Exploiting Multi-hop Connectivity for Dynamic Routing in VANETs

Michele Rondinone and Javier Gozalvez
Uwicore, Ubiquitous Wireless Communications Research Laboratory, www.uwicore.umh.es
University Miguel Hernández of Elche, Spain
mrondinone@umh.es, j.gozalvez@umh.es

***Abstract*— Recent vehicular routing proposals dynamically select forwarding paths based on real-time traffic information, mostly the vehicular density, and route the packets to the final destination using the sender-based forwarding approach. However, estimating the vehicular density can require a significant communications overhead, and the adoption of sender-based forwarding can increase the presence of unreliable radio links in multi-hop transmissions. In this context, this paper presents a novel contention-based forwarding protocol that dynamically selects routing paths based on their multi-hop connectivity. The paper outlines the design of the proposal, and the optimization of some its design parameters. The obtained results show that the technique proposed in this paper achieves high packet delivery ratios, while reducing the overhead and efficiently managing the communications channel.**

Keywords- Vehicular Ad-hoc Networks; Routing; Multi-hop Connectivity; Contention-based Forwarding

I. Introduction

Vehicular Ad-Hoc Networks (VANETs) use V2V (Vehicle-to-Vehicle) communications to improve traffic safety and efficiency through the dynamic exchange of information among vehicles and with road side units (RSUs). V2V communications are generally based on the IEEE 802.11p and WAVE (Wireless Access for Vehicular Environments) standards that are currently been adapted at European level by the ETSI ITS G5 work item [1]. VANETs enable the exchange of information (e.g. the occurrence of a traffic jam or accident) among distant vehicles through multi-hop transmissions using intermediate relaying forwarders. However, the effectiveness of such multi-hop transmissions is affected by the challenges deriving from the high vehicular mobility and the adverse V2V radio propagation conditions. To cope with such challenges, different types of routing protocols have been presented in the literature. V2V communication standards currently define periodic broadcast beacon messages that can be used to inform neighboring nodes of the geographical position of a vehicle. Greedy forwarding schemes exploit this feature to select forwarding vehicles providing a higher progress towards the final destination. Basic examples of this approach are the Greedy Perimeter Stateless Routing (GPSR) [3] and Contention-Based Forwarding (CBF) [4]. These techniques may suffer the so-called local maximum problem every time a packet reaches a node that has no neighbors offering more progress to the destination. This problem can be particularly frequent in urban scenarios where the presence of buildings can hide best possible local forwarders [5]. In this case, a protocol might try to recover the forwarding at the expense of additional overhead, or drop the packet, reducing the end-to-end delivery performance. To overcome these problems, map-assisted protocols like Spatially Aware Routing (SAR) [6] target forwarding vehicles placed at intermediate road intersections. However, SAR fixes the set of intersections to traverse based on the shortest distance between source and destination, which can compromise the packet delivery depending on the experienced traffic conditions. To account for such conditions, Vehicle-Assisted Data Delivery (VADD) [7] proposed to route packets over forwarding paths having high vehicular density. To select such paths, VADD assumes the use of GPS systems providing a statistical characterization of the roads' vehicular density. Although this approach might result valid on average, it cannot permanently ensure multi-hop connectivity, especially if unexpected changes in the distribution of road traffic flows occur. Proposals like Landmark Overlays for Urban Vehicular Routing Environments (LOUVRE) [8] can handle these situations by making use of real-time traffic information. In LOUVRE, vehicles locally estimate real-time vehicular densities, and proactively disseminate their estimates to obtain a shared connectivity map of the road network. Although exhibiting good performance, LOUVRE requires a considerable amount of overhead to maintain updated its connectivity map. SADV (Static-node Assisted adaptive Data dissemination protocol for Vehicular networks) [9] solves this drawback by routing packets through static nodes placed at every road intersection. Estimations of the delay needed for a packet to be forwarded between adjacent intersections are disseminated by vehicles, so that the protocol can adequately select forwarding paths according to the road traffic distribution. Despite this adaptive ability, SADV relies on the improbable assumption that static nodes are fully deployed at every intersection. The Improved Greedy Traffic Aware Routing (GyTAR) protocol [10] dynamically updates the forwarding path every time a packet is received at a road intersection. GyTAR selects the next intersection where packet needs to be routed based on its progress towards the final destination, and the estimated real-time vehicular density.

Most of the discussed vehicular routing protocols adopt a sender-based forwarding approach, where packets are unicasted to the forwarding nodes exhibiting a higher progress to the final destination. This procedure can reduce the latency and number of hops, but it can also result in operating through unreliable links that increase the retransmissions overhead [11]. On the other hand, contention-based forwarding schemes broadcast the packets to be transmitted, and the receiving nodes

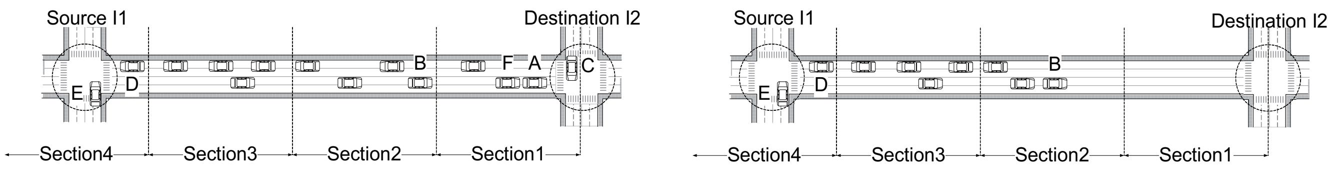

Figure 1: Road segment with full multi-hop connectivity (a), and partial multi-hop connectivity (b)

activate contention mechanisms to determine the next forwarder in a distributed manner. This approach forces multiple nodes to receive and process the same packet, but it also increases the probability at each hop that at least one node will retransmit the packet. In addition to CBF, the CBRP (Contention Based Routing Protocol) [12] and CLA-S (Connectionless Approach for Streets) [13] proposals also apply contention-based routing. CBRP assumes the use of static nodes at intersections to indicate vehicles the reliable forwarding paths to use. On the other hand, CLA-S introduces the concept of forwarding area as a set of parallel streets and intersections where packets are replicated. This replication increases the chances to find a multi-hop connected path to the final destination, but also the communications overhead.

To take advantage of the benefits that contention-based forwarding and real-time traffic information offer to vehicular routing, this paper proposes TOPOCBF (Road Topology-Aware Contention-Based Forwarding), a novel routing mechanism that dynamically selects the forwarding paths based on a direct estimation of their multi-hop connectivity. As the paper will show, the proposed approach can ensure good packet delivery ratios and guarantee an efficient use of the communications channel through an adequate optimization of its design parameters.

II. TOPOCBF PROPOSAL

Following the approach of GyTAR [10], TOPOCBF dynamically selects routing paths at intersections, but rather than estimating vehicular density, it bases its decisions on multi-hop connectivity estimates for each road segment achieved by the DiRCoD (Distributed and Real Time Communications Road Connectivity Discovery) algorithm [14]. As [14] demonstrated, directly estimating the roads' multi-hop connectivity requires a much lower overhead compared to vehicular density. In addition, routing decisions based on the roads' multi-hop connectivity can help to distribute and balance the routing overhead over the road network, and avoid routing packets always through the densest road paths that are more prone to suffering channel congestion.

A. DiRCoD

DiRCoD exploits vehicular communications to compute the multi-hop connectivity status of a road segment and notify this information to the intersections that delimit it. For its operation, it uses the periodic beacon messages currently being defined in international standards [2]. To explain DiRCoD's operation, let us consider the scenario depicted in Figure 1 where a road segment is delimited by two intersections I1 and I2. In the depicted scenario, vehicle E entering I1 needs to be informed on the connectivity status of the road segment in the direction of I2 to decide whether it is convenient to forward a routing packet in this direction or not. To this aim, DiRCoD adds Connectivity Fields (CFs) of a few bits indicating the connectivity status of the road segment to the network beacons issued by vehicles along the road. To represent this connectivity status, the road segment is divided into sections numbered with increasing values depending on their distance from I2 (Figure 1), and with a length equal to the vehicles' average communications range. DiRCoD defines the "virtual distance" separating I1 from I2 as the number of road sections (or hops) between I2 and the closest vehicle to I2 that can be reached from I1 through multi-hop transmissions. Figure 1b) depicts a road segment offering partial multi-hop connectivity: the virtual distance evaluated at I1 for I2 is 2 hops since a packet transmitted from I1 can only reach a vehicle placed at 2 hops distance from I2. On the contrary, Figure 1a) illustrates a road segment with full multi-hop connectivity. In this case, the virtual distance separating I1 from I2 is '0' since the packet can reach I2 through multi-hop transmissions.

DiRCoD's CFs are appended to beacons only by vehicles placed in the inner part of a road segment, excluding the circular regions centered at intersections (DiRCoD's intersection zones). A vehicle appends a CF indicating the road section it is placed at, unless it detects (through beacons receptions) that other vehicles are closer to I2 or are placed in the intersection zone of I2. Referring to Figure 1b), since vehicle B does not detect any vehicle closer to I2 than itself, it includes a CF indicating a virtual distance of '2' in its beacon. On the contrary, vehicle F in Figure 1a) (that initially would append '1' to its beacon) does not append any CF since it detects the presence of vehicle C at I2. Vehicle F appends a CF indicating '0' hops to I2 only upon receiving a beacon from vehicle C. Similarly, vehicle B placed at section 2 in Figure 1a), appends a CF of '0' only after receiving from F a beacon carrying this same value. Through this sequential process, CFs are forwarded to I1. Vehicles placed at I1 will receive a beacon message with a CF of '0' indicating full multi-hop road connectivity in Figure 1a), and a CF of '2' indicating partial connectivity in Figure 1b). If all vehicles along a road included a CF in their beacons, DiRCoD would generate redundant connectivity assessments which would compromise its scalability. To avoid this problem, the algorithm defines a contention-based mechanism in which only one node among all the receiving vehicles forwards the CF towards I1 [14]. DiRCoD has also been designed to control the period between two consecutive road connectivity assessments. A connectivity field generation period is defined as the time that vehicles have to wait before generating or forwarding new CFs. In this context, if the road traffic does not vary rapidly, the CF generation period can be set to higher values so that connectivity assessments are repeated with lower frequency, consequently reducing the overhead on the communications channel.

B. TOPOCBF

TOPOCBF is an evolution of the Contention-Based Forwarding protocol CBF [4] designed to exploit DiRCoD's road connectivity information in its dynamic routing decisions. In CBF, packets are forwarded using broadcast transmissions. Receiving nodes activate a forwarding timeout that is inversely proportional to the progress provided towards the final destination. When the forwarding timeout expires, the packet is retransmitted first by the closest node to the final destination. By overhearing the retransmission of the packet, nodes with the timer active suppress their forwarding attempt. The results reported in [11] showed that CBF achieves higher packet delivery ratios than simple sender-based forwarding schemes. As the authors point out, sender-based schemes need many transmission retries to cope with packet failures, and require that beacons are exchanged with higher frequency to detect reliable forwarders.

Taking advantage of the benefits and simplicity of CBF's forwarding approach, TOPOCBF is designed to iteratively address intermediate anchor points (in this case intersections) placed on the way to reach the packet's final destination, and to dynamically select next forwarding road segments based on their real-time multi-hop connectivity. Once the next forwarding road segment is selected, the target of TOPOCBF is reaching the nearest vehicle to the center of the next intersection using a greedy forwarding scheme. The selection of such vehicle will permit a better knowledge of the connectivity status of adjacent road segments, and consequently, a more efficient selection of the next anchor point. To reach the selected vehicle, TOPOCBF operates a contention-based forwarding approach, for which it is necessary that TOPOCBF packets carry the geographical coordinates of the next intersection through an additional next intersection field. To select the next anchor point or intersection, a vehicle receiving a routing packet in the addressed intersection zone will use DiRCoD's connectivity information of the adjacent road segments. The process to select the subsequent intersections, or anchor points, is repeated until the packet reaches a vehicle that can directly address the destination. Considering the scenario depicted in Figure 1 and the need of vehicle E at I1 to route a packet towards a final destination D, TOPOCBF complies with the following properties to select the next intersection:

1. *Progress towards the destination.* Only adjacent intersections providing progress towards D are considered;
2. *Freshness of the road connectivity information.* When vehicle E enters the intersection zone I1, it processes the received beacons carrying DiRCoD's CFs information referring to the adjacent intersections. At the instant of forwarding a TOPOCBF packet, E checks the times at which the last CFs referring to the intersections holding property 1. were received. If the received CF information is older than DiRCoD's CF generation period, E will interpret that the corresponding road segment does not provide multi-hop connectivity (as explained in section II.A, E will receive a CF every CF generation period independently of whether the road is fully or partially connected). In this case, E would only consider, among its candidate anchor points or intersections, those for which the last CF has been received within the last connectivity expiry time (CET) seconds (CET is defined as a longer time period than the DiRCoD's CF generation period).
3. *Road connectivity status.* Following DiRCoD, adjacent road segments are considered fully or partially connected depending on the virtual distance's value contained in the received CFs. If more than one adjacent intersection holds both properties 1. and 2., the vehicle will select as next intersection the one providing the lowest virtual distance. If two or more intersections have the same virtual distance, the vehicle will select one of them randomly. On the other hand, if no intersection provides the above listed conditions, then the packet is dropped.

An important difference between CBF and TOPOCBF is that CBF computes the forwarding timeout as a function of the distance of each vehicle to the final destination. On the other hand, TOPOCBF computes such timeout as a function of the distance of each vehicle to the next intersection, which can be quite smaller than the distance to the final destination. This allows TOPOCBF to significantly lower the duration of the timeout in the proximity of the addressed intersection, and hence prevents from cumulating unnecessary delays. It is also important to remark that TOPOCBF reduces the problem of creating parallel paths that can suffer CBF under urban or sub-urban scenarios with non line of sight conditions [5]. The uncontrolled broadcast nature of CBF results in that packets are duplicated at road intersections since the presence of buildings might prevent competing forwarders to hear each others' retransmissions. This results in that the packet is replicated over parallel forwarding paths towards the destination with a redundant generation of communications overhead. TOPOCBF eliminates this problem since packets are routed to the following next intersection. As a result, the vehicles that are not placed on the road segment leading to the addressed intersection just discard the packet as they do not provide any progress towards the next target intersection.

III. Performance Evaluation

A. Evaluation Environment

The performance of TOPOCBF has been investigated through simulations using the iTETRIS (an Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions, http://ict-itetris.eu/) platform and its vehicular communications simulator implemented in ns-3 (http://www.nsnam.org/). TOPOCBF is compared to CBF and the basic iTETRIS' geounicast protocol (GEOUNICAST in the following), which is a simple sender-based scheme specified by the GeoNet project [15] and corresponding to the greedy forwarding method used in GPSR [3]. In GEOUNICAST, a node chooses as next forwarder the neighbor node that is closest to the final destination; the candidate neighbor nodes are those stored in its location table for a period of 5s from the last beacon's reception. The implementation of CBF and GEOUNICAST packets fully complies with the format defined by ETSI for geonetworking transmissions [2]. Based in this format, TOPOCBF adds 8 bytes to include the next intersection field. The implementation of DiRCOD in this paper assumes a

CF generation period of 2s, and a CF length of 4 bits. The simulations aim at reproducing the routing of a geounicast notification message between an originating vehicle and a fixed RSU. Notification messages have a fixed application payload of 300 bytes and are issued at a rate of 1Hz for 1000s, which is the simulated time period. Using the SUMO traffic simulator, (http://sourceforge.net/apps/mediawiki/sumo/), a Manhattan scenario is created with 6 horizontal and 6 vertical roads crossing each other to form road segments of 300m as separated by buildings, where the maximum allowed speed is 50 km/h. The reproduced average vehicular density is 11 vehicles/km/lane. Based on Skycomp's classification [17], the generated vehicular traffic pattern would correspond to a LOS (Level-Of-Service) of 'C', indicating moderate traffic conditions. The LOS metric was proposed by Highway Capacity Manual (HCM) [16], and aims to provide a measure to describe road operational conditions. Skycomp extended HCM proposals for the case of interrupted highways and city scenarios, and defined a system that categorizes the LOS based on the average number of vehicles within the formed vehicular platoons. In the simulations, the vehicles communicate using ETSI's ITS G5A radio interfaces [1], the European adaptation of the IEEE 802.11p/WAVE standards. Given the significant impact of radio propagation on V2V communications, propagation conditions including pathloss, shadowing and multipath fading in both line-of-sight (LOS) and non-line-of-sight (NLOS) conditions are modeled using the urban micro-cell propagation model for the 5 GHz band developed by the European project WINNER [18], and included in iTETRIS. Thanks to WINNER, the shielding effect of buildings on the radio propagation between vehicles in NLOS conditions is taken into account. The transmitting power for all vehicles is 20dBm (100 mW). With this transmitting power and the used realistic propagation model, an average packet reception rate of 70% is experienced between two vehicles separated by 200m. Considering this, the value of 200m has been used as the average communications range to set the length of the DiRCoD's road sections. This conservative choice permits DiRCoD to return stable multi-hop road connectivity estimates that are not affected by instantaneous favorable propagation conditions.

B. *Simulation Results*

Figure 2 compares the performance achieved by the three simulated routing protocols. Figure 2a) depicts the Packet Delivery Ratio (PDR), and Figure 2b) the total amount of transmitted information to route packets to the final destination. As demonstrated in [5], CBF duplicates packets at intersections, and creates parallel forwarding paths. This results in an excellent PDR performance close to 99%. On the other hand, CBF also results in a significantly higher routing overhead compared to the other techniques. GEOUNICAST exhibits a very poor PDR performance due to the choice of forwarding nodes with unreliable radio links as a result of its sender-based forwarding mechanism. The results depicted in Figure 2 for TOPOCBF have been obtained considering a DiRCoD's intersection zone's radius R of 20m, and a connectivity expiry time CET of 2.5s. Despite not using parallel paths as CBF, TOPOCBF is still capable to achieve a PDR of 72% with a 38% less communications overhead than CBF. The TOPOCBF routing overhead differentiates between routing packets and the additional bytes introduced by DiRCoD. In this context, it is interesting to analyze the PDR-overhead trade-off represented in Figure 3 through the "useful overhead" metric defined as the ratio between the overhead

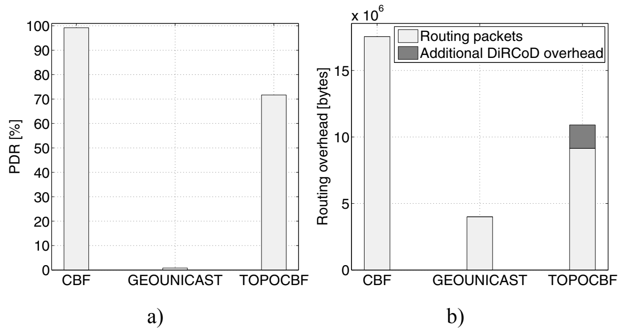

Figure 2: PDR (a) and routing overhead (b) comparison

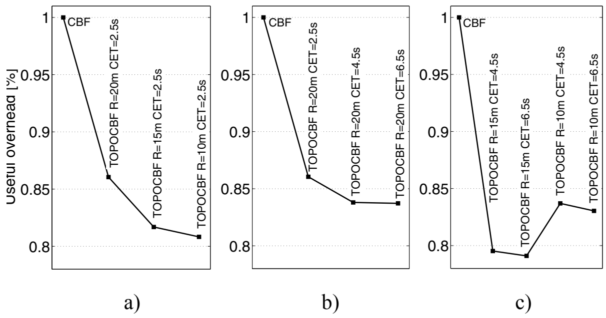

Figure 3: CBF and TOPOCBF useful overhead with decreasing DiRCoD's intersection zone radius R (a), increasing connectivity expiry time CET (b), and combined R and CET values (c)

generated by each routing protocol and the achieved PDR. This metric is aimed at measuring how useful in terms of final packet delivery are the overheads introduced in the routing process. In principle, the lower the useful overhead, the more efficient is the overhead introduced by each routing protocol. Figure 3 only represents the useful overhead for the CBF and TOPOCBF protocols since the very low GEOUNICAST's PDR results in a very high useful overhead. To facilitate the comparison, the represented metric is normalized by the CBF's useful overhead. Figure 3 shows that with the initial TOPOCBF configuration (R=20m and CET=2.5s), TOPOCBF reduces by 14% the useful overhead compared to CBF, and could hence be considered more efficient.

To further optimize the performance and operation of TOPOCBF, this paper analyses the optimization of some of its key parameters, in particular R and CET. Figures 4 and 5 depict the effect of decreasing R and increasing CET on TOPOCBF's PDR and routing overhead. The obtained results show that by keeping fixed the CET at 2.5s, decreasing the radius R of the DiRCoD's intersection zone results in a higher PDR (82% compared to 72% in Figure 2). This is due to the fact that decreasing R results in that more vehicles are involved in the generation and forwarding of CFs in the inner part of a road. Consequently, more CFs are correctly received at intersections, and fewer TOPOCBF packets are drop due the lack of updated road connectivity information when they reach an intersection. Similarly, with a fixed initial R of 20m, increasing the CET also augments the PDR (78%) as it allows

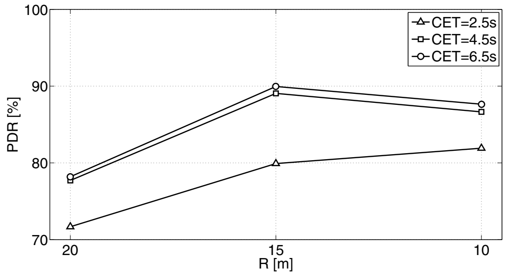

Figure 4: TOPOCBF's PDR for varying R and CET

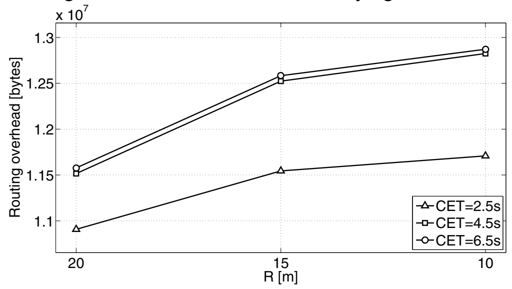

Figure 5: TOPOCBF's routing overhead for varying R and CET

TOPOCBF the possibility to forward packets at intersections even if the road connectivity estimates have not been updated very recently. The increase of the PDR is achieved at the expense of increasing the communications overhead (Figure 5). However, the results depicted in Figure 3a) and 3b) show that the increase of the routing overhead does not increase the useful overhead. These results motivated the analysis of whether combining low values of R and high values of CET can further optimize TOPOCBF's performance. As depicted in figure 4, the best combination is achieved with R set to 15m and CET to 6.5s, where the PDR reaches a value of 89%. It is important to note that this PDR, significantly closer to CBF than the original TOPOCBF implementation, is obtained with a significantly lower routing overhead (Figures 2 and 5). Using a very low R combined to higher CETs leads to collisions between routing packets and DiRCoD beacons at intersections, which causes a lower PDR. In terms of useful overhead, Figure 3c) shows that with a proper combination of design parameters, TOPOCBF reduces by up to 21% the useful overhead compared to CBF.

IV. CONCLUSIONS

Vehicular routing protocols have recently evolved towards schemes that dynamically select the forwarding paths by considering real-time traffic information. To avoid the implementation cost of estimating vehicular densities, the authors propose to base routing decisions on a direct multi-hop connectivity estimation of each road segment. In this context, this paper has presented TOPOCBF, a contention-based forwarding scheme that uses the multi-hop road connectivity assessments to dynamically select the forwarding paths. The paper has also investigated how to efficiently configure the TOPOCBF proposal to maximize its performance and communications efficiency. The obtained results have shown that the proposed scheme can achieve high packet delivery ratios while still limiting the communications overhead.

ACKNOWLEDGMENT

This work has been partly supported by the Spanish Ministry of Industry, Tourism and Trade under the project INTELVIA (Reference number: TSI-020302-2009-90) and by the FP7 EU Project iTETRIS: An Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management (Project number: 224644).

REFERENCES

[1] ETSI TC ITS, "Intelligent Transport Systems (ITS); European profile standard on the physical and medium access layer of 5 GHz ITS", Standard ETSI ES 202 663 v1.1.0, Jan. 2010

[2] ETSI TC ITS, "Intelligent Transport Systems (ITS); Communications; Architecture; Vehicular Communications, Part 4: Geographical Addressing and Forwarding for Point-to-Point and Point-to-Multipoint Communications; Sub-part 1: Media-Independent Functionality", Draft ETSI TS 102 636-4-1 v0.1.1, Febr. 2011

[3] B. Karp and H. T. Kung, "GPSR: greedy perimeter stateless routing for wireless networks", Proc. of the ACM/IEEE 6th annual international conference on mobile computing and networking, MOBICOM'00, pp. 243–254, Aug. 2000

[4] H. Fussler, J. Widmer, M. Kasemann, M. Mauve, and H. Hartenstein, "Contention-based forwarding for mobile ad hoc networks", Ad Hoc Networks, Elsevier, vol. 1, issue 4, pp.351-369, Nov. 2003

[5] J. Gozalvez, M. Sepulcre, and R. Bauza, "Impact of the radio channel modelling on the performance of VANET communication protocols", Telecommunication Systems, Springer, pp. 1-19, Dec. 2010

[6] J. Tian, L. Han, K. Rothermel, "Spatially aware packet routing for mobile ad hoc inter-vehicle radio networks", Proc. of IEEE Intelligent Transportation Systems 2003, vol.2, pp. 1546- 1551, Oct. 2003

[7] J. Zhao, G. Cao, "VADD: Vehicle-Assisted Data Delivery in Vehicular Ad Hoc Networks", IEEE Transactions on Vehicular Technology , vol.57, no.3, pp.1910-1922, May 2008

[8] K.C. Lee, M. Le, J. Harri, M. Gerla, "LOUVRE: Landmark Overlays for Urban Vehicular Routing Environments," Proc. of the 68th IEEE Vehicular Technology Conference VTC Fall 2008, pp.1-5, Sept. 2008

[9] Y. Ding, C. Wang, and L. Xiao, "A static-node assisted adaptive routing protocol in vehicular networks", Proc. of the 4th ACM international workshop on Vehicular ad hoc networks, pp. 59-68, 2007

[10] M. Jerbi, S.-M. Senouci, T. Rasheed, Y. Ghamri-Doudane, "Towards Efficient Geographic Routing in Urban Vehicular Networks," IEEE Transactions on Vehicular Technology, vol.58, no.9, pp.5048-5059, Nov. 2009

[11] H. Fussler, H. Hartenstein, J. Widmer, M. Mauve, and W. Effelsberg, "Contention-based Forwarding for Street Scenarios", Proc. Of the 1st International Workshop in Intelligent Transportation, March 2004

[12] Tonghong Li, Yuanzhen Li, Jianxin Liao, "A Contention-Based Routing Protocol for Vehicular Ad Hoc Networks in City Environments", Proc. of the 29th IEEE International Conference on Distributed Computing Systems, pp.482-487, June 2009

[13] A. Ho, Y.H. Ho, K.A. Hua, "A connectionless approach to mobile ad hoc networks in street environments", Proc. of Intelligent Vehicles Symposium 2005, pp. 575- 582, June 2005

[14] M. Rondinone and J. Gozalvez, "Distributed and Real Time Communications Road Connectivity Discovery through Vehicular Ad-hoc Networks", Proc. of the 13th International IEEE Conference on Intelligent Transportation Systems, pp.1079-1084, Sept. 2010

[15] GeoNet Consortium, "D2.2 Final GeoNet Specification", Jan. 2010

[16] "Highway Capacity Manual - HCM 2000", Transportation Research Board, National Research Council, 2000

[17] Skycomp, Inc., Parsons Brinckerhoff Quade & Douglas, Inc., "Performance Ratings of Traffic Flows on Selected New York Metropolitan Area Highways Fall 2007", 2007

[18] WINNER Consortium, "D1.1.2. WINNER II channel models", WINNER European Research project Public Deliverable, Sept. 2007