Performance Assessment of DTN and VANET Protocols for Transmitting Periodic Warning Messages in High Vehicular Density Networks

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***Abstract*—In recent years, routing protocols for Delay Tolerant Networks (DTN) have become appealing for vehicular ad-hoc networks (VANET), particularly for communication between vehicles in highly sparse environments. In such scenarios, network disconnections are frequent, and the establishment of stable source-destination links is scarce. This work addresses the performance of four DTN and two traditional VANET protocols when the vehicular density becomes high in a short-scale scenario. In this case, vehicles may need to communicate with near-located neighbors, and traffic conditions can rapidly change from low to high congested areas. Specifically, we evaluate how DTN and traditional VANET routing protocols deal with the transmission of warning messages that require message generation rates higher than usually found in the literature. The results show that the traditional VANET protocols outperform the DTN approaches considered in this work for transmitting warning messages in high vehicular-density scenarios. The results also shed light on features that DTN protocols should consider to improve the performance in such scenarios.**

***Index Terms*—High vehicular density network, Routing protocol, Delay-tolerant network, Vehicular ad-hoc network.**

I. Introduction

VEHICULAR ad-hoc networks (VANET) are a subcategory of the Mobile Ad-Hoc Networks (MANET) with particular features, such as high mobility and dynamic topology [1]. VANETs can play a pivotal role in supporting services of Intelligent Transportation Systems (ITS) [2], such as the transmission of traffic warning messages, which can contain information about the occurrence of an event, for instance, the presence of a broken vehicle. Such data can help drivers avoid traffic congestion and find a more appealing route.

The transmission of waning messages has been commonly addressed using one-hop transmission with the so-called beacons [3]. However, the transmission of such messages enables only near-located neighbors to be aware of potential risks downstream. To achieve a high number of informed vehicles, many scholars considered routing protocols for more effective dissemination of messages by using traditional VANET protocols as in [4], [5], and [6], or Delay Tolerant Networks (DTN) as in [7], and [8].

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Unlike traditional VANETs, the DTN protocols, which operate under the principles of storage, carry, and delivery, are well known for not needing a stable path to deliver a message. Additionally, they are aimed to cope with high sparse scenarios, where vehicles can communicate with far-located nodes. However, in real situations, vehicles also need to communicate with nearby vehicles, and traffic conditions are likely to change from sparse to highly congested scenarios.

Several works comparing VANET protocols have been presented so far [10]–[12]. Only one addresses the impact of a wide range of car densities [13]. In the case of DTN, most works seek to evaluate the impact of buffer size and time to live (TTL) of messages. Few of them study the influence of the number of vehicles [2], [14], [15]. In addition, these approaches consider only low-density scenarios, and most of them employ a fixed number of vehicles. Moreover, they use a long time interval for generating messages, which is not an option for traffic warning applications, where vehicles receive frequent updates about traffic conditions or hazardous events.

This work presents a comparison of relevant DTN and VANET protocols focusing on high-density scenarios, particularly in a crossing intersection with a traffic light. The utmost motivation is to study the behavior of DTN and VANET protocols in high-dense urban scenarios and their capabilities to transmit traffic information. Approaches for assessing routing protocols usually employ high-sparse networks, where vehicles try to deliver a message to an unknown and far-located destination. In opposition, we aim to study how closely-located vehicles perform in a high-dense network using DTN or VANET to exchange traffic information.

The contributions of this work are threefold. First, we comprehensively compare DTN and VANET routing protocols in a small-scale but high vehicular-density scenario using the IEEE802.11p standard. To the best of our knowledge, it is the first time this scenario has been addressed to compare both types of protocols. Second, different from previous works, we provide insights into the relationship between traffic density and transmission range for DTN and VANET in high-dense urban scenarios. Third, we provide criteria to select the best choice among some relevant DTN and VANET protocols for transmitting warning messages in high-dense vehicular networks.

The remaining of the paper is organized as follows. Section II presents the related work, and section III contains a background on the routing protocols considered in our evaluation. The simulation scenario is described in section IV, with results and discussion presented in sections V and V-C, respectively. Concluding remarks are presented in section VI.

II. Related Work

The evaluation and comparison of routing protocols in vehicular networks is a topic of increasing interest in recent years. As the VANET protocols are primarily oriented to cope with low vehicular densities, many works study their performance in highly-sparse networks. Moreover, most of them evaluate the use of the protocols for transmitting non-critical information among vehicles. Few of them evaluate the performance of protocols for transmitting warning messages.

For transmission of warning messages, the authors of [4] propose a routing protocol named DABFS, aimed to forward warning messages in a greedy manner using movement direction and distance. The comparison is performed regarding the Path Aware-Greedy Perimeter Stateless Routing (PA-GPSR), the Improved Directional Location Added Routing (ID-LAR), the Connectivity-Aware Data Dissemination (CADD), and the GPSR protocols. The authors employed a bidirectional highway with a maximum density of 88 vehicles/km^2. Results show a better performance of DABFS over the other protocols.

In [5] a cluster-based routing protocol for transmitting warning messages using a combination of multicast and broadcast strategies is studied. The authors employ a highway scenario with a length of 2 km using up to 180 vehicles and compare it with the VMaSC-LTE and HCVC-PROB protocols. The results show that the performance of all protocols becomes lessened as long as the vehicle density increases. The results show that the proposed protocol receives a low impact from the increasing density.

Another proposal for transmission of warning messages is addressed in [6]. The authors employ a broadcast-based protocol targeting a bidirectional road in a highway scenario. The comparison is performed using the AG and OCAST protocols as references, and the number of vehicles ranges from 1 to 15 per kilometer per line. The results show that the number of broadcasted messages per vehicle decreases as density increases.

The authors in [16] study the use of Distributed Vehicular Broadcast (DV-CAST) and Urban Vehicular broadcast (UV-CAST) protocols for the transmission of warning messages in an urban scenario with a maximum traffic density of 100 vehicles/km^2. They found that the number of informed vehicles increases, and the warning notification time is shortened as long as the traffic density increases.

In the case of DTN, the authors of [8] study a real VDTN test-bed for transmitting warning messages and traffic jam information. The authors equipped three vehicles with IEEE 802.11b/g compliant devices, one for emission, one for reception, and the third as the forwarder. The test consists of transmitting a one-second periodic alert about a broken vehicle. The authors conclude that the higher the speed of the vehicles is, the lower the capacity to deliver a message. Although the authors added other vehicles to the scene, they behave as passive agents and do not participate in the transmission test. Hence, assessing the impact of the traffic density is not possible.

In [7], the authors put forward the directional propagation protocol, which harnesses the custody transfer mechanism of DTN to transmit a warning message among clusters. The results show that the longer the distance the data need to travel, the higher the End-To-End Delay (E2E Delay). However, no information about the scenario or response of the protocol to high traffic-dense situations is provided.

For transmission of non-critical information, the Connectivity-Aware Routing (CAR) protocol has been studied in urban scenarios in [17] and [18] with maximum car densities of 40 vehicle/km^2 and 50 vehicles/km^2, respectively. Likewise, the Greedy Traffic-Aware Routing protocol (GyTAR) was studied in [19] with a maximum density of 56 vehicles/km^2, and 20 vehicles/km^2 in [20]. The authors compare GyTAR with the Ad-hoc On-demand Distance Vector (AODV) protocol in this work. Unlike GyTAR, AODV seems to reduce the E2E delay as density increases.

The Greedy Perimeter Coordinator Routing (GPCR) is addressed in [21] and [22] using urban scenarios with maximum densities of 187 vehicles/km^2 and 5.1 vehicles/km^2, respectively. They are compared with GPSR and GpsrJ+ as well. Moreover, the Anchor-based Street and Traffic-Aware Routing (A-STAR) protocols are studied in [23] using an urban area with a maximum density of 51.7 vehicles/km^2. The A-STAR protocol is compared with Vehicle Assisted Data Delivery (VADD) in [24]. The results show that GPCR performs very similarly to GPSR for low densities, and GpsrJ+ slightly outperforms GPCR for any traffic density. The VADD protocol outperforms A-STAR for packet delivery rate. Despite the E2E Delay of VADD being higher than A-STAR, this metric tends to be lower as density increases.

The MUlti-hop Routing protocol for Urban VANETs (MURU) is analyzed in [25] within an urban scenario with a maximum car density of 75 vehicles/km^2. The results show that the E2E Delay increases, and the number of hops decreases as density grows. However, the authors do not assess the packet delivery rate regarding vehicle density.

In the case of DTN for non-critical messages, the authors of [14] present a comparative analysis using urban scenarios for assessing the Spray & Wait (SNW) and Probabilistic Routing protocols using the History of Encounters and Transitivity (PRoPHET) protocol with maximum densities of 12.8 vehicles/km^2. In [15], the authors study the Epidemic, SNW, PRoPHET, Encounter Based Routing (EBR), Contact Duration Based Routing (CDBR), and Inter-Contact Routing (ICR) protocols using a maximum density of 13.1 vehicles/km^2. In the first one, the authors evaluate the performance using the so-called Trend to Deliver (ToD) approach, which is a mechanism to assist in forward decisions [26]. Both works show that protocols like SNW, PRoPHET, EBR, and ICR benefit the most as the number of vehicles increases, as metrics like delivery rate (DR), overhead, and goodput are improved when traffic increases.

The works described above explore a traffic density lower than the one we studied, and most of them evaluate the protocols using a large-scale scenario. In addition, the protocols that transmit warning messages do not employ an urban

TABLE I
SHARED AND DISTINCTIVE FEATURES REGARDING SIMILAR WORKS

Approach	Shared features	Distinctive features of this work
[4]	Transmission of warning messages; position based-protocols	High and broad range of vehicular densities; comparison of traditional VANET with DTN
[5], [6]	Transmission of warning messages for many densities; traditional VANET protocols	High densities; study of the impact of the transmission range; urban scenario and comparison of traditional VANET with DTN
[16]	Transmission of warning messages in an urban scenario; traditional VANET protocols	High density and many transmission ranges; comparison of traditional VANET with DTN
[8]	Transmission of warning messages in an urban scenario using DTN protocols	
[17]–[22], [25]	Evaluation of traditional VANET protocols in an urban scenario	Transmission of warning messages; high vehicular densities with various transmission ranges; comparison of traditional VANET with DTN
[14]	Study of various DTN protocols in an urban scenario	

scenario or a non-broadcast transmission scheme. Although most protocols have shown high performance in low-density scenarios, little information about the behavior of such protocols in high vehicular density is currently available in the literature. Moreover, metrics like E2E Delay and overhead show different behaviors as density increases depending on the considered protocol. Unfortunately, the source code of most of these approaches is not available for public use. Table I summarizes our approach's shared and distinctive features regarding similar works of the literature.

In this work, we evaluate the performance of the protocols AODV, GPSR, Epidemic, Binary Spray &Wait and Wait (BS&W), PRoPHET, and Direct Delivery for transmission of periodic warning messages in high vehicular-density networks. A set of vehicular densities ranging from 3 to 280 vehicles/km^2 are employed. They are higher than the vehicular densities used in similar works.

III. BACKGROUND

A. Protocols of VANETs

Fig. 1 presents the taxonomy of VANET protocols. For instance, routing protocols can be classified either as topology-based routing (TBR) or position-based routing (PBR) [27]. TBR protocols can be either proactive or reactive, or even hybrid. A typical example of a proactive protocol is the Destination-Sequenced Distance Vector (DSDV) protocol, in which a routing table containing information about each node is continuously updated. A typical reactive protocol is the Ad-hoc On-demand Distance Vector (AODV), which creates routes as long as needed. Among the PBR options, we find the Delay Tolerant Networks (DTN), the Vehicle-Assisted Data Delivery (VADD) [28]; the Non-DTN protocol, such as the Greedy Perimeter Stateless Routing (GPSR) [29], and the Hybrid protocols, such as the Hybrid Location-Based (HLAR) [30].

1) AODV: AODV is one of the most common routing protocols for mobile ad-hoc networks [31]. AODV combines both the destination sequence number and the on-demand route technique. This technique can cause low overhead as nodes do not need to maintain unnecessary route information. To handle route information, AODV utilizes three different kinds of route messages: Route Request (RREQ), Route Reply (RREP), and Route Error (RERR). The route discovery consists of two phases: i) sending RREQ through the network; ii) looking for a destination and waiting for RREP [31]. Besides using RREQ, RREP, and RERR, AODV employs locally periodic broadcast messages, the so-called beacons or *Hello* packets.

Such packets can periodically exchange a wide variety of information, such as position, velocity, density, and direction of the vehicles [32]. The *Hello* messages are employed to keep a node aware of the localization of other nodes into the transmission range and to detect the loss of connectivity with a specific neighbor.

2) GPSR: The PBR protocols, different from TBR, do not need to create a routing table or store information about routes. They make the next-hop selection by considering the neighbor's and the own vehicle's position information. The Greedy Perimeter Stateless Routing (GPSR) protocol is a PBR protocol that selects the next hop for transmission in a greedy manner. If the greedy mode fails, the algorithm switches to the perimeter mode, and the next forward node is selected using the right-hand rule [33].

Each node should be aware of its position information, which is available via GPS or short-range localization. Additionally, each node can exchange such information to its one-hop neighbor through beacon messages (*Hello* packets), as in the case of AODV. However, in the case of GPSR, *Hello* packets are not optional as in AODV.

Based on the information of *Hello* packets, the source node chooses the closest node to the destination. However, if the source does not receive any response from a neighbor within a time-out interval, it considers the communication link broken. There may be a situation where the source does not find a better neighbor than itself. This situation is known as the local-maximum condition in which GPSR can no longer follow the greedy forwarding strategy. In this case, the protocol switches to the perimeter mode [32].

B. DTN Protocols

Delay tolerant networks (DTN) were first proposed for enabling communication between satellites, surface rovers, and other appliances in the interplanetary network (IPN) [2]. This network paradigm operates under the concept of Store, Carry, and Forward (SCF); and was envisioned to perform in very harsh environments, such as space exploration. However, due to the remarkable advantages of DTN, they became to be applied to other kinds of networks, such as the Wireless sensor

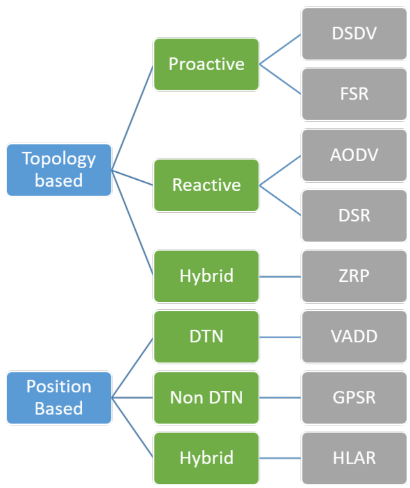


Fig. 1. Taxonomy of VANET routing protocols.

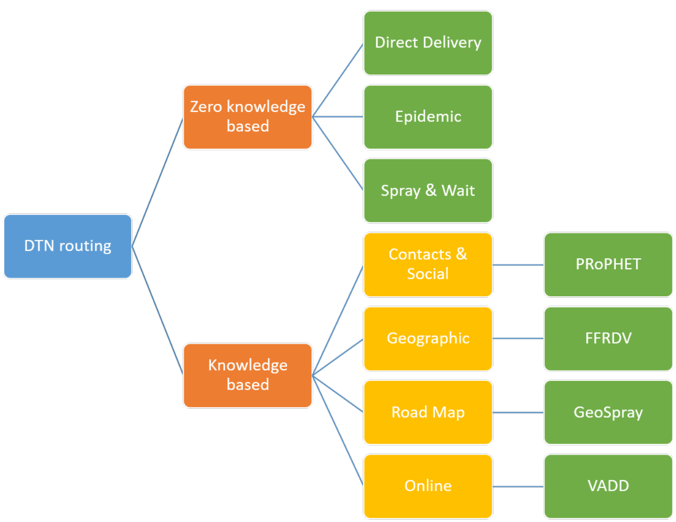


Fig. 2. Taxonomy of DTN routing protocols according to knowledge degree.

(WSN), the Mobile Ad-Hoc Networks (MANET), and the opportunistic vehicular networks (VANET).

Unlike traditional VANET, a DTN does not require a stable connection between sender and recipient to transmit a message [2]. In DTN, a forwarder vehicle stores a message and waits for a suitable hop. Therefore, these kinds of networks are well-adapted to network disconnections and disruptions. It makes the DTN the most suitable option for traditional routing protocols in VANETs [14].

The DTN can be classified using a large variety of criteria. However, in this work, we categorize them according to the dependence upon knowledge. Hence, we can find both the knowledge-based and the zero knowledge-based, as depicted in Fig. 2. The former, in turn, can also be classified in Contact & social, geographic, Road Map, and Online. Fig. 2 provides the classification and a representative example of each category.

1) Direct Delivery: The Direct Delivery is the most straightforward DTN protocol and was presented by Spyropoulos, Psounis, and Raghavendra [34] in 2004. In this zero-prior knowledge protocol, a node A, which intends to communicate with a node B, hosts and carries the message until it attains direct contact with node B, and finally delivers the data [14]. The direct delivery makes no intermediate forward, so the major drawback is the possibility of the sender not finding the recipient. Therefore, the Direct Delivery is likely to feature the lowest delivery ratio and the highest delay among all DTN approaches, as stated by the same authors [2].

2) Epidemic: Proposed by Vahdat et al. in [35], the epidemic is a multi-copy protocol that implements flooding in a DTN and does not need prior knowledge of the network [36]. Each bundle is exchanged with every node at a contact opportunity. Hence, thanks to the multiple-path options, each bundle is expected to fast arrive at its final destination. However, the epidemic protocol needs to compare which bundles are not in common with other nodes, which can lead to an increase in delay and generate more overhead than the non-DTNs [37].

The flooding nature of the epidemic protocol could permit a high delivery rate. However, when the buffer achieves the maximum capacity, the arrival of a new message can lead to the drop of the older ones. This fact, in turn, reduces the delivery rate. To overcome this burden and other issues, the Epidemic needs higher storage capacity and bandwidth than other protocols. Moreover, the Epidemic protocol could be the optimal solution in an environment with no buffer space/bandwidth limits [36].

3) Binary Spray and Wait: The Spray&Wait protocol (SNW) [38] is also a zero-knowledge DTN protocol, which combines features of both Epidemic and Direct Delivery approaches. However, unlike Epidemic, the Sprat&Wait limits the number of copies created per bundle to N. As its name suggests, Spray&Wait encompasses two phases. In the spray phase, a node disseminates a certain number of copies of a message, and in the Wait phase, when only one copy remains, the node hopes to find a suitable node to deliver the last copy of the message [14].

The SNW can operate in two different Spray modes [38]. The normal Spray, where the source node forwards one of the copies to each neighbor node, and the Binary spray mode (BS&W), where the source node forwards (N/2) copies to the neighbor node and keeps (N/2) for itself. If only one copy remains, the BS&W switches to direct transmission and enters the Wait phase as before mentioned [37].

4) PRoPHET: The Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) [39] is an information-based forwarding protocol and was the first contact history-based protocol [2]. In PRoPHET, the transmission of a message to a forwarded node depends on the probability of that node contacting the destination node. This protocol uses a metric called delivery predictability, which defines the probability of a node a to meet a node b ($P(a, b)$) and, consequently, the chance to deliver a message successfully. Hence, a suitable forwarder node is the one that has a high probability of meeting the recipient one.

The predictably enhances as long as the nodes meet each other more times. Hence, the more frequent the encounter of the two nodes, the higher the probability of delivering a message, and the more suitable the node a becomes to be a forwarder. On the other hand, if the nodes a and b lose contact, the value of $P(a, b)$ must age and will be reduced since the probability of meeting each other becomes lower [14].

As stated in its name, the PRoPHET also employs the so-called transitivity metric. This property extends the concept of predictability to involve a third node. The transitivity represents the potential of a node a to meet a node c given that a meets a node b and b meets the node c. As in the previous case, the higher the transitivity, the more suitable the node a becomes to be a forwarder.

IV. Simulation scenario

The main objective of this work is to evaluate the performance of DTN and VANET protocols for the transmission of traffic information in scenarios of high-density of vehicles. Such a situation can occur in a typical urban scenario, represented by a road intersection with traffic lights. In this case, the vehicular density can reach a very high level depending on the traffic conditions. A crossing-road scenario with traffic lights allows evaluating how much a large number of neighbors can enhance or lessen the communication performance for transmitting warning messages among vehicles.

In this work, we use a four-legged urban crossing with a road length of 300 m in an area of 0.36 km^2. In this scenario, each road is composed of four lanes divided in two ways. Vehicles can turn right or continue straight ahead with a probability of 0.5, as depicted in Fig. 3.

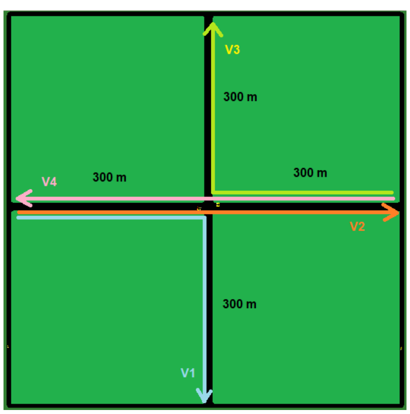


Fig. 3. Four-legged urban crossing scenario for simulation (vehicles can move straight ahead or turn right).

Vehicles can enter the scenario from two sides, left (V1, V2) and right (V3, V4). All vehicles should leave the mobility scenario once they have completed one of the four paths defined in Fig. 3. The maximum allowed speed is 12 m/s or 43.2 km/h, and the number of vehicles gradually grows from 4 to 100. The mobility patterns are generated by SUMO simulator [40].

Four vehicles have been defined as sender and receiving nodes, while the others remain as potential forwarding nodes. The four communicating vehicles are headers of the traffic flow and run in opposite directions. All of them must stop at the intersection at the same time, as depicted in Fig. 4a

We configure the four vehicles involved in the communication as headers of the traffic flow. On the other hand,

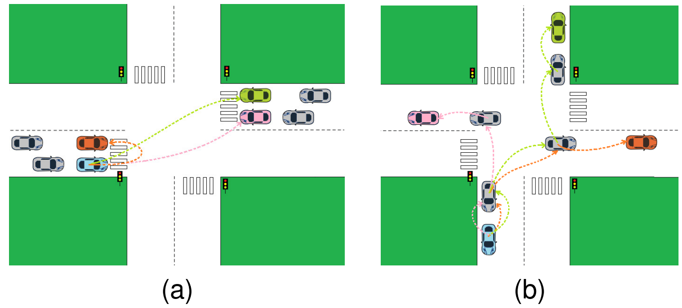


Fig. 4. Communication among four vehicles of the traffic flow. (a) Four vehicles communicate at the intersection. (b) Communication links once the traffic light opens.

forwarding vehicles come into the scene in different amounts, ranging from 0 to 100, with uniform distribution over the considered space. In our communication scheme, one of the vehicles (source vehicle) tries to inform the others about the previous occurrence of a set of events.

The communication starts when the four vehicles are completely stopped at the red light, as shown in Fig. 4a. Then, the source vehicle starts a transmission with information about ongoing events. Depending on the amount of data to transmit, the necessary communication time exceeds the stop time interval. Hence, the transmission routine continues with vehicles resuming their trips on the green light. From this moment on, vehicles initially located behind the four headers (gray-colored) are supposed to be responsible for transmission hops, as depicted in Fig. 4.

For data transmission simulation in the network, we have considered open-source software. In this category, the most popular options are the ONE simulator [41], ns-2 [42], OMNeT++ [43], and ns-3 [44]. The ONE simulator is the most employed software for DTN. It is a contact-orient simulator that has been created for DTN as a tool for developing new protocols. However, it does not support the propagation and channel models, DSRC and IEEE802.11p standards, or integration with vehicular mobility generators such as SUMO. The OMNeT++ simulator is the most advanced framework for vehicular network simulation. However, none of the reviewed works for DTN used this software. Despite ns-3 being a recent software, ns-2 is a reliable, well-known, and widely employed network simulator. Likewise, a large set of knowledge bases for ns-2 are available, allowing fast integration of additional features such as DSRC and basic DTN routing protocols. Hence, ns-2 has been chosen for simulation.

A. Simulation Parameters

The simulation was carried out with four DTN protocols (Direct Delivery (DD), Epidemic, Binary Spray&Wait (BS&W), and PRoPHET), and two VANET protocols (AODV and GPSR). We chose these protocols mainly because they are publicly available and have been used as references in similar works [4], [20].

We adopt the recommendation of the European Telecommunications Standards Institute (ETSI) for the generation period Tms of messages. The institute defines lower and upper

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Simulation area	(0.6 x 0.6) km^2
Number of nodes	{4, 8, 12, 20, 28, 36, 52, 68, 84, 100}
Mobility model	Traffic lights crossing
Lane configuration	Two flows / four ways
Maximum speed of nodes	12 m/s
Car following model	Krauss
Channel type	Wireless
Communication time interval	30 s
Traffic type	Bundle / CBR-UDP
Propagation model	Nakagami-m (m=2)
MAC/PHY	IEEE 802.11p
Radio range	{100, 200, 300, 400, 500} meters
Message size	512 bytes
Buffer size	100 GByte
Bundle lifetime	60 s
Bundle generation period	1 s
Number of initial copies	16 (Binary Spray & Wait only)
Simulation replications	10
Confidence interval	95 %

bounds of Tms in milliseconds as $100 \leq Tms \leq 1000$ for Cooperative Awareness Messages (CAM) [45]. The lower bound period is usually employed in most time-critical approaches, like in Cooperative Adaptive Cruise Control (CACC) applications [46], [47]. In our case, the warning messages contain information about events that are meant to improve traffic dynamics but are not to be used for self-driving purposes or collision avoidance. Therefore, we have chosen the generation period of 1000 ms, which is a prudential time to keep vehicles aware of traffic events while avoiding excessive flooding of messages in the network. Table. II summarizes the communication parameters.

B. Performance Metrics

Four metrics are used for evaluation and performance comparison of the routing protocols: i) delivery ratio, ii) average end-to-end delay, iii) overhead, and i) average number of hops.

Delivery Ratio (DR) is the ratio between the number of successfully delivered messages and the number of sent messages. Better performance of a routing protocol is obtained for high DR values [15].

End-To-End Delay [48] is the average time interval between sending and receiving a message from source to destination as in (1)

$$E2E\ Delay = \sum_i (T_{a,i} - T_{d,i})/N_{rm} \quad (1)$$

with the arrival time $T_{a,i}$ and departure time $T_{d,i}$ of message i for a total number of N_{rm} received messages.

Overhead is the ratio between the number of messages necessary to send user data in the network [15] and the number of messages with user data. The overhead can be expressed as in (2)

$$Overhead = N_t/N_s \quad (2)$$

where N_t is the total number of messages, and N_s is the number of messages sent with user data. For DTNs, $N_t = B_c + B_{tc} - B_r$, with B_c as the number of copies of bundles made during transfers, B_{tc} the number of transfers of bundles during routing, and B_r as the number of received bundles [14]. In the case of VANET protocols, N_t represents the number of additional routing packets [49]. The overhead should be reduced for better performance.

Average number of hops is the average number of hops a message needs to perform in order to meet the final destination. It represents how many intermediary nodes are necessary to complete the path between source and destination. In the case of DTN, fewer hops usually mean longer carrying intervals, implying an increase in delay [37].

V. RESULTS AND DISCUSSION

In order to assess the performance of DTN and VANET protocols, we explore wide transmission ranges (TR) from 100 to 500 m. First, we evaluate the impact of traffic density by considering the minimum and maximum TR. We then perform extensive simulations to obtain results for four metrics: Delivery Rate, End-To-End Delay, Overhead, and the Average number of hops. Each simulation uses the same number of vehicles and transmission range for each protocol as described in Algorithm 1. The results are averaged over ten observations (simulation runs) considering a confidence interval of 95%.

Algorithm 1 Pseudo-code for generating the simulation results

```
for each Protocol ∈ {Epidemic, BS&W, PRoPHET, DD, GPSR, AODV} do
    for each TR ∈ {100,200,300,400,500} do
        for each # Nodes ∈ {4,8,12,20,28,36,52,68,84,100} do
            repeat
                Run simulation in ns-2 with parameters of Table II
            until # simulation runs ≤ 10
            Compute DR, E2E Delay, Overhead, and # Hops
            averaged over ten runs
        end for
    end for
end for
Plot the results
```

We also present a complete TR-Density analysis for each protocol and metric in addition to the maximum and minimum TR cases. This analysis aims to understand the evolution of each metric according to both density and transmission range. Moreover, we explore the trade-off between density and transmission range that leads to better performance of each protocol.

Secondly, we present an assessment of the evolution of Delivery Rate and Delay regarding the average distance among vehicles. This evaluation clarifies how each routing protocol performs as vehicles move away from each other. Similar to the previous case, the simulation is performed according to the Algorithm 1. However, the results are gathered every five seconds in this case, and the mean inter-vehicular distance reached in each time interval is employed as the independent variable for plotting.

A. The Impact of Vehicular Density

We first assess the effect of vehicular density for a short transmission range of 100 m, which is lower than the most

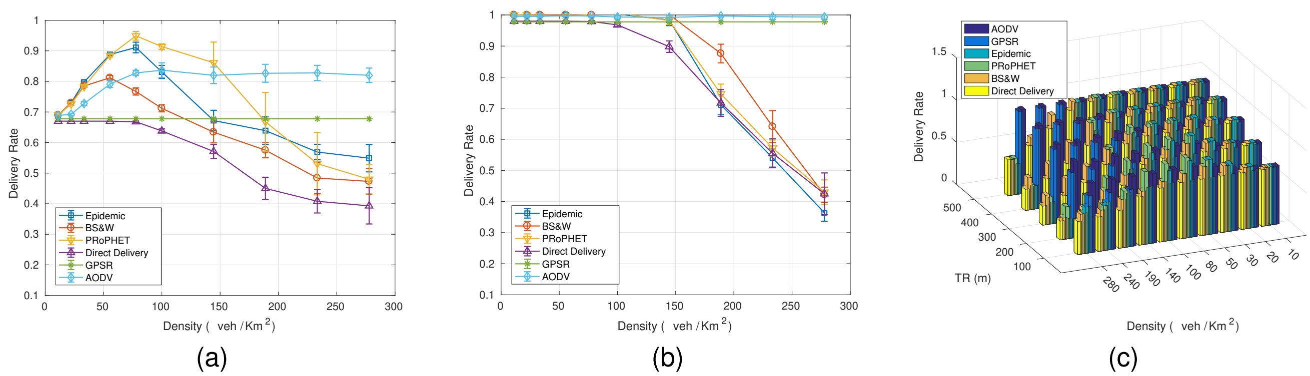


Fig. 5. Delivery Rate for different transmission ranges and vehicular densities. (a) TR=100 m. (b) TR=500 m. (c) TR-Density comparison.

common values used to simulate vehicular networks. A transmission range as short as 100 m reveals how vehicles benefit from the traffic density to successfully deliver a message when the destination node is located out of the transmission range. In this case, the low traffic density represents a condition where vehicles have a minimum direct contact, which is the case of sparse networks most studied in the literature.

We then evaluate the same metrics but using a transmission range of 500 m. This value of 500 m is among the highest values found in the literature. It allows the evaluation of the effect of a large number of vehicles in the transmission range. In this case, the vehicular density lets us know how the routing protocols perform when multiple paths are available.

Finally, we present a complete analysis of all the considered values of transmission range and density, giving an overview of the evolution of each metric.

1) Delivery Rate (DR): Fig. 5a shows the results for Delivery Rate (DR) versus vehicular density. The results show that multi-copy DTN protocols (i.e. Epidemic, BS&W, PRoPHET) and AODV outperform Direct Delivery (DD) and GPSR at low densities. Fig. 5a also reveals that those protocols benefit the most from increasing densities until 50 vehicles/km^2.

For densities higher than 75 vehicles/km^2, DR for all DTN protocols decreases as density increases. In the case of AODV and GPSR, DR remains almost the same. Moreover, the density change does not affect the delivery rate of GPSR and AODV.

The results for a high transmission range of 500 m are depicted in Fig. 5b. For low densities (under 100 vehicles/km^2), all protocols achieve maximum DR, which is an evident improvement regarding the results with TR=100 m. The results for high densities indicate that DR is lower than those with TR=100 m for all DTN protocols. For AODV and GPSR, the results are better for all densities.

Fig. 5c shows more clearly the effects of TR and density on DR. For low density, every protocol benefits from enhancing the transmission range. For high densities, DR abruptly drops for DTN protocols as of TR=200 m. Although better results for all protocols seem to be associated with high TR, the operation at this regime is not a suitable choice. A good starting point for most DTN protocols seems to be TR=300 m, achieving maximum DR for 15 vehicle/km^2.

Depending on the density, the TR plays a different role for traditional VANET and DTN. In the case of AODV and GPSR, an increase of TR leads to improving the DR for all density values. In the case of DTN, the DR benefits from a higher TR only at low densities. At high traffic densities, the DR reduces dramatically in DTN.

The results suggest that DTN is unsuitable for transmitting periodic warning messages in high congested areas. Traditional options such as AODV and GPSR can perform better than DTN in these situations. In particular, AODV is the only one that benefits from increasing densities to deliver messages more effectively.

2) Average End-To-End Delay: The results for End-To-End Delay with the shortest transmission range are depicted in Fig. 6a. The results show that E2E-Delay for DTN protocols increases as the vehicular density increases. The Epidemic protocol has the highest delay, and Direct Delivery has the lowest one. Furthermore, the results for AODV and GPSR are just a few milliseconds, which seem negligible if compared with DTN. However, for low-density conditions (under 50 vehicles/km^2), the results for DTN protocols are comparable with those of AODV and GPSR.

The results for the highest transmission rate, plotted in Fig. 6b, show that for DTN protocols, the E2E Delay increases as long as the density does too. For higher density (over 100 vehicles/km^2), the E2E Delay of all DTN approaches becomes higher than in the case of TR=100 m. On the other hand, contrary to DTN protocols, in AODV and GPSR, the E2E Delay becomes lower for a higher transmission range for any density.

As observed in the previous section, Fig. 6c shows that AODV and GPSR offer the lowest average delay and remain almost at the same value for any combination of TR and density. On the contrary, all DTN protocols exhibit a short delay increment as of 50 vehicles/km^2 upwards.

Among DTN protocols, the Epidemic exhibit the highest delay in most cases. However, as in the case of PRoPHET, its value is constant for high variations of the transmission range. On the contrary, the average E2E Delay for BS&W and Direct Delivery increases quickly as TR and density increase.

As in the case of Delivery Rate, the results of the average E2E Delay indicate that DTN protocols are not a suitable

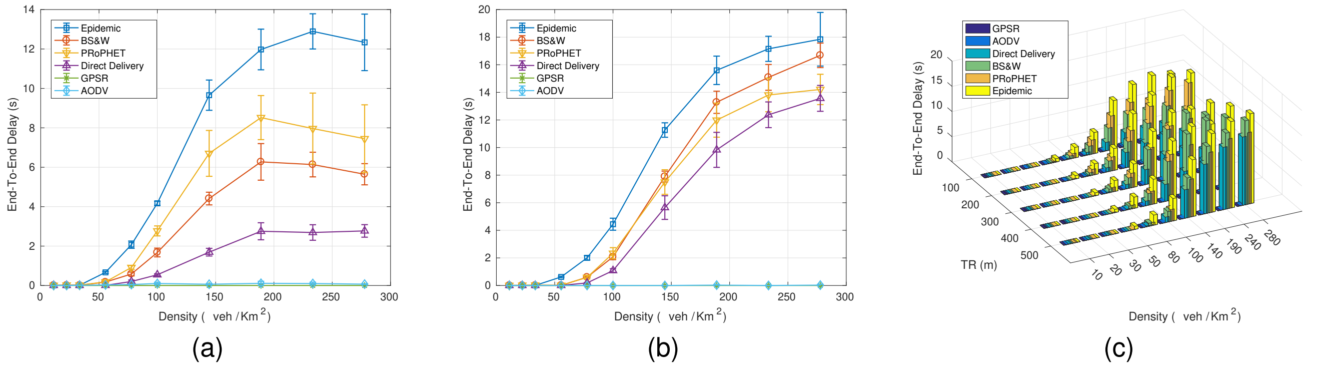


Fig. 6. Average End-To-End Delay for different transmission ranges and vehicular densities. (a) TR=100 m. (b) TR=500 m. (c) TR-Density comparison.

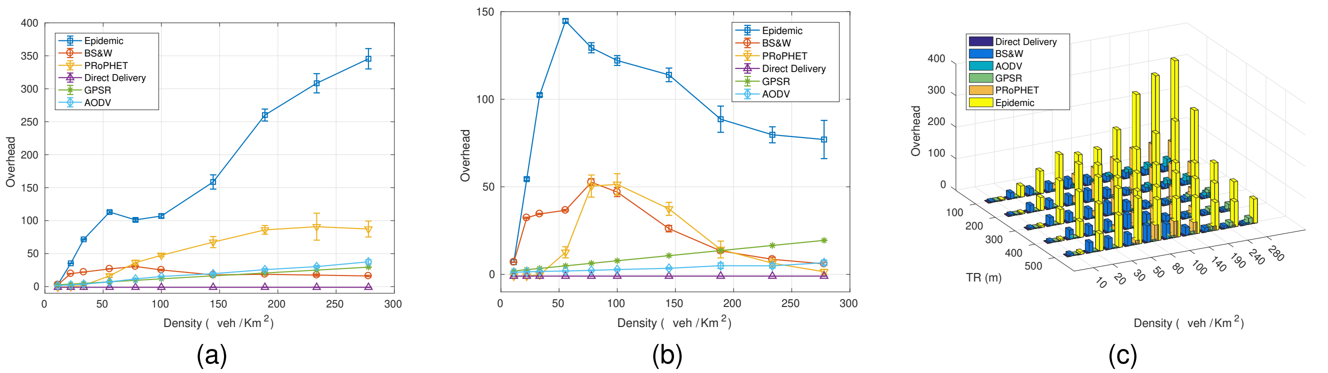


Fig. 7. Overhead for different transmission ranges and vehicular densities. (a) TR=100 m. (b) TR=500 m. (c) TR-Density comparison.

option for transmitting warning messages in high dense scenarios. The E2E Delay for densities higher than 60 vehicles/km^2 is higher than the message generation period of one second. Hence, DTN is not a time-effective option.

3) Overhead: Fig. 7a shows the results for overhead using the minimum TR. The response of DTN protocols with no spread control (e.g. Epidemic and PRoPHET) shows an enhancement of overhead as the density increases. In the case of Epidemic, the vast number of copies causes a buffer overflow and leads the network to achieve a local maximum at a density of 55 vehicles/km^2. Thereupon, any further increase of density implies an increase in delay and reduction of DR, which leads to reducing the overhead. However, a high density and short TR entail exchanging the messages with more neighbors beyond the TR coverage, which increases the overhead again.

Fig. 7b shows the results of the overhead for TR=500 m. As in the case of TR=100 m, for all protocols except DD and at low densities, the overhead tends to increase. In the case of DTN, the overhead reaches a peak value with 55 vehicles/km^2 and 75 vehicles/km^2 for epidemic and BS&W, respectively. Those points coincide with the first peak values obtained with TR=100 m. In the case of PRoPHET, the maximum overhead occurs earlier (75 vehicle/km^2) than that for TR=100 m.

Unlike GPSR and AODV, whose overhead increases with density for both TR values, the non-controlled multi-copy DTN protocols (i.e. Epidemic, and PRoPHET) show different responses for each value of TR. The overhead of these two DTN protocols for TR=100 m increases as density is very high, whereas the overhead decreases for TR=500 m in the same condition. In the case of TR=100 m, when a vehicle does not find the message's destination within the transmission range, it must transmit copies to every neighbor. This process is replicated to each neighbor, increasing the overhead. In the case of TR=500 m, there is no need to share messages with a large number of vehicles due to the presence of more neighbors within the transmission range.

The overall results are depicted in Fig. 7c. It shows that Epidemic has the highest value for any combination of density and TR. As mentioned before, the overhead of Epidemic and PRoPHET rises as the density increases and TR decreases. In the case of BS&W, minimum changes occur when TR is modified. It reflects the importance of spray control to avoid flooding of the network. In the case of traditional VANETs, the overhead of AODV and GPSR increases with density and decreases with TR increments.

The overhead may not directly impact the transmission of periodic warning messages. However, our results show the effect of the overhead on the general performance of the network. The results suggest that long TRs cause a low impact of periodic warning transmissions on the network performance. In this case, the DD protocol appears to be the best choice, whereas the results for BS&W and PRoPHET are not as different from AODV and GPSR as previous metrics

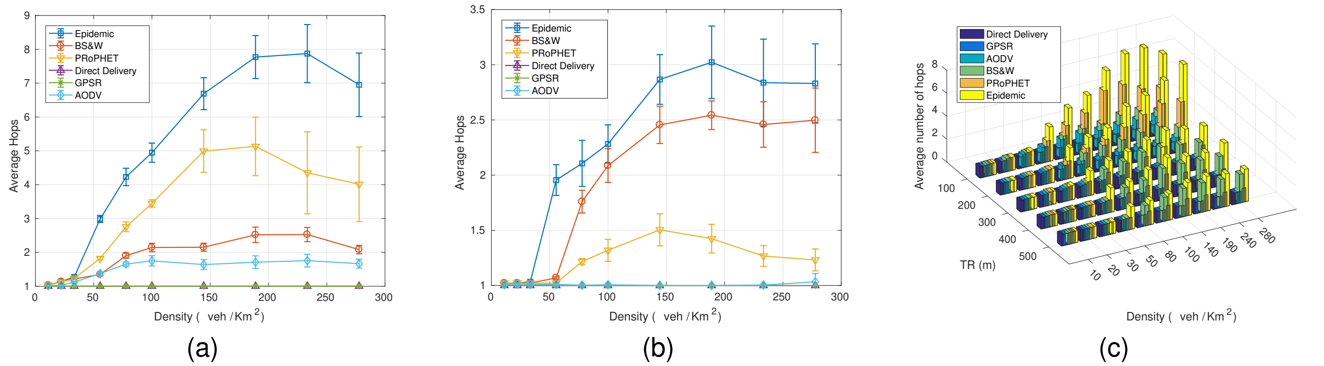


Fig. 8. Average number of hops for different transmission rates and vehicular densities. (a) TR=100 m. (b) TR=500 m. (c) TR-Density comparison.

for a high density.

4) Average number of hops: Fig. 8a shows the results of the average number of hops for the lowest TR. As expected, the results of the epidemic are higher than in other protocols, and as with other DTN protocols, the number of hops grows as the density increases. Nonetheless, this metric appears to reduce at the highest densities. For those conditions, the high delay and dropped messages contribute to reducing the final count of hops.

Fig. 8a also let us conclude that multi-copy DTN protocols employ more hops than the traditional VANET options. Surprisingly, the GPSR performs quite similarly to DD, delivering the messages using just one hop transmission. It suggests that the greedy search strategy is not fast enough to find optional paths when vehicles turn away from each other. It is worth noting that delivering a message from one node to another is regarded as a one-hop transmission in the context of this work.

The results in Fig. 8b show the average number of hops for TR=500 m. Compared with Fig. 8a, we observe a significant reduction of this metric for Epidemic, PRoPHET, and AODV. On the contrary, the BS&W and the GPSR tend to keep similar behavior to that of TR=100 m. It means protocols with no copy limitations can deliver messages to farther neighbors within their transmission range, thus achieving the destination node with fewer hops.

Similar to the overhead for low TR, the average number of hops of Epidemic and PRoPHET increases as the density grows, as shown in Fig. 8c. The reason is the same given before for the overhead. The fragmentation of the network in multiple domains leads to sharing the messages with a huge number of neighbors. On the contrary, BS&W remains almost constant for every TR but becomes higher as the density increases.

The results show that, for this kind of application and scenario, traditional approaches, such as GPSR and AODV, tend to employ fewer hops than DTN options. In the case of GPSR, the protocol uses only one hop regardless of density and TR values. In the case of AODV, the protocol employs more than one hop for shorter transmission ranges and higher traffic densities.

The high number of nodes used by DTN protocols is consistent with the results of the Average End-To-End Delay. The use of paths with a higher number of nodes, even when the source node can directly contact the destination nodes, indicates that DTN protocols do not choose the fastest route. Hence, they are not suitable for exchanging periodic warning messages with specific nodes in high dense areas.

B. The Impact of Inter-Vehicle Distance

In this section, we evaluate the performance of routing protocols by considering the average distance between the source node and the destination ones. Distances were taken at 15, 20, 25, and 30 seconds after the communication started. The Euclidean distance was employed in (3) to compute the average value between source and recipients.

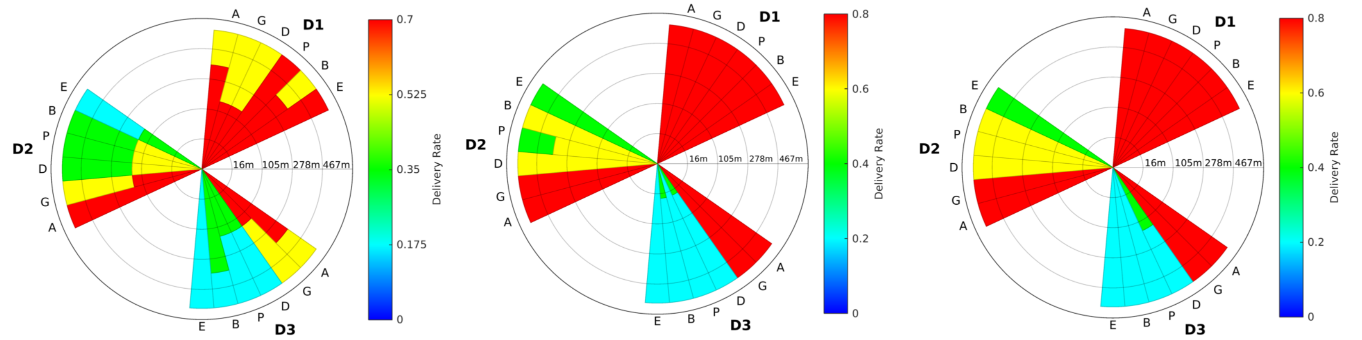
$$AvDist = (\sum_{i=1}^{N} \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2})/N \qquad (3)$$

Where x_i, y_i represents the position of a destination node, x_0, y_0 is the position of the source node, and N stands for the total number of communicating vehicles. The results for each time interval were 16, 105, 278, and 467 meters, respectively.

For evaluating the impact of distance, we adopt three traffic densities: 55, 144, and 233 vehicle/km^2, hereinafter labeled D1, D2, and D3, respectively. These values were chosen because they appear to be representative in Figs. 5, 6, 7, and 8. On one side, D1 represents those densities where the DR is either the highest or increasing with density. This point also stands for a low E2E Delay (less than one second for all protocols). On the other side, D3 represents a high traffic density, where no traffic saturation has occurred, so the highest E2E Delay is reached. Finally, the D2 corresponds to a transition point between D1 and D3.

Likewise, we evaluate the impact of transmission range using 100, 300, and 500 meters. Those values are also representatives of the ranges employed in figures 5, 6, 7, and 8. With TR=100 m as the minimum value, TR=500 m as the maximum, and TR=300 m as the mean value and the most commonly employed transmission range for evaluating vehicular networks.

On the other hand, two features become significantly important when considering the transmission of periodic traffic notifications in vehicular networks: the reliable delivery of a



(a) (b) (c)

Fig. 9. Delivery Rate for different transmission ranges, distances and densities; D1=55, D2=144, and D3=233 vehicle/km^2; A=AODV, G=GPSR, D=Direct Delivery, P=PRoPHET, B=Binary Spray & Wait, and E=Epidemic (a) TR=100 m. (b) TR=300 m. (c) TR=500 m.

message and the time effectiveness of the information. Hence, we employ the Delivery Rate and the Average End-To-End Delay as the evaluation metrics for this section.

Fig. 9 shows the evolution of the Delivery Rate for each protocol, with A=AODV, G=GPSR, D=Delivery Rate, P=PRoPHET, B=Binary Spray & Wait, and E=Epidemic, when the density increases from D1 to D3 for each average distance. We present the results of DR for each protocol and density using a TR of 100, 300, and 500 m.

As depicted in Fig. 9a, for low densities and short transmission range, the multi-hop DTN protocols deliver in a spread fashion, achieving high DR even with high distances. In these conditions, the Epidemic and PRoPHET outperform the other ones, whereas a non-DTN option, as the GPSR, tends to deliver quite similar to DD, transmitting the bulk of messages in the shortest distance.

It is worth noting that each result is cumulative, which means that each result is an average value that includes the previous ones. Hence, the DR for Direct Delivery can not be zero beyond the TR boundary.

Fig. 9a also shows that the only protocol which significantly benefits from the increase of density as the distance grows is the AODV. The results reveal that AODV can harness the neighborhood to extend the delivery range as the inter-vehicle distance grows. On the other hand, other traditional protocol, such as the GPSR, remains unchanged for any density.

As commented in previous sections, different from traditional VANET protocols, the DR reduces as the density increases for DTN. Particularly, the Epidemic achieves a high DR for all distances with TR=100 m and D1. Fig. 9a shows that the DTN protocols tend to deliver the messages at short distances as the density increases.

As observed in section V-A, the increase of the transmission range yields an enhancement of the DR of each routing protocol at low densities. This effect continues within a certain traffic density margin (D2 in our case), as depicted in Figs. 9b, and 9c. However, at higher densities (as high as D3), the increase of TR makes the DR fall even in short distances for most DTN protocols, while traditional VANET protocols get to extend their DR results.

In Fig. 10 we present the results of the Average End-To-End Delay (E2E Delay). For a density as low as D1 with any transmission range, all protocols achieve a low E2E Delay. As the density increases (D2 and D3), the E2E Delay of all DTN protocols rapidly grows, not just with the density itself but with the increasing inter-vehicular distance. On the contrary, in traditional VANET, the E2E Delay remains at low levels for all density and transmission range combinations.

As shown in section V-A, we observe the Epidemic protocol exhibiting the highest final E2E Delay, particularly for low TR and high densities. However, from Fig. 10 we see that such difference begins even at short distances when all vehicles are yet into the same TR of the source node. That means the presence of the destination node in the TR is not a guarantee for timely delivery with DTN.

Such inter-TR increasing delay can also be observed in other DTN protocols, for instance, in BS&W. However, in the case of BS&W, the increase of E2E Delay is less significant than in Epidemic (Fig. 10a for a distance of 105m, and Fig. 10b for 278 m). Therefore, the uncontrolled spreading of messages performed by the Epidemic makes it hard to find the destination in a short time, even in the same TR.

Other DTN protocols, such as PRoPHET or Direct Delivery, show a lower and more stable E2E Delay for connections within the same TR, especially for TR=100 m and TR=300 m. For TR=500 m with D3, the E2E Delay of PRoPHET becomes very similar to that of Epidemic and BS&W. That is, the E2E Delay rapidly increases as the inter-vehicular distance grows.

C. Discussion

The results show that increasing vehicular density negatively impacts DTN protocols more than AODV and GPSR. The results in Figs. 5 and 9 demonstrate the low delivery rate of DTN for high vehicular densities if compared with AODV and GPSR. Moreover, Figs. 9 and 10 show that even for distances shorter than the transmission range, the DTN protocols do not meet either a full delivery or a timely message transmission. Other results such as the End-To-End Delay, Overhead, and Average Number of Hops are also favorable to AODV and

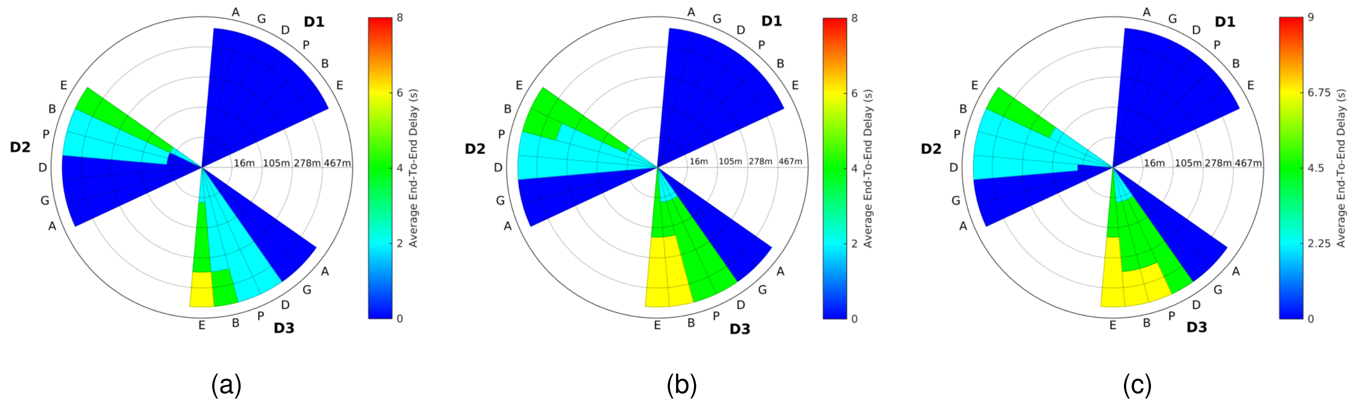


Fig. 10. Average End-To-End Delay for different transmission ranges, distances and densities; D1=55, D2=144, and D3=233 vehicle/km^2; A=AODV, G=GPSR, D=Direct Delivery, P=PRoPHET, B=Binary Spray & Wait, and E=Epidemic (a) TR=100 m. (b) TR=300 m. (c) TR=500 m.

GPSR. Although no results were found in the literature for comparing DTN performance at high density, references [12] and [13] confirm for traditional VANETs that AODV and GPSR can harness the vehicle density to enhance the delivery rate for a particular transmission rate in similar scenarios. According to our results, the GPSR shows the lowest delay, even more than AODV. However, the GPSR fails to maintain active paths or even to find better path choices to extend an ongoing transmission. Although GPSR is a better choice than DTN for high density, it is not as suitable as the route-storage-based protocols such as AODV.

The comparison among DTN protocols at high density shows that DR in Epidemic reduces more quickly than in other protocols as the transmission range increases, as evidenced in Fig. 5b, and in Fig. 9 for D3. On the other hand, the BS&W, which does not show the best delivery performance for a short TR, as seen in Fig. 5a, becomes the best DTN choice for delivering in the highest TR, as shown in Fig. 5b. Additionally, the BS&W shows a similar overhead and number of hops for any TR, as seen in Figs. 7 and 8.

These results suggest that the spread control of BS&W helps the protocol reduce the dropping of messages in high-dense conditions and makes the protocol less sensitive to variations of the transmission range. It occurs because the existence of more forwarding domains does not imply using a higher number of hops, as shown in Fig. 8b. Hence, in situations with a higher TR, protocols featuring spread controls, like the BS&W, perform better than other DTN options.

Despite the better DR results of BS&W compared to other DTN approaches, the Average E2E Delay grows faster than in other DTN protocols as the TR increases, as evidenced in Figs. 6a, and 6b. Nevertheless, the maximum values remain lower than in Epidemic for most of the densities. Therefore, the BS&W continues to be a better option for traffic warning messages in high-congested networks than Epidemic.

The results in Fig. 9 show that the non-controlled multi-copy DTNs (PRoPHET and Epidemic) achieve the highest DR for low density and any TR, whereas the copy-controlled ones (BS&W and DD) match or even outperform the other ones as density increases. Such results suggest that the DTN protocols featuring copy control can be more appealing to prolong the communication between source and destination once the vehicles start to run away from each other in a high-congested situation.

On the other hand, the results in Fig. 10 show that the E2E Delay of BS&W can be higher than in the case of DD and PROPHET for high vehicular density situations. These results can make us reason about the reliability of BS&W compared with other DTN approaches. However, as the BS&W achieves a higher DR in most cases, we can say that the selection of BS&W for transmission of warning messages implies a trade-off between warranty of delivery and time effectiveness on transmission.

Another remarkable result of this study is the behavior of the Direct Delivery protocol. Although this protocol has the worse behavior among DTN protocols for low TR and density, the results for high TR and density show that DD can deliver more messages than Epidemic with a lower E2E Delay in high congestion scenarios, as evidenced in Figs. 5b and 6b. Moreover, the results in Figs. 9, and 10 show that for densities of 144 vehicles/km^2 and onward, the Direct Delivery outperforms the other DTN options with a high or similar DR in the worse case if compared with other protocols. Such affirmation is true at least in distances under the TR boundary. Although we found the DTN approaches are not feasible for transmitting periodic warning messages in high density and short-scale scenarios, the Direct Delivery seems to be an acceptable option, at least for low transmission ranges.

Despite the aim of our work, which is the evaluation in a high-dense scenario, our findings for low densities confirm that Epidemic, BS&W, and prophet benefit from the increase of density and a stable end-to-end delay in sparse networks, as claimed by [15], and [14]. However, our results show that the most effective protocol (Epidemic) for those conditions, according to [2], [15] is also the worst choice for high-dense networks. Although a higher DR than in other DTN approaches is observed for Epidemic at the maximum density of Fig.5a, the average delay and number of hops are also higher than in other protocols. Moreover, the DR decreases rapidly as TR increases. Hence, for a typical TR of 300 m and upwards, the Epidemic protocol is no longer a good option for transmitting periodic warning messages in the proposed scenario, as evidenced by Fig. 9b.

VI. Conclusion

This work has studied the performance of some DTN and VANET protocols when employed to transmit periodic warning messages across a vehicular network in a crossing road scenario with a traffic light. The utmost target was to describe the effect of the vehicular density and the transmission range for prolonging the communication among the vehicles.

The DTN protocols used were Epidemic, PRoPHET, BS&W, and Direct Delivery, whereas the VANET ones were AODV and GPSR. All of them are commonly-employed protocols for comparison in each category. For performance evaluation, four metrics have been employed, Delivery Rate, End-To-End Delay, Overhead, and the average number of nodes. Those metrics were applied using the vehicular density and the transmission range as variable parameters.

The results show that DTN protocols exhibit a great difficulty to perform in high density and high transmission range scenarios. In such conditions, the number of hops and overhead improve, whereas the delivery rate and average end-to-end delay worsen. It means that a higher number of neighbors in the transmission range demands a high amount of resources, which makes the DTN protocols fail. The low delivery rate and high end-to-end delay, specifically, make the DTN unreliable for transmitting warning messages in high-dense scenarios.

On the other hand, AODV and GPSR have shown a better performance than DTN for high density with any transmission range. In that case, the high number of vehicles guarantees the existence of a path between source and destination nodes, which is a suitable scenario for traditional VANET protocols. Moreover, the route storage capacity of AODV leads to better performance than in GPSR when vehicles are moving away from each other.

Finally, the wide range of densities studied in this work allows us to observe that DTNs outperform traditional VANETs in sparse networks. The difference in the effect of the transmission range for both densities, high and low, makes us conclude that a reliable vehicular DTN approach must consider the use of density-aware transmission power adaptation strategies, route-storage features, and the application of spread control policies. Future work will explore these strategies.

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