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# GeoSpray: A geographic routing protocol for vehicular delay-tolerant networks

Vasco N.G.J. Soares [a,b], Joel J.P.C. Rodrigues [a,*], Farid Farahmand [c]

[a] Instituto de Telecomunicações, University of Beira Interior, Portugal
[b] Superior School of Technology, Polytechnic Institute of Castelo Branco, Portugal
[c] Department of Engineering Science, Sonoma State University, CA, USA

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ABSTRACT

Vehicular networks are characterized by a highly dynamic network topology, and disruptive and intermittent connectivity. In such network environments, a complete path from source to destination does not exist on the most part of the time. Vehicular delay-tolerant network (VDTN) architecture was introduced to deal with these connectivity constraints. VDTN assumes asynchronous, bundle-oriented communication, and a store-carry-and-forward routing paradigm. A routing protocol for VDTNs should make the best use of the tight resources available in network nodes to create a multi-hop path that exists over time. This paper proposes a VDTN routing protocol, called GeoSpray, which takes routing decisions based on geographical location data, and combines a hybrid approach between multiple-copy and single-copy schemes. First, it starts with a multiple-copy scheme, spreading a limited number of bundle copies, in order to exploit alternative paths. Then, it switches to a forwarding scheme, which takes advantage of additional contact opportunities. In order to improve resources utilization, it clears delivered bundles across the network nodes. It is shown that GeoSpray improves significantly the delivery probability and reduces the delivery delay, compared to traditional location and non location-based single-copy and multiple-copy routing protocols.

## 1. Introduction

Vehicular networks have gained an increasing research interest in the last recent years, due to their wide range of potential application scenarios including, but not limited to, networks to disseminate safety related information (e.g., emergency notification, traffic condition, and collision avoidance) [1,2] or information advertisements (e.g., marketing data), networks to distribute multimedia content [3,4], and monitoring networks to collect data (e.g., pollution data and road pavement defects) [5]. Vehicular networks can also be employed to provide connectivity to remote rural communities and regions, enabling non-real time services, such as file-transfer, electronic mail, cached Web access, and telemedicine [6–8]. Catastrophe hit areas lacking a conventional communication infrastructure can benefit from the deployment of a vehicular network to provide support for communication between rescue teams and assist communication between the rescue teams and other emergency services [9].

To make such applications possible, it is necessary to design networking protocols that can overcome relevant problems that arise from vehicular environments. The high mobility and speed of vehicles is responsible for a highly dynamic network topology and short contact durations [10,11]. Limited transmission ranges (due to radio coverage), physical obstacles (e.g., buildings in urban environments), and interferences, make these networks prone to disruption and intermittent connectivity issues [12]. As a result, these networks may be partitioned, because of the large distances usually involved and to variable node densities, resulting in discontinuities along the path from source to destination.

Conventional routing and forwarding protocols designed for fully connected vehicular networks, called vehicular ad hoc networks (VANETs) [13] aim to establish end-to-end connectivity among network nodes and support end-to-end semantics of existing transports and applications [14]. Thus, they fail data delivery in sparse, intermittent, partially connected, and opportunistic vehicular networks [15–17]. To surpass these problems, vehicular networks may deliver data using the store-carry-and-forward (SCF) paradigm of delay-tolerant networks (DTNs) [18]. This paradigm does not assume that an end-to-end network path is currently available, but rather that such path exists over time. SCF maximizes the probability of data delivery, particularly in sparsely populated environments, allowing delay-tolerant data traffic from a variety of vehicular applications to be routed over time [5,19].

Vehicular delay-tolerant networking (VDTN) [20] is an example of a new architecture that employs a store-carry-and-forward operation principle. Distinctive characteristics of this network architecture are the use of out-of-band signaling, with separation between control and data planes, and the use of an IP over VDTN

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* Corresponding author. Tel.: +351 275242081.

*E-mail addresses:* vasco.g.soares@ieee.org (V.N.G.J. Soares), joeljr@ieee.org (J.J.P.C. Rodrigues), farid.farahmand@sonoma.edu (F. Farahmand).

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approach. Datagrams (IP packets) are assembled in variable length data packets, called bundles, and transmitted asynchronously through the network. At an ingress edge node, bundles are assembled and sent to the VDTN, using the data plane. A data channel is reserved for a bundle by the corresponding control message already sent to the network through the control plane.

Various store-carry-and-forward routing protocols have been presented in the DTN related literature [21–25]. The main differences among these protocols come from the type of information they consider to make routing decisions (e.g., absence of knowledge, history of node encounters, location information), and their forwarding or replication strategy (i.e., the number of copies created per bundle). Nonetheless, there is a consensus in the research community that there is no perfect routing protocol for all kinds of DTN networks. Each routing protocol has its own strengths in some specific application scenarios.

Geographic routing (also known as location-based routing) appears as a promising approach for enhancing the routing efficiency in VDTNs. The availability of vehicle navigation systems, which are becoming standard equipment, motivates the increasing interest in this routing approach. With this in mind, this paper proposes GeoSpray, a novel geographic location-based routing protocol designed for VDTNs. GeoSpray is based on the following design principles:

(i) Supporting an opportunistic networking paradigm (where vehicles are opportunistically used for carrying data among nodes) and the delivery of bundles based on the store-carry-and-forward paradigm.
(ii) Using geographical location information provided by positioning devices to make routing decisions.
(iii) Employing a multiple-copy routing scheme, with a strict upper bound on the number of copies per bundle, combined with a forwarding routing strategy, to improve the timely delivery of bundles across multi-hop routes.
(iv) Clearing bundles (on intermediate nodes) that have already been delivered to the destinations.

GeoSpray aims to optimize the resources used in the network, including, storage, bandwidth, and energy, while maximizing the delivery probability, and minimizing delay and overhead.

The operation principles and design of GeoSpray are presented in this paper. The performance of this protocol is evaluated through simulation experiments against four well-known DTN routing protocols, namely the non location-based multiple-copy protocols Epidemic [26], Spray and Wait [27], and PRoPHET [28]; and the location-based single-copy routing protocol GeOpps [29]. The performance metrics considered are the delivery probability, the average delivery delay, the number of initiated bundles transmissions, the number of dropped bundles, and the overhead ratio.

Performance evaluation results, based on simulation, show that the proposed protocol improves significantly the delivery probability and reduces the delivery delay, compared to the considered location-based single-copy routing scheme, and non-location-based multiple-copy routing schemes. Moreover, it presents a lower rate of dropping bundles and a lower overhead ratio than the other evaluated multiple-copy routing schemes.

The remainder of the paper is organized as follows. Section 2 overviews the VDTN network architecture and Section 3 describes existing popular routing protocols that can be used in VDTNs. Section 4 presents the GeoSpray routing protocol for VDTNs proposed in this work, including its operation principles and design. Section 5 focuses on the performance evaluation of GeoSpray, and results discussion. Section 6 concludes the study and points further research directions.

## 2. Vehicular delay-tolerant networks

Vehicular delay-tolerant networks (VDTNs) [20] aim to support a class of vehicular network applications characterized by delay tolerant and asynchronous data traffic. Such applications, at the time of decision-making, do not need end-to-end connectivity and can even tolerate some data loss. VDTN architecture is inspired on the delay tolerant networking (DTN) concept of end-to-end, asynchronous, and variable-length message (i.e., bundle) oriented communication [18]. It features a layered architecture that differs from DTN architecture in the following main aspects: (i) considers an Internet protocol (IP) over VDTN approach and (ii) control and data planes separation, using out-of-band signaling.

A comparison between DTN and VDTN network architectures is shown in Fig. 1. DTN architecture introduces a bundle layer between the transport and application layer, creating a store-and-forward overlay network that allows the interconnection of highly heterogeneous networks. On the contrary, VDTN architecture places the bundle layer under the network layer introducing an IP over VDTN approach. Bundles are also defined as the protocol data unit at the VDTN bundle layer, and represent aggregates of IP datagrams with common attributes, such as destination node, application, and quality of service.

In order to implement control and data planes separation, the VDTN bundle layer is split into two sub-layers: the bundle signaling control (BSC) and the bundle aggregation and de-aggregation (BAD). The BSC sub-layer is responsible for executing the control plane functions, which include, among others, signaling, routing, node localization, resources reservation (at the data plane), and other network protocols that are used to set up, maintain, and terminate data plane connections. The data plane functions, which are executed at BAD sub-layer, deal with data bundles, and include, namely, buffer management (queuing), scheduling, traffic classification/differentiation, data aggregation/de-aggregation, and forwarding.

In a VDTN, out-of-band signaling is for data plane setup and corresponding resources reservation [20,30]. This approach allows the control plane to exchange signaling information through a separate, dedicated, low-power, low-bandwidth, and long-range link. This link is always active to detect contact opportunities. The data plane can use a high-power, high bandwidth, and short-range link for data bundles exchange among nodes. The data plane link connection is active only during the estimated contact duration time and if there are data bundles to be exchanged between the network nodes. Otherwise, it is not activated. This approach is considered very important because it is more efficient in order to optimize the available data plane resources and allows power saving, which is very important for energy-constrained network nodes [20,31]. The concept of out-of-band signaling and data-plane link activation and de-activation is illustrated in Fig. 2.

Fig. 2 also shows the three types of network nodes that may exist in a VDTN. Terminal nodes are the access points to the VDTN network (edge nodes) and are usually fixed. Mobile nodes (e.g., vehicles) are opportunistically exploited to collect and disseminate data bundles. They move on roads and carry data that must be delivered to the terminal nodes. Stationary relay nodes are fixed devices with store-and-forward capabilities that are located at road intersections. Mobile nodes communicate with them to store and pickup data. Relay nodes increase the number of contact opportunities in scenarios with low node density, contributing to increase the data bundles delivery probability and to decrease their delivery delay [32].

At the ingress edge nodes (where data bundles are assembled), bundle aggregation is considered to be an important design aspect of VDTN networks. This process involves aggregating and assembling network layer protocol data units (e.g., IP packets) into a data

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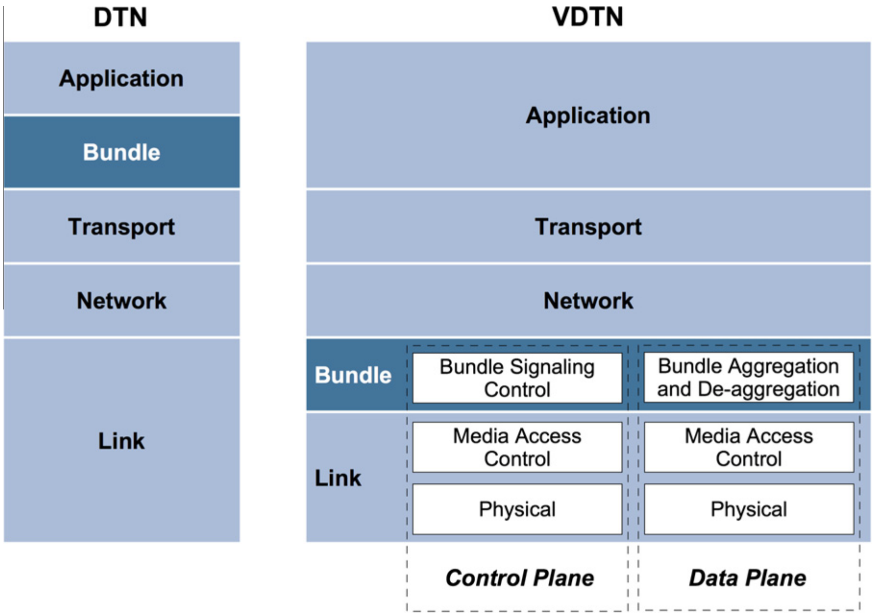

**Fig. 1.** DTN and VDTN network architecture layers.

bundle. The bundle is then transmitted over a VDTN network, from source to destination node, via a store-carry-and-forward approach that may involve some intermediate nodes. Several techniques may be considered for the assembly process. In application-based bundle assembly, a data bundle is created by the aggregation of IP packets that carry data to the same application destination. Another criteria for bundle assembly can be based on quality of service issues, which can be used for traffic prioritization [33]. Under this technique, IP packets with the same quality of service requirements are aggregated together. Another possibility is aggregating packets based on the same destination node irrespective of the final application. Bundle assembly techniques must take into account a size threshold that establishes a limit to the maximum number of IP packets contained inside the payload of a bundle. Timer-based approaches may also be considered (alone or in conjunction with other above-presented criteria) in order to define the time interval between bundle generations.

It is important to note that the bundle aggregation process can be further refined with the use of summarization functions [34]. Such functions can rely on the analysis of data requests similarities, to reduce the amount of data carried by the VDTN network.

## 3. Routing in VDTNs

In order to handle intermittency, disconnections, and long delays in sparse opportunistic vehicular network scenarios, VDTN

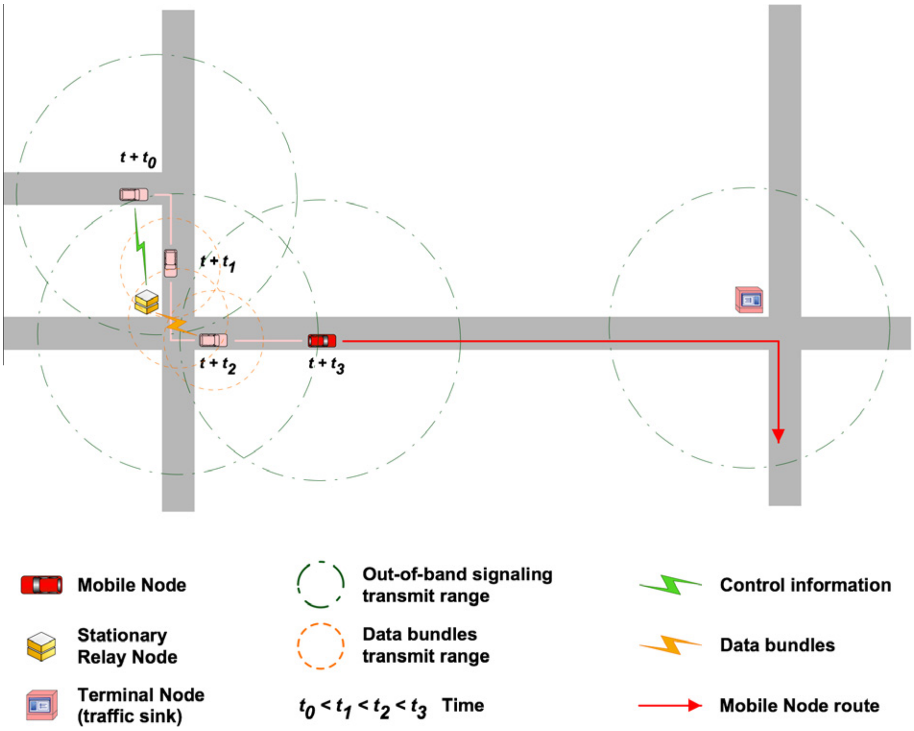

**Fig. 2.** Control information and data bundles exchange in a VDTN network.

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uses an underlying store-carry-and-forward DTN-based approach that can be described as follows. A network node stores a bundle, using some type of persistent storage, and waits for a future opportunistic connection. When a communication opportunity arises (i.e., two nodes are in range), the bundle is forwarded to an intermediate node, according to a hop-by-hop forwarding/routing scheme. Then, this process is repeated and the bundle will be relayed hop-by-hop until eventually reaching its destination node. Fig. 3 illustrates this paradigm, following the sequence of times $t_0$, $t_1$, $t_2$, $t_3$, and $t_4$.

### 3.1. Deploying generic DTN routing protocols in VDTNs

Numerous proposals of DTN routing protocols have been reported in the literature. Theoretical background and surveys about these protocols may be found in [21–25]. Although some of the available routing protocols have been targeted at specific application environments/scenarios (e.g., interplanetary networking [35], pocket switched networks [36], and message ferry networks [37]), others are aimed at generic application scenarios. Therefore, they can be potentially used in any DTN-based network, such as VDTNs.

Some well-known examples of widely applicable DTN routing protocols include Epidemic [26], Spray and Wait [27], and PRoPHET [28]. The main characteristic that these protocols have in common is the use of a multiple-copy routing strategy that replicates bundles at contact opportunities. Different copies of the same bundle can be routed independently to increase security [38] and robustness, thus improving the delivery probability and reducing the delivery delay. However, such approach increases the contention for network resources (e.g., bandwidth and storage), potentially leading to poor overall network performance, as discussed in [39,40]. These routing protocols make different assumptions about the knowledge available to network nodes (e.g., absence of knowledge, history of node encounters), as discussed below.

Epidemic [26] does not require any prior knowledge about the network. Under this routing protocol, each node maintains a list of the bundles it carries. At each encounter, network nodes exchange all bundles that they don't have in common. Using this strategy, all bundles are eventually spread to all nodes, including their destination. Epidemic is shown to be effective, but suffers from the disadvantages of flooding as the node density increases. It creates high contention for buffer space and required bandwidth, resulting in many bundle drops and retransmissions in resource-constrained network environments. In an environment with infinite buffer resources and bandwidth, this protocol provides an optimal solution, since it delivers all the bundles that can possibly be delivered in the minimum amount of time. For this reasons, it is considered "unbeatable" and used as a benchmark to compare with other routing protocols [24].

Spray and Wait [27] limits the number of bundle replicas (i.e., copies) per bundle in the network to control flooding. This routing protocol assumes two main phases. In the "spray phase", for each bundle originated at a source node, $L$ bundle copies are spread to $L$ distinct nodes. If the destination node is not found during the "spray phase", then at the "wait phase" direct transmission is performed. Hence, it waits until one of the $L$ relays finds the destination node. Two different spraying schemes are proposed for the "spray phase", namely, *source spray* and *binary spray*. In the *source spray* scheme, the source node starts with $L$ bundle copies. Each time the source node encounters a new node, it hands one of the $L$ copies, and reduces its number of copies left by one. In the *binary spray* scheme, the source node also starts with $L$ bundle copies. But, whenever a node with $L > 1$ copies encounters a new node, it hands half of the copies that it stores in its buffer. For both spraying schemes, when a node carries only a single copy of the bundle, it only forwards it to the final destination (i.e., "wait phase").

PRoPHET [28] considers that network nodes move in a non-random pattern and applies the concept of "probabilistic routing". This protocol uses the history of node encounters and transitivity information, to calculate a probabilistic metric called delivery predictability. This metric is calculated in all network nodes for each known destination and it is used to decide whether or not to forward bundles at communication opportunities. When a contact opportunity occurs, the involved nodes exchange their delivery predictability information. The nodes use this information to update their estimated delivery predictability information. Then, based on this information and on the destination of the bundles, a bundle is transferred to the other node if the delivery predictability of the destination of the bundle is higher at the other node.

### 3.2. Incorporating geographic information into routing decisions in VDTNs

Geographic routing relies mainly on location information and other mobility parameters provided by positioning devices such as global positioning systems (GPSs) [41]. In this class of routing protocols, routing decisions are made with the goal that each step

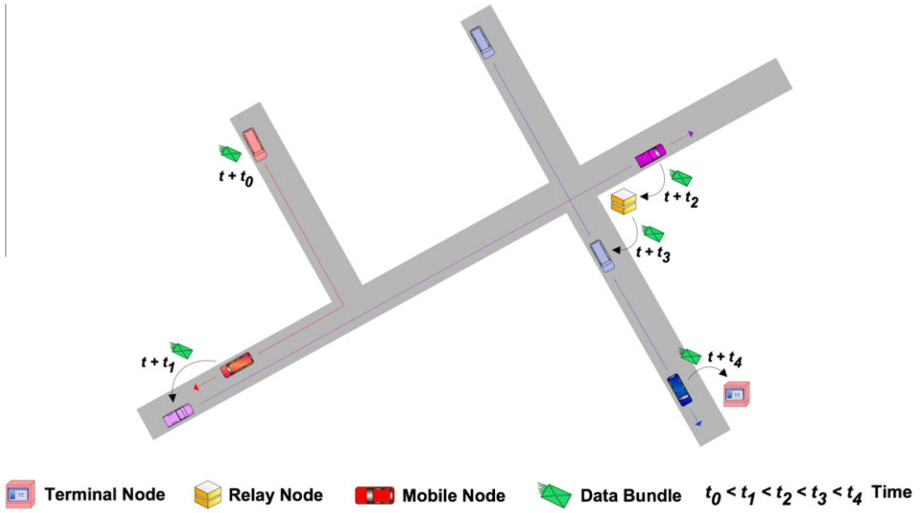

**Fig. 3.** Store-carry-and-forward paradigm of DTN-based networks.

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reduces the geographic distance to the destination node(s). Hence, it is assumed that nodes know their geographical location and the geographical location of the destination node(s).

The increasing availability of vehicle navigation systems (NSs) has sparkled the development of geographic routing approaches to vehicular networks. A NS features location hardware (typically a GPS), a roadmap database containing several information, such as, maximum pre-defined speed limit and average speed, and a shortest path algorithm. With this plethora of information it is possible to estimate the arrival time to a specific location (namely, to a given destination node).

Although several geographic routing protocols have been proposed for vehicular communications, the majority of proposed approaches cannot be applied to sparse (low node density) scenarios. For example, the position-based routing strategies for VANETs presented in [42–44], are not able to deal with intermittency, disruption or frequent network partitions that can last for a long period of time. On the contrary, Geographical Opportunistic Routing (GeOpps) [29] is an example of a routing protocol that follows the store-carry-and-forward paradigm to cope with these issues. Therefore, it can be applied on VDTNs.

GeOpps is a forwarding routing protocol that maintains a single-copy of each bundle in the network, and its routing decisions are made as follows. A vehicle moving along a suggested route (determined in function of its destination) uses its navigation system to determine the nearest point (*NP*) on its route to a location (*D*) where a data bundle must be delivered. Then, the navigation system is used to estimate the time of arrival (ETA) of the vehicle to the *NP*, and to determine the ETA needed to go from *NP* to *D*. The sum of these values is called the minimum estimated time of delivery (METD) as shown in Eq. (1), and it is used as an utility function to make routing decisions.

$$\mathrm{METD} = \mathrm{ETA\ to}\ NP + \mathrm{ETA\ from}\ NP\ \mathrm{to}\ D \tag{1}$$

Upon an encounter, moving vehicles only forward a bundle if the METD required by the encountered vehicle to deliver the bundle is lower than the METD of the vehicle that currently carries the bundle. This would mean that the encountered vehicle is likely to move closer and/or faster to the bundle's destination. This process is repeated until the bundle reaches its destination or its time-to-live expires.

Fig. 4 shows an example where a vehicle $X$, which is carrying a bundle to be delivered to $D$, meets a vehicle $Y$ at location $P_1$. The $NP$ calculation for $X$ and $Y$ shows that $Y$'s METD value is lower than $X$'s METD. This happens because the time required to go from $P_1$ to $NP_Y$ and then to $D$ is lower than time required to go from $P_1$ to $NP_X$ and then to $D$. Hence, $X$ forwards the bundle to $Y$. Afterwards, while moving along its route $Y$ may forward the bundle to other encountered vehicle if it is going quicker/closer to $D$.

## 4. GeoSpray routing protocol

This section presents GeoSpray, a new multiple-copy geographic routing protocol designed for VDTNs. The protocol exploits the mobility of vehicles and the location information provided by positioning devices, such as GPS to assist routing, according to a store, carry, and forward paradigm. GeoSpray is intended to be used on sparse vehicular scenarios where communication opportunities are based on sporadic and intermittent contacts, frequent link disconnections and reconnections occur, and the probability of forming a contemporaneous multi-hop path between the source and the destination is negligible. Next subsection describes the operation details of GeoSpray protocol. The protocol design and its pseudo-code are presented in the last subsection.

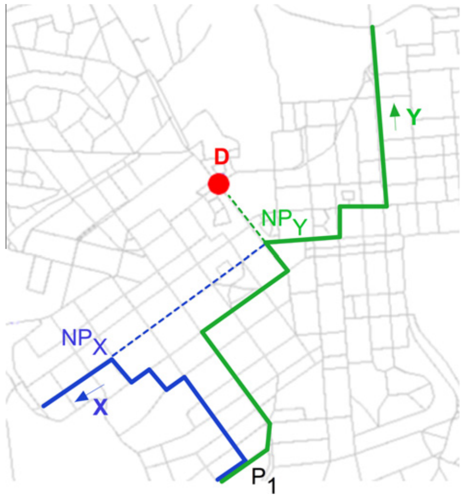

**Fig. 4.** Example of GeOpps calculation of the nearest point (*NP*) from bundle's destination (*D*), for vehicles *X* and *Y*.

### 4.1. Protocol operation

The GeoSpray routing protocol assumes that VDTN network nodes are aware of their location (geographical position) that is provided by a positioning device like a GPS navigation system. This system includes a GPS device, a map, and it is able to calculate the route, distance, and time between two map points. It also assumes that the location of terminal nodes (traffic sinks) is previously known, and that mobile nodes know their speed, and current route. It is important to notice that data bundles replicated or forwarded following the routing decisions of GeoSpray represent aggregates of datagrams that are destined for the same terminal node (traffic sink).

GeoSpray is inspired in the general guidelines of GeOpps geographic forwarding routing protocol [29] described in the previous section. It uses geographic position information and other mobility parameters, together with bundle destination addresses, making sure that bundles are forwarded towards the destination. However, contrary to GeOpps that maintains at most one copy of a bundle in the network, GeoSpray combines selected replication and forwarding with explicit delivery acknowledgment.

The GeoSpray routing protocol employs the concept of "spray phase" from binary Spray and Wait [27], where a small/fixed number of bundle copies are distributed to distinct nodes in the network. However, instead of doing blind replication (as proposed in Spray and Wait), GeoSpray guarantees that bundle copies are only spread to network nodes that go closer (and/or arrive sooner) to the bundle's destination. Furthermore, instead of waiting until one of these network nodes meets the destination and delivers its bundle copy (as proposed in the Spray and Wait "wait phase"), GeoSpray 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).

GeoSpray provides robustness by allowing a limited number of copies of the same bundle to be routed independently. The protocol controls flooding by setting an upper bound on the number of copies created per bundle, while minimizes the transmission overload and resource consumption. Furthermore, GeoSpray uses the concept of active receipts presented in [45] to explicitly clear delivered bundles. Network nodes send receipts to inform all the nodes they meet about bundles that have already been delivered. These bundles, which are buffered at intermediate nodes, are removed and storage capacity for upcoming bundles is improved. This is a very important feature because network nodes have limited

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storage capabilities. Moreover, it also helps to stop replicating/forwarding already delivered bundles thus also saving bandwidth resources.

Fig. 5 illustrates the operations performed by GeoSpray when any two nodes meet each other in the network. Note that operations are mirrored between both nodes. As expected, routing information exchanged at the control plane is used in conjunction with other signaling information for resource allocation at the data plane level. More data plane resources (e.g., storage and bandwidth) are allocated to bundles that will be carried more close to their destination and that have been less replicated.

As a conclusion, GeoSpray fuses several control data sources to perform routing decisions. Fig. 6 shows the fusion scheme, with the different data sources above-explained. The source control data "minimum estimated time of delivery" may combine information about vehicles routes with their average speed to compute a utility function that puts emphasis on distance or delay [29]. As a result, "greater quality" information for this routing metric is obtained. Furthermore, source control data, such as "location information", can be the result of information fusion, as may be seen in [46]. It elaborates on how information provided by a number of localization techniques (e.g., GPS, map matching, dead reckoning, cellular localization, image/video processing, localization services, and relative distributed ad hoc localization) can be combined to compute a more accurate position for vehicles.

The "Geospray routing algorithm" block works combining information from several data sources to perform the appropriate routing decisions. Further details about data-fusion can be found in [34].

### 4.2. Protocol design

The GeoSpray protocol operation described in the previous subsection is presented in Fig. 7, in the form of a pseudo-code that describes the sequence of steps executed at a node *X* when a new contact opportunity is detected with node *Y*. The protocol is symmetric. Hence, *Y* executes the same sequence of steps. As expected, these steps involve the interaction between the control plane and the data plane.

In the first step, *X* sends to *Y* a list containing information about the bundles that it knows that have been delivered in the network. This information includes the identification, source and destination addresses, and a hash of the content of each known delivered bundle, among others. Based on the same type of information received from *Y*, *X* deletes any bundles stored on its buffer that *Y* announces as delivered. Then, *X* updates its list of delivered bundles with the information received from *Y* in order to notify other nodes at future contact opportunities.

The second step executed on *X* consists in checking if *Y* is the final destination for any of the bundles stored in *X's* buffer. If it happens, these bundles are scheduled for being transmitted first to *Y*, followed by the remaining bundles sent in an order determined by the execution of the next steps. As expected, bundles whose final destination is *Y* after being delivered are removed from *X's* buffer and are added to *X's* list of delivered bundles.

The third step involves the determination of the best carrier for each bundle stored in *X* and *Y*. *X* sends a list to *Y* containing information about the bundles that it stores. This information includes

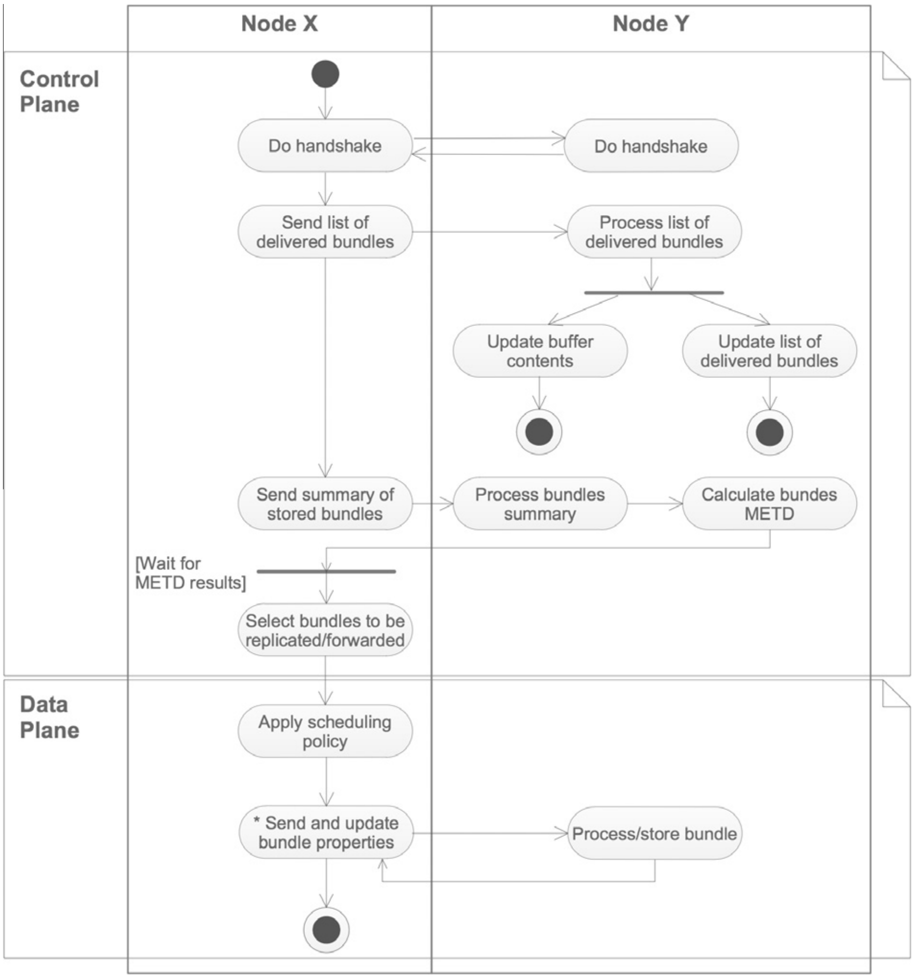

**Fig. 5.** UML activity diagram describing the sequence of main actions executed in GeoSpray when two nodes exchange data among them.

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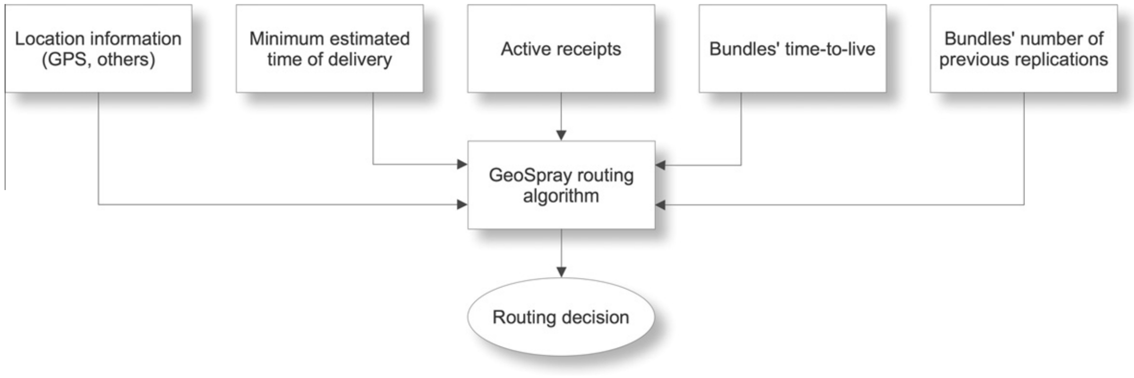

**Fig. 6.** Routing control data-fusion model for GeoSpray.

```
Protocol GeoSpray (X,Y)

1. Explicitly clear delivered bundles:
    • Send to Y information about the X's list of known delivered bundles.
    • Receive information from Y about its list of known delivered bundles.
    • For each bundle i stored in X's buffer
        o If i is in Y's list of known delivered bundles, delete i.
    • Update X's list of known delivered bundles, by merging X and Y information.

2. Delivery to final recipient:
    • For each bundle i stored in X's buffer and destined to Y
        o X delivers i to Y, and deletes i from its buffer.
        o X adds i to its list of known delivered bundles.

3. Carrier choice:
    • Send information to Y about the bundles stored in X's buffer.
    • Receive information from Y about the bundles stored in its buffer
        o For each bundle i stored in Y's buffer
            ▪ If i is already in X's buffer, ignore i.
            ▪ Else
                • Calculate the METD required by X to deliver i to its
                  destination.
                • Include this information in i.

    • Send information to Y about X's METD for Y's bundles.
    • Receive information from Y about its METD for X's bundles.

4. Replication/forwarding decisions:
    • For each bundle i in X's buffer
        o If i is already in Y's buffer, ignore i.
        o Else if X's i METD > Y's i METD
            ▪ If the remaining number of copies (L) of i > 1
                • X hands over to Y L/2 copies of i.
            ▪ Else
                • X forwards i to Y, and deletes i from its buffer.

5. Schedule bundles for transmission:
    • Bundles selected to be replicated/forwarded to Y are arranged in ascending
      order of their METD (METD ASC). The tiebreaker rules are: (1) smaller number
      of replications (RC ASC), (2) longer remaining TTL (RL DESC).
```

**Fig. 7.** GeoSpray protocol pseudo-code.

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the identification, source and destination addresses, size, TTL, number of copies (L), hash of the content, and *X's* minimum estimated time of delivery (METD) of each bundle, among others. METD is a concept introduced by GeOpps, which was described in the previous section and it is calculated as proposed in [29]. Based on the same type of information received from *Y*, *X* calculates the METD that it requires to deliver each bundle stored by *Y* that they do not have in common. This information is sent to *Y*. *X* also receives from *Y* its calculation of the METD for *X*'s bundles.

In the fourth step, *Y's* calculation of the METD for *X's* bundles is used at *X* to decide which bundles should be sent to node *Y*. *X* only replicates/forwards the bundles for which *Y* will be closer to their destination or sooner in time (i.e., the *Y*'s METD value for these bundles is lower than *X*'s METD). A bundle selected for being transmitted to node *Y* is (i) replicated if *X* carries more than one copy of that bundle, thus handing half of the remaining copies to *Y* or (ii) forwarded to *Y* and removed from *X's* buffer (because *X* carries only one copy left of that bundle). It is assumed that each bundle has a header field indicating the "number of copies" it represents. As expected, the bundle is not replicated within *X's* buffer.

The fifth and final step is required because of the restricted amount of data that can be transferred in a contact opportunity. Due to short contact durations and limited bandwidth, it may not be possible to transfer all the bundles stored in *X* that node *Y* can carry closer to their destination or deliver earlier. Therefore, there is the need for scheduling data bundles for transmission based on their *METD*, *L*, and *TTL* header field parameters, as shown in Fig. 8. As expected, data bundles that have the lowest METD are the first to be transmitted (METD ASC). When two bundles have the same METD value, the tie is broken by first scheduling the bundle that has been less replicated (RC ASC). A secondary tiebreak criterion is applied for bundles that have the same METD and have been replicated the same number of times. In such cases, bundles with longer remaining TTLs are scheduled to be sent first (RL DESC). In a previous work [47], it was shown that the combination of RC ASC and RL DESC scheduling policies improves the network performance in terms of delivery probability and average delivery delay.

## 5. Performance evaluation

This section analyses the performance assessment of the proposed GeoSpray routing protocol in comparison with above-described routing schemes: Epidemic, Spray and Wait, PRoPHET, and GeOpps. The simulation experiments use a modified version of the Opportunistic Network Environment (ONE) simulator [48], called VDTNsim [49]. VDTNsim supports the VDTN layered architecture model proposed in [20]. In the context of this work, additional modules were introduced to VDTNsim in order to support the simulation of GeoSpray and GeOpps routing protocols. Next subsections describe the simulation scenario, the performance metrics considered in this study, and the corresponding results analysis.

### *5.1. Simulation setup*

The simulation scenario is based on the map-based model of a part of the city of Helsinki presented in Fig. 9. It assumes a fully cooperative opportunistic environment without knowledge of the traffic matrix and contact opportunities.

Ten terminal nodes are placed at the map positions presented in Fig. 9. During the simulated 6 h period of time (e.g., from 8:00 to 14:00), 100 mobile nodes (e.g., vehicles) move on the map roads with an average speed of 50 km/h, between random locations, and with random pause times between 5 and 15 min. Each mobile node has a 25 megabytes buffer. To increase the number of contact opportunities, five stationary relay nodes were placed at the road intersections shown in Fig. 9. Each stationary relay node has a 100 megabytes buffer.

Data bundles are originated at random mobile nodes (i.e., the *traffic sources*) and are destined to random terminal nodes (i.e., the *traffic sinks*). To generate data bundles with different sizes (representing traffic created by three different VDTN applications), three event generators are considered. Each one generates bundles with sizes uniformly distributed in the ranges of [25 KB, 100 KB], [250 KB, 500 KB], and [750 KB, 1 MB] (Bytes) respectively. All event generators assume an inter-bundle creation interval time in a range (uniformly distributed) of [25,35] seconds.

Data bundles time-to-live (TTL) changes between 60, 90, 120, 150, and 180 min, across the simulations. TTL is a timeout value that expresses the amount of time that bundles should remain in a node's buffer before being discarded, since they are no longer meaningful. Increasing the TTL will lead to have more bundles stored at the network nodes' buffers during larger periods of time. Therefore, more bundles can be exchanged between network nodes and this will potentially increase contention for network resources (e.g., bandwidth, buffer space). All network nodes use a data plane link connection with a transmission data rate of 4.5 Mbps and an omni-directional transmission range of 30 m, as considered in [50].

Epidemic, Spray and Wait, PRoPHET, GeOpps, and GeoSpray are applied as underlying routing schemes and their performance is evaluated for each simulation scenario. In all simulation scenarios, the configuration of PRoPHET protocol parameters is set according to the values proposed in [28] (i.e., *P_encounter* 0.75, *beta* 0.25, and *gamma* 0.999), and a GRTRMax [28] forwarding strategy is considered. Both Spray and Wait and GeoSpray use a *binary spraying* scheme that minimizes the spraying time [27,51]. Regarding the *number of copies* parameter (*L*), [27] provides information on how to choose this value for Spray and Wait to achieve a required expected delay, or when network parameters are unknown. Since this study assumes that the total number of network nodes is known, then based on the conclusions presented in [51], *L* value was chosen equal to 15% of the mobile nodes available in the simulation scenario. Hence, for both Spray and Wait and GeoSpray, *L* has been set to 15, since the scenario has 100 vehicles.

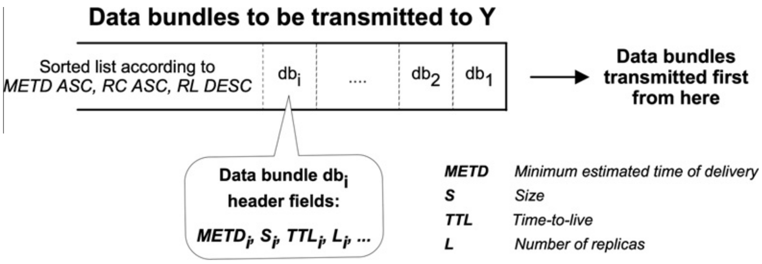

**Fig. 8.** Position of data bundle *i* in a queue of data bundles to be transmitted from the node *X* to the node *Y*.

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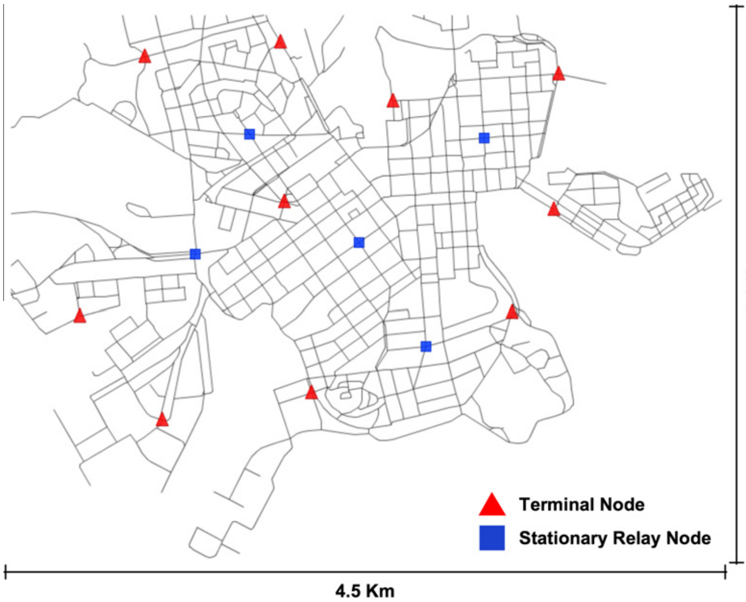

**Fig. 9.** Simulation scenario: Helsinki downtown (area of 4500 × 3400 m), with the locations of the terminal nodes and the stationary relay nodes.

### 5.2. Performance metrics

Routing protocols are commonly evaluated according to the main performance metrics delivery probability (i.e., successful delivery) and average delivery delay. However, for better understanding of the network resources utilization, it is also important to study the behavior of the routing protocols on the basis of performance metrics such as the number of initiated bundles transmissions, the number of dropped bundles, and the overhead ratio. These performance metrics are defined as follows. The one-way overall delivery probability is measured as the relation between the number of unique delivered bundles and the number of bundles sent. The average delivery delay is measured as the time between bundles creation and delivery. The number of initiated bundles transmissions corresponds to the number of started transmissions between network nodes. Notice that one bundle can cause multiple transmissions due to its possible replication. The number of dropped bundles reports the number of bundles that have been discarded from the nodes' buffers due to buffer overflow. Finally, the overhead ratio is a measure of the bandwidth efficiency of the routing protocol. It measures how many "extra" bundle transfers were needed for each bundle delivery.

In order to get representative and meaningful results, each simulation scenario was executed 30 times using different random seeds. The results presented for each performance metric represent the average values calculated from the obtained results. Only average values are represented in the graphs, as the standard deviations were negligible.

### 5.3. Performance Analysis

The performance analysis starts with the behavior evaluation of the routing protocols in respect to the number of initiated bundles transmissions. As expected, Fig. 10 shows that Epidemic registers the largest number of initiated bundles transmissions across all simulations. This is caused by its flooding approach that simply replicates bundles at contact opportunities. Furthermore, it is aggravated when bundles have larger TTLs because nodes store bundles during larger periods of time that will be replicated even more. On the contrary, due to its single-copy routing approach GeOpps registers the lowest number of initiated transmissions, and is not significantly affected by increasing the bundles TTL.

Although the proposed protocol (GeoSpray) is inspired on the Spray and Wait replication strategy it initiates more transmissions than Spray and Wait. Nevertheless, this behavior was expected because after replicating the bundle copies using geographic routing decisions, GeoSpray allows nodes that carry bundles to further forward them to other nodes that move closer or arrive sooner to the bundles destinations. On the contrary, in Spray and Wait routing, after the "spray phase" nodes only forward bundles to their destination (i.e., performing direct delivery). Both GeoSpray and Spray and Wait are not significantly affected by increasing the bundles TTL across the simulations. Finally, as it can be concluded from the analysis of this figure, PRoPHET's operating principle limits flooding using the history information of node encounters and transitivity.

In respect to the number of bundles dropped, Fig. 11 shows that Epidemic flooding results in severe buffer overflow and consequent high bundle drop rate. This Fig. also allows concluding that buffer sizes considered in the simulation scenario were large enough for GeOpps single-copy approach that did not drop any bundle. A very interesting conclusion that can be drawn from the analysis of Figs. 10 and 11, is that although GeoSpray initiates more transmissions, it presents much lower bundle drop rates than Spray and Wait, across all simulations. This is caused by GeoSpray's module that is responsible for explicitly clearing delivered bundles across network nodes. For bundles with TTLs lower than 180 min, PRoPHET presented lower numbers of drops compared to Spray and Wait.

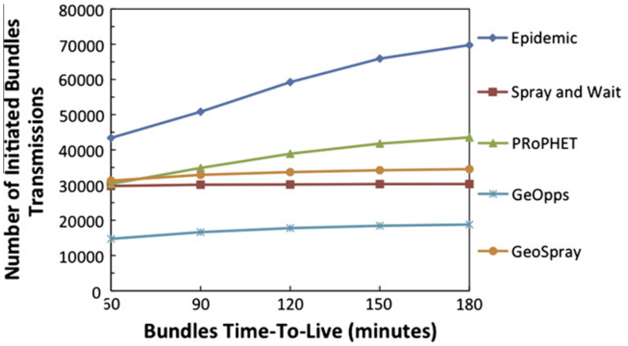

**Fig. 10.** Number of initiated bundles transmissions as function of bundles TTL for Epidemic, Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

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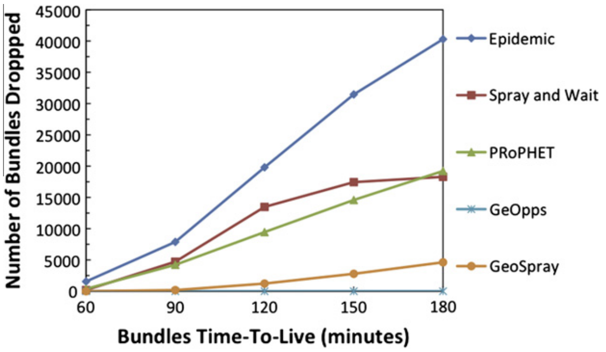

**Fig. 11.** Number of bundles dropped as function of bundles TTL for Epidemic, Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

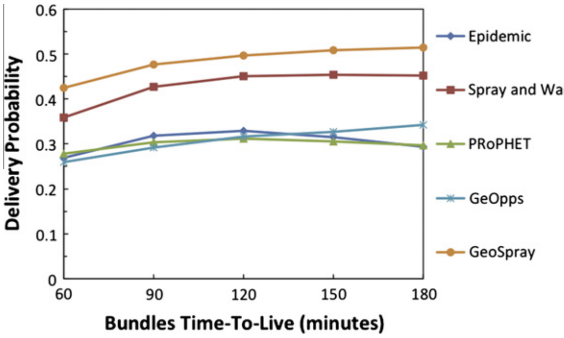

**Fig. 12.** Bundle delivery probability as function of bundles TTL for Epidemic, Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

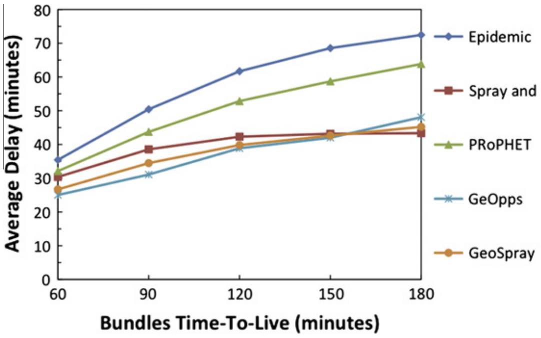

**Fig. 13.** Bundle average delay as function of bundles TTL for Epidemic, Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

Now, the study focuses on comparing the delivery probability and the average delivery delay. As mentioned above, one of the main problems of single-copy routing schemes is that they suffer from low delivery ratios. This is demonstrated in Fig. 12. Although GeOpps uses geographic location information to make intelligent forwarding decisions, it registers much lower delivery ratios than the less complex multiple-copy routing strategy of Spray and Wait.

GeoSpray protocol, with its hybrid approach between GeOpps and Spray and Wait (combining the best of these two protocols), registers higher delivery ratios than any other routing protocol considered in the context of this work. When compared to GeOpps, GeoSpray increases approximately 18% the bundle delivery probability for each considered value of bundles TTL. This difference in the delivery ratio would be increased further in scenarios with larger areas and with lower node densities. It is also important to notice that GeoSpray multiple-copy geographic routing also outperforms PRoPHET routing strategy based on node encounter information. PRoPHET is also outperformed by GeOpps when bundles have a TTL superior to 120 min.

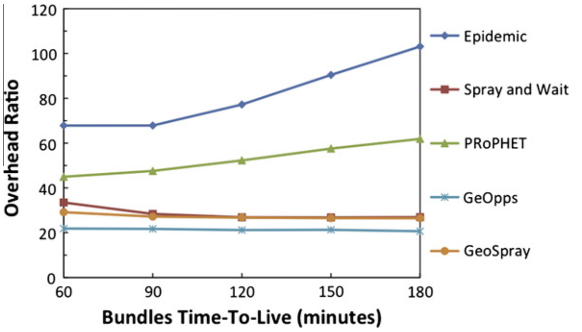

**Fig. 14.** Overhead ratio as function of bundles TTL for Epidemic, Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

The combined analysis of Figs. 12 and 13 reveals that, in addition to increase the bundle delivery probability, GeoSpray offers average delivery delays similar to those observed in GeOpps. Fig. 13 also shows that Epidemic and PRoPHET routing protocols provide the longest average delays across all simulations.

The last performance metric for the evaluation of the proposed routing protocol for VDTNs is the overhead ratio. This metric represents the bandwidth efficiency of the routing protocols, since it measures how many bundle transfers were needed for each bundle delivery. Fig. 14 shows that GeOpps has the lowest overhead ratio among all the compared routing protocols. This was expected since GeOpps uses a single-copy (i.e., forwarding strategy) that maintains at most a single copy of each bundle in the network. Both Epidemic and PRoPHET variants of flooding register the largest overhead ratios, but Epidemic naturally presents the worst performance. GeoSpray registered only a slightly larger overhead ratio than GeOpps. This was caused by its strict limit on the maximum number of bundle replicas, inspired on Spray and Wait.

## 6. Conclusions and future work

This paper proposed a multiple-copy geographic routing protocol for vehicular delay-tolerant networks (VDTNs), called GeoSpray. VDTNs are characterized by the lack of an end-to-end contemporaneous multi-hop path, which is caused by a highly dynamic network topology, sporadic and intermittent contacts, and network partitioning due to low node density and large distances.

GeoSpray enables routing in such challenged scenarios by combining a store-carry-and-forward paradigm with routing/forwarding decisions based on geographical location information provided by positioning devices. GeoSpray presents a hybrid approach between multiple-copy and single-copy routing schemes. First, it starts with a multiple-copy scheme, which spreads a limited number of bundle copies in order to exploit alternative paths. Then, it switches to a forwarding (single-copy) scheme, which takes advantage of additional opportunities to improve delivery success and reduce delivery delay. In order to further improve resources utilization, the protocol applies the concept of active receipts to clear delivered bundles across the network nodes.

The performance evaluation of the proposed GeoSpray protocol was achieved in comparison with other geographic location-based single-copy and non location-based multiple-copy routing protocols. The following performance metrics were considered: delivery probability, average delivery delay, number of initiated bundles transmissions, number of dropped bundles, and overhead ratio. It was shown that the proposed GeoSpray routing protocol improves

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the delivery probability and reduces the delivery delay, comparing with the other single-copy and multiple-copy routing schemes under study. Furthermore, it presents a lower rate of dropped bundles and a lower overhead ratio compared to the other evaluated popular multiple-copy routing protocols.

As for the future work, experiments on GeoSpray protocol will be conducted in a laboratory testbed for VDTNs, called VDTN@Lab, which is presented in [52]. This will allow evaluating the protocol's performance in a more realistic environment, although at a smaller scale than the one provided by this simulation study. Further studies using realistic vehicular traces from different scenarios (e.g., urban or rural connectivity) with different node densities can also be performed to evaluate GeoSpray's feasibility and limitations as well as a scalability analysis.

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