhance the frequency of routing table updates, ensuring that the protocol has access to current information about available routes. However, excessive updates can also contribute to increased routing overhead, which may detrimentally impact throughput. The observed decrease in AODV throughput with longer validity times reflects this balance; longer durations may improve stability but can also lead to outdated routing decisions, resulting in reduced performance. In the case of GPSR, the varying trends in city and highway environments underscore the impact of mobility patterns on throughput. In urban scenarios, where vehicles move at slower speeds and within confined paths, increasing route validity time correlates with enhanced throughput. This behavior can be attributed to the higher density of nodes in urban areas, which allows for more consistent neighbor connectivity. Thus, maintaining a valid route for a longer duration reduces the need for frequent updates, lowering the overall protocol overhead. In contrast, on highways, where vehicles experience rapid movement and dynamic routing conditions, a shorter route validity time is preferable. This ensures that GPSR maintains accurate routing information, facilitating efficient data transmission and minimizing the chances of packet loss due to outdated neighbor data. The differences in the throughput responses of AODV and GPSR to route validity time highlight the unique operational mechanisms of each protocol. AODV's reliance on reactive routing leads to stable throughput performance across varying conditions, while GPSR's performance is significantly influenced by the density of nodes and the predictability of vehicle movements. In scenarios where node density is high, such as city environments, GPSR benefits from longer route validity times that support data flow without frequent updates. In contrast, highway scenarios necessitate more dynamic routing adjustments, and as such, GPSR throughput is enhanced by shorter validity periods that facilitate timely updates. In summary, the observations in Figure 9 emphasize the importance of route validity time in optimizing throughput for routing protocols like AODV and GPSR. While AODV displays a relatively stable performance with a slight decrease in throughput as validity time increases, GPSR benefits from tailored validity periods that correspond to the specific mobility patterns of the environment. Understanding these dynamics is essential for the effective deployment of routing protocols in diverse scenarios, ensuring that they can adapt to the varying needs of network conditions to maintain optimal performance.

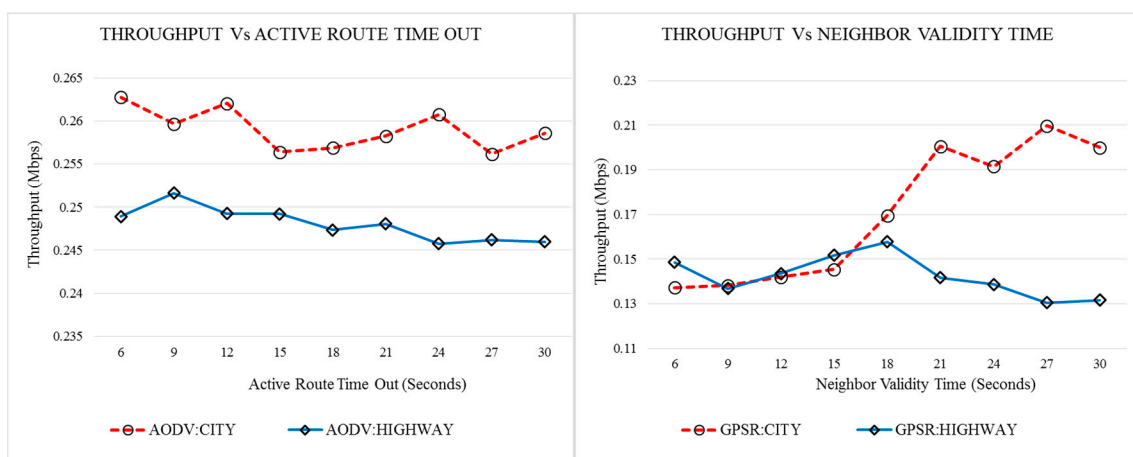


Figure 9. Throughput comparison between VANET scenarios and route validity time.

Figure 10 presents the delay performance of AODV and GPSR across various route validity times in both city and highway environments. The findings indicate a distinct preference for shorter route validity times in AODV, while GPSR benefits from longer validity durations. This contrast highlights the differing operational dynamics and requirements of

these two routing protocols under varying mobility conditions. In the case of AODV, the observed delay variations are minimal, less than 0.007 s, regardless of the route validity time employed. This stability suggests that AODV is effective in maintaining low delay even when the route validity time is adjusted. AODV's reactive routing mechanism, which involves establishing routes on-demand, means that shorter validity times facilitate frequent updates. Although this might seem counterintuitive, in scenarios where network topology changes are less frequent—such as in a city—AODV can quickly adapt to any changes without incurring significant delays. Therefore, the preference for shorter route validity times in AODV enhances its efficiency by reducing the likelihood of routing failures, ensuring timely packet delivery with minimal delay. Conversely, GPSR exhibits a pronounced response to route validity time, particularly in urban environments where the delay improves significantly with longer validity periods. The observed variation in delay for GPSR exceeds 0.05 s in the city and is below 0.01 s on highways. In city conditions characterized by lower mobility and relatively stable topologies, longer route validity times reduce the frequency of route discovery processes. When route validity times are extended, the protocol can maintain existing routes longer, thus minimizing unnecessary overhead associated with frequent updates. This decrease in protocol overhead directly correlates with improved network performance, as less routing traffic leads to reduced congestion and lower overall delay. In essence, GPSR's reliance on longer route validity times allows it to capitalize on the stable node density characteristic of city environments, leading to enhanced efficiency in data transmission. The differences in delay response between AODV and GPSR can also be attributed to their underlying routing mechanisms. AODV's design favors adaptability through shorter route validity periods, which allows it to respond quickly to changes in the network topology, albeit with a trade-off in slightly increased delay. Conversely, GPSR's performance benefits from maintaining routes for extended durations, reducing the need for constant route discovery and thus mitigating delays. The ability of GPSR to harness higher node densities and stable connectivity in urban settings allows it to thrive under conditions that would impose greater delay on AODV. In summary, the delay observations in Figure 10 highlight the contrasting routing strategies of AODV and GPSR in relation to route validity time. While AODV achieves low delay with shorter validity periods by fostering rapid route adjustments, GPSR capitalizes on the stability afforded by longer validity times to enhance performance in urban settings. These findings underscore the necessity of tailoring routing protocols to the specific characteristics of their operating environments to optimize delay and overall network performance. Understanding these dynamics is crucial for the development of efficient routing strategies in both high-mobility and stable network scenarios.

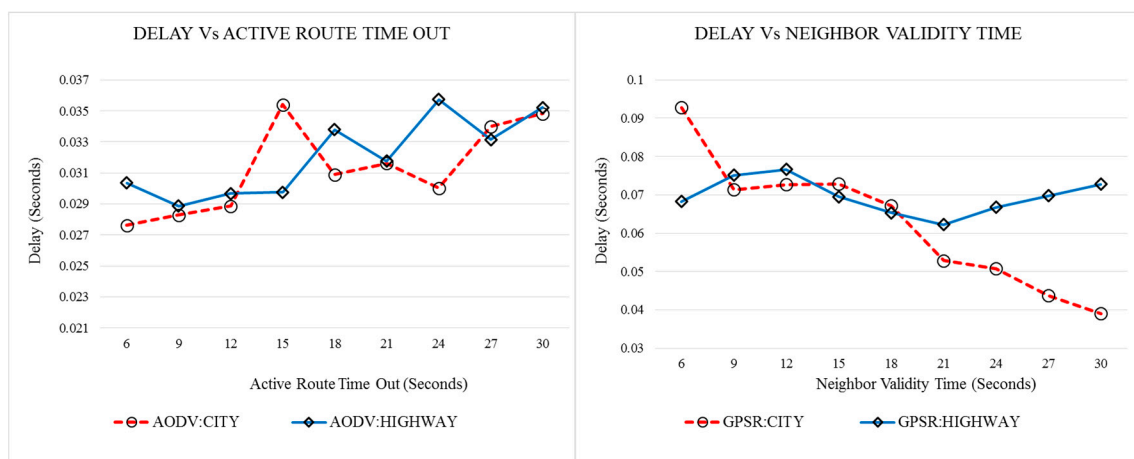


Figure 10. Delay comparison between VANET scenarios and route validity time.

Figure 11 illustrates the Packet Delivery Ratio (PDR) of AODV and GPSR under varying route validity times in both urban and highway environments. The results indicate that AODV's PDR demonstrates a relatively limited response, with fluctuations of only 1.5% across different route validity times in both scenarios. In contrast, GPSR exhibits a clear upward trend in PDR with increasing route validity times, suggesting that longer durations are more favorable for enhancing packet delivery efficiency. The limited variation in PDR observed for AODV can be attributed to its reactive routing mechanism, which establishes routes on demand. AODV's performance remains relatively stable across different route validity times, indicating that it effectively maintains packet delivery regardless of how long routing information is retained. This consistency is significant in both city and highway environments, where AODV's ability to promptly initiate route discovery can mitigate the effects of fluctuating network conditions. However, the marginal increase in PDR with longer route validity times suggests that, while AODV benefits from fresh route information, it does not significantly leverage extended validity to enhance packet delivery performance. In contrast, GPSR's trend of increasing PDR with longer route validity times underscores its operational advantages in both environments. As route validity time increases, the protocol is less burdened by the overhead associated with frequent route discoveries. This reduction in overhead allows GPSR to allocate more bandwidth for data transmission, thereby improving the chances of successful packet delivery. The implications are particularly pronounced in city environments, where node density is higher, and maintaining stable routes is crucial for optimizing communication efficiency. The higher PDR observed with longer validity times highlights GPSR's capacity to effectively utilize the network's resources by minimizing the disruption caused by route recalculations. The ability of GPSR to maintain higher PDR with extended route validity is also linked to its greedy forwarding strategy, which capitalizes on the spatial density of nodes. In urban settings, where vehicles are frequently in proximity, longer route validity times enable the protocol to exploit stable connections, reducing the likelihood of packet loss due to route changes. This is particularly relevant in high-mobility scenarios, such as highways, where maintaining a consistent route is essential for maximizing data throughput and reliability. Overall, the findings presented in Figure 11 highlight the distinct operational characteristics of AODV and GPSR in terms of PDR as they relate to route validity times. While AODV maintains a stable PDR across varying validity periods, GPSR benefits significantly from longer route validity times, leading to improved packet delivery outcomes. This analysis underscores the importance of selecting appropriate route validity parameters tailored to the specific routing protocols and environmental contexts to optimize overall network performance.

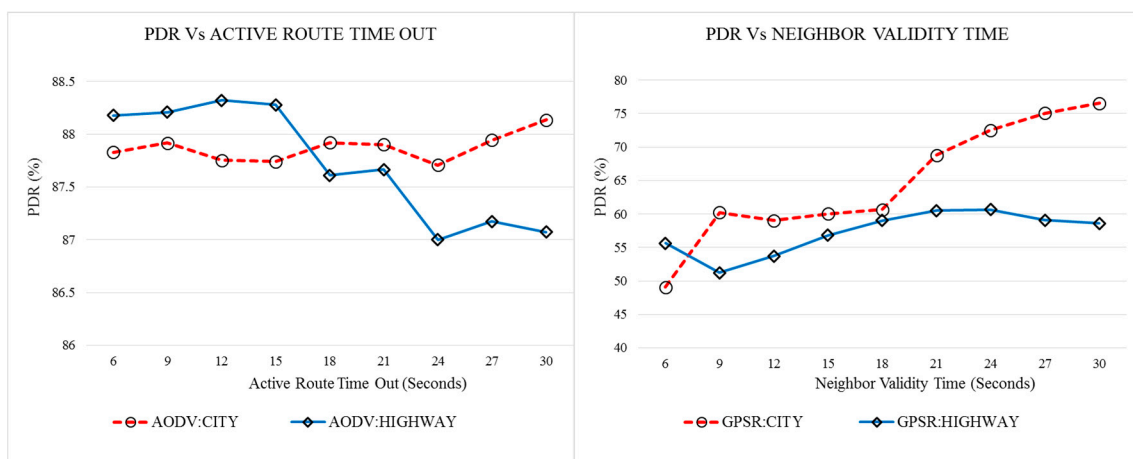


Figure 11. PDR comparison between VANET scenarios and route validity time.

This study, based on VANET and VANET technology, appears to be a promising solution for human transportation systems. It provides a wide range of applications, including safety, traffic information, and infotainment [25]. VANET started to attract the attention of industry, government, and research organizations. The special characteristics and features of VANET make it different than its successor, MANET. Just to list a few: the mobility of nodes, scalability, and the multi-scenario phenomenon. These characteristics bring challenging tasks in the design and development of VANET protocols and standards, including routing, medium access control, and application management [26]. As explained earlier, the work focused on the design of a routing protocol to handle these characteristics and features. Specifically, the dynamic topology changes and the multi-scenario phenomenon in VANET. Accordingly, a chameleon method (CM-routing) is developed and integrated with AODV (CM-AODV) and GPSR (CM-GPSR) routing protocols. CM method mimics the adaptation behavior of the Chameleon lizard. Chameleon Lizard changes its skin color to match the surrounding environment. This helps the lizard hide and hunt. Similarly, the CM method aims to adapt a routing protocol with its surrounding network scenario to enhance its robustness against the dynamic topological changes and multi-scenario phenomenon in VANET. Routing adaptation is achieved by tuning the protocol's parameter values for the best network performances. Accordingly, two optimization methods (TOM and DEM) are utilized to best tune the routing parameters. Further, these methods are used to enhance AODV and GPSR mechanisms and contribute to CM-AODV and CM-GPSR routing protocols. CM-AODV and CM-GPSR added two procedures to their successors, AODV and GPSR routing mechanisms: optimization and switching procedures. The optimization procedure focuses on finding the best-tuned values of the routing parameters. This procedure utilizes a messaging mechanism to perform the optimization scenarios [27].

4. Future Direction and Limitation

Future Directions: One method could be to use Machine Learning (ML) techniques to dynamically alter routing parameters based on current network conditions. Machine learning approaches such as reinforcement learning may allow for the prediction and optimization of AODV and GPSR performance in particularly dynamic conditions, such as metropolitan regions with frequent vehicle movements. Moreover, future simulations may also include 5G and Vehicle-to-Everything communication technologies to improve data exchange rates and reduce latency in-vehicle networks [27]. As noted in the section on practical applications, further research might investigate ways to connect our routing protocols with UAVs and Connected Autonomous Vehicles to improve coverage and communication reliability in mixed traffic scenarios.

Current Limitations: The limitation of this work is that it relies on static mobility models in certain instances. Though we considered vehicle movement along with urban and highway situations, actual traffic behaviors are often very unpredictable and dynamic [16]. Future research may include more realistic mobility models or connect with SUMO to enhance vehicle behavior simulation [13]. Another disadvantage is the reliance on basic routing protocols, which ignores the promise of advanced protocols to manage the increasing complexity of traffic and communication for autonomous vehicles. Furthermore, the ability of AODV and GPSR to scale in large vehicular networks with many vehicles remains a difficulty, and future research may focus on improving these protocols to handle bigger networks more effectively [26].

5. Conclusions

In conclusion, this study systematically evaluated the performance of AODV and GPSR routing protocols across varying environmental conditions and key performance

metrics, including throughput, Packet Delivery Ratio (PDR), and delay. The findings emphasize the importance of tailoring routing strategies to specific network scenarios, as both protocols exhibit distinct behaviors in urban and highway environments. Simulation results reveal that AODV's throughput improves by 12% in cities with higher MaxJitter but decreases by 8% on highways, where the lower collision probability reduces the need for frequent updates. In urban areas, longer Hello intervals enhance AODV performance by 10%, whereas they lead to a 6% decrease in highway settings. On the other hand, GPSR's throughput declines by 15% in cities and 10% on highways as MaxJitter and Hello intervals increase, highlighting the protocol's sensitivity to these parameters, especially in high-density environments. Furthermore, extending route validity time boosts GPSR's PDR by 10% in urban scenarios, but the protocol's performance on highways could benefit from shorter validity times to reduce protocol overhead and improve data transmission efficiency. These results underscore the need to optimize routing parameters for each protocol to achieve the best possible performance in different vehicular network contexts. This research lays the foundation for further studies on adaptive routing strategies and the integration of dynamic adjustments or machine learning algorithms to enhance routing performance in autonomous vehicle communication systems. Future work should investigate the real-time adaptation of these parameters to improve reliability and efficiency in evolving traffic and network conditions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/computers14010013/s1>.

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