VAR^2: Novel Vehicular Ad-Hoc Reliable Routing Approach for Compatible and Trustworthy Paradigm

Farooque Hassan Kumbhar, and Soo Young Shin, *Senior Member, IEEE*

***Abstract*— Communications and routing protocols for vehicular ad-hoc networks (VANETs) are affected by dynamic vehicular constraints like high mobility, efficient delivery, reliable path, and trustworthiness. We propose a novel "VAR^2" scheme that enables autonomous trust and selects routes with the longest connectivity time to efficiently deliver messages. In multi-hop and multi-path VANETs, the proposed scheme ensures reliability by selecting compatible and trustworthy routes with minimum additional communications. Our Python simulations on sparse and dense SUMO traffic traces show that the proposed VAR^2 routes have $100 \sim 400$ s connectivity with only $3 \sim 4$ hops and achieve $6 \sim 15\%$ PDR, which are comparatively more efficient results than that of existing schemes.**

***Index Terms*— Ad-hoc routing, compatibility, reliable routing, trustworthiness, VANET.**

I. Introduction

ADVANCES in communication technologies and connected applications are accelerating the transition of vehicular networks into vehicular ad-hoc networks (VANETs) and the Internet of vehicles [1]. Smart vehicular networks can disseminate useful information related to accidents, emergencies, or congestion in nearby traffic or share multimedia to vehicles. Electric and autonomous vehicles can significantly reduce carbon emission, traffic congestion, and travel delays in collaborative and cooperative traffic. Vehicular communications technology with standards such as wireless access in vehicular environment (WAVE) (1609.(1, 2, 3 and 4)), dedicated short-range communications (DSRC) (802.11p) and cellular vehicle-to-any (C-V2X) mode 3, provide vehicle-to-vehicle (V2V) and V2X communications using roadside units (RSUs) and vehicular onboard units (OBUs) [1]. Unlike mobile ad-hoc networks (MANETs), VANETs are high in mobility with predictable road topology and can perform intensive computations. Currently, the major challenges in vehicular networks are autonomous reliable communications and message delivery due to unreliable links and the dynamic characteristics of vehicles [2]. Previously reported bio-inspired and cross-layer approaches cannot achieve the desired performance, owing to the dynamic constraints of VANETs. In [3], ant colony optimization (ACO) was investigated to select the best path with the highest pheromone levels. However, the solution relies on traditional ad-hoc on-demand vector routing (AODV), which involves MANET-based assumptions. In an exhaustive study, [4], existing MANET routing protocols in real urban dense vehicular networks were analyzed. The authors highlighted that vehicular density and scalability are major challenges in existing protocols. In another interesting work [5], reliable links between vehicles were investigated by establishing a trust mechanism using existing AODV and dynamic source routing (DSR) protocols. The need for a trust-based mechanism in vehicles and received information also requires a swifter and simpler solution in the high mobility wireless networks [6], [7]. Authors in [8] consider multi-level 3D road scenario with overhead bridges and underpasses and propose a connectivity aware routing protocol. However, the solution requires prior knowledge of the environment including geographical structure, vehicles and road segments. In a multi-metric study [9], a clustering-based routing, scheme CACA-OLSR, was proposed by focusing on link quality, cluster head coverage range, and distance between a source and a destination. In another multi-parametric study [10], four metrics were utilized: distance, position, bandwidth and node density. The proposed scheme requires packet success probability estimation as a function of distance, bandwidth and density for each neighbor to select the best path. An intelligent forwarding protocol highlighted the importance of efficient emergency message delivery for VANETs [11].

Our exhaustive literature review of above mentioned and some other important studies ([12]–[18]) has raised several questions: a) How can one improve message delivery in dynamic high mobility, multi-hop and multi-path networks? [2]; b) Is it possible to ensure reliability by having longer connectivity and trustworthiness in VANET routing protocols?; c) Can VANET characteristics (speed, location and direction) be used as a foundation to efficiently choose routes?. In this study, we developed a routing protocol by identifying VANET characteristics and trustworthiness in a vehicular environment to deliver crucial messages with essential trust. We innovate and feed our curiosity by proposing a cross-layer light-weight solution, "VAR^2: vehicular ad-hoc reliable routing", which caters to high mobility VANETs and enables trust in message delivery. Our max-min strategy selects routes from multi-hop and multi-path VANETs by combining compatibility and trust to ensure reliability in high mobility scenarios. We formulated the compatibility time between vehicles using the Euclidean distance and relative velocity from basic safety message (BSM) beacons. Control channels (50 ms long) are used to transmit BSM messages on regular intervals having a frequency of 2∼10 packets/ s, containing information

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The authors are with the Department of IT Convergence Engineering, Kumoh National Institute of Technology, Gumi 39177, South Korea (e-mail: wdragon@kumoh.ac.kr).

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like 3D positioning, motion, and direction. To the best of our knowledge, we are the first to propose an autonomous trust and compatibility based cross-layer routing protocol for high mobility networks.

II. System Model

Consider a vehicle traveling from one location to another with velocity γ_i, 2D location $l_i(x_i, y_i)$, and transmission range R_i. The Euclidean distance ΔD_{ij} and relative velocity ΔV_{ij} of vehicle j for vehicle i can be calculated as follows:

$$\Delta D_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{1}$$

$$\Delta V_{ij} = |\gamma_i - \gamma_j| \tag{2}$$

It is essential for route reliability to identify "the time" a vehicle will be in contact with another vehicle before establishing a communication path. Considering that two vehicles might have same velocity (i.e. $\Delta V_{ij} == 0$), the compatibility time (CT_{ij}) can be calculated as follows [3]:

$$CT_{ij} = \begin{Bmatrix} \dfrac{R - \Delta D_{ij}}{\Delta V_{ij} + 1} & if\ \Delta V_{ij} == 0 \\ \dfrac{R - \Delta D_{ij}}{\Delta V_{ij}} & otherwise \end{Bmatrix} \tag{3}$$

$$\Rightarrow CT_{ij} = \begin{Bmatrix} \dfrac{R - \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{|\gamma_i - \gamma_j| + 1} & if\ \gamma_i == \gamma_j \\ \dfrac{R - \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{|\gamma_i - \gamma_j|} & otherwise \end{Bmatrix} \tag{4}$$

The $+1$ in the above piece-wise functions avoid zero denominators with a trade-off of slight off-set in time prediction for few cases. In Equation 3 and 4, we assume that the vehicles do not drastically change velocity or make any immediate stop in the next few seconds of this calculation. A real road topology structure contains intersections, curves, and cross-roads where vehicles move with distinct velocities and mobility directions. The CT value is highly dependent on the position and the direction of vehicles with respect to each other. The aforementioned equation can be modified to address various scenarios as follows:

$$CT_{ij} = \begin{Bmatrix} \dfrac{R - \theta\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{|\gamma_i - \vartheta\gamma_j| + 1} & if \gamma_i == \gamma_j \\ \dfrac{R - \theta\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{|\gamma_i - \vartheta\gamma_j|} & otherwise \end{Bmatrix} \tag{5}$$

The values of θ and ϑ can be configured to facilitate the following cases: 1)Same direction but vehicle i is ahead of vehicle j: $\theta = 1$ and $\vartheta = 1$, 2) Same direction but vehicle i is behind vehicle j: $\theta = -1$ and $\vartheta = 1$, 3) Opposite direction but vehicle i and j are approaching to each other: $\theta = -1$ and $\vartheta = -1$, 4)Opposite direction but vehicle i and j are moving away from each other: $\theta = 1$ and $\vartheta = -1$.

Same direction is identified when the angle difference ($\Delta\theta_{ij}$) between two vehicles (i & j) is less than 90, and opposite direction if the difference is equal to or higher than 90, where $\Delta\theta_{ij} = |((\theta_i - \theta_j + 180)\%360 - 180)|$ and θ_i vehicle i's direction. A vehicle can calculate that it is ahead or behind by subtracting the location ordered pair (x, y) of the target vehicle from its own, where a positive answer means ahead of and negative is behind, assuming the vehicle's direction heading over the x-axis. Equation 5 covers nearly all possible vehicular dynamics, but our single equation model still has some limitations for some sub-cases. Information regarding compatibility can enable improved routing decisions in a dynamic and high mobility environment. Location, velocity, and direction information is available at the MAC layer in the BSMs shared in the DSRC protocol using a beacon. Cross-layer information exchange can enable efficient routing decisions on the network layer. Meanwhile, the trust of a vehicle can be estimated using peer opinion a and previous experience b. The trust of a vehicle j, as seen from vehicle i, can be calculated as follows [5]:

$$T_{ij} = \phi a_{ij} + (1 - \phi) b_{ij} \tag{6}$$

where $\phi \in [0, 1]$ is the weight to incline the trust dependency towards direct or indirect transactions.

$$a_{ij} = \frac{\sum_{k=1\&k\neq i}^{CP} b_{kj}}{CP} \tag{7}$$

where CP represents the number of common peers.

$$b_{ij} = \frac{msgs_{ij}}{Total\ msgs_i} \tag{8}$$

where $msgs_{ij}$ is the number of message transactions between i and j, and $Total\ msgs_i$ is the total number of messages sent by i in a predefined window of time.

III. VAR^2: Vehicular Ad-Hoc Reliable Routing

Most previous protocols [2], [3] rely upon hops (AODV protocol), network performance (throughput, SINR, etc.) or geographical information of intersections, traffics lights, etc. for route selection in vehicular networks, resulting in intermediate nodes with brief and transitory connections. Considering trust and vehicular characteristics such as speed, direction, and location, we propose that each node in the path should be compatible with the source and destination to build a reliable and long connection. Our proposed VAR^2: vehicular ad-hoc reliable routing protocol utilizes CT and trustworthiness (T) of routes to ensure reliable routing. We revamp the existing AODV based data structure to include additional information, i.e. the maximum CT ($MaxCT_{i,Dst}$) and the number of transactions for destinations. Table I outlines the routing table (RT) data structure for existing protocols, i.e. the AODV [4], ad-hoc on-demand multi-path distance vector (AOMDV) [4], trust cryptographic secure routing protocol (TCSR) [5] and the proposed VAR^2 scheme.

In our proposed scheme, each vehicle monitors known routes in a RT using the afore-mentioned information. According to Algorithm 1, if a destination (Dst) does not exist in the RT, the source vehicle broadcasts a route request (RReq) to all neighbors in step 2 and waits for their responses, i.e. route reply (RRep). To assess each RRep, the source vehicle estimates the minimum CT throughout the entire route towards the destination using $MinCT_{RRep} = \arg\min(CT_{ij}, MaxCT_{j,Dst})$ in step 5, where CT_{ij} is calculated using 5 for the next-hop j. The proposed scheme utilizes lightweight beacon BSM messages shared in the MAC Layer of local communications technologies (DSRC and C-V2V

TABLE I
COMPARATIVE DATA STRUCTURE OF ROUTING TABLE (RT)

AODV [4]	**AOMDV [4]**
Destination	Destination
Destination Sequence #	Destination Sequence #
Hop Count	Advertised Hop Count
Next Hop	Route List (Next Hop, Hop Count)$_1$, ...
Expiration Timeout	-

TCSR [5]	**Proposed VAR^2**
Destination	Destination
Destination Sequence #	Destination Sequence #
Route List (Next Hop, Hop Count, PathTrust, Expiration Time)$_1$, (Next Hop, Hop Count, PathTrust, Expiration Time)$_2$ ...	Route List (Next Hop, $MaxCT_{i,Dst}$)$_1$, (Next Hop, $MaxCT_{i,Dst}$)$_2$, (Next Hop, $MaxCT_{i,Dst}$)$_3$ ...
-	**No. of Transactions**

Algorithm 1 On-Demand Message Procedure

1: **if** Dst $\notin$ RT **then**
2: Broadcast Route Request (RReq)
3: **for all** Route Reply (RRep) = {NextHop, MaxCT } **do**
4: Calculate CT_{ij} using BSM messages
5: Calculate $MinCT_{RRep} = \arg\min(CT_{ij}, MaxCT_{j,Dst})$
6: **if** trustworthiness required **then**
7: Calculate $T_{ij} = \phi a_{ij} + (1-\phi) b_{ij}$
8: **if** $MinCT_{RRep} \geq CT_{th}$ & $T_{ij} \geq T_{th}$ **then**
9: add $MaxCT_{RRep}$ to $MaxSet$
10: **end if**
11: **else**
12: **if** $MinCT_{RRep} \geq CT_{th}$ **then**
13: add RRep to $MaxSet$
14: **end if**
15: **end if**
16: **end for**
17: Select path by $MaxCT = \arg\max(MaxSet)$
18: **end if**

mode 3). If message trustworthiness is required, the source calculates T_{ij} for the next-hop j using Equation 6 in step 7. It is noteworthy that the proposed trust is only estimated for immediate neighbors and transitively assumed for all adjacent nodes in the path. Subsequently, if the $MinCT_{RRep}$ for a route is higher than a predefined threshold CT_{th} then the route's $MinCT_{RRep}$ is included in a set $MaxSet$, which contains all candidate routes $MinCT_{RRep}$. After estimating $MinCT_{RRep}$ for all RRep messages, a reliable path is selected having $MaxCT = \arg\max(MaxSet)$ in step 17. The proposed scheme determines a reliable path that exhibits longer connectivity and trustworthiness, thus allowing better message delivery and communications. Fig. 1 illustrates a highway scenario, where each arrow annotation represents the expected CT between vehicles in seconds. The proposed scheme opts for path SEHD because it has the highest minimum CT as compared to other paths such as SCD and SFGD. Our scheme considers longer connectivity to establish multi-hop communications between vehicles as compared to shorter hops. In a high mobility scenario, the proposed scheme can connect vehicle for longer periods, resulting in reliable communications and few packet drops or re-transmissions.

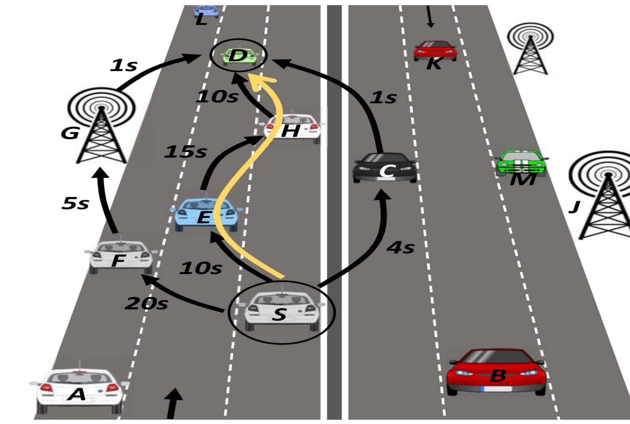

Fig. 1. Proposed VAR^2 path selection.

The CT_{th} directly affects the route selection and can be estimated by each vehicle as follows [19]:

$$CT_{th} = \frac{Pkt_{size}}{BW_{802.11p} \times \log_2\left(1 + \frac{P_c \Delta D_{ij} f_{ij}}{N_0}\right)} \quad (9)$$

where Pkt_{size} is the average packet size, $BW_{802.11\ p}$ the bandwidth of the communication technology (DSRC 802.11p), P_c the transmission power, N_0 the noise (dBm), and f_{ij} the small-scale fading channel coefficient.

The proposed scheme VAR^2 prioritizes routes based on the CT and trust value. Assuming ideal channel conditions, a packet of size (Pkt_{size}) in a bandwidth of BW is successfully transmitted in the proposed VAR scheme, as following:

$$Pkt_{R,ij}^{T-VAR} = \left\{ \begin{array}{ll} 1 & \text{if } \frac{Pkt_{size}}{BW} < CT_{ij}^{mm} \text{ \& } T_{ij} > T_{th} \\ 0 & \text{otherwise} \end{array} \right\} \quad (10)$$

where $CT_{ij}^{mm} \triangleq \arg\max_{i \to j \in \{1,\cdots,paths\}} \{\min\{CT_{ix}, CT_{xy}, \cdots, CT_{zj}\}\}$

Considering a variation in the proposed scheme with only the CT, a successful packet can be estimated as follows:

$$Pkt_{R,ij}^{VAR} = \left\{ \begin{array}{ll} 1 & \text{if } \frac{Pkt_{size}}{BW} < CT_{ij}^{mm} \\ 0 & \text{otherwise} \end{array} \right\} \quad (11)$$

Equation 11 can be modified for AOMDV [4] based routing system, which relies upon the minimum hop counts only, as follows:

$$Pkt_{R,ij}^{AOMDV} = \left\{ \begin{array}{ll} 1 & \text{if } \frac{Pkt_{size}}{BW} < CT_{ik}^{AODV} \\ 0 & \text{otherwise} \end{array} \right\} \quad (12)$$

where CT_{ik}^{AODV} is the compatibility time of first hop k in the selected path on the basis of minimum hop counts.

The average packet delivery ratio (PDR) can be estimated as the ratio between the sum of all successfully received packets ($Pkt_{R,ij}$) and all sent packets ($Pkt_{S,ij}$), i.e., $\sum \frac{Pkt_{R,ij}}{Pkt_{S,ij}}$. It should be noted that the Equation 10, 11 and 12 are used for the performance evaluation of the proposed scheme and existing AOMDV protocol. The bandwidth used in the equations is based on the standard 802.11p.

IV. PERFORMANCE EVALUATION

We comparatively evaluate our proposed scheme under two (sparse and dense) realistic simulation of urban mobility (SUMO) traffic simulator traces in python simulation.

TABLE II
SIMULATION PARAMETERS

SUMO Trace		Python Simulation	
Location	Seoul (37.570355 126.995214)	Vehicles	100 $\sim$ 2,500
Width×Height	2.515×1.540 km	Bandwidth	1Mbps
Intersections	30+	Packet Size	500 KB
Driving	Right hand	Packets	10k / trace
Duration	3600 s	CT_{th}	2 s
Through factor	2	T_{th}	0.5
Count	20, 50, 100, ... /hour/lane	Communications Range	50 m

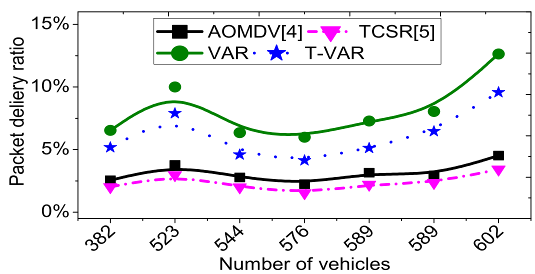

Fig. 2. PDR for a sparse traffic trace.

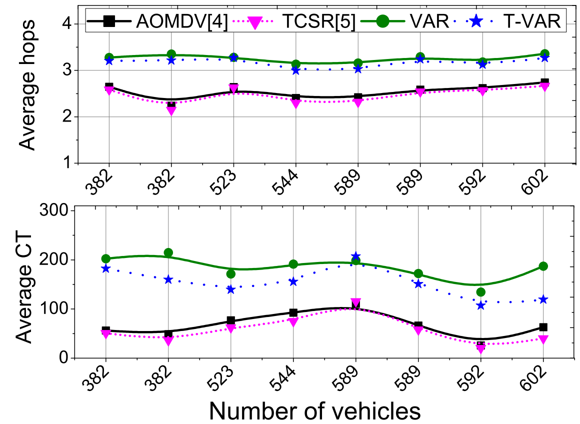

Fig. 3. Average hop and CT count / path for sparse traffic.

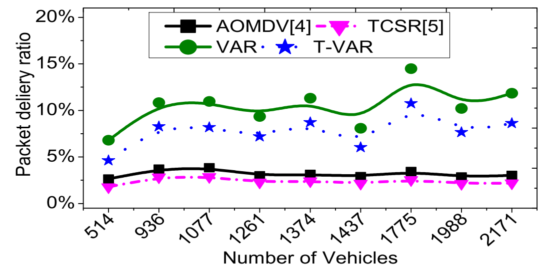

Fig. 4. PDR for a highly dense traffic trace.

The simulation uses OpenStreetMap generated real road typologies where simulated vehicles are positioned for our protocol evaluation [20]. The traces measured approximately 2.5 km $\times$ 1.5 km, with 30+ intersections for more than 60 minutes of traffic, as outlined in Table II. The mobility trace area location is central Seoul, Korea with 20 $\sim$ 100 vehicles generated /hour/lane, where vehicle experience realistic cross-roads, intersections and curves. Other simulation parameters included 100 $\sim$ 2500 vehicles installed with OBUs, exhibiting a 1 Mbps bandwidth and capable of generating 500 KB packets in a 50 m communication range under 5.9 GHz of DSRC frequency. Each vehicle object in simulation has properties of the timestep, unique identifier, speed, direction and lane ID, which are shared with nearby vehicles using BSM messages of size 500 KB. A vehicle can communicate with nearby vehicles or RSUs using ad-hoc connections. The CT threshold (CT_{th}) and trust threshold (T_{th}) were arbitrarily set to 2 s and 0.5, respectively. It should be noted that the CT_{th} and T_{th} are programmable and operator dependent parameters. Our simulation generated approximately 10,000 packets, where each packet can use a maximum of four hops to connect a random source to a destination. We evaluated two variations of the proposed scheme based on route selection criteria, a) VAR (only compatibility), and b) T-VAR (trust and compatibility).

Fig. 2 shows that the proposed scheme VAR^2 (VAR and T-VAR) significantly outperformed AOMDV (multi-path routing) [4] and TCSR (multi-path trust-based routing) [5]. The proposed solution achieved a 6 $\sim$ 12% PDR, when a random source and destination are selected out of a total of 382$\sim$600 vehicles, whereas that of the existing solutions provided 1 $\sim$ 6% PDR, in the same scenario. Please note that the reason for overall low PDR is that the simulation chooses random source and destination from a total number of vehicles with a maximum of 4 hops to connect. The successful transmission in the proposed VAR^2 scheme is a result of route selection based on the CT, which is a function of vehicle speed, direction and location. It is noteworthy that the proposed trust-based variation provides a lower PDR value than its counterpart, which is a trade-off between trustworthy communication and a high delivery ratio. A similar trend was observed between the AOMDV and TCSR results. Fig. 3 shows that the proposed scheme VAR^2 prefers three to four hops, whereas existing schemes tend to select hops of only two to three. Routes with minimum hops are preferred in the existing solutions, thereby resulting in fewer propagation delays compared with the proposed scheme. However, if we observe the average CT value, the paths used in the proposed scheme exhibit a significantly higher CT of approximately 100 to 200 s than those of existing schemes, which only have a short link of 50 s. Long connections can facilitate vehicular networks into sharing useful information with reliable traffic companions and enable futuristic sharing schemes. Our experiments with highly dense traffic are illustrated in Figs. 4 and 5. With dense traffic, the existing solutions select short but unreliable paths, thereby resulting in a smaller PDR value of 1 $\sim$ 3%. However, the proposed scheme provides a PDR of approximately 6 $\sim$ 15%. With an increased number of vehicles, the existing solutions (AOMDV and TCSR) establish routes with reduced CTs ($< 100\ s$), whereas the proposed scheme builds longer connections of up to 400 s with 2 $\sim$ 4 hops. The proposed scheme offers a longer connection between vehicles having high mobility as compared to existing schemes where the vehicles in the chosen route swiftly pass by which results in link re-establishment and additional delays.

It is important to note that the proposed solution broadcasts RReq only if no existing path is available. In a best-case scenario, the address is already present in the RT. However, in a worst-case scenario, the source vehicle needs to compute three data segments which impose additional communication

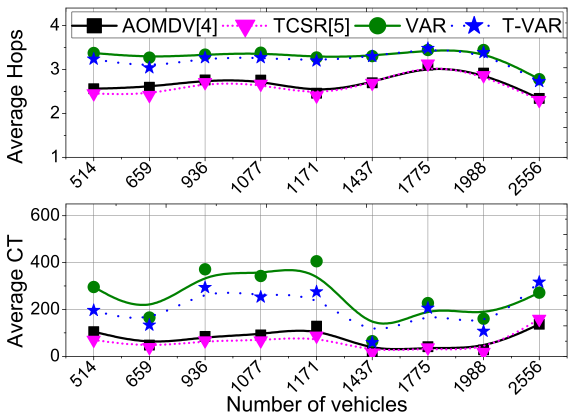

Fig. 5. Average hop and CT count/path for highly dense traffic.

overhead. The information required to execute our scheme includes three segments, i.e. 1) RRep message containing information about path, 2) BSM messages used for compatibility 3) transaction history to estimate trustworthiness. Nevertheless, the BSM messages are already shared and RRep only requires one additional field of MaxCT. The proposed scheme only calls for trust estimation as our additional overhead which is needed as a trade-off for trustworthy data transfer. The communication security in the proposed ad-hoc system can be achieved using authentication and encryption against malicious access and medium security, respectively [21]. IEEE 802.15.4 with six advanced encryption standard (AES) message encryption variations (e.g. AES-CBC-MAC-32, AES-CCM-128, etc.) on MAC layer, Internet engineering task force's (IETF's) constrained application protocol (CoAP) bound with datagram transport-layer security (DTLS) for data on the application layer and IETF's routing protocol for low-power and lossy networks (RPL) with unsecure, preinstalled and authenticated modes for packets on Network layer, provide a way of secure communication in ad-hoc networks. In this study, we included a light-weight on-demand trust mechanism for trustworthy cooperative communication. However, a sophisticated security mechanism for the proposed compatibility-based routing in vehicular ad-hoc networks is still an open research challenge.

V. Conclusion

The effects of hop count (AOMDV), hops with trust (TCSR), and the proposed compatibility with trust (VAR^2)-based algorithms on vehicular networks were investigated in this study. Our proposed VAR^2, vehicular ad-hoc reliable routing protocol, considers compatibility and autonomous trustworthiness among high mobility traffic to achieve long connections. Realistic SUMO traces with sparse and highly dense traffic were used in our exhaustive experiments; the results demonstrated that VAR^2 achieved a PDR that was $6 \sim 15\%$, outperforming the existing solutions having a PDR of $1 \sim 6$. Moreover, we demonstrated that the proposed solution preferred long CT values than short hop counts, which resulted in $100 \sim 400$ s connections with only $3 \sim 4$ hops. The proposed scheme can also be extended to consider not only the vehicular compatibility but also network congestion in the intermediate vehicles for hybrid solutions.

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