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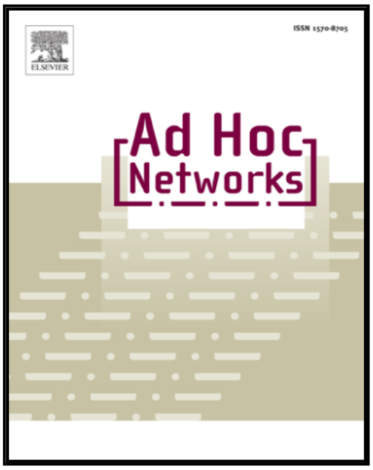

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On the Performance of Social-based and Location-aware Forwarding Strategies in Urban Vehicular Networks

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Abstract

High vehicular mobility in urban scenarios originates inter-vehicles communication discontinuities, a highly important factor when designing a forwarding strategy for vehicular networks. Store, carry and forward mechanisms enable the usage of vehicular networks in a large set of applications, such as sensor data collection in IoT, contributing to smart city platforms. This work evaluates the performance of several location-based and social-aware forwarding schemes through emulations and in a real scenario. Gateway Location Awareness (GLA), a location-aware ranking classification, makes use of velocity, heading angle and distance to the gateway, to select the vehicles with higher chance to deliver the information in a shorter period of time, thus differentiating nodes through their movement patterns. Aging Social-Aware Ranking (ASAR) exploits the social behavior of each vehicle, where nodes are ranked based on a historical contact table, differentiating vehicles with a high number of contacts from those who barely contact with other vehicles. To merge both location and social aforementioned algorithms, a HYBRID approach emerges, thus generating a more intelligent mechanism. For each strategy, we evaluate the influence of several parameters in the network performance, as well as we comparatively evaluate the strategies in different scenarios. Experiment results, obtained both in emulated (with real traces of both mobility and vehicular connectivity from a real city-scale urban vehicular network) and real scenarios, show the performance of GLA, ASAR and HYBRID schemes, and their results are compared to lower- and upper-bounds. The obtained results show that these strategies are a good tradeoff to maximize data delivery ratio and minimize network overhead, while making use of mobile networks as a smart city network infrastructure.

Keywords: Vehicular Networks, Urban Delay Tolerant Networks, Forwarding Strategies, Performance Evaluation, Real Connectivity Traces

1. Introduction

In the near future, vehicles are expected to be equipped with communication devices, mostly connected with smart city platforms [1]. Performing the connection bridge between vehicles, buildings and other devices embedded with software, sensors and actuators will enable a new myriad of applications in Internet-of-Things (IoT) and Vehicular Ad-hoc Networks (VANETs). As expected,

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these devices will generate huge amounts of traffic, thus consuming a substantial portion of the communication resources [2]. Generally speaking, data traffic in smart cities can be categorized according to two taxonomies: delay-tolerant traffic and delay-sensitive traffic [3]. Thus, an opportunity emerges through the exploitation of the vehicles' mobility and also the store, carry and forward mechanisms to offload delay-tolerant traffic from existing telecommunication networks, not only benefiting the delay-sensitive data flows through network congestion relief but also enabling smart city applications [4].

Vehicular networks comprise a group of nodes that communicate with each other despite the lack of a fixed infrastructure support. Vehicles equipped with On-Board Units (OBUs) are able to provide Vehicle-to-Vehicle (V2V) communications, and are also able to connect to roadside units (RSUs) by Vehicle-to-Infrastructure (V2I) communications. Given the challenging propagation channels in high-mobility VANETs, the possibility of broadcast storm events, where a large number of vehicles start to disseminate information at the same time, and the intermittent connectivity due to the highly dynamic nature of this scenario, the information in these networks must be transmitted to destinations through multi-hop wireless communications via intermediate vehicles [5, 6]. Therefore, these networks must be able to deal with long and inconsistent delays. Even though urban scenarios can be challenging from the signal propagation point of view, due to the high density of buildings, vehicles and other objects, the high number of vehicles, their social behavior and their respective mobility patterns can be exploited to overcome such difficulties [7, 8].

In this scope, this work aims to explore the vehicle mobility properties in the data collecting chain through a dynamic and self-organized architecture with no infrastructure requirements, and how mobility can be used to improve the performance of data gathering through vehicular networks. Considering V2V and V2I communications and to enhance this type of network efficiency, this work evaluates three novel forwarding strategies based on location-aware and social-based metrics. Gateway Location Awareness (GLA), a location-aware ranking classification, makes use of velocity, heading angle and distance to the gateway, to select the vehicles with higher chance to deliver the information in a shorter period of time, thus differentiating nodes through their movement patterns. Aging Social-Aware Ranking (ASAR) exploits the social behavior of each vehicle, where nodes are ranked based on a historical contact table, differentiating vehicles with a high number of contacts from those who barely contact with other vehicles. A third strategy, entitled HYBRID, merges both location and social characteristics of the aforementioned proposals thus generating a more intelligent process. For each strategy, we evaluate the influence of several parameters in the network performance, as well as we comparatively evaluate the strategies in different scenarios. Experiment results, obtained using real traces of both mobility and vehicular connectivity from a real city-scale urban vehicular network, are used to evaluate the performance of GLA, ASAR and HYBRID schemes, and their results are compared to lower- and upper-bounds. Additionally, and in order to validate the robustness and functionality of each approach, the evaluation process was extended to a real scenario. The obtained results show that these strategies are a good tradeoff to maximize data delivery ratio and minimize network overhead, while making use of mobile networks as a smart city network infrastructure.

The remainder of this paper is organized as follows. Section 2 presents the related work on forwarding strategies for data collecting in VANETs. Section 3 overviews the network architecture. Section 4 proposes new forwarding strategies and presents their analytic models. Section 5 extensively evaluates and compares the proposed forwarding algorithms. Finally, conclusions and directions for future work are provided in Section 6.

2. Related Work on VANET Forwarding Strategies

A significant number of works has presented strategies to forward messages across a vehicular network in a data collecting process. These strategies focus on selecting the next hop that has the best chance to deliver the message to a specific element in an efficient way. In this section we overview the related work on forwarding strategies when considering both delay-tolerant and vehicular networks. Besides single copy approaches, we discuss a number of probability-based, location-based and social-based strategies. A comparative table summarizing the main characteristics of each strategy is presented in the end of this section.

Within the class of single-copy protocols, *First Contact* [9] aims to minimize the usage of bandwidth and resources (e.g., energy, storage), where a message is forwarded along an edge chosen randomly among all the current contacts. However, messages may oscillate among a set of nodes, or be delivered to a dead end. Therefore, the delay is high and the delivery capacity is very low. *Direct Contact* [10] does not require network knowledge to make forwarding decisions. The source node carries a message until it meets its final destination. The usage of bandwidth and resources is minimum, but the delivery capacity is very low and the delay is very high (in specific scenarios, infinite). Flooding-based forwarding approaches, such as Epidemic [11] and MaxProp protocol [12] can achieve high delivery ratios and low latency, but introduce a very high overhead. MaxProp deals with the problem of scheduling packets for transmission to other peers and deleting packets when buffers are low on space recurring to multiple mechanisms. Spray and Wait [13] is a zero-knowledge routing protocol that reduces flooding of redundant messages in a delay-tolerant network (DTN), by limiting the number of bundle copies created per bundle.

2.1. Probability-based forwarding

The PROPHET protocol [14, 15] estimates the delivery probability based on the history of encounters. A metric called Delivery Predictability, $P_{(a,d)} \in [0, 1]$, is calculated for every node a and each known destination d: node a forwards the message to node b only if b has a greater Delivery Predictability to the destination d, that is, $P_{(a,d)} < P_{(b,d)}$. The NECTAR protocol [16] uses the occurrence of an opportunistic contact to calculate a neighbourhood index and spread messages in a controlled manner. It contains a message scheduling algorithm, which determines the delivery priority of each message in the storage area, and a time-to-live field which considers the number of time slots elapsed since the receipt of a message from a specific node to perform the message aging index calculation.

The HPR (Hybrid of Probability and message Redundancy) algorithm [15] implements parallel message transfer in multi-path mode in order to improve the delivery ratio of a message. In this process, a maximum number of copies is established per source node. Moreover, to minimize the overhead of the network, this algorithm adopts the nodes delivery probability value as the basis to forward the message. Greedy with Min Cost Reliable Path (GMCRP) [17] makes use of a timeliness-aware trajectory data mining algorithm to mine frequent trajectories and generate movement patterns so that node's future location can be predicted. The prediction algorithm will then be used to generate a space-time graph model.

2.2. Location-based forwarding

The GeoSpray routing protocol [18, 19] assumes that nodes are aware of their location (geographical position). GeoSpray considers the replication approach of the Spray and Wait protocol to limit the amount of duplicated copies. However, GeoSpray guarantees that bundle copies are only spread to network nodes that go closer (and/or arrive sooner) to the bundle destination; and it allows each node to forward its bundle copy further to another node that can take the data closer to the destination (or sooner in time).

CaD (Converge and Diverge) [20] estimates the movement radius of the destination using its historical location, speed and time elapsed. During the converge phase, the node carrying the bundle replicates it to the encountered node only if that node is moving faster towards the movement area of destination. The diverge phase is started once the node is within the destination movement area. To enhance routing efficiency, it is used delegation replication (similar to delegation forwarding [21]), that originally enables messaging to cache an updated threshold value equal to the recorded utility metric for the message destination, promoting message replication to the candidate node with a better utility metric.

VeloSent routing protocol [22] operates in three consecutive phases. First, an analysis of the environment is performed to detect neighbouring nodes and their respective contexts. Then, the neighbours that met the destination more recently are considered using the context information about time, location, and velocity of the destination node, that will be used to estimate the new location of the destination node. In the third phase, the estimated location of the destination is used to determine which of the neighbouring nodes will most likely meet the destination node.

2.3. Social-based forwarding

SimBet routing [23] uses betweenness centrality and similarity metrics to take forwarding decisions. Betweenness centrality is the measurement of a nodes bridging capabilities between different communities. When two nodes belong to same community, they are more likely to meet each other. SimBetTS [24] extended the utility to include tie strength, resulting in an improvement of the aforementioned protocol. BUBBLE Rap [25] uses community affiliation labels with betweenness centrality measures to forward messages. When a source sends a packet to a destination, then a global bubble forwarding takes place so that the packet is hierarchically forwarded using global centrality until it reaches a node belonging to the community of the destination. After that, local centrality is used to forward the packet inside the community until it reaches the destination. A modified version of BUBBLE, BUBBLE-B [26], deletes the message from the buffer of the original carrier once the message is transferred to the destination community.

DelQue (Delegation Query) [27] focuses on sources initializing interest-based queries and selects relays by considering their capabilities for both query and response. The chosen relays take charge of both querying the relevant interest data and returning it to the demander. DelQue uses geo-community and mobility prediction in its algorithm. Spatio-temporal prediction is also used, in order to exploit the information that some nodes obtain at a given location and at a given interval of time. CAF (Community Aware Framework) [28] considers a combination of geolocation with social characteristics in order to take forwarding decisions. Messages are forwarded relying on rank-based techniques toward nodes which belong to the same sub-community. Particular nodes operate as an inter-community backbone and circulate messages to other sub-communities.

The work in [29] proposes Clustering Coefficient-Degree (CC-Degree) a data dissemination solution for VANETs that considers the daily road traffic variation of large cities and the relationship among vehicles. Their approach is to select the best vehicles to rebroadcast data messages according to social metrics, in particular, the clustering coefficient and the node degree. These metrics guarantee the best performance in higher density regions and reach sparse regions with a low cos which is possible because the metrics computation only use the beacons packets ex-changed among the vehicles.

An Active Area based Routing (AAR) [30] analyzes the vehicle traces and searches for i) active subareas frequently used and ii) vehicles that frequently meets each other inside each subarea. Then, the routing algorithm distributes the packet copy to each active subarea of the target vehicle using a traffic-aware shortest path spreading algorithm, and then in each subarea, each packet carrier tries to forward the packet to a vehicle that has higher encounter frequency with the target vehicle. An improved version, Advanced AAR (AAAR), exploits the spatio-temporal correlation of the visiting times of target vehicles on different RSUs.

Table 1: A summary of forwarding strategies for Vehicular DTNs [31].

Algorithms	Type	Single/ Multiple copy	Replication rate	Information needed	Objectives/comments
First Contact	Probabilistic	S	Very Low	N/A	Random search is used to deliver the bundle to its destination
Direct delivery	Direct	S	None	N/A	Source moves and delivers the bundle directly
Epidemic	Flooding	M	Very High	N/A	Rapid propagation of data
MaxProp	Flooding	M	High	N/A	Use of the delivery likelihood as a cost assigned to each destination
Spray and Wait	Controlled Flooding	S/M	Medium	N/A	Sets a limit on the number of copies
PRoPHET	Probabilistic	M	High	N/A	Forwards packets based on past node encounter history
NECTAR	Probabilistic	M	N/A	N/A	Spreads messages based on a calculation of a neighbourhood index
HPR	Probabilistic	M	N/A	N/A	Messages sent to increasing delivery probability nodes using mechanisms that reduce network overhead
GMCRP	Probabilistic	S	N/A	Location associated with time	Mines frequent trajectories and generate movement patterns
GeoSpray	Geo	S/M	Medium	Navigation	Does not tackle mobile destination
CaD	Geo	S/M	Medium	Navigation, destination trajectory	Replicate at end to reach the destination
VeloSent	Movement Prediction	M	N/A	Location and velocity associated with time	Tries to predict destination movement, routing accordingly
SimBet	Social	M	Medium	Global contact info	Uses betweenness centrality and similarity metrics to take forwarding decisions
BUBBLE Rap	Social	M	Medium	Global contact info	Uses two phases: global and local forwarding
DelQue	Social	M	Medium	Spatio-temporal mobility	Receiver driven approach
CAF	Social	M	Medium	Geolocation	Combines geolocation with social characteristics
CC-Degree	Social	M	Medium	Geolocation	Combines geolocation with social characteristics to calculate node degree and clustering coefficients
AAR	Social	M	Medium	Location associated with time	Searches for active subareas frequently used and vehicles that frequently meets each other inside each subarea

Table 1 summarizes the forwarding strategies addressed, showing the differences and trade-offs among them. Single copy routing and flooding mechanisms have problems of low delivery ration or wasted network resources, respectively. Probability strategies achieve high delivery ratios while reducing the consumption of resources, but some of these mechanisms require immense storage capabilities. Also, some are based on timers, which degrades their performance in high mobile environments, resulting in inaccuracies at the encounter stage. On the other hand, location-based schemes use the location of nodes to perform routing decisions, hence decreasing the usage of resources expended. Coupled with geographic based forwarding, mobility and movement prediction algorithms also make use of geolocation, but in order to predict movement and anticipate events. Undoubtedly, social-based forwarding can indeed enhance the routing decisions of a community. Nevertheless, these metrics are not easy to obtain and suffer from subjectiveness. A good exploitation of features according to the application at hand may be the best approach since it eliminates unnecessary variables.

3. Architecture Overview

IoT in large cities is expected to produce a significant amount of data. Moreover, the variety and heterogeneity of data are also a concern when collecting this type of information. In order to address these challenges, the proposed architecture, illustrated in Figure 1, makes use of opportunistic communications through mobile nodes to disseminate the data collected from data collecting units to gateways.

The elements that support this architecture are Data Collecting Units (DCUs), Mobile Nodes or On Board Units (MNs/OBUs), Gateways or Road Side Units (GWs/RSUs) and the Server. In a real deployment, MNs are comprised in two parts: the network controller device and the vehicle itself. Examples of suitable transportation vehicles are bicycles, cars, buses, among others.

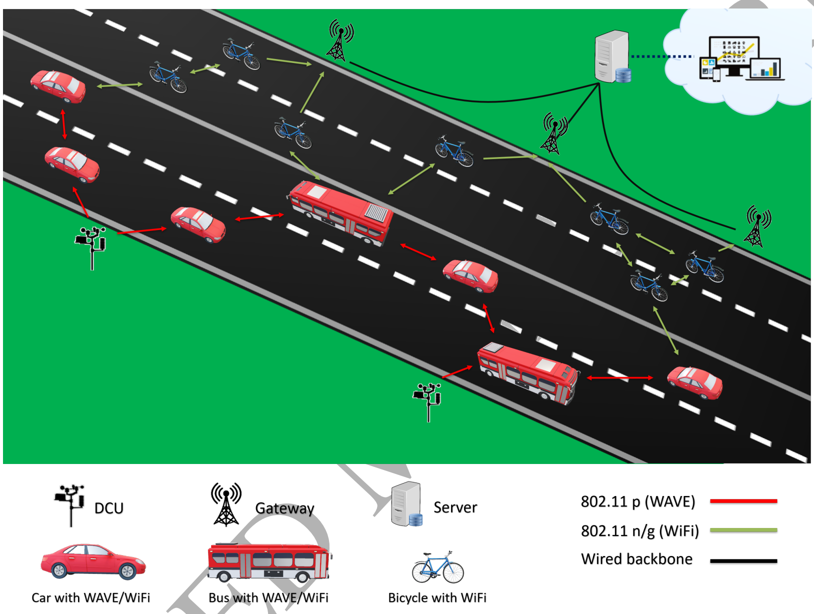


Figure 1: Network architecture.

This architecture provides the following features to support the collection of data in the cities:

- Heterogeneous sensor data gathering;
- Opportunistic communications (through vehicles movement);
- Forwarding strategies based on GPS location and social metrics to enhance the ratio of data delivery vs resource usage in the network;
- Multi-technology dynamic communication platform:
  - IEEE 802.11g/n (WiFi) for short range communications and high bit rate;
  - IEEE 802.11p/WAVE for mid range communications.
- Software modularity to allow integration with new types of sensors, communication technologies and different types of mobile nodes.

3.1. Data Collecting Units (DCUs)

DCUs are devices whose purpose is to detect and collect a physical property of interest. Usually these devices do not have energy restrictions; however, an end-to-end connectivity to a gateway cannot be assured. Therefore, these devices must be able to store their information and deliver it later in an opportunistic communication.

3.2. Mobile Nodes / On Board Units (MNs/OBUs)

MNs are devices that can be aggregated to any kind of vehicle and whose network function is to fill the distance/connectivity gap between DCUs and gateways through their mobility patterns. Since no end-to-end connection bridge is possible (for most cases), this type of node must be able to store the packets received from DCUs to later deliver them to a gateway. This is possible through the implementation of a DTN, resulting in a store, carry and forward mechanism. Such devices can also be used as sensing units, with some hardware addition. Generally, all the gathered information is associated with a GPS position, which can also be useful to support multi-hop data transmission decisions.

3.3. Gateways / Road Side Units (GWs/RSUs)

Gateways act as the final element in the data gathering chain. Being a stationary type of node whose function is to populate a database, a gateway has connectivity to the server through a wired backend. To achieve such a goal, a gateway has seamless and transparent data swapping with the Server, using sensor identification through predefined IDs. Gateways can also act as sensing units, also with additional hardware. In this case, information is directly delivered to the server.

4. Forwarding Strategies for Vehicular Delay Tolerant Networks

Defining a good forwarding strategy is of crucial importance to select which neighbors are the best ones to forward the information. Objectively, selected neighbors should minimize the resources and packet delay, and maximize the delivery ratio. By default, if a node has a constant connection to a gateway, it can continuously deliver its collected packets. On the other hand, if a node only has mobile nodes as neighbours, it is important to assess which are the best candidates to forward the data packets. This paper evaluates the performance of strategies that explore the vehicle mobility properties to assess their ability to forward data packets.

Nodes announce their presence in the network through control packets, also used to exchange their respective ranks. The knowledge about neighbor ranking is then employed in the decision of packet forwarding options. Three neighboring rank classification techniques are proposed: Gateway Location Awareness (GLA), Aging Social-Aware Ranking (ASAR) and a Hybrid version of both GLA and ASAR, which will be referred in this document as HYBRID. Since multi-hop transmissions - through mobile nodes - are considered, two additional mechanisms were used to control the replication of packets: Loop Avoidance and Congestion Minimization. These mechanisms were proposed in [32] and are considered for the strategies proposed in this work.

4.1. Gateway Location Awareness (GLA)

Mobile nodes are aware of the gateways' location. Gateways are static network elements, and therefore, a mobile node can use that information to make forwarding decisions. Considering GPS acquaintance, each node will use a set of metrics to calculate a network rank, namely its velocity and the best combination of distance and heading angle to a gateway. Each metric is then normalized between 0 and 1 in order to facilitate weighted rank computation.

4.1.1. Distance to the gateway and respective normalization

The distance between the mobile and the gateway, d, can be computed using the mobile node location $[Lat1, Lon1]$ and the gateway location $[Lat2, Lon2]$ as [33]

$$d = \arccos(\sin(Lat1) \times \sin(Lat2) + \cos(Lat1) \times \cos(Lat2) \times \cos(Lon2 - Lon1)) \times R, \quad (1)$$

where R is the radius of the earth (6371 kilometers). This formula uses the spherical law of cosines, which gives well-conditioned results down to distances as small as a few meters on the earth's surface, and constitutes a light processing computation compared to other alternatives (such as the *haversine* formula).

In order to normalize the distance considered between two nodes, a maximum distance between a mobile node and a gateway of interest ($maxD_{MG}$) needs to be outlined. Moreover, the technology's maximum communication range (T_{maxR}) should also be considered. Thus, half of the normalization interval $[0.5, 1]$ is given to the technology communication range, thus decreasing linearly with the distance increase. The remaining normalization interval $[0, 0.5[$ refers to distances between the technology maximum communication range and the previously referred $maxD_{MG}$, where an exponential decay is considered so that a higher weight is given to nodes closer to gateways.

The proposed function to normalizes the distance to a gateway, N_{GD}, is given by

$$N_{GD}(d) = \begin{cases} 1 - \frac{2 \times d}{T_{maxR}} & , d < T_{maxR} \\ a \times (1-r)^d & , T_{maxR} < d < maxD_{MG} \\ 0 & , d > maxD_{MG} \end{cases} \quad (2)$$

where a represents the initial amount, and r the decay rate. Therefore, knowing that $f(T_{maxR}) = 0.5$ and selecting a decay rate r, the parameters a and $(1-r)$ can be obtained. Also, if the distance is higher than $maxD_{MG}$, that gateway is of no interest to the mobile node, thus reducing the computational effort of processing all gateway distances in the network.

4.1.2. Heading Angle to the gateway and respective normalization

Calculating the heading angle to the gateway requires several steps. First, the angle to the gateway is calculated. Using both mobile node and gateway locations, $[Lat1, Lon1]$ and $[Lat2, Lon2]$, the angle to the gateway $\theta_{[0\to360]}$ is given by

$$\theta_{[0\to360]} = \left| \left[360 - \left[180 + atan2\left(\frac{\phi}{\psi}\right) \%360 \right] \right] - MN_{HA} \right| \quad (3)$$

where

$$\phi = \sin(Lon2 - Lon1) \times \cos(Lat1) \quad (4)$$

and

$$\psi = \cos(Lat2) \times \sin(Lat1) - \sin(Lat2) \times \cos(Lat1) \times \cos(Lon2 - Lon1). \quad (5)$$

MN_{HA} is the heading angle measured from the GPS module in the mobile node. $\theta_{[0\to360]}$ represents the angular difference between the direction that a mobile is moving towards and the direction where the gateway is located. The result is comprised between 0 and 360 degrees. From the mobile nodes' perspective, it only matters if it is moving towards or in the opposite direction of the gateway, therefore the obtained value is converted to an interval between 0 and 180 degrees as follows

$$\theta_{[0\to180]} = \begin{cases} \theta_{[0\to360]} & , \theta_{[0\to360]} < 180^\circ \\ 360 - \theta_{[0\to360]} & , \theta_{[0\to360]} \geq 180^\circ. \end{cases} \tag{6}$$

In order to normalize the heading angle, an exponential decay is applied to the increasing heading angle to the gateway. Furthermore, three distinct direction intervals are considered: aligned with the gateway $\theta \in [0 \to 45]$; perpendicular direction to the gateway $\theta \in [45 \to 90]$ and opposite direction to the gateway $\theta \in [90 \to 180]$. Increasing decay rates are set for each interval, accordingly to the normalized gateways heading angle function (N_{GHA}) as follows

$$N_{GHA}(\theta) = \begin{cases} \alpha_1^\theta & , 0^\circ < \theta \leq 45^\circ \\ \alpha_2^\theta & , 45^\circ < \theta \leq 90^\circ \\ \alpha_3^\theta & , 90^\circ < \theta \leq 180^\circ \end{cases} , \tag{7}$$

where $\alpha_1 > \alpha_2 > \alpha_3$. As a result, the interval of direction where the mobile node is found greatly influences the normalized gateway heading angle. Moreover, the exponential factor also contributes largely to the normalized result.

4.1.3. Velocity and respective normalization

The velocity of a mobile node is directly obtained from the GPS module. Using velocity as a metric prioritizes nodes that cover larger distances in lower time instances while preventing, to some extent, the viability of static nodes.

The proposed normalized velocity is obtained using the following function

$$N_V(v) = \begin{cases} 0 & , v \leq 0 \\ \frac{v}{V_{avg}} & , 0 < v < V_{avg} \\ 1 & , v \geq V_{avg} \end{cases} , \tag{8}$$

where v represents the mean velocity of the mobile node, and V_{avg} is an acceptable value of mean velocity that grants the mobile node with a good neighbor ranking in terms of velocity. This value will be addressed in Section 5, and will take into consideration the targeted scenario.

4.1.4. Ranking computation

Since all metrics are normalized between 0 and 1, rank computations are weighted as follows

$$Rank_{GLA} = W_{GwDist} \times N_{GD} + W_{GwHA} \times N_{GHA} + W_{Vel} \times N_V, \tag{9}$$

where W_{GwDist}, W_{GwHA} and W_{Vel} correspond, respectively, to the weights assigned to the distance to the gateway, the heading angle to the gateway and the velocity.

Coping with the presented features, this forwarding strategy considers three novel network features: i) heterogeneous node mobility characteristics; ii) gateway selection from the multiple gateways available in the network; and iii) adaptability to the connectivity technology. Regarding the first point, the model can be calibrated to the mobility characteristics of each type of vehicle. E.g., a bicycle can change its heading angle much faster than a car, but cannot travel as fast as the car. Regarding the second point, both distance and heading angle are calculated as a combination for each gateway in the network in order to provide the best network ranking classification for each node. Finally, for distinct connectivity technologies, the distance to the gateway metric parameters can be adapted accordingly, thus providing algorithmic adaptability to the technology used. Algorithm 1 synthesizes the work flow for GLA strategy.

Algorithm 1 GLA rank calculation algorithm

```
procedure GETRANKGLA()
    N_V ← getVelocityNormalized()                                          ▷ Equation 8
    GLA_Rank ← W_Vel × N_V
    for GatewayLocations do
        GW_distance ← calculateDistance(GW_Latitude, GW_Longitude)          ▷ Equation 1
        if GW_distance < maxD_MG then
            N_GD ← getDistanceNorm(GW_distance)                             ▷ Equation 2
            N_GHA ← getHeadingAngleNorm()                                   ▷ Equation 7
            Current_GatewayRank ← W_GwDist × N_GD + W_GwHA × N_GHA + W_Vel × N_V   ▷ Equation 9
            if Current_GatewayRank > GLA_Rank then
                GLA_Rank ← Current_GatewayRank
            end if
        end if
        NextGateway
    end for
    return GLA_Rank
end procedure
```

4.2. Aging Social-Aware Ranking (ASAR)

It is well-known that *humans are creatures of habits*. To take advantage of such behavior, this forwarding strategy considers the distinct neighbor connections to network elements in a temporal sliding window. A ranking classification is placed and performed in several phases, resulting in a normalized value between 0 and 1.

4.2.1. Sliding time window phase

This phase aims to determine the number of different neighbors in the sliding window, and the last moment of contact with each one of the nodes. For a practical example, refer to Figure 2.

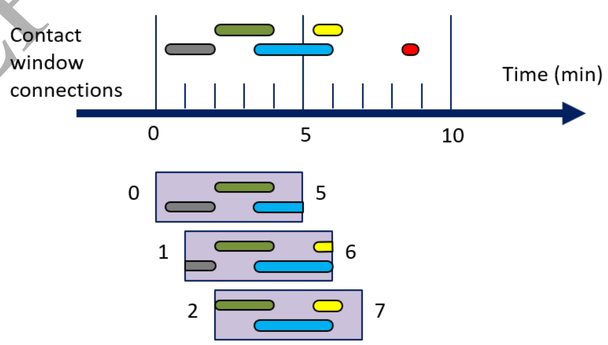


Figure 2: Sliding time window example.

A 5 minute sliding window ($T_w = 5 \times 60$) is considered. Different colors represent distinct contacts with mobile nodes, and the time that the connection lasts is represented in the time axis.

For instance, when the current timestamp is at 5 minutes, the considered time window is from $[0 \rightarrow 5]$ minutes. In that window, three different contacts were verified: pink, green and blue. The last moment of connection was, respectively, 3 minutes ago; 1 minute ago; and still connected.

When the time window advances, conditions may change. For example, at timestamp 6, four distinct contacts were verified: pink, green, blue and yellow. Respectively, the last moment of connection can also change: 4 minutes ago; 2 minutes ago; still connected; and still connected. The objective of the sliding time window is to characterize the historical connection model of a node, thus helping to make a forwarding decision. To facilitate model calibration, the sliding window interval will be represented in several parameters.

4.2.2. Ranking quantitative classification

Not all neighbors in the network have the same importance in terms of forwarding decisions. For instance, a connection to a gateway is far more important than a connection to a mobile node. Therefore, from the connections detected in the sliding time window, the number of connections to different network elements is used to set a ranking to each mobile node based on its type.

Five ranking intervals are considered, as illustrated in Table 2. Two thresholds are defined to set the difference between *low* and *high* number of contacts with mobile nodes and gateways, τ_{MN} and τ_{GW}, respectively. s_{MN} and s_{GW} are used to denote the number of occurrences in the observed time window.

Table 2: Ranking quantitative classification.

$R_{interval}$	**Quantitative Classification**
1	No Gateway contacts, low number of Mobile Node contacts ($s_{GW} = 0 \wedge s_{MN} < \tau_{MN}$)
2	No Gateway contacts, high number of Mobile Node contacts ($s_{GW} = 0 \wedge s_{MN} \geq \tau_{MN}$)
3	Low number of Gateway contacts, no Mobile Node contacts ($s_{GW} < \tau_{GW} \wedge s_{MN} = 0$)
4	Low number of Gateway contacts, Mobile Node contacts ($s_{GW} < \tau_{GW} \wedge s_{MN} > 0$)
5	High number of Gateway contacts, Mobile Node contacts ($s_{GW} \geq \tau_{GW} \wedge s_{MN} > 0$)

4.2.3. Ranking qualitative classification

After determining in which ranking interval each mobile node belongs, the aging factor is associated with each connection. Furthermore, a distinct aging constant per type of network element is considered, where a connection to a mobile node deteriorates faster than to a gateway in terms of ranking. The aging factors are represented by γ_{MN} and γ_{RSU}, respectively.

These values are directly related to the sliding window interval. The calculation of both γ_{MN} and γ_{RSU} were obtained through interpolation, so that distinct time intervals are normalized with the same aging dependency, e.g., a $T_w = 6$ minutes must have the same aging dependency with the time elapsed than a $T_w = 3$ minutes, which is obtained through distinct aging constants for each respective T_w. This process withholds the calculation of these constants from the network size and instead makes it dependent on the time window (T_w) considered. The following equation relates the aging constant for the mobile with the sliding time window:

$$\gamma_{MN} = 0.902 + 0.791 \times 10^{-3} \times T_w - 2.663 \times 10^{-6} \times T_w^2 + 3.927 \times 10^{-9} \times T_w^3 - 2.091 \times 10^{-12} \times T_w^4, \quad (10)$$

while the following equation translates the sliding time window into the aging constant for the gateway:

$$\gamma_{RSU} = 0.917 + 0.698 \times 10^{-3} \times T_w - 2.408 \times 10^{-6} \times T_w^2 + 3.603 \times 10^{-9} \times T_w^3 - 1.937 \times 10^{-12} \times T_w^4. \quad (11)$$

The practical benefit of the aforementioned functions is to standardize the relation between time windows and normalized weight of these aging constants. Finally, each connection needs to be associated with an aging function, a process that is done using a normalization equation based on the five ranking intervals previously presented, as follows

$$Rank_{ASAR} = \begin{cases} \left(1 - \frac{1}{1+\sum_{i=1}^{NumMNs} \gamma_{MN(i)}^{k}}\right) \times 0.2 \times \frac{R_{interval}-1}{5} & , R_{interval} = \{1, 2\} \\ \left(1 - \frac{1}{1+\sum_{i=1}^{NumRSUs} \gamma_{RSU(i)}^{k}}\right) \times 0.2 \times \frac{R_{interval}-1}{5} & , R_{interval} = 3 \\ \left(1 - \frac{1}{1+\sum_{i=1}^{NumMNs} \gamma_{MN(i)}^{k} + \sum_{i=1}^{NumRSUs} \gamma_{RSU(i)}^{k}}\right) \times 0.2 \times \frac{R_{interval}-1}{5} & , R_{interval} = \{4, 5\} \end{cases} \tag{12}$$

where k represents the time elapsed since the last contact with a Gateway or a Mobile Node.

This equation merges both qualitative and quantitative parts of the ASAR ranking computation: inside the brackets, it refers to the qualitative part, where an increase in the number of contacts translates into an increase in the ranking computation, considering multiple node types and the time elapsed for each connection (k); the remaining formula outside the brackets represents the quantitative classification, where the five intervals in Table 2 classify the social viability of the node and 0.2 normalizes the classification.

Taking into consideration all the configurable parameters (T_w, τ_{MN} and τ_{GW}), this forwarding strategy is highly dependent on the size of the network. Knowing the connectivity model and how many nodes of each type the network portrays will significantly facilitate the choice of such parameters. However, a good performance is expected for networks where nodes typically connect with a high frequency, such as in smart city environments. Algorithm 2 synthesizes the work flow for ASAR strategy.

Algorithm 2 ASAR rank calculation algorithm

```
procedure getRankASAR()
    sumRSU ← 0
    sumMN ← 0
    numRSUs ← 0
    numMNs ← 0
    UpdateTimeWindow()
    for DifferentContacts do
        if ContactisRSU then
            numRSUs ← numRSUs + 1
            sumRSU ← sumRSU + τ_GW^TimeElapsedSinceContact
        else
            numMNs ← numMNs + 1
            sumMN ← sumMN + τ_MN^TimeElapsedSinceContact
        end if
        NextContact
    end for
    ASAR_Rank ← getContactsRankNorm(numRSUs, sumRSU, numMNs, sumMN)    ▷ Equation 12
    return ASAR_Rank
end procedure
```

4.3. Hybrid between GLA and ASAR (HYBRID)

This forwarding strategy aims to combine a mobility contribution with the social behavior, thus resulting in a smarter protocol. In terms of characteristics, all the previously presented features for GLA and ASAR are applied in this model. Therefore, mobile nodes calculate their rank in the network resorting to the expression

$$Rank_{HYBRID} = W_{Mobility} \times Rank_{GLA} + W_{Social} \times Rank_{ASAR}, \tag{13}$$

where $W_{Mobility}$ and W_{Social} represent the weights of the mobility and location criteria, respectively. This easy conversion is possible since both GLA and ASAR rankings are normalized between 0 and 1. Finally, even though this strategy is computationally heavier than the previously presented strategies, the improved intelligence level aims to reduce other resources expenditure, such as diminishing the cases of unnecessary packet replication. Algorithm 3 synthesizes the work flow for HYBRID strategy.

Algorithm 3 HYBRID rank calculation algorithm

procedure GETRANKHYBRID()
    $N_V \leftarrow getVelocityNormalized()$ ▷ Equation 8
    $Mobility_{rank} \leftarrow W_{Vel} \times N_V$
    $sumRSU \leftarrow 0$
    $sumMN \leftarrow 0$
    $numRSUs \leftarrow 0$
    $numMNs \leftarrow 0$
    $UpdateTimeWindow()$
    for DifferentContacts **do**
        if $ContactisRSU$ **then**
            $numRSUs \leftarrow numRSUs + 1$
            $sumRSU \leftarrow sumRSU + \tau_{GW}^{TimeElapsedSinceContact}$
        else
            $numMNs \leftarrow numMNs + 1$
            $sumMN \leftarrow sumMN + \tau_{MN}^{TimeElapsedSinceContact}$
        end if
        NextContact
    end for
    $Social_{Rank} \leftarrow getContactsRankNorm(numRSUs, sumRSU, numMNs, sumMN)$ ▷ Equation 12
    for GatewayLocations **do**
        $GW_{distance} \leftarrow calculateDistance(GW_{Latitude}, GW_{Longitude})$ ▷ Equation 1
        if $GW_{distance} < maxD_{MG}$ **then**
            $N_{GD} \leftarrow getDistanceNorm(GW_{distance})$ ▷ Equation 2
            $N_{GHA} \leftarrow getHeadingAngleNorm()$ ▷ Equation 7
            $Current_{GatewayRank} \leftarrow W_{GwDist} \times N_{GD} + W_{GwHA} \times N_{GHA} + W_{Vel} \times N_V$ ▷ Equation 9
            if $Current_{GatewayRank} > Mobility_{rank}$ **then**
                $Mobility_{rank} \leftarrow Current_{GatewayRank}$
            end if
        end if
        NextGateway
    end for
    HYBRID$_{Rank} \leftarrow W_{Mobility} \times Mobility_{rank} + W_{Social} \times Social_{Rank}$
    return HYBRID$_{Rank}$
end procedure

5. Parameterization and Performance Evaluation

In this section we evaluate the performance of the forwarding strategies. First, we define the test conditions and explain the evaluation setup. Then, considering a specific scenario, we find the best parameters for each strategy and we compare their performance in different network scenarios. The evaluation process includes emulation, with mobility and connectivity traces from a real VANET, and real experimentation.

5.1. Setup

The evaluation process resorts to a vehicular network emulator, mOVERS [34], developed in *Instituto de Telecomunicações*. The emulator runs a DTN, which allows the creation of multiple processes that run DTN software, and is capable of scaling for larger networks with the same software as the one currently running in the OBUs/RSUs of a real Oporto vehicular network [35]. With this approach, the large scale evaluation can be performed in the emulator, and the resulting software will be ready to be operated in real OBUs and RSUs for the experimentation in a real scenario. Beyond using the same software as in real OBUs and RSUs, the emulator uses the extracted datasets, with real traces from vehicle's behavior and real connectivity maps (considering IEEE 802.11p/WAVE communication), reproducing exactly real events and real communication links within the vehicular network.

To evaluate the proposed forwarding strategies, two connectivity datasets, collected from a real VANET operating in the city of Oporto, Portugal, were used: one collected during a rush hour period, in the morning of 12^{th} February of 2015 (between 6am and 10am), and the other collected during a non-rush hour period for the same day (between 10am and 2pm). The rush hour dataset was used to parameterize the forwarding strategies, to evaluate different network loads, to study the impact of having different number of DCUs and RSUs, and also to assess the impact of having Mobile Nodes generating traffic. The non-rush hour dataset was mainly used to assess the performance of the proposed strategies in different mobility and connectivity patterns.

For the rush hour dataset, seven scenarios were considered, each one presenting distinct data gathering challenges. Some properties are equal for all the scenarios, namely:

- A maximum of 161 vehicles (OBUs) operating at the same time, whose velocity profiles are presented in Table 3;
- Vehicles are using IEEE 802.11p/WAVE communication technology;
- DCUs generate data packets every 16 seconds;
- Packets are generated during the first 3 hours of emulation and 1 additional hour is given to deliver packets without generating new ones.

Table 3: Average vehicle's speed for the rush hour morning dataset.

Hour interval	**Average vehicle's speed (km/h)**
6am - 7am	30.27
7am - 8am	26.05
8am - 9am	23.19
9a - 10am	22.14

Table 4 summarizes the adjacent properties of all rush hour scenarios, which are categorized in groups to facilitate the understanding of tendencies. For each group, only one input parameter varies. The location of static nodes for all 4 combinations is illustrated in Figure 3. The non rush hour scenario has the same number of DCUs and RSUs as in the rush hour Scenario 1, *i.e* 8 RSUs, 8 DCUs, and Mobile Nodes do not generate traffic.

Table 4: Characteristics of rush hour scenarios.

Group	**Scenario**	**n^o of RSUs**	**n^o of DCUs**	**MNs generate packets?** ($periodicity = 60sec$)
1 and 3	Scenario 1	8	8	No
1	Scenario 2	8	12	No
1	Scenario 3	8	16	No
2	Scenario 4	8	8	Yes
2	Scenario 5	8	12	Yes
2	Scenario 6	8	16	Yes
3	Scenario 7	12	8	No

5.2. Setting up the forwarding strategies

In this subsection, we address the parameterization of variables that affect the forwarding decision performance. To do so, three metrics are used: the delivery ratio, the network delay and the network overhead. The objective is to better understand the impact of each variable and to select the combination with better results for each forwarding strategy. The relevant results are shown in table format, where best and worst metric values are highlighted in green and red, respectively.

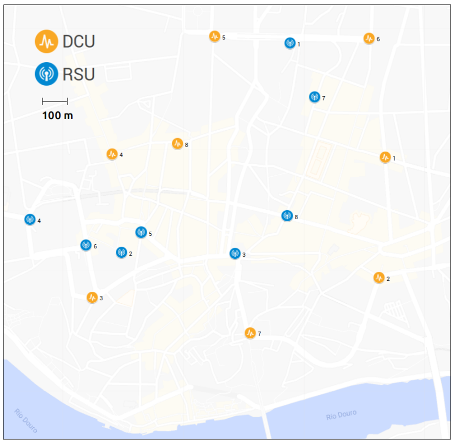
5.2.1. GLA

To assess the best paramterization of the GLA algorithm we need to set some configurations, namely, the maximum communication range, set to T_{maxR} = 800 meters (IEEE 802.11p/WAVE), the maximum distance of interest, set to $maxD_{MG}$ = 2000 meters, the mean velocity, set to V_{avg} = 13.9 m/s, and finally, the heading angle attenuation constants, set to $\alpha_1 = 0.990$, $\alpha_2 = 0.988$, $\alpha_3 = 0.986$.

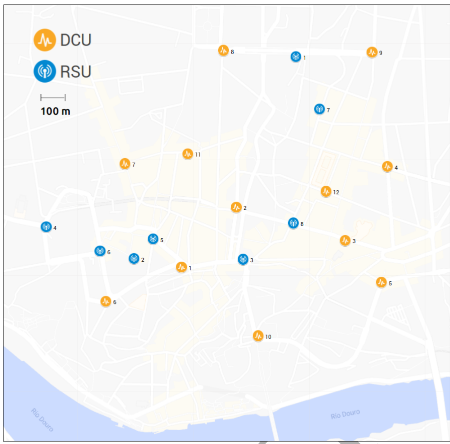
First, emulations using a single metric were considered (e.g., $W_{GwDist} = 1$ and $W_{GwHA} = W_{Vel} = 0$), allowing individual influence evaluation in the forwarding decision for each metric. These emulations allowed us to understand that the velocity was the parameter with the highest preponderance for this specific connectivity model. Afterwards, distinct metric weights were explored. Table 5 summarizes the obtained results. Through the analysis of the network metrics (delivery ratio, network overhead and network delay), we have selected the set $W_{Vel} = 0.6$, $W_{GwDist} = 0.2$ and $W_{GwHA} = 0.2$ (last line in the table), which provides a good overall network performance: it has the highest delivery ratio and the lowest network delay, with a low network overhead.

5.2.2. ASAR

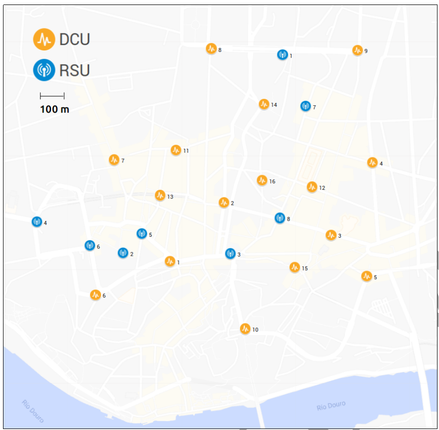
In ASAR we have considered distinct sliding windows (T_w), and thresholds distinguishing between *low* and *high* in the number of both mobile nodes (τ_{MN}) and gateways (τ_{GW}). The influence of the several parameters in the network is presented in Table 6: the change in the parameters is



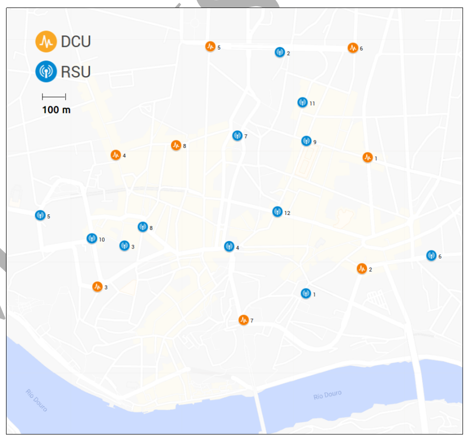
(a) 8 RSUs and 8 DCUs (Scenarios 1 and 4).



(b) 8 RSUs and 12 DCUs (Scenarios 2 and 5).



(c) 8 RSUs and 16 DCUs (Scenarios 3 and 6).



(d) 12 RSUs and 8 DCUs (Scenario 7).

Figure 3: Location of static nodes (DCUs and RSUs).

Table 5: GLA strategy: the impact of its parameters.

Parameters	**Delivery Ratio (%)**	**Network Overhead (%)**	**Network Delay (sec)**
$W_{Vel} = 1; W_{GwHA} = 0; W_{GwDist} = 0$	69.41	403.95	145.77
$W_{Vel} = 0; W_{GwHA} = 1; W_{GwDist} = 0$	66.83	366.16	132.31
$W_{Vel} = 0; W_{GwHA} = 0; W_{GwDist} = 1$	66.82	379.34	131.99
$W_{Vel} = 0.34; W_{GwHA} = 0.33; W_{GwDist} = 0.33$	69.25	357.55	141.36
$W_{Vel} = 0.2; W_{GwHA} = 0.4; W_{GwDist} = 0.4$	69.44	354.49	141.07
$W_{Vel} = 0.2; W_{GwHA} = 0.6; W_{GwDist} = 0.2$	70.03	351.06	142.73
$W_{Vel} = 0.2; W_{GwHA} = 0.2; W_{GwDist} = 0.6$	69.22	362.59	142.81
$W_{Vel} = 0.4; W_{GwHA} = 0.2; W_{GwDist} = 0.4$	69.42	363.14	139.64
$W_{Vel} = 0.4; W_{GwHA} = 0.4; W_{GwDist} = 0.2$	69.29	356.79	142.77
$W_{Vel} = 0.6; W_{GwHA} = 0.2; W_{GwDist} = 0.2$	70.22	360.86	137.40

more pronounced in the network overhead metric. With this in mind, a good compromise between all metrics is achieved by using $T_w = 6$, $\tau_{MN} = 3$ and $\tau_{GW} = 1$, which has the lowest network overheads and the lowest overall delay, although with a fair delivery ratio.

Table 6: ASAR strategy: the impact of its parameters.

Parameters	Delivery Ratio (%)	Network Overhead (%)	Network Delay (sec)
$T_w = 3; \tau_{MN} = 3; \tau_{GW} = 1$	71.58	391.43	138.57
$T_w = 3; \tau_{MN} = 3; \tau_{GW} = 2$	71.68	413.12	139.71
$T_w = 3; \tau_{MN} = 6; \tau_{GW} = 1$	72.67	539.76	147.30
$T_w = 3; \tau_{MN} = 6; \tau_{GW} = 2$	71.77	561.13	142.26
$T_w = 3; \tau_{MN} = 9; \tau_{GW} = 1$	72.09	593.24	143.68
$T_w = 3; \tau_{MN} = 9; \tau_{GW} = 2$	71.59	618.05	143.55
$T_w = 6; \tau_{MN} = 3; \tau_{GW} = 1$	68.70	322.17	131.55
$T_w = 6; \tau_{MN} = 3; \tau_{GW} = 2$	70.87	349.86	138.62
$T_w = 6; \tau_{MN} = 6; \tau_{GW} = 1$	71.02	478.51	140.52
$T_w = 6; \tau_{MN} = 6; \tau_{GW} = 2$	71.18	495.20	146.57
$T_w = 6; \tau_{MN} = 9; \tau_{GW} = 1$	70.94	542.97	138.43
$T_w = 6; \tau_{MN} = 9; \tau_{GW} = 2$	71.97	570.06	145.64

5.2.3. HYBRID

Since this strategy combines both GLA and ASAR strategies, the idea is to find the best combination between a location and a social based algorithm. The base parameters for the GLA and ASAR strategies are the ones that achieved a better output in the individual analysis. For the GLA strategy, the following parameters were selected $W_{Vel} = 0.6$, $W_{GwDist} = 0.2$ and $W_{GwHA} = 0.2$, while for the ASAR strategy, $T_w = 6$, $\tau_{MN} = 3$ and $\tau_{GW} = 1$ were the selected weights.

Because the HYBRID ranking computation is obtained from two strategies already studied, the variations for the several emulations are quite smaller when compared to the two first forwarding strategies. However, from the results presented in Table 7, it is possible to understand that $W_{Mobility} = 0.2$ and $W_{Social} = 0.8$ provides the lowest delay, a similar delivery ratio, when compared to other parameterizations, and one of the lowest network overheads. Thus, these will be the HYBRID weights to be used in the remaining evaluations.

Table 7: HYBRID strategy: the impact of its parameters.

Parameters	Delivery Ratio (%)	Network Overhead (%)	Network Delay (sec)
$W_{Mobility} = 0.2; W_{Social} = 0.8$	69.02	321.87	132.99
$W_{Mobility} = 0.3; W_{Social} = 0.7$	69.18	323.76	136.70
$W_{Mobility} = 0.4; W_{Social} = 0.6$	69.37	324.97	136.11
$W_{Mobility} = 0.5; W_{Social} = 0.5$	68.98	327.06	136.32
$W_{Mobility} = 0.6; W_{Social} = 0.4$	69.05	319.33	137.67
$W_{Mobility} = 0.7; W_{Social} = 0.3$	69.10	316.64	139.62
$W_{Mobility} = 0.8; W_{Social} = 0.2$	69.29	311.83	140.14

5.3. Evaluating the strategies

To better understand the performance of the proposed strategies, two simple state-of-the art schemes were implemented: Direct Contact and Epidemic. These strategies, previously described in Section 2, represent both extremes in terms of delivery ratio, delay and network overhead. These strategies will be evaluated in the rush hour morning scenario, since the strategies' parameters were previously parameterized for this case. The results on the number packet of hops and packet delay represent a mean of all the packets delivered during the 4 hours of evaluation, along with the 95% confidence intervals for some metrics.

The evaluation process will take place in several phases. First we will compare the performance of the forwarding strategies for Scenario 1, the rush hour morning period used to parameterize the strategies. Then, we will evaluate their performance in new scenarios for the same rush hour morning period, *i.e.*, we will change the number of DCUs and RSUs in the network, as well as change the possibility of having Mobile Nodes generating traffic. In a third phase we will evaluate the impact of the traffic load on the forwarding strategies. For that we will adopt the topology presented in Scenario 4 of rush hour morning period, and change the amount of packets generated by Mobile Nodes. After that, we will assess the performance of the proposed forwarding strategies in a new scenario, a non-rush hour morning dataset. Finally, performance results obtained through real experimentation will be presented.

5.3.1. Network performance over Scenario 1

Figure 4 illustrates the effective percentage of data packets delivered from DCUs to gateways during the experiments (duplicated received packets by the gateway do not contribute to this percentage). These results show the benefit of using multi-hop approaches in forwarding algorithms, as the packet replication translates into an increase in the network delivery ratio. Comparing the delivery ratio between Epidemic and Direct Contact, they show both extremes, with Epidemic representing the potential delivery ratio increase through a multi-hop approach. The results achieved by the Epidemic strategy show that, for the considered time period, it is impossible to deliver 100% of the data packets using only the vehicular network. ASAR is the best overall in terms of delivery ratio, approaching the one of Epidemic. However, the differences between the 3 proposed strategies are small.

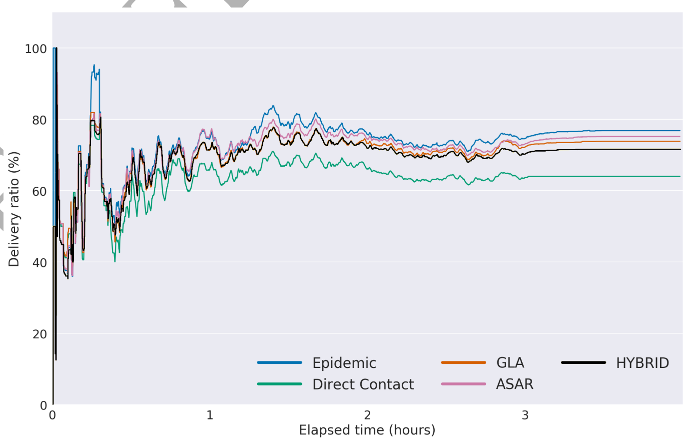


Figure 4: Overall delivery ratio per forwarding strategy (scenario 1).

The results of the network overhead are illustrated in Figure 5, representing the amount of redundant information that each strategy introduced in the network to deliver the collected information. In Epidemic routing, the unmediated packet replication translates into an enormous amount of network overhead. In the Direct Contact strategy, the network overhead is very close to 100%, since there is no packet replication. The reason why it is not exactly 100% lays on the ACK control packets. In the proposed forwarding strategies, the network overhead is below 400%, much lower than in the Epidemic, which means that making a neighborhood selection in the forwarding decision translates into a lower resource consumption. Ideally, the proposed forwarding mechanisms aim to reduce the resource expenditure to a minimum, but a multi-hop approach will always have the associated cost. As observed in Figure 4, the proposed strategies have a similar delivery ratio when compared to Epidemic. However, the amount of network resources expended to obtain such delivery ratio are significantly lower.

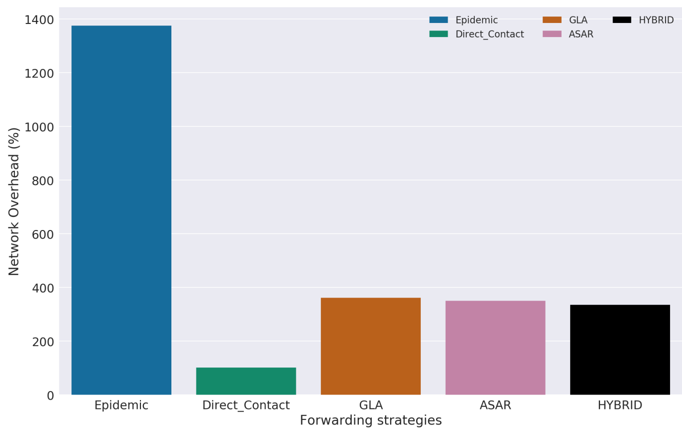


Figure 5: Network overhead per forwarding strategy (Scenario 1).

Figure 6 depicts the mean number of packet hops per forwarding strategy, which is the mean number of nodes that a packet traverses to reach a gateway. In the Direct Contact strategy, the average number of hops is static and 1, since packets are directly delivered from a mobile node to a gateway[1]. However, in the multi-hop forwarding strategies, the mean number of hops is increased. As expected, the Epidemic strategy has the highest mean number of hops per packet, because the flooding mechanism will blindly forward each packet to the network. ASAR forwarding strategy has a higher mean number of packet hops when compared to GLA and HYBRID, because the ranking metrics decide the forwarding neighbors in distinct manners. However, this higher number of hops translates in a higher delivery ratio, as illustrated in Figure 4.

The results of the network delay are shown in Figure 7, representing the mean delay of the packets that were effectively delivered to a gateway. The delay is measured from the moment where the packet is generated until it reaches the first gateway. If the same packet reaches another gateway, the packet considered is the one with the lowest delay. The Direct Contact strategy, as expected, has the highest mean network delay. It is observed that the mean delay decreases through multi-hop mechanisms, supported by cases where nodes that received the replicated packets delivered them faster to a gateway, in comparison with the direct delivery.

5.3.2. Network performance for different scenarios

As stated before, this evaluation will be conducted grouping adjacent characteristics (Table 4) for several scenarios. The obtained results will be depicted in the following figures with all the forwarding strategies compared among themselves.

[1]We start counting the number of hops from the moment the packet enters the vehicular DTN.

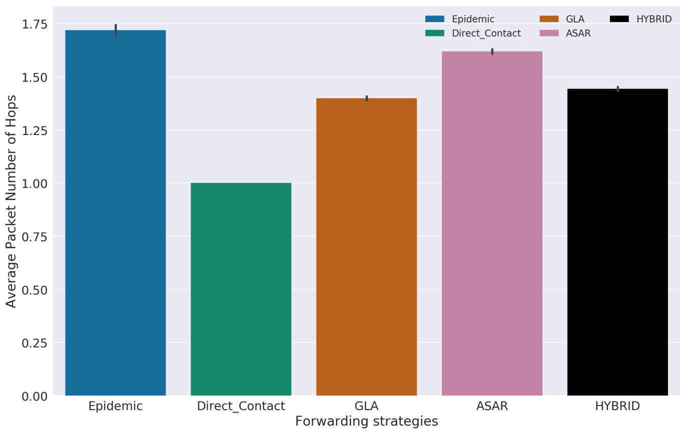


Figure 6: Average number of packet hops per forwarding strategy (Scenario 1).

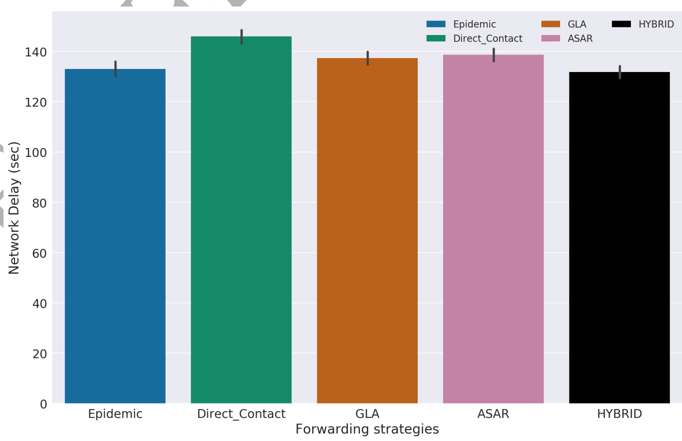


Figure 7: Overall network delay for the same packets, per forwarding strategy (Scenario 1).

Figure 8 illustrates the mean delivery ratio of all strategies in all scenarios. Considering group 1, the average delivery ratio increases with the increase of the number of DCUs. Even though more packets are generated, the location of the DCUs is closer to the location of the gateways (as illustrated in Figures 3a, 3b and 3c), thus contributing to this increase. In group 2, an increment in the number of DCUs located closer to the location of the gateways also contributes to an increment in the delivery ratio. However, when comparing with group 1, the delivery ratio for scenarios 4, 5 and 6 is lower, because the number of packets per mobile node is higher due to the periodic mobile packet generation. In group 3, an increase of the number of RSUs translates into an increase in the delivery ratio. Since the number of gateways available to deliver the packets increases, the delivery ratio also increases.

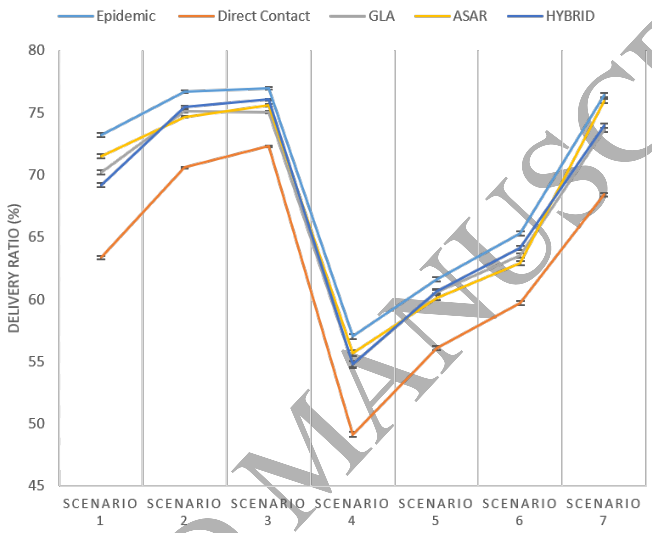


Figure 8: Mean delivery ratio per scenario and forwarding strategy.

Figure 9 illustrates the mean network overhead per forwarding strategy and per scenario. This metric translates the percentage of overall data used to deliver the effective amount of data to a gateway. In group 1, the overall network overhead decreases with the increment of DCUs, which is expected since additional DCUs are closer in distance to the gateways, and then additional packets do not need to be replicated so many times in order to reach the gateway. When comparing groups 1 and 2, the network overhead is higher for group 2. Since the difference relies on packets generated by mobile nodes in group 2, some of these packets require a larger number in replications to reach a gateway, causing a higher network overhead. In group 3 the network overhead is lower than in scenario 1. Since the number of gateways is higher in scenario 7, a lower number of packet replications is needed for a packet to reach a gateway, resulting in a lower network overhead.

Figure 10 depicts the average number of nodes travelled by a packet before it reaches a gateway (only multi-hop forwarding strategies may have a different number of packet hops). A decrease in the number of packet hops is observed as the number of DCUs increases, which is again related to the location of the added DCUs (scenarios in groups 1 and 2). Because new DCUs are closer to the gateways, the mean number of packet hops decreases. Comparing groups 1 and 2, the number of hops decreases with a lower rate, denoting that packets generated periodically in group 2 mobile nodes have a lower mean number of hops than packets generated at DCUs. This is observed for this connectivity model, but it is highly dependent on the considered network. In group 3, the

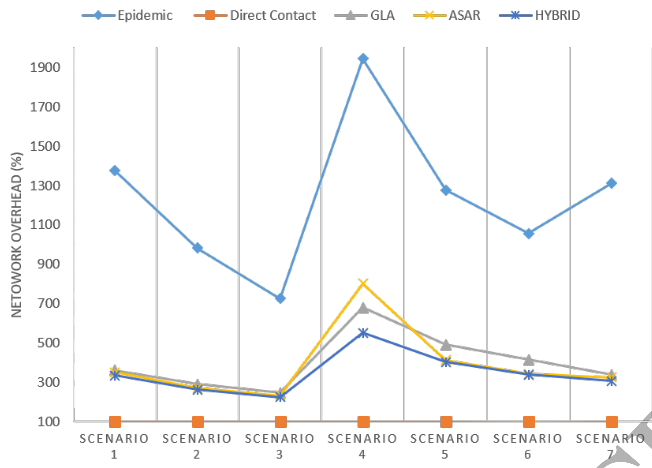


Figure 9: Mean network overhead per scenario and forwarding strategy.

mean number of hops per packet decreases with the increase in the number of RSUs, being also related with the location of the gateways both in scenario 1 and 7 (Figures 3a and 3d).

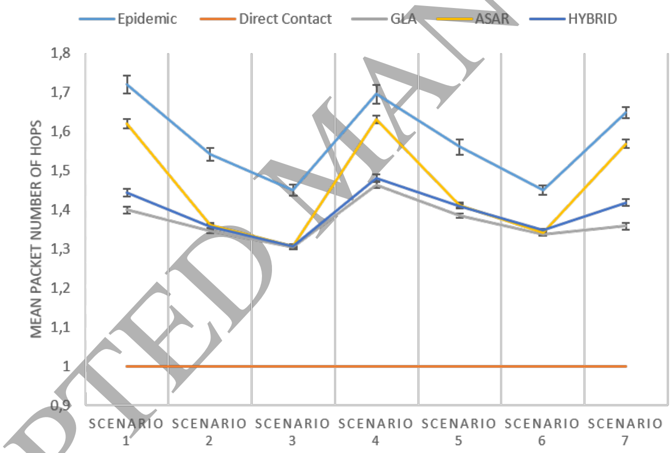


Figure 10: Average number of packet hops per scenario and forwarding strategy.

Figure 11 shows the mean network delay per forwarding strategy and per scenario. This metric depicts the amount of time elapsed since a packet is created until it reaches a gateway. In group 1, scenario 1 is the one that has the highest delay, followed by scenario 3 and finally scenario 2. Since in scenario 1 DCUs and gateways have the most distance between them, it is expected that this scenario is effectively the one with the highest delay for this group. The added DCUs in scenario 2, in comparison with scenario 1, are much closer to the gateways, which greatly contributes for the decrease on the network delay. The added DCUs in scenario 3, when compared to the ones added in scenario 2, are a compromise in distance between the two aforementioned scenarios, thus translating in a network delay comprised between the ones observed in scenarios 1 and 2. Since the locations for the DCUs in group 2 are the same, an equivalent pattern is observable.

Comparing group 1 and 2, there is an increase in the network delay caused by the packets generated periodically by the mobile nodes. Since all the network nodes can generate packets, those

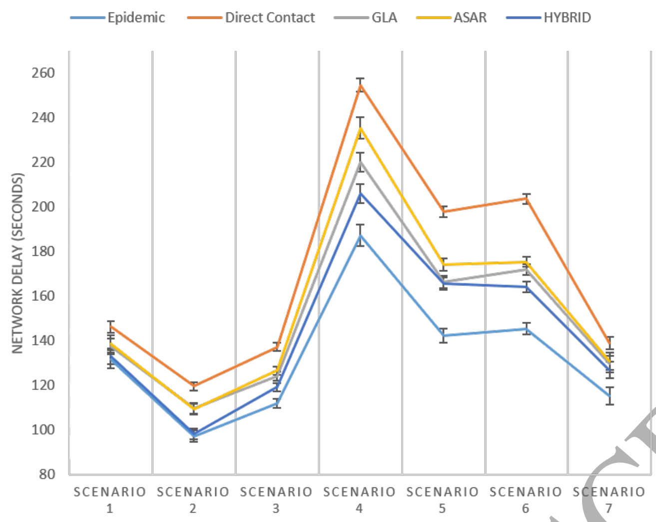


Figure 11: Mean network delay per scenario and forwarding strategy.

which do not frequently have contact with the gateways, or have as many forwarding opportunities, will increase the overall network delay. Finally, in group 3 it is observed a decrease in the mean delay with the increase of number of gateways. Having more gateways to deliver the information, while keeping the same overall number of packets, it is expected that delivered packets arrive faster.

5.3.3. Network performance under different traffic loads

Results regarding the impact of distinct network loads are shown in Table 8. Following Scenario 4, we have changed the packet generation rate of every mobile node. Increasing the network load, *i.e.*, increasing the number of generated packets, results in a lower delivery ratio, lower network overhead and higher network delay across all strategies. Since the number of vehicles and their neighbourhood is the same, the increased network load negatively impacts the overall network due to the lack of connectivity with any RSU, regardless the forwarding scheme. Nevertheless, the performance of the presented strategies is the same for all the network load scenarios, where HYBRID strategy performs better in terms of network overhead and delay, and slightly worst in terms of delivery ratio.

5.3.4. Network performance in a different connectivity dataset

In order to evaluate distinct urban traffic densities, we have compared the performance of the proposed forwarding strategies in two scenarios with different mobility and connectivity datasets. In this section we introduce a non-rush hour period with less Mobile Nodes and, as expected, with less neighboring contacts: in the first scenario, Mobile Nodes (represented by public buses) perform a bigger amount of trips when compared to the second one. The results are provided in Table 9 where, across all strategies, the delivery ratio and network overhead decreases, and the network delay increases. As mentioned before, the number of neighboring nodes is lower, and therefore the number of opportunities to forward the packet is also smaller, motivating an increase in the network delay and a reduction in the delivery ratio. However, it is important to notice that every strategy follows the rationale on keeping the number of duplicated data packets in the network as small as possible, which is observed by the reduction of the network overhead, even in a smaller network.

Table 8: Network performance for different traffic loads.

Network load (mobiles nodes packet generation periodicity)	Forwarding Scheme	Delivery Ratio (%)	Network Overhead (%)	Network Delay (sec)
1 packet every 60 seconds	Epidemic	57.01	1945.42	187.28
	Direct Contact	49.15	101.22	254.76
	GLA	54.75	679.63	220.04
	ASAR	55.65	801.82	235.47
	HYBRID	54.80	551.74	206.08
1 packet every 30 seconds	Epidemic	53.28	1794.97	201.66
	Direct Contact	46.42	101.14	310.08
	GLA	49.95	614.20	227.16
	ASAR	52.65	750.89	246.21
	HYBRID	51.47	520.73	214.16
1 packet every 15 seconds	Epidemic	50.21	1724.62	214.96
	Direct Contact	43.13	101.09	324.42
	GLA	46.45	580.46	253.52
	ASAR	48.35	674.22	276.61
	HYBRID	46.57	492.90	238.63

Table 9: Network performance according to the connectivity dataset.

Connectivity dataset	Forwarding Scheme	Delivery Ratio (%)	Network Overhead (%)	Network Delay (sec)
Rush hour morning period (6am to 10am)	Epidemic	73.20	1375.06	131.79
	Direct Contact	63.35	101.20	146.27
	GLA	70.22	361.11	137.40
	ASAR	71.49	350.14	138.63
	HYBRID	69.2	335.30	132.99
Non-rush hour morning period (10am to 2pm)	Epidemic	69.26	1136.41	141.05
	Direct Contact	61.98	100.85	213.46
	GLA	67.52	310.67	164.38
	ASAR	68.73	305.65	170.79
	HYBRID	67.42	293.47	158.58

5.3.5. Network performance under real experimentation

This section focuses on validating the proposed algorithms in a real scenario. Since the network conditions are in constant change in a real scenario, it is harder to compare the proposed algorithms among them (already addressed through emulation). However, it is important to validate the robustness and functionality of each approach, as well as the architecture as a whole.

In order to evaluate the forwarding strategies in a real scenario, a use case was formulated making use of the mobility of typical boats ("moliceiros") in the "Ria" of Aveiro, Portugal. These boats are used as touristic attraction, making trips of around 45 minutes through the canals of the "Ria" of Aveiro. Therefore, the mobility is used to gather information in specific places (through the connection of boats with DCUs) and deliver it to another boat or a gateway. Figure 12 illustrates the location of the network nodes, where the mobile nodes' location shows the resting point between trips of each boat.

Figure 12: Location of network elements using in the real experimentation.

Some definitions and considerations were taken into account for this specific scenario, namely. In this scenario, 4 mobile nodes, 2 DCUs and 1 RSU comprise the network elements, where two of the mobile nodes resting points are in contact range with a DCU, thus being elements with more packets during the experiments. Each forwarding strategy was evaluated for $\simeq$ 8 hours, starting at 9am and ending at 5pm at all days. DCU 204 is distanced 165 meters away from RSU 10, and DCU 239 is distanced 132 meters from RSU 10. Even considering line of sight, which is not the case, these nodes are not in connectivity range, thus justifying the need of the DTN architecture. Both DCUs generate data packets every 5 seconds, resulting in 5760 total generated packets per DCU. Only DCUs are generating data packets for these experiments, even though it is possible for mobile nodes to do the same, with extended hardware. The GPS position was tracked for each mobile node every 5 seconds in order to better evaluate the network performance between mobile nodes and forwarding strategies. Some parameters were configured according to the practical scenario, namely, the maximum communication range, set to $T_{maxR} = 84$ meters (WiFi practical experiment), the maximum distance of interest, set to $maxD_{MG} = 1000$ meters, the mean velocity, set to $V_{avg} = 6.94$ m/s (around 25 Km/h), and finally, the heading angle attenuation constants, set to $\alpha_1 = 0.990$, $\alpha_2 = 0.988$ and $\alpha_3 = 0.986$.

Figure 13 illustrates the delivery ratio that represents the effective percentage of data packets delivered from DCUs to gateways. Considering all previously tests, these follow the same pattern, where multi-hop approaches outperform single-hop strategies, as it can be seen through the comparison of Direct Contact with the remaining strategies. For the multi-hop strategies, Epidemic has the highest delivery ratio, due to its flooding mechanism. GLA, ASAR and HYBRID reach similar delivery ratios, where ASAR delivery ratio is slightly higher than GLA and HYBRID. The delivery ratio can reach higher values if the number of mobile nodes in the networks is higher or if more trips are performed by the existing ones. This happens since higher node mobility translates into more frequent contacts, and consecutively into higher delivery ratio.

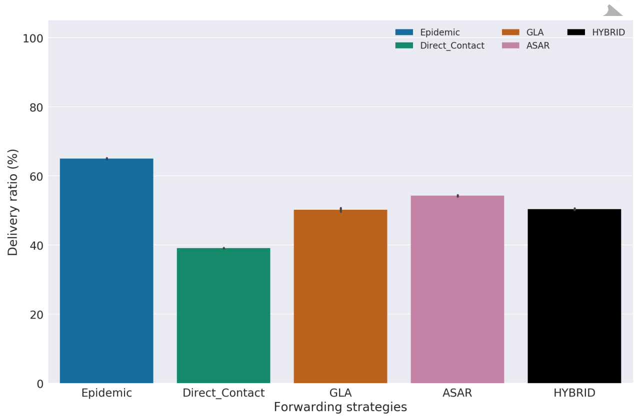


Figure 13: Overall delivery ratio per forwarding strategy, real network.

The results of the network overhead are presented in Figure 14, representing the amount of redundant information that each ranking combination introduced in the network. As expected, the flooding mechanism of the Epidemic strategy has the highest network overhead. Coping with this, the direct delivery approach from the Direct Contact strategy translates into almost no overhead. The proposed strategies have values slightly higher than the Direct Contact mechanism; however having a higher delivery ratio as previously observed in Figure 13. Among the proposed forwarding strategies, ASAR has the highest network overhead, which is related with the trade-off from the higher delivery ratio obtained.

Figure 15 shows the results for the network delay, representing the mean delay of the packets that were effectively delivered to a gateway. It should be remembered that boat trips have a typical duration of 45 minutes, and the time interval between trips is highly dependent on the presence of customers. Therefore, it is expected that delays for this specific scenario to be high. This metric is the most influenced by the entropy associated with evaluating the strategies in distinct days. However, it is possible to observe that multi-hop approaches usually translate in lower mean packet delays when compared to the single-hop one. From the proposed forwarding strategies, ASAR has the highest delivery ratio, illustrated in Figure 13. However, the network delay is lower for GLA and HYBRID when compared to ASAR. This is expected, due to the lack of social behavior between boats. However, their trips are always confined between the same canals, where location metrics are able to perform better delay-aware decisions.

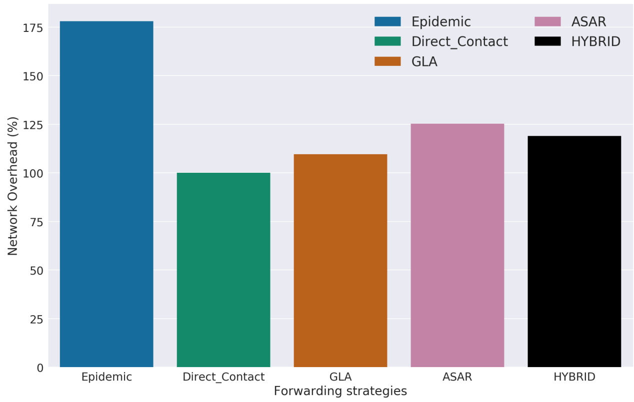


Figure 14: Overall network overhead per forwarding strategy, real network.

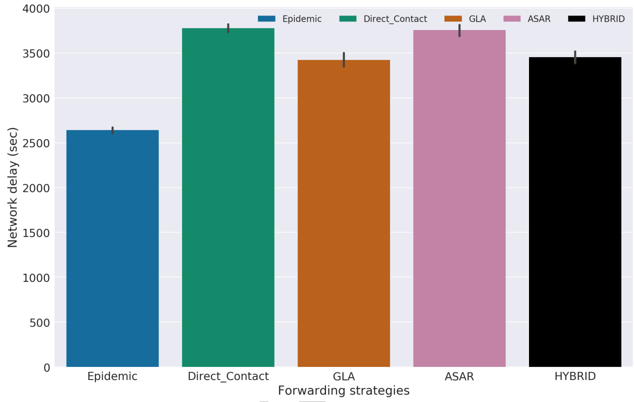


Figure 15: Overall network delay per forwarding strategy, real network.

6. Conclusions

In this work, several forwarding strategies for urban vehicular networks were presented and their performance was evaluated in different scenarios. Through the evaluation process we were able to understand the impact of both social and location metrics in the forwarding strategies. For instance, GLA, a location-aware ranking classification, makes use of velocity, heading angle and distance to the gateway, to select the vehicles that have higher chance to deliver the information in a shorter period of time, thus differentiating nodes through their movement patterns. On the other hand, a social-based algorithm, ASAR, exploits the social behaviour of each vehicle, where nodes are ranked based on a historical contact table, differentiating vehicles with a high number of contacts from those who barely contact with other vehicles. Finally, a compromise between the aforementioned strategies was evaluated (HYBRID), where the improvement in the classification criterion resulted in a better resource management, with a lower network overhead, while maintaining the same level of delivery ratio. The performance of social and location metrics on the evaluated strategies show that these are able to closely follow the two extreme strategies, in terms of minimizing overhead (close to Direct contact overhead) and maximizing delivery ratio (close to Epidemic delivery), thus comprising good tradeoffs for the data gathering through vehicular networks in urban scenarios.

Future work will provide an evaluation of the proposed strategies in new urban scenarios considering different mobility and connectivity patterns. There is also space for improvement in the forwarding strategies in order to find a way to dynamically change their parameters according to the scenario involved. This way, the strategies could be always optimized for the scenario. Finally, other metrics such as energy consumption and the prioritization of data packets should be considered in the forwarding strategies.

7. Acknowledgments

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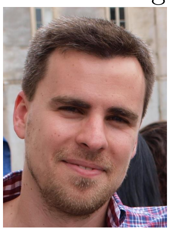

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