

A New Model for Effective Use of Robustness as a Measure of QoS in Vehicular Ad-hoc Networks

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Abstract— Applications of VANETs, as used in Intelligent Transportation Systems may have requirements of robust network and robust route for communication over it. This work aims at modeling robustness as a significant measure of QoS for the effective use in VANETs, first of its kind. Here, robustness has been defined as a qualitative QoS parameter of communication links that depends on link lifetime and error rate over the link. The forms of robustness considered here include Link-Robustness and Route-Robustness. Modeling and quantification of Link-Robustness has been carried out by synthesizing temporal, spatial and environmental dependencies of the network. It is so because these dependencies are responsible for variation of link-lifetime and link-error rate in VANETs environment. Similarly, Route-Robustness has been defined and modeled as a part of the overall network environment. Moreover, quantification of Link-Robustness and Route Robustness has been proposed and illustrated with the help of an example scenario. Based upon the proposed model and robustness as the QoS measure in VANETs a route selection strategy has been proposed that is an important and integral component of any routing protocol. Subsequently, an algorithm has been presented that involves route selection and route request procedures. Finally, validation and analysis of the proposed model and consequent route selection strategy have been carried out the basis of results obtained from the associated simulations of AoDV and AoDV-R in addition to that of proposed model.

Keywords—Robustness; Quality-of-Service; Link-Robustness; Route-Robustness; Modelling robustness in VANETs; Robust route selection strategy in VANETs

I. INTRODUCTION

A. Motivation

Intelligent transportation Systems (ITS) has been receiving a lot of attention globally in the wake of the continually growing operational complexity of road-traffic and its management, thanks to ever-increasing traffic-volume. Such systems invariably require an underlying computer communication network to support their varying needs. The applications and services which run on top of these communication networks ranges from human safety, traffic management to on-the fly comfort of the users. To serve ITS, Vehicular Ad-hoc Networks (VANETs) are the workhorse.

VANETs consist of on-road vehicles equipped with required wireless system, which can establish interconnection

among themselves. Thus, source vehicle relies on its neighboring vehicles for data dissemination. Discovery of route and preserving paths form a complex task in VANETs. Frequent disconnections and errors may occur in the intermittent wireless links. This is because of (a) higher mobility, (b) varying patterns of mobility resulted by traffic signals, road conditions, driver's nature etc. and (c) various environments in which vehicle operates i.e. urban, rural, highways and expressways. Thus it becomes highly challenging task to maintain connectivity while assuring QoS in VANETs during data exchanges. Both types of QoS i.e. qualitative e.g. robustness, reliability and quantitative e.g. delay, bandwidth etc. are needed to be guaranteed for the improvement of VANETs performance [1]. Therefore it is required to model, develop and deploy strategies which can not only perform routing but also must provide QoS support efficiently. This should be based upon the requirements of target applications running on top of VANETs. One way of enriching these in VANETs could be by selecting robust routes i.e. the routes which are less error prone and remain available for long time.

In light of such challenges it became important to correctly model various QoS parameters for VANETs environment. As far as modeling of qualitative QoS parameters is concerned, importantly robustness, issue remains unresolved. It is essential to address and incorporate robustness in VANETs because the network should cope-up with abnormalities and error, on-the-fly, without degrading network performance.

B. Related Works

In the limited context of the VANETs, several attempts have been made to address issues pertaining to QoS provisioning and consequent QoS-enabled routing. However, as of now, no known approach has been found to be commonly acceptable as a practicable solution. Select approaches reported in literature with respect to such a work are as follows: (a) Prediction Based Routing (PBR) [2] (b) Delay and Reliability Constrained QoS (DeReQ) [3] and (c) QoS-enabled Multipath Routing Protocol [4].

PBR is an approach that focuses on prediction of a route lasting time, defined as the time for which a route would be available for a given pair of source and destination vehicles. It aims to help in reducing the number of route failures and even identifies new or alternative routes before existing ones fail.

Whereas, DeReQ target the dual factors of link delay and link reliability in QoS routing approach. Link reliability is defined as the predicted time for which a communication link is expected to remain available. A route with maximum link reliability and a link delay with a cut-off value considered optimal for routing in this case. Lastly, QoS-enabled Multi-path Routing is a multi-constrained protocol that exploits topological information for taking routing decisions. QoS parameters considered in this case are end-to-end delay, packet delivery ratio and overhead.

In all mentioned approaches, no credible model has been used to provide a reliable estimate or a guaranty of finding acceptable route within a given range of one or more QoS parameter and assumption.

Focusing on modeling of quality based QoS parameters; a reliability model is proposed in [5]. Reliability, in such case, is defined as the predicted lifetime of a wireless communication link between a pair of neighboring vehicles. In this model using information of location, direction and velocity of vehicles reliability is predicted. Furthermore a reliability-based routing protocol AoDV-R which is a modified version of Ad-hoc On-Demand Distance Vector (AoDV) [6] routing protocol, has been proposed. The latest in the league is a reliability and security oriented, multi-constrained QoS based routing protocol [7]. In this work Ant Colony Optimization technique has been employed to find multiple QoS constraints path.

As far as robustness as a measure of QoS is concerned not much prior work has been carried out in the context of VANETs. An exception to that is Multi-Hop Routing Protocol for Urban VANETs (MURU) [8], that was originally derived by combining position information and weighted measure of Link-Lifetime and hop count namely Estimated Disconnection Degree (EDD) as proposed by Mo et al. [8]. It has been claimed that MURU provides a robust routes which are evaluated by EDD. However, like earlier approaches Link-Robustness has not been used. Therefore, the scope for better modeling of robustness as QoS measure is there.

C. Contributions of the Presented Work

Applications of VANETs, as used in Intelligent Transportation Systems may have varying QoS requirements. Consequently it becomes important to correctly model QoS parameters qualitatively and quantitatively. In such networks, communication links are prone to errors and intermittent loss of connectivity due to variations in mobility, network topology and environmental conditions. Ensuring a robust communication mechanism therefore becomes a challenge. Present work considers robustness as a qualitative QoS parameter of communication links and models it for effective use in VANETs. Robustness is defined as quality of link which includes lifetime and error rate. Here, it is classified as Link-Robustness and Route-Robustness. Modeling and quantification of Link-Robustness has been carried out by synthesizing temporal, spatial and environmental dependencies of the network. Similarly, Route-Robustness has been defined and modeled as a part of the overall network environment. Subsequently, a route selection strategy has

been proposed for facilitating robust routing in VANETs. The validation of the proposed model has been carried along with a comparison of the results obtained from the associated simulations with those of AoDV and AoDV-R suggests that the presented model significantly improves the network performance with respect to parameters like average number of link failures, packet delivery ratio and delay, in varying conditions such as varying velocity of the vehicles, shape factor of the environment and size of the transmitting data.

Apart from this, the benefits of adopting this model for VANETs include: effective use of robustness as a QoS measure in VANETs, creating a self-organized robust vehicular ad-hoc network, quantification of Link-Robustness and Route-Robustness which are till now considered as qualitative parameters, the presented mathematical model could singly be used in VANETs simulations for representing combined and realistic effects of various environmental phenomena, namely, interference, noise, fading and shadowing in various road scenarios such as highway, freeway, expressways, urban, sub-urban, rural, multi-lane, single-lane etc. and route selection strategy presented with this model could be used for devising a robust routing protocol.

II. MODELLING LINK-ROBUSTNESS IN VANETs

Robustness of a model is typically defined as its ability to produce results consistently under varied protocols, conditions and occurrence of errors [9]. In case of ad-hoc networks, robustness refers to providing intermittent connectivity from source to destination for a given amount of time with provision to cope-up with any error that could occur because of dynamic nature of network [10]. Considering robustness as a QoS measure in course of identification of optimal route in VANETs, this work first models Link-Robustness by defining it as the robustness of a direct link between two vehicles.

A. Defining Link-Robustness

In the context of VANETs, Link-Robustness can be defined as *"ability of the link to provide continuous connectivity for a specific time period with low error rate so that connected vehicles can communicate over it successfully, even if error rate increases up to a given threshold level during communication"*. It can be also represented and quantified as a weight/probability of a direct link between two vehicles. Let Δt be the time period for which a direct communication link between two vehicles i and j remains active. If these vehicles are D_{ij} distance apart and given that L_{ij} is directly connected via a communication link at time t , the robustness $R(L_{ij})$ of that link could be defined as:

$$R(L_{ij}) = \text{error correctness factor} \times \text{Probability of availability of link } L_{ij} \text{ for time } (t + \Delta t) \quad (1)$$

The robustness of the link depends upon the Link-Lifetime and the errors that occur over a link, throughout the duration of continuous existence of a link. The Link-Lifetime depends on spatial and temporal characteristics of the network, whereas the error depends mostly on the environmental

conditions. Generally, these errors are represented in terms of error rates. A link L_{ij} is said to be more robust than a competing link if it has lower error rate and higher probability of link availability. As the relative distance between two nodes increases, the error rates also increase due to above mentioned environmental effects. Consequently, there exists a distance D_c for which error rate is minimal. It can be shown that if D_c along with the predicted time for which a link is going to exist are considered as criteria, better Link-Robustness could be achieved. The logic here is that the communication link which is smaller in length than D_c is likely to have lower error rate for a given period of time. It has been independently established that error rates are proportional to the relative distance between sender and receiver vehicles [11] and this reinforces the logic referred above. Thus, error correctness factor c can be calculated as:

$$c = \begin{cases} 1, & D_{ij} \leq D_c \\ \frac{1}{D_{ij}}, & D_c < D_{ij} \leq D_r \\ 0, & D_r < D_{ij} \end{cases} \quad (2)$$

Here D_r is the radio range of the vehicles and D_c is the distance till which it is guaranteed that the packets will be successfully transferred over the links in a given wireless environment. It could be obtained by calculating the distance whose corresponding message error rate is low (close to 0%), or the probability of reception of a packet correctly is high (close to 1). Considering the scenarios the value of D_c would differ. Ideally, it should be calculated on-the-fly. In the following subsection, the process involved and due justification have been described.

B. Justification for Adoption and Formulation of Error Correctness Factor

Error correctness factor c is considered inversely proportional to the error rate and proportional to the message reception probability. Hence, product of c and link-lifetime for L_{ij} shall provide Link Robustness $R(L_{ij})$ as shown in (1). As $c \rightarrow 1$, $\text{error rate} \rightarrow 0$. This relationship, thus, helps in determining links with comparatively low error rate.

Next, in (2) first condition shows that for $D_{ij} \leq D_c$, $c = 1$. This is so because, if $c \propto D_{ij}$ then for $D_{ij} \leq D_c$, the route computed as the most robust route between nodes S and D , would involve significantly high number of corresponding hops. Hence, such routes are likely to exhibit low network performance. Also, it has been observed that when $D_{ij} \leq D_c$, the increment in error rate is not significantly high with corresponding increment in distance, as explained in the following subsection (see Figure-1). Therefore, in order to avoid both of the aforementioned situations, for the conditions, c has been taken as 1. However, at times it becomes hard to find an appropriately robust route because of lesser number of links fitting into the criterion, even if multiple links with $D_{ij} > D_c$ remains available at a given point of time. Effectively, such situations lead to low network

performance. For dealing with it, only the links having $D_{ij} > D_c$ are considered. It has been observed that such links have large increments in corresponding error rates with increment in distances involved, as illustrated in the following subsection (see Figure-1). Therefore, when the condition: $D_c < D_{ij} \leq D_r$ is true, c is considered inversely proportional to the distance involved. Lastly, for the condition $D_{ij} > D_r$, two nodes are not in the radio range of each other, which indicates that no connecting link exists and hence, $c = 0$.

C. Evaluation of D_c

The IEEE 802.11p, a member of 802.11 family, is considered as a credible standard for physical (and link level) communication in VANETs [12]. In order to calculate D_c , it is, thus, required to consider an IEEE 802.11p compliant communication link, applicable wireless environment and surrounding scenario. Consequently, it is required to consider wireless environmental losses for evaluation of packet reception success rate and corresponding distance D_c .

Because of wireless environment and its surroundings, the major factors contributing towards error are: (a) *Path-loss*: caused by radio signal attenuation during transmission over a larger distance, (b) *Fading*: occurring due to multi-path transmission, (c) *Shadowing*: effect of signal attenuation due to select elements of infrastructure like concrete structures etc. falling in the path of signals, (d) *Interference*: caused by signals emanating from other sources like those due to another on-going communication and (e) *Noise*: arising from select thermal conditions at the receiver's end.

First three of these effects have been modelled as follows, whereas the last two effects have been modelled with Signal-to-Interference-Noise Ratio (SINR) and presented immediately afterwards:

In ideal case, wireless signal propagates through free space or could be assumed as the 2-ray ground model. In such cases, the average power received at some distance D from transmitter can be obtained by:

$$P \propto D^{-\gamma} \quad (3)$$

Here γ is the propagation path loss exponent and is subject to a given propagation scenario. But the corresponding mean path-loss at distance $d \geq d_0$ is given by the following expression [10]:

$$PL_d = PL_0 + 10\gamma \log \left(\frac{d}{d_0} \right) + L_F + L_S \quad (4)$$

Here PL_0 is the path loss at distance d_0 , which is in the far-field region of the transmitter [11]. L_S and L_F are the losses due to shadowing and fading effects respectively. As mentioned above, γ is the propagation path loss exponent. On highways, relatively lesser amount of infrastructure is available around the road and consequently lesser multi-path propagation is likely. Usually, $\gamma \approx 2$ is considered for reflecting the effect of such highway characteristics. In

contrast to highways, in a given urban scenario, various buildings and other infrastructures are mostly located around roads and the severity of path loss thus increases with corresponding γ . Hence, for urban scenario, $\gamma \approx 4$ is taken as the considered value.

It has been proven in the literature that Nakagami-m fits well as a multi-path fading model in case of vehicular environment [13], [14], [15]. It is described by a probability density function (PDF) [16]. Aiming VANETs, Nakagami-m distribution for the PDF for a signal level of l is:

$$f_f(l; m; P_{avg}) = \frac{2}{\Gamma(m)} \left(\frac{m}{P_{avg}} \right)^m l^{2m-1} \exp\left(-\frac{m}{P_{avg}} l^2\right) \quad (5)$$

Here $l > 0$, $m \geq 1/2$ and $\Gamma(\cdot)$ is the Gamma function i.e. the corresponding power to l is gamma distributed. m is an integer shape factor called as fading figure [16]. In this case, P_{avg} is the average power received at a particular distance from a transmitting vehicle. For incorporating the shadowing effect (obstruction by an object), which is very common phenomenon in VANETs, lognormal shadowing model is used as a common practice [11]. The shadowing effect is model by lognormal distribution and written by PDF as [18]:

$$f_s(l; \mu, s) = \frac{4.343}{\sqrt{2\pi}sl} \exp\left(-\frac{(10\log l - \mu)^2}{2s^2}\right) \quad (6)$$

Where, s and μ are the standard deviation and logarithmic mean for the given signal level. Thus, in the proposed model, both fading and shadowing effect on signal propagation have been duly considered. Combined effect of both the phenomena can be computed as composite Nakagami-lognormal distribution. In such case, the PDF for the reception of signal with level l is given by [17]:

$$f_{f-s}(l; m; s; P_{avg}) = \int_0^\infty f_f(l; m; P_{avg}) f_s(l; \mu, s) . dl \quad (7)$$

The cumulative density function (CDF) approximation for a signal to be received with power l [18] may be worked out as follows:

$$F_{f-s}(l; m; s; P_{avg}) = \frac{1}{2} \left(1 + \operatorname{erf}\left(\frac{10\log l - \mu_c}{\sqrt{2}s_c}\right) \right) \quad (8)$$

Here, $\operatorname{erf}(\cdot)$ is the Gauss error function. s_c and μ_c are the approximated values of standard deviation and logarithmic mean for the given signal level can be calculated as [10]:

$$\mu_c = 10\log P_{avg} + 4.343(\Psi(m) - \ln(m)) \quad (9)$$

$$s_c = \sqrt{s^2 + (4.343)^2 \zeta(2, m)} \quad (10)$$

Where $\zeta(\cdot, \cdot)$ denotes the Hurwitz zeta function and $\Psi(\cdot)$ represents the digamma functions which are well defined functions. Now, the probability for a message to be successfully received can be calculated using probability that the reception power is greater than threshold P_r i.e. on the edge of the radio range. Therefore, in this case the probability depends upon signal strength and can be calculated as [19]:

$$P_{l>P_r}^{f-s} = 1 - F_{f-s}(P_r; m; s; P_{avg}) \quad (11)$$

Now, on substituting (3), (8) (9) and (10) in (11) to find the probability that a message is successfully received, given the radio range D_r with channel parameters m , s and γ is:

$$P_d^{f-s} = \frac{1}{2} \operatorname{erfc}\left(\frac{10\gamma \log\left(\frac{d}{D_r}\right) + 4.343(\ln(m) - \Psi(m))}{\sqrt{2(s^2 + (4.343)^2 \zeta(2, m))}}\right) \quad (12)$$

Here, $\operatorname{erfc}(\cdot)$ is the complementary Gauss error function. Using (12), d can be calculated by putting the values of all other parameters. Now D_c the maximum distance for which the probability of packet being in error remains minimal. Thus, $D_c = d$ when $P_d^{f-s} \approx 1$. Note that D_c is dependent upon the communication channel parameters of 802.11p including radio range. Also, it depends on the environmental parameters in which vehicles operate. So D_c will vary accordingly and needs to be calculated on run. Consider a VANET operating on a highway. Accordingly, the parameters are required to be set as $D_r = 450$ meters, $s = 4$ dB, $\gamma = 2$ and $m = 3$ for the given scenario [20], to calculate D_c .

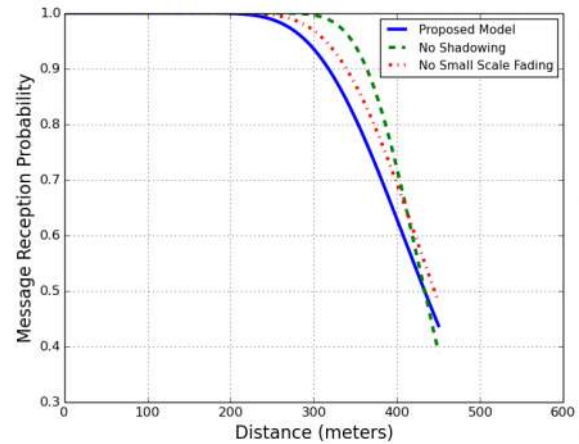


Figure 1. Message reception probability varying with distance (meters)

Figure-1 shows the probability of message reception varying with the distance. In this plot, it can be seen that the composite effect of shadowing and small-scale fading along with path-loss affects the packet reception probability more than the cases wherein no shadowing ($s = 0$) and no small scale fading $m \gg 1$ occurs [21]. Also, it has been found that the probability of successful message reception till 200 meters is almost equal to 1. Beyond this distance, probability of successful message reception decreases suddenly and therefor, for this scenario, the value chosen as D_c is 200 meters. This

behaviour of the graph in Figure-1 justifies the claims made in subsection-B.

Next, interference and noise effects in the VANETs have been represented as SINR and therefore, may be expressed as:

$$SINR = \rho = \frac{\alpha^2 P_{avg}}{P_N + \beta^2 P_I} \quad (13)$$

Here, P_N and P_I denote power as observed at the receiver's end due to noise and interference respectively, whereas, α and β represent the channel gain for the signal 'I' and relevant interfering signals, respectively. The PDF for instantaneous SINR with Nakagami-m fading is formulated as [22]:

$$f_{SINR}(\rho, \bar{\rho}_I, m) = \frac{1}{2\sqrt{\pi}\rho\Gamma(m)} m^{2m} \left(\frac{1}{\bar{\rho}_I}\right)^m \left(\frac{\rho}{\bar{\rho}_I}\right)^m e^{-m\left(\frac{\rho - \rho\bar{\rho}_I}{2\rho\bar{\rho}_I}\right)} \left(m\left(\frac{\rho}{\bar{\rho}_I} + \frac{1}{\bar{\rho}_I}\right)^{\frac{1}{2}-m}\right) \left(K_{\frac{1}{2}-m}\left(\frac{m\bar{\rho} + \rho\bar{\rho}_I}{2\rho\bar{\rho}_I}\right) + K_{-\frac{1}{2}-m}\left(\frac{m\bar{\rho} + \rho\bar{\rho}_I}{2\rho\bar{\rho}_I}\right)\right) \quad (14)$$

$K_k(.)$ is the Bessel Function of second kind and $\bar{\rho}_I$ is the Interference-Noise-Ratio i.e. P_I/P_N . Using this formula and (7), composite PDF for SINR along with fading and shadowing could be calculated as:

$$f_{f-s-SINR}(lm; s; P_{avg}, \rho, \bar{\rho}_I) = \int_0^\infty f_f(lm; P_{avg}) f_s(l; \mu, s) f_{SINR}(\rho, \bar{\rho}_I, m) . dl \quad (15)$$

Consequently, combined probability $P_d^{f-s-SINR}$ that a message is received correctly at distance d in presence of path losses and SINR could be calculated according to (11) and (12). Based on which D_c can be calculated by the vehicles. Now, hence calculated value of D_c will provide the distance for which error rate over the link will be nominal in presence of path-loss, shadowing, fading, noise and interference.

D. Prediction of Link-Lifetime

Lifetime of a link can be defined as the time for which direct communication link between two vehicles will remain available for communication purpose. In reality, due to dependencies of temporal, spatial and behavioral kinds, the lifetime of a link is hard to predict. In this work, Link-Lifetime has been estimated probabilistically. In this case, for such calculations, temporal and spatial information of the two involved vehicles are needed. However, in pure VANETs, no infrastructural support is provided and hence the only way to know about the positions and speed of the respective vehicles involves using on-board mechanism such as accelerometer, a digital map, and, at times, Global Positioning System (GPS) assisted coordinates. It is assumed that vehicles equipped with such devices.

The distance D_{ij} between two vehicles i and j can be expressed by a function of time and relative velocity. On

roads, various conditions are needed to be considered to calculate the relative velocity, such as: information about (a) vehicles which are moving in the same direction (is the vehicle approaching from behind and has higher velocity or is the vehicle relatively ahead and has higher velocity); (b) vehicles which are moving in opposite direction (is both vehicles are approaching each other or they are moving away from each other; and (c) the direction change in any one of the vehicle. Incorporation of such conditions while calculating relative velocity can be done by considering it as a vector quantity. The maximum distance between two vehicles for which a link L_{ij} exists is possible to be estimated by the radio range D_r . Thus, D_r can be computed by taking the magnitude of sum of current displacement ($\hat{D}_{ij}$) and displacement, which takes place in time interval Δt .

$$D_r = |\hat{D}_{ij} + \Delta \hat{v}_{ij} \Delta t| \quad (16)$$

On solving (16), a quadratic equation for Δt is obtained. The positive root of the equation gives the value for Δt . The maximum time for which the communication between two vehicles exists can be determined by time required to cross $2D_r$. Also, the relative velocity can be expressed as $\Delta v_{ij} = D_{ij}/\Delta t$.

In order to perform the probabilistic calculations, the relative velocities of the vehicles are assumed to be normally distributed; and even if it changes, the resultant would also be normally distributed. Therefore, by considering (16), above arguments and referred assumptions, the probability that at time t , the link L_{ij} will remain available for duration Δt is expressed as [5] follows:

$$P_{t+\Delta t > t} = \text{erf}\left(\frac{\frac{2D_r}{t} - \mu_{\Delta v_{ij}}}{\sqrt{2}\sigma_{\Delta v_{ij}}}\right) - \text{erf}\left(\frac{\frac{2D_r}{t+\Delta t} - \mu_{\Delta v_{ij}}}{\sqrt{2}\sigma_{\Delta v_{ij}}}\right) \quad (17)$$

Where $\Delta t > 0$. $\sigma_{\Delta v_{ij}}$ and $\mu_{\Delta v_{ij}}$ are the variance and the mean of relative velocity Δv_{ij} , respectively.

Now, focusing on prediction of Link-Lifetime, also, consider that vehicles are moving on a three-lane highway, wherein lane-1, lane-2 and lane-3 has an average velocity 22.22, 16.66 and 11.11meters/second respectively (see Figure-2).

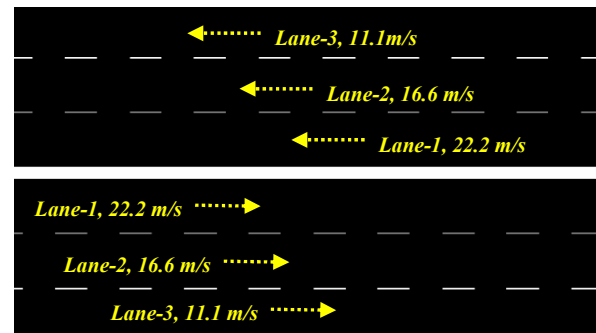


Figure 2. Mobility Scenario

If assumed that two vehicles moving in the same lane are having a communication link connecting them. The probability that the link will exist that may be depicted as shown in Figure-3. It can be seen that the link will exist with higher probability between the vehicles which have relatively constant velocity (i.e. the variation in the velocities of the two vehicles remains constant, preferably zero) and wherein in the very recent past link already existed. Now, using error correctness value and predicted Link-Lifetime value which could be obtained on-the-fly using (2) and (17) respectively, Link-Robustness values can be calculated. Next section shows the quantification of Link-Robustness for highway scenario, which will also be used for analysis of the results.

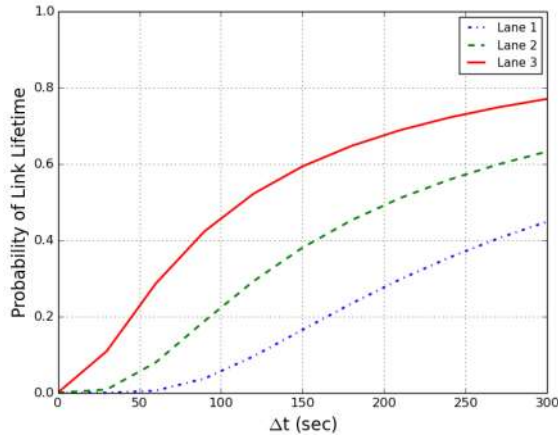


Figure 3. Probability of link lifetime.

III. QUANTIFICATION OF LINK-ROBUSTNESS

As per proposed model, Link-Robustness depends upon the distance dependent losses and the availability of that link. Therefore, from (1), (2) and (17) the derived equation for quantification of Link-Robustness for $\Delta t > 0$, is given by:

$$R_{(L_{ij})} = c \left[\operatorname{erf} \left(\frac{2D_r}{t} \frac{\mu_{\Delta v_{ij}}}{\sqrt{2}\sigma_{\Delta v_{ij}}} \right) - \operatorname{erf} \left(\frac{2D_r}{t+\Delta t} \frac{\mu_{\Delta v_{ij}}}{\sqrt{2}\sigma_{\Delta v_{ij}}} \right) \right] \quad (18)$$

For a specific scenario (i.e. a given highway), the calculated value for D_c has been taken as 200 meters and c has been evaluated accordingly. As indicated earlier, it depends upon channel and environmental parameters namely, D_r , m , s and γ . Similarly, the probabilistic Link-Lifetime value depends upon the temporal and spatial parameters of the involved vehicles. Therefore, in the chosen scenario, it depends on $\sigma^2_{\Delta v_{ij}}$ and $\mu_{\Delta v_{ij}}$. These parameters are needed to be set according to the scenario e.g. urban, suburban, highway, expressways etc., in which a particular VANET is operational.

In order to quantify Link-Robustness, assume that the two vehicles are moving in same lane and have a communication link between them. Let the vehicles have an assumed communication range of 450 meters. Let the average speeds of lanes be 11.11, 16.66 and 22.22 meters/second respectively. In such a case, $m = 3$, $s = 4\text{dB}$ and $\gamma = 2$ are set as values, as needed in case of the chosen highway. Here $D_c = 200\text{ m}$.

Table I. Link-Robustness Values

Distance D_{ij} (meters)	Vehicles in Lane No.	Link-Robustness Value ($R_{(L_{ij})}$)
$D_{ij} \leq D_c$	Lane-1	0.83
	Lane-2	0.72
	Lane-3	0.58
$200 < D_{ij} \leq 300$	Lane-1	0.003-0.0025
	Lane-2	0.0029-0.0023
	Lane-3	0.0023-0.002
$300 < D_{ij} \leq 400$	Lane-1	0.0023-0.002
	Lane-2	0.002-0.0018
	Lane-3	0.0016-0.0014
$D_{ij} \geq D_r$	Lane-1	0.00
	Lane-2	0.00
	Lane-3	0.00

Based upon these parameters, using (18), the quantified link bound robustness is calculated next, against the varying distance between two vehicles. It can be observed from Table-1, that for a fixed Link-Lifetime, the Link-Robustness value varies according to spatial features of the environment. The Link-Robustness decreases nonlinearly in case of $D_{ij} > D_c$. Thus, it can be concluded that for a specific case, robustness is a relative concept and can be judged on the basis of quantified value. For instance, the link L_{ij} is more robust for $D_{ij} = 200$ meters as compared to $D_{ij} = 300$ meters, for a specific Link-Lifetime and relative velocity.

If assumed that two vehicles moving in the same lane are having a communication link connecting them. The probability that the link will exist may be depicted as shown in Figure-3. It can be seen that the link will exist with higher probability between the vehicles which have relatively constant velocity and wherein in the very recent past link already existed. Now, using error correctness value and predicted Link-Lifetime value which could be obtained on-the-fly using (2) and (17) respectively, Link-Robustness values can be calculated. Next section shows the quantification of Link-Robustness for highway scenario, which will also be used for analysis of the results.

IV. ROUTE-ROBUSTNESS AND ROUTE SELECTION STRATEGY

In VANETs, vehicles which are at fair distance apart and not in radio range of each-other need intermediate connected vehicles to forward data. This constitutes a path from source to destination vehicle. A *path* is an ordered combination of communication links. In most cases, more than one such path might become or remain available. Therefore, there should be a strategy to select best or optimal path from the available paths. Hereafter, best considered or selected optimal path has been termed as *route* and all other potential paths, if present,

have been termed as *paths*. Naturally, a route, such designated, needs to be robust apart from having the preferred ability to improve network performance. Here, a robust route selection strategy has been proposed wherein, individual quantified Link-Robustness values are used to estimate robustness of a path. The strategy RSS for route selection is been defined as:

$$RSS: \underset{\omega \in W(S,D)}{\operatorname{argmax}} R_{(RSD)}^{\omega} \text{ such that } R_{(RSD)}^{\omega} \geq \partial \quad (19)$$

Here, $R_{(RSD)}^{\omega}$ is the robustness of a path: $\omega \in W(S,D)$. $W(S,D)$ is the set of all available paths from source vehicle S to destination vehicles D , ∂ is the threshold value that can be set by an application. Let ϕ be the number of links in path ω . The robustness of a path ω is defined as:

$$R_{(RSD)}^{\omega} = \prod_{L_{ij}=1}^{\phi} R_{(L_{ij})} \text{ for } \omega \in W(S,D) \quad (20)$$

Algorithm 1. Route selection and route request strategy

Input: $S, D, D_r, m, s, \gamma, \sigma^2_{\Delta v_{ij}}, \mu_{\Delta v_{ij}}, \partial, D_{ij}, v_{ij}$
Output: Robust Route for a pair of S and D
if S has some data to send to D , **then**
 broadcast a route request to direct neighbours;
end if
if a node j gets route request from node i , **then**
 compute D_c using equation (12);
 compute c using D_c and equation (2);
 compute Link-Lifetime for L_{ij} using equation (17);
 compute Link-Robustness $R_{(L_{ij})}$ for L_{ij} using c and Link-Lifetime;
 insert/update routing table for neighbouring node using $R_{(L_{ij})}$;
 update Robustness value in route request message by multiplying $R_{(L_{ij})}$ to it;
 if j is destination D , **then**
 select route using equation (19) and insert/update routing table based on Route-Robustness value $R_{(RSD)}^{\omega}$;
 send route reply message to S with $R_{(RSD)}^{\omega}$;
 else insert/update reverse route to the source node;
 if j has a route to D , **then**
 send route reply message to S with $R_{(RSD)}^{\omega}$;
 else forward route request;
 end if
 end if
end if

The robustness of a path can be defined as the product of all Link-Robustness values that are available for a particular path. The path robustness could also be defined as minimum of all Link-Robustness values over the path, instead of product of all Link-Robustness values; however, in such a case, if there are three available paths with same minimum Link-Robustness values than it gets hard to differentiate between them. It is this reason due to which product of Link-Robustness has been used in the presented approach in place of simply picking up the minimum of all Link-Robustness values as the path robustness. Also, the Route-Robustness

value is defined as the maximum of all path robustness values that are available for a pair of source and destination vehicle. The catch here is that the application can determine or indicate a threshold and those paths which satisfy the threshold value ∂ for robustness can only be considered as potential paths for selection of the route. Here, it can be inferred that the path ω is more robust than path ω' if $R_{(RSD)}^{\omega}$ and $R_{(RSD)}^{\omega'}$ are their respective robustness values which are greater than the robustness threshold ∂ and $R_{(RSD)}^{\omega} > R_{(RSD)}^{\omega'}$. Also, depending upon application and situation, the strictness of the strategy can be adjusted by setting up ∂ . In a nutshell; the concept of Route-Robustness is based on relativity and can be compared on the basis of quantified values.

Using above mentioned Strategy RSS, a routing protocol can be devised for VANETs. The pseudo code illustrating the route selection and route request strategy that aids in routing protocol has been presented in Algorithm-1. Herein, route request and route reply messages are passed between nodes to find the most robust route. Details about these message passing schemes are provided in next section along with simulation and result analysis.

V. SIMULATION, VALIDATION AND RESULT ANALYSIS

As of this writing, no publicly available real vehicular networking dataset is available that fits well in the evaluation of the proposed model. The dataset like DieselNet [23] does not quite qualify as an acceptable dataset in this investigated scenario as it belongs to delay tolerant networks realm. In the absence of such suitable real dataset, therefore, simulation has been chosen for evaluation.

A. Evaluation Scheme

In order to evaluate this model, the strategy RSS is incorporated in AoDV [6], a well-known protocol for routing in MANETs. Due to higher mobility and ever changing VANET topology, AoDV directly does not fit well for VANETs [21]. It uses hop count for selection of a route from available paths. AoDV is a reactive routing protocol and searches out for route on demand with the help of Route-Request (RREQ) and Rout-Reply (RREP) messages. RREQ is triggered when a node needs to send data to a destined node and want to discover the route for same purpose. RREP is triggered when a destination node wants to reply back to a source node in response of its RREQ. Also, it requires a maintenance mechanism to re-establish the route in case a route breaks down while transferring data or control messages. Route-Error (RERR) message is triggered for this purpose.

This work opts for same routing mechanism with slight modifications (as needed). Instead of using hop count for selecting a route from available paths, robustness value has been utilized here as the parameter for route selection, as expressed in (19) and (20). RREQ and RREP message formats of AoDV had to be modified as well. They were extended with position, speed and robustness information as and when required. Thus, when source broadcasts RREQ, it embeds its additional information to this request. When a

neighbor vehicle receives RREQ with additional information, it calculates Link-Robustness value based on (10). Afterwards, Route-Robustness value is calculated by multiplying the calculated Link-Robustness value to already existing value in RREQ. The neighbor then updates this value and adds its own information in RREQ before broadcasting it. Remaining route maintenance and route discovery strategies are adopted as it is. It may be noted here that here focus is on evaluation of robustness and devising routing protocol is out of scope, as of now, in the first phase of the work carried out. Pseudo code for the algorithm presented in the previous section illustrates the incorporated RSS with route request mechanism.

B. Mobility scenario

A highway with 6 lanes, with three-lanes in each direction was considered for the experiments. The lane towards the divider is considered the fastest lane and the lane towards the pavement is assumed to be the slowest. Lanes are reserved for vehicles depending upon their speeds and directions. In real situations, the acceleration or deceleration of the vehicles depends much upon the vehicular driver. Other factors like road condition, over-bridges and intersections can be initially neglected for the sake of simplicity. Highway based studies indicate that a huge percentage of drivers (~75%) who like to accelerate beyond average velocity [2]. This also reflects in the used model.

The highway section has been considered here is of 5000 meters long. The width of each lane has been taken as 3.7 meters. A total of 300 vehicles were considered moving at any given point of time in the referred set of experiments. This was realized by maintaining on-road average density of the vehicles as 10 vehicles per lane per thousand meters. The speed of the vehicles was considered to follow a normal distribution pattern. The threshold value of robustness that can be set by an application has not been considered here and the selection criterion is based upon robustness values.

C. Simulation Setup

The purpose of simulation was served by OMNET++ which is an open-source, simulation package built on C++ foundations [24]. To enable the support for VANETs, INET Framework was used. The mobility model patterns were generated by Simulator for Urban Mobility (SUMO) [25], and fed to OMNET++ which handled the primary aspect of network simulation. Experiments were performed on a server class machine with 8-physical cores, i.e. Intel® Xeon® Processor E5-2609 using 64 GB RAM. 200 such runs were performed to calculate average of a chosen evaluation parameter. Simulation time for each run was 300 seconds. The communication range of all the vehicles was considered as 450 meter, which remained constant throughout the evaluation. At lower layers, support of 802.11p was provided. UDP packets, with transmission rate= 10 packets/second were used for sending data. For the sake of simplicity, although effects of noise and interference included in the devised model, were not considered in this simulation, in the current phase of work. Nakagami-m and lognormal shadowing were

considered with propagation model for setting up the effect of external environment and introduction of errors on wireless communication links.

D. Validation of the Proposed Model

Here, the hypothesis is that the path which is more robust would be able to relatively better cope-up with more errors (if introduced or present in the network) and links would stay valid for longer period of time. Consequently, in view of such increased link availability, the network should perform better. In order to validate this, the devised route selection strategy RSS was simulated in VANET's environment. In addition, parameters which affect the link quality (i.e. fading and velocity of the vehicles) were also duly considered and varied for being able to analyses the network performance. The logic here is that if the above hypothesis is correct, the proposed strategy should be able to exhibit desired improvement in the network performance under relevant conditions.

Table-2 shows the average Packet Delivery Ratio (PDR) with respect to Nakagami-m shape factor m . Also, without any loss of generality, $s = 4$ db and $\gamma = 3.4$ were set in this simulation. The entries in this table show the impact of small-scale fading on the proposed model as well as on AoDV and AoDV-R. Here, in this simulation, with m , severity of fading varies [26]. The average PDR should decrease with increase in m as can be seen from the results of AoDV and AoDV-R simulation. Average PDR drops drastically when $m \rightarrow 5$ in case of AoDV and AoDV-R. However, in case of the proposed model, D_c gets adjusted with m and consequently loss due error reduces and this, in turn, improves the PDR as compared to both the compared strategies. This proves the hypothesis correct and validates the proposed robustness model.

Table II. Packet Delivery Ratio against Nakagami-m Shape Factor "m"

Shape factor	Proposed Model	AoDV-R	AoDV
$m = 1$	0.70	0.67	0.63
$m = 2$	0.63	0.65	0.41
$m = 3$	0.62	0.54	0.44
$m = 4$	0.37	0.08	0.11
$m = 5$	0.24	0.07	0.07

Next, the proposed model has been validated against varying velocities of the vehicles in the network, which inherently affects the Link-Lifetime. It is, thus, one of the key components in the calculation of Link-Robustness. In the presented case, data size chosen was 500 bytes and varying average velocity from 22.22, 16.66 and 11.11 meters/second to 38.88, 33.33 and 27.22 meters/second were set to perform the simulation experiments. Without effecting any loss of generality, $m = 3$, $s = 4$ db and $\gamma = 3.4$ were set.

Figure-4 shows that proposed model leads to reasonably lesser link failure than AoDV and AoDV-R. In general, any increment in link failure with velocity is due to the fact that dynamism of network topology and link instability increases when velocity increases. However, in case of the proposed strategy presented here, it may be seen that the average link

failure is considerably lesser than other two strategies. This is because determination of the most robust link out of all relevant links leads to the selection of the most robust route and thus the proposed scheme is likely to cope-up fairly well even with link breakages occurring due to varying velocities of the vehicles. This means that probability of invocation of route maintenance and route discovery process decreases in case of the proposed scheme. Consequently, need for less route discovery translates into lesser overhead, lesser average end-to-end delay and improved *PDR* which is what is desirable in such networks. This, thus, validates the presented hypothesis and the corresponding model.

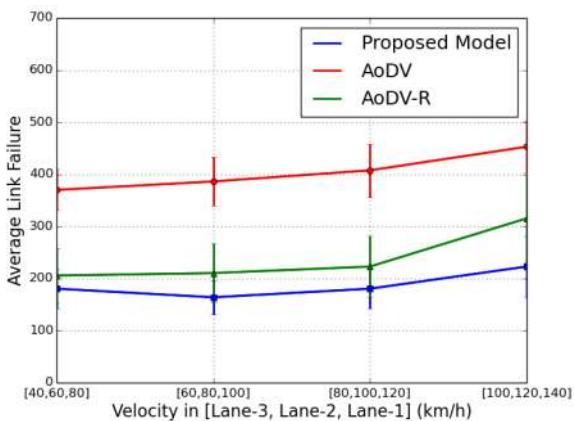


Figure 4. Average link failure for varying velocity

E. Experiments and Result Analysis

Evaluation of the proposed model was been carried out on the basis of various network parameters which were (a) number of link failures (b) Packet Delivery Ratio (PDR), (c) end-to-end delay and (d) overhead. In order to make results more reliable, average of 200 runs and confidence interval of 95% were computed as indicated in every result.

The purpose of this experiment was to analyse the effect of size of data on proposed model. Applications in VANETs may have variable length data to send. Average velocity of lanes are 22.22 (lane-1), 16.66 (lane-2) and 11.11(lane-3) meters/second respectively (see Figure-2). Simulations were performed with data size varying from 500 -3500 bytes.

In Figure-5, via simulation results it has been shown that the average number of link breakages in proposed model is lesser than that in case of AoDV and AoDV-R, even if the data size increases. The proposed scheme achieves up to 55% lesser link failures when compared with AoDV and 25% in comparison to AoDV-R. This can be explained by argument that AoDV is a hop-count based strategy which is more prone to link failures if topology of the network is moderately or highly dynamic. AoDV-R always counts on route which has better Link-Lifetime and maintains lower link failures than AoDV and does not consider the errors that occur due to the variation in environmental phenomenon. Because of this, in case of AoDV-R, link might fail even if source and destination vehicles are in range of each other.

Figure-6 shows that the proposed strategy achieves higher PDR over AoDV and AoDV-R for different data packet sizes.

Here, for larger data sizes multiple packets have been sent. Link failure during transmission of packets can cause retransmission of data and could lead to fresh route discovery process. This causes more overheads and decreases network performance. Importantly, it is required to use relatively more robust route to avoid such cases. Therefore, it can be stated that proposed model performs better than AoDV and AoDV-R in terms of PDR as it has lower probability of link breakages.

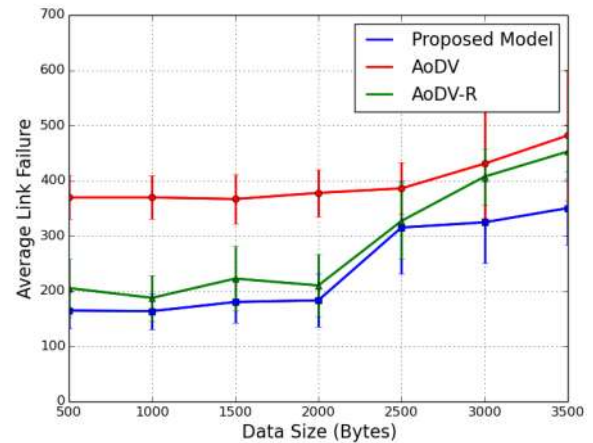


Figure 5. Average link failure for variable data size

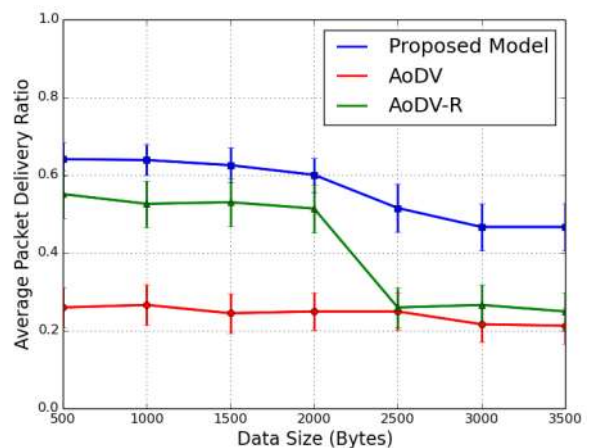


Figure 6. Average PDR for variable data size

In Figure-7, simulation result shows that proposed route selection strategy achieves significantly lower average end-to-end delay than AoDV and AoDV-R irrespective of varying data size. The route establishment in proposed scheme takes almost the same time as in AoDV-R but fractionally longer time than AoDV. The selected route is the most robust one and likely to be used for a longer period of time, with less chance of link failure during data transmission. On the other hand, AoDV has shortest path as a parameter of route selection without considering other parameters such as Link-Lifetime and probability of a link being error prone (i.e. robustness of the link). Thus, number retransmissions required in AoDV, leads to larger end-to-end delay. It can be, therefore, concluded that the proposed strategy performs better.

The average routing control overhead of the proposed scheme reaches close to that of AoDV as shown in Figure-8. A higher rate of link breakages in AoDV eventually leads to more retransmissions and more route error messages (RERR) to be triggered. Thus, additional route discovery is needed which increases overhead. On the other side, proposed strategy uses more information (bytes) in RREP and RREQ to establish the route, but has lesser link losses. Thus, effectively, the proposed scheme maintains reasonable and affordable overhead as compared to AoDV. It may be noted that AoDV-R and the proposed route selection strategy have same number of fields in RREQ and RREP messages. It does not make much sense, therefore, to compare these two strategies as far as related overheads are concerned.

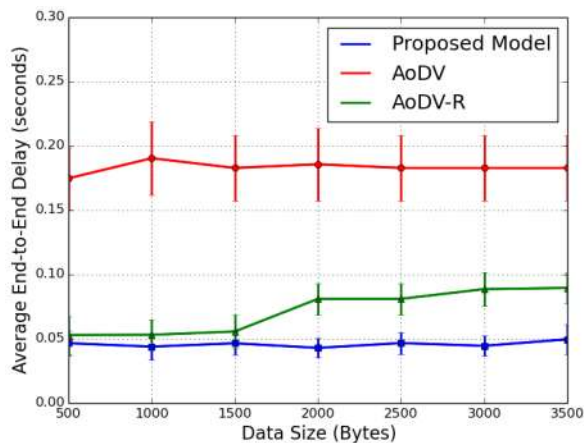


Figure 7. Average end-to-end delay for variable data size.

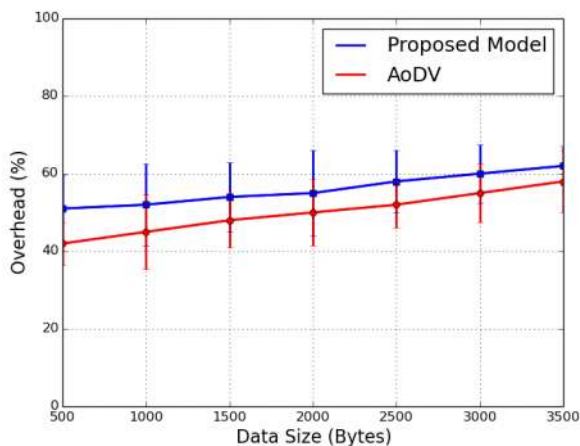


Figure 8. Average overhead (in %) for variable data size.

VI. CONCLUSION

ITS related self-organized mobile communication networks, like VANETs, must perform with relatively strict guarantee of performance since one or more safety-critical or mission-critical applications may have to run on top. It may be seen that the proposed model shall inherently suit such requirements. It may be seen that the proposed model is the first of its kind in terms of inclusion of Link-Robustness, Route-Robustness and consequent route selection strategy.

Moreover, it is unique and first in including spatial, temporal and environmental dependencies together for modeling robustness. Simulation result suggests an improvement in the range of 25-55% in case of average link failure depending upon the scenario, as compared to other strategies. Also, end-to-end delay drops down while the average PDR increases significantly on applying the proposed approach to VANETs both of which are significant. Improved value of network parameters indicates the suitability of this robustness model for VANETs. Based on this work, in the next phase, a routing protocol can be devised utilizing the concepts of Link-Robustness, Route-Robustness and route selection strategy. Thus the evolved protocol is expected to be adaptive as well as robust while being able to improve overall performance.

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