An Evolving Graph-Based Reliable Routing Scheme for VANETs

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***Abstract*—Vehicular ad hoc networks (VANETs) are a special form of wireless networks made by vehicles communicating among themselves on roads. The conventional routing protocols proposed for mobile ad hoc networks (MANETs) work poorly in VANETs. As communication links break more frequently in VANETs than in MANETs, the routing reliability of such highly dynamic networks needs to be paid special attention. To date, very little research has focused on the routing reliability of VANETs on highways. In this paper, we use the evolving graph theory to model the VANET communication graph on a highway. The extended evolving graph helps capture the evolving characteristics of the vehicular network topology and determines the reliable routes preemptively. This paper is the first to propose an evolving graph-based reliable routing scheme for VANETs to facilitate quality-of-service (QoS) support in the routing process. A new algorithm is developed to find the most reliable route in the VANET evolving graph from the source to the destination. We demonstrate, through the simulation results, that our proposed scheme significantly outperforms the related protocols in the literature.**

***Index Terms*—Evolving graph, quality of service (QoS), routing reliability, vehicular ad hoc network (VANET), vehicular networks.**

I. Introduction

Every day, a lot of people die, and many more are injured in traffic accidents around the world. The desire to disseminate road safety information among vehicles to prevent accidents and improve road safety was the main motivation behind the development of vehicular ad hoc networks (VANETs). VANETs are a promising technology to enable communications among vehicles on roads [1]. They are a special form of mobile ad hoc networks (MANETs) that provide vehicle-to-vehicle communications. It is assumed that each vehicle is equipped with a wireless communication facility to provide ad hoc network connectivity. VANETs tend to operate without an infrastructure; each vehicle in the network can send, receive, and relay messages to other vehicles in the network. This way, vehicles can exchange real-time information, and drivers can be informed about road traffic conditions and other travel-related information. VANETs have attractive and unique features, distinguishing them from other types of MANETs, such as normally higher transmission power, higher computational capability, and some kind of predictable mobility, in comparison with general MANETs [2]. The special behavior and characteristics of VANETs raise important technical challenges that should be considered to deploy these networks effectively. The most challenging issue is potentially the high mobility and the frequent changes of the network topology [3], [4]. In VANETs, the network topology could vary when the vehicles change their velocities and/or lanes. These changes depend on the drivers and road situations and are normally not scheduled in advance.

The graph theory can be utilized to help understand the topological properties of a VANET, where the vehicles and their communication links can be modeled as vertices and edges in the graph, respectively. Recently, a graph theoretical model called evolving graph [5], [6] has been proposed to help capture the dynamic behavior of dynamic networks when mobility patterns are predictable. This model has shown its promising results in MANETs and delay-tolerant networks [7], [8]. However, the current evolving graph theory can be only applied when the topology dynamics at different time intervals can be predicted; these are known as fixed scheduled dynamic networks (FSDNs). VANETs cannot be treated as FSDNs, and hence, the existing evolving graph theory cannot be directly applied to VANETs. Fortunately, the pattern of topology dynamics of VANETs can be estimated using the underlying road networks and the available vehicular information. Hence, we can categorize this type of dynamic network as a *predicted pattern dynamic network*. Consequently, the current evolving graph theory could be extended to deal with VANETs.

The objective of this paper is to propose a novel evolving graph-based reliable routing scheme for VANETs. The novelty of this work lies in its unique design of a reliable routing protocol that considers the topological properties of the VANET communication graph using the extended evolving graph. Considering that vehicles travel at high speeds on highways, the data delivery service could have many disruptions due to frequent link breakages. It is very important to ensure that the most reliable links are chosen when building a route. The major contributions of this paper are given here.

1) A new link reliability model based on the mathematical distribution of vehicular movements and velocities on the highway is developed.
2) The current evolving graph model is extended to capture the evolving features of the VANET communication graph, and the link reliability metric is considered.

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3) A reliable routing protocol is designed to benefit from the advantages of the extended evolving graph model to find the most reliable route without broadcasting the routing requests each time a new route is sought. This way, the routing overhead is significantly reduced, and the network resources are conserved.

In this paper, we assume that vehicles move at a constant velocity along the same direction on the highway and that the source vehicle has full knowledge of a VANET communication graph at any given time. Bidirectional traffic and variable vehicular velocities are left for future study.

The rest of this paper is organized as follows: Section II overviews the related work in this field. Section III presents our vehicular reliability model. Section IV illustrates the evolving graph theory and our proposed VANET-oriented evolving graph (VoEG) model. Section V presents our proposed reliable routing protocol, i.e., the evolving graph-reliable ad hoc on-demand distance vector (EG-RAODV). Section VI shows the simulation environments and performance metrics to be evaluated. Section VII discusses the different simulation results. Finally, Section VIII concludes this paper.

II. Related Works

To the best of our knowledge, there are no previous studies on the development of reliability-based routing using the evolving graph theory in VANETs on highways. The routing reliability and the use of the evolving graph theory were studied separately.

Routing reliability is addressed in the literature mainly on MANETs (e.g., [9] and [10]). For VANETs, Taleb *et al.* [11] proposed a scheme that uses the information on vehicle headings to predict a possible link breakage prior to its occurrence. Vehicles are grouped according to their velocity vectors. When a vehicle shifts to a different group and a route involving the vehicle is about to break, the proposed scheme searches for a more stable route that includes other vehicles from the same group.

In [12], a velocity-aided routing protocol is proposed that determines its packet-forwarding scheme based on the relative velocity between the forwarding node and the destination node. The region for packet forwarding is determined by predicting the future trajectory of the destination node based on its location information and velocity.

The authors in [13] introduced a prediction-based routing (PBR) protocol for VANETs. It is specifically designed for the mobile gateway scenario and takes advantage of the predictable mobility pattern of vehicles on highways. PBR predicts route lifetimes and preemptively creates new routes before the existing routes fail. The link lifetime is predicted based on the range of communication, vehicles' location, and corresponding velocities. Since a route is composed of one or more links, the route lifetime is the minimum of all its link lifetimes. PBR allows the processing of multiple routing requests to check all the available routes to the destination. If the source node receives multiple replies, then it uses the route that has the maximum predicted route lifetime.

In [14], a movement prediction-based routing (MOPR) algorithm is proposed. MOPR predicts the future position of a vehicle and searches for a stable route. If several potential routes between the source vehicle and the destination vehicle exist, MOPR chooses the route that is the most stable when considering the movement conditions of the intermediate nodes with respect to the source and destination nodes. This is done by using the location, direction, and velocity information of each vehicle. An extension for the routing table in each node is added to fulfill the requirements of this algorithm.

In the context of the evolving graph theory, some recent work has started to extend the evolving graph model to better understand the properties of dynamic networks such as MANETs and VANETs.

Monteiro [15] used the evolving graph model to design and evaluate least cost routing protocols for MANETs with known connectivity patterns. The *NS2* network simulator is used to first implement an evolving graph-based routing protocol, and then, it is used to provide a benchmark when comparing four major ad hoc routing protocols. Monteiro showed that an evolving graph-based routing protocol is well suited for networks with known connectivity patterns and that the model, as a whole, may be a powerful tool for the development of routing protocols.

The objective of [16] focuses on providing a thorough study of the topological characteristics and statistical features of a VANET communication graph. Specifically, answers are provided for some critical questions such as the following: How do VANET graphs evolve over time and space? What is the spatial distribution of these nodes? Which are the critical link duration statistics in a VANET when the vehicles move in urban areas? How robust is a VANET? The obtained results could have a wide range of implications for the development of high-performance, reliable, scalable, secure, and privacy-preserving vehicular technologies.

In summary, no direct work has been done to design an evolving graph-based reliable routing scheme for VANETs on highways, which is the subject of this paper.

III. Vehicular Reliability Model

On highways, where vehicles travel at high speeds, it is a complicated task to develop a reliable routing scheme for VANETs because it is influenced by many factors. The vehicular mobility pattern and the vehicular traffic distribution are examples of factors that affect the reliable routing process [17]. To define the vehicular reliability model precisely, we need to determine the mobility model and the vehicular traffic characteristics. The understanding of the vehicular traffic flow characteristics can help predict the time duration of a reliable communication between two vehicles.

A. Basis of Vehicular Traffic Flow Models

There are two major approaches to describe the spatiotemporal propagation of vehicular traffic flows [18], namely, macroscopic and microscopic traffic flow models. The macroscopic approach pictures the traffic flow as a physical flow of a continuous fluid. It describes the traffic dynamics in terms of aggregated macroscopic quantities such as traffic density $p(x, t)$, traffic flow $q(x, t)$, and average velocity $v(x, t)$ as a function of space x and time t corresponding to partial differential equations. These parameters can be related together by their average values using the following relations [19]:

$$d_m = \frac{1000}{\rho_{\text{veh}}} - l_m \tag{1}$$

$$\tau_m = \frac{d_m}{v_m} = \frac{1}{v_m}\left(\frac{1000}{\rho_{\text{veh}}} - l_m\right) \tag{2}$$

$$q_m = \frac{1}{\tau_m} = v_m\left(\frac{1}{\frac{1000}{\rho_{\text{veh}}} - l_m}\right) \tag{3}$$

where d_m is the average distance between vehicles (in meters), ρ_{veh} is the traffic density on the freeway section considered (in vehicles per kilometer), l_m is the average length of vehicles (in meters), τ_m is the average time gap between vehicles (in seconds), v_m is the average velocity of vehicles on the road (in kilometers per hour), and q_m is the average traffic flow (in vehicles per hour). On the other hand, the microscopic approach describes the motion of each individual vehicle. It models actions such as accelerations, decelerations, and lane changes of each vehicle as a response to the surrounding traffic. It is known that the macroscopic approach can be used to describe both general traffic flow status and individual vehicles [20]. Hence, we use the macroscopic traffic flow model to describe the vehicular traffic flow and utilize the average velocity to consider the mathematical distribution of vehicular movements over the traffic network.

In the following, we utilize the velocity of vehicles' parameter from the macroscopic viewpoint to develop our *link reliability* model. We consider the velocity distribution over the vehicular traffic flow to determine the network connectivity status. The velocity of vehicles is the main parameter that determines the network topology dynamics. It also plays an important role in determining the expected communication duration between two vehicles.

B. Link Reliability Model

Definition: Link reliability is defined as the probability that a direct communication link between two vehicles will stay continuously available over a specified time period. Given a prediction interval T_p for the continuous availability of a specific link l between two vehicles at t, the link reliability value $r(l)$ is defined as follows:

$$r(l) = P\{\text{To continue to be available until } t + T_p \mid \text{available at } t\}.$$

To calculate the link reliability, we utilize the vehicle's velocity parameter. It is assumed that the velocity of vehicles has a *normal distribution* [21], [22]. Based on this assumption, let $g(v)$ be the probability density function of the velocity of vehicle v and $G(v)$ be the corresponding probability distribution function; then

$$g(v) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(v-\mu)^2}{2\sigma^2}} \tag{4}$$

$$G(v \le V_0) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^{V_0} e^{-\frac{(v-\mu)^2}{2\sigma^2}} dv \tag{5}$$

where μ and σ^2 denote the average value and the variance of velocity, respectively [23]. The distance d between two vehicles can be calculated using the relative velocity Δv and the time duration T, i.e., $d = \Delta v \times T$, where $\Delta v = |v_2 - v_1|$. Since v_2 and v_1 are normally distributed random variables, Δv is also a normally distributed variable, and we can write $\Delta v = d/T$. Let H denote the radio communication range of each vehicle. The maximum distance where a communication between any two vehicles remains possible can be determined as $2H$, i.e., when the relative distance between the two vehicles changes from $-H$ to $+H$. Let $f(T)$ denote the probability density function of the communication duration T. We can calculate $f(T)$ as follows:

$$f(T) = \frac{4H}{\sigma_{\Delta v}\sqrt{2\pi}} \frac{1}{T^2} e^{-\frac{\left(\frac{2H}{T} - \mu_{\Delta v}\right)^2}{2\sigma_{\Delta v}^2}} \qquad \text{for } T \ge 0 \tag{6}$$

where $\mu_{\Delta v}$ and $\sigma_{\Delta v}^2$ denote the average value and the variance of relative velocity Δv, respectively. We suppose that each vehicle is equipped with a Global Positioning System device to give the location, velocity, and direction information. T_p is defined as the continuous availability of a specific link l between two vehicles i and j. It can be determined as

$$T_p = \frac{H - L_{ij}}{v_{ij}} = \frac{H - \sqrt{(y_i - y_j)^2 + (x_i - x_j)^2}}{|v_i - v_j|} \tag{7}$$

where L_{ij} is the Euclidean distance between vehicles i and j, and v_{ij} is the relative velocity between vehicles i and j. We can integrate $f(T)$ in (6) from t to $t + T_p$ to obtain the probability that, at time t, the link will be available for a duration T_p. Thus, the link reliability value $r_t(l)$ at time t is calculated as follows:

$$r_t(l) = \begin{cases} \int_t^{t+T_p} f(T)dT, & \text{if } T_p > 0 \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

The integral in (8) can be derived using the Gauss error function Erf [24]. It can be obtained as

$$r_t(l) = \text{Erf}\left[\frac{\left(\frac{2H}{t} - \mu_{\Delta v}\right)}{\sigma_{\Delta v}\sqrt{2}}\right] - \text{Erf}\left[\frac{\left(\frac{2H}{t+T_p} - \mu_{\Delta v}\right)}{\sigma_{\Delta v}\sqrt{2}}\right] \qquad \text{when } T_p > 0 \tag{9}$$

where Erf is defined as follows:

$$\text{Erf}(\tau) = \frac{2}{\sqrt{\pi}} \int_0^{\tau} e^{-t^2} dt, \qquad -\infty < \tau < +\infty. \tag{10}$$

C. Route Reliability Definition

In VANETs, multiple potential routes could exist between the source vehicle s_r and the destination vehicle d_e, where each route is a set of links between the source and the destination. Without loss of generality, for any given route, let us denote the number of its formed links by $k:\ l_1 = (s_r, n_1), l_2 = (n_1, n_2), \ldots, l_k = (n_k, d_e)$. For each link $l_w\ (w = 1, 2, \ldots k)$, we denote by $r_t(l_w)$ the link reliability value as defined in (8). The route reliability for a route P, which is denoted by $R(P(s_r, d_e))$, is defined as follows:

$$R\left(P(s_r, d_e)\right) = \prod_{w=1}^{k} r_t(l_w), \qquad \text{where } l_w \in P(s_r, d_e) \quad (11)$$

i.e., the route reliability is defined as the multiplicative product of reliability values across the formed links of this route. Suppose that there are z potential multiple routes from the source s_r to the destination d_e. If $M(s_r, d_e) = \{P_1, P_2, \ldots, P_z\}$ is the set of all those possible routes, then the optimal route will be chosen at the source node based on the following criteria:

$$\arg\max_{P \in M(s_r, d_e)} R(P) \quad (12)$$

i.e., if multiple routes are available, then we choose the most reliable route.

IV. VANET-Oriented Evolving Graph Model

A. Motivation

The current evolving graph theory cannot be directly applied to VANETs. We mentioned before that the evolving topological properties of the VANET communication graph are not scheduled in advance. Moreover, the current evolving graph model cannot consider the reliability of communication links among nodes. To fulfill VANETs' requirements, we extend the current evolving graph model. The extended version of the evolving graph model, called VoEG, is evolving based on the predicted dynamic patterns of vehicular traffic. These patterns are predicted based on the underlying road network and vehicular information. In addition, VoEG considers the reliability of communication links among vehicles. In the following, we briefly introduce the basis of the evolving graph theory and then extend the current evolving graph model to propose the VoEG model.

B. Basis of the Evolving Graph Theoretical Model

The evolving graph theory [25] is proposed as a formal abstraction for dynamic networks. The evolving graph is an indexed sequence of λ subgraphs of a given graph, where the subgraph at a given index corresponds to the network connectivity at the time interval indicated by the index number, as shown in Fig. 1.

It can be observed from Fig. 1 that edges are labeled with corresponding presence time intervals. Note that $\{A, D, C\}$ is not a valid journey since edge $\{D, C\}$ exists only in the past

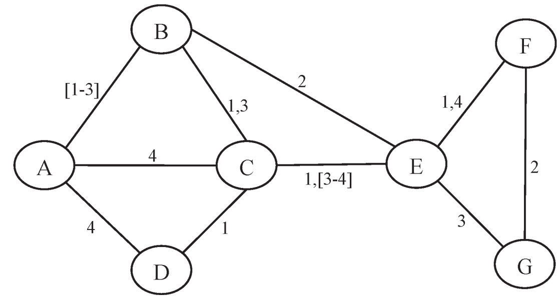

Fig. 1. Basic evolving graph model [15].

with respect to edge $\{A, D\}$. Thus, the journey in the evolving graph is the route in the underlying graph where its edge time labels are in increasing order. In Fig. 1, it is easy to find that $\{A, B, E, G\}$ and $\{D, C, E, G\}$ are valid journeys, whereas $\{D, C, E, G, F\}$ is not.

Let $G(V, E)$ be a given graph and an ordered sequence of its subgraphs, i.e., $S_G = G_1(V_1, E_1), G_2(V_2, E_2), G_3(V_3, E_3) \ldots, G_\lambda(V_\lambda, E_\lambda)$, such that $\cup_{i=l}^{\lambda} G_i = G$. The evolving graph is defined as $\mathcal{G} = (S_G, G)$, where the vertices set of $\mathcal{G}$ is $V_{\mathcal{G}} = \cup V_i$, and the edges set of $\mathcal{G}$ is $E_{\mathcal{G}} = \cup E_i$. Suppose that the subgraph $G_i(V_i, E_i)$ at a given index i is the underlying graph of the network during time interval $\mathcal{T} = [t_{i-1}, t_i]$, where $t_0 < t_1 < \cdots < t_\tau$, the time-domain $\check{T}$ is now incorporated into the model.

Let Ω be a given route in the evolving graph $\mathcal{G}$, where $\Omega = e_1, e_2, e_3, \ldots, e_k$ with $e_i \in E_{\mathcal{G}}$ in G. Let $\Omega_\sigma = \sigma_1, \sigma_2, \sigma_3, \ldots, \sigma_k$ with $\sigma_i \in \check{T}$ be the time schedule indicating when each edge of the route Ω is to be traversed. We define a journey $J = (\Omega, \Omega_\sigma)$ if and only if Ω_σ is in accordance with Ω, $\mathcal{G}$, and $\mathcal{T}$. This means that J allows the traverse from node u to node v in $\mathcal{G}$. Note that journeys cannot go back to the past.

In the current evolving graph theory, three *journey metrics* are defined [15]: the *foremost*, *shortest*, and *fastest* journey. They are introduced to find the earliest arrival date, the minimum number of hops, and the minimum delay (time span) route, respectively. Let $J = (\Omega, \Omega_\sigma)$ be a given journey in $\mathcal{G}$, where $\Omega = e_1, e_2, e_3, \ldots, e_k$, and $\Omega_\sigma = \sigma_1, \sigma_2, \sigma_3, \ldots, \sigma_k$.

1) The hop count $h(J)$ or the length of J is defined as $h(J) = |\Omega| = k$.
2) The arrival date of the journey $a(J)$ is defined as the scheduled time for the traversal of the last edge in J, plus its traversal time, i.e., $a(J) = \sigma_k + \check{t}(e_k)$.
3) The journey time $t(J)$ is defined as the past time between the departure and the arrival, i.e., $t(J) = a(J) - \sigma_1$.

C. VoEG

We propose the VoEG model to address the evolving properties of the VANET communication graph and consider the reliability of communications links among vehicles. Fig. 2 shows an example of the VoEG on a highway at two time instants: $t = 0$ s and $t = 5$ s. Each node in Fig. 2 shows a vehicle on the highway. Different from the corresponding presence time intervals for each edge (link) used in the conventional evolving graph, we associate the following 2-tuple $(t, r_t(e))$ with each edge, where t denotes the current time, and $r_t(e) = r_t(l)$

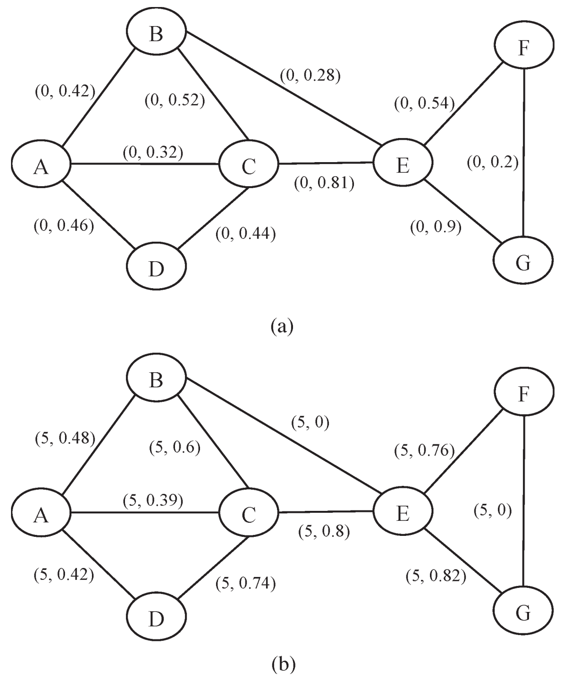

Fig. 2. Proposed VoEG model at (a) $t = 0$ s and (b) $t = 5$ s.

denotes the link reliability value at this time t, as defined in (8) in Section III.

In the VoEG model, the communication link between two vehicles is not available if its reliability value $r_t(e)$ is equal to zero. Unlike the conventional evolving graph, the presence time of the link in the VoEG model is continuous and depends on the current vehicular traffic status. In this case, there is no need to check the order of the presence times of the link when searching for a valid journey. Let $e = \{A, B\}$ be a link in the VoEG, where V_{VoEG} is the set of vertices and E_{VoEG} is the set of links. Let Trav(e) be a function that determines whether this link e can be traversed or not, i.e.,

$$\text{Trav}(e) = \begin{cases} \text{True}, & \text{if } 0 < r_t(e) \leq 1 \\ \text{False}, & r_t(e) = 0. \end{cases} \tag{13}$$

Fig. 2(a) shows the VoEG status and the corresponding reliability values associated to each link at $t = 0$ s. All links are eligible to be traversed because $\forall e \in E_{\text{VoEG}}$, Trav$(e) =$ true. However, if the link e is eligible to be traversed, it does not necessarily mean that it will be chosen to be part of the optimal journey. The optimal (*most reliable*) journey will be discussed later in Section V. Fig. 2(b) shows the VoEG status at $t = 5$ s, where the associated links' reliability values change due to the evolution of the VoEG. It can be noticed that edges $\{B, E\}$ and $\{F, G\}$ are now not eligible to be traversed, i.e., Trav$(\{B, E\}) =$ Trav$(\{F, G\}) =$ false at $t = 5$ s, where $r_5(\{B, E\}) = r_5(\{F, G\}) = 0$.

Furthermore, we introduce a new metric called *journey reliability* to our VoEG model to specifically address the routing dynamics of VANETs. Our objective is to find the most reliable journey (MRJ) instead of using the conventional approaches of finding the foremost, shortest, or fastest journey. The MRJ has the highest journey reliability value among all possible journeys from the source to the destination. The new journey reliability metric is defined based on (11). Let k be the number of edges that constitute a valid journey $J(u, v)$ between u and v in $\tilde{G}$, and let $r_t(e_w)$ be the reliability value of the edge e_w at time t, where $J = (\Omega, \Omega_\sigma)$ and $w = (1, 2, \ldots, k)$. The journey reliability, which is denoted by $R(J(u, v))$, is defined as follows:

$$R\left(J(u, v)\right) = \prod_{w=1}^{k} r_t(e_w), \qquad \text{where } e_w \in J(u, v) \tag{14}$$

i.e., the journey reliability value is equal to the product of reliability values of all its formed links, where

$$0 \leq R\left(J(u, v)\right) \leq 1. \tag{15}$$

Suppose that there are z potential multiple journeys from u to v. If $MJ(u, v) = \{J_1, J_2, \ldots, J_z\}$ is a set of all those possible journeys, then the MRJ will be chosen based on the following criteria at the destination vehicle:

$$\arg\max_{J \in MJ(u,v)} R(J) \tag{16}$$

i.e., we will choose the MRJ among all possible journeys from u to v.

V. Evolving Graph Reliable Ad Hoc On-Demand Distance Vector Routing Protocol

In the previous section, we proposed VoEG to model and formalize the VANET communication graph. For the purpose of routing data packets reliably in VANETs, we design a new routing protocol that can benefit from the VoEG advantages and properties. The new routing protocol utilizes the VoEG model and considers the routing reliability constraint while searching for the route from the source to the destination. A new routing algorithm to find the MRJ is needed first. Then, this algorithm will be applied to design the route discovery process for our proposed EG-RAODV routing protocol. Note that AODV stands for the Ad hoc On-Demand Distance Vector routing protocol [26].

A. Prediction Algorithm

To predict the location of vehicles at time t, we need to apply a *mobility model*. In this paper, we assume that vehicles travel at a constant velocity v_0 along the same direction α_0 on the highway. This assumption is reasonable in constrained topologies with similar traffic flows such as city streets and highway topologies [12]. Based on this assumption, each vehicle i is defined with the following parameters: current Cartesian position at $t : x_i(t)$ and $y_i(t)$, current velocity $v_i(t) = v_0$, and direction of movement $\alpha_i(t) = \alpha_0$. The following relations describe the mobility model using the city section mobility (CSM) model introduced by [27]

$$\Delta x_{i,j} = v_0 \times \Delta t \times \cos \alpha_0 \tag{17}$$

$$\Delta y_{i,j} = v_0 \times \Delta t \times \sin \alpha_0 \tag{18}$$

where $\Delta x_{i,j}$ and $\Delta y_{i,j}$ are the travelling distances along the x and y directions during $\Delta t = (t_j - t_i)$.

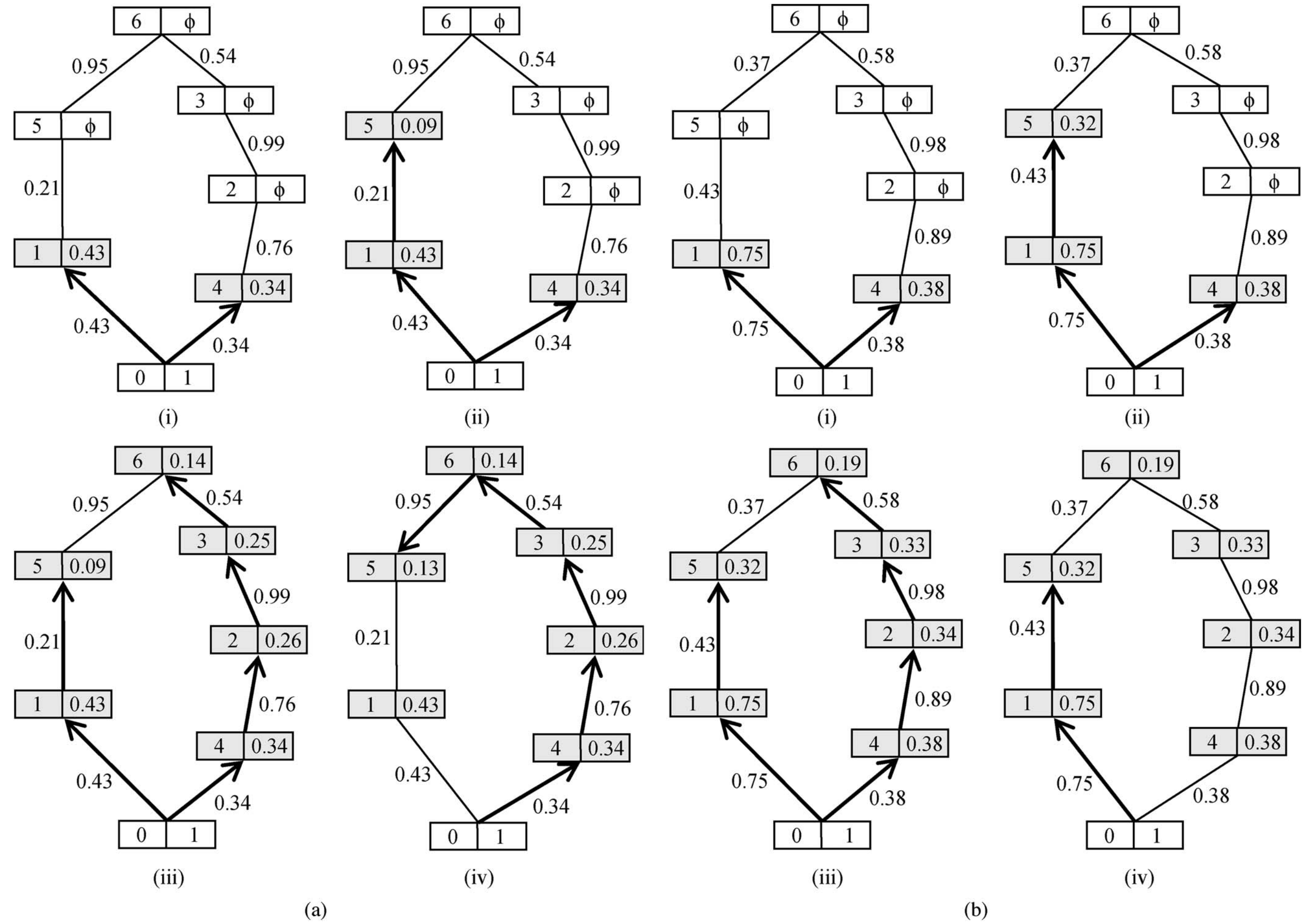

Fig. 3. EG-Dijkstra algorithm example on VoEG when (a) $t = 0$ s and (b) $t = 5$ s.

B. EG-Dijkstra

Finding the most reliable route in the VoEG model is equivalent to finding the MRJ. The normal *Dijkstra* algorithm [28] cannot be directly applied in this context. We modify it and propose the evolving graph Dijkstra's algorithm (EG-Dijkstra) to find the MRJ based on the journey reliability definitions in (14) and (16).

The proposed EG-Dijkstra algorithm maintains an array called the *reliable graph* (RG) that contains all vehicles and their corresponding MRJ values. EG-Dijkstra starts by initializing the journey reliability value $\mathrm{RG}(s_r) = 1$ for the source vehicle and $\mathrm{RG}(u) = \phi$ for other vehicles. Then for all unvisited vehicles from the source, it finds the journey reliability value based on (14) and (16). When all neighbors of the current vehicle have been considered, it will be marked as visited, and its journey reliability value is marked as final. In the following, a pseudocode for the EG-Dijkstra algorithm is provided.

Input: *A VoEG and a source vehicle* s_r.
Output: *Array RG that gives the most reliable routes from* s_r *to all other vehicles.*
Variables: *A set* Q *of unvisited vehicles.*
1. Set route reliability $\mathrm{RG}(s_r) = 1$ and $\mathrm{RG}(u) = \phi$ *for all other vehicles;*
2. Initialize array Q *by inserting* s_r;
3. While Q *is not empty do*
(a) $x \leftarrow$ *the vehicle with the highest reliability value in* Q;
(b) Mark x *as visited vehicle*;
(c) For each open neighbor v *of* x *do*
i. if $\mathrm{Trav}(e)$ *is True*
  1. Set $\mathrm{RG}(v) \leftarrow r_t(e) \times \mathrm{RG}(x)$;
  2. Insert v *if not visited in* Q;
(e) Close x;
4. Return the array RG;

Fig. 3 shows a simple example of the EG-Dijkstra algorithm with a simple VoEG at two different time instances: $t = 0$ s and $t = 5$ s. In this example, the source vehicle s_r is node 0, and the destination vehicle d_e is node 5. For ease of illustration, we do not use the 2-tuple notation on the links. Instead, we put the link reliability value only. Each vehicle holds its ID and its $\mathrm{RG}(\mathrm{ID})$ value.

At $t = 0$ s, the prediction algorithm determines the current locations of vehicles. Then, the links' reliability values are calculated based on our definition in (8). EG-Dijkstra discovers vehicles 1 and 4 and assigns the MRJ value, depending on (14), as shown in Fig. 3(a) (i). Then, it chooses the greatest reliability value and continues to discover vehicle 5. It assigns

0.09 as the MRJ value based on (16). Although vehicle 5 is the destination, the algorithm will not stop at this stage, as shown in Fig. 3(a) (ii), because it has to check all possible journeys. In Fig. 3(a) (iii), the algorithm continues to discover vehicles 2, 3, and 6 and assigns the MRJ value for each vehicle. At the end, it arrives at vehicle 5 again from a different journey, but it is more reliable. Thus, the final reliability value will be 0.13, and the MRJ from vehicle 0 to vehicle 5 at $t = 0$ s is $0 \rightarrow 4 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 5$.

Similar to above, Fig. 3(b) shows the same process at $t = 5$ s. It can be noticed from Fig. 3(b) (iv) that the MRJ now is changed to be $0 \rightarrow 1 \rightarrow 5$, and its reliability value is 0.32 instead of 0.13 at $t = 0$ s.

C. Computational Complexity of the EG-Dijkstra Algorithm

The computational complexity of the EG-Dijkstra algorithm is similar to the normal Dijkstra algorithm. Let the number of vertices be $|V|$ and the number of edges be $|E|$. The while loop at step indexed 3 in the EG-Dijkstra algorithm is executed $|V|$ times. In step 3(a), we extract the vertex with the highest reliability value in Q; thus, each vertex will be added exactly once to Q and deleted only once from Q. This task in step 3(a) takes $O(|V|)$ in the worst case. However, if Q is implemented as a heap, then the computational complexity to extract the vehicle with the highest reliability value at step 3(a) will be $O(\log |V|)$. The edge relaxation process and updating reliability values in the RG array takes $O(|E| + |V|)$. We assume that EG-Dijkstra's algorithm is proposed to work in the VANET communication graph on highways, i.e., a sparse graph. Thus, we can conclude that the total computational complexity of the EG-Dijkstra algorithm is $O((|E| + |V|) \log |V|)$.

As the computational complexity of EG-Dijkstra's algorithm is similar to the Dijkstra algorithm, we can say that EG-Dijkstra's algorithm is a polynomial-time algorithm solving the most reliable route problem [29]. In the worst case, when more vehicles enter the highway, i.e., the sparseness of VoEG decreases, the computational complexity will be $O(|V|^2 \log |V|)$. However, it is noted that the number of vehicles that can enter the highway is controlled by the highway capacity. The adjacency lists in the source vehicle, where VoEG is represented, do not grow quickly. Hence, the computational complexity of the algorithm does not increase much. Nonetheless, if more vehicles enter the highway, it is suggested to apply some clustering techniques (e.g., [16] and [30]) to keep the computational complexity reasonable.

D. Route Discovery Process in EG-RAODV

It is assumed that the source vehicle has information on the current status of VoEG. When the source vehicle has data to send at time t, it calculates the reliability value for each link in the current VoEG. Then, the EG-Dijkstra algorithm finds the MRJ from the source vehicle to the destination vehicle. At this stage, the source vehicle knows the most reliable valid journey to the destination. It will create a routing request message (RREQ) and assign the hops of the MRJ as extensions to this RREQ. Note that this extension field in the RREQ is not used in the traditional ad hoc routing protocols and was left for future use. In EG-RAODV, by utilizing the extension information in the RREQ, intermediate nodes are able to forward the routing request to the next hop without broadcasting.

At each vehicle along the route, when an RREQ is received, the information about from which vehicle it heard is recorded. Then, the RREQ will be forwarded to the next hop based on the extension's information. Intermediate vehicles are not allowed to send a routing reply message (RREP) to the source vehicle, even if they have a valid route to the destination. Since the time domain is incorporated in the routing process and the mobility of nodes is highly dynamic, the reliability values at intermediate vehicles might be outdated. When the RREQ arrives at the destination vehicle, an RREP will be sent back to the source vehicle to start data transfer. In the following, a pseudocode of the EG-RAODV route discovery process is illustrated.

Input: *A VoEG and a source vehicle s_r and a destination vehicle d_e.*
Output: *The MRJ from s_r to d_e.*
1. Get VoEG current status using the prediction algorithm;
2. *Calculate the reliability value for all links in VoEG based on* (8);
3. MRJ $\leftarrow$ EG-Dijkstra(VoEG, s_r);
4. While the MRJ is not empty
(a) $x \leftarrow$ *the first node from the MRJ;*
(b) *Record x in the RREQ header as extension*;
(c) Remove x from the MRJ;
4. Send an RREQ from s_r to d_e along the MRJ;
5. While an RREP is not received, wait;
6. Start sending data;

It is noted that EG-RAODV works on a *hybrid reactive* and *proactive* basis. The reactive feature in EG-RAODV means that the route will be sought on demand. On the other hand, it finds the route to the destination vehicle based on the VoEG information before sending any routing request, i.e., proactively. By eliminating the broadcast of routing requests, EG-RAODV is expected to significantly save the network resources. In addition to that, EG-RAODV does not use the *HELLO* messages technique to check the status of links because the whole VoEG is predicted in advance in the source vehicle. In terms of route maintenance, EG-RAODV uses the same mechanism used in AODV, where routing error messages (RERRs) are issued when a link breakage occurs to start a new route discovery process.

VI. Performance Evaluation Settings

The main objective of this performance evaluation is to identify the impact of the high dynamic topology on the routing process performance. In addition to that, we want to check the benefits of using the proposed VoEG model in the highway scenario with different data packet sizes and data rates. We construct our performance evaluation using the OMNet++ network simulator [31]. OMNet++ is an extensible modular component-based C++ simulation library and framework. For each simulation experiment, we perform ten runs to obtain its average results. The simulation results are compared between AODV,

TABLE I
VELOCITY DISTRIBUTIONS

μ [km/h]	*V [km/h]*	*σ [km/h]*
30	*≈ 40*	*9*
50	*65*	*215*
70	*≈ 90*	*21*
90	*≈ 120*	*27*
110	*≈ 145*	*33*
130	*≈ 170*	*39*
150	*195*	*45*

optimized link-state routing (OLSR) [32], PBR protocol, and our EG-RADOV routing protocol.

A. Simulation Environment

We constructed a simulation scenario that uses a 5000-m-long highway with three lanes for vehicles to move. The number of vehicles is 30 (*low traffic density*). Only one direction for vehicle motion is considered. When vehicles reach the end of the highway, they will exit the simulation area. The average velocity of vehicles for each lane is 40, 60, and 80 km/h, respectively. Three simulation experiments will be performed.

1) *Experiment A:* We change the transmission data rate from 32 to 512 kb/s. The data packet size is 1500 bytes. Here, the average velocity of vehicles will stay constant in the three lanes: 40, 60, and 80 km/h, respectively.
2) *Experiment B:* We change the data packet size from 500 to 3000 bytes. The transmission data rate is 128 kb/s. Here, the average velocity of vehicles will stay constant in the three lanes: 40, 60, and 80 km/h, respectively.
3) *Experiment C:* We change the average velocity of vehicles in the third lane only: from 60 to 120 km/h. The data packet size is 1500 bytes. The transmission data rate is 128 kb/s.

The vehicular velocities in each lane follow the normal distribution. We use the typical values of velocity distributions calculated in Table I.

B. Performance Metrics

Five performance metrics will be considered for the simulation experiments.

1) *Packet delivery ratio (PDR):* It represents the average ratio of all successfully received data packets at the destination node over all data packets generated by the application layer at the source node.
2) *Link failures:* It represents the average number of link failures during the routing process. This metric shows the efficiency of the routing protocol in avoiding link failures.
3) *Routing requests ratio:* It expresses the ratio of the total transmitted routing requests to the total successfully received routing packets at the destination vehicle.
4) *Average end-to-end (E2E) delay:* It represents the average time between the sending and receiving times for packets received.

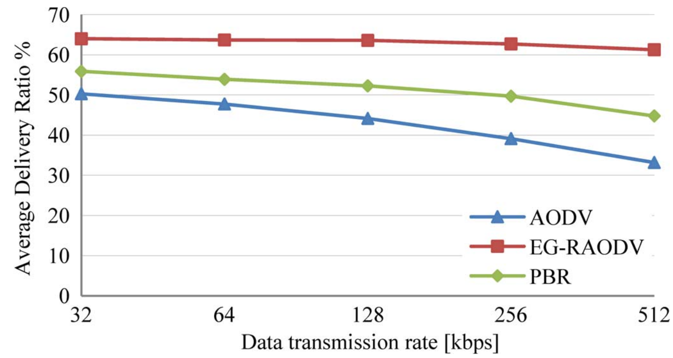

Fig. 4. Experiment A: Average PDR.

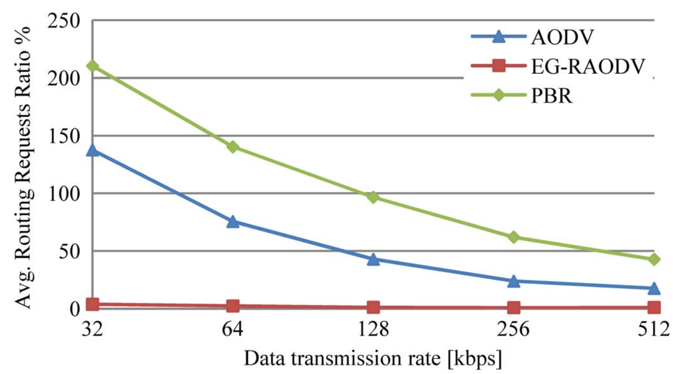

Fig. 5. Experiment A: Average routing requests ratio.

5) *Route lifetime*: It represents the average lifetime of the discovered route. A longer lifetime means a more stable and more reliable route. This metric is used in Experiment C only.

VII. SIMULATION RESULTS

A. Effect of Different Data Rates on the Routing Performance

Fig. 4 shows that our proposed EG-RAODV achieves a higher PDR than both PBR and AODV. It is also shown that EG-RAODV obtains a stable PDR performance, whereas the PDR performance of PBR and AODV degrades when the data transmission rate increases. This advantage comes from the fact that EG-RAODV chooses the most reliable route by utilizing the extended evolving graph model. Unlike PBR and AODV, a no-routing-requests broadcast is needed in EG-RAODV. This saves network bandwidth resource and contributes to a higher data delivery ratio.

Fig. 5 shows that the average routing requests ratio of EG-RAODV is much smaller than that of both PBR and AODV. This is due to fact that EG-RAODV proactively finds the most reliable route using VoEG and directs RREQs based on the chosen route. On the other hand, AODV and PBR keep broadcasting RREQs until they find the destination vehicle. It is noticed that PBR causes the highest average routing requests ratio because it has to process multiple RREQs to find a route with its maximum predicted route lifetime to the destination.

As shown in Fig. 6, the average number of link failures of the EG-RAODV protocol is lower than that of both AODV and PBR. AODV chooses the shortest route, regardless of whether

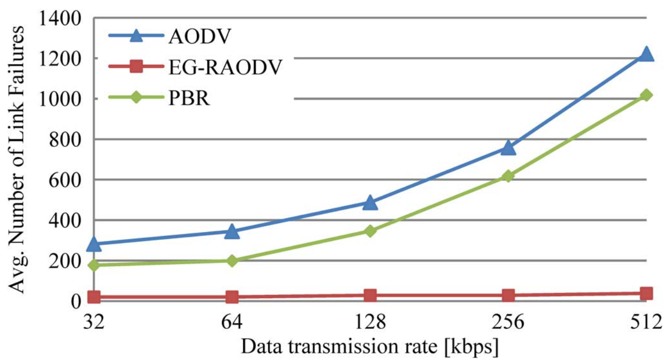

Fig. 6. Experiment A: Average number of link failures.

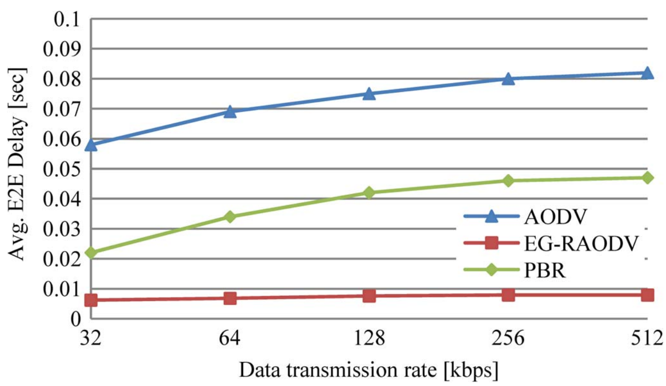

Fig. 7. Experiment A: Average E2E delay.

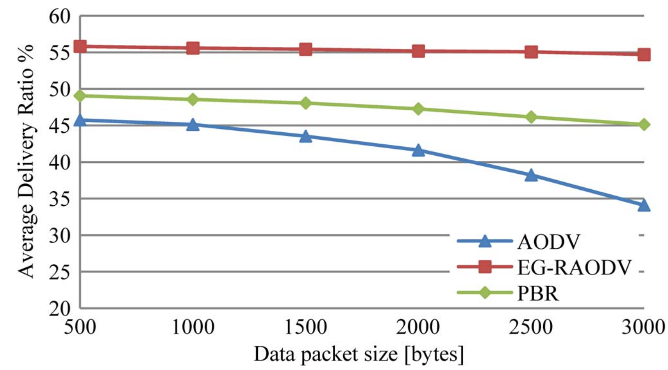

Fig. 8. Experiment B: Average PDR.

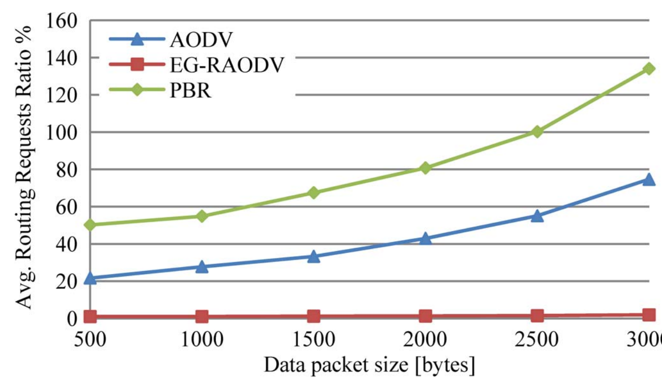

Fig. 9. Experiment B: Average routing requests ratio.

it is reliable or not. PBR outperforms AODV in terms of link failures because it predicts the link lifetime and creates a new alternative route before a link breakage. Note that with all different data transmission rates, EG-RAODV performs the best. In particular, the gain becomes higher when the data rate increases because more packets are generated to be sent and more link failures occur with AODV and PBR.

Another important advantage of EG-RAODV is its much lower average E2E delay performance in comparison with both AODV and PBR, as shown in Fig. 7. The lowest delay achievement of EG-RAODV comes from the proactive principle it uses when a new route is sought. As it holds the information about the whole VoEG, EG-RAODV can easily predict the current locations of other vehicles and find the most reliable route without broadcasting control messages. On the other hand, AODV causes the highest delay values among the three schemes because it uses a pure reactive approach to find a new route. PBR obtains a lower delay value than AODV since it checks all possible routes to find a stable route to reduce some link breakages.

B. Effect of Different Data Packet Sizes on the Routing Performance

In Fig. 8, we can see that EG-RAODV always achieves the highest and stable PDR performance over different data packet sizes. Note that large packets may be fragmented. Any link breakage during the delivery process of a fragment of a packet can cause the failure of the whole data packet delivery. If the delivery fails, then a new route discovery process is needed. PBR performs better than AODV again because it searches for all possible routes to the destination and chooses the route with the maximum predicted route lifetime.

Once again, in Fig. 9, the average routing requests ratio of PBR is higher than that of both AODV and EG-RAODV. With the increase of the size of data packets, the number of fragments increases. More routing requests are generated for the route discovery processes due to higher delivery failures caused by additional fragments. This explains why the average routing requests ratio increases with AODV and PBR. Fortunately, EG-RAODV is not affected by this issue because the most reliable route is discovered using the VoEG information.

In Fig. 10, the average number of link failures in AODV is confirmed to be the highest, which explains its lowest PDR in Fig. 8. EG-RAODV obtains the lowest and stable number of link failures because it chooses the most reliable route. PBR is designed to choose a route with its maximum predicted route lifetime; thus, it outperforms AODV. However, the simple link lifetime prediction algorithm in PBR is unable to find the most reliable route, and hence, it causes more link failures than EG-RAODV.

In this experiment, EG-RAODV also achieves a lower average E2E delay value than AODV and PBR, as shown in Fig. 11. The delay performance of EG-RAODV is not affected by varying packet size. The slight increase of the delay according to packet size in EG-RAODV is because of the fact that a larger data packet means more fragments to be delivered over the network. One packet is considered fully delivered only when all its fragments are delivered.

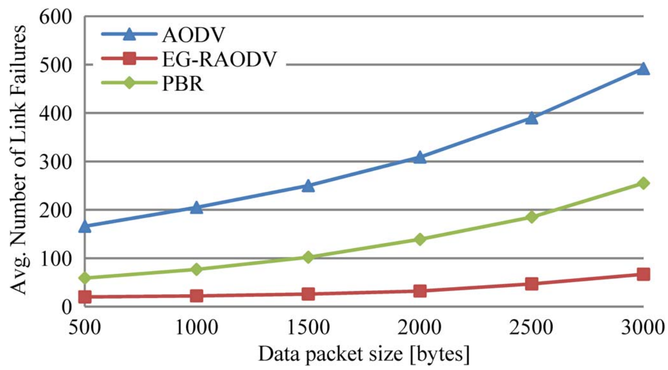

Fig. 10. Experiment B: Average number of link failures.

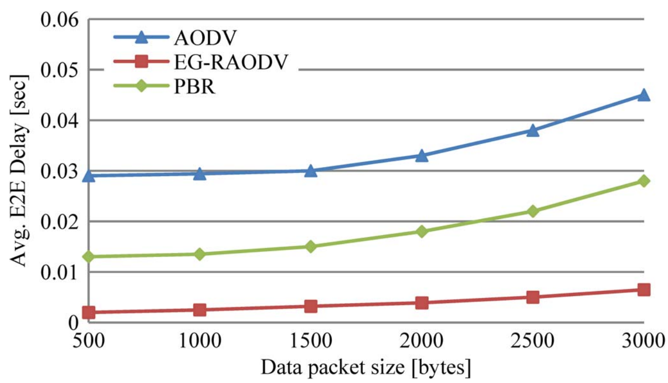

Fig. 11. Experiment B: Average E2E delay.

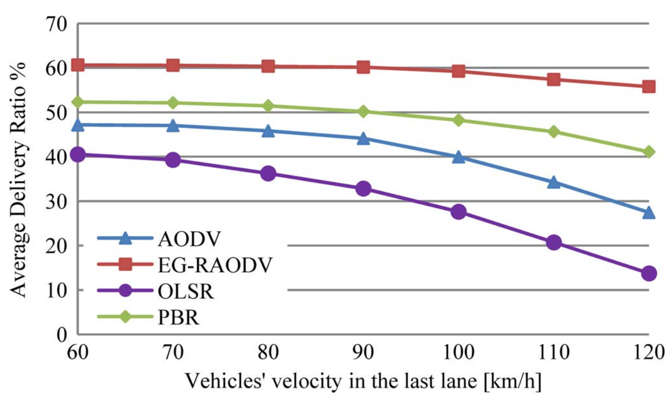

Fig. 12. Experiment C: Average PDR.

C. *Effect of Different Velocities on the Routing Performance*

The aim of Experiment C is to investigate the impact of different velocities on the routing performance. In this experiment, we also compare with OLSR as a proactive routing protocol. We consider the HELLO and topology control messages in OLSR corresponding to the RREQs in reactive routing protocols.

As shown in Fig. 12, the average PDR reduces for all routing protocols when the average velocity in the third lane increases from 60 to 80 km/h. This reduction comes from the fact that the routing topology becomes more dynamic and unstable when velocity increases. The decrease of the PDR of AODV and OLSR is much more rapid than that of EG-RAODV and PBR. To keep the routing tables updated in OLSR, topology control messages are sent to exchange information about the current vehicular status. It is clear that OLSR is not suitable for highly dynamic networks such as VANETs. Again, EG-RAODV performs the best in this experiment. In EG-RAODV, choosing the most reliable route helps reduce the possibility of a link breakage and keeps the highest PDR among the three schemes.

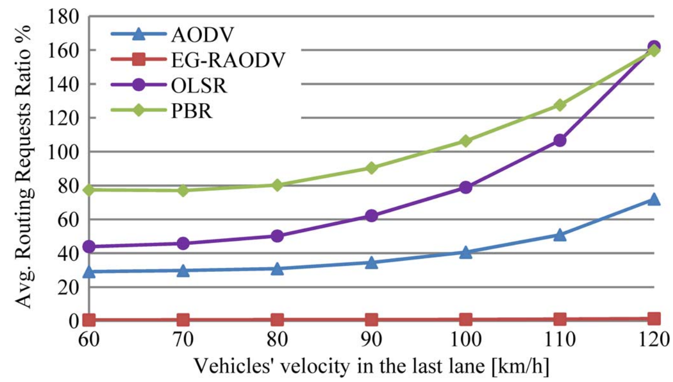

Fig. 13. Experiment C: Average routing requests ratio.

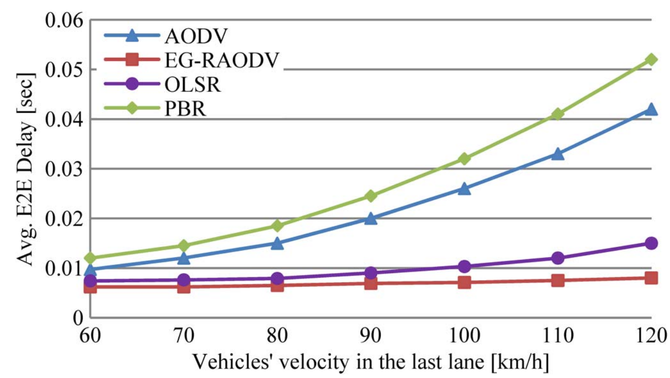

Fig. 14. Experiment C: Average E2E delay.

In Fig. 13, the average routing requests ratio generated by EG-RAODV is almost unaffected by the network topology changes. In EG-RAODV, the mobility prediction algorithm deals with the changes of the network topology. This process is carried out with no need to broadcast routing requests. On the other hand, all other routing protocols in this experiment are considerably impacted by the changes of the network topology. In particular, PBR creates the highest routing requests ratio due to the need to process multiple routing requests. As more topology control messages are sent in OLSR when velocity increases, its routing requests ratio increases significantly.

In Fig. 14, EG-RAODV and OLSR show lower E2E delay values than AODV and PBR. OLSR is a proactive or table-driven approach that helps achieve a low E2E delay value, although its delivery ratio is the worst among all the considered schemes, as shown in Fig. 12. The average E2E delay values of EG-RAODV are again the lowest and are not affected by the network topology changes. AODV and PBR cause much higher E2E delay values when the velocity increases.

As shown in Fig. 15, EG-RAODV obtains the lowest average number of link failures among all the considered routing protocols. The number of link failures of AODV and PBR increases when the velocity increases. The shortest route selection

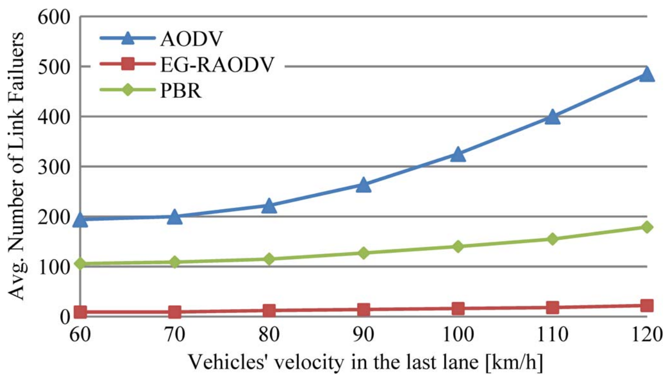

Fig. 15. Experiment C: Average number of link failures.

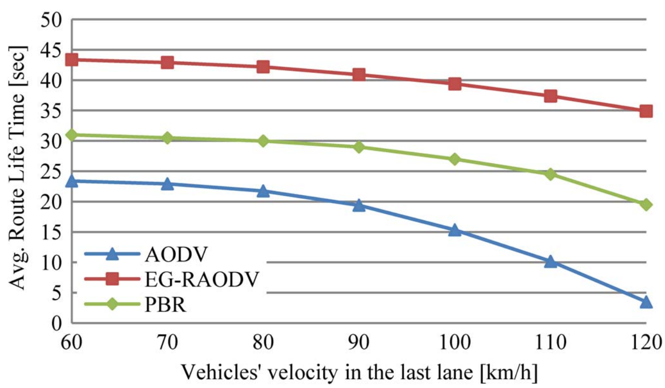

Fig. 16. Experiment C: Average route lifetime.

algorithm in AODV is highly prone to link breakages when the velocity of vehicles increases. The PBR prediction algorithm cannot accurately capture the changes of vehicular velocities, and hence, it performs worse than EG-RAODV. OLSR is not considered in this figure because no link failures are counted in the OLSR simulation experiment since it depends on HELLO messages to maintain the status of links.

In Fig. 16, we show the average route lifetime obtained by AODV, PBR, and EG-RAODV routing protocols. EG-RAODV achieved a longer route lifetime than both AODV and PBR because it uses the most reliable route in the network, where AODV gets the lowest route lifetime value among the three schemes. This observation explains their corresponding PDR relation shown in Fig. 12.

VIII. Conclusion

In this paper, we have extended the evolving graph theory and proposed our VoEG model. A new EG-Dijkstra algorithm was developed to find the MRJ in the proposed VoEG. We designed and formalized our EG-RAODV routing protocol to provide a reliability-based routing scheme for VANETs. The performance of EG-RAODV has been compared with reactive, proactive, and PBR routing protocols using extensive simulations with different transmission data rates, data packet sizes, and vehicular velocities. The results showed that EG-RAODV achieves the highest PDR among all the tested routing protocols. It obtains the lowest routing request ratio because the broadcasting technique is not needed in the route discovery process. As it chooses the most reliable route to the destination, it achieves the lowest number of link failures, the highest route lifetime, and the lowest average E2E delay values.

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