LLA: A New Anypath Routing Scheme Providing Long Path Lifetime in VANETs

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***Abstract*—Vehicular ad-hoc networks (VANETs) are a promising solution to improve the road traffic safety, reduce the environmental pollution, or simply provide the on-board infotainment services. However, these actions are often not possible due to high mobility of vehicles causing frequent failures of VANET links.**

In this paper, we focus on anypath routing to improve the reliability of multihop VANET communications. In particular, the paper is the first one to address the link stability issues and to propose a method called *Long Lifetime Anypaths* (*LLA*) providing stable communication paths. Advantages of our approach, presented in comparison to the reference Shortest Anypath First (SAF) scheme, are confirmed throughout simulations.

***Index Terms*—VANETs, path lifetime, anypath routing.**

I. Introduction

VEHICULAR Ad hoc NETworks (VANETs) have recently gained much attention as an important means to enable the inter-vehicle communications. In particular, VANETs are a promising solution to improve the vehicular traffic safety (e.g., by warnings sent in case of accidents, low bridges, ice, or oil on road [1]), reduce the impact of vehicles on environmental pollution (e.g., traffic light scheduling to help the driver to move in the green phase), or simply provide the on-board infotainment services such as Internet access [2].

As proposed by the U.S. Federal Communications Commission (FCC) and defined in the 802.11p standard, VANETs utilize seven 10 MHz channels in the 5.880-5.925 GHz band (known as Dedicated Short Range Communications – DSRC) with the typical link length limited to about 300 m [2]-[3]. However, high mobility of vehicles causes frequent failures of inter-vehicle links. Therefore, lifetime of a multi-hop path is often shorter than the time needed to install the path [4].

In order to improve the reliability of multi-hop transmission, multipath algorithms have been proposed (e.g., AODVM [5], CBM-AODV [6], being extensions to the common *Ad hoc On-demand Distance Vector* routing – *AODV*). However, due to topological constraints, finding multiple end-to-end disjoint paths is often hardly possible.

Another way to increase the multihop communications reliability in VANETs is to use the concept of *anypath* (*opportunistic*) *routing* [7]. In this scheme, unlike in unicast transmission where a packet is sent to only one next hop, a node sends the packet to a set of its neighbors called *forwarding set* (Fig. 1) chosen in the route planning phase [8].

Nodes from this set act cooperatively to send the packet towards the destination[1]. In order to avoid unnecessary duplicate forwarding, under anypath routing only one of these neighboring nodes will next forward the packet towards the destination. For this purpose, relay priorities are assigned to neighboring nodes by a reliable anycast scheme [8].

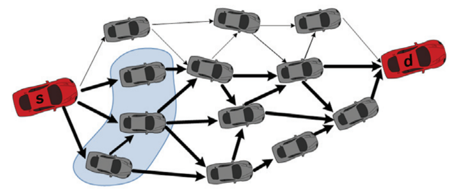

Fig. 1. Example anypath between vehicles s and d marked with bold arrows. Forwarding set for node s towards node d is marked with a blue area.

In general, higher priorities are given to relay nodes with lower costs to the destination. A certain lower-priority next hop will forward the packet only if all the respective higher-priority neighbors fail to receive it, e.g., if in a given timeslot, no MAC acknowledgement (ACK message) is sent by a higher-priority node upon receiving the packet [9]. The packet is lost, only if none of neighbors receive it [8].

The size of a forwarding set is a compromise between the forwarding cost (in general, this cost decreases with the increase of a number of forwarding relays [7]), and transmission delay (too many nodes in the forwarding set may result in longer paths, or even create loops). Compared to unicast transmission, reliability of anypath forwarding is improved, since for each transit node, probability of delivering a packet to at least one neighboring node is greater than the probability of delivering it to a specified forwarding node only [7], [9][2].

However, since there is no deterministic rule for selecting the next hop, each packet may traverse a multitude of possible paths (forming anypath) to reach the destination (Fig. 1). Therefore, the negative outcome of this opportunistic forwarding is route flapping due to choosing a particular route in a non-deterministic way on a per packet basis by link- and network-layer protocol mechanisms. As a result, traversing different routes by consecutive packets may degrade the level of QoS perceived by end users (i.e., QoE).

In this paper, we focus on link stability as an important factor preventing from route flapping in anypath communications. This issue is very important for many real-time safety services with stringent QoS requirements, e.g., emergency warnings, or safe driving assistance including real-time video transmission [10]. Even though there are some proposals available in the literature concerning anypath routing in VANETs (e.g., [11]–[13]), this paper is the first one to introduce a method to remarkably improve the anypath stability.

The main contributions of this paper include: **1)** definition of the Long Lifetime Anypaths (LLA) routing scheme that uti-

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[1]Different forwarding sets can be used for different destination nodes.

[2]Other advantages of anypath routing include: reduced cost of retransmissions, improved throughput, and better energy efficiency.

lizes the proposed metric of link cost based on the introduced link stability index; **2)** details of LLA solution deployment followed by evaluation of algorithm characteristics.

In particular, Section II outlines the details of our LLA anypath routing concept, while Section III shows evaluation of LLA algorithm properties. Section IV concludes the paper.

II. Long Lifetime Anypaths (LLA) Concept

In order to model the point-to-multipoint links characteristic to anypath routing (see Fig. 2), the network is represented here by a hypergraph $G = (V, E)$, where V is the set of nodes (vehicles), and E is the set of hyperlinks, each hyperlink being an ordered pair (i, J), where i denotes a given vehicle connected with the forwarding set J of neighboring vehicles[3].

The cost of anypath from a given vehicle i to the destination vehicle d can be defined by the following Bellman equation:

$$c_{id} = c_{iJ} + C_J \tag{1}$$

where c_{iJ} is a cost of a hyperlink (i, J) from node i to J, while C_J is the remaining anypath cost from J to node d [11]. Assuming independent packet losses [7], c_{iJ} can be defined as:

$$c_{iJ} = \frac{1}{p_{iJ}} = \frac{1}{1-\prod_{j\in J}(1-p_{ij})} \tag{2}$$

where p_{iJ} is the probability of delivering the packet from node i to at least one node from J based on individual probabilities of packet delivery p_{ij} for links (i, j).

c_{iJ} value thus represents the expected number of anypath transmissions (EATX metric from [7]) needed to successfully deliver the packet sent by node i to any node from J.

The cost C_J of anypath from J to d can be defined as the weighted average of costs of all paths from J to d:

$$C_J = \sum_{j\in J} w_{ij} C_j \tag{3}$$

where C_j is the cost of a path between vehicle j from J and the destination vehicle d, while weight w_{ij} denotes probability of node j being the forwarding node of a packet received from vehicle i [7]. In the simplified case of independent packet losses, w_{ij} values can be defined based on p_{ij} as:

$$w_{ij} = \frac{p_{ij}\prod_{k=1}^{j-1}(1-p_{ik})}{1-\prod_{j\in J}(1-p_{ij})}; \qquad \sum_{j\in J} w_{ij} = 1 \tag{4}$$

However, future values of p_{ij} depend on mobility characteristics of vehicles, and, in particular, on their time-dependent movement vectors. Any two vehicles i and j connected at t_0 will remain connected after Δt time, if distance r_{ij} between them does not exceed the max. communication range r_{max}:

$$r_{ij}(t_0 + \Delta t) = |\Phi_i(t_0 + \Delta t) - \Phi_j(t_0 + \Delta t)| \le r_{max} \tag{5}$$

where $\Phi_i(t_0{+}\Delta t)$ is a position vector of node i at $t_0{+}\Delta t$:

$$\Phi_i(t_0 + \Delta t) = \Phi_i(t_0) + S_i(t_0, \Delta t) = \begin{bmatrix} x_i(t_0) \\ y_i(t_0) \end{bmatrix} + \begin{bmatrix} s_i^x(t_0, \Delta t) \\ s_i^y(t_0, \Delta t) \end{bmatrix} \tag{6}$$

$S_i(t_0,\Delta t)=[s_i^x(t_0,\Delta t),\ s_i^y(t_0,\Delta t)]^T$ - movement vector of node i.

To reduce changes of a transmission path for consecutive packets, when establishing the anypath at time t_0, we need

[3]In each forwarding set J, indices 1, 2,..., n are assigned to nodes ascending the remaining path costs C_j to the destination node ($C_1 \le C_2 \le \dots \le C_n$).

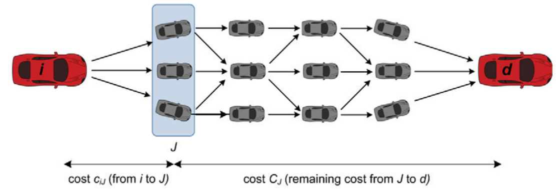

Fig. 2. Scheme of anypath cost calculation based on division into two costs.

Long Lifetime Anypath (G, d)

Indices	Algorithm
V set of vehicles C_j the upper bound on the cost of the shortest anypath from j to d D the set of nodes having the anypath to node d already defined N the queue of nodes that do not have the shortest anypath to d yet calculated (ordered ascending the C_i values) J forwarding set J_i forwarding set for vehicle i to reach d	1. for each node i from V, set: $C_i = \infty$; $J_i = 0$ 2. set $C_d = 0$; $D = \varnothing$; $N = V$ 3. while $N \ne \varnothing$: $j = \min_{k:\, node\, k\in N} C_k$ $D = D \cup \{j\}$ for each incoming edge (i,j) $J = J_i \cup \{j\}$ if $C_i > C_j$ $C_i = c_{iJ} + C_J$ (using Eqs. 8-10) $J_i = J$

Fig. 3. LLA procedure.

to identify "stable links", i.e., links between vehicles moving in similar directions with similar speeds. For this purpose, we define *the stability index* s_{ij} of link (i, j) at any time t_0 based on information on vehicles movement in the previous interval (t_0-Δt, t_0), as the normalized increase of distance between vehicles i and j in the past (t_0-Δt, t_0) interval (Eq. 7).

$$s_{ij} = 1 - \frac{min\left(\sqrt{(s_i^x(t_0-\Delta t,t_0)-s_j^x(t_0-\Delta t,t_0))^2+(s_i^y(t_0-\Delta t,t_0)-s_j^y(t_0-\Delta t,t_0))^2};r\right)}{r} \tag{7}$$

The best value of s_{ij}=1 is thus assigned to links between vehicles i and j having equal movement vectors (i.e., with constant inter-vehicle distance). The worst value of s_{ij}=0 is assigned to links with the change of length exceeding the maximum value r in Δt time (based on max. allowed speed).

Link stability is also an important factor influencing the packet delivery ratio p_{ij} at vehicle j in the near future. In general, probabilities p_{ij} are negatively correlated with link lengths [10]. Therefore, in order to reduce the frequency of anypath route flapping, we propose to include the value of stability index s_{ij}[4] in the link cost c_{ij}, as given in Eq. 8.

$$c_{ij} = \frac{1}{p_{ij}\cdot s_{ij}} \tag{8}$$

The lowest costs c_{ij} are thus assigned to links having both high values of stability index s_{ij} (i.e., long-lifetime links), as well as high values of packet delivery ratio p_{ij} (i.e., in case of short links). In case of our LLA scheme, the respective costs c_{iJ} and weights w_{ij} are defined as given in Eqs. 9-10.

$$c_{iJ} = \frac{1}{1-\prod_{j\in J}(1-p_{ij}\cdot s_{ij})} \tag{9}$$

$$w_{ij} = \frac{p_{ij}\cdot s_{ij}\prod_{k=1}^{j-1}(1-p_{ik}\cdot s_{ik})}{1-\prod_{j\in J}(1-p_{ij}\cdot s_{ij})} \tag{10}$$

[4]similar to *end-to-end path reliability* being a product of p_{ij} values for path l links [6], [14], *end-to-end transmission stability* S_{sd} between vehicles s and d can be defined as a product of stability indices s_{ij} of path links. For more information on transmission reliability, please see [15], [16].

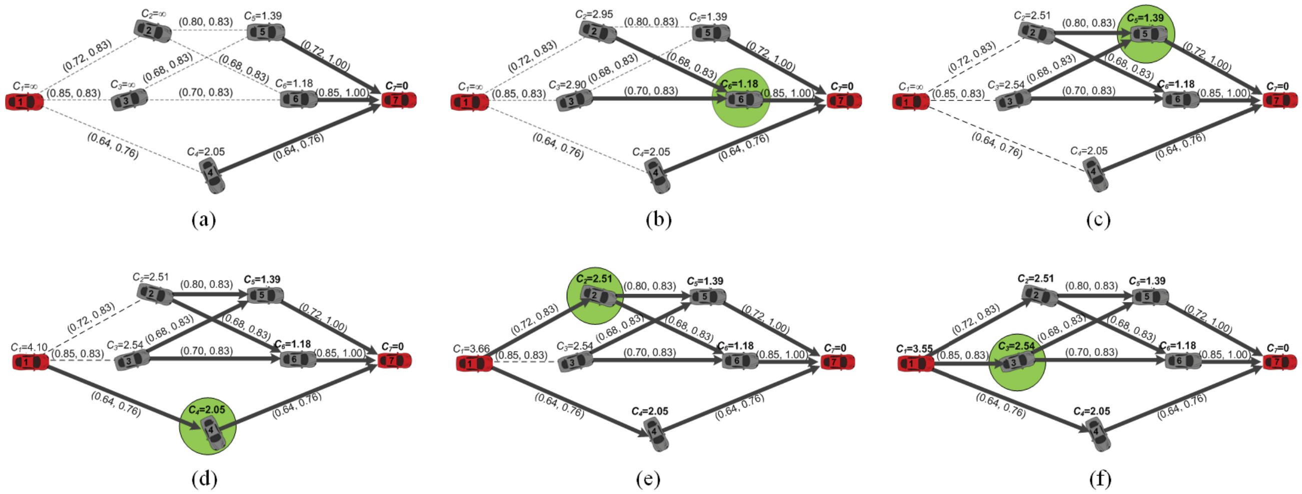

Fig. 4. Example execution of the algorithm to determine the Long Lifetime Anypath between vehicles 1 and 7: (a) initial graph with link stability indices s_{ij} and one-hop anypaths; (b)-(f) results of successive iterations of LLA algorithm.

The anypath between vehicles s and d can be established by means of our LLA procedure (Fig. 3) being a modification of the Shortest Anypath First (SAF) approach [8]. Since no similar approach to LLA exists in the literature, we use SAF as a reference in all comparisons. In general, SAF calculates the shortest anypaths from any vehicle to vehicle d. To obtain the LLA characteristics, the only needed update is to replace the costs and weights from Eqs. 2 and 4 by Eqs. 9-10.

A. Example

As an example, we consider the task to find the anypath between vehicles 1 and 7 in the network from Fig. 4a. Example values of probabilities of packet delivery p_{ij} and instant stability indices s_{ij} in a given (t_0-Δt, t_0) interval are assigned to links as ordered pairs (p_{ij}, s_{ij}). Following the LLA procedure, initially all costs C_j are set to infinity, except for the cost C_7 of a destination vehicle, which is set to 0. In each *i*th iteration (Step. 3 of LLA procedure), the algorithm determines the final anypath cost for one transit vehicle j from N having the minimal value of C_j. The procedure terminates after setting the final anypath cost C_j to all vehicles.

In general, the algorithm terminates after $|V|$ iterations. Assuming that in each iteration, selection of a vehicle with the current minimal cost C_j can be done in $O(\log|V|)$ steps (e.g., using the binary search algorithm), the overall complexity of our LLA approach is bounded in above by $O(|V|\cdot\log|V|)$.

As can be seen in Fig. 4, for any transit vehicle j, the set of next hops (candidate relays) is formed in a way to minimize the cost C_j. After finding the anypath, packets are forwarded based on general rules of anypath routing. In particular, for each forwarding set J, relay priorities of vehicles j are determined based on costs C_j using our formulas (9) and (10).

B. Details of LLA Approach Deployment

In order to apply the proposed LLA technique to the anypath routing scheme, it is necessary to add functionality responsible for determining the link stability indices s_{ij}. These values should be calculated periodically by each transit node i, based on the respective MOVEMENT structures shown in Fig. 5,

Vehicle ID	X axis movement	Y axis movement

Fig. 5. MOVEMENT messages of neighbors *j* stored at vehicles *i*.

stored at node i for each neghboring vehicle j. The respective information on X and Y axis of vehicle j movement from Fig. 5 can be in turn calculated by node i every Δt units of time based on Cooperative Awareness Messages (CAMs) [17], broadcast via the Control Channel (CCH [11], [18]) every 0.1-1 s by vehicles j. These messages include information on vehicle current location (X and Y coordinates) obtained from the Global Positioning System (GPS).

Individual link delivery ratios p_{ij} for (t_0-Δt, Δt) interval can be calculated by broadcasting the common Hello messages from each vehicle i via CCH followed by receiving the ACK messages from vehicles j [19].

III. Performance Analysis

Evaluation of our LLA approach characteristics was focused on analyzing the values of path cost, hop count, message transmission delay, minimal and average path link stability, as well as end-to-end transmission stability (all calculated for each anypath and next averaged over all considered anypaths). For each anypath, we analyzed these characteristics with respect to its primary path (i.e., path of the lowest cost). Evaluation was done for a 53-node network from Fig. 6. We investigated 50 scenarios. In each scenario:

- the set of transmission demands included all vehicle pairs,
- at the analyzed time t_0, vehicles were allowed to move in directions compliant with the roadmap from Fig. 6,
- following municipal regulations, speeds at time t_0 were uniformly distributed in range 0-16 m/s, with the max. change of inter-vehicle distance in Δt=1 s set to r=16 m.

Movement vectors S_i of vehicles in future interval (t_0, t_0+Δt) were estimated based on the respective ones from the past interval (t_0-Δt, t_0), where Δt = 1 s. Since transmission delay times can be regarded as negligible ones [20], during path computations, network topology (including location of vehicles and their speeds) was assumed to be "frozen", i.e., it did not change during path computations.

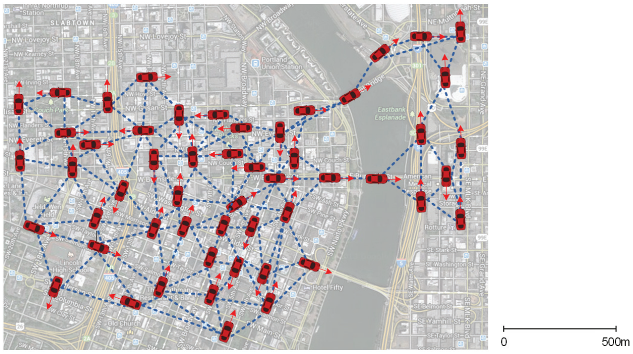

Fig. 6. Example VANET network (Portland, US).

Table I. Average values of characteristics and 95% confidence intervals.

Algorithm		Path cost	Min. link stability	Avg. link stability	End-to-end stability (S_{sd})	Hop count	Transmission delay [ms]
LLA	Average value	**36.60**	0.25	0.55	0.09	5.61	15.36
	Length of 95% conf. intervals	6.56	0.02	0.03	0.01	0.28	0.08
SAF	Average value	**150.20**	0.11	0.33	0.06	4.38	12.01
	Length of 95% conf. intervals	23.55	0.02	0.03	0.01	0.26	0.06

Results of LLA algorithm execution were compared to the respective ones of the reference SAF algorithm from [8]. Link delivery ratios p_{ij} were estimated based on link lengths using Eq. 1 from [10]. Path cost values were calculated according to the metric from Eq. 1 based on introduced formulas (8)-(10).

Table I and Fig. 7 present the average values of analyzed characteristics together with the lengths of the respective 95% confidence intervals. Due to choosing links having both high values of packet delivery ratios and link stability indices in anypath computations (by using the metric from Eq. 8), results referring to the average path cost obtained by our LLA algorithm were about 76% better than the respective ones for the reference SAF algorithm (36.60 against 150.20). Paths selected by LLA approach were also characterized by better ratios of minimal link stability (0.25 against 0.11) as well as the average link stability (0.55 against 0.33). Our technique also achieved 50% better values of end-to-end stability. All these results showed that LLA is able to establish paths characterized by improved stability compared to the common SAF technique (also shown in Fig. 7 presenting detailed characteristics of min. and avg. values of path link stability indices).

However, due to omitting links characterized by low stability indices, primary paths found by LLA approach were about 28% longer on average (which implied a small increase of the average message transmission delay of about 3.3 ms).

IV. Conclusions

In this paper, we addressed the problem of stability of anypath communications in VANET networks in the presence of inter-vehicle link failures being result of vehicles mobility. In order to improve stability of anypaths, we introduced a special metric of link costs that, apart from being based on packet delivery ratios, also included information on the level of link stability. Simulations confirmed benefits of our approach in comparison to the reference SAF scheme. In particular, the average total path cost based on link delivery and link stability ratios was reduced by over 75%.

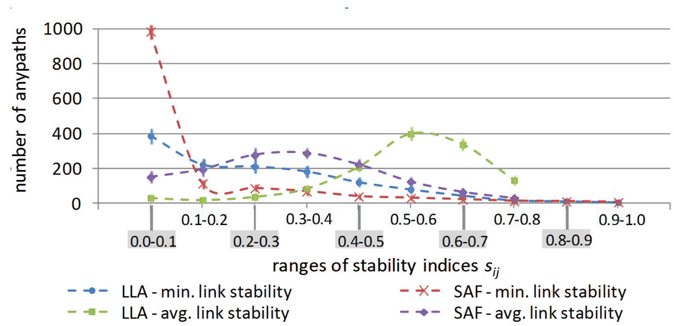

Fig. 7. Detailed characteristics of link stabilities.

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