Quantitative model for evaluate routing protocols in a vehicular ad hoc networks on highway

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Abstract—**Our main goal is to provide the best management protocols for vehicular Ad Hoc network (VANET), more precisely, to determine the best routing protocol. In this paper, we focus on VANET built on highway where cars run in the same direction. We introduce a quantitative model in order to evaluate existing routing protocols. We use this model to compare two main classes of routing protocols, topological protocols and geographic protocols. The studied criterium is the scalability property, i.e. performance preservation in spite of the substantially increasing of network size.**

I. INTRODUCTION

Drivers and vehicles need more and more safety functions using in-vehicle sensors to prevent crashes, to help driving, to track vehicles and to help users to reach a given position. Vehicular Ad hoc Network (VANET) is a new capability for drivers to enhance more safety on roads by exchanging weather alerts, emergency alerts and traffic information. In VANET, each node acts as a router : it may have to transmit a packet to its neighbors. We consider a particular VANET where cars run on a highway in the same direction. As the total lanes width is much less than the radio coverage radius, the network topology has only one dimension, i.e. a line. Moreover, the line topology of a highway limits the spatial frequency reuse since all the nodes located between a pair of communicating nodes will be on their path. Secondly, on a highway, cars move very quickly and can pass each other. Fast moving cars and vehicle passing cause frequent topology changes (as absolute geographical node position and relative position) inducing a lot of routing messages to update the routes.

Our study concerns inter-vehicle communications, commonly called V2V (Vehicle-to-Vehicle). The choice of a routing protocol must take into consideration the network dynamics. Proactive ad hoc protocols have shown strength for static or quasi-static networks [1], whereas reactive or geographic protocols are better suited for highly dynamic networks. Routing protocol should exhibit good properties such as robustness, fault tolerance, fast reconfiguration and scalability. This last property allows a protocol to preserve good performance when the network size or the number of nodes increases: generated overhead, delivery delay, routes length and rate of routes breaking.

Thus, we study the two main classes of routing protocols [2]: topological and geographical for vehicular network. Many works [2], [3], [4], [5] perform a comparison of aforementioned protocols using simulations. These studies evaluate performance criteria like the delay, the overhead rate and the packet delivery ratio. A protocol overhead is evaluated as the amount of sent information or more precisely, the number of sent messages in order to provide the routing tasks. The common belief is that geographical routing protocols are more efficient than reactive topological ones. The major drawback of these studies comes from their approach: simulation. Indeed, the simulators complexity, their heterogeneity, the protocol implementation issue, the lack of justification for all assumptions (explicit or implicit) induce questionable and not reproducible results.

Therefore a quantitative model (counting the sent signalling messages), with well specified assumptions, allows a better comparison insensitive to the implementation choices or values of the multiple parameters. A quantitative model for evaluating location protocols has been addressed in [6], but only static networks model is analysed, whereas dynamical networks model is simulated. In [7] authors propose a model to evaluate the scalability of ad hoc topological (proactive, reactive, and hybrid) protocols; they also define a metric, named *total overhead*, corresponding to the overhead generated by a protocol. In this study, for DSR (Dynamic Source Routing) protocol, only a lower bound of the overhead is computed in a static context, (I.e. none route is broken and built again). In [8], authors introduce a model to compute the lifetime of links in a highway VANET. Unfortunately, no protocols comparison is provided.

In this paper, we propose an approach for the evaluation of routing protocols using a quantitative model and very few simulations - the simulation is only used to compute some basic mobility parameters of the complex quantitative model - . We used our approach to determine the scalability of the main routing protocols in vehicular ad hoc networks on highways.

In the section II, we introduce the main features of reactive and geographic routing protocols. The section III is devoted to the partially quantitative model that we have developed. Finally, we effectively compare the routing protocols.

II. VANET ROUTING PROTOCOLS

We consider two main classes of routing protocols which are best-suited for VANET [1], i.e. to deal with fast moving nodes and frequent topology changes.

The first protocol class is topology-based (i.e., the nodes must discover and maintain the routes by exchanging messages between neighbors). Processing of routage tasks can be either proactive or reactive. Only the main reactive protocols like DSR [9], AODV (Ad hoc On-Demand Distance Vector) [10] or DYMO (DYnamic MANET On-demand) [11] are well-adapted to the dynamic networks. We find also in this class, hybrid protocols which combine the advantages of both reactive and proactive protocols, like ZRP (Zone Routing Protocol) [12].

The second class is the geographical-based (i.e., each node must know its own geographical position which can be obtained with a global navigation system like GPS). No network topology knowledge is needed for routing packets. Therefore, they are adapted to dynamic networks. However, geographical routing protocols required a location service that provides the location of specific node [6], [13], [14], [15].

Before explain we model, we remind the routing mechanismes for these protocols.

A. Reactive topological protocols

When a source node wants to communicate with a destination node, it broadcasts a message in the network, called RREQ (Route Request) in order to find a route to the destination. On RREQ message reception, the destination node sends a reply to the source node: a Route Reply message (RREP).

When a node (except the destination) receives for the first time a RREQ message, it forwards it to all its neighbors. The processing of a RREQ message depends of the routing protocol. In the case of a protocol requiring routing tables, like AODV or DYMO, the intermediate nodes update their routing table (to add a route to the source of the RREQ message). In the case of a source-routing protocol, like DSR, at the reception of a RREQ message, the intermediate nodes add their identifier to the route from the source contained in RREQ message. Thereby, the completed route is recorded in the RREQ message when it reaches the destination node.

The reply message (RREP) follows the reverse route followed by the RREQ message. The reverse route is computed with the help of routing table in intermediate nodes - in case of routing table based protocols as AODV or DYMO -. Or the reverse route is recorded in the RREQ message - in case of source routing protocols as DSR -.

The protocol must also update the routes using the comminication link break detection. During the data exchange, an intermediate node must check the packet reception by the next node on the route. If a intermediate node has not receive the acknowledgment after a predefined delay t; it assumes that the next node is *unreachable*. The t value is a parameter that depends on the network. When a node has detected a comminication link break along the route, it sends a message called Route error (RERR) to the source node. As a consequence, the source node start again the process to discovers a route to the destination node. If the process fails, then the destination node is assumed to be unreachable from the source node.

B. Geographical protocols

With a geographical protocol, two requirements influence the overhead: the knowledge of location of neighbor nodes and the knowledge of the destination node location. Notice that each node has to know its own geographical position with a positioning system, like GPS.

The routing principle is the following: a node sends its messages in the direction of the location of destination node. The neighbor with the closest position to the destination forwards the message. Therefore, in basic geograhical protocols, each node must know the position of its neighbors. For that, each node broadcasts a position advertissement message, called Hello, to its neighbor nodes periodically (proactive method), or on demand (reactive method).

This discovery of neighbor positions constitutes a part of geographical protocols overhead. In [16], authors introduce a method called CBF (Contention-Based Forwarding) used by the nodes in order to decide to forward or not a packet in its neighborhood. This decision is taken by a node without any knowledge of its neighbors localisation (unlike). The forwarding node transmits the packet to all neighbor nodes. At the reception of the packet, each node starts a timer with a value proportional to its distance to the destination node. The first neighbors node whose the timer stops, forwards the packet (it is the nearest node of the location of the destination), the other neighbors stop their timer: they will not forward the packet.

The location service is used to discover the geographical position of the destination by the source node. In case of greedy protocol, a request, called LREQ (Location Request) is broadcasted on the network. When the destination receives this request, it sends a reply to the source, called LREP (Location Reply) containing its geographical position. Thereby, this location process is similar to the route discovering process of the reactive topological routing protocols. Two Techniques based on *encounters* was proposed in order to limit the overhead generated by a greedy protocol : GLS (Grid Location Service) [15] and its variant, GHLS (Geographic Hashing Location Service) [6]. GHLS is simpler and more efficient than GLS [6], in consequence, only GHLS is considered in following.

In GLHS, each node has a location server. When a source node wants to know the destination node position, it sends a location request message to the server corresponding to the destination node. The server node replies by sending the position of destination node to the source node. The location of the server node is computed by a hash function (the input data of hash function being the destination node identifier). The server node is the closest node to the geographical position computed by the hash function. So a location request and its reply are sent in unicast fashion.

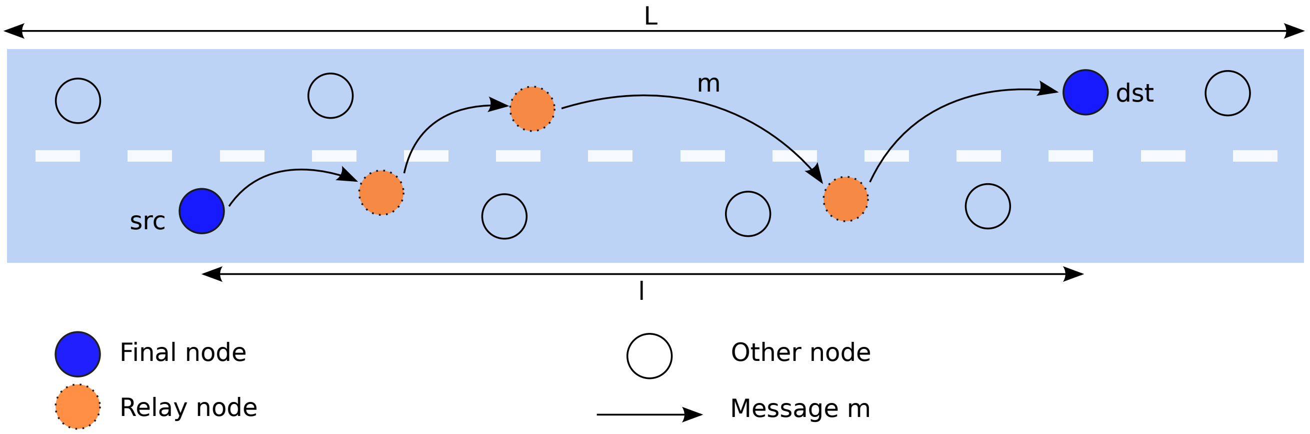

Fig. 1. Communication model. In the figure, the number of relay node is $r(m) = 3$

In the next section, we introduce our model to evaluate the number of signalling messages sent by both topological and geographical routing protocols.

III. OVERHEAD EVALUATION MODEL

This study is focused on the scalability property that can be characterized by many performance criteria like delays or overhead. As we have explained in the previous section, each protocol class generates overhead due to either route discovery process or destination location discovery process. Obviously, minimal overhead increases the actual throughput of a VANET. As the size of control messages is quite small with respect to the size of layer two trame, we study the number of control messages, instead of the amount of information transmitted. Indeed, in wireless network, the scalability is limited to channel sharing and the medium access is costly. Then, for small messages, the cost is not the message size but the number of medium access, i.e. the number of message.

We aim to quantify the number of signalling messages for given network configurations, in terms of number of nodes, route length, area size, etc. Firstly, we introduce our overhead evaluation model. Next, we describe the pertinent parameters for the evaluated protocols. Then, we determine generated overhead by a protocol for one communication.

A. *Model principle*

The model described in the following is depicted in Figure 1 We consider a VANET taking place on a highway (thus the netwok has a line topology). We study a single communication between a source node, called src, and a destination node, called dst. In an ad hoc network, a message sent by the source can be relayed by one or several nodes, called *relay nodes*.

Let $M(P)$ the set of control messages for a protocol P. For DSR example, $M(DSR) = \{RREQ, RREP, RERR\}$. The Equation 1 determines the total number of messages forwarded per second N_P for one communication between src and dst for the P protocol.

$$N_P = \sum_{m \in M(P)} N(m) \tag{1}$$

We must compute N_P for each compared protocol.

Let us compute the $N(m)$ value : number of messages of type m forwarded by second in case of a single communication between src and $dest$ with the routing protocol p.

$N(m)$ depend on two parameters: $f(m)$ and $r(m)$. $f(m)$ is the sending frequency of m (number of transmissions per second) and $r(m)$ is the number of relays for m.

$$N(m) = f(m)r(m)$$

The route length taken by a m message in meters is denoted $l(m)$. The value of $d(m)$ is the relays density for m (i.e; the number of relay nodes that transmit a message m per meter). We have $r(m) = d(m)l(m)$

Then, we have to estimate the values of three parameters: $l(m)$, $d(m)$ and $f(m)$ to compute $N(m)$.

Theses values depend one the m forwarding mode. We have identified three forwarding modes used in the studied protocols:

- A message is transmitted on the network in *unicast*, if the source and the relay node forward the message only to one neighbor.
- A message is transmitted on the network in *broadcast*, if both relay and source node forward the message to every neighbor.
- A message is transmitted on the network in *unicast with knowledge of neighborhood*, if the source and the relay nodes forward the message to a single neighbor, but the source node and the relay have to know the geographic position of their neighbors.

In the follow sections, we etablish the formule computating $l(m)$, $d(m)$ and $f(m)$

B. Route lenght taken by m : $l(m)$

In case of a message m_b transmitted in broadcast mode, $l(m_b)$ is L, L being the highway length in meter.

In case of a message m_u transmited in unicast mode (with or without knowledge of neighborhood), $l(m_u)$ value depends on the average distance between the source and the destination. Let x_{src} (respectively x_{dst}) be the node position of src (respectively dst). We consider an uniform distribution of vehicles on the highway lanes. In this case, the average uni-dimensionnal distance between src and dst is expected to $E(|x_{src} - x_{dst}|)L$. We can verify

$$E(|x_{src} - x_{dst}|) = \int_0^1 \int_0^1 |x_1 - x_2| dx_1 dx_2 = \frac{1}{3}$$

We note that uniform distribution for vehicular on a highway is a strong hypothesis. But this distance $l(m)$ is not decisive to evaluate the overhead evolution according to the highway lenght L.

C. Relays density : $d(m)$

Let d_t the density of vehicles in the highway. If a message is transmitted in *broadcast*, then

$$d(m) = d_t$$

We denote by R the the coverage zone radius of the VANET. If a message is transmitted in *unicast*, then

$$d(m) \geqslant \frac{1}{R}$$

Indeed, only the intermediate nodes send m's message. In wireless communication, as VANET, a sending packet by a node x can be received by all n's *neighbors* i.e. all nodes in the coverage zone of x. The distance between two intermediate nodes is at maximum R, hence $d(m) \geqslant \frac{1}{R}$.

If a message is transmitted as *unicast with knowledge of neighborhood*, two cases are possible according if neighborhood discovery protocol is reactive or pro-active.

In case of a reactive neighborhood discovery protocol then

$$d(m) = d_t$$

Indeed, for the reactive neighborhood discovery, each intermediate node must know the positions of its neighbors. Hence, the intermediate nodes send a NREQ (Neighbor Request) message to theirs neighbors, and the neighbors repply by sending their position with a NREP (Neighbor Reply) message. All nodes in the neighborhood of a relay send a message, thus the density sent message is the vehicle density: d_t.

For the pro-active neighborhood discovery protocol, the relay nodes do not need to send a message to know the position of their neighbors. However, the Hello messages are regularly sent to update the neighborhood knowledge, and the sending of the Hello message must be taken into account in the model.

$$d(m) \geqslant \frac{1}{R}$$

D. Sending frequency for reactive topological protocols : f_b

With a reactive ad hoc protocol, the transmission frequency of a signalling message depends directly on route failure frequency. Indeed, when a route is broken, the protocol sends a new path finding request in the network.

The sending frequency f_b depends on network mobility. Indeed, in case of static network, it is not necessary to send a message for path reconstruction or routing table update, thus the number of route request is one and the sending frequency is close of zero. On the other hand, more the network is dynamic, more the sending frequency increases.

To compute the route break frequency, we need the communication link failure probability between two nodes. Communication link is a direct communication channel between two mobile nodes. A communication link is broken when the two connected nodes cannot longer communicate directly. The duration between the opening of the communication link and its breaking is called *link lifetime*. We name the communication link break probability, noted $l_b(t)$, the communication link break probability during the time interval t.

The communication link break probability estimation cannot be properly done in an analytic manner. Thus, we compute this value using simulation in subsection IV-A.

We assume that communication link breaks are independent events : the occurrence of communication link break on the route between src and dst makes it neither more nor less probable that another communication link breaks on the same route.

The communication link break independence hypothesis is confirmed by simulations in section IV-B.

With the preceding hypothesis and knowing the communication link break probability $l_b(t)$, we compute the route failure probability during the time interval t denoted $r_f(t, n)$ where n is the number of relay nodes on the route :

$$r_f(t, n) = 1 - (1 - l_b(t))^n$$

We call *route failure frequency*, the number of failure on the route between the source and the destination per second, denoted $f_b(n)$. The route failure frequency is function of the route failure probability:

$$f_b(n) = \frac{r_f(t, n)}{t}$$

The average distance between the source and the destination is $\frac{1}{3}L$ where L is the highway length. We denote n_{avg} the average number of relay nodes between src and dst. We have $n_{avg} = \frac{L}{3R}$. Thus

$$f_b(n_{avg}) = \frac{r_f(t, n_{avg})}{t} = \frac{1 - (1 - l_b(t))^{\frac{L}{3R}}}{t}$$

To conclude, the sending frequency of RREQ, RREP and RERR is $f_b(n_{avg})$.

TABLE I

TRANSMISSION AND FREQUENCY OF GENERATED MESSAGES BY TOPOLOGICAL AND GEOGRAPHICAL PROTOCOLS.

Reactive topologic		
Class of message m	**Forwarding mode**	$f(m)$
RREQ	Broadcast	$f_b(n_{avg})$
RREP	Unicast	$f_b(n_{avg})$
RERR	Unicast	$f_b(n_{avg})$

Geographic (proactive)		
Class of message m	**Forwarding mode**	$f(m)$
Hello	Broadcast	$\frac{1}{C_{to}}$

Greedy location service		
Type de Message m	**Forwarding mode**	$f(m)$
With CBF		
LREQ	Broadcast	f_l
LREP	Unicast	f_l
Without CBF		
LREQ	Broadcast	f_l
LREP	Unicast neighborhood	f_l

Rendez-vous based location service		
Class of message m	**Forwarding mode**	$f(m)$
With CBF		
LREQ	Unicast	f_l
LREP	Unicast	f_l
LUpdate	Unicast	$\frac{1}{U_L}$
Without CBF		
LREQ	Unicast neighborhood	f_l
LREP	Unicast neighborhood	f_l
LUpdate	Unicast neighborhood	$\frac{1}{U_L}$

E. Location frequency for a geographical protocols: f_l

A geographical frequency is also sensitive to network dynamics. Indeed, when a packet reaches the node closest to the destination position (position indicated by the source in the message), then the node checks if it is the real destination, comparing with its identifier. If the destination identifier does not match, it means the destination position has changed, then the packet cannot reach the destination. The source must send a new location request LREQ, that induces further overhead traffic.

We can estimate the average vehicle speed on a highway, in case of smooth traffic, this value is the speed limit on the highway. We note this average speed v_{avg}. A packet reaches the destination if the gap between the real destination position and the one recorded by the source is lower than the value of R (the coverage zone rayon).

Therefore, the *location frequency* is $f_l = \frac{v_{avg}}{R}$.

To conclude, the sending frequency of LREQ and LREP messages is $\frac{v_{avg}}{R}$.

F. Parameter values for each protocol

Table I shows the main parameter values needed to estimate (1) reactive topological protocol overhead, (2) the greedy location service protocol overhead and (3) a rendez-vous based location service protocol overhead like GHLS. For each protocol, we present the forwarding mode and the sending frequency.

TABLE II

LINK BREAK PROBABILITY $l_b(1.5)$. DENSITY IN VEHICULAR PER KM WITH THREE LANES

Density	Probability	Relative Speed
12	0.022	2.02
24	0.026	1.82
30	0.028	1.88
36	0.040	2.09
42	0.056	2.23
48	0.065	2.49
54	0.079	2.55
60	0.091	3.24
84	0.156	4.57
132	0.243	6.66
240	0.242	5.12

We consider two constant parameters of the geographic protocols: C_{to} and U_L.

U_L is the sending frequency of the geographical position by a node to its location server in case of geographical protocol enhanced with GLS or GHLS.

In basic geographical protocol the neighbor positions are recorded in a cache. The cache lifetime is the value of C_{to}.

IV. ROUTE FAILURE FREQUENCY EVALUATION

For the RREQ, RREP or RERR reactive protocol class messages, the frequency depends on the link failure probability. In this section, we estimate this probability depending on vehicular density, and verify the link failure independence hypothesis by comparing the model with the values obtained by simulation.

The simulator used to estimate the breaking frequency and breaking is based on the highway traffic model presented in [17] and [18]. Our team has developed a micro-mobility simulator where each vehicle computes its position and its speed depending on its environment [4]. This part of the simulator computes the node position on the network at regular intervals during the simulation process. The graph nodes are vehicles. A link between two nodes exists if and only if the distance between two nodes is lower than R. In other words, a vertices between two nodes i et j exists if and only if $\|x_i - x_j\| < R$.

Our interest is only in estimating the links and routes lifetime. The link lifetime is computed from the inter-distance and relative speed between two nodes. The route lifetime is computed as the lowest link lifetime on a route. The link failure probability $l_b(t)$ is the proportion of a link with a link lifetime lower than t. Also, the route failure probability $r_f(t)$ is the proportion of a route with a lifetime lower than t.

A. Link break probability $l_b(t)$ evaluation

To complete the model, we estimate the link break probability and the average relative speed between vehicle (in m/s). The results are shown on Table II. The parameter $t = 1.5s$ is defined as the time without any reception of acknowledgement before considering that a communication link is broken. $l_b(1.5)$ is a input parameter for the model ; route failure frequency is infered from this parameter.

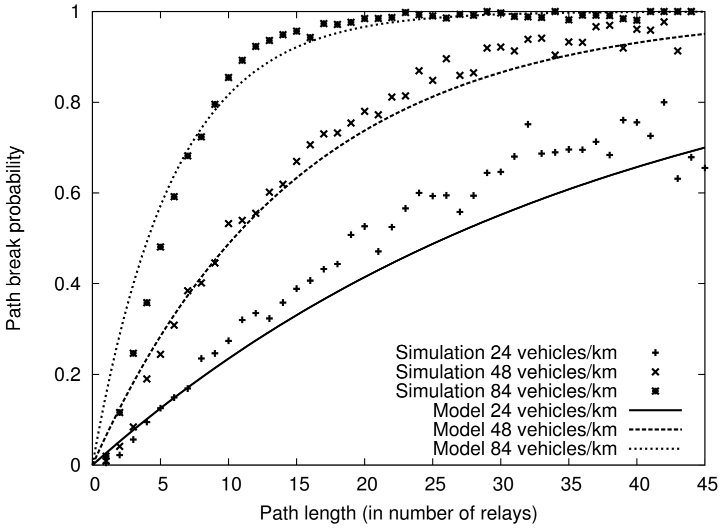

Fig. 2. Route failure probability vs route length, and the vehicular density.

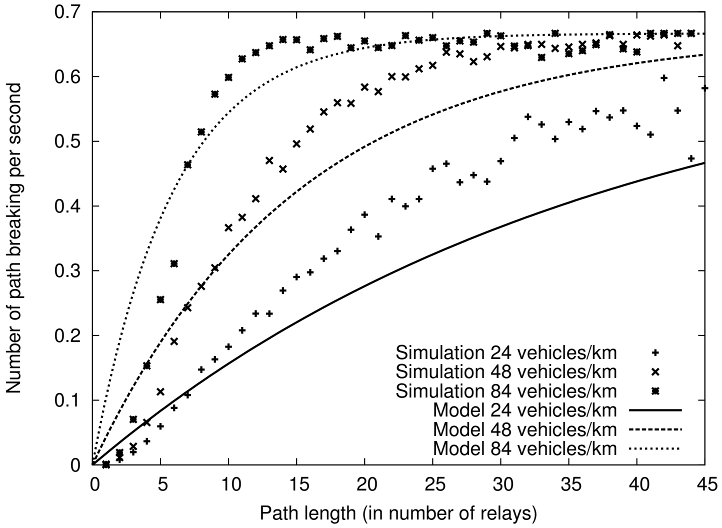

Fig. 3. Route failure frequency vs route length, and the vehicular density.

B. *Confrontation of route failure probability model*

We verify the link break independence hypothesis (communication link breaks on the route are independent events) by comparing the model with the values obtained by simulation.

For that, we evaluate the route failure $r_f(t,n)$ probability. The Figure 2 shows the curves obtained from the model for different values of road traffic density d_t depending on route length. This figure allows a comparison of the computed values from the model with estimated values by simulation. The points follow the theoretical curve computed from the model. The model is more reliable with a high vehicular density. Then, the link break independence hypothesis is confirmed.

In same way, Figure 3 shows the route failure frequency $f_b(n)$ computed from the model, compared to the frequency estimated values by simulation. From this two figures, we conclude than values computed with model is similar to the values computed by simulation.

C. *Confrontation with network simulation*

We use the JiST/SWANS network simulator to validate the number of signaling message sent by DSR protocol (reactive routing protocol) estimated with the quantitative model. The simuation time is fixed to 30 s and the communication bitrate at 512 kbit/s for one communcation. For 30 vehicles per kilometer, the number of signaling message sent per seconds match with our quantitative model prediction (Figure 4). This results show a good evaluation with our hybrid model, i.e. simulation for $l_b(t)$ parameter and a quantiative model for evaluated the number of signaling message sent.

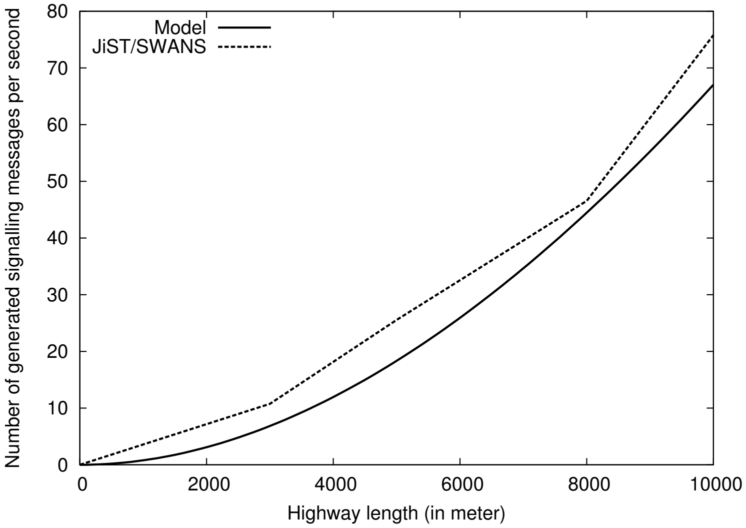

Fig. 4. Number of signaling message sent by DSR protocol evaluated with the quantitative model and JiST/SWANS.

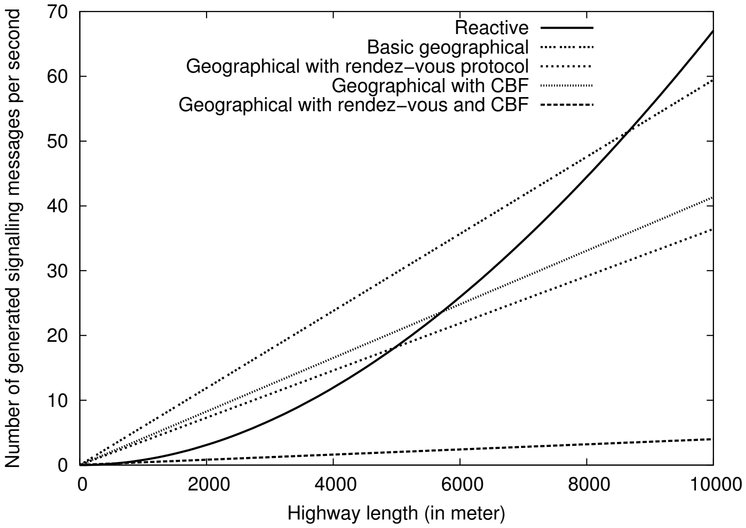

Fig. 5. Number of control messages depending on the highway length. Density is 30 vehicles per km

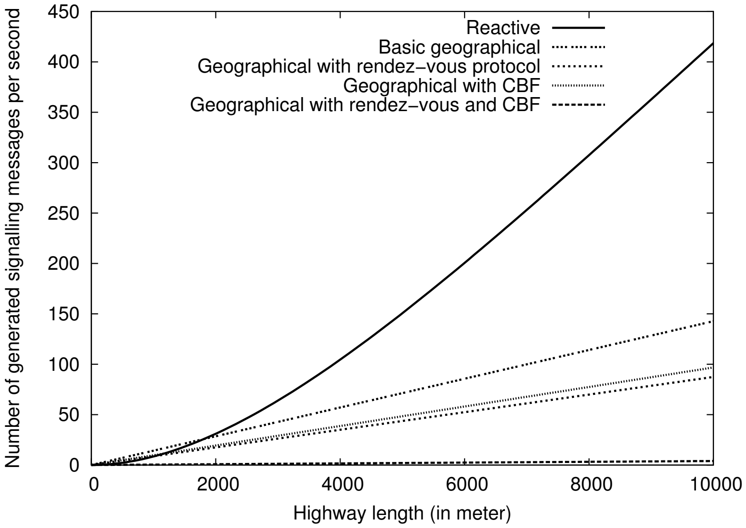

Fig. 6. Number of control messages depending on the highway length. Density is 72 vehicles per km

V. QUANTITATIVE RESULTS

In this section, we apply the model described in section III. Depending on expression and link failure probability evaluation results (sub-section III-D), we calculate the number of control messages to compare both classes of routing protocols for VANET: topological and geographical. For some results, we vary the density and the route length. The fixed parameter values are shown in Figure 7.

Fig. 7. Fixes parameters

v_{avg}	$33\ m/s$
t	$1.5\ s$
R	$250\ m$
C_{to}	$30\ s$
U_L	$30\ s$

The average target speed is fixed at speed limit on highway 120 km/h (33 m/s). After a delay t without receive a acknowledgement, the node is unreachable. Three message are send before considering the node unreachable. The first message send at $t_0 = 0$. If not acknowledgement received, the second message is send at $t_1 = 500\ ms$. And the last try is send at t_2 (twice t_1 after): $t_2 = 1500\ ms$, hence $t = 1.5\ s$. $R = 250\ m$ is the radius for 802.11a with 250 mW power and the threshold at -64 dBm. C_{to} and U_L is fixed to maximum average time for the gap between two vehicle is superior at R. The maximum relative average speed is about $max(v_{rel}) = 7\ m/s$ (Table II), thus $C_{to} = U_L = \frac{R}{max(v_{rel})} \approx 30\ s$.

For each studied protocol, we compares the number of generated signalling messages for two different density. The Figure 5 is the result for density fixed to 30 vehicles per km with 3 lanes. This density corresponds to network connected. We vary the highway length. The graphic shows that a reactive protocol generates more messages than a geographical protocol beyond 9 km length, and is more sensitive to the highway length. Below 4 km length, only CBF with a rendez-vous protocol is better that a reactive protocol. We explain that by the effect of a high frequency route reconstruction that forces the source to send a lot of messages in broadcast mode (RREQ).

The Figure 6 is the result for density fixed to 72 vehicles per km with 3 lanes. This density corresponds to highway overloaded. The graphic shows that a reactive protocol generates more messages than a geographical protocol beyond 2 km length. The impact of density on the performance is significative.

In a geographical protocol context, we show the interest of using CBF with a rendez-vous protocol. With this combination, the routing protocol do not need to issue broadcast messages, and to send hello messages. Therefore, all messages are sent in unicast and the protocol is insensitive to the number of vehicles as well as to the highway length and vehicular density.

VI. CONCLUSION

We have compare the most suitable routing protocols for vehicular network quasi-independently of a simulator. We have studied the process of generation of signaling messages to characterize the overhead. Precisely, we give of formula that compute the number of signaling messages generated according to the communication link failure probability. Then, we determine the frequency of route failures using simulation. Using our formula and the estimation of route failures probability, we compared two more prominent families of routing protocols: geographical class and reactive one. We conclude that a geographic protocol using CBF (Contention-Based Forwarding) and GHLS (Geographic Hashing Location Service) has a better scalability than any other existing routing protocol on vehicular network on highways. Our perspective is to extend this study to a vehicular network in an urban context and take into account some optimization processes (like piggyback message).

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