Would Current *Ad-Hoc* Routing Protocols be Adequate for the Internet of Vehicles? A Comparative Study

Armir Bujari, *Member, IEEE*, Ombretta Gaggi, Claudio Enrico Palazzi, *Member, IEEE*, and Daniele Ronzani

***Abstract*—In recent years we have seen a great proliferation of smart vehicles, ranging from cars to little drones (both terrestrial and aerial), all endowed with sensors and communication capabilities. It is hence easy to foresee a future with even more smart and connected vehicles moving around, occupying space and creating an Internet of Vehicles (IoV). In this IoV, a multitude of nodes (both static and mobile) will generate a continuous multihop flow of local information to support local smart environment applications. Therefore, one interesting environment for the IoV would be in the form of 3-D mobile ad-hoc networks (MANETs). Unfortunately, MANET routing protocols have generally been designed and analyzed keeping in mind a 2-D scenario; there is no guarantee on how they would support a 3-D topology of the IoV. To this end, we have considered routing protocols deemed as the state-of-the-art for classic MANETs and tested them over 3-D topologies to evaluate their assets and technical challenges.**

***Index Terms*—Internet of Vehicles (IoV), performance, position-based, routing, topology-based.**

I. Introduction

MOBILE ad-hoc networks (MANETs) have been a challenging research topic for a while now, thanks to their versatility, which has been demonstrated to be useful in numerous scenarios (e.g., emergency deployments and community networking). Yet, they have now gained new interest due to recent technological revolutions palpable in our everyday life. Consider, for instance, smartphones, cars and drones (both terrestrial and aerial): they have all become smart, with computational, sensing and communication capabilities. These devices can hence now be interconnected, creating real MANETs supporting new and innovative service provisioning schemes [1]–[3].

In fact, the popularity of mobile phones have created the potential for actual MANETs, whereas thanks to the IEEE 802.11p a lot of research has now been devoted to vehicular ad-hoc networks (VANETs) [4], [5]. Furthermore, groups of micro aerial vehicles and unmanned airborne vehicles (UAVs) have been considered as possible flying ad-hoc networks [6]. In this context, drone ad-hoc networks (DANETs) are considered as the next logical evolution, comprising ad-hoc networks composed of both micro aerial and terrestrial vehicles.

In this paper, we intend to focus on ad-hoc networks composed of any sort of vehicle (e.g., cars, drones, etc.) that could be present in our towns. These networks could be used to gather, elaborate, and disseminate a lot of information having a local scope: traffic condition, local message exchange, pollution sensing, coordinated movements, warnings, etc. In other words, they would form an Internet of Vehicles (IoV), with multihop communications flowing amongst its nodes. Even in case some information has to go through the Internet, we can still consider the possibility of having some node acting as Internet gateway and other nodes in our ad-hoc network resorting to multihop connectivity to communicate with the Internet gateway [7], [8]. Note that we consider the case in which drones may become more and more popular and able to perform smart autonomous purposes; i.e., we assume that drones will have an increment of popularity and functions similar to what happened with cellular phones (beside being interesting, this currently seems to be a plausible trend [9]).

It is hence easy to see how multihop, *ad-hoc* routing represents a fundamental task in the envisioned IoV. One may say that finally we will have the chance to apply all those decades of research in MANET routing. Unfortunately, the depicted IoV scenario has peculiar features that make it different from a general MANET. First of all, since the assumed presence of numerous flying objects, we have to consider a 3-D topology. Then, we have to assume that mobility conditions may change greatly from case to case; we may have scenarios where all nodes are moving, as well as scenarios where just a small percentage of nodes are moving whereas the majority is static or nomadically moving by now and then (and hence can be assumed as static during the duration of a data flow). Furthermore, the scenario where most nodes are static also includes those cases where the IoV is interconnected with static sensors with communication capabilities (e.g., some sensors on top of roadside lamps or buildings' roofs), thus making the considered scenarios even more representative.

As MANET routing protocols have generally been designed and analyzed keeping in mind a 2-D scenario, there is no guarantee on how they would support the 3-D topology of the envisioned IoV. To this end, we have considered routing

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protocols deemed as the state-of-the-art for classic MANETs and tested them over 3-D topologies to evaluate current assets and technical challenges. In particular, we have considered two main classes of protocols: 1) topology-based and 2) position-based. For each of these classes, we have taken main representatives and analyzed them in the 3-D scenario in order to highlight main pros and cons in using them. Given the absence of a reference mobility model for DANETs, we simulate this network by employing a synthetic mobility model while adopting realistic, well-established mobility models for other components of the network. While there have been efforts in devising mission or application-specific mobility models for drones, this paper is not tailored to a specific use-case and goes beyond the specific application scenario. The goal is to assess the feasibility of current routing proposals for a general IoV.

The rest of this paper is organized as follows. In Section II, we discuss general background information related to the IoV scenario, whereas Section III overviews the state-of-the-art of routing protocols in the context. Section IV presents the first experimental results, discussing the tradeoffs that emerge. Following the same objective, in Section V, we assess a realistic IoV deployment consisting of heterogeneous IoV devices engaged in communication with each other. Finally, the conclusions are drawn in Section VI.

II. Background

A. Application Scenario

Ad-hoc networking seems a promising paradigm, able to support new and innovative applications in scenarios involving vehicles, drones, and personal devices such as smartphones [10]–[12]. As anticipated, these networks could be used to gather, elaborate, and disseminate information in an IoV through multihop connectivity. Communication among vehicles has been categorized in recent years into various declinations, e.g., vehicle-to-vehicle, vehicle-to-road, vehicle-to-human, vehicle-to-sensor, and vehicle-to-drone; it is hence clear how an IoV could be composed by much more than just cars. On the contrary, we can expect an IoV to be a 3-D topology ad-hoc network involving terrestrial and flying vehicles as well as sensors, computers, smartphones, Internet gateways, and any other device with communication capabilities present in the environment.

There are many applications that could exploit ad-hoc communication in the context of IoV, ranging from environmental monitoring to safety and entertainment [13]. For instance, one might envisage VANETs being employed to disseminate information regarding vehicular movements, general traffic conditions, or even advertisement toward the Internet (e.g., to Web services such as Google Maps) and vice versa [7].

A timely and very challenging application regards the distributed control over wireless links in order to enable autonomous driving. Autonomous vehicles would in fact need to get as much information as possible from the IoV to determine their best course of action to ensure efficiency, reliability, and safety [14], [15]. This means obtaining information, even through multihop, from surrounding vehicles, from cameras placed on top of lamps and buildings, from sensors around, from hovering UAVs, etc. Automated driving or flying, and the need for IoV-based, distributed control could be used even in case of rescue operation based on autonomous terrestrial and aerial vehicles [16].

Indeed, flying drones are becoming frequently seen vehicles with communication and sensing capabilities. We can expect them to evolve in terms of functionalities and reach similar popularity peaks as smartphones. It is even possible that, in future, each person will have a personal drone helping her/him with creating material to populate a social account (e.g., automatically created logs composed by pictures, videos, etc. [17]). Drones may include any unmanned aircraft or self-driving vehicles, ranging in size from a palm-sized to several meters; they may also carry small amounts of cargo. Another possible application is the traffic monitoring, safety and law enforcement over the streets, in which drones can communicate amongst themselves, or to a specific car, or to a group of vehicles.

IoV communication could be exploited even for local message exchange amongst passengers of cars in a certain area and people nearby. They might share text, voice, images, videos, online gaming, music, news, and advertisement, even resorting to data generated elsewhere (e.g., a drone in the sky above them). Regarding local news and advertisement dissemination, data floating solutions could be adopted by having an IoV supporting them [18].

B. Routing in 3-D MANETs

The highly dynamic and heterogeneous nature of 3-D MANETs clearly raises questions on the suitability of current routing protocols. Route discovery and maintenance in ad-hoc networks is related to the topology changes; thus, the system performance depends on how reactive is the routing protocol to link changes.

The simplest approach to data delivery would be flooding. In essence, every node transmits each data packet to every other neighboring node. Nevertheless, this type of data propagation does not scale with the network size or density, because of redundant transmissions.

Classic topology-based *ad-hoc* routing protocols, such as ad-hoc on demand distance vector (AODV) or destination-sequenced distance-vector (DSDV), can be used for this type of networks, although they are not appropriate for highly dynamic scenarios. Another class of protocols are the position-based (geo-routing) approaches, which exploit node locations to determine the next hop. Typically, nodes resorting to geo-routing exploit a location service, such as the global positioning system. Position-based approaches were introduced to eliminate some inherent limitations of topology-based protocols, such as the route maintenance. Nodes in this context exploit local information mirrored in a neighboring table, containing geographical positions of nodes. In general, neighbor discovery relies on a beaconing service whereby nodes periodically broadcast positional information. Clearly, the beaconing period is an important factor that shapes the performance of a position-based protocol [19].

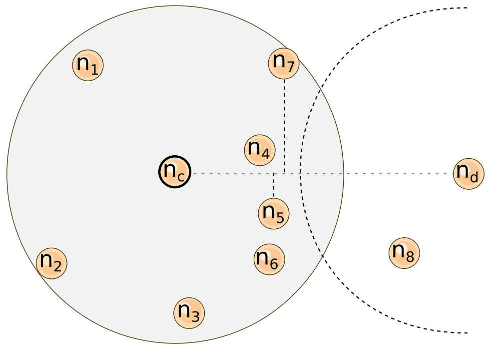


Fig. 1. Illustration of several next-hop nodes chosen by n_c using the progress-based forwarding strategies. With greedy, n_c chooses n_5 as the next-hop node.

A well known technique exploiting location information to route data packets is the *greedy* approach [20]. In this approach, the neighbor node closest to the destination is the one eligible to further advance their data packet into the network. So far, many geographic routing protocols have been proposed and they can be categorized in three classes: 1) *progress-based*; 2) *randomized-based*; and 3) *face-based*. In progress-based routing protocols, the current node holding the packet forwards it to the node making the most progress toward a destination. An illustration of the progress-based strategy is shown in Fig. 1. The randomized-based strategy is similar to progress-based method but in this case the next node is chosen randomly or according to a probability distribution, from the set of candidate nodes. The face-based strategy uses an algorithm, called *Face* [21], that advances the packet between the faces by considering the *right-hand* rule, always guaranteeing the packet delivery to the destination in the context of planar (2-D) networks. Position information is used to extract a planar subgraph containing the faces whose vertices are the nodes.

More recently, there have been a number of practical deployments of 3-D networks (sensor networks, drone networks, vehicle networks). Many actual real applications require a 3-D node arrangement. To the best of our knowledge, a lot of research has been devoted to devise efficient geographic routing protocols in 2-D networks and many 3-D geographic routing protocols proposed are mainly studied in a theoretical interest. Indeed, they have been designed and analyzed in ideal topologies, abstracting from the intricacies of the wireless medium (like unit ball graphs [22]). Geographic routing in 3-D space is intrinsically harder than routing in 2-D topologies. For example, a greedy forwarding approach tends to reach more local *minima* in a general 3-D topology, than in a 2-D counterpart. Moreover, many of the geographic protocols are not extensible to the third dimension and often the extension of 2-D routing protocols into 3-D ones is not trivial, since some assumptions made in the 2-D context break down (e.g., the ability to extract planar subgraphs). Durocher *et al.* [22] showed the impossibility of routing protocols to guarantee delivery in 3-D ad-hoc networks, when nodes are constrained to rely only on information related to their *k*-hop neighborhood (with *k* strictly lower than the network diameter). This is in contrast to the results from 2-D environments, where a protocol relying on local information, e.g., face routing, does guarantee delivery. This leads the problem of finding other solutions able to guarantee the delivery of packets, with the least use of resources.

III. Description of Routing Protocols

Our goal is to assess the feasibility of current state-of-the-art routing protocols for the IoV environment. To this end, we chose some representative approaches for each considered classes. In the following, we provide a concise overview for each of them.

A. Topology-Based Protocols

DSDV [23] is based on the Bellman Ford algorithm. DSDV is a proactive protocol that is enhanced by the use of sequence numbers in the routing tables to avoid the loop problem. In this way, the most recently updated paths have a higher sequence number. Each node updates its sequence number every time that it sends an update and maintains a routing table with an entry for each other network node. Each entry holds a sequence number, which is updated with each change, used to avoid cycles and discriminate between old routes and new ones. Updates are transmitted by nodes periodically or as soon as major changes take place. When a node receives two different paths to the same destination, it chooses the one with the greater sequence number, or the one with less hops in case of equal sequence number. To reduce the overhead of network traffic, this routing protocol uses two types of update packets.

1) *Full Dump:* All complete routing information are sent.
2) *Incremental Dump:* Only updates are sent.

AODV [24] is a reactive protocol whereby routes are established on-demand, as they are needed. In AODV, the network is silent until a connection is needed. When a node needs to find the path toward a certain destination, a route request (RREQ) packet is sent in broadcast over the network. Other nodes that receive this RREQ packet forward it and record the node from which they have received it by creating or updating the temporary route to reach the source node in their routing table. When a node possessing the information about the route to the destination receives an RREQ, it answers by sending an RREP packet through a temporary route to the requesting node. The requesting node then begins to use the route that has the least number of hops through other nodes. When a link fails, a routing error is passed back to a transmitting node sending a route error packet, and the process repeats. Nodes use a sequence number so that they do not repeat RREQs that they have already forwarded. The advantage of AODV is that it does not create extra traffic in maintaining the routing tables if cases they are not used. On the other hand, it requires more time to establish a route when compared to DSDV.

Dynamic source routing (DSR [25]), like in AODV, the source node initiates a route discovery process generating an RREQ packet which is flooded into the network. The RREQ packet contains a list of hops which are incrementally added into the RREQ packet header as it is propagated through the network. Once the RREQ reaches the destination or a node that has a path toward the destination, an RREP is sent back along the reverse path collected in the RREQ. The main difference between DSR and AODV is in the way the route information is kept: in DSR it is stored at the source and in the header of the transmitted control packet, while in AODV it is stored at the intermediate nodes.

B. Position-Based Protocols

Position-based routing protocols (*geo-routing*) exploit nodes coordinates to route packets toward a destination. Several geographic routing protocols have been proposed; they can be categorized among three main classes: progress, randomized and face-based. Clearly, we also have hybrid approaches that combine the strengths of the various strategies. In this paper, we hence consider and analyze three representative hybrid protocols considered to be as the state-of-the-art amongst position-based routing protocols for 3-D ad-hoc networks.

Greedy-face-greedy (GFG [21]), also referred to as greedy perimeter stateless routing algorithm [26] for 2-D networks, uses a combination of greedy and face methods. With GFG, a flag is stored in each data packet. This flag can be set into greedy and face-mode, indicating whether the packet is forwarded with a greedy approach (using the greedy forwarding algorithm) or a face approach, respectively.

The greedy approach uses a deterministic method to deliver the packet. Typically, the greedy algorithm [20] is used: a node that receives a packet searches among its neighbors the node that is closest to the destination. If this node exists, the packet is transmitted to it, otherwise the packet is dropped and the current node is called a local minimum.

The face approach adopts the Face algorithm, which makes uses graph planarization to forward the packet. The Face algorithm is a prominent solution proposed to address the local *minima* problem which a greedy approach is subject to. In a 2-D network, Face obtains a guaranteed packet delivery, but in 3-D scenarios its benefits are inhibited since the concept of 3-D graph planarization is not so straightforward. However, some works [27]–[29] have proposed techniques whereby nodes are projected over a 2-D plane so that the Face algorithm could still be used, although it is not clear with which limitations. As the face algorithm representative, we have chosen the method described in [29] which is considered as the state-of-the-art for this class of algorithms, achieving the best performance in terms of packet delivery.

In detail, GFG starts from the source node with the greedy algorithm. When along the route the packet gets stuck into a local minimum, the packet is marked to switch from greedy to face-mode and GFG performs the Face forwarding algorithm in the projected planar graph defined in [29]. Moreover, when a packet enters in face-mode at node x, GFG records in the packet the location of x as the node when greedy forwarding mode failed. This information is then used at next hops to determine whether and when the packet can be forwarded in a greedy fashion. Upon receiving a face-mode packet, the current node compares the location of x as stored in the packet with the forwarding nodes location. GFG returns in greedy-mode if the distance from the forwarding node to the destination node is less than the distance x to the destination node. In this case, the packet is set into greedy-mode and the algorithm continues the greedy progress toward the destination. Otherwise, GFG continues with the face-mode forwarding. Fig. 2 shows an example of the GFG protocol.

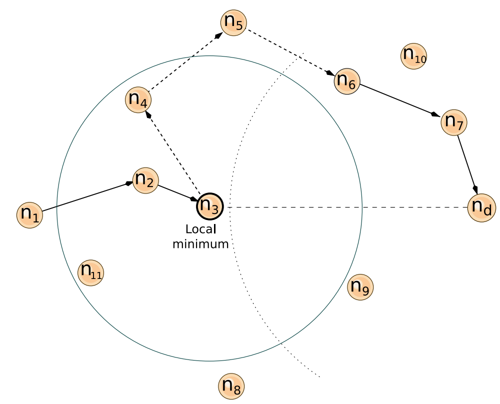


Fig. 2. GFG algorithm over a 2-D graph. Solid arrows represent greedy-mode forwarding and dashed arrows represent face-mode forwarding.

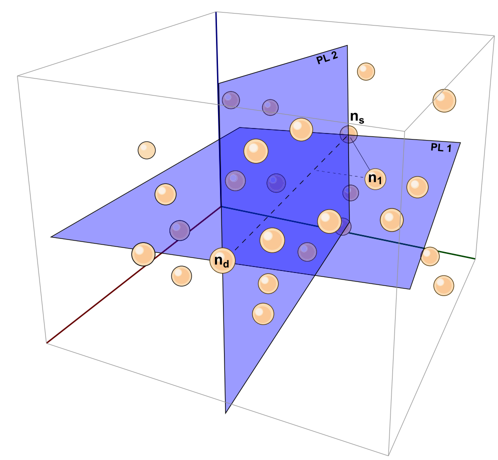


Fig. 3. In AB3D, plane PL_1 passes through n_s, n_d, and n_1, and plane PL_2 is orthogonal to PL_1. Both planes contain the line $(n_s n_d)$.

Greedy-random-greedy (GRG [30]) is yet another hybrid approach belonging to the progress/randomized-based class. GRG uses greedy as the primary scheme and a randomized algorithm as a recovery strategy. A randomized approach tries to solve the local minimum problem stated previously by randomly choosing the next node toward destination from a subset of the current neighbors. Typically, a 2-D randomized algorithm [31] chooses a neighbor node above the line passing through the current node and the destination node, and a neighbor node below the same line. The two nodes are selected using a greedy approach. Then, from these two neighbors, the next node is chosen randomly or according to a distribution of probability. A 3-D extension of this approach, named AB3D, is proposed in [28] and [32] and uses planes passing through the source and the destination to divide the neighbor selecting regions. In our comparison we have chosen this method as the randomized approach. Fig. 3 shows a typical region subdivision of the AB3D protocol.

GRG starts with a greedy approach until it finds a local minimum. At this point, GRG stores the distance from this local minimum and the destination immediately before switching to the random phase as a recovery strategy. In this phase, the node randomly selects one of its neighbors using the steps defined in [28]. If the distance between the next node and the destination is less than the distance between the previous local minimum and the destination, then the algorithm resumes the greedy forwarding, otherwise it continues with the random phase.

Depth first search (DFS [33]) is a distributed approximation of the classical depth-first search algorithm from where the name derives. The proposal follows a progress-based forwarding strategy like greedy and the forwarding strategy takes place as follows: each node has a list in its local memory that contains the *id* of received packets. If a packet arrives in a node, its *id* is stored in this list. If a packet *id* is not found in the local memory of a node, this node is marked as white; otherwise, if the packet *id* is present, the node is marked as gray (which means that it has received packet at least once). The process of visiting nodes coincides with sending packets between nodes. If a node receives a packet for the first time, it memorizes also the node that forwarded that packet. So, each node stores a list of tuples $id, from$, where *id* is the packet id and *from* is the node from which the packet arrived.

The source node s starts DFS coloring itself as gray and storing the *id* packet in its list (the *from* field is empty). Each DFS packet has one bit that indicates whether the message is forwarded or returned. When a node c receives a packet for the first time, it adds a tuple $(id, from)$ into its memory and orders its neighbors according to their distance to the destination d (hence following a greedy method). The only node not to be taken into account in the ordered list is node *from* that sent the packet to c. The packet is then forwarded to the first choice u among the neighbors (the first node chosen is the node that is closest to the destination). If there is no choice, the packet is returned to *from*.

If receiving a packet forwarded from any node b, a gray node c will reject it immediately, returning it to b (returned message). A gray node b, upon receiving a returned message from node c, will forward the message to the next choice e in its sorted list of neighbors, if such a neighbor exists. If b has no more neighbors in its list, the packet will be returned to the node *from*, which originally sent the message to b (memorized in the list of packets). An index L is used to know which is the next node to forward the packet in the ordered list. L is the index, in the list, of the last neighbor u selected for packet forwarding. When a new node has to be chosen, L is increased.

IV. Performance Evaluation

The adopted simulation environment is the well-known and widely used Network Simulator 2 [34]. While the simulator is equipped with a native implementation of the topology-based protocols, we had to implement from scratch the position-based ones. It is noteworthy to mention, that the targeted simulation environment does not natively support 3-D environments. To this end, we had to apply a publicly available patch [35]. In the following, we provide some details regarding the simulation parameters and evaluation strategy.

TABLE I
Simulation Parameters

Parameter	Value
MAC type	IEEE 802.11g
Simulation area	1000 m x 1000 m x 1000 m
Transmission range	250 m
Node max speed	10 m/s
Traffic type	CBR
Number of data flows	10
Data packet size	64 bytes
Packet rate	2 pckt/s
Queue type	Drop Tail
Number of nodes	50, 100, 150, 200
Pause times (sec)	5, 20, 40, 100 (static)

A. Simulation Environment

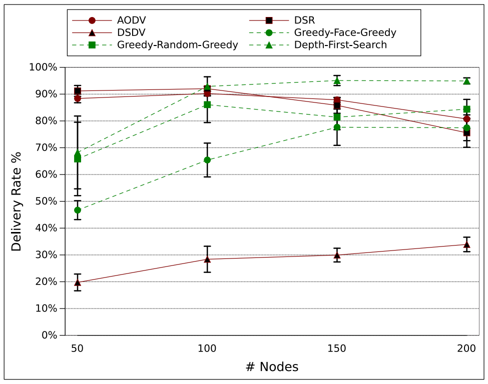
Our main goal is to show how the considered protocols behave in an environment different from the one they were designed for. Our simulator environment consists of a set of nodes randomly generated in a cube of side length 1000 units with a transmission range of 250 units. We considered four different cardinalities for the set of nodes in the network: 50, 100, 150, and 200 nodes, in order to evaluate the protocol performance variation. Mobility models proposed in the past have been focused, for instance, on VANETs but not on drone networks [4]; we have hence considered the recommended mobility model but we had to adapt to our considered 3-D environment. In essence, nodes alternate movement and stationary periods. For each cardinality of the set of nodes, four mobility constraints are chosen, in terms of pause time: 5, 20, 40, and 100 s, during which the node remains stationary, before resuming to move toward a new destination in the 3-D space. The simulation duration is set to 100 s, so that the case with 100 s of pause time corresponds to a network with static nodes. The traffic scenario consists on ten flows (ten different sources and ten different destinations) of CBR traffic. These and the other mobility parameters are summarized in Table I. For position-based protocols, the proactive beaconing process period (i.e., the time between two consecutive beacon transmissions) is set equal to 0.5 s.

The metrics of interest used to assess the protocols are as follows.

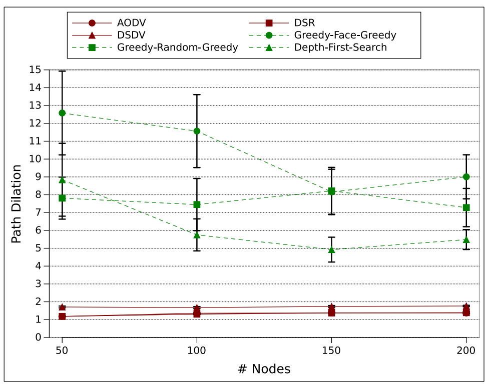
1) *Packet Delivery:* It is the average ratio of the data packet delivered to the destination to those generated by the source.
2) *Path Dilation:* It is also called *stretch factor* and corresponds to the average ratio of the number of hops traversed by the packet to reach the destination, to the minimum path length from source to destination.

B. Simulation Results and Discussion

In this section, we show the performance results of routing protocols in a set of networks of 50, 100, 150, and 200 nodes,

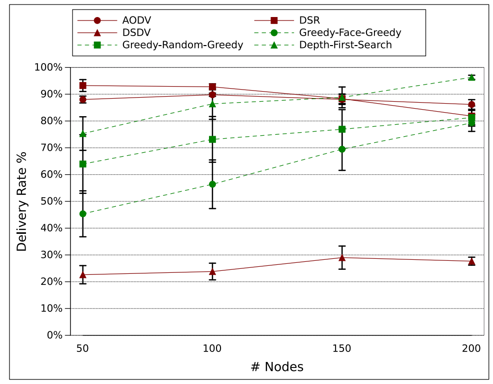


(a)

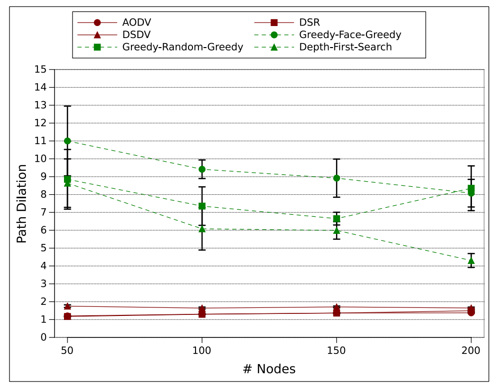


(b)

Fig. 4. Performance comparison among the protocols in a 3-D MANET varying the number of nodes. The nodes are mobile with pause time 5 s. (a) Delivery rate. (b) Path dilation.



(a)



(b)

Fig. 5. Performance comparison among the protocols in a 3-D MANET varying the number of nodes. The nodes are mobile with pause time 20 s. (a) Delivery rate. (b) Path dilation.

with pause times 5, 20, 40, and 100 s. Basically, with a 5 s of pause time the nodes moves frequently, whereas with 20 and 40 s of pause time the network has less mobility and with 100 s of pause time all the nodes are still during the whole 100 s of simulation.

C. Pause Time of 5 s

Topology-based and position-based protocols perform in a heterogeneous way. For instance, in Fig. 4 we can notice the different performances for each of the considered metrics. The delivery rate in low density scenarios (50 nodes) is quite low for position-based protocols, especially when employing the GFG scheme, while AODV and DSR perform at an acceptable level. When increasing the number of nodes, the packet delivery rate of the position-based protocols increases as well. The best performance when considering a network density of 200 nodes, is reached by the DFS scheme (about 95%). In terms of path dilation, position-based protocols achieve the worst performance. This is intuitively expected as these schemes rely solely on local knowledge. Instead, all the topology-based protocols perform well, with packets traversing a path of length close to the optimal length. We can also notice that when increasing the number of nodes, the path dilation decreases. This effect is explained due to the fact that having a denser network increases the chances of finding a straight path toward the destination. On the contrary, if a node has a low number of neighbor nodes, it may unfortunately happen that a few out-of-date information from neighbors could lead to a loop among the nodes, and hence to higher values of path dilation, until the neighbor table settles.

D. Pause Time of 20 s

The results evidenced in Fig. 5 show that there are not many differences when compared to the prior configuration. We see a little growth in the delivery rate for AODV and DSR and the position-based protocols. Also, position-based approaches present a reduction of values, whereas packets in the topology-based schemes on average traverse almost the same number of hops as in the case of 5 s pause time. In general, we can see that AODV and DSR achieve very good performance indexes both in terms of delivery rate and path dilation. In particular, DFS is able to achieve the best data delivery rate when the number of nodes is higher or equal to 100. Unfortunately, this comes at the cost of a path dilation that, although lower than other position-based schemes, results even three or four times wider than with AODV and DSR.

E. Pause Time of 40 s

With a pause time of 40 s, we are considering a network composed by nodes with seldom mobility. DSDV performs

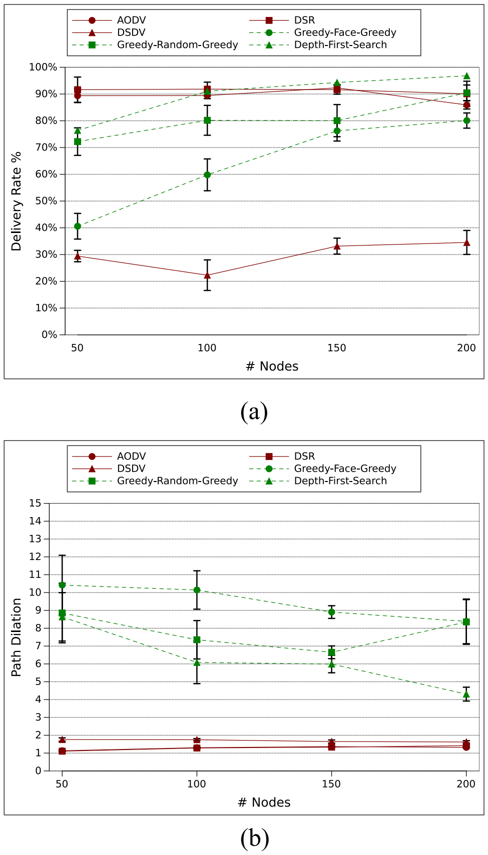


Fig. 6. Performance comparison among the protocols in a 3-D MANET varying the number of nodes. The nodes are mobile with pause time 40 s. (a) Delivery rate. (b) Path dilation.

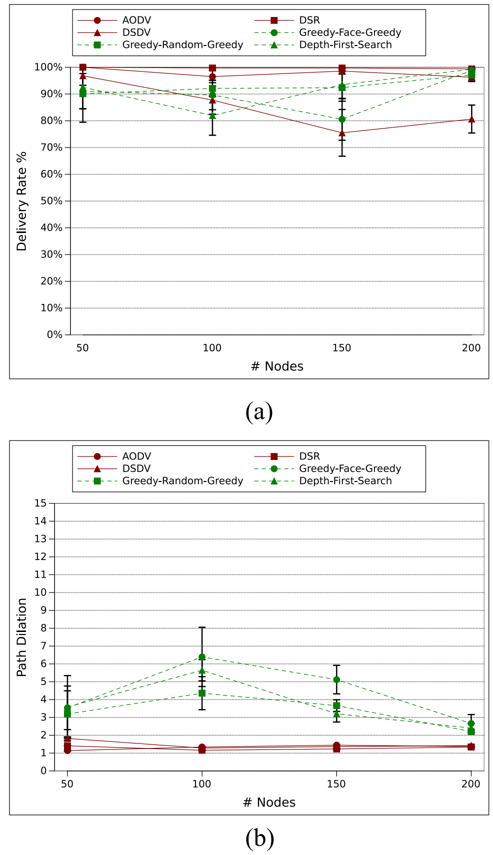


Fig. 7. Performance comparison among the protocols in a 3-D MANET varying the number of nodes. The nodes are static. (a) Delivery rate. (b) Path dilation.

well in terms of delivery rate when compared to prior configurations. Even the position-based approaches show better delivery rates than the case of 20 s pause time; furthermore, increasing the node density we achieve higher delivery rates due to the increment of alternative routes that a node can choose. The path dilation values are reduced for position-based protocols, which take a better decision for the next node, since the nodes are stationary for longer periods. In the case of topology-based protocols the path dilation remains between 1 and 2. In general, even in this case, AODV and DSR seem to be the best protocols to constantly ensure high delivery rate and low path dilation.

F. Pause Time of 100 s (Static Network)

In a static network, the delivery rate is as expected very high for all the routing protocols. If a protocol is not able to ensure the delivery of all packets it is due to the unreliable nature of the wireless link. Furthermore, the GFG algorithm still experiences some problems in delivering the packets, since the planarization of a 3-D graph is not optimal and the algorithm gets stuck in a loop. The lowest performance of position-based protocols are shown in the case of 100 nodes, while with 200 nodes they are all able to reach more than 95% of delivery rate.

Fig. 8. Multitier IoV network comprised of moving cars, drones, and traffic intersections equipped with sensing and communication capabilities. In this envisaged scenario communication takes place amongst entities in a multihop fashion. Cars could exploit the IoV sensing capabilities, gathering and merging information from different complementary sources in order to extend the drivers' perception beyond direct line of sight.

V. Performance of Routing Protocols in Realistic Urban Environment

Fig. 8 depicts a potential deployment consisting of a heterogeneous, general purpose IoV network. The area represents a portion of a city with static sensors positioned in lamps and/or at traffic intersections, moving cars and drones flying above

TABLE II
SIMULATION PARAMETERS FOR THE ENVISAGED IoV SCENARIO

Parameter	**Value**
Simulation area	500 m x 500 m x 200 m
Transmission range	125 m
vehicle movement characteristics	
Positioning	random
Mobility model	Manhattan grid (3 x 3) blocks
Number of nodes	40
Speed of nodes	[17, 20] m/s
Pause time	0 s
drone movement characteristics	
Positioning	random, altitude from 50 to 200 m
Mobility model	Random Waypoint
Number of nodes	20
Speed of nodes	10 m/s
Pause time	5 s
static nodes	
Positioning	one at each intersection
Number of nodes	4

them (all these nodes are also endowed with communication capabilities). In specifics, the scenario consists of a total of 64 nodes arranged in different ways moving according to a specific mobility model. In particular, there are 40 mobile vehicles, arranged on a 4 × 4 grid of length 500 m, whose streets have a width of 10 m. Each vehicle is initially positioned at a random crossroad. Moreover, each vehicle randomly selects an axis (either x or y) and a crossroads on that axis, proceeding toward that point. The speed is randomly chosen from 14 to 20 m/s (50–72 km/h). Next, there are 20 nodes representing flying drones, randomly deployed above the vehicles' grid at a random altitude ranging between 50 and 200 m. These flying drones follow a random waypoint mobility model, with a fixed speed of 10 m/s and a pause time of 5 s, during which the drone is assumed to perform some task (e.g., taking a picture, sensing environmental conditions, collecting/distributing some data, etc.). As stated earlier, we employ a synthetic mobility model given the absence of a reference mobility model for DANETs. Along with the mobile nodes, at each crossroad there is one static node, representing, e.g., access points (on buildings, stations, or simple poles). A summary of the simulation parameters is reported in Table II.

As we can see in Fig. 9, DSDV has the lowest performance in terms of delivery rate, with an average of 10% of the packets reaching the destination. This is due to node mobility causing path disruptions with the protocol not being able to counteract the effects. On the other side, the rest of the protocols achieve acceptable performance indexes, but none is capable to guarantee absolutely reliable packet delivery. When analyzing the path dilation in Fig. 10, AODV and DSR achieve a good performance, along with DSDV. Instead, in position-based approaches data packets traverse long paths before finally reaching the destination. This could easily lead to the undesirable effect of packets queuing up in the nodes' buffers, and

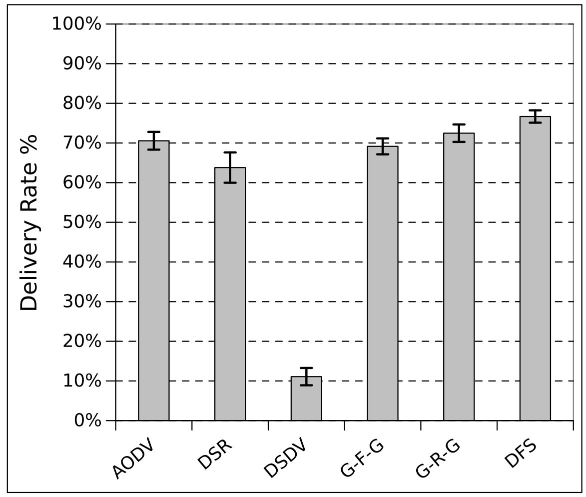


Fig. 9. Performance comparison (delivery rate) among the considered protocols in the scenario depicted in Fig. 8.

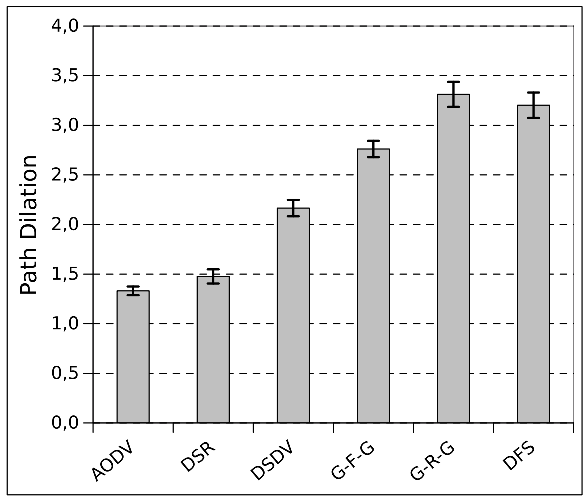


Fig. 10. Performance comparison (path dilation) among the considered protocols in the scenario depicted in Fig. 8.

flows ending up interfering with each other. Considering all, there is no clear winner amongst the studied protocols and no one seems to provide outstanding performances. We believe this represents a crucial technical challenge that needs the researchers' attention in order to enable IoV.

VI. CONCLUSION

In this paper, we have explored some basic behaviors of topology-based and position-based routing protocols on a variety of network graphs that represent a possible IoV scenario. The considered topologies are different by number of nodes and by pause times. Using a well-known simulator, we showed the performance results in terms of delivery rate and path dilation achieved by state-of-the-art routing protocols for ad-hoc networks.

Our results shed lights on which are the technical challenges open in routing messages over an IoV. More in detail, we have noticed that topology-based protocols such as AODV and DSR achieve acceptable performance in terms of both delivery rate and path dilation, whereas position-based protocols achieve higher data rates in high density scenarios but at the cost of a large path dilation.

In general, these tests assessed the efficacy of state-of-the-art topology-based protocols in supporting general data transmissions over an IoV, with no one capable of providing any delivery guarantee. We believe that this would be crucial to support applications in IoV scenarios (e.g., to support safety and distributed control for automated vehicles, or just for entertainment applications) and we hence encourage researchers in devising new routing solutions specifically designed for this purpose.

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