MAD: A Dynamically Adjustable Hybrid Location- and Motion-based Routing Protocol for VANETs

Ioannis Manolopoulos [#*1], Kimon Kontovasilis [#2], Ioannis Stavrakakis [*3] , and Stelios C. A. Thomopoulos [#4]

[#] *Institute of Informatics & Telecommunications, National Center for Scientific Research "Demokritos", P.O. Box 60228, GR-15310 Agia Paraskevi, Greece*

{[1] imanolo, [2] kkont, [4] scat}@iit.demokritos.gr

[*] *Department of Informatics & Telecommunications, National & Kapodistrian University of Athens, GR-15784 Ilissia, Greece*

[3] ioannis@di.uoa.gr

***Abstract*—This paper proposes a routing protocol that jointly exploits location and motion information in a dynamically adjusted way, towards self-adaptability in different combinations of mobility and node density conditions. The protocol employs a metric of the rate at which a packet approaches its destination over a multihop path, as an effect of both the forwarding to the next hop node and the carry action due to the movement of the receiving node. The metric employs an estimation of the time that a next-hop candidate will retain the message, if selected. This time determines the relative importance of the forwarding and the carry actions. Simulation results demonstrate that the protocol is successful in adapting to a very wide range of mobility and density conditions and compares favorably with other protocols designed for a particular network condition.**

I. Introduction

Vehicular Ad Hoc Networks (VANETs) are becoming one of the most interesting and quickly evolving multihop ad-hoc network paradigms. VANETs are very flexible by nature, but this flexibility also poses great challenges: Indeed, inherent highly dynamic characteristics, such as mobility (of varying patterns, according to the time of the day and the nature of the vehicle's surrounding area) may result in non-uniform network density conditions or, more severely, network partition and route breakage.

Existing routing protocols have been designed assuming networks of a presupposed fixed degree of topology invariance. One end of the spectrum covers networks with "static" topology (in the sense that it may be considered constant throughout the end-to-end delivery of a message, from source to destination). This category includes infrastructure-based networks, as well as many classes of well-connected mobile ad hoc networks with nodes of restricted mobility. In such contexts topology-based routing protocols perform best. Their purpose is to find an end-to-end path from the message source to its destination, using only identity information for each node. This information is sufficient because in the considered context the identity of a node is directly (and statically) associated with the node's proximity to the destination (in a topological and/or geographic sense).

When the mobility of the network nodes increases, the network topology becomes more dynamic and the identity of a node must be supplemented with additional location information. This is exploited by position-based routing protocols [1], [2], which take single-hop decisions based on the positions of the neighboring and destination nodes, without trying to find or maintain an end-to-end path.

Both the topology-based and position-based routing protocols come under the category of the forward-based multihop routing protocols. These protocols fit well in networks with a relatively high node density. Their routing strategy is based on the *forwarding action*, i.e., the spatial transposition of messages effected by hops from one node to the next, towards the final destination.

If the node density is low, as in Delay Tolerant Network (DTN) topologies [3], forward-based multihop routing protocols fail, because connectivity is not guaranteed and non-temporary disconnections may arise. As a result, the message carrier may need to wait a significant amount of time before it encounters a suitable next-hop node. Moreover, the mobility of the nodes, combined with the potentially long time the message is retained by each carrier, make the original location of candidate nodes an unsuitable metric for next-hop selection.

Despite these difficulties, mobility is a source of opportunities in sparse topologies: In the presence of low node densities, mobility is a necessary condition for maintaining connectivity. Even in denser environments with assured connectivity, mobility may improve throughput [4]. However, as just explained, routing protocols aiming at the exploitation of mobility must base their decisions not on the forwarding action, as is done by forward-based multihop routing protocols, but on the *carry action*, i.e., the spatial transposition of the message due to the movement of the carrier node towards the final destination. Such protocols are called carry-based multihop protocols [5]. They implement a store-carry-forward mechanism, using information about the velocity of the nodes when selecting the next-hop node to forward the message.

Clearly, it would be desirable to combine the merits of both forward-based and carry-based routing protocols, towards ensuring effective routing even in networks with a varying degree of node mobility and density. Work [6] has contributed in this direction, by proposing a routing metric based on a combination of information about the relative position and the velocity of each candidate node. The main drawback is that the said combination uses *static* weights, thus attributing a fixed relative importance to the forwarding and carry actions. Consequently, even if the weights are tuned for a particular network setting, this scheme cannot adapt when mobility and node density conditions change.

In this paper, we propose the *Maximum Advance Decision* (MAD) routing protocol, which jointly exploits location and motion information *in a dynamically adjusted way*, in order to be self-adaptable in all possible combinations of density and mobility conditions. The protocol employs the, so called, *advance* metric, which assesses the total spatial transposition of the message towards the final destination per unit of time, due to both the forwarding and carry actions. The advance metric employs an estimation of the time that a next-hop candidate node will retain the message, if selected. This time determines the relative importance of the forwarding and carry actions and thus serves in adapting the operation of the protocol under varying mobility and node density conditions. We propose a method for estimating the retaining time of each candidate node, on the basis of this node's velocity and the local node density. Results from an extensive set of simulations demonstrate that the protocol is very successful in adapting to a very wide range of mobility and density conditions encountered in real-world environments and performs more effectively than (or, at least equally well as) other protocols designed for a particular network condition.

The rest of this paper is organized as follows: Section II describes the MAD protocol (and the advance metric in particular) and compares it with other protocols proposed in the literature. A way to assess the estimated retaining time is also discussed there. Section III presents simulation results and a performance comparison with other routing protocols. Section IV concludes the paper.

II. The MAD Routing Protocol

A node in the VANET can communicate directly with its neighbors, i.e., all other nodes within range R_{tr}. Each node carrying a packet (henceforth called the "current node") examines its neighbors, one by one, in order to determine if it should forward the packet to any of them. This assessment is made on the basis of the advance metric, as described in Subsection II-A. If a next hop node emerges, the packet is forwarded to it and this node becomes the packet's current node. Otherwise, the current node retains the packet and periodically checks its neighborhood every T_{check} time units, until a next hop node is found. Additionally, if the current node encounters the destination node within its range, it immediately delivers the packet to it.

In order to apply the advance metric, the current node collects location and motion information for each of its neighbors, by means of a beacon-based process. Specifically, each node in the VANET broadcasts every T_{beacon} time units a message containing information about its motion and geographic location.

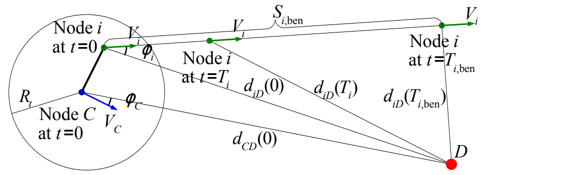

Fig. 1. Packet forwarding and carry actions, and associated quantities

Listening nodes collect this information in routing tables (one per listening node), for use when they act as current nodes.

The application of the advance metric to the current node's neighbors for next hop selection and the subsequent packet forwarding require some time, depending on the number of neighbors checked and on the MAC/PHY layer details (affecting the time required for packet forwarding). The maximum time interval that may be required under the worst case conditions is referred to in the following as the *decision time* T_{d}. The advance metric makes use of this value. Accordingly, the MAD routing protocol enforces a constant time interval equal to T_{d} from the commencement of the next hop selection process until the packet is forwarded to the next hop (or retained by the current node). It follows that, once a node receives (or generates) a packet, it will retain that packet for time at least equal to T_{d} before forwarding it to another node.

A. The Advance Metric

The metric is intended to assess the rate at which the packet will approach its destination, if the respective node is selected as the packet's next hop. In the following, we refer to the reduction of a packet's distance (actually, the carrier node's distance) from its destination as *progress* (measured in units of length) and the rate of progress as *advance* (measured in units of speed).

Figure 1 depicts the packet forwarding from the current node to a neighbor (forward action) and the subsequent carry action, as the new packet carrier moves. We denote the distance between any two nodes i and j at time t by $d_{ij}(t)$. The indices C and D are reserved for the current node and the packet's destination, respectively. Finally, V_i and ϕ_i refer to the magnitude of node's i velocity and the angle between this velocity and the line segment from, node i to the destination node D, respectively, at time $t = 0$. Zero time corresponds to the instant when the current node forwards the packet to the next hop node. This convention implies that the current node has started the examination of its neighbors for next hop selection at time $t = -T_d$. During this examination, the current node adjusts the data stored in its routing table to determine each node's location (including its own) at $t = 0$.

When the current node considers its neighbor i as a next hop candidate, it takes into account the progress due to both the forward and carry actions. The first of these is due to passing the message from node C to node i, at time $t = 0$, so

$$\text{prog}_{Ci,\text{fwd}} = d_{CD}(0) - d_{iD}(0) \tag{1}$$

The progress due to forwarding occurs as an effect of the neighbor selection process, which takes time T_d to complete.

Therefore, the corresponding advance is

$$\text{ADV}_{Ci,\text{fwd}} = \text{prog}_{Ci,\text{fwd}}/T_d \tag{2}$$

Note that $\text{prog}_{Ci,\text{fwd}}$ and $\text{ADV}_{Ci,\text{fwd}}$ take negative values when the destination is closer to the current node than to neighbor i.

In order to assess the effect of the carry action, the current node needs to estimate the time T_i that node i will retain the packet, if it is selected as the next hop node. As remarked earlier, always $T_i \geq T_d$. Given an estimate of this retaining time, the progress due to the carry action is equal to

$$\text{prog}_{i,\text{car}}(T_i) = d_{iD}(0) - d_{iD}(T_i) \tag{3}$$

and occurs in a time interval of length T_i, so the corresponding advance is equal to

$$\text{ADV}_{i,\text{car}}(T_i) = \text{prog}_{i,\text{car}}(T_i)/T_i \tag{4}$$

The function $\text{ADV}_{i,\text{car}}(t)$ reflects the velocity of node i: $\text{ADV}_{i,\text{car}}(t) \approx V_i \cos\phi_i$ for small values of t (the equality being exact for all t when $|\cos\phi_i| = 1$). Whenever $\cos\phi_i < 0$, i.e., node i moves away from the destination and $\text{prog}_{i,\text{car}}(T_i)$ and $\text{ADV}_{i,\text{car}}(T_i)$ take negative values.

Clearly, the overall progress is the sum of the forward and carry components in (1) and (3), respectively, and occurs over time $T_i + T_d$, for an overall advance equal to

$$\begin{aligned} \text{ADV}_{Ci,\text{tot}} &= \frac{d_{CD}(0) - d_{iD}(T_i)}{T_i + T_d} \\ &= f_{\text{fwd}}\text{ADV}_{Ci,\text{fwd}} + f_{\text{car}}\text{ADV}_{i,\text{car}}(T_i), \end{aligned} \tag{5}$$

where the second form follows from (2) and (4) with $f_{\text{fwd}} = T_d/(T_i + T_d)$ and $f_{\text{car}} = T_i/(T_i + T_d)$.

The second equality in (5) demonstrates that the estimated retaining time T_i, besides determining the value of the carry component $\text{ADV}_{i,\text{car}}(T_i)$ through (3) and (4), it also acts as a parameter for tuning the relative importance of the forward and carry actions: Indeed, when the retaining time takes the smallest possible value $T_i = T_d$, then $f_{\text{fwd}} = f_{\text{car}} = 1/2$ and the forward and carry components contribute equally to the value of the overall metric. On the contrary, when T_i is big $f_{\text{fwd}} \approx 0$ and $\text{ADV}_{Ci,\text{tot}} \approx \text{ADV}_{i,\text{car}}(T_i)$ so the value of the metric is predominantly due to the carry action.

As mentioned earlier, the value of the metric $\text{ADV}_{Ci,\text{tot}}$ expresses the rate at which the packet will approach its destination if node i is selected as the next hop. Such a selection will be reasonable only if this rate is higher than the one achieved when the current node retains the message. To determine this, the current node also calculates its own advance metric $\text{ADV}_{CC,\text{tot}}$, setting $i = C$ in (5), but maintaining the same value of the retaining time T_i used when calculating $\text{ADV}_{Ci,\text{tot}}$ (the reason being that the advance of both nodes should be determined over the same time interval). Clearly, $\text{ADV}_{CC,\text{tot}}$ is only due to the carry effect. (This can be seen by (1), applied with $i = C$.) The relative merit of the neighbor node i over the current node C is expressed by the difference

$$\Delta_i = \text{ADV}_{Ci,\text{tot}} - \text{ADV}_{CC,\text{tot}} = \frac{d_{CD}(T_i) - d_{iD}(T_i)}{T_i + T_d} \tag{6}$$

If $\Delta_i > 0$, node i is more beneficial than the current node and becomes a next hop candidate.

The same procedure is repeated for all neighbors of the current node and ultimately the packet is forwarded to the node with index $j = \arg\max_i \Delta_i$, justifying the name of the protocol (as Maximum Advance Decision or, alternatively, Maximum Advance Difference). Note that the selection works correctly even if $\Delta_j < 0$ for all neighbor indices j, since, by definition, $\Delta_C = 0$ and the current node will retain the message. (Ties with other nodes featuring also a zero Δ-value are resolved in favor of the current node.)

The success of the advance metric relies on the appropriate estimation of the retaining time T_i. This is discussed in the next subsection.

B. Estimating The Retaining Time T_i

The estimation procedure is based on the assumption that the velocity of node i remains constant for the whole duration of the node's packet retaining time. This assumption, also shared by other routing protocols (e.g., MoVe [5]), implies that the examined node will follow a straight-line trajectory at a constant speed equal to V_i. (Moreover, distances from the destination are expressed simply as $d_{iD}(t) = \sqrt{(V_i t)^2 + d_{iD}(0)^2 - 2V_i t d_{iD}(0)\cos\phi_i}$, for all $t \geq 0$.)

If $V_i > 0$ and $\cos\phi_i > 0$, then node i moves towards the destination. In this case the retaining time is set equal to $T_{i,\text{ben}} = S_{i,\text{ben}}/V_i = d_{iD}(0)\cos\phi_i/V_i$ (see Figure 1), i.e., the time required for the node to reach the point closest to the destination, along its straight-line trajectory. Node i shouldn't keep the packet further, because after time $T_{i,\text{ben}}$ the distance from the destination will keep increasing.

In the complementary case ($V_i = 0$ or $\cos\phi_i \leq 0$), the node's motion is counterproductive. This node will become a next hop either because the respective forward action is very beneficial, or because it is the least negative choice. In both cases, node i should find a next hop to forward the packet as soon as possible. The time required for that will be a decreasing function of the number of neighbors that the node will encounter and this number, in turn, is proportional to the network's node density in the vicinity of the node. In view of these comments, the retaining time is set equal to α/ρ, where ρ is the local node density (i.e., the number of nodes in the coverage region divided by its area πR_{tr}^2), as measured by the current node, and α is a constant, whose value is chosen so that the highest expected node density corresponds to the smallest possible value of the retaining time, equal to T_d. The value of the density ρ may be obtained as an average over a rolling window of previous observations.

Combining both cases,

$$\hat{T}_i = \begin{cases} T_{i,\text{ben}} = d_{iD}(0)\cos\phi_i/V_i, & V_i > 0,\ \cos\phi_i > 0, \\ T_d\,\rho_{\max}/\rho, & \text{otherwise.} \end{cases} \tag{7}$$

There is another issue that must be taken into account: As explained in Subsection II-A, the difference of the advance metrics for the neighbor node i and the current node C has to be calculated, through (6), and both metrics in the difference refer to the same retaining time. In view of this, the estimate $\hat{T}_C$ is also calculated, by applying (7) with $i = C$, and finally the value of the retaining time is obtained as

$$T_i = \min\{\hat{T}_C, \hat{T}_i\} \tag{8}$$

Obviously, a single computation of $\hat{T}_C$ suffices for the calculation of the retaining times of all current node's neighbors.

The determination of the retaining time just described has desirable properties: Assuming a given value $V_i = V_C$ expressing the degree of mobility in the area, when the packet is far from its destination and both the current node and the examined node i head towards the destination, both $T_{i,\text{ben}}$ and $T_{C,\text{ben}}$ are relatively big, so T_i, as obtained from (8) and (7), is also big and the advance metric emphasizes the carry action. This is appropriate, because when the packet is far from the destination the carry action is more effective than the forward action for enabling a rapid approach. By a similar reasoning, as the packet gets closer to the destination, T_i becomes smaller and the advance metric takes into account both the carry and the forward actions (the latter being effective in this regime). When both the current node and the examined node i move away from the destination, the value of T_i is governed by the local node density, through the second branch in (7). In high density conditions the retaining time is small and the advance metric emphasizes the forwarding action (effective in such conditions). Low densities result in a big retaining time and the carry action (which now yields negative values) prevails, so MAD seeks the least harmful next hop.

C. Comparison With Other Routing Protocols

Most existing routing protocols exploit separately either the forward or the carry action. A typical representative of the protocols focusing on the forward action is the greedy MFR protocol [1], which selects the candidate node maximizing the distance between the current node and the candidate node's projection point on the line connecting the current and destination nodes. Such protocols usually suffer from wrong forwarding decisions in environments with low density, where carry-based protocols perform better. A typical representative of this category is the MoVe protocol [5], which uses a metric based on the direction of the nodes' motion. The carry-based advance component of MAD in (4) improves on that because, as discussed in Subsection II-A, it also takes into account the magnitude of the velocity vector, instead of just its direction.

Because of the dynamic way the forward and carry components are weighted in its advance metric, MAD has an advantage over standalone forward-based and carry-based protocols, as well as over hybrid protocols like DGR [6], which combines position and direction information in an ad hoc static way, thus being less than optimally adaptable to varying network conditions.

III. Simulation Results, Validation and Comparative Evaluation

We now discuss simulation results obtained with the use of the OPNET Modeler network simulator. In accordance with the discussion in Subsection II-C, MAD was compared with the forward-based MFR protocol, the carry-based MoVe protocol and the hybrid DGR protocol. In the last case, the fixed weight factors were set to the values used in [6], namely 0.9 for the position-based component of the metric and to 0.1 for the motion-based component.

The simulations addressed a network topology where the mobile nodes moved within a rectangular area of size 10km$\times$10km. The source and destination were static nodes at diagonally opposite corners of the rectangle; the destination's position was globally known. The mobile nodes were used to deliver data between the fixed source and destination, which were otherwise disconnected from each other. Mobile nodes could communicate with other nodes in a range $R_{\text{tr}} = 250\,\text{m}$ and moved according to the random waypoint mobility model with zero pause time and constant speed [7]. The PHY and MAC layers were treated at an abstract level, using $T_d = 0.2\text{s}$. The value of T_{check} was set equal to 1s.

A wide range of speed values were examined, from 2.8 m/s (10 km/h) to 33.3 m/s (120 km/h) in incremental steps of 2.8 m/s (10 km/h). For each value of speed, a wide range of node densities were examined, from a total number of 75 nodes in the rectangular area (i.e., 7.5×10^{-7} nodes/m^2) up to a total of 4750 nodes (4.75×10^{-5}nodes/m^2, the value used for $\rho_{\max}$ in (7)). Due to space constraints, here we report results for two different densities corresponding to a total number of 75 (low density) and 4750 (high density) nodes in the area. Omitted results are consistent with those presented here.

The performance metrics considered were the end-to-end delay and the number of hops for packet delivery from source to destination. The corresponding values reported here were obtained as averages over 100 packets. The time between packet generation events was chosen sufficiently large, to ensure that the topologies "seen" by any two consecutive packets were completely different.

Figures 2–3 and 4–5 display end-to-end delays and hop counts, respectively, as a function of the nodes' speed, for low and high node densities. The results indicate clearly that, generally, both the average end-to-end delay and the number of hops to delivery decrease as either the density or the mobility (i.e., the value of speed) increases. This happens because a higher value of any of these two parameters results in an increased number of forwarding opportunities observed by the current node per unit of time.

Moreover, it can be observed from Figure 2 that the carry-based routing protocol (MoVe) is more efficient than the forward-based routing protocol (MFR) in sparse topologies, in the whole mobility range. Indeed, in such environments the time that the current node retains the packet is relatively big, so the effect of the carry action is magnified and protocols that base their decisions on it perform better. On the contrary, as shown in Figure 3, in relatively dense topologies the location-based routing protocol (MFR) is more efficient than the carry-based routing protocol (MoVe) in the whole mobility range. This happens because the high density leads to a big number of neighbor nodes observed per unit of time, so it is quite

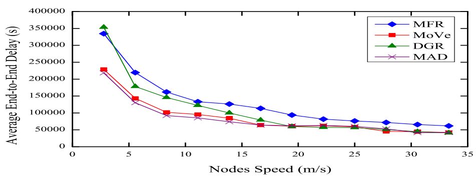

Fig. 2. Average e2e delay vs speed for low node density (75 nodes)

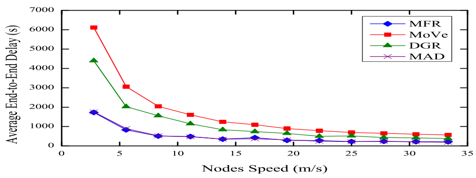

Fig. 3. Average e2e delay vs speed for high node density (4750 nodes)

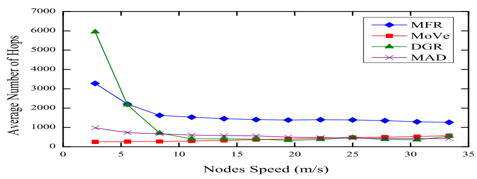

Fig. 4. Average # hops vs speed for low node density (75 nodes)

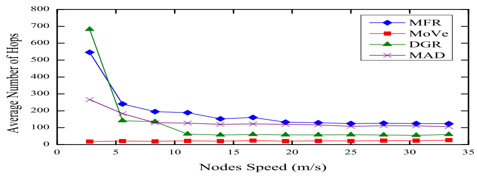

Fig. 5. Average # hops vs speed for high node density (4750 nodes)

likely that the current node will find a good next hop in a very short time. Consequently, the packet retaining time is now shorter and the motion of the nodes (the carry action) has lower impact than their location.

The end-to-end delay performance of the DGR protocol is between that of MFR and MoVe, but not always close to the best performing of the two. This is due to the static weight factors used by this hybrid scheme. On the contrary, MAD always exhibits the best performance, regardless of conditions, because of its ability of dynamically adjusting the weights between the forward and carry components of its metric. Another reason is that, while MoVe (and DGR) uses only the direction of the node's velocity, the carry component of MAD's advance metric also takes advantage of the magnitude of the velocity (i.e., the node's speed).

With respect to the number of hops, Figures 4 to 5 suggest that MoVe, which relies exclusively on motion information, exhibits a smaller number of hops than MFR, which is based on relative position information. This is because in the MoVe protocol the current node takes long stretches in possession of the packet and forwards it only when a better carrier is found. This behavior inherently results in a smaller number of hops than schemes that rely on position rather than motion. DGR exhibits a behavior comparable to MoVe (except in very low mobility environments, when its position-base component prevails). However, it should be noted that a smaller number of hops is not necessarily accompanied by better performance: Comparison of Figure 5 against 3 reveals that in dense environments the fewer hops of MoVe (and DGR) prevent them from attaining the better end-to-end delay exhibited by MFR and MAD.

The number of hops in MAD decreases as mobility and/or density increase. Note that MAD cannot be expected to feature a smaller number of hops than MoVe (or even the same as MoVe) in all cases, even with a perfect estimation of the retaining time, because MAD also exploits (dynamically, when appropriate) the forward action, based on position. As explained, this necessarily entails a larger number of (short-lived) hops, but also leads to better end-to-end delay performance.

IV. Conclusions

Towards contributing to the routing problem for VANETs under highly diverse mobility and node density conditions, we have developed the MAD protocol, a comprehensive, self-adapting, hybrid routing scheme. This protocol uses the advance metric, which exploits information related to the position and the velocity of each node and combines the relative merits of the two kinds of information through appropriate weight factors that arise naturally from the form of the metric. The weighting factors are dynamically adjusted by means of the estimated time that the next hop node will retain the packet. A methodology for calculating this retaining time has also been proposed. The MAD protocol has been extensively evaluated in a wide range of mobility and density conditions, by means of simulations. The results verify that the protocol adjusts optimally to different network conditions and outperforms, in terms of the end-to-end delay, other state-of-the-art methods.

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