An Analytical Evaluation of a Map-based Sensor-data Delivery Protocol for VANETs

Sergio Martínez Tornell, Enrique Hernández-Orallo, Carlos T. Calafate, Juan-Carlos Cano and Pietro Manzoni
Universitat Politècnica de València
Camino de Vera, s/n, 46022 Valencia, Spain
sermarto@upv.es, {ehernandez, calafate, jucano, pmanzoni}@disca.upv.es

***Abstract*—Intelligent Transportation Systems (ITS) applications make an increasing use of intelligent vehicles as mobile sensors, so-called "floating cars", for traffic monitoring and management. One of the key issues is to provide a fast and efficient transmission of the information gathered in the vehicles to the traffic management centers.**

The Delay Tolerant Networks (DTN) approach is considered the best strategy to address the specific issues of the VANETs, namely high mobility, variable node density or frequent radio obstacles. Several protocols have been proposed for DTNs, being the epidemic routing (and variations of it) the most representative protocol. Nevertheless, the availability of navigation systems, thanks to which each vehicle is aware of its location within a map, introduces the possibility for a new routing approach, known as Geographic Routing.

In this paper we introduce a Map-based Sensor-data Delivery Protocol (MSDP), which combines the information about the road map and the node's routes to improve data delivery. In order to evaluate the performance of our protocol we introduce an analytical model that takes into account the effect of constrained buffers. We also present, through simulation, the effect of both network congestion and realistic mobility patterns. The results show that adopting the Map-based Sensor-data Delivery Protocol (MSDP) routing mechanism allows achieving a reasonable delivery time with an insignifficant overhead compared with epidemic routing. Furthermore, our proposal is very efficient at reducing channel usage, avoiding the congestion effects of epidemic routing.

***Index Terms*—Wireless Networks, DTNs, VANETs, Wireless sensor networks, GPS.**

I. Introduction

Vehicular Ad-Hoc Networks (VANETs) turn every mobile car into a wireless router with forwarding capabilities. For the automotive industry, VANETs are proposed to improve safety-related and data communication among vehicles and between vehicles and Road Side Units (RSUs). Regarding safety-related communications, vehicles have different sensors which collect information not only about engine status, or speed, but also context information (e.g. weather or traffic status). This information must be collected and sent to data centers using VANET technologies as a way to improve road security and traffic management.

Although VANETs are considered as a subset of Mobile Ad-hoc NETworks (MANETs), they present some specific characteristics, like high speed and the presence of obstacles, like buildings, that produce a high variability in the network topology. Common MANET protocols assume the existence of a connected path between sender and receiver, and they do not fit appropriately in VANET scenarios. Under these conditions, where only intermittent connectivity and opportunistic contact takes place, we propose the use of Delay Tolerant Networks (DTNs) to deliver data obtained from the vehicles to an RSU. DTNs allow sharing information even in the presence of high delays. In DTNs, when a route to the destination of a message does not exists, the message is stored and carried until a route becomes available (this is known as the "store-carry-forward" paradigm).

Several protocols have been proposed for DTNs. The Epidemic Protocol [1] is based on copying the sender packet to a new node when a contact occurs (it *infects* the node) until one of the *infected* nodes contacts the destination node. This approach leads to a waste of resources when the number of nodes increases. To reduce the amount of generated network traffic some modifications have been proposed; in [2] and [3] the authors propose limiting the number of copies. In order to keep a high delivery ratio, they try to choose the best node to send a copy to; however, they do not take advantage of multi-hop communication. In [4] the metric used to determine which will be the next forwarding node is a parameter obtained from the list of previous encounters of a node, *i.e.* nodes with more previous encounters are considered better forwarders. There have been some improvements, like PRoPHET+ [5] or MaxProp [6], that also consider some general parameters such as buffer space availability, energy consumption, etc. However, we believe that the use of the previous encounters to determine the forwarding node is not an efficient choice for the application under evaluation in this paper. We consider that, although human mobility patterns tend to be repetitive due to their daily routines, using the list of previous encounters as a routing parameter would produce a high delay.

A common characteristic of VANET nodes is the availability of a Navigation System. This way, each vehicle is aware of its geographical location, as well as its neighbors. This information can be used to increase the efficiency of packet delivery in DTNs. This introduces a second group of routing algorithms usually called *Geographic Routing*. Some authors have focused on protocols that make an intensive use of the deployed infrastructure [7], which leads to a huge infrastructure cost. Some other authors have focused on the direction of nodes as a decision parameter [8], obviating that in VANETs node mobility is constrained by street topology, and so the direction of the nodes, especially in urban environments, is rarely going to be constant. In this context, GeOpps [9] is one of the most advanced protocols proposed for DTN routing in VANETs. It uses the information obtained from the Navigation System (NS) to determine the closest point to the destination along the route of a node. The next forwarding node is the one whose route passes closer or arrives sooner to the destination; this proposal has some problems that have been partially solved in GeoDTN+NAV [10]. GeoDTN+NAV adds a preceding step: before starting the DTN routing, it tries to find a path using GPSR [11] in order to reduce the delay. GeoSpray [12] is another protocol closely related with GeOpps that uses a multicopy scheme.

However, none of the previous protocols considers important parameters like the amount of data in the forwarding node's buffer, or the amount of data that the forwarding node will be able to send to the destination, neither do they consider the need for fragmenting messages when their size surpasses the Maximum Transfer Unit (MTU) supported by the network.

In this article we propose the Map-based Sensor-data Delivery Protocol (MSDP), a DTN routing protocol that, using the information obtained from a Geographic Information Service and the real street/road layout obtained from a Navigation System, attemps to find the best next forwarding node. The novelty of our proposal is that to efficiently deliver the collected information to the control center, it bases its routing decisions not only on distance or directions, but also on the programmed routed of the node, the amount of data stored in the vehicles' buffer, and the trustworthiness of the data source.

We evaluate the performance of MSDP using both analytical models and simulations. We compare our protocol with the Epidemic routing protocol since the latter achieves an optimal delivery time when there are no buffer restrictions or congestion issues [13]; however, itintroduces a great overhead due to the high number of messages transmitted. Since mobile nodes have limited storage capacity and work under congestion conditions, we also compare MSDP with the more realistic *restrained* Epidemic routing protocol.

Firstly, we introduce analytical models for MSDP and the Epidemic routing which return the time it takes for a packet to arrive to the destination nodes (that is, the RSU nodes) and the overhead (the number of messages transmitted). For a more realistic evaluation, these models also include the effect of buffer load in a buffer restricted scenario. The results of the analytical model show that MSDP routing has a reasonable delivery time with a insignifficant overhead compared with the unrestricted epidemic routing. However, if we compare the results with the buffer-restricted epidemic routing, we can observe that, as we increase the load in the network, the delivery time also increases, reaching higher values than those obtained by the MSDP approach. Furthermore, under MSDP routing, the load has no effect on the delivery time or the overhead.

The effect of network congestion (*i.e.* collisions and exponential back-off) and realistic mobility patterns can only be evaluated through simulation. Thus, we evaluate the performance achieved under accurate mobility and non-deterministic propagation models using the ns3 simulator. Simulation results confirmed the analytical results and also that MSDP achieves a higher delivery ratio and a smaller delay with much less channel congestion than the restricted epidemic routing strategy.

This paper is organised as follows: in Section II we describe our proposal. In Section III we model our protocol analytically. The simulation environment, settings and results are presented in Section IV. Finally, section V concludes this paper and provides details about future work.

II. MSDP OVERVIEW

The goal of MSDP is to efficiently transmit the information gathered from vehicular sensor networks to the RSUs. The RSUs locations have been chosen by an involved entity, and are connected to a traffic control center using a backbone network. Two networks interfaces are involved in this information delivery: an IEEE 802.11p interface for Car-to-Car (C2C) communication, and an IEEE 802.11n interface for Car-to-Infraestructure (C2I) communication (that is, between vehicles and RSUs). In addition, it is mandatory that all mobile nodes (vehicle) have a certain degree of knowledge about their own route retrieved from a Navigation System (NS). The NS is defined as an interface which provides some minimal services, and it may simply be a preloaded static route plus a location service.

The basis of the MSDP protocol is a defined *UtilityIndex* (UI). This index is used to make the routing decisions and it is based on several factors, such as the trustworthiness of the NS, the time to reach an RSU, and the transmission availability. In other words, a higher UI value indicates that the node is a better candidate to reach the RSU.

Figure 1 presents a typical situation for MSDP, where dashed lines represent the movement of the nodes, while solid lines represent wireless transmissions. In this example, the sender node is m_1. Our protocol can be shortly explained as follows: information messages are generated by bundling information from different sensors of the vehicle. Large messages are split into packets that are stored in the node's buffer. In MSDP, those nodes which have packets in their buffers are called *custodians*. Initially the sender node m_1 is a *custodian*. *Custodians* periodically broadcast messages

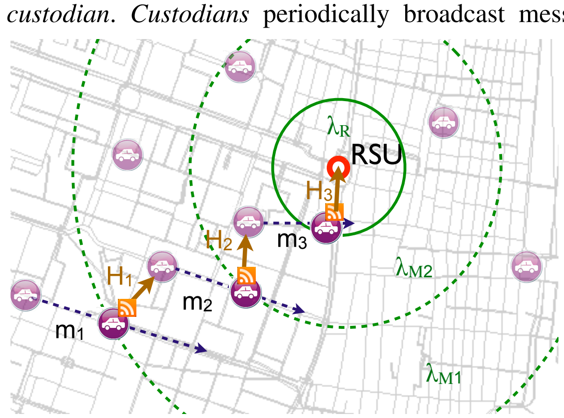

Fig. 1: Typical situation for MSDP, dashed lines represent the movement of the nodes, while solid lines represent wireless transmissions.

announcing their presence and their UI. Nodes which receive those announcements are called *candidates*. *Candidates* will respond those announcements by broadcasting their presence and their UI. If the UI of the *candidate* is higher than the UI of the *custodian* it can transmit the packets to this *candidate*. If a transmission occurs, the *candidates* must confirm the reception of the packets through an ACK message. It is important to remark that a *custodian* will never remove a message until a *candidate* confirms itself as the new *custodian*. For example, in figure 1 the *custodian* node m_1 has contact with the *candidate* node m_2, which has a higher UI, and so it decides to transmit its packets to m_2. So, from now on, m_2 is the new *custodian* node. Finally, when a *custodian* reaches an RSU, it will try to use this communication opportunity to deliver as many packets as possible. RSUs will send the packets to the control center, which will reassemble and process the original information messages, through the backbone network. This is the final hop of our example, when *custodian* node m_3 transmits the packet to the RSU.

A. Routing decision

The main innovation of our proposal is the way our protocol makes routing decisions. In MSDP, the value of a function, called UtilityIndex (UI), is used to choose the best *candidate* to forward packets. *Custodians* also compare themselves against *candidates* and, in case that they are the best node, the transmission opportunity will be ignored. The UI is computed locally and communicated to neighbor nodes through messages. The higher the UI is, the better the candidate. The UI is defined by the following function:

$$\text{UI} = \frac{P^2}{T} * Q \tag{1}$$

The three parameters, P, T, and Q, are defined as follows:

Trustworthiness factor (P): This parameter tries to quantify the reliability of the information obtained from the NS related with the future route of the node. It is defined between 0 and 1, being 0 associated with the most unreliable vehicles, as a vehicle without a defined route, and 1 with the most reliable vehicles, as a train or a bus with a fixed route. We have introduced it with the objective of penalizing those nodes prone to cause wrong routing decisions.

Time to reach an RSU (T): Nodes can estimate the time to reach an RSU by using the information obtained from the NS. Evidently, better *candidates* present lower times to reach an RSU. In an attempt to emphasize the differences between small times, T is defined as follows:

$$T = \frac{log(t+1)}{log(\tau)} \tag{2}$$

being t the time to reach the next RSU expressed in seconds, and τ the maximum admitted delay.

Transmission availability (Q): Nodes can obtain the average transmission rate of each RSU through the NS. Combining this information with the opportunity estimated duration, nodes are able to make an estimation of the amount of data that they will be able to interchange with an RSU. Using the ratio between the amount of data contained in its buffer and the previously described estimated value, our protocol prioritize those nodes whose ratio is closer to zero. Q represents this availability, and it is defined by the following function:

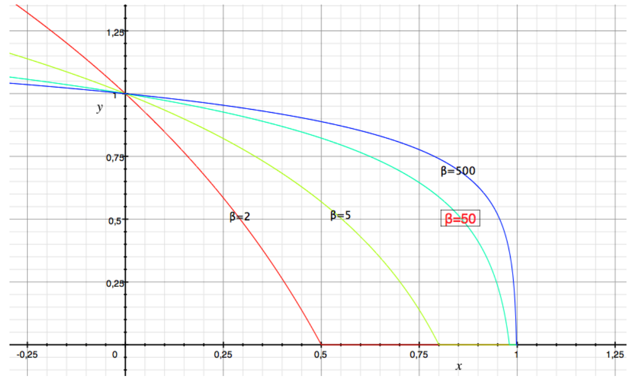

Fig. 2: Variation of Q for different values of β.

$$Q = max[\frac{log(\beta * (1-q))}{log(\beta)}, 0] \tag{3}$$

being q the rate previously mentioned, and β an application parameter that modifies the slope of the logarithmic function and the maximum value that q can reach before a node is disabled as *candidate*. Figure 2 shows the variation of Q for different values of β. It can be appreciated that the higher is the value of β, the lower is the value of q which disables a node, *i.e.* makes Q, and thereby the UI, equal to zero.

Finally, for a full description of the MSDP protocol see [14].

III. Analytical Evaluation

In this section we model the performance of the MSDP and the Epidemic routing using Markov chains. The goal is to obtain the time that a packet needs to be delivered to the destination nodes (that is, the RSU nodes) and the cost (the number of hops or transmitted messages). Using this model we can compare our MSDP scheme with the Epidemic routing approach. The Epidemic routing is optimal in delivery time, but assumes that all nodes have sufficient space to store all packets. However, mobile nodes have limited storage capacity, so we also compare the MSDP routing with the more realistic constrained buffer Epidemic routing (we call it, the *restricted* epidemic routing).

For our models we assume that the rate of contacts between two mobile nodes and a mobile node and a static node (that is, the RSU node) follows an exponential distribution. Recent works show that the occurrence of contacts between two mobile nodes follows an exponential distribution with rate λ [15]–[17]. This has been shown valid specially for VANETs, considering vehicle-to-vehicle communications as well as with the roadside infrastructure (vehicle-to-roadside communications) [16]. There is some controversy about whether or not this exponential distribution can reflect some real mobility patterns. Empirical results have shown that the aggregated inter-contact times distribution follows a power-law and has a long tail [18]. In [19] it is shown that, in a bounded domain (such as the one selected along this paper), the inter-contact distribution is exponential but in an unbounded domain, it follows a power-law distribution instead. The work in [20] analyzed some popular mobility traces and found that over 85% of the *individual pair distributions* fit an exponential distribution. Therefore, we consider that using an exponential fit is a good choice to model inter-contact times. Moreover, by using exponential distributions we can formulate analytical models using Markov chains.

The network is modeled as a set of M wireless mobile nodes and R fixed destination nodes (RSU nodes). There are two vehicles contact rates: λ_M is the mean contact rate between mobile nodes (that is, inside the set of M nodes) and λ_R is the mean contact rate between mobile nodes and RSU nodes (that is, between the two sets). Upon contact, the packet can be transmitted. Nevertheless, a contact does not always imply a transmission. There are several factors that can reduce this transmission, for example the contact duration is too short to transmit the packet, other packets are transmitted before, or error transmissions occur. Thus, we introduce two new parameters into the model: the probability that a packet is successfully transmitted (or forwarded) between mobile nodes (p_{tM}), and the probability of transmission between a mobile node and the RSU nodes (p_{tR}).

A. Modelling Epidemic diffusion

In this section we derive a model for evaluating the time and cost of reaching the destination node for epidemic routing. First, we introduce a model for unrestricted epidemic diffusion (there is no buffer limitation in the nodes), and then we introduce a model for constrained buffer epidemic diffusion.

Several models has been proposed to evaluate the performance of Epidemic routing. Markov chain models were introduced in [15] for epidemic routing and 2-hop forwarding, deriving the average source-to-destination delivery delay and the number of existing copies of a packet at the time of delivery. The model in [13], which is based on Ordinary Differential Equations (ODE), obtained similar results. The previous models assume that all nodes are mobile with a unique contact rate and full probability of transmission when a contact occurs ($p_{tM} = 1$). Thus, we extend the Markov Chain model to include the mobile and destination set of nodes with their different contact rates (λ_M and λ_R) and the probabilities of transmission (p_{tM} and p_{tR}).

The basis of the model is a 2D Continuous Time Markov chain (2D-CTMC) with states $(d(t), m(t))_{t\geq 0}$, where $m(t)$ (and $d(t)$) represents the number of mobile (and destination) nodes that have the packet at time t. At the beginning only one mobile node (the sender node) has the packet. Then, when a mobile contact occurs, m can be increased by one with probability p_{tM}. Alternatively, when a mobile contacts with a destination node (with rate λ_R), d can be increased by one with probability p_{tR}. The final absorbing states are when $d > 0$. Thus, this 2D-CTMC has an initial state $s_1 = (0,1)$, M transient states (from $s_1 = (0,1)$ to $s_\tau = (0,M)$ states) and M absorbing states (from $s_{\tau+1} = (1,1)$ to $s_{\tau+\upsilon} = (1,M)$). We define τ as the number of transient states ($\tau = M$) and υ as the number of absorbing states ($\upsilon = M$). This model can be expressed using the following transition matrix $\mathbf{P}$ in the canonical form:

$$\mathbf{P} = \begin{pmatrix} \mathbf{Q} & \mathbf{R} \\ \mathbf{0} & \mathbf{I} \end{pmatrix} \quad (4)$$

where $\mathbf{I}$ is a $\upsilon \times \upsilon$ identity matrix, $\mathbf{0}$ is a $\upsilon \times \tau$ zero matrix, $\mathbf{Q}$ is a $\tau \times \tau$ matrix with elements p_{ij} denoting the transition rate from transient state s_i to transient state s_j and $\mathbf{R}$ is a $\tau \times \upsilon$ matrix with elements p_{ij} denoting the transition rate from transient state s_i to the absorbing state s_j.

Now, we derive the transition rates p_{ij}. Given the state $s_i = (d,m)$[1] the following transitions can occur:

- (d,m) to $(d,m+1)$: A new mobile node has the packet, due to a contact between mobiles nodes with rate λ_M. Thus, the transition probability is $t_m = \lambda_M p_{tM} \cdot m(M-m)$ where $(M-m)$ represents the number of pending mobiles nodes that can receive the packet.
- $(0,m)$ to $(1,m)$: An RSU node has the packet, due a contact between a mobile node and a destination node with rate λ_R. Thus, the transition probability is $t_r = \lambda_R p_{tR} \cdot mR$.
- (d,p) to (d,p): This is the probability of no changes and is $1 - \sum_{j\neq i} p_{ij}$.

Using the transition matrix $\mathbf{P}$ we can derive the delivery time T_d. From the 2D-CTMC we can obtain how long will it take for the process to be absorbed. Using the fundamental matrix $\mathbf{N} = (\mathbf{I} - \mathbf{Q})^{-1}$, we can obtain a vector $\mathbf{t}$ of the expected time to absorption as $\mathbf{t} = \mathbf{N}\mathbf{v}$, where $\mathbf{v}$ is a column vector of ones ($\mathbf{v} = [1, 1, \ldots, 1]^T$). Each entry t_i of $\mathbf{t}$ represents the expected time to absorption from state s_i. Since we only need the expected time from state $s_1 = (0,1)$ to absorption, the delivery time T_d, is:

$$T_d = E[T] = \mathbf{v_1}\mathbf{N}\mathbf{v} \quad (5)$$

where T is a random variable denoting the delivery time for all nodes and $\mathbf{v_1} = [1, 0, \ldots, 0]$.

Now, we calculate the overhead, that is, the mean number of copies (or replicas) of the packet until the delivery time. If we assume that a packet is not transmitted again to a node that already has it, the number of copies is equivalent to the number of transmissions. Therefore, the number of copies is done calculating the average number of packets transmitted in each state s_i. To do this, we obtain the duration of each state s_i using the fundamental matrix $\mathbf{N}$. By definition, the elements of the first row of $\mathbf{N}$ are the expected times in each state starting from state 0. Then, the duration of state s_i is $\mathbf{N}(1,i)$. In state $s_1 = (0,1)$ only one node has the packet, and this packet can be transmitted to all nodes (except himself), that is $M-1$ nodes, for the duration of this state (denoted as $\mathbf{N}(1,1)$) with a rate λ_M and probability p_c. Then for state $s_2 = (0,2)$ two nodes have the packet and it can be transmitted to $M-2$ nodes. Thus, for state $s_i = (0,m)$, $i \leq \tau$, the average number

[1]For simplicity, we omit the time in the states (that is $(d,m) = (d(t), m(t))$)

of copies in this state is $\lambda_M p_{tM} \mathbf{N}(1,i)m(M-m)$. Summing up, the overhead (or the expected number of copies) is:

$$O_d = E[C] = \lambda_M p_{tM} \sum_{m=1}^{\tau} \mathbf{N}(1,i)m(M-m) \quad (6)$$

Note that previous expressions for time and copies obtain the same results than equations in [13] when $\lambda_M = \lambda_R$, $R = 1$ and $p_{tM} = p_{tR} = 1$, that is, $T_d = \frac{\log M}{\lambda(M-1)}$ and $O_d = \frac{M-1}{2}$.

B. Constrained buffer

In the *unrestricted* epidemic routing there are no constraints on the number of packet replicas in the network. Now we derive a model for Epidemic routing under constrained buffer (the *restricted* epidemic routing). In this case, we assume that mobile nodes have a limited buffer of size B (that is, they can only store B packets). For the destination nodes, we keep the assumption of unrestricted buffer size (they are fixed nodes, so memory is not a problem).

First, we need to obtain the average buffer occupancy. We consider the approximation derived in [13] for the case of F unicast flows. Each flow generates packets following a Poisson process with rate δ. Then, the average queue size is:

$$E[Q] = \frac{F\delta}{M\lambda_M} 2E[C] \quad (7)$$

Using this expression we simply define a new probability of transmission P_t that will depend on the average buffer occupancy. That is, if the buffer is full then we can transmit the packet if another one is dropped from the buffer. Assuming a random dropping, we have the following probability of transmission:

$$P_t = \begin{cases} p_{tM} & E[Q] < B \\ \frac{B}{E[Q]+1} p_{tM} & E[Q] \geq B \end{cases} \quad (8)$$

This value is used for calculating the transition probability of (d, m) to $(d, m+1)$, $t_m = \lambda_M P_t \cdot m(M-m)$. Using this new transition probability we can obtain the time and overhead using equations 5 and 6. Note, that in order to obtain $E[Q]$ we need a prior value of $E[C]$, that is one of the results of the model. So this value is iteratively approximated from an initial value $E[C]^0$ obtained with the unrestricted epidemic model, and then calculating values of $E[C]^{x+1}$ using the restricted epidemic model with $E[C]^x$ until a given convergence criteria is reached (that is, the difference between the successive values is less than a given error ϵ)

C. Modeling MSDP

Now, we are going to model our MSDP protocol. Without loss of generality we focus our study to only one destination node ($R = 1$). In the MSDP protocol there is only one packet in the network that is stored in the *custodian* node. When a contact occurs the packet is transmitted to a new node if the *UtiliyIndex* (UI) of the receiver (*candidate*) node is greater than the UI of the sender node. This way the UI reflects how near is a node to the destination RSU node. Basically, the higher the UI, the nearer to the RSU node. Figure 1 shows

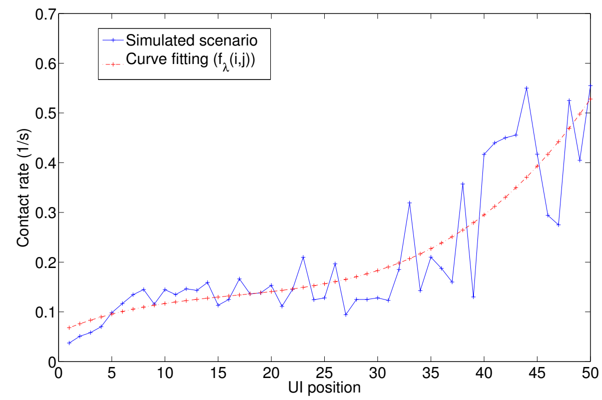

Fig. 3: Contact rate depending on the UtilityIndex.

an example of packet delivery. It starts with m_1 as the sender node. When a contact occurs with m_2, this node has an UI greater than m_1 so the packet is transmitted (first hop, H_1). For the following hop (H_2), the UI of the node that has the packet is increased. Finally, the packet reaches the destination node. The UI has another property, the locality. Two nodes with similar UI values are prone to be neighbors. So it is more frequent that a contact occurs between these nodes and other nodes in their neighborhood (that is, they have a greater contact rate). Following the example of figure 1, when the packet is in m_1, the contact rate with all the nodes inside the circumference defined by the boundary of the node is λ_{M1}. When the packet is transmitted to m_2, the circumference is reduced and the contact rate is increased $\lambda_{M2} \geq \lambda_{M1}$. Therefore, we expect a direct relation between the UI of a node and the contact rate.

This is confirmed with the following experiment. From the simulation scenario used in section IV-A we obtained all the inter-contact times between nodes and the UI of the sender node when a contact occurs. If we sort the nodes by increasing UI values, the UI position is the index on this list. Figure 3 shows the plot of the contact rate depending on the UI position for M nodes. We can clearly observe that the contact rate increases with the UI position. That is, if we have M mobile nodes, the list is: $\{\text{UI}_1, \text{UI}_2, \ldots \text{UI}_i, \text{UI}_j, \ldots \text{UI}_M\}$, so $\text{UI}_j \geq \text{UI}_i \; \forall \; j > i$. This list is dynamic, so a node can change its position over time. The probability of changing one position is defined as p_u. As we sort nodes by their UI values, we can establish a direct relation between the UI position and the contact rate. Thus, we can fit a third degree polynomial function $f_\lambda(i,j)$, that gives the contact rate of two nodes with position index i and j:

$$f_\lambda(i,j) \approx c_4 + c_3 k + c_2 k^2 + c_1 k^3 \quad k = \min(i,j) \quad i \neq j \quad (9)$$

Note that $k = \min(i,j)$ reflects the fact that the contact rate for two nodes is determined by the lowest index. In the example of figure 3, the contact rate between nodes m_1 and m_3 is λ_{M1}. Finally, figure 3 shows the result of fitting this curve to the values obtained from the scenario. We can see the effect of the logarithm effect in the calculus of the time to reach factor (T) of the UI expression, specially for UI positions greater than 30.

The contact rate for the destination nodes (RSU nodes) follows a similar distribution, so the higher the index i of a node the higher the contact rate, and we can also fit a similar equation $f'_\lambda(i)$.

Using a CMTC we can obtain the time to reach the destination and the overhead (in this case, the number of hops until the packet arrives to any of the RSU nodes). We introduce H as the maximum number of possible hops ($H \leq M$). Following the same process that in the epidemic model, we have a 3D-CMTC with states $(d(t), u(t), h(t))_{t\geq 0}$ where $h(t)$ is the number of hops at time t, $u(t)$ is the position on the list of UI at time t and $d(t)$ represents if the destination node have the packet at time t. At the beginning we start with $h = 0$ hops, but we assume that the sender can be any node of the mobile nodes so its average index position u is in the middle: $\lfloor M/2 \rfloor$. Therefore, the starting state is $s_\alpha = (0, \lfloor M/2 \rfloor, 0)$[2]. The final (absorbing) states is when $d = 1$. Thus, this 3D-CTMC has $M(H + 1)$ transient states (from $s_1 = (0, 1, 0)$ to $s_\tau = (0, M, H)$ states) and $M(H + 1)$ absorbing states (from $s_{\tau+1} = (1, 1, 0)$ to $s_{\tau+\upsilon} = (1, M, H)$).

Now, we derive the transition rates p_{ij}. Given the state $s_i = (d, m, h)$ the following transitions can occur:

- (d, u, h) to $(d, u + \Delta, h + 1)$, $\Delta = 1 \ldots (M - u)$: The packet is transmitted to a new node with a greater UI. The contact rate depends on the difference of the UI of the nodes contacted: $f_\lambda(i, j)$. Thus, the transition probability is $t_{uh} = f_\lambda(i, j) \cdot p_{tM}$.
- (d, u, h) to $(d, u \pm 1, h)$: This transition reflects that the node that has the packet increases (decreases) one position in the UI list. The transition probability is simply p_u.
- $(0, u, h)$ to $(1, u, h + 1)$: An RSU node has the packet. The contact rate depends on the value of u : $f'_\lambda(u)$. Thus, the transition probability is $t_d = f'_\lambda(u) \cdot p_{tR}$.
- (d, u, h) to (d, u, h): This is the probability of no changes and is $1 - \sum_{j\neq i} p_{ij}$.

Using the transition matrix $\mathbf{P}$ we derive the delivery time T_d using an expression similar to equation 5:

$$T_d = E[T] = \mathbf{v}_\alpha \mathbf{N} \mathbf{v} \quad (10)$$

where $\mathbf{v}_\alpha$ is a vector with a 1 in the start state α.

Now, we derive the overhead (the number of hops or retransmissions). First, we obtain the matrix of absorption probabilities as $\mathbf{B} = \mathbf{N} \cdot \mathbf{R}$. Then, we obtain the probability of absorption (p_H) depending on the number of hops starting from state number α:

$$p_H(h) = \sum_{u=1}^{M} B(\alpha, State(0, u, h)) \qquad h = 1 \ldots H \quad (11)$$

Thus, p_H is the probability mass function (*pmf*), that gives the probability of absorption (that is, the packet reaches the destination) with h hops. Using this *pmf* we can obtain the cumulative distribution functions $F_H(h)$. Then, the average number of hops needed to reach the RSU node $E[H]$ is the greater value of h that make true the expression $F_H(h) \leq 0.5$. That is:

$$O_d = E[H] = \max\{h \mid F_H(h) \leq 0.5\} \quad (12)$$

As in the Epidemic model, we can also consider the effect of the buffer, although in the MSPD its influence will be limited. Assuming the same F unicast flows, the arrival rate of new packet to the network is $F\delta$, and by Little's law, the average number of packets in the system is $F\delta E[T]$, where $E[T] = T_d$ is precisely the average packet lifetime. If all these packets are equally divided among the M nodes we have that the average queue size is:

$$E[Q] = \frac{F\delta}{M} E[T] \quad (13)$$

Using this average queue size we can obtain the probability of transmission P_t using equation 8 in order to calculate the new transition probability $t_{uh} = f_\lambda(i, j) \cdot P_t$.

IV. Performance Evaluation

In this section we evaluate the performance of our MSDP protocol first by using the proposed analytical models, and then using realistic simulations. We compare our MSDP protocol against the Epidemic protocol. Since the analytical models use several parameters obtained from the simulation scenarios, we first describe the simulation environment.

A. Simulation Environment

We have implemented MSDP using the ns3 [21] simulator, which is an event-driven simulator that includes detailed implementations of the 802.11 physical and MAC layers.

One of the most important issues in DTN simulations is the mobility pattern. The mobility patterns of our simulations have been generated using the Simulation of Urban MObility (SUMO) [22] tool. It is important to notice that route duration is unpredictable, and to remove a node means lose all the packets contained in its buffer. Our mobility traces were generated for an area of 4 km^2 in the city of Valencia, Spain, represented in figure 4. We believe that this map is a good

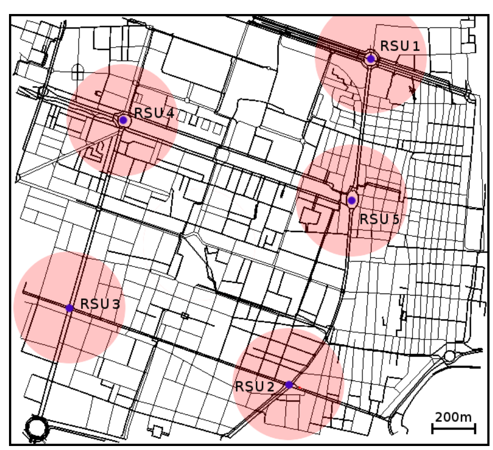

Fig. 4: Map of the city of Valencia used in our simulations.

[2]We can convert from an state (d, u, h) to a state number i using the following expression: $i = State(d, u, h) = d \cdot M(H+1) + u(H+1) + h + 1$, so the starting state number α is $\lfloor M/2 \rfloor (H + 1)$

example of an average sized European city. In this scenario we located five different RSU in different avenues of the city.

In our simulations every node has two different interfaces: an 802.11n, interface used for C2C communication, and an 802.11p interface, used for C2I communication. UDP parameters, as well as IP, ARP, and MAC parameters, take their default values. Both interfaces transmit at the maximum allowed power in Europe: 20 dBm and 33 dBm, respectively.

We consider that the use of too simplistic propagation models is one of the main drawbacks of previous studies in this topic. In an attempt to accurately model real world conditions, we decided to combine the two ray ground propagation model and the Nakagami fading model.

Every node in our network scenario generates a message with a size of 2500 Bytes every 5 seconds. The size of the fragments is 231 Bytes plus headers, making a total size of 256 Bytes. We have configured the protocol to add a 20% of redundancy. The traffic generation will be stopped after the first 100 seconds of our simulation. The simulation will last 3600 seconds.

We have generated four different scenarios with 30, 63, 125 and 188 nodes. Each scenario has been simulated 30 times varying the mobility traces and the initial seed of the random number generator. All the obtained results are represented with a 95% of confidence interval.

B. Analytical performance evaluation

In this section we make an analytical comparison of the performance of the MSDP protocol with the epidemic routing approaches. In this evaluation we use the following parameters that were derived from the simulation scenario described previously: $\lambda_M = 0.141$, $\lambda_R = 0.046$, $p_{tM} = 0.5$, $p_{tR} = 0.7$, $p_U = 0.05$, $H = 20$, $R = 1$. The coefficients of the f_λ functions were obtained through a curve fit based on the simulation results, as shown previously. Figure 5 presents the time and overhead depending on the number of mobile nodes. In figure 5a we can see the delivery time. Regarding the unrestricted protocols, results show that for MSDP the delivery time is about ten times greater than for Epidemic. Note that the epidemic routing is optimal in delivery time, but has a great overhead, as we can see in figure 5b. The average number of transmissions for the Epidemic protocols increases linearly with M, while for MSDP it increases more slowly.

The results for buffer restricted epidemic protocols are totally different. We used the following values: a buffer of 50 packets ($B = 50$) and all nodes send a message to the RSU ($F = M$) every five seconds (a similar load that in the simulated scenario). This message is fragmented in ten packets so $\delta = 2$. Note that MSDP has only one copy of each packet in the network, and so this does not imply an increase on network load; also, the effect of the buffer restriction in this evaluation is negligible. Regarding the overhead, we also see that the number of copies is reduced when the load increases. Finally, in figure 5c we can see the efficiency of the protocols obtained as $(O_d \times T_d)^{-1}$, so a higher value implies a more

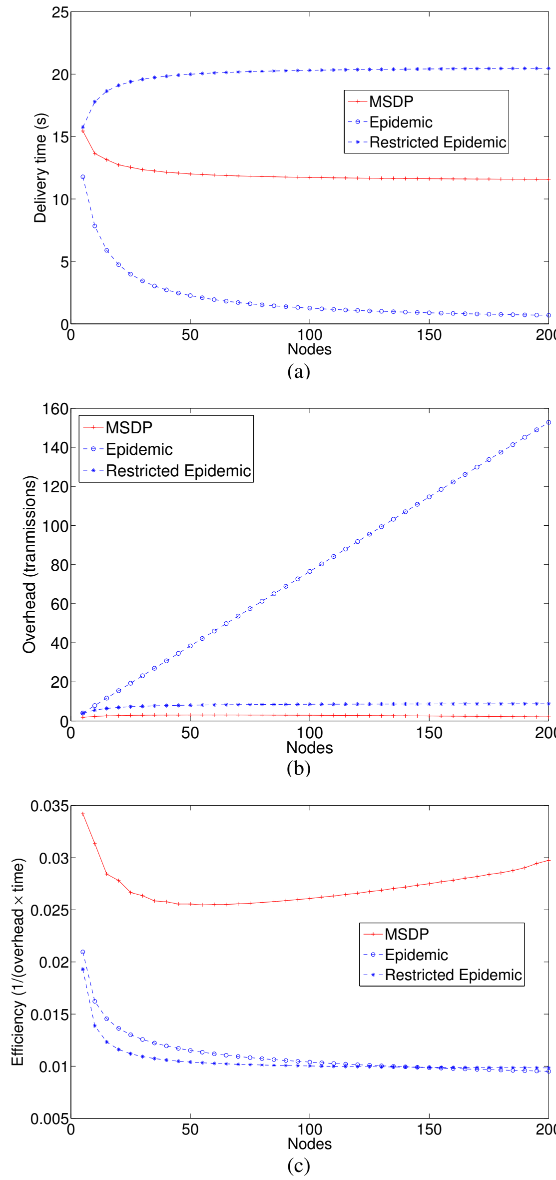

Fig. 5: Evaluation of the MSDP protocol with the Epidemic protocols. a) Delivery time; b) Overhead: average number of transmitted packets; c) Efficiency of the protocols.

efficient protocol. Thus, MSDP is about 10-20 times more efficient than the epidemic protocols.

Figure 6 shows the delivery time depending on the number of flows (F) in a network with 100 mobile nodes ($M = 100$) using the same parameters of previous experiments. We can see an exponential growth of the time for low values of F. The limit is reached when the network buffers are saturated, so the delivery is made through a direct contact between the sender and the receiver. For restricted MSDP, as only one copy of each packet is present in the network, he effect is quite reduced, as we can apreciate it in the same figure. The increase on the delivery time is minimal (about 5% for 1000 flows of load).

The previous evaluations show that the effect of network load has low influence on the efficiency of the MSDP protocol, allowing to obtain good delivery times in a very efficient way.

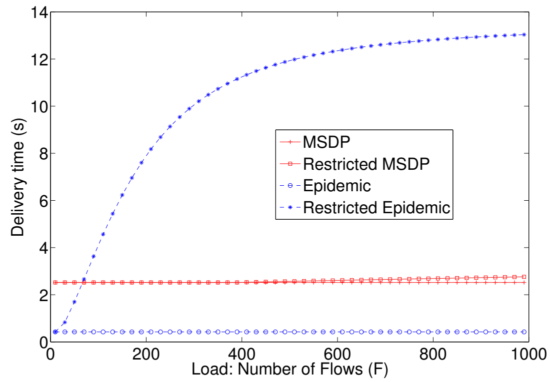

Fig. 6: Delivery time depending on load (F=number of flows)

C. Simulation Evaluation

The goal of the simulation is to evaluate the performance of the MSDP protocol in a realistic scenario. This includes the effect of mobility patterns and network congestion due to collisions, exponential back-off times, and other effects that are more complex to be modeled analytically. Therefore, in these evaluations the Epidemic results always refer to *restricted* Epidemic diffusion.

Figure 7 shows the average delivery probability for both protocols at different node densities. At low node densities the Epidemic protocol behaves slightly better than our proposal. This is because the Epidemic protocol ensures the optimal route is used when the available resources, in terms of channel capacity and node mobility, are enough. However, our protocol can miss some multi-hop paths. The maximum delivery probability is obtained with a moderate network density; at this point our protocol performs a 13 % better than the Epidemic protocol. When the number of nodes increases beyond this value, the delivery probability decreases.

Figure 8 shows the average total number of MSDP message transmissions per information message generated. This metric accounts for every type of message sent to the wireless channel. The Epidemic protocol, even for low densities, generates many more transmissions than our proposal (as shown in the analytical evaluations). At high densities, the high congestion generated by the Epidemic protocol drastically reduces the transmission opportunities between nodes and, as a consequence, the total number of transmitted messages per information message decreases. From our point of view, this metric is really important since it is expected that information collecting applications will coexist with several other applications, and so the imposed overhead will be even higher.

Figure 9 represents the average delay for the received information messages. It shows that, when using our protocol, the mean delay decreases when the amount of nodes in the network increases. On the other hand, when using the Epidemic protocol, the mean delay increases when the number of nodes increases. This behavior is a consequence of the huge overhead introduced by the Epidemic protocol, which saturates the network capacity. We have also represented the cumulative distribution of the information messages delay in figure 10, which is a better metric to evaluate the complete behavior of a protocol. It shows that, when using our MSDP, only a small percentage of the received information messages will experiment a delay higher than 15 seconds while, when using the Epidemic protocol, a high number of messages are received more than 1 minute later. This result clearly shows the effect of network congestion due to the high rate of packet transmissions associated to the epidemic routing protocol.

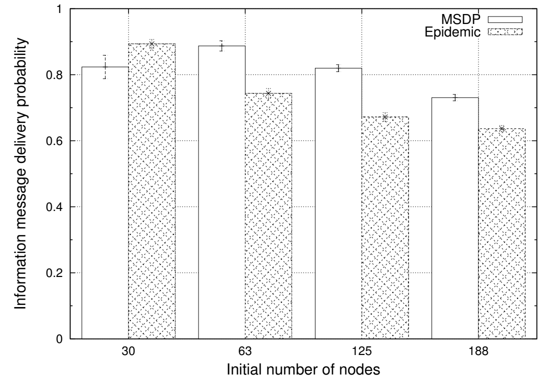

Fig. 7: Delivery probability.

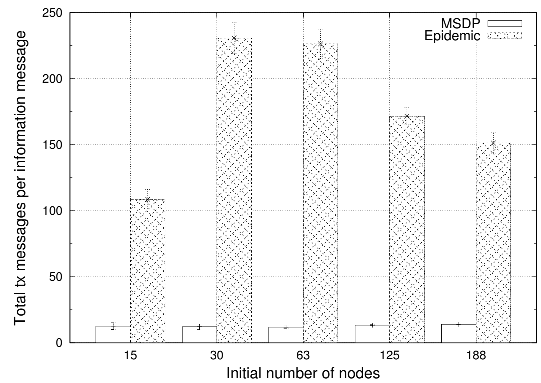

Fig. 8: Total transmissions.

The simulation results confirm the results of the analytical evaluations: our proposal performs better than the Epidemic protocol mainly due to the reduced load. That is, as the number of packets is much lower, the congestion in the network is significantly reduced compared to the epidemic protocol.

V. Conclusions and Future Work

This paper evaluates the performance of our proposed Map-based Sensor-data Delivery Protocol (MSDP). MSDP is a DTN geographic routing protocol that uses the locations and routes of vehicles, coupled with information obtained from the Navigation System (NS), in order to determine the best forwarding node. Moreover, the protocol considers other parameters such as the buffer load or the trustworthiness of the node. Therefore, when a packet is transmitted to a new node, its probability of reaching the destination node increases. As long as there is only one packet in the network, the overhead incurred is low in comparison to multi-copy schemes.

To evaluate our protocol we have compared it with the Epidemic routing protocol. Firstly, we introduced the analytical models of the epidemic and MSDP protocols. These

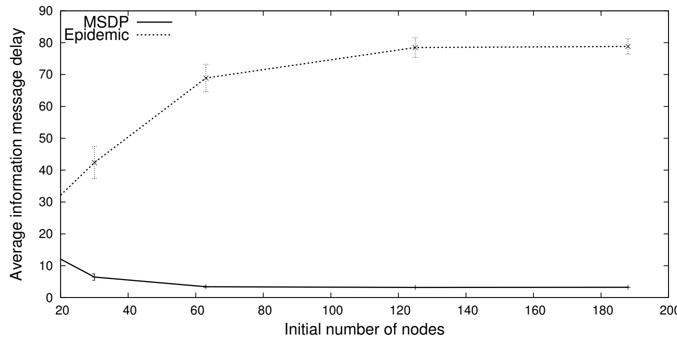

Fig. 9: Average information messages delay.

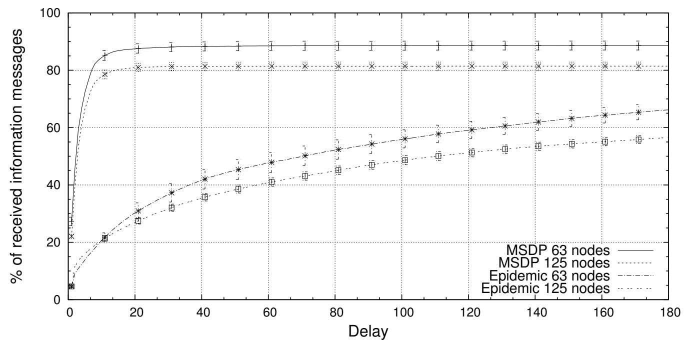

Fig. 10: Cumulative distribution of information message delay.

models take into account the buffer constraints, whose effects are especially important when evaluating the performance of epidemic routing. To evaluate the effect of mobility patterns and network congestion that are not reflected in the analytical models, we have also performed realistic simulations of both protocols.

The evaluations showed that MSDP has a reasonable delivery time with a reduced overhead compared with the epidemic routing solutions evaluated. Considering real network restrictions (buffer and congestion), the MSDP delivery time is lower than the epidemic routing, while behaving more efficiently. This is due to the low channel usage associated to our MSDP approach, which avoids the congestion effects of epidemic routing.

ACKNOWLEDGMENTS

This work was partially supported by the *Ministerio de Ciencia e Innovación*, Spain, under Grant TIN2011-27543-C03-01.

REFERENCES

[1] A. Vahdat and D. Becker, "Epidemic Routing for Partially Connected Ad Hoc Networks," in *Technical Report CS-200006*, Apr. 2000.

[2] T. Spyropoulos, K. Psounis, and C. S. Raghavendra, "Spray and wait: an efficient routing scheme for intermittently connected mobile networks," in *Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking*, ser. WDTN '05. New York, NY, USA: ACM, 2005, pp. 252–259.

[3] J. Xue, X. Fan, Y. Cao, J. Fang, and J. Li, "Spray and Wait Routing Based on Average Delivery Probability in Delay Tolerant Network," in *Networks Security, Wireless Communications and Trusted Computing, 2009. NSWCTC '09. International Conference on*, vol. 2. IEEE, Apr. 2009, pp. 500–502.

[4] A. Lindgren, A. Doria, and O. Schelén, "Probabilistic routing in intermittently connected networks," in *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 7. New York, NY, USA: ACM, Jul. 2003, pp. 19–20.

[5] T.-K. Huang, C.-K. Lee, and L.-J. Chen, "PRoPHET+: An Adaptive PRoPHET-Based Routing Protocol for Opportunistic Network," in *Advanced Information Networking and Applications (AINA), 2010 24th IEEE International Conference on*. IEEE, Apr. 2010, pp. 112–119.

[6] J. Burgess, B. Gallagher, D. Jensen, and B. N. Levine, "MaxProp: Routing for Vehicle-Based Disruption-Tolerant Networks," in *Proceedings IEEE INFOCOM 2006. 25TH IEEE International Conference on Computer Communications*. IEEE, Apr. 2006, pp. 1–11. [Online]. Available: http://dx.doi.org/10.1109/INFOCOM.2006.228

[7] R. Frank, E. Giordano, P. Cataldi, and M. Gerla, "TrafRoute: A different approach to routing in vehicular networks," in *Wireless and Mobile Computing, Networking and Communications (WiMob), 2010 IEEE 6th International Conference on*. IEEE, Oct. 2010, pp. 521–528.

[8] Z. Li and H. Shen, "A Direction Based Geographic Routing Scheme for Intermittently Connected Mobile Networks," in *Embedded and Ubiquitous Computing, 2008. EUC '08. IEEE/IFIP International Conference on*, vol. 1. IEEE, Dec. 2008, pp. 359–365.

[9] I. Leontiadis and C. Mascolo, "GeOpps: Geographical Opportunistic Routing for Vehicular Networks," in *World of Wireless, Mobile and Multimedia Networks, 2007. WoWMoM 2007. IEEE International Symposium on a*. IEEE, Jun. 2007, pp. 1–6. [Online]. Available: http://dx.doi.org/10.1109/WOWMOM.2007.4351688

[10] P. C. Cheng, K. C. Lee, M. Gerla, and J. Härri, "GeoDTN+Nav: Geographic DTN Routing with Navigator Prediction for Urban Vehicular Environments," *Mob. Netw. Appl.*, vol. 15, pp. 61–82, Feb. 2010. [Online]. Available: http://dx.doi.org/10.1007/s11036-009-0181-6

[11] B. Karp and H. T. Kung, "GPSR: greedy perimeter stateless routing for wireless networks," in *Proceedings of the 6th annual international conference on Mobile computing and networking*, ser. MobiCom '00. New York, NY, USA: ACM, 2000, pp. 243–254.

[12] V. N. G. J. Soares, J. J. P. C. Rodrigues, and F. Farahmand, "GeoSpray: A Geographic Routing Protocol for Vehicular Delay-Tolerant Networks," *Information Fusion*, Nov. 2011. [Online]. Available: http://dx.doi.org/10.1016/j.inffus.2011.11.003

[13] X. Zhang, G. Neglia, J. Kurose, and D. Towsley, "Performance modeling of epidemic routing," *Computer Networks*, vol. 51, no. 10, pp. 2867 – 2891, 2007.

[14] S. M. Tornell, C. T. Calafate, J.-C. Cano, and P. Manzoni, "A Map-Based sensor data delivery protocol for vehicular networks," in *2012 The 11th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net) (Med-Hoc-Net'12)*, Ayia Napa, Cyprus, Jun. 2012.

[15] R. Groenevelt, P. Nain, and G. Koole, "The message delay in mobile ad hoc networks," *Performance Evaluation*, vol. 62, pp. 210–228, October 2005.

[16] H. Zhu, L. Fu, G. Xue, Y. Zhu, M. Li, and L. M. Ni, "Recognizing exponential inter-contact time in vanets," in *Proceedings of the 29th conference on Information communications*, ser. INFOCOM'10. Piscataway, NJ, USA: IEEE Press, 2010, pp. 101–105.

[17] Y. Li, G. Su, D. Wu, D. Jin, L. Su, and L. Zeng, "The impact of node selfishness on multicasting in delay tolerant networks," *Vehicular Technology, IEEE Transactions on*, vol. 60, no. 5, pp. 2224 –2238, jun 2011.

[18] A. Chaintreau, P. Hui, J. Crowcroft, C. Diot, R. Gass, and J. Scott, "Impact of human mobility on opportunistic forwarding algorithms," *IEEE Transactions on Mobile Computing*, vol. 6, pp. 606–620, June 2007.

[19] H. Cai and D. Y. Eun, "Crossing over the bounded domain: From exponential to power-law intermeeting time in mobile ad hoc networks," *Networking, IEEE/ACM Transactions on*, vol. 17, no. 5, pp. 1578 –1591, oct. 2009.

[20] W. Gao, Q. Li, B. Zhao, and G. Cao, "Multicasting in delay tolerant networks: a social network perspective," in *Proceedings of the tenth ACM international symposium on Mobile ad hoc networking and computing*, ser. MobiHoc '09. New York, NY, USA: ACM, 2009, pp. 299–308.

[21] "Ns3 website," http://www.nsnam.org/, December 2011.

[22] M. Behrisch, L. Bieker, J. Erdmann, and D. Krajzewicz, "Sumo - simulation of urban mobility: An overview," in *SIMUL 2011, The Third International Conference on Advances in System Simulation*, Barcelona, Spain, October 2011, pp. 63–68.