Position-Based Multipath Route Switching Protocol for Intelligent VANETs Using Wiedemann Car-Following Model

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***Abstract*—The high dynamicity in VANET topology increases the possibility of frequently broken links and degraded the type of service provided to its customers (i.e., comfort and safety services) that may lead into a catastrophe. In this paper, a Quality-of-Service (QoS)-aware position-based multipath route switching protocol for VANETs-based intelligent transportation systems is proposed. The proposed protocol adopts one of three main route switching criteria: Least Connection Delay (LDD), least number of path-switching (LPS), and the least number of path-switching with the minimum delay (LPSMD). The proposed protocol finds multiple paths between the source and the destination and predicts the future connectivity of each path using the Wiedemann Car-Following Model (Wiedemann and Reiter-99). According to the requested QoS and the route switching criterion adopted, the route switching protocol dynamically switches between the pre-defined multiple paths such that the Network Performance Metrics (NPMs) are guaranteed for the entire VANET. Using different network parameters such as vehicular node density, vehicular node speed, and the time-period for collecting vehicle information, extensive simulation results show that the proposed LDD-based route switching protocol outperforms the other route switching criteria in guaranteeing the studied NPMs (i.e., 1) Packet delivery ratio with a 3.6% enhancement over LPSMD and 8.6% enhancement over LPS; 2) Average end-to-end total packet delay with a 4.2% enhancement over LPSMD and 3.4% enhancement over LPS).**

***Index Terms*—Intelligent Transportation System (ITS), multipath, prediction, routing, safety, Vehicular Ad-Hoc Networks (VANETs)**

I. Introduction

Recently, the concept of IntelliDrive (connected vehicles) where vehicles use wireless communication technologies, sensors, GPS, and smart equipment on board to communicate wirelessly in a Vehicular Ad-Hoc Network (VANET) becomes a hot research topic [1]-[3]. According to such connected environment, researchers have developed many transportation applications that depend on the ability of such communicated vehicles to share its vehicular information [4]-[6] (i.e., speed, location, heading, etc.) via Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication protocols (i.e., vehicle to Road-Side Units (RSUs)) [7], [8].

The most common standard used for such communications is the Dedicated Short-Range Communication (DSRC) based on the the IEEE 802.11p standards [9]. The transportation applications provide passengers with safety services (i.e., collision warning messages, emergency braking, traffic alerts, road merging, etc.) [10], [11], comfort services (i.e., Internet access, updated climate information, geo-location for nearby services such as hotels, restaurants, and gas stations) or traffic efficiency services (i.e., services to avoid congestions and traffic delays) [12], [13]. For effective implementation for such applications specially those safety ones, necessary criteria should be met such as time-sensitivity, delivery (broadcast-oriented), latency, reliability, and accuracy [14], [15]. The key behind guaranteeing such criteria is by designing the appropriate routing protocol [16]-[18]. Such protocol should have the ability to handle the challenges of the VANET environment such as the high dynamicity in VANET topology, the high mobility of vehicular nodes, the unpredicted driver's behavior, and the surrounding effect (i.e., blocking objects, lane structures, security threats, etc.) [19], [20].

Two main categories for routing protocols in VANETs, single-path and multipath routing protocols [21], [22]. Conventional single-path routing protocols are not sufficient when dealing with critical safety applications, especially for those VANETs with frequent disconnected links [23]. Safety applications requires high reliability and accuracy in data transmission along with strict Quality-of-Service (QoS) guarantees such as delivery, end-to-end delay, and latency [5]. For VANETs with frequent disconnected links, single-path routing protocols add more overhead in the route discovery process, where extra route request control messages (RREQ) are generated to find a reliable-connected path to destination [24]. Such overhead degrades the quality of service provided (i.e., more end-to-end delays and less packet delivery) which may lead into a catastrophe for such safety applications [10]. From the other side, multipath routing protocols are more robust when dealing with such heterogenous VANET with frequently failure paths (disconnected paths), where multiple paths are utilized (i.e., load distribution) to eliminate the extra overhead generated by the route-discovery process [25].

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Accordingly, the overall network performance metrics (NPMs) such as end-to-end delay, delivery, and latency are guaranteed for the real-time data packet flows [26].

Multipath routing protocols are mainly classified into six categories: cluster-based routing protocols, topology-based routing protocols, geo-cast routing protocols, position-based routing protocols, adaptive routing protocols, and broadcast routing protocols, as shown in Fig. 1 [27]-[29]. Among the previous routing protocols, position-based routing protocols are the most efficient protocols for safety applications where packet forwarding, and route discovery processes depend on the geographical information for the vehicles that are collected periodically by the Global-Position-System (GPS) services [30]. Accordingly, no route exchange process neither routing tables are needed by such routing mechanism. As a result, the overall NPMs are maintained (i.e., delivery, end-to-end delays, and latency) [31]. One of the limitations of using such routing schemes is their dependency on the strength of the GPS signal received. Conditions such as the atmospheric ones or signal-blocking conditions may degraded the quality of signal received and thus the accuracy of routing process are negatively affected [32]. Accordingly, traffic prediction system becomes an essential part of the Intelligent Transportation System (ITS) [33], where traffic conditions are calculated in advanced via different prediction models using the initial collected data by the GPS systems regarding the vehicles information [34]. Such systems are integrated to the position-based routing protocols to provide a route to the destination in advance. An updated vehicle information is needed to check the accuracy of the prediction model and correct it, where natural causes and unpredictable driver's behavior affects the accuracy of the prediction process [35].

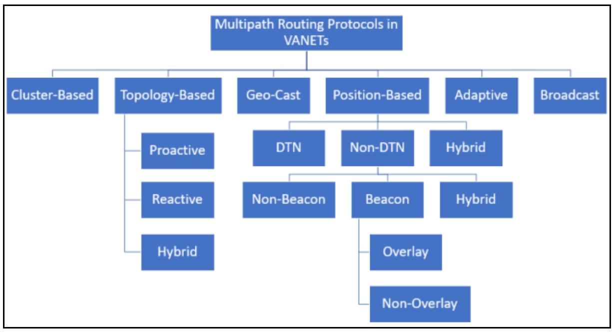

Fig. 1. Multipath routing protocols in VANETs

In this research, an integration between a multipath discovery unit and a QoS position-based routing unit for VANET-based intelligent transportation system was proposed. The multipath discovery unit adopts the Wiedemann Car-Following Model to predict the connectivity of multiple-paths from the source to the destination [36], [37], while the QoS routing unit guarantees the requested QoS requirements for the traffic flows following one of three route switching criteria: least connection delay (LDD), least number of path-switching (LPS), and the least number of Path-Switching with the minimum delay (LPSMD) route switching criteria. The key features of the proposed system are as follows:

1) The proposed system integrates a multipath discovery unit with a QoS routing unit, such that the overall integrated units are installed on a central server in an intelligent transportation system.
2) The multipath discovery unit adopts the Wiedemann Car-Following Model to predict the connectivity of multiple-paths from the source to the destination ((Wiedemann and Reiter-99).
3) The QoS routing unit guarantees the requested QoS requirements for the traffic flows following one of three route switching criteria: least connection delay (LDD), least number of path-switching (LPS), and the least number of Path-Switching with the minimum delay (LPSMD) route switching criteria.

The rest of the paper is structured as follows: Section II briefly introduces the related work. The intelligent system components and its design is presented in Section III. Section IV illustrated the Wiedemann location prediction model adopted by the multipath discovery unit. The overall system methodology is described in Section V. The performance evaluation of the proposed system is fully performed with extensive simulations in Section VI. Finally, conclusion and future work are drawn in section VII.

II. Related Work

To provide a robust connectivity and reliable data transmission in a VANETs-based intelligent transportation system, different optimized multipath routing protocols were proposed. Such routing solutions preserve the overall NPMs for the VANET and guarantee the QoS requirements for the real-time data flows in both comfort and safety applications. In [38], a multipath routing protocol using the Ant Colony Optimization (ACO) methodology was proposed to optimize relay bus in a bus based VANET. In selecting the multiple paths, the proposed algorithm uses the probability of path and street consistency. Experimental results show the efficiency of the proposed protocol in reducing the end-to-end delay and the overhead of route discovery process. In [39], an efficient multipath routing protocol for video streaming transmission in VANET using the genetic algorithm (GA) was proposed. Extensive simulations using the NS-2 simulator show that the protocol outperforms the GPSR, AODV, and ReIDD protocols in terms of packet delivery, number of hops, and end-to-end delay NPMs.

In [40] a road-based QoS-aware multipath routing protocol was proposed for urban VANETs (RBVT-R). The proposed algorithm predicts the connectivity of multiple paths using a space-time planar graph. Compared to other multipath routing protocols, the proposed protocol efficiently reduces the packet miss ratio and end-to-end delays. In [41], a novel multipath reliable vehicular ad-hoc network routing protocol was proposed for high-mobility VANET. The protocol combines compatibility and trustworthy criteria to select the longest trusted and reliable path to destination from a set of pre-defined paths. Extensive python simulations on sparse matrices and simulation of urban mobility (SUMO) traffic traces show the positive enhancement of the proposed protocol in terms of path connectivity, packet delivery, and number of hops.

An optimal video packet distribution model in multipath routing was proposed for urban VANETs in [42]. The protocol defines a probability model for the connectivity of multiple paths to destination and selects multiple paths to distribute the video packets through according to their lifetimes. Performance evaluation of such protocol shows an enhancement in terms of packet loss ratio, end-to-end delay, and delivery NPMs.

An Integration between the Moth search algorithm and the Whale optimization algorithm to provide a multipath routing algorithm for video transmission in VANETs was proposed in [43]. The optimal path to destination was selected among multiple paths using geographical routing algorithm according to a fitness function. The proposed algorithm shows an efficiency in guaranteeing the QoS metrics in terms of end-to-end delay, packet delivery ratio, and throughput. In [44], an adaptive multipath geographic routing in urban VANETs was proposed. The proposed scheme estimates the connectivity probability of each path to destination and establishes a video on demand (VOD) transmission mechanism over the selected connected paths according to the volume of the video stream and the path lifetime. Compared with junction-based multipath routing, the proposed algorithm shows an enhancement in terms of freezing delay and delivery.

A multipath routing protocol using cubic Bezier curves for VANETs was proposed in [45]. The proposed algorithm estimates the connectivity of multiple paths to destination and use the longest paths that guarantee the QoS for the real-time traffic during data communication. Compared to the improved multi-cast AODV multipath routing protocol, the proposed protocol shows a higher efficiency in load balancing, reliability, and stability. In [46], a QoS adaptive multipath routing protocol in urban VANETs for video streaming was proposed. The routing protocol converts the routing problem into an optimization one and uses the ant colony technique for solving it. It uses a fuzzy logic-based algorithm for the optimal multipath selection mechanism. Extensive simulations show the efficiency of such optimized protocol in guaranteeing the NPMs in terms of peak signal to noise ratio, end-to-end delay, delivery, and overhead.

A multipath video streaming using field-based anycast routing (FAR) was proposed for VANETs in [47]. Using Poisson's equation, the routing algorithm utilizes the best-connected paths in a high-dynamic topology inspired by an electrostatic field model. Compared to AODV and FDMR routing protocols, the proposed protocol efficiently enhances the QoS metrics in terms of delivery, reliability, and robustness especially for those congested VANETs. A centralized routing protocol with a mobility prediction scheme for VANET was proposed in [48]. The proposed scheme uses the centralized artificial intelligence SDN controller for the mobility process through the artificial neural network technique. In cooperation with the RSUs, the proposed algorithm selects the optimal path among a set of pre-define connected paths by the SDN controller to minimize the end-to-end delay and to enhance to reliability of the transmission in a highly congested VANET.

In [49], a multipath routing algorithm using predictive Geographic information was proposed for high-mobility urban VANET. The protocol predicts the location of every vehicle in each path using gathered GPS information (i.e., acceleration) and selects the longest connected path to destination. Compared to other routing protocols (i.e., PDGR, GPSR and GPCR), simulation results show the efficiency of the proposed protocol in terms of average number of hops, end-to-end delays, and packet delivery ratio.

III. System Components & Design

In designing our intelligent proposed system, the overall system was decomposed into four main components: source and destination nodes, intermediate vehicular nodes, Virtual Road-Segments and Intelligent RSUs, and central server that is mainly consists of three units (i.e., coordination unit, multipath discovery unit, and QoS routing unit). The functionalities and the behaviors of each unit are defined according to a well-defined modelling criterion. From the other side, the overall communication scheme and interactions between the main system components are defined based on a well-designed communication protocol. Fig. 2 shows the overall intelligent system components.

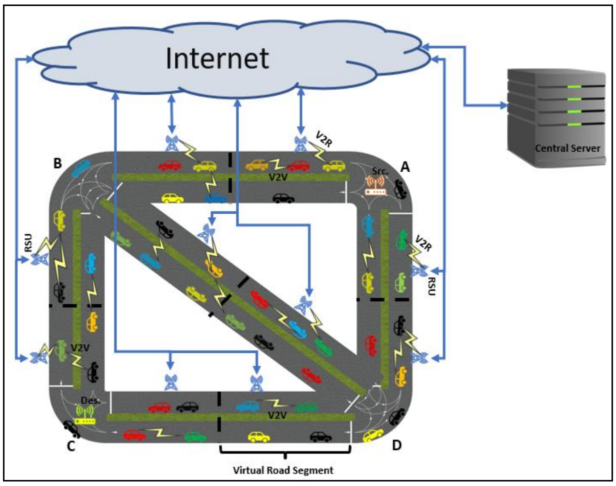

Fig. 2. VANET-based intelligent transportation system components.

A. Source & Destination Nodes

The source node in our system is a transmission unit (i.e., transmission tower) that is located at a specific location as shown in Fig. 2 (i.e., at node A). It's responsible for generating a real-time data traffic that will be transmitted through the VANET to a well-defined receiving unit as shown in Fig. 2 (i.e., at node C). The source node interacts with the intelligent road-side-unit RSU requesting for a route that guarantees specific quality-of-service requirements for the real-time data flow. The source node sends the traffic information (i.e., sending rate (λ), the size of bulk data (B), and Packet length (l). Upon receiving the route information from the

RSU, the source unit starts transmission its real-time traffic using the dedicated short-range communications scheme (DSRC) till be notified by route updates from the RSU that guarantees the QoS requirements requested by the source station.

B. Vehicular Nodes

The vehicular nodes act as intermediate nodes (hops) that are responsible for delivering the real-time flow from the source to destination in a VANET. Each vehicular node is identified by a unique address (i.e., plate number) that will be used for the hop-to-hop delivery. The vehicular nodes change their velocity (v) and acceleration (a) according to the traffic conditions. They interact with the associated RSU and respond to their requests regarding vehicles information (i.e., position and speed) via a DSRC Vehicle-to-RSU (V2R) communication scheme. Such communication scheme is also adopted by the vehicular nodes during the Vehicle-to-Vehicle (V2V) communications.

C. Virtual Road-Segments & Intelligent RSUs

Our design depends on a virtual segmentation for the road path from the source to destination. Each virtual road segment (VRS) is served by an intelligent road-side-unit (RSU). Each RSU keeps track of the vehicles belonging to the VRS it serves through periodic control messages. The collected vehicular information will be passed to the central server via cellular internet connections (i.e., 4G or 5G). Such information will be used to evaluate the optimized route to the destination. The information about the route to the destination will be passed from the server unit to the primary RSU (The RSU at the segment that the source belongs to) via the cellular internet connections. Accordingly, the primary RSU notifies the source with such route via DSRC communication scheme. The time-period (τ) that is adopted by the RSUs to collect the vehicle information depends on different factor such as road traffic conditions, vehicles speed, the source sending rate, and the amount of bulk data to be sent to the destination.

D. Central Server

To gather and process such large amount of instantaneous traffic information in a VANET, our intelligent system uses a central server. The central server is the core of the proposed ITS that integrates three main units to provide the proper services in a VANET. The integrated units at the server side include: the coordination unit, the multipath discovery unit, and the QoS routing unit as follows:

1) Coordination Unit

The coordination unit represents the entry point to the central server that collects the VANET information and passes them to the multipath discovery unit. It sends periodic control messages to the RSUs via wireless cellular network connections requesting for vehicular information collected from each VRS. It queues the requests and passes them to the multipath discovery unit. From the other side, the coordination unit receives the multipath routing information evaluated by the QoS routing unit and passes them to the primary RSU that in turns passes them to the source node.

2) Multipath Discovery Unit

The multipath discovery unit is the unit responsible for predicting the connectivity of the multipaths from the source to the destination based on the information received from the coordination unit about the traffic status of the VANET. This unit adopts the Wiedemann Car-Following Model (Wiedemann and Reiter-99) to predict and estimate the positions of the vehicles (the unequipped ones) according to the behaviors of the equipped vehicles. Accordingly, this unit provides a report about the time intervals where each path is connected or disconnected among all possible paths from the source to the destination. The predicted time slots for each path depends on the evaluated time-period (τ), such as an updated prediction will be periodically carried on every such time-period (τ). Upon generating the prediction report about the status of the multiple paths, the multiple-path discovery unit will pass it to the QoS routing unit to generate the optimized route to the destination during such time-period.

3) QoS Routing Unit

The QoS routing unit receives the prediction report from the multipath discovery unit regarding the connectivity for each path from the source to the destination. It also receives the source QoS requirements from the coordinator that has been received to it by the primary RSU (i.e., throughput, the miss ratio, end-to-end delay). By knowing the connectivity time periods for each path and the required QoS requirements, the QoS routing unit adopts a routing algorithm that guarantees such QoS requirements and generates a well-defined route to the destination according to such algorithm. Such route will specify the path that will be used at each time interval among the pre-defined multiple paths to the destination. Accordingly, this route may require the source node to dynamically switch between the paths at some time intervals such that the QoS requirements are guaranteed. Upon generating the route, the QoS routing unit passes the route information to the Coordination unit that in turns sends it to the primary RSU. The primary RSU then passes such received routing information to the source that starts transmitting its real-time traffic according to such routing information. The communication scheme between the central server components is shown in Fig. 3.

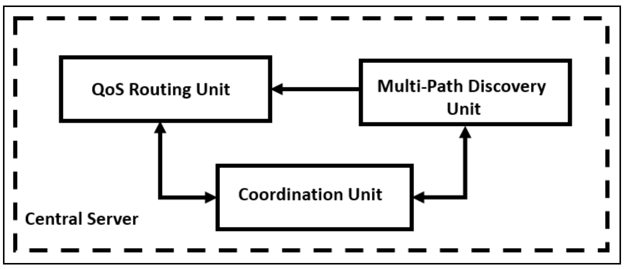

Fig. 3. Central-server components and communication scheme.

IV. LOCATION PREDICTION USING WIEDEMANN MODEL

According to our design, the multipath discovery unit adopts the Wiedemann car-following model (Wiedemann and Reiter-99) to estimate the position of each vehicle according to the behavior of the nearest vehicle ahead in the same lane for a multipath road [36], [37]. The Wiedemann car-following model is a psychophysical model that uses different types of thresholds as guidance points that control the driver's behavior, that is to determine the rate of acceleration the driver should follow (i.e., accelerate or decelerate) [50]. According to the position and speed of the vehicle relative to the nearest vehicle ahead in the same lane and by using the estimated threshold values, the model defines the regime that a vehicle should follow among four main different regimes as the following:

1) Free Regime: The nearest leading vehicle does not affect the behaviour of the driver. The driver may use the maximum acceleration to maintain the vehicle's desired speed.
2) Closing Regime: The nearest leading vehicle has a slower speed. The driver should decelerate till having a zero relative speed (equals to the leading vehicle speed).
3) Following Regime: The driver enters this regime after being in the closing one, where the driver uses low accelerations/decelerations to keep an ideal distance gap with the leading vehicle.
4) Emergency Regime: In this regime, the distance gap between the vehicle and the leading one falls within the critical threshold. Accordingly, the driver should decelerate to the maximum to return to the following regime such that collisions are avoided.

The boundaries of the regimes are shown in Fig. 4 [50]. Such regimes are defined according to the value of the thresholds defined by Wiedemann car-following model. By using the system parameters defined in Table I, the thresholds are defined as follows.

1) AX: The minimum average stopped headway that is the minimum desired gap (distance) between the two successive vehicles while in a stopping state, such that:

$$\mathrm{AX} = L_v + \mathrm{CP}_1 \tag{1}$$

TABLE I: WIEDEMANN MODEL CALIBRATION PARAMETERS FOR REGIME'S THRESHOLDS

Parameter	Description	Unit
L_v	The length of the leading Vehicle	M
CP_1	Desired gap calibration factor in a stopping condition	M
CP_2	Time for safety-gap calibration factor in the following process	S
CP_3	Gap range calibration factor in following regime	M
CP_4	Beginning time for deceleration calibration factor	S
CP_5	Speed difference calibration factor in a following process	m/s
CP_6	Distance on speed effect calibration factor in a following process	1/ms
v_{min}	The minimum speed between the two vehicles (follow, leader)	m/s
Δx	The distance between the follow and leader vehicles (Headway)	M

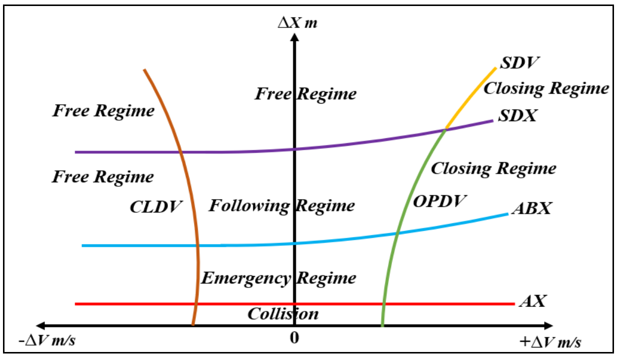

Fig. 4. The boundaries of the Wiedemann model regimes

2) ABX: The minimum average moving headway, that is the minimum safe gap (distance) between two successive vehicles while in a moving state, such that:

$$\mathrm{ABX} = \mathrm{AX} + \mathrm{CP}_2\sqrt{v_{\min}} \tag{2}$$

3) SDX: The maximum following distance, that is the upper boundary of the following regime, such that:

$$\mathrm{SDX} = \mathrm{AX} + \mathrm{CP}_2\sqrt{v_{\min}}\,\mathrm{CP}_3 \tag{3}$$

4) SDV: The starting notification point to the following vehicle to take a reaction due to a slower leading vehicle, such that:

$$\mathrm{SDV} = \left(\frac{\Delta x - (L_v + \mathrm{AX})}{\mathrm{CP}_4}\right)^2 \tag{4}$$

5) CLDV: The starting notification point to the following vehicle to take a reaction due to a higher speed than the leading vehicle. In VISSIM, such threshold is equals to the SDV, while by using different calibration factor the value is slightly different, such that:

$$\mathrm{CLDV} = \left(\frac{\Delta x - (L_v + \mathrm{AX})}{\mathrm{CP}_5}\right)^2 \tag{5}$$

6) OPDV: The starting notification point to the following vehicle to reacts to the increasing in the distance over time with the leading vehicle, such that:

$$\mathrm{OPDV} = \mathrm{CLDV} \cdot \mathrm{CP}_6 \tag{6}$$

To estimate the new location of the following vehicle (subject), the multipath discovery unit should first evaluate the threshold values (Equations (1) to (6)) to determine the regime where the following vehicle belongs. Using the system parameters in Table II and by knowing the regime where the following vehicle belongs to, the multipath discovery unit evaluates the expected vehicle acceleration as the following:

1) Free Regime: The driver may use the maximum acceleration to maintain the vehicle's desired speed, such that the expected acceleration (a_f) is given by:

$$a_f = CP_7\left(v_{\max} - v\left(\frac{v_{\max}}{v_{\mathrm{des}} + CP_8\left(v_{\max} - v_{\mathrm{des}}\right)}\right)\right) \tag{7}$$

TABLE II: WIEDEMANN MODEL CALIBRATION PARAMETERS FOR REGIME'S ACCELERATION

System Parameter	Description	Unit
CP_7	Free regime acceleration calibration factor	1/s
CP_8	Normal distributed random number in free regime calibration factor	-
CP_9	Free regime acceleration calibration factor	m/s^2
CP_{10}	Emergency regime acceleration calibration factor	m/s^2
CP_{11}	Emergency regime velocity calibration factor	1/s
$v_{\max}$	The maximum capable speed for the following (subject) vehicle	m/s
V	The speed of the following vehicle	m/s
v_{des}	The desired speed for the following vehicle	m/s
Δv	The relative velocity between the follow and leader vehicles	m/s
a_l	The acceleration of the leading vehicle	m/s^2
A	Normal distributed parameter for the following vehicle	-
B	Normal distributed random number	-

2) Closing Regime: The driver should decelerate till having a zero relative speed (equals to the leading vehicle speed) to avoid collisions, such that the expected deceleration (a_c) is given by:

$$a_c = 0.5\left(\frac{(\Delta v)^2}{\mathrm{ABX} - (\Delta x - L_v)}\right) + a_l \quad (8)$$

3) Following Regime: The driver uses low accelerations/decelerations to keep an ideal distance gap with the leading vehicle, such that the deceleration rate is the negative value of the acceleration rate (a_F) and is given by:

$$a_F = \mathrm{CP}_9(\alpha + \beta) \quad (9)$$

4) Emergency Regime: The driver should decelerate to the maximum to return to the following regime such that collisions are avoided, such that the expected acceleration (a_e) is given by:

$$a_e = 0.5\left(\frac{(\Delta v)^2}{\mathrm{AX} - (\Delta x - L_v)}\right) + a_l + a_{\min}\left(\frac{\mathrm{ABX} - (\Delta x - L_v)}{CP_2\sqrt{v}}\right) \quad (10)$$

where $a_{\min}$ is the minimum acceleration (maximum deceleration) of the following vehicle, such that:

$$a_{\min} = \mathrm{CP}_{10} + \mathrm{CP}_{11} v \quad (11)$$

Upon evaluating the expected acceleration of the following vehicle (a_i) where $i = \{f, c, F, e\}$, the multipath discovery unit evaluates the expected velocity ($v_{\exp}$) and the expected distance ($D_{\exp}$) that the subject vehicle passes within the next time unit. Given ψ as the expected velocity calibration factor, then:

$$v_{\exp} = \max\{(v + \psi a_i), 0\} \quad (12)$$

$$D_{\exp} = \mathrm{ABX} - 0.5\left(\frac{(\min\{(-\psi a_i), v\})^2}{a_i}\right) \quad (13)$$

Accordingly, the subject vehicle will be inserted into the Wiedemann Car-Following Model algorithm at the new expected values for the distance, acceleration, and velocity.

V. SYSTEM METHODOLOGY

The proposed intelligent system periodically finds an optimized route from a well-defined source node (i.e., point A in Fig. 2) to a well-defined destination node (i.e., point C in Fig. 2) among a set of multiple paths between the source and the destination. The routing algorithm adopts a prediction technique that finds the connectivity of each path from the source to the destination during a specific time interval. The prediction model adopts the Wiedemann Car-Following Model (Wiedemann and Reiter-99) to estimate the position of each vehicle according to the behaviour of the nearest vehicle ahead in the same lane for a multipath road. Upon performing the prediction scheme, the QoS routing unit uses such prediction model to find an optimized route to the destination following a specific multipath switching protocol that guarantees the QoS requirements of the source real-time flow.

The overall process begins when the source node (i.e., at node A in Fig. 2) initiates a multipath route discovery to serve its real time data flow. It sends a request to the primary RSU (The RSU at the virtual segment that the source belongs to) via a dedicated short-range communications scheme (DSRC). The request includes the following traffic information: the size of bulk data (B), sending rate (λ), Packet length (l), source and destination addresses, and the QoS requirements (Φ) such as throughput, miss ratio, and end-to-end delay. Upon receiving the request, the primary RSU sends such request to the coordination unit at the server via cellular internet connections (i.e., 4G or 5G). Accordingly, the coordination unit evaluates the time-period (τ) needed to collect the vehicle information such that:

$$\tau = \gamma B \lambda^{-1} \quad (14)$$

where γ is the time-interval parameter such that ($0 < \gamma \leq 1$). Such parameter depends on different factor such as road traffic conditions, vehicles speed, the source sending rate, and the amount of bulk data to be sent to the destination. With lower values of γ, the prediction process will be more accurate. Such high-accuracy levels trade-off with the efficiency of the system in terms of total system overhead.

Every time-period (τ), the coordination unit broadcasts a request to the RSUs via cellular internet connections requesting for vehicle information (i.e., position (X, Y) and speed (v)). Upon receiving such request, each RSU broadcasts a request to the virtual segment it serves requesting for such information. Each vehicle responds to the associated RSU by a reply message (i.e., source address is the vehicle plate number, and the destination address is the RSU address) via a DSRC vehicle-to-RSU (V2R) communication scheme. The collected information by each RSU about the vehicular nodes at each VRS will be sent to the coordinator unit at the server side via cellular internet connections. Upon receiving such information, the coordinator unit passes the information to the multipath discovery unit that adopts the Wiedemann Car-Following Model for vehicle-parameters (speed, position, and acceleration). The multipath discovery unit runs the estimation algorithm provided in section III using such information for a time-period ($T=\tau$), where the location, speed, and acceleration will be estimated every second during the time-period. The main goal of such estimation scheme is to check the lifetime (how long it remains connected?) of each path from the source to the destination. For example, in Fig. 2, four main paths are predefined from the source to destination:

$$P_1: A \rightarrow B \rightarrow C$$
$$P_2: A \rightarrow B \rightarrow C$$
$$P_3: A \rightarrow B \rightarrow C \rightarrow D$$
$$P_4: A \rightarrow D \rightarrow B \rightarrow C$$

To check the connectivity of each path during the time-period ($T=\tau$), the multipath discovery unit tracks the existence of a vehicle in the virtual road segments (VRSs) along each path and in the two-directions (forward and backward) using the adopted estimation mechanism. Accordingly, a path is considered connected if there is at least one vehicular node in each VRS (backward or forward) belonging to such path. For example, if path1 (P_1: A $\rightarrow$ B $\rightarrow$ C) was served with four RSUs (i.e., consists of four VRSs) and the results of the estimation mechanism through a time-period (T=3 sec) was as shown in Fig. 5.

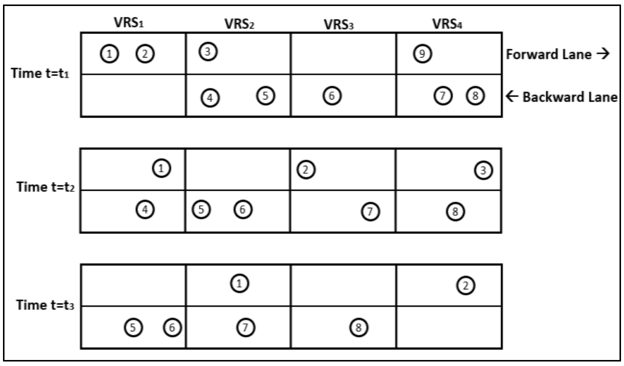

Fig. 5. Prediction of vehicles locations in the virtual road segments.

The multipath discovery unit estimates the positions of the vehicles during the three-time units according to the received information from the coordinator unit and following the Wiedemann Car-Following Model. As shown in Fig. 5, the path is considered connected during the time-period (T=3 sec) since there is at least one vehicular node in each VRS (backward or forward) during the whole period and thus the communication from the source to the destination through such path is stable. Note that node 9 is leaving the lane after the first time slot, while nodes 3 and 4 are leaving in the third time slot. Due to road traffic conditions, vehicles speed, the source sending rate, and the amount of bulk data to be sent to the destination, the parameter γ is adjusted such that the accuracy of the prediction system is enhanced. The prediction process will be repeated every $T=\tau$, such that new vehicles entering the path is encountered and new realistic vehicular positions are running the estimation algorithm.

Upon estimating the connectivity of each path during the time-period $T=\tau$, the multipath discovery unit sends such results to the QoS routing unit. Such unit also receives the QoS requirements requested by the source from the coordinator unit (i.e., throughput, the miss ratio, end-to-end delay). By knowing the connectivity time periods for each path and the required QoS requirements, the QoS routing unit adopts a routing algorithm that guarantees such QoS requirements and generates a well-defined route to the destination according to such algorithm. Accordingly, this route may require the source node to dynamically switch between the paths at some time intervals such that the QoS requirements are guaranteed.

For example, assuming a source node is requesting to serve its real-time video stream where the QoS requirements (Φ) is the playout buffer time. Accordingly, the disconnection in the path (packet delay) should be less than such playout buffer time to consider the path as a stable and reliable path for data transmission. Assume that the QoS ($\Phi \leq 2\times$time units)). If the multipath discovery unit generates the connectivity report regarding the four paths (P_1, P_2, P_3, and P_4) as shown in Fig. 6, where τ= 7×time units (i.e., 7 sec.) and sends such report to the QoS routing unit.

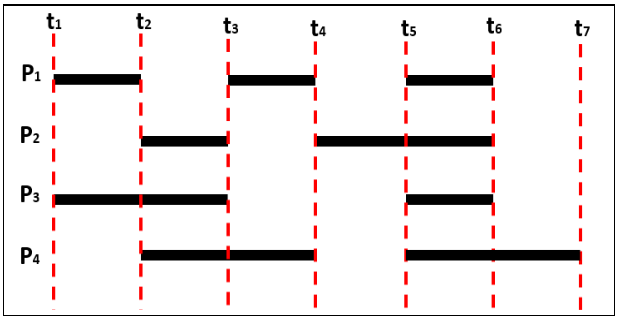

Fig. 6. Path connectivity report for VRSs

The QoS routing unit then adopts a multipath route switching criterion to generate a reliable path from the source to the destination within the requested QoS requirements.

In this research we propose three main multipath route switching criteria that all selects the longest connected path first (i.e., P_3) and then at the first disconnection, it may switch to another path according to the switching criteria as the following:

1) Least Disconnection Delay (LDD): In this criterion, the QoS routing unit selects a route to the destination such that the route has the least disconnection delay (longest connected route) within the requested QoS (most reliable path). According to Fig. 6, the QoS routing unit the path will be as the following:

Time Period	$[t_1, t_3]$	$[t_3, t_4]$	$[t_4, t_5]$	$[t_5, t_7]$
Path	P_3	P_1 or P_4	P_2	P_4

2) Least Number of Path-Switching (LPS): In this criterion, the QoS routing unit selects a route to the destination such that the number of switching between paths is the minimum. That's as soon as the path guarantees the QoS requirements, no path switching occurs. According to Fig. 6 we will start with the longest path (P_3) till the first disconnection at t_3, the QoS routing unit should switch to another path, where the total disconnection delay in P_3 is 3-time units that is $(([t_3, t_5]+[t_6, t_7]) \geq \Phi)$. So, the switching will be to any path of the remaining paths, where the total disconnection delay for paths P_1 and P_2 equal 2×time units which is equal to the requested QoS, while the total disconnection delay for P_4 is one time unit which is less than the requested QoS (Φ). Accordingly, the path is given as the following:

Time period	$[t_1, t_3]$	$[t_3, t_7]$
Path	P_3	P_1 or P_2 or P_4

3) Least Number of Path-Switching with the Minimum Delay (LPSMD): In this criterion, the QoS routing unit selects a route to the destination using a hybrid criterion. It selects a route that has the minimum number of switching as the first condition (criterion 2) and among these routes that guarantee the previous criterion, it selects the path with the minimum delay. Accordingly, it starts with the longest path as in all previous multipath route switching criteria, then as in previous criterion (LPS), it must select among paths $\{P_1, P_2$ and $P_4\}$. Since P_4 is the one with the minimum delay (one time unit) then the route will be as the following:

Time period	$[t_1, t_3]$	$[t_3, t_7]$
Path	P_3	P_4

Upon generating the route, the QoS routing unit passes the route information to the Coordination unit that in turns sends it to the primary RSU. The primary RSU then passes such received routing information to the source that starts transmitting its real-time traffic according to such routing information. The timing diagram for the overall process is shown in Fig. 7.

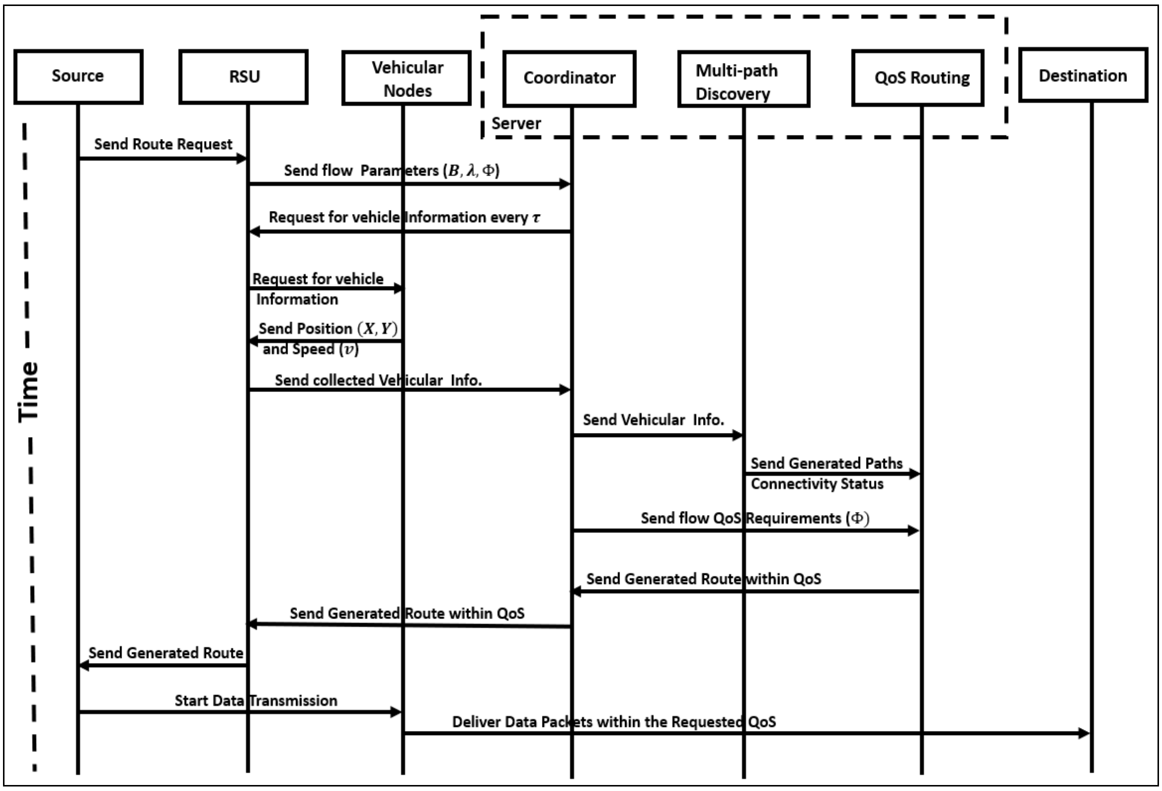

Fig. 7. The ITS timing diagram.

VI. Simulation & Results

To design and simulate our complex real-time heterogenous VANET, we have used the QualNet simulator. The QualNet simulator is based on GloMoSim network simulator which is a discrete event simulator with the capabilities of designing, planning, optimizing, and testing real-time traffic models in a heterogenous VANET (i.e., lane changing model, traffic light model, car-following model, intersection management model, etc.).

A. System Parameter, Assumptions, and Motion Model

According to the simulation, the real-time data flow parameters are shown in Table III.

TABLE III: Real-Time Data Flow Parameters

Parameter	Value
Sending rate for the vehicle (λ)	100 packets/s
Packet length (l)	512 bytes
The MAC (CSMA/CA) data rate	2 Mbps
Flow's mean inter-arrival time	$1/\lambda$
The size of bulk data (B)	1Kbytes
The time-interval parameter (γ)	0.4
The QoS (Φ)	2 s

TABLE IV: VEHICULAR NODE PARAMETERS & VIRTUAL-ROAD CHARACTERISTICS

Parameter/Assumption	Value
The length of the leading Vehicle (L_v)	3.75 m
Area Dimensions	[1000 m×1000 m]
Transmission range for Vehicles	200 m
Number of paths from source to destination	4 paths
Number of intersections	4 intersections
Number of VRS between any two intersections	4 segments
Location for the source vehicle (X_s, Y_s) (Fig.1)	(1000, 1000)
Location for the destination vehicle (X_d, Y_d)	(0, 0)
Average speed for the following vehicle (v)	Random in [20 m/s, 65 m/s]
Initial Acceleration for the leading vehicle (a_l)	0.0 m/s^2
The expected velocity calibration factor (ψ)	0.8 s
Normal distributed parameter for the following vehicle (α)	1
Normal distributed random number (β)	Random in [0, 1]

TABLE V: WIEDEMANN CAR-FOLLOWING MOTION MODEL CALIBRATION PARAMETERS

Parameter/Assumption	Value
Desired gap-calibration factor in stopping condition (CP_1)	1.75 m
Time for safety-gap calibration factor in the following process (CP_2)	0.8 s
Gap range calibration factor in following regime (CP_3)	2.5 m
Beginning time for deceleration calibration factor (CP_4)	5 s
Speed difference calibration factor in a following process (CP_5)	0.3 m/s
Distance on speed effect calibration factor in a following process (CP_6)	10 (1/ms)
Free regime acceleration calibration factor (CP_7)	0.25 (1/s)
Normal distributed random number in free regime calibration factor (CP_8)	0.35
Free regime acceleration calibration factor (CP_9)	3 m/s^2
Emergency regime acceleration calibration factor (CP_{10})	1.5 m/s^2
Emergency regime velocity calibration factor (CP_{11})	0.25 (1/s)

The vehicular node parameters along with the virtual-road segment characteristics are described in Table IV, while the calibration factors needed to set-up the Wiedemann Car-Following motion model are initialized in Table V.

In this research, two network performance metrics (NPMs) were studied, that are the packet delivery ratio and the average end-to-end total packet delay. To measure such NPMs, the simulation studies were performed extensively for different network parameters such as vehicular node density (N), vehicular node speed (v), and the time-period (τ). For each simulation run, the NPMs were evaluated using the three proposed multipath route switching criteria: 1) Least Disconnection Delay (LDD); 2) Least Number of Path-Switching (LPS); and 3) Least Number of Path-Switching with the Minimum Delay (LPSMD).

B. *Effect of Vehicular Node Density (N)*

To measure the effect of the vehicular node density on the two NPMs. We simulate a real-time VANET using the real-time data flow parameters in Table III, the vehicular node parameters & virtual-road characteristics in Table IV, and the Wiedemann Car-Following motion model calibration parameters in Table V. For each simulation run, the node density (N) was varied with a step of 10 vehicular nodes starting from 10 vehicular nodes up to 100 vehicular nodes for the last simulation run, that is N={10, 20, 30, 40, 50, 60, 70, 80, 90, 100}. The average speed for the following vehicle (v) was set to 40 m/s, while the time-interval parameter (γ) was set to 0.4 (i.e., the time-period (τ) =1 sec.).

Fig. 8 shows the effect of the node density on the overall packet delivery ratio when adopting the three multipath route switching criteria. The simulation results show that the packet delivery ratio for the proposed multipath routing protocol using the three route switching criteria will be improved for higher values of vehicular node density (N), where the probability for path disconnection decreases (i.e., the probability for the existence of a vehicle in all virtual road segments increases). Among the three route switching criteria, the simulation results show that the proposed multipath routing protocol that adopts the Least Disconnection Delay (LDD) criterion outperforms the other two route switching criteria in the overall packet delivery ratio. Such result is due to the longest connected path criterion adopted by the LDD and thus more probability to deliver the real-time data packets within the QoS requirements. From the other side, the LPSMD shows higher efficiency than the LPS in delivering real-time data packets. Such enhancement is due to the extra condition regarding the playout buffer time imposed by the LPSMD in the selection process of the optimized path to the destination among a set of paths that all guarantees the QoS requirements.

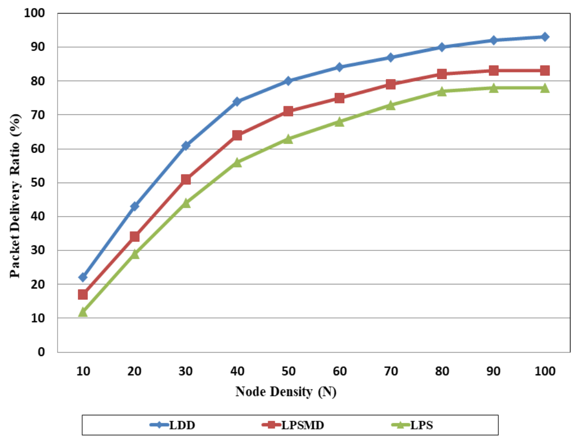

Fig. 8. Node density effect on packet delivery ratio. (v= 40 m/s; τ =1 sec.)

The effect of the vehicular node density (N) on the average end-to-end packet delay is shown in Fig. 9. Simulation results show the negative effect of increasing the node density on such NPM when using the proposed system with any route switching criteria. The reason behind that is the increased routing overhead associated with such high node density. In finding the next-hop in the route to the destination, the vehicular node broadcasts a RREQ to recognize its neighbors. The first reply from a neighbor node (the closest) will be considered as the next hop. With more node density, more hops will be in the route to the destination and thus more associated routing overhead. As a result, the overall average end-to-end delay increases. Among the three route switching criteria, simulation results show that the proposed system adopting the LDD criterion outperforms all other route switching criteria. From the other side, the proposed routing protocol that Adopting the LPSMD route switching criterion outperforms adopting the LPS route switching criterion regarding such NPM. The reason behind that is the longest path criterion adopted by the LDD route switching criterion that minimizes the additional route discovery delays associated with the path disconnections as in both LPSMD and LPS. Among the other two criteria, the LPS adds more route discovery delays, where the selected path by the LPS is not the optimal one (i.e., it guarantees the QoS requirements without selecting the one with the least playout buffer time as adopted by the LPSMD).

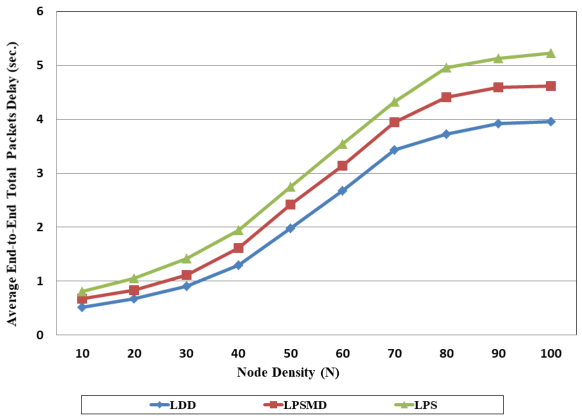

Fig. 9. Node density effect on packet delivery ratio. (v= 40 m/s; τ =1 sec.)

C. *Effect of the Following-vehicle Average Speed (v)*

In this section, we have studied the effect of the second network parameter (i.e., average speed for the following vehicle) on the two NPMs (i.e., packet delivery ratio and the average end-to-end total packet delay). Accordingly, we simulate a real-time VANET of 60 vehicular nodes using the same data flow parameters, vehicular node parameters, and Wiedemann Car-Following motion model calibration parameters described in Table III, Table IV, and Table V, respectively. To measure NPMs in such simulated VANET, the average speed for the following vehicle (v) was varied starting from 20 m/s in the first simulation run up to 65 m/s in the last simulation run with a step of 5 m/s average speed, that is v= {20, 25, 30, 35, 40, 45, 50, 55, 60, 65}.

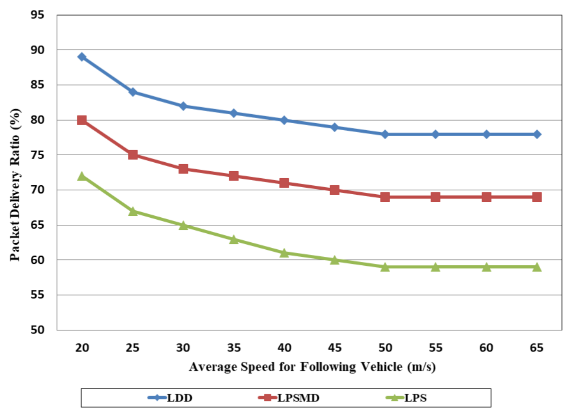

Fig. 10. Node density effect on packet delivery ratio. (N= 60 nodes; τ =1 sec.)

Fig. 10 shows the effect of the average speed for the following vehicle on the packet delivery ratio. As the average speed increases, the packet delivery ratio decreases for the proposed protocol when adopting any of the three route switching criteria. Such result is due to the frequent path disconnections, where vehicular nodes are leaving the virtual road segments quickly (i.e., leaves empty VRs behind) at higher average speeds and thus decreasing the packet delivery ratio. The results also show that the proposed multipath routing protocol adopting the LDD route switching criterion outperforms the other route switching criteria in delivering the real-time data packets due to its longest path adopted criterion.

As the average speed for the following vehicle increases, the end-to-end packet delay increases for the proposed protocol when adopting any of the three route switching criteria as shown in Fig. 11. For higher average speed values, the probability for path disconnection increases and thus vehicular node will perform the RREQ to recognize its neighbors frequently till finding an adjacent vehicle in its range to be part of the route to the destination. Such frequent route discovery process adds more delays on the data stream trip to destination and thus the overall end-to-end packet delay increases. The longest-path criterion adopted by the LDD minimizes the overhead of the route discovery process thus making it the most efficient criterion in comparison with the other two criteria (LPSMD and LPS). The multi-condition route selection criterion adopted by the LPSMD makes its selected path more optimized than it in the LPS and thus less-route discovery delays.

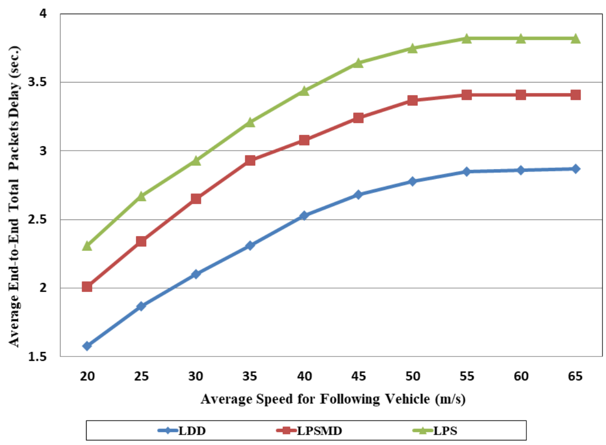

Fig. 11. Node speed effect on average end-to-end packets delay. (N= 60 nodes; τ =1 sec.)

D. *Effect of the Time-Period (τ)*

The effect of the time-period (τ) on the NPMs was studied by simulating a real-time VANET of 60 vehicular nodes. The average speed for the following vehicle (v) was set to 40 m/s. To measure the NPMs in such real-time simulated network, we vary the values for the time-period (τ) starting from 1 sec. (i.e., γ = 0.1) for the first simulation run and up to 10 sec. (γ = 1) for the last one with a step of 1 sec, that is τ = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10}. Fig. 12 shows that the average packet delivery ratio decreases as time-period value increases for when adopting any of the three route switching criteria. Such result is due to the efficiency of the prediction process for the vehicles information (i.e., the location, speed, and acceleration). As the time-period (τ) decreases, the system will use the new actual updated values for the vehicle information and thus the prediction process will be more accurate as shown in Table VI (i.e., max. efficiency of 100% at τ = 1 sec) which yields into higher delivery packet ratios. Among the three criteria, the results show that the proposed multipath routing protocol adopting the LDD route switching criteria outperforms the other two criteria in the packet delivery ratio. Such result is due to the efficiency of the prediction scheme when dealing with LDD criterion as shown in Table VI (i.e., 89.5% prediction efficiency for LDD in comparison with 85.5% and 80.9% for LPSMD and LPS respectively). The delivery prediction efficiency (DPE) at (τ = i sec.) in Table VI is given by:

$$\mathrm{DPE}[i] = \frac{\mathrm{Delievery}[i]}{\mathrm{Delievery}[1]} \times 100\% \qquad (15)$$

where Delivery [1] is the highest delivery ratio achieved at (τ = 1 sec) (i.e., 88% for LDD, 82% for LPMSD, and 74% for LPS). Delivery [i] is the delivery ratio at (τ = i sec).

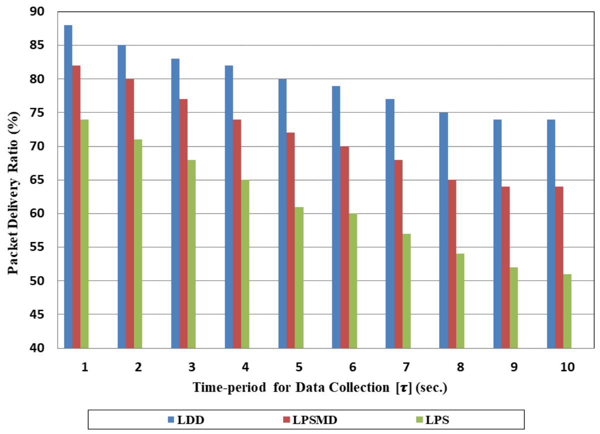

Fig. 12. Time-period effect on packet delivery ratio. (N= 60 nodes; v= 40 m/s).

TABLE VI: PREDICTION EFFICIENCY ACCORDING TO THE DELIVERY RATIO

τ	Delivery (LDD)	DPE	Delivery (LPSMD)	DPE	Delivery (LPS)	DPE
1	88%	100%	82%	100%	74%	100%
2	85%	96.6%	80%	97.6%	71%	95.9%
3	83%	94.3%	77%	93.9%	68%	91.9%
4	82%	93.2%	74%	90.2%	65%	87.8%
5	80%	90.9%	72%	87.8%	61%	82.4%
6	79%	89.8%	70%	85.4%	60%	81.1%
7	77%	87.5%	68%	82.9%	57%	77%
8	75%	85.2%	65%	79.3%	54%	73%
9	74%	84.1%	64%	78%	52%	70.3%
10	74%	84.1%	64%	78%	51%	68.9%
		Avg.= 89.5%		**Avg.= 85.9%**		**Avg.= 80.9%**

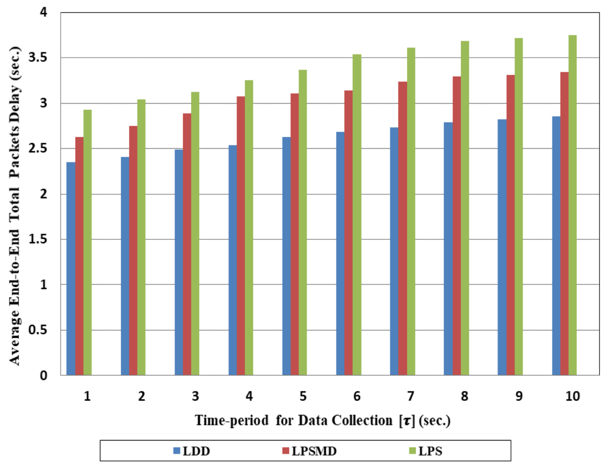

Fig. 13. Time-period effect on average end-to-end packets delay. (N= 60 nodes; v= 40 m/s)

TABLE VII: PREDICTION EFFICIENCY ACCORDING TO THE END-TO-END DELAY

τ	Delay (sec.) (LDD)	EEDPE	Delay (sec.) (LPSMD)	EEDPE	Delay (sec.) (LPS)	EEDPE
1	2.35	100%	2.63	100%	2.93	100%
2	2.41	97.5%	2.75	95.6%	3.04	96.3%
3	2.49	94.4%	2.89	91%	3.12	93.3%
4	2.54	92.5%	3.07	85.7%	3.25	90.2%
5	2.63	89.4%	3.11	84.6%	3.37	86.9%
6	2.68	87.7%	3.14	83.8%	3.54	82.8%
7	2.73	86.1%	3.24	81.2%	3.61	81.2%
8	2.79	84.2%	3.29	79.9%	3.68	79.6%
9	2.82	83.3%	3.31	79.5%	3.72	78.6
10	2.85	82.5%	3.34	78.7%	3.75	78.1%
		Avg. = 88.6%		**Avg. = 84.4%**		**Avg. = 85.2%**

The simulation results in Fig. 13 shows the impact of varying the time-period (τ) on the end-to-end packets delay. As the time-period value decreases, the prediction process for the vehicle information will be more efficient as shown in Table VII. Such improvement in the prediction process is due to updating the system with the accurate information of the vehicle information and thus the estimated connectivity of the paths will be more accurate.

As a result, the updated values of the vehicle information will insert new vehicles in the virtual road segments and thus the route discovery process will be minimized due to the less path disconnections and thus less end-to-end packet delays. Among the three criteria, the results show that the proposed multipath route switching protocol that adopting the LDD criterion outperforms all other criteria in such NPM. Such result is due to the to the efficiency of the prediction scheme when using the LDD criterion as shown in Table VII (i.e., 88.6% prediction efficiency for LDD in comparison with 84.4% and 85.2% for LPSMD and LPS respectively).

As we can see from the efficiency prediction calculations in Table VII, the LPS outperforms the LPSMD in the prediction scheme for such NPM but the end-to-end packet delay for LPSMD is less than that for LPS. The reason for that is the extra condition regarding the playout buffer time imposed by the LPSMD in the selection process of the optimized path to the destination. The end-to-end delay prediction efficiency (EEDPE) at (τ = i sec) in Table VI is given by:

$$\text{EEDPE}\left[i\right]=\frac{\text{Delay}\left[1\right]}{\text{Delay}\left[i\right]}\times 100\% \quad (16)$$

where Delay [1] is the lowest end-to-end delay achieved at (τ= 1 sec) (i.e., 2.35 sec for LDD, 2.63 sec for LPMSD, and 2.93 sec. for LPS). Delay[i] is the delay at (τ = i sec).

VII. Conclusion

In this research, an integration between the QoS-routing unit and the multipath discovery unit was designed to provide a robust connectivity and reliable data communication in a VANETs-based intelligent transportation system. A prediction model based on the Wiedemann Car-Following Model was adopted to define the connectivity of multiple paths to the destination, while three route switching criteria (i.e., least connection delay (LDD), least number of path switching (LPS), and the least number of path-switching with the minimum delay (LPSMD)) were adopted by the proposed multipath routing protocol to preserve the overall NPMs. With extensive simulations using different network parameters, the results show that the proposed multipath routing protocol adopting the LDD route switching criterion outperforms the other criteria in terms of packet delivery ratio (i.e., 3.6% enhancement over LPSMD and 8.6% enhancement over LPS) and average end-to-end total packet delay (i.e., 4.2% enhancement over LPSMD and 3.4% enhancement over LPS). Among the other two route switching criteria, results show the efficiency of using the LPSMD route switching criterion over the LPS criterion in guaranteeing the previous NPMs. The future work of this research includes the integration of a security unit at the server side in cooperation with the QoS route switching unit to detect different types of malicious nodes in the route to destination and generates a secure route that's robust against such different classes of security threats.

Conflict of Interest

The author declares no conflict of interest.

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