Time Constrained Message Delivery Probability in VANETs

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Abstract—Vehicular Ad-hoc Networks (VANETs) have recently attracted a lot of attention, as a tool to disseminate information among vehicles with the dual purpose of increasing road safety and comfort in driving. The majority of messages exchanged by vehicles are characterized by a finite lifetime period, after which, their level of usefulness is greatly reduced. Thus, an important problem in VANETs is to pursue efficient routing policies which can ensure information delivery in target areas, before this deadline expires. The routing problem has been studied extensively in the literature and a number of solutions have been proposed. However, no previous work has investigated the problem based on the probability to deliver messages to a specific area in a certain amount of time, in a setting where no static infrastructure is used. In this paper we study the problem using a graph theoretical approach. We model the road map and the traffic characteristics using a directed weighted graph which we refer to as the Road-Graph. We use the Road-Graph to calculate the probability of disseminating information along any given path, in a specific amount of time. So, for any two points on the Road-Graph we can find the path with the maximum probability of successful information delivery in the chosen time interval. This information is of great significance since it can be utilized by routing protocols to optimally route packets in the vehicular network. We validate our analytical findings by comparing them with data obtained using the VISSIM simulator. The simulation model that we consider represents a section of the Highway network in the Los Angeles area and is tuned using real data. We observe good matching between the analytical and simulation results thus demonstrating the validity of our approach.

I. INTRODUCTION

Road traffic accidents is a major concern worldwide: 1.2 million casualties and 35 million injuries are reported annually making it the primary cause of deaths for people under the age of 34 [27]. Government agencies and automotive industries are responding by investing billions of dollars in an effort to reduce this terrifying numbers, as well as the tremendous costs associated with vehicle damages and treating crash victims [23].

Wireless technologies are playing a vital role in this effort. Dedicated Short Range Communication (DSRC) [22] is the IEEE 802.11a [13] variant which supports vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications forming what are widely known as Vehicular Ad Hoc Networks (VANETs). VANETs are expected to accommodate the new generation of cooperative road safety applications.

Messages exchange in VANETs increase the range of awareness of drivers beyond their line-of-sight thus significantly improving safety and comfort of all passengers in a vehicle. Information on emergency actions like emergency braking or hazards on the road can provide measures for active safety. In addition, a variety of other applications can be supported by the Vehicular Network such as collision avoidance and dynamic route scheduling [6], [11], [29], real-time traffic condition monitoring [2], [4], [19] and entertainment of passengers including interactive games, chatting, file sharing [5], [12], [20] etc.

Many applications in VANETs, especially safety related ones, require time sensitive message delivery over large distances. In many cases information needs to propagate several kilometers away in a certain amount of time otherwise, message delivery loses its usefulness. For example, in case of a car accident, information needs to travel to the nearest hospital as soon as possible or in the case of road hazards to the nearest police station which can be far away from the incident. With recent advances in multimedia technologies, information may also include photos or even videos of the situation helping the authorities to have a better understanding of the seriousness of the case. In addition, non-safety applications such as queries of weather conditions or traffic jams of a remote area or even interactive games with remote users, involve the exchange of messages between vehicles which reside some distance away from each other. In all these cases, messages need to cover distances of several kilometers in a multi-hop fashion in variable density traffic conditions. This density variations can significantly affect the time taken to deliver the message. High traffic densities lead to smaller delivery times due to higher probabilities of the network being connected from source to destination. On the other hand, low traffic densities often cause the network to be intermittently connected in which case, the message delivery speed is bottlenecked by the speed of the vehicle which is used to convey the information. So, when the application poses constraints on the delivery time, the probability to satisfy these constraints can be greatly affected by the chosen path. It is thus important to design efficient routing protocols which make routing decisions taking into consideration the need to increase the probability of successful delivery in a specific amount of time.

Many routing protocols have been proposed in literature. Since VANETs can be considered a subclass of Mobile Ad Hoc Networks (MANETs), a common approach has been to adopt routing policies specifically designed for MANETs. This approach however, does not always lead to effective solutions since VANETs have unique characteristics which
differentiate their study, VANETs are not constrained by scarce energy resources but are rather characterized by high mobility patterns and confined movement. High mobility is a result of the large speeds, which the vehicles can attain, leading to dynamic and rapidly changing network topology and network fragmentation. The dynamic nature of the topology is enhanced by the unpredictable nature of the drivers’ response to various events. VANETs are also characterized by the constrained, largely one-dimensional movement of the vehicles along the roadway network which is fixed. The for-mentioned characteristics pose design and modeling challenges different from traditional MANETs in the development of various network protocols.

A. Related Work and Our Contribution

In this section we give an overview of the main approaches adopted in literature to develop routing protocols for VANETs [1].

In [8] authors examine the applicability of existing ad hoc routing protocols to VANETs. Specifically, they compare the famous Dynamic Source Routing (DSR) with the Greedy Perimeter Stateless Routing (GPSR) protocol. They conclude that, when communication sessions are comprised of more than 2 or 3 hops, position-based ad hoc routing is preferable over reactive non-position-based approaches.

The Mobility-Centric Data Dissemination Algorithm (MDDV) [25] is one of the few that provide a complete architecture for vehicular routing. It combines the ideas of opportunistic forwarding, trajectory-based forwarding and geographical forwarding. The protocol disseminates data to intended receivers, while maintaining some design demands, e.g. high delivery ratio, low delay and low memory occupancy. Even though MDDV can be applied to hybrid architectures, it is considered in VANETs scenarios only.

The Geographic Source Routing (GSR) protocol proposed in [16] examines the problems appearing with base-line position-based routing in two-dimensional urban scenarios. GSR combines position-based routing with topological information. The adoption of the Reactive Location Service (RLS) [15] system is assumed. The source uses flooding to request the position of a node identifier. After discovering the location of the recipient, the source uses a digital map of the roads to calculate the set of junctions that the packet will follow.

In [17] authors present A-STAR, an Anchor based Street and Traffic Aware Routing scheme. They use information on city bus routes to identify an anchor path with high connectivity for packet delivery. The model is designed based on position-based routing, specifically to facilitate VANETs in urban areas. In such environments, vehicle density is larger in some famous (for their traffic) roads than in others. Connectivity in such roads can be higher and more stable due to regular bus passes. A-STAR constructs a graph, based on how many bus lines go through certain roads. Since each vehicle may be aware of the bus route information through digital maps, an anchor route may be constructed using the Dijkstra’s algorithm for least-weight.


Chisalita and Shahmehri in [3] propose a distributed protocol for decentralized network organization. The protocol requires the receivers to analyze the exchanged messages so as to figure out if they are the intended destinations. For this filtering the current traffic conditions are taken into account. The protocol includes mechanisms for message acceptance/denial, local maintenance of neighborhood information and transmission of basic safety (as well as non-safety) messages.

In [18] authors present a formal model of data dissemination in VANETs and study how the characteristics of Vehicular network, specifically the bidirectional mobility on well-defined paths, affect the performance of data dissemination. Information can be disseminated using vehicles moving on the same direction, vehicles moving in the opposite direction, or vehicles moving in both directions.

It is evident from the above that no routing protocol has been developed taking into account the need to increase the probability of delivering a message when the latter has to be done in a specific amount of time. In this work we contribute towards this direction by deriving an analytic expression which can be used to calculate the probability to deliver a message within a predefined time interval along a specific path. For any source destination pair we use this expression to find the optimal path which maximizes the probability of successful delivery. A key feature of our work is that it is based on a graph theoretic approach. We represent a road map of arbitrary topology and the characteristics of the traffic within this map using a weighted directed graph which we refer to as the Road-Graph. We then utilize this Road-Graph to derive the desired probabilities and the optimal path for any given source destination pair. We then validate our analytical findings with simulation results obtained using the VISSIM simulator [24]. The reference model that we use in simulations represents a section of the freeway system in the Los Angeles area. We observe good agreement between our theoretical predictions and the simulation results thus demonstrating the validity of our approach. This indicates that the obtained results can be used as a baseline to develop an effective routing protocol for VANETs whose objective will be to maximize the probability of successful message delivery when the latter has to be done in a specific amount of time. This will be the topic of future research.

The remainder of this paper is organized as follows. In section II we present the framework and main assumptions which are used to formulate the problem mathematically. In section III we present the algorithm which results in the Road-Graph and in section IV we use the Road-Graph to calculate the successful delivery probabilities. In section V we apply our methods to a section of the Highway system in the Los Angeles and in section VI we validate our analytical findings by comparing them with simulation results obtained using the VISSIM simulator. Finally, in section VII we
conclude our work and give guidelines for future research.

II. ASSUMPTIONS

In this section we present the considered framework and the main assumptions made in order to formulate the problem mathematically.

A. Framework

Vehicles participating in VANETs travel on static road networks. These roads can be described by their length, the number of lanes, the arrival rate of vehicles and the speed range. Vehicles can communicate with each other if their distance is less than their transmission range. Roads with heavy traffic density (i.e., the distance between the vehicles is very small) have high information propagation speed as the message is transmitted from vehicle to vehicle in multi hops, instead of being carried by them with the speed of the vehicle, as it happens in light traffic conditions. Dedicated Short Range Communications (DSRC) is a proposed variant of IEEE 802.11a, designed to operate within a frequency band (5.9 GHz), licensed solely for the purposes of vehicular communications. Typically, a message of 1 Kb with a 2 Mbps wireless channel needs around 6 ms to be received and processed. By assuming a transmission range of 250 m and that the two vehicles communicating are apart a distance equal to the transmission range, we can achieve propagation speeds up to $150 \times 10^3$ Km/h.

B. Assumptions

We consider that we are given a road map of an area which consists of the main roads and Highways of the area and the corresponding intersections. We don’t take into consideration small roads with insignificant traffic or roads in city centers since buildings constrain the signal propagation. Hence, it is more difficult to establish wireless connectivity in urban areas and the network efficiency is decreased. Furthermore, the complexity of the vehicle movements in cities which include traffic lights, stop signs and different speed limits makes the theoretical analysis of information propagation more complex which is out of the scope of this research work. We also assume that we are given the traffic conditions of each main road and Highway with the arrival rate of vehicles and their speed range on the specific road. We assume that a vehicle travels with a constant speed, selected uniformly and independently from the speed range of the road. We also assume that the number of vehicles entering a road is a random variable that follows the Poisson process since several experiments have shown that the outcomes of such a model are in good agreement with real measurements obtained in practice [7]. In the case of Highways where there are many exits and entrances along them, we consider the number of vehicles entering each Highway separately since vehicles may enter or leave during their driving. For simplicity reasons we assume that traffic conditions remain constant along the Highway, at least on the parameters that affect our analysis, given that vehicles can enter or exit from smaller roads on the side. This assumption influences the traffic integrity in the intersections of the Highways. However, the analysis of the traffic flow and the calculation of the arrival rate of vehicles in each Highway is not considered in this paper. We consider that each Highway follows an independent Poisson process.

We also assume one-way and one-lane traffic along the roads. In the case where the Highway is multilane we only consider the lane with the highest density. For two-way Highways we consider that they consists of one-lane in each direction and in the Road-Graph that we construct to model the road map, we add a different directed edge for each direction. We study the information propagation to the direction of the traffic using vehicles moving on this direction. Also, we consider that all vehicles have a constant transmission range denoted by $r$, which is the same for all vehicles. Informed vehicles are the vehicles that have the information while uninformed vehicles are vehicles that do not. Exchange of messages occurs when an uniformed vehicle enters the transmission range of an informed vehicle.

Finally, since traffic conditions vary depending on the period of the day that are measured (i.e., morning, noon, afternoon or night), the same road map has different traffic characteristics during different hours of a given day. Therefore, the same road map is modeled by different Road-Graphs for different periods of the day.

III. ROAD-GRAph CONSTRUCTION

In this section we outline the steps followed to create the Road-Graph. The resulting Road-Graph contains all the necessary data to study the information delivery probability in VANETs. We consider that we are given the road map of the area that we study which includes the roads and their intersections, the arrival rate and the vehicle speed range of each road during a specific time period in a day. We begin by presenting the basic notations used in our analysis.

$I_i$: the ith intersection in the road map

$n_i$: the node of the Road-Graph that corresponds to the ith intersection of the road map

$h_{ij}$: the road connecting intersection $I_i$ with intersection $I_j$. The traffic direction is from $I_i$ to $I_j$

$L_{ij}$: the length of the road $h_{ij}$

$e(n_i, n_j)$: the directed weighted edge of Road-Graph that joins $n_i$ to $n_j$

$w(n_i, n_j)$: the weight of the edge $e(n_i, n_j)$ in the Road-Graph which represents the average time needed for a message to travel the distance: $L_{ij}$ - $r$

$v_{ij}$: the average message propagation speed on the road $h_{ij}$ in the direction of vehicles drive

prob$_{ijk}(t)$: the probability that a message will propagate from road $h_{ji}$ to road $h_{ik}$ in a time period $t$

We now provide an algorithmic representation of the steps that must be followed in order to generate the Road-Graph.

**Algorithm: Construction of the Road-Graph**

**Input:** a road map (roads and their intersections), the arrival rate and the vehicle’s speed range for each road

**Output:** the corresponding Road-Graph $(V, E)$
BEGIN

1) FOR ALL intersections $I_j$ in the road map do
   - Create a node $n_j$ and add it in the Road-Graph
     (i.e., $V = V \cup \{n_j\}$)
2) FOR ALL roads $h_{ij}$ in the road map do
   - add a directed weighted edge $e(n_i, n_j)$ in the Road-Graph
3) FOR ALL roads $h_{ij}$ in the road map do
   - calculate the average message propagation speed $v_{ij}$ in the direction of vehicles drive [26]
   - $w(n_i, n_j) = \frac{(L_{ij} - r)}{v_{ij}}$
4) FOR ALL nodes $n_i$ in the Road-Graph do
   FOR ALL pairs of edges $e(n_j, n_i)$ and $e(n_i, n_k)$ do
   - prob$_{jik}(t) = f_{jik}(t)$ [28]

END

A. Analysis of the Algorithm: “Construction of the Road-Graph”

The first two loops are straightforward and do not need any further analysis. In the third one, we need to calculate the average message propagation speed on a single road. In order to do this, we use the analytical model proposed in [26]. In this research work, authors take into consideration that information can propagate in two modes, either by multi-hop forwarding or by the mobile node movement. The specific model reveals several important vehicle traffic parameters significantly impacting information propagation: the vehicle density, average vehicle speed and relative speed among vehicles. Using simulation they have validated their theoretical analysis showing how information propagation speed increases with the increase of traffic density for a specific road. Figure 1 shows their theoretical and simulation results. The vehicle speed range is from 40 Km/h to 70 Km/h and the transmission range is 50 m.

The reason we divide the length $L_{ij}$ of road $h_{ij}$ minus the transmission range $r$, with the average message propagation speed is because, in distance $r$ from the intersection $I_j$ information can propagate to a road intersecting $h_{ij}$ on intersection $I_j$. The probability that a message will propagate to the next road in a given time period is calculated in the last loop. This calculation requires the lower bound on the probability of information propagation between two intersecting roads in a given time period. For this calculation, we use the results of our research work in [28]. In this work, we derive a formula which gives a lower bound on the probability that informed vehicles driving on a road will be able to propagate the information to vehicles driving on an intersecting road given that, at least one informed vehicle is of distance less than or equal to their transmission range from the intersection. To conduct our analysis we consider two ways with which information can propagate on an intersection. The transmission way where an informed vehicle transmits the information to an uninformed vehicle which resides in the destination road and the driving way where an informed vehicle drives into the destination road and propagates the information. The equation that computes the probability of having the message be propagated, combining the two ways is:

$$p_{h_{ij}h_{jk}} = p_{tr}^{h_{ij}h_{jk}} + (1 - p_{tr}^{h_{ij}h_{jk}}) \cdot p_{dr}^{h_{ij}h_{jk}}$$

where $p_{h_{ij}h_{jk}}$ is the message propagation probability from road $h_{ij}$ to road $h_{jk}$ on their intersection $I_j$, $p_{tr}^{h_{ij}h_{jk}}$ is the probability of the transmission way where an informed vehicle on road $h_{ij}$ transmits the information to an uninformed vehicle on road $h_{jk}$ and $p_{dr}^{h_{ij}h_{jk}}$ is the probability of driving way where an informed vehicle on road $h_{ij}$ turns into road $h_{jk}$. Figures 2 and 3 shows the two ways of information propagation on an intersection. $R$ is the point on $h_{ij}$ that is $r$ apart from intersection $I_j$ and $M$ the corresponding point of road $h_{jk}$. The angle between roads $h_{ij}$ and $h_{jk}$ is denoted by $\varphi$. The analysis is based on the fact that, in order to have the information transmitted from road $h_{ij}$ to $h_{jk}$, an informed vehicle should be in road segment $R \cup M$ and an uninformed vehicle in road segment $I_jM$. The distance between the informed and uninformed vehicles should be less than or equal to $r$.

![Fig. 1. Theoretical and Simulation results of Information Propagation speed on a single lane road](image1)

![Fig. 2. Information Propagation by the Transmission way on Intersections](image2)
Fig. 3. Information Propagation by Driving way on Intersections

increases. The validation of the analysis was performed via simulation.

In figure 4 we show the information transmission probability (which is the propagation probability considering only the transmission way of propagation) and the way it increases with time for different arrival rates. In this paper, we only consider message propagation at intersections using wireless transmission only.

B. A simple example

For clarity of presentation, we provide a simple example which helps the reader get a better understanding of the method used to derive the Road-Graph and how it looks like given a specific road map. We assume that we are given the road map as depicted in figure 5. The road map comprises of 3 roads and 4 intersections. Road $h_{12}$ starts from intersection $I_1$ and ends on intersection $I_2$. Vehicles arrive on the road from intersection $I_1$ with arrival rate 1200 Veh/h and drive with a constant speed chosen randomly from the range 70 Km/h to 90 Km/h. The length of the road is 18 Km. The other two roads are road $h_{23}$ and road $h_{24}$. The arrival rate, vehicle speed range and length of roads are shown in figure 5. The direction of car movement is defined by the direction of the arrows. Since we consider Highways with adjacent roads at their side that can be used by vehicles in order to enter or leave the Highway, the sum of the arrival rates of the roads $h_{23}$ and $h_{24}$ does not need to be equal to the arrival rate of $h_{12}$.

Following the aforementioned “Construction of the Road-Graph” algorithm, we create the Road-Graph from the road map provided in figure 5. We first create the four nodes, $n_1$, $n_2$, $n_3$, $n_4$ representing the four intersections $I_1$, $I_2$, $I_3$, $I_4$ respectively. Then, for each road in the map we create an edge in the Road-Graph with the direction as defined by the direction of traffic flow. Thus, we have $e(n_1, n_2)$, $e(n_2, n_3)$ and $e(n_2, n_4)$. According to the algorithm, we proceed to the calculation of the average time needed for the information to propagate along the road and we assign this value to the weight of the respective road. Finally, for node $n_2$, which is the only one that has input and output edges we provide the two functions of time for the computation of a lower bound of the information dissemination probability, from road $h_{12}$ to road $h_{23}$ and to road $h_{24}$. These functions are denoted by $f_{n_1n_2n_3}(t)$ and $f_{n_1n_2n_4}(t)$, respectively. For the precise definition of these functions see [28]. The resulting Road-Graph is shown in figure 6.
IV. MESSAGE DELIVERY PROBABILITY

In this section we explain how to calculate the probability of a message, starting from the source area, will be delivered to the target area in a given time period $T$, using the Road-Graph. For simplicity and without loss of generality, we use intersections as source and target areas. We denote by $n_s$, the node of the Road-Graph that corresponds to the source intersection and $n_d$ as the node corresponding to the destination intersection.

Firstly, we need to find the most probable paths from source to destination that the information will follow in order to be delivered. To do so, we find the 10 shortest paths with respect to the weight of the edges, ignoring the time needed for information propagation on intersections. The algorithm we use is described in [9] which enumerates the $k$ shortest simple (loopless) paths in a directed Graph with $n$ nodes and $m$ edges, with time complexity $O(knm + n \log n)$ in worst case. For the enumeration, we only consider the time needed by the message to travel the distance of each road, ignoring the time spent on the intersections. The reason that we choose the 10 shortest paths is because, experimental results have shown that investigating the probability of delivery using only 10 shortest paths is more than enough to find the path with the highest probability. The paths are sorted starting from the shortest one.

We call $p_q = (n_{q1}, \ldots n_{qm})$ the $q$th shortest path that join the source of the message to the destination of the message, i.e., $n_{q1}$ is the starting node $n_s$ and $n_{qm}$ is the destination node $n_d$. The number of nodes in the path is $m$ and the number of edges is $m - 1$. We define as $c(p_q)$ as the cost of path $p_q$, which is equal to the sum of the weights of the edges of the path, ignoring the time spent by information to travel between roads on their intersection. So,

$$c(p_q) = \sum_{j=1}^{m-1} w(n_{qj}, n_{qj+1}) \quad (2)$$

In order to be able to calculate the probability that the message will be delivered using a specific path in the given time period $T$, the cost of path $c(p_q)$ must be less than or equal to $T$. This is because, path $p_q$ needs on average, more time than $T$ to carry the information even by ignoring the time spent for information propagation on each intersection.

We define as $t_{p_q}$ the extra time that we can distribute to the $m_q - 2$ internal intersections of the path $p_q$ and calculate the probability of each one. We do not consider the nodes $n_1$ and $n_{m_q}$ since the first, as source of information, starts to provide the information as soon as there is a vehicle there and the second one is the destination node, where information will not need to travel any more. The equation giving $t_{p_q}$ is:

$$t_{p_q} = T - c(p_q) \quad (3)$$

Now we need to find the probability that the information will pass from all internal intersections in the given time $t_{p_q}$. To do so, we have to, first find the probability of each intersection independently, given the portion of time that we can spend on each one which is $\frac{t_{p_q}}{m_q-2}$. Then, the overall probability of path $p_q$ is given by the product of all the probabilities of the internal intersections of the path. So, the message delivery probability using path $p_q$ denote by $P_{Del}(p_q)$, is given by equation:

$$P_{Del}(p_q) = \prod_{j=2}^{m_q-1} f_{j-1,j+1}(t_{pq}/(m_q - 2)) \quad (4)$$

Finally, once we find the delivery probabilities of the 10 shortest paths, we select the path with the highest delivery probability. So equation 5 gives the message delivery probability, $P_{max}$ from source to destination in the given amount of time $T$.

$$P_{max} = \max_{1 \leq q \leq 10} (P_{Del}(p_q)) \quad (5)$$

V. REAL WORLD EXAMPLE

In this section we apply the proposed methodologies and the obtained theoretical results on a real world example. We consider a section of the Highway network in the Los Angeles area which includes 210 Highways. The road map, as obtained from Google Earth [10], is depicted in figure 7.

![Fig. 7. Major Highways around the city of Los Angeles](image)

To characterize the traffic conditions on each Highway we use Google Earth to obtain approximations of the traffic density and SIGALET [21] to obtain average vehicle speeds. We assume that the vehicles can attain speeds between 10 kilometers below the average value and 10 kilometers above the average value.

We follow the algorithm described in section III to obtain the desired Road-Graph. For each intersection in the road map we initially create a node on the Road-Graph. Then, for each Highway we create a directed, weighted edge following the vehicle driving direction as shown in figure 8. By following loop 3, for all the edges on the Road-Graph we find the time needed for the information to travel along the corresponding Highway and we assign this value to the weight of the edge. Finally, as described in loop 4, for each node $n_i$ and for all pairs of edges $e(n_j, n_i)$ and
Having obtained the Road-Graph, we can now calculate the information delivery probability versus time for any combination of source and destination intersections, using the method described in section IV. In figure 10 we present the probability of message delivery from intersection $I_{13}$ to the destination intersection $I_{53}$.

In this case, the highest delivery probability is provided by the shortest path for all the values of time period $T$. The shortest path is $p_1: n_{13} - n_{14} - n_{15} - n_{16} - n_{17} - n_{18} - n_{27} - n_{28} - n_{41} - n_{44} - n_{51} - n_{52} - n_{53}$, with cost $c(p_1): 468$ sec. The total distance of the path is 180 km.
which implies that the best case average information speed along this path is 1384 Km/h. In figure 10 we also show the message delivery probability along the second and third shortest paths. The figure indicates that for all values of T the highest probability is offered by the shortest path.

The second source - destination pair that we consider is from intersection I₁ to intersection I₅₁. The information delivery probability versus time is presented in figure 11.

In this case, the highest probability is not always given by the shortest path. We observe that after 490 seconds the highest probability is offered by the fifth shortest path and after 1200 seconds the highest delivery probability is given by the second shortest path. This is possible since the formula that gives the information propagation probability on intersections does not increase in the same way for all intersections. The probability strongly depends on traffic conditions of the intersected Highways especially on the arrival rate of the Highway that the information needs to be transmitted. So, different paths with different intersections will have different increasing modes of information delivery probability as time period T increases. The first five shortest paths for this combination of source and destination intersections with their cost, total distance and best case average message propagation speed are listed below.

1) $p₁ : n₁ - n₂ - n₃ - n₇ - n₉ - n₆₇ - n₁₆ - n₁₇ - n₁₈ - \ldots - n₂₇ - n₂₈ - n₄₁ - n₄₃ - n₄₄ - n₅₁$. $c(p₁) : 365$ sec, Total distance: 156 Km, Best case average message propagation speed: 1538 Km/h
2) $p₂ : n₁ - n₂ - n₃₁ - n₁₄ - n₁₅ - n₁₆ - n₁₇ - n₁₈ - n₂₇ - n₂₈ - n₄₁ - n₄₃ - n₄₄ - n₅₁$. $c(p₂) : 383$ sec, Total distance: 180 Km, Best case average message propagation speed: 1691 Km/h
3) $p₃ : n₁ - n₂ - n₄₃ - n₇ - n₉ - n₆₇ - n₁₉ - n₁₇ - n₁₈ - n₂₇ - n₂₈ - n₄₃ - n₄₄ - n₅₁$. $c(p₃) : 389$ sec, Total distance: 155 Km, , Best case average message propagation speed: 1434 Km/h.
4) $p₄ : n₁ - n₂ - n₃₄ - n₇ - n₉ - n₆₇ - n₁₆ - n₁₅ - n₁₈ - n₂₇ - n₂₈ - n₄₃ - n₄₄ - n₅₁$. $c(p₄) : 390$ sec, Total distance: 162 Km, , Best case average message propagation speed: 1495 Km/h.
5) $p₅ : n₁ - n₂ - n₃₈ - n₁₄ - n₁₅ - n₁₈ - n₂₇ - n₂₈ - n₄₃ - n₄₄ - n₅₁$. $c(p₅) : 398$ sec, Total distance: 169 Km, , Best case average message propagation speed: 1528 Km/h.

Even though the field of Vehicular Ad Hoc Networks is widely studied and concept of proof tests are already taking place, many years will pass until all vehicles are suitably equipped to participate in VANETs. So, it is very interesting to see how the information delivery probability will behave in more realistic scenarios where only a portion of vehicles are appropriately equipped to participate in VANETs. In figure 12 we show the information propagation probability versus time for three different percentages of equipped vehicles, out of all vehicles traveling on the Highways.

We can observe from the figure that the higher the percentage of vehicles that are able to participate in VANETs, the greater the probability of information delivery. This is because, having more equipped vehicles in the Highways, increases the opportunities of information transmission which increases the speed of message traveling.

VI. SIMULATION VALIDATION

In this section we validate our theoretical findings with simulation results obtained using the microscopic simulator.
VISSIM. The topology of the reference model that we use in simulations is shown in figure 8. We assume identical traffic conditions (vehicle arrival rate and vehicle speed range) to the ones used in the previous section. In order to make the simulation more realistic we assume that not all vehicles are equipped to participate in VANETs. More specifically we assume that 50% of the vehicles have the appropriate equipment that allows them to participate in VANETs, a situation which is expected to hold in the near future. Since we would like the simulation setup to match as closely as possible the theoretical setup considered in the previous section, in the reference model we ignore the on ramp entries and exits of the considered Highways. We assume that all vehicles enter each Highway at its beginning and exit the Highway at its end. This property can easily be implemented on VISSIM since VISSIM provides the option of creating equipment that allows them to participate in VANETs, a total distance of the path is 60 Km and the cost of the path is 295 seconds.

![Figure 13. Information Delivery Probability versus Time from intersection $I_{15}$ to intersection $I_{41}$](image13.png)

Figure 13 indicates that the theoretical results are very similar to the ones obtained using simulations. The small deviations observed are due to the relatively small number of simulation runs which are used to calculate the delivery probability. We observe that the delivery probability calculated using simulations is nonzero for a subset of the range of time values that the theoretical probability is equal to zero. This is due to the fact that the weight of each edge represents the average message propagation time which implies that in some simulation experiments the reported propagation time can be less than the average.

In figure 14 we compare the theoretical and simulation results for a different scenario. We consider message delivery from intersection $I_{3}$ to intersection $I_{22}$. In a way similar to the previous case, the maximum probability of information delivery is provided by the shortest path at all time intervals in both cases. The shortest path is the following: $n_3 - n_7 - n_9 - n_{21} - n_{20} - n_{22}$. The total distance of the path is 76 Km and the cost of the path is 931 seconds.

![Figure 14. Information Delivery Probability versus Time from intersection $I_{3}$ to intersection $I_{22}$](image14.png)

Again, we observe in figure 14, good agreement between the theoretical and simulation results. Also for the same reasons outlined above, the simulation delivery probability has a nonzero value (between 0 and 0.1) in the time period where the theoretical value is equal to zero.
VII. Conclusions and Future Work

In this paper we study the problem of information dissemination in VANETs and we provide a measure of the probability to have the information be delivered to the destination in a given amount of time where no static infrastructure is used. We present a road map modeling which results in the corresponding Road-Graph given the traffic conditions of the roads. Using the resulting Road-Graph we provide the theoretical analysis to calculate the information delivery probability given a period of time. We validate our results with simulation evaluation using VISSIM, a widely used micro-simulator. We use close-to-reality traffic conditions from the Highways around the city of Los Angeles and we study the propagation of information between intersections of the Highways.

One area of future work is to study the information propagation using roads of opposite directions. This will increase the speed with which information can travel and eventually the information delivery probability. In addition, we will study the improvement that the installation of static infrastructure will bring to the speed of information propagation.

Finally, we plan to study more realistic traffic conditions, where vehicles have accelerated and decelerated, their movement depends on the movement of other vehicles, lights can be introduced on intersections, etc. In addition, we plan to add more lanes in roads which will increase the possible ways to propagate information. This will definitely speed up the overall message propagation.

REFERENCES


