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Survey paper

# Performance evaluation and comparative study of main VDTN routing protocols under small- and large-scale scenarios

Arslane Hamza-Cherif[a,*], Khaled Boussetta[b,c], Gladys Diaz[b], Fedoua Lahfa[a]

[a] Department Computer sciences, University of Tlemcen, Tlemcen, Algeria
[b] L2TI, Institut Galilée, Université Paris 13, Sorbonne Paris Cité, France
[c] Agora, INRIA, Lyon, France

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ABSTRACT

This paper presents a performance evaluation through simulations and a comparative study of main routing protocols dedicated to Vehicular Delay-Tolerant Networks. The assessment is conducted under small- and large-scale scenarios with realistic vehicle mobility patterns as defined in the TAPAS Cologne simulation scenario. Through the literature, several evaluations have been conducted on routing for Vehicular Networks, but with an abstraction or a simplification regarding the delay tolerant aspect. Furthermore, considered scenarios were relatively small and too idealistic compared to the real-world environment and its multiples challenges. Moreover, to the best of our knowledge, this is the first extensive study that compares, in the same realistic simulation environment, the main flag-carriers of various categories of VDTN routing protocols, namely Epidemic, Direct Delivery, Prophet and GeoSpray protocols. Simulation results reveal better performance for the geographical approach advocated by GeoSpray compared to the predictive one of Prophet, under all considered scenarios. Moreover, they highlight the possibility for a minimalist and naive protocol such as Direct Delivery to perform well, under specific network conditions, as when considering an anycast communication scheme. Finally, deeper analysis was undertaken on both GeoSpray and Prophet. The studies reveal the potentialities to increase the performances of GeoSpray to some extent and highlight the difficulties of adapting Prophet settings for optimal performance in realistic scenarios.



## 1. Introduction

### 1.1. Context

The rapid population growth and the large expanse of urban areas have led to real-life transportation problems like accidents and traffic jams, which by a domino effect, have resulted in economic and ecologic concerns, namely: a notable increase in goods delivery delays, a waste of precious resources, especially oil, and a rise in pollution. In fact, the World Health Organization (WHO) reported in [1] that more than 1.2 million people die each year due to road injuries, making it the first cause of death among people aged between 15 and 29 years. In the meantime, the Texas Transportation Institute has estimated the cost of congestion to be up to 160 billion dollars with 6.9 billion hours lost and 11.7 billion litres of oil wasted in 471 major urban areas of the United-States in 2014 alone [2].

In order to tackle these problems, researchers proposed a Traffic Information System (TIS) that specifically addresses traffic jams thanks to notification systems based on GPS-capable equipment. Despite the use of TIS which provides directional guidance, the lack of cooperation between vehicles, the limited application scope of TIS along with the development of affordable information technology nowadays, such as cellular networks and Wi-Fi, foster the emergence of enhanced and augmented TIS, called Intelligent Transportation Systems (ITS). These differ ostensibly from their predecessors. Firstly, their application scope is threefold: road safety, road traffic information and any third-party application with multimedia content. Secondly, unlike TIS, they make use of global and on-board sensors to gather information on the state of road traffic. They also introduce the concept of Inter-Vehicle Communication (IVC) which involves a wide range of technology and standards dedicated to communication from a car to any other entity in the network (C2X), like Dedicated Short Range Communication (DSRC) [3] and IEEE 802.11p Wi-Fi standard [4,5]. With IVC,

* Corresponding author.
*E-mail addresses:* arslane.hamzacherif@gmail.com (A. Hamza-Cherif), khaled.boussetta@univ-paris13.fr (K. Boussetta), gladys.diaz@univ-paris13.fr (G. Diaz), f_didi@mail.univ-tlemcen.dz (F. Lahfa).

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vehicles play an active role in gathering information, cooperating with other vehicles and finally reporting information to the main system [6].

In this global context, networks constituted by vehicles, commonly named Vehicular Networks or Vehicular Ad-hoc Networks (VANETs) have emerged as a hot research topic with the goal of providing the ITS applications cited before to road network users. However, running such applications over VANETs is a challenging task because routing protocols must overcome relevant problems that arise from vehicular environments. Indeed, the high mobility and speed of vehicles engender a very dynamic network topology with short contact durations, whereas urban environments limit transmission ranges due to physical obstacles and radio interference. Therefore, in a realistic VANET context, it is often hard to establish and maintain an end-to-end path between the sender and the recipient due to network issues like topology partitioning and intermittent connectivity. This severely limits the potential use of the conventional routing approach based on the TCP/IP protocol suite. Consequently, and to overcome these problems, VANETs are extended using main Delay-Tolerant Networks (DTNs) principles, leading to the advent of two categories of vehicular networks. The first ones, conventionally called VANETs, are delay-sensitive and operate only when full connectivity exists to support the end-to-end semantics of existing transport and application network layers. Thus they are strongly adapted to road safety applications where data must be delivered on-time. The latter ones are Vehicular Delay Tolerant Networks (VDTNs)[7], characterised by a good resilience to delay and to network disconnections, thanks to the Store, Carry and Forward (SCF) concept inherited from DTNs, which allows a forwarder to carry messages until it finds a suitable relay. Therefore, VDTNs can support applications with intermittent connectivity, such as road traffic information, or third-party services that range from emails, web access or any time unconstrained applications like multimedia content download or geographic services discovery. This work addresses the VDTN category with a focus on routing protocols that can support road traffic information and the kind of application operating with intermittent connectivity.

### 1.2. Motivations

Many VDTN routing protocols are proposed in the literature following various forwarding approaches and replication strategies which differ ostensibly regarding the information needed to make the forwarding decision. Nevertheless, in practice, there are still few operational use cases and almost no wide-ranging implementations. In fact, whilst modelling VDTNs and studying their topology & behaviour can be achieved through theoretical approaches like temporal networks, to extract key facts which are able to provide general guidance for researchers, the evaluation of routing protocols dedicated to VDTNs requires a more concrete and straightforward approach, by relying, for instance, on real world experimentation or on realistic and sufficient large-scale testbeds. However, since these experiments are difficult to conduct and existing testbeds are not largely accessible to the research community for large-scale evaluation, computer simulations remain the main tool for large-scale assessment of VDTN routing protocols, especially when multiple simulators and tools exist and are widely available. Regarding the investigated protocols, in many cases, they are envisioned to provide data routing for a specific range of applications/services. Therefore, their evaluation scenarios are limited to the targeted use cases. It is then difficult to extend and reproduce the obtained results to other scenarios, protocols, and applications. In some cases, a simplification of the simulation scenario is introduced with the aim of reducing the processing time, which can be prohibitive when simulating realistic VDTN environments. While such an approach can help to quickly allow observation of general trends in the performance of some protocols, the obtained results have limited and contextual validation, since the evaluation context is not reflective of the characteristics of a realistic vehicular environment.

In [8], the authors identify three key aspects that are essential to ensure the validity, the compatibility and the reproducibility of the assessment through simulations of VDTN routing protocols. The first one is related to the considered network simulation tool. For instance, some simulation frameworks focus mainly on the behaviour of the routing protocol, at the networking layer, and make a partial or total abstraction of other components in the communication stack, the underlying transmission conditions and application traffic patterns. Such approaches are useful for understanding the behaviour of a VDTN routing protocol in an isolated manner but are far from being realistic and cannot be considered to offer a valid overall evaluation. The second and third aspects are related to the specificities of the vehicular environment: namely, the considered vehicles mobility model and the road topology. Indeed, these two aspects have an important impact on the routing protocol performances because they dictate the dynamics of Vehicle-To-Vehicle (V2V) communication. Consequently, in order to avoid overestimating the performances of VDTN routing protocols, the researchers are invited to use realistic road topologies and detailed representations of the vehicular traffic both at microscopic level (individual vehicle physical characteristics and behaviour) as well as macroscopic level (flow patterns based on diurnal cycles, population synthesis and activities). These last two points can be satisfied with real vehicle mobility traces and road topology extracted from real street maps [9].

Another important practical issue that arises when evaluating VDTN routing protocols is related to the availability of implementation codes of these protocols in the same simulation environment. While several VDTN routing protocols were evaluated in different simulation frameworks, each having its own degree of realism and parameter setting, only a limited number of implementation codes are publicly available. Moreover, most of the implementations are dedicated to different simulators. Thus, an important gap that must be addressed is the availability of DTN routing protocol implementations in a common simulation environment.

### 1.3. Contributions

Through this work, we aim to contribute to the research on VDTN routing protocols by presenting a performance evaluation and a quantitative comparison of main VDTN routing protocols, based on the joint use of realistic simulators/tools and vehicle mobility datasets. To the best of our knowledge, this is the first extensive study that compares, in the same realistic simulation environment, the main flag-carriers of various categories of VDTN routing protocols, namely Epidemic, Direct Delivery, Prophet and GeoSpray protocols. We analyse the obtained results under different simulation scenarios, ranging from small-scale topologies to a realistic large-scale scenario defined in the TAPAS Cologne simulation scenario. We discuss the sensitivity of the results for the considered small-scale vs large-scale scenarios and we extract some key facts and recommendations that can guide future work in order to improve the performance of current VDTN protocols.

The rest of this paper is organised as follows. Taxonomy of VDTN routing protocols and the state of the art on their performance evaluations are presented under Sections 2 and 3, respectively. In Section 4, we describe in detail four VDTN protocols that we selected as representative of proposed forwarding strategies and metrics, replication policies, etc, namely Epidemic [10], Direct-Delivery [11], Prophet protocol [12,13] and GeoSpray [14]. Then, in Section 5, we discuss various criteria for choosing an adapted simulation tool and we justify our choice for Omnet++ [15] and the vehicular simulation framework Veins [16] from among the plethora of available network simulators. We then describe the architectural design, which forms the basis of our common implementation of the four above-mentioned protocols in the same Omnet++/Veins simulation framework. In Section 6, a performance evaluation of the considered protocols is conducted under a synthetic small-scale scenario as well as under a large-scale scenario provided by the TAPAS-Cologne dataset [9]. We provide a deep analysis of the observed performances of each protocol with respect to different metrics (Delivery Ratio, Overhead, Average Delay and Hop Counts) and discuss the sensitivity of the observations for the considered simulation settings (e.g. small-scale vs. large-scale topologies). After comparing the different protocols, we focus on GeoSpray to reveal the potentiality to increase its performance. Finally, we conclude this paper in Section 7 by summarising some key facts and observations that arise from this study.

## 2. VDTNs routing protocols

### *2.1. From VANETs and DTNs to VDTNs*

As stated before, VDTNs are derived from VANETs and DTNs and as a consequence, understanding the former must be preceded by a good comprehension of their historical background. The following section provides a step-by-step overview of research work about vehicular networking and more specially, VDTNs.

#### *2.1.1. The origin: Vehicular Ad-Hoc Networks*

Early research works in the VANETs context try to apply some well-known Mobile Ad-Hoc Networks (MANETs) routing protocols, like AODV [17] and DSR [18], due to the relative closeness of context application and because a vehicle can be viewed as a simple mobile node. But these protocols failed to perform correctly, because of the frequently changing topology and the expensive topology maintenance costs. So, researchers shifted to the proposal of dedicated VANETs routing protocols like GPSR [19], GPCR [20] and so on. However, their design was still driven by an Internet protocol overview where strong assumptions are made about the network, as it assumes that most of the time, and if a delay is affordable, a route can be found from a given source to a given destination. Consequently, these protocols cannot function if there are long disruptions or their efficiency can significantly deteriorate as delays become longer. Such extreme network conditions are far from being strange to vehicular networking and may occur very often. Therefore, Delay/Disruption tolerant networking appears to be an encouraging approach to address such requirements.

#### *2.1.2. The promising approach: Delay Tolerant Networks*

Initially, the concept of DTNs was designed with a substantial focus on interplanetary networks and the objective of enabling and ensuring communication between satellites, surface rovers and other devices within the Inter Planetary Network (IPN) [21]. However, the elegant solution and multiple advantages offered by DTNs when facing harsh network conditions, like intermittent connections, low bandwidth, high error rates and delays, led researchers to expand the DTN field. It was extended to include regular networks, such as the wireless sensor network (WSN), opportunistic MANETs or opportunistic vehicular networking (the focus of this paper), in parallel with some specific terrestrial networks like disaster networks or those deployed on battlegrounds or in remote/underdeveloped areas, for instance.

Through the Delay-Tolerant Networking Research Group (DTNRG) formed in 2002 and part of the Internet Research Task Force (ITRF), key concepts and principles of DTN have been formalised under the DTN architecture [7], ensuring the Internet or network connectivity to isolated nodes in an opportunistic manner. The following section provides an overview of DTN principles recurrent in the VDTNs context.

1. The Bundle Protocol: standardised in the RFC5050 [22], it defines the basic data transmitted across DTN nodes in the form of messages of varying lengths called bundles, containing all the information needed by the destination for the completion of a transaction in one go, including protocol and authentication data. This is useful since several round trips between nodes may not be feasible at all. The bundle protocol allows the storage of bundles in a permanent manner. It is also responsible for the bundle forward in a hop-by-hop scheme instead of an end-to-end one, whenever a new transmission opportunity appears, which happens when two DTN nodes enter into contact and establish a connection between them. Finally, it is important to note that this protocol does not provide any error detection or correction capabilities and so they must be assumed by upper layers.
2. The Store-Carry and Forward (SCF): this transmission paradigm is the most notable aspect since it contrasts highly with the store and forward operation mode used by Internet routing where incoming packets are stored in the buffer temporarily upon receipt and then forwarded to the next hop. Indeed, SCF allows a DTN node to store a bundle permanently, due to the Bundle protocol, then carry it until resuming the bundle forwarding whenever the carrier node finds a suitable relay/forwarder.
3. The Custody mechanism: by default, a DTN node is responsible for the bundles that it carries until their delivery or transmission to another DTN node. Sometimes, it is interesting for a DTN node to transfer to another node the responsibility for the replication, modification or deletion of its carried bundles. This may happen, for instance, when the current bundle carrier is no longer a suitable forwarder and only one replica of the bundle remains.

#### *2.1.3. The current trend: Vehicular Delay Tolerant Networks*

Recently, and in an attempt to clearly assess the potential benefits of using DTN principles, multiple works have conducted in-depth studies of VANETs, in parallel with a thorough analysis of their topology and its temporal evolution, or their behaviour when introducing a Store-Carry and Forward paradigm. Some of the major works that fall within this context are those in [23,24]. In [23], the authors show that under real conditions, VANETs are partitioned into thousands of small vehicle platoons; thus routing data can be achieved only by taking advantage of the temporal connectivity of VANETs, and by adopting the store-carry & forward paradigm. Moreover, the authors of [24] conclude that the adoption of this paradigm increases the overall network reachability, by a factor of up to 90% in sparse networks, while facilitating the implementation of some features such as the local dissemination of data at road junctions.

These research works fostered the emergence of a hot research topic, namely Vehicular Delay Tolerant Networks, at the crossroads of DTNs and VANETs. These new networks target a class of vehicular applications characterised by delay tolerant and asynchronous data traffic. At the time of decision-making, these applications can tolerate some data loss and do not need end-to-end connectivity. Instead, they may continue to operate efficiently by relying on DTN principles. In this context, researchers noticed that VDTNs share some unique characteristics inherited from DTNs and VANETs which should be taken into account when designing protocols for them. Authors in [25] summarised these unique characteristics as follows:

1. Vehicular applications: VDTNs are far from being suited for all vehicular applications since some of them may have some hard delay constraints like crash awareness and emergency braking, for which DTN concepts are not optimal or not applicable at all. Aside from previous applications, VDTNs can support various other ones that do not have such stringent requirements like road traffic information or third-party application, which may range from Internet connectivity and multimedia contents to non-real-time services such as file transfer, email application or more unexpectedly, applications for localising parking lots and repair garages.
2. High mobility and frequent disruptions: high speed and mobility of vehicles induce a very quick changing topology whereby the relatively short contact duration and limited communication range of IVC result in frequent disruption. To put that in perspective, the contact duration between two vehicles on opposite sides of a highway, moving towards each other at a speed of 100 km/h, with a maximum range of up to 100 m is less than 3.6 s. Therefore, VDTNs have to take advantage of this opportunity before the disconnection occurs. Readers should note also that vehicles may evolve in dense as well as sparse traffic regions, thus ideal VDTN routing protocols must perform correctly in both conditions.
3. Geographical awareness & Mobility predictions: a growing trend in modern transportation is the use of embedded GPS devices, a trend that is also fostered with GPS capable smartphones. As a consequence, the current location of vehicles can be easily determined. Furthermore, the future trajectory can be predicted given the speed or the fixed trajectories as it is for buses and public transportation. Finally, VDTNs can exploit these mobility patterns for message delivery by taking the optimal decisions. This characteristic facilitates the development of applications dedicated to the dissemination of information within a specific region, following a geocast communication scheme.
4. Storage and computation capabilities: in contrast with other DTN environments, VDTNs do not suffer from storage, computation or energy limitations, since the de-facto nodes will be cars, buses or any other types of road transportation which have sufficient capabilities.

### 2.2. VDTNs routing protocol taxonomy

Across the diverse literature, numerous DTN routing protocols have been proposed. Although some of them were designed to suit specific application environments/scenarios, others were aimed at generic application scenarios. Therefore, they can be easily applied in the vehicular context and consequently, the taxonomy of VDTN routing protocols may include these DTN protocols.

Beyond that, researchers used to classify VDTN routing protocols on the basis of different criteria: the replication strategy of the protocol, meaning whether it uses single or multiple copies of a unique bundle in order to route it; the transmission scheme (unicast, multicast, broadcast or geocast); or in rare cases, the number of dimensions considered in the use case scenario of the protocol (1D, 2D, 3D). However, most researchers agree to classify them based on the existence or not of a forwarding metric and its nature. This is mainly due to a global consensus about the crucial importance of the considered forwarding metric in each VDTN routing protocol. Without being exhaustive, we present this commonly assumed taxonomy below based on multiple surveys, [25–27], and summarised in Fig. 1.

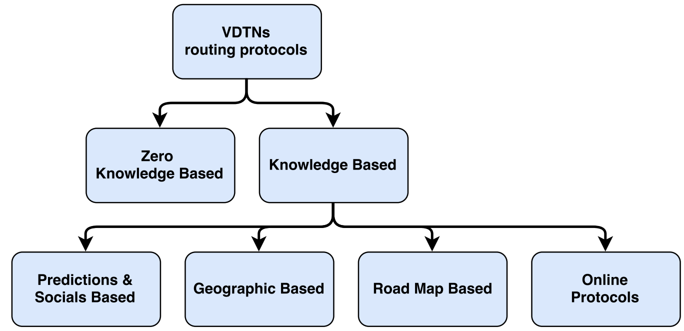

**Fig. 1.** Taxonomy of VDTNs routing protocol based on knowledge.

1. Zero Knowledge-based: this family regroups first proposed DTN routing protocols like Epidemic which disseminates bundles in the whole network [10], Direct Delivery which carries the bundle until meeting the final recipient [11] or the well-known DTN protocol Spray&Wait [28] which makes use of two distinct phases to deliver bundles by, firstly, a controlled and contained bundle spreading in the network, and then switching to waiting for a possible contact with the final recipient.
2. Knowledge-based: since a flooding or a random approach is less prone to success in vehicular environments, the majority of protocols belong to this family. Its existing subcategories are described below.
   (a) Contact predictions & social relationship: this subcategory includes regrouped protocols that obey contact predictions like the DTN protocol Prophet [13] which tries to predict future contacts based on the history of contacts or to make the forwarding decision thanks to newly introduced social concepts such as community, centrality, similarity, friendship and selfishness. SimBet [29] & ZOOM [30] protocols fall into this class.
   (b) Geographic based: protocols included in this subcategory use geographic data to make the forwarding decision while assuming that the nodes are aware of their position and direction. Earlier protocols inherited or inspired from MANETs fall under this category like, for instance: Greedy-DTN [31], MoVe [32] or GeoDTN+Nav[33].
   (c) Road Map based: such protocols also use geographic data to make the forwarding decision but with a sensible difference compared to the previous subcategory. In fact, they assume that nodes which are vehicles evolve in a road map network, and thus they are not constraint-free and move according to routes and intersections. This approach shows good performance and is amongst the most promising ones. Many protocols belong to this family but the most well-known are GeOpps [34] & GeoSpray [14]. In the rest of the paper, we will refer to this routing protocol family as a geographic-based one, since the pure geographic-based family, as presented previously, is no longer considered a viable approach.
   (d) Online protocols: under this subcategory fall protocols that require a fully connected approach with high knowledge of the current state of the road network, notably the number of nodes, average speed and road congestion. The main protocols included in this section are: VADD [35] and Can Deliver [36].

Readers should also note that some protocols make use of multiple approaches to operate and forward data, therefore they are hybrid. Some good examples are DTFR [37] and Rena [38] routing protocols, both relying partially on the Spray&Wait protocol or the Orion routing protocol [39].

## 3. Related work

Performance evaluation of multiple VDTN routing protocols is an active research topic with numerous pieces of related work. It is possible to classify these works easily into two distinct categories: those which propose a new routing protocol and therefore run a performance evaluation of their proposal against other well-known routing protocols, and those which consist of doing a pure performance evaluation of already established routing protocols without proposing a new one. Our work falls into this latter category.

However, good performance evaluations must meet some criteria as highlighted in Section 1.2, namely: realistic network simulator, road topology that reflects the real-world map and mobility patterns that mimic daily life routines of drivers, without omitting another important aspect which is the evaluation of the protocol scalability. Therefore, it clearly appears that only a few works meet these requirements, as for GeOpps [34] or the DAER routing protocol [40], and more recently in [41]. These statements are supported by Table 1, which compares the performance evaluations done by the cited research studies.

In order to correctly evaluate GeOpps, the authors run it against two other protocols using real-world traffic traces (ETHZ) from the canton of Zurich, Switzerland [42] under a realistic network simulator with an area of 15 km × 15 km and up to 21,500 cars. The DAER authors conducted evaluation against the Epidemic protocol and introduced large-scale traffic traces extracted from taxi mobility in Shanghai with more than 4000 cars. Finally, the authors in [41] performed simulations of multiple routing protocols such as Louvre, VADD and GPCR under an NS-3 network simulator [43] and TAPAS-Cologne mobility dataset with approximatively 4670 nodes.

Another interesting study was conducted by the authors in [44], where Static protocol, Epidemic, and Prophet were evaluated first under a small-scale simulation, then with a real testbed in the harbour of Porto city, Portugal, by means of the IBR-DTN software [45]

Apart from the works cited before, other ones fail to fulfil the necessary requirements by omitting one or more criteria. Even major works presenting well-known DTN routing protocols deployed on vehicular environments or pure VDTN routing protocols suffer from this lapse. The above statement is true for Prophet which has been evaluated under the opportunistic network environment simulator (ONE Simulator) [46] which allows a good understanding of the routing protocol behaviour but at the expense of a total abstraction of lower layers, making it inconsistent with a high degree of network simulation realism. The same goes for GeoSpray and comparative works done in [47–49], with a notable difference for this latter work whereby efforts were made regarding the realism of vehicle mobility by relying on the SUMO traffic simulator [50] which is widely recognised as one of the top simulators.

Finally, the respective authors of the GeoDTN+Nav routing protocol [33] and the VADD protocol [35] make use of the TIGER dataset [51] without explaining the underlying mobility of vehicles. Besides, the evaluation is done under a limited number of nodes. Whereas those involved in the TGRP routing protocol are insufficiently clear about compared protocols by choosing pseudo protocols to represent different approaches such as DTN routing or Geo-routing [52].

## 4. Presentation of protocols

### 4.1. Choice of protocols

For the purpose of evaluating the performance of VDTN routing protocols under both realistic network simulators and scenarios, we selected, in this work, four well-known protocols, namely: Direct Delivery, Epidemic, Prophet, and GeoSpray. This selection was not undertaken lightly since it relates to different criteria and is

**Table 1**
Comparison of performance evaluations of routing protocols in cited related works.

| | [14] | [33] | [34] | [35] | [40] | [41] | [44] | [47] | [48] | [49] |
|---|---|---|---|---|---|---|---|---|---|---|
| Proposal of a new protocol | Yes | Yes | Yes | Yes | Yes | No | No | No | No | No |
| Network Simulator | VDTNsim[a] | QualNet | Omnet++/MF[b] | NS-2 | Self-Developed | NS-3 | IBR-DTN[c] | ONE | ONE | ONE |
| Realistic Mobility (Dataset Name) | No | Tiger | ETH Zurich | Tiger | SUVNet | TAPAS Cologne | Yes[c] | No | No | No |
| Considered Topology | Helsinki City | ND[d] | Zurich Canton | ND | Shangai City | Cologne City | Porto City | Tirana City | Helsinki City | Fukuoka City |
| Simulation Area (Km) | 4,5 × 3,4 | ND | 15 × 15 | ND | 100 Km | 20 × 20 | ND | 5 × 3.5 | 4,5 × 3,4 | ND |
| Simulation Duration | 6 h | ND | 24 h | ND | 1200 s | 1000 s | ND | 4 h | 12 h | 660 s |
| Maximum Vehicles | 115 | 50 | 21,500 | 210 | 1000 | 4670 | 30 | 200 | 100 | 220 |
| Comparison with VANETs/VDTNs protocols | Yes/Yes | Yes/No | Yes/No | Yes/Yes | Yes/Yes | Yes/Yes | Yes/Yes | Yes/Yes | Yes/Yes | Yes/Yes |

[a] Self developed network simulator based mainly on ONE.
[b] MF for Mobility Framework is a framework for Omnet++ with a great focus on low layers and radio transmission technologies (Ancestor of Mixim).
[c] Software for conducting on field experimentations under live conditions with support of 802.11p.
[d] ND: Not Defined

somewhat dictated by a global consensus across the research community.

Basically, we tried to pick the most representative or the best routing protocols for some routing approaches as highlighted in Section 2.2 in relation to the VDTN routing protocol taxonomy. Other approaches were deliberately excluded as their inaccuracies or assumptions make them less suited to the vehicular context, especially when the delay/disruptive tolerance constitutes a requirement.

As confirmed by different works such as [25,27], the pure geographical approach which is not constrained by road topology, along with on-line protocols, fall into this last category and consequently, they have been excluded. Therefore, we selected both Direct Delivery and Epidemic protocols as representative of the zero-knowledge routing family, in parallel with Prophet and GeoSpray protocols, representative of the predictive/social and the road map routing family respectively.

The selection of the two former protocols responds to different criteria. First, Direct Delivery and Epidemic make use of single versus multiple copy replication schemes respectively, which allows us to compare the pros and cons of each replication scheme. Secondly, due to their protocol design, they may constitute an ideal benchmark for VDTN routing protocols since they potentially provide the lower and upper bounds for crucial networking metrics such as delivery rate or delay [27]. Finally, the zero-knowledge family is historically the first one from which all others derive, so it is an opportunity for us to measure the progress made in this research field.

When shifting to the remaining approaches, namely predictive/social and road map, it is clear through the literature review that they are competing to provide the best routing protocol. When the first one tries to extract a pattern from the vehicle mobility that is induced by a daily routine, the last one is fostered by the large availability and easy use of GPS devices.

Prophet is a well-established predictive/social-based routing protocol, with a solid background and good documentation, compiled under the RFC6693 [53], since its proposal research community conducts different works aimed at enhancing its performances, leading to the release of a second version that grants better performance and resolves some issues.

GeoSpray is a promising road map-based routing protocol since it is one of the newest protocols with a good presentation of protocol routines, a clear attention to making use of the best scheduling/dropping bundle policies and finally, a good trade-off between performance and replication overhead. Therefore, it succeeds in capturing the interest of researchers.

### 4.2. Presentation of protocols

#### 4.2.1. Direct delivery routing protocol

Among the multitude of VDTN routing protocols, Direct Delivery is the simplest one, proposing a very minimalist forwarding scheme that does not require any prior knowledge. In fact, the authors of [11] proposed in 2004 the use of the sender node mobility as a key factor for data delivery to the final recipient instead of building an end-to-end path between them. Hence, the sender node A carries data until it meets the recipient node B and finally delivers data.

Such a protocol design implies the use of a single replication scheme and the need to wait for a possible encounter between the sender and the recipient in order to deliver data, which may or may not happen after a very long delay, making this last point the major drawback of the routing protocol. Consequently, and as stated by the authors, this routing protocol may represent a lower bound for the delivery ratio and an upper bound for the delay.

#### 4.2.2. Epidemic routing protocol

Proposed by Vahdat & Becker in [10], the Epidemic routing protocol is one of the oldest DTN routing protocols upon which many other DTN routing protocols have been based or inspired by such as MaxProp [54] and RAPID [55].

The protocol is based on a simple design that does not require any prior knowledge to route data, but it floods the network with multiple replicas of data and, along the way, explores all possible paths to reach the destination, until the optimal path is found. Therefore, under ideal conditions such as when there are no resource constraints or network congestion, Epidemic may find the shortest path to reach the destination and provide an upper bound for the delivery ratio and a lower bound for the delay as claimed by the authors and many researchers. However, the creation of a large amount of data replication along with the exploration of all possible paths have some important drawbacks in terms of wasting resources or in a more drastic and disastrous manner, congestion of the network by saturating the bandwidth with unnecessary replica transmission.

The Epidemic protocol operations are based on a three-step information exchange process, starting with an exchange between each part of the offered and the requested bundle lists which contain the corresponding meta-data and are referred to as Summary Vectors (SVs). This process is concluded by the forwarding of requested bundles and, optionally, their acknowledgements. In other words, if node X is the current bundle carrier and node Y is a possible relay or the final recipient, X starts by sending a summary vector of offered/proposed bundles that it holds, denoted by $SV_X$, then Y replays to it by sending a summary vector denoted by $SV_Y$ and including required bundles not already held, excluding those which are stored by both X & Y. Upon the receipt of $SV_Y$, X starts forwarding the requested bundles. Finally, if Y is the final recipient for some bundles, it can optionally generate acknowledgements (ACKs) for those bundles, then send them back to X and consequently allow the whole system to release more resources for the remaining ones.

#### 4.2.3. Prophet routing protocol

Prophet, which stands for Probabilistic Routing Protocol using History of Encounters and Transitivity, is the first contact history-based routing protocol. It was first presented in [12], then enhanced in the second version in [13] and later used as a basis for the RFC standard 6693 [53].

For the purpose of routing data and so making a forwarding decision after a node encounter, Prophet follows a multiple copy replication scheme and relies on a self-defined delivery predictability metric denoted by $P$ with $P \in [0, 1]$. This metric reflects the probability of encountering a specific node and thus delivering its associated data. The higher this value is, the more likely becomes the encounter of this node. Consequently, a suitable forwarder is one with a higher predictability of encountering the bundle recipient, whereas multiple encounters between a specific pair of nodes lead to a higher predictability of encountering each other. Concretely, the RFC6693 defines the computation and the management of the delivery predictability for each known node Y by the current node X, denoted by $P_{(x,\ y)}$, according to three mathematical formulas/equations. Eq. (1) updates the delivery predictability $P_{(x,\ y)}$ after each encounter between X and Y based on the previous predictability, denoted by $P_{(x,\ y)old}$, and the encountering factor, denoted by $P_{enc}$. The latter is computed according to different criteria, mainly, the maximum delivery predictability, denoted by $P_{max}$, the interval of time since the last encounter between the node pair, denoted by $Intvl_y$, and lastly the typical interval time between two successive encounters of a node pair, denoted by $I_{typ}$. Readers should note that $P_{(x,\ x)}$ is always equal to 1, whilst $P_{enc}$ is set to the first contact delivery predictability, denoted by $P_{first\_contact}$, instead of $P_{max}$, in the absence of any prediction $P_{(x,\,y)}$ for Y.

$$P_{(x,y)} = P_{(x,y)old} + (1 - P_{(x,y)old}) \times P_{enc} \quad (1)$$

$$\text{With } P_{enc} = \begin{cases} P_{max} \times (Intvl_y / I_{typ}), & \text{if } 0 \le Intvl_y \le I_{typ} \\ P_{max}, & \text{otherwise} \end{cases}$$

Meanwhile, Prophet defines the transitivity property for the delivery predictability. Indeed, if X frequently encounters Y and this latter often encounters Z, then X is a potential good forwarder of bundles to Z. Eq. (2) reflects this behaviour by allowing the update of $P_{(x,\,z)}$, where $\beta$ is a constant that quantifies the impact of the transitivity.

$$P_{(x,z)} = max(P_{(x,z)old}, P_{(x,y)} \times P_{(y,z)} \times \beta) \quad (2)$$

Finally, in contrast with previous equations that allow delivery predictability to be updated and consequently increased, the latter equation does the reverse process by aging delivery predictability and decreasing it after a period without node encounters. This is done according to Eq. (3) that makes use of the aging constant $\gamma$ with $\gamma \in [0,\,1]$ and the number of time units $K$ that have elapsed since the last aging. The time unit used, denoted by $T_{unit}$, should be defined based on the considered scenario/application where $K$ should be a multiple of it.

$$P_{(x,y)} = P_{(x,y)old} \times \gamma^k \quad (3)$$

Furthermore, the standard describes the whole process needed to deliver data between a sender X and a relay or final recipient Y, as illustrated in Fig. 2. Y starts the process by successively aging then sending predictions to X for all known nodes according to Eq. (3). Upon the reception of such a message, X also ages its own predictions for all known nodes according to Eq. (3). Then it updates $P_{(x,\,y)}$ according to Eq. (1) and at last updates $P_{(x,\,z)}$ according to Eq. (2) for each node known by Y and contained in the predictions sent to X. Upon the completion of prediction updates, X selects bundles for which Y is a good forwarder. This is done according to the selected forwarding strategy and generally means that $P_{(y,bundle\_dest)}$ is higher than the bundle final destination $P_{(x,bundle\_dest)}$. Based on selected bundles, X and Y exchange between them bundle offers and bundle responses that contain meta-data related to those offered by X to Y respectively and, inversely, those requested by Y from X. Finally, the bundle forwarding from X to Y is triggered after the receipt of bundle responses and may engender an additional message to acknowledge the bundle receipt if Y is the final recipient. It should be noted that these processes occur in parallel without any interference in both directions from X to Y and Y to X, while offered bundles from X to Y may incorporate the list of already delivered bundles.

#### 4.2.4. Geospray routing protocol

GeoSpray is one of the most recent and promising routing protocols belonging to the road map-based family. It assumes that vehicles navigate by means of GPS-based navigation systems and follow a hybrid approach by taking advantage of both GeOpps and Spray&Wait (S&W) routing protocols. So, GeoSpray makes use of a limited multiple copy replication scheme by fixing at the start the maximum number of replicas that can exist through the network, denoted by $R$, as defined by S&W, and it relies on a position-based forwarding metric as introduced by GeOpps.

This forwarding metric is called the Minimum Estimated Time of Delivery and abbreviated to *METD*. it can be summarised as follows: a vehicle moving along a suggested route (determined by 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, as depicted in Fig. 4. Then, the navigation system is used to calculate the estimated time to arrive at *NP*,

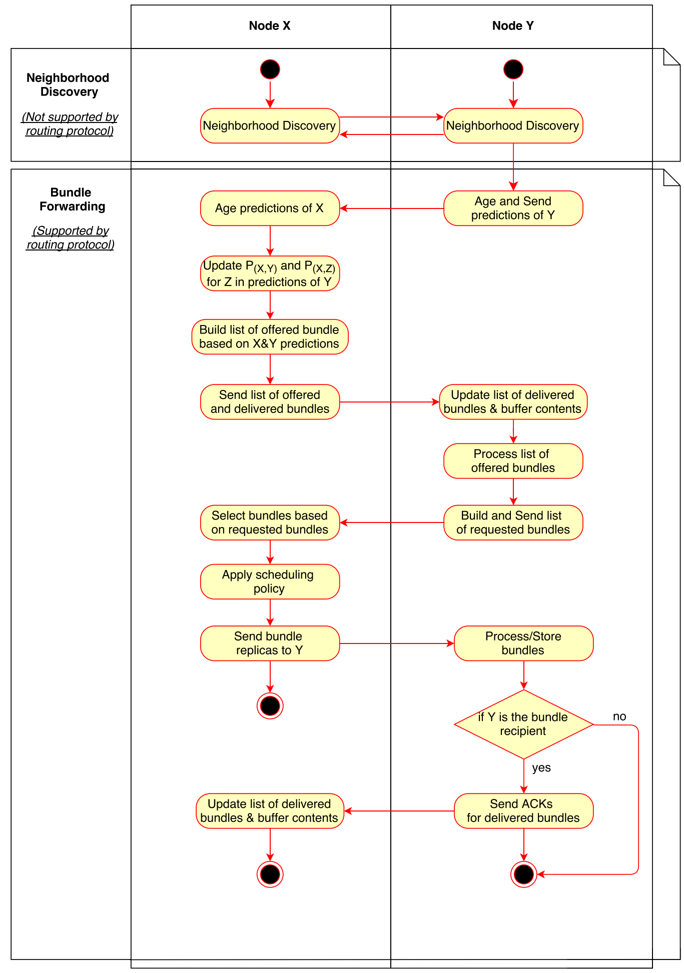


**Fig. 2.** UML activity diagram describing the sequence of main operations executed by Prophet protocol to route data at each node encountering.

denoted by $ETA_{\text{to NP}}$, and to determine the similar time needed to go from *NP* to *D*, denoted by $ETA_{\text{NP to D}}$, based on the length and maximum speed of each considered road for both paths. Therefore *METD* is the sum of these values as shown in Eq. (4), while the choice of a suitable forwarder can be explained in the following manner: forwarding bundles to the vehicle that is converging more quickly or is closer to the final destination means selecting the vehicle that minimises *METD*.

$$METD = ETA_{\text{to NP}} + ETA_{\text{NP to D}} \quad (4)$$

For clarity about the GeoSpray behaviour, operations performed by it whenever two nodes meet each other are illustrated in Fig. 3. Note that operations are mirrored between both nodes. As expected, bundle forwarding occurs as a last resort, preceded by information exchange between a bundle carrier X and a bundle relay/recipient Y and organised as follows: the former node starts by sending the list of already delivered bundles in order to update the acknowledgement list of Y and to purge the network by releasing more resources for bundles still waiting to be delivered. This operation is followed by the sending of stored bundle lists of X which allows Y to calculate *METD* for those bundles, subsequently returning this critical information to X. Upon their receipt, X selects bundles for which Y minimises the *METD* metric and is therefore considered as a suitable forwarder. Also, X must set the amount of replica to handover to Y in order to stay consistent with the limited replica scheme of GeoSpray. This last operation is done with respect to the Spray&Wait strategy and then results in a handover

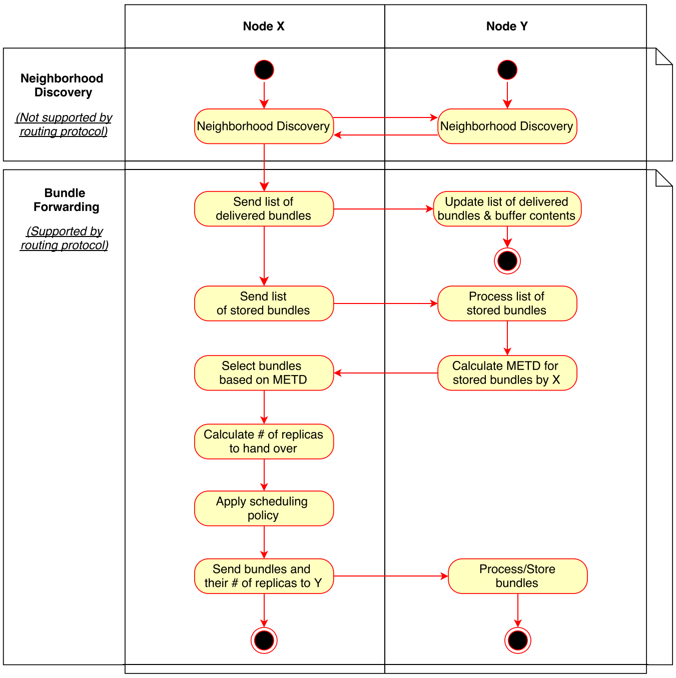


**Fig. 3.** UML activity diagram describing the sequence of main operations executed by GeoSpray protocol to route data at each node encountering.

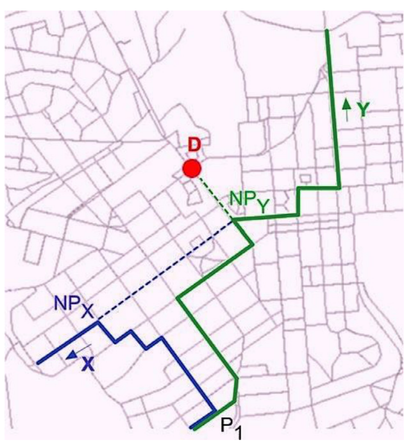


**Fig. 4.** Example of GeoOpps and GeoSpray calculation of the nearest point (NP) from bundle's destination (D), for vehicle X and Y [14].

of $L/2$ copies to Y whenever $L > 1$ or 1 copy if $L = 1$, with $L$ being the remaining number of replicas whose value is equal to $R$ at the bundle generation. Finally, X reorders bundles that must be forwarded to Y according to its scheduling policy before sending them.

## 5. Implementation of protocols

### *5.1. Choice of simulator*

As explained above, the evaluation of the performance of VDTN routing protocols is commonly built upon simulations and therefore based on a single or a set of tools and/or simulators. While it makes sense that the process of selecting the right tools/simulators may be guided by researcher preferences or some specific constraints, it should be noted that this process is a critical aspect since simulator characteristics may differ ostensibly so that simulators may simulate with a high degree of realism some key factors or conversely, make a total abstraction of them.

A significant factor that influences the realism of a network simulation result is the considered radio propagation model. In fact, the propagation of radio signals in the real world is influenced by various physical phenomena like free-space path loss, shadowing, reflection, diffraction, fading and Doppler shift. Therefore, researchers have developed different models to simulate these phenomena as free space, two-ray ground, log-normal shadowing, Rayleigh, Longley-Rice or Nakagami. Thus a suitable simulator is one which makes use of a realistic radio propagation model or at least doesn't neglect this highly important factor.

Another major factor is the considered mac layer. Indeed, while it is understandable that early research work was conducted under various mac layer specifications or protocols due to a large degree of specification freedom, newer research work must be built upon the 802.11p standard which is, nowadays, the de facto standard for vehicular networking. It fosters the Wi-Fi radio coverage and speeds up communication by allowing it without the need for association or authentication.

Finally, it is no secret that vehicle mobility is induced by daily driver routines with a regular shift between rush and off-peak times. However, it is also constrained by road map topology which may alternate between urban and highway. Therefore, a realistic vehicular simulation must take into account and mimic correctly all these aspects by considering daily driver routines with the emergence of a great number of vehicles for some hours, leading to the creation of traffic jams, while ensuring simulation scalability. Below, the characteristics of some well-known simulators are briefly described, then the choice of the selected simulator is justified.

- NS-2: this is one of the most popular network simulators. It integrates advanced propagation & channel models and supports various wireless technologies like Wi-Fi, satellite communication or cellular networks, while mobility models can be obtained from the most advanced traffic simulator SUMO. However, it does not support the 802.11p standard, and furthermore, its design combined with the use of C++/OTcl language complicates and slows down the development of network simulations [56].
- Opportunistic Network Environment (ONE): this is one of the rare simulators specifically designed for DTN. It is written in Java language which limits its capacity to scale. Moreover, it makes a total abstraction of network lower layers and the mobility models are limited to random mobility or some real traces. However, its major benefit is its great simplicity combined with its high-speed execution which fosters the proposal and development of newer protocols. This is why ONE is recommended for early research stages when evaluating different proposals, their logic and behaviours [46].
- QualNet: this is a non-open source simulator and consequently its correctness cannot be verified. It implements various wireless technologies such as Wi-Fi, WiMAX, GSM, UMTS, LTE, and ZigBee, along with complex propagation models and interference channels. Regarding mobility models, it supports the use of traces obtained from different traffic simulators like SUMO or its equivalent VanetMobiSim [57].
- Veins framework for Omnet++: Omnet++ is a network simulator and a development environment at the same time, providing different tools for that purpose as a UI, a language for network definition, tools for result collection and visualisation, a solid programming base for developing dedicated simulators and more [15]. Veins is one of the dedicated simulators developed under Omnet++, and to the best of our knowledge, it is the most advanced simulation framework for vehicular networking, with support for the 802.11p standard in parallel with the implementation of different propagation and interference

**Table 2**
Summary of network simulators and simulation frameworks used in the vehicular research field.

| Network Simulator[a] + Simulation framework | ONE | NS-2 | NS-3 + iTetris | Omnet++ + Veins | QualNet |
|---|---|---|---|---|---|
| License | GNU GPLv3 | GNU GPLv2 | GNU GPLv3 | Academic | Commercial |
| Written language | Java | C++ | C++ | C++ | C/C++ |
| Simulation language | Java | C++/OTcl | C++/Python | C++/NED | C/C++ |
| GUI IDE | Yes | No | Yes (with iTetris) | Yes | Yes |
| Officialy supported wireless technology | None[b] | Wi-Fi/Satellite/Cellular | Wi-Fi/WiMax/LTE | Wi-Fi/802.11p/ WiMax (with Veins) | Wi-Fi/WiMax/ GSM/UMTS/ LTE/Zigbee |
| Scalability | Small | Medium | Large | Large | Large |
| Coupled with a traffic simulator | No | No | bidirectionally with SUMO | bidirectionally with SUMO | No |

[a] Allows a great interaction between dedicated simulators (Network & Traffic simulators).
[b] Makes a total abstraction of network lower layers and instead focus only on routing and applicative layers.

models [16]. Veins also embeds the TraCI server that allows full bidirectional coupling and interaction between the Omnet++ and SUMO traffic simulator. Therefore, network simulation can interact and influence vehicle motions instead of being solely used as a simple input. This is of special interest for us, since we aim to change the vehicle motion at run-time in some scenarios, as will be highlighted later.

- iTetris framework for NS-3: while the latter is the successor of the well-known NS-2 simulator, upgraded and updated with the support of more recent technologies [43], the former is a framework simulation dedicated to the study of intelligent transportation systems and vehicular networking. It also supports the 802.11p standard with respect to European specifications originating from ETSI, along with facilities for providing bi-directional coupling between NS-3 and SUMO [58]. However, limited project maintenance and access to resources restrain its uses.

Hence, and in accordance with Table 2 which summarises previously presented simulators, we selected the Veins framework and Omnet++ for our work, because, as explained above, this is one of the most advanced simulators dedicated to vehicular networking, with support for the 802.11p standard. Furthermore, its bidirectional coupling with SUMO allows the use of real-world mobility traces such as those of the TAPAS Cologne project. Finally, the framework is in continuous development with good support from the maintainers and community.

### 5.2. Implementation design

After selecting the routing protocols that will be compared, and picking up the right tool for vehicular simulations, we discuss, in the following section, details behind the common implementation of protocols under the Veins framework.

More specifically, we begin by presenting an important aspect, though very often neglected by researchers when presenting new protocols, namely the mechanism of neighbourhood discovery. Moreover, we introduce a simple architecture that serves as common ground for the implementation of the four (04) protocols and can be easily used to develop other protocols into the same environment. Finally, we expose a minimalist self-developed Python Server dedicated to the GeoSpray protocol, its primary mission being the computation of the Nearest Point (*NP*) and the *METD* metric, in replacement of traditional navigation systems embedded in vehicles.

- NeighbourHood Discovery Mechanism: to the best of our knowledge, the authors of the TGRP protocol are the only ones to pay attention to the mechanism of neighbourhood discovery and rely on the NeighbourHood Discovery Protocol (NHDP) standardised in the RFC 6130 to ensure it. However, since NHDP is designed for MANETs, which differ ostensibly from VANETs and VDTNs, we proposed minimalist neighbourhood discovery based on periodic beaconing and timer triggering, where a node periodically broadcasts beacons according to a beacon period denoted by $Period_B$; upon their receipt, a receiver node adds the sender node to the list of known neighbours then triggers two distinct timers that are the pending and the expire one denoted respectively by $Timer_{Pend}$ and $Timer_{Exp}$. The latter timer is used to delete a previously known neighbour after missing several beacons while the former is used to mark the node in pending mode since it is not connected, nor already disconnected after missing a few beacons; in fact, such a transient mode occurs very often in vehicular networks where researchers have observed a connectivity that is prone to micro-disconnection and may be re-established or not after the receipt or the miss of following beacons. It should be noted that both timers are multiples of $Period_B$ and $Timer_{Pend} < Timer_{Exp}$.
- Common architecture for implementing routing protocols: since none of the four protocols is already implemented under the Veins framework and for the purpose of ensuring fair implementation and comparison between protocols, we developed a C++ common network layer interface named *DtnNetwLayer*, inherited from a basic network layer named *BaseNetwLayer*, provided by Veins. The *DtnNetwLayer* class provides primary methods for implementing core mechanisms of a delay tolerant network as an SCF paradigm (by retaining bundles instead of passing them to lower layers), bundles management, neighbourhood discovery and management, node type definition (whether the node is an On Board Unit (OBU) or a Road Side Unit (RSU)) and more besides. Therefore, implemented routing protocols inherit all these required methods from *DtnNetwLayer* and implement methods related to their own routing approaches, as depicted in Fig. 5.
- Python Server as a navigation system for GeoSpray protocol: for the purpose of computing the *NP* and *METD* metrics, the authors of the GeoSpray protocol proposed the use of embedded navigation systems. Due to some limitations regarding the SUMO traffic simulator and computational costs of shortest paths between two random points of the map, we rely jointly on SumoLib [50] and Networkx [59] libraries to develop a small Python Server that translates the road map into a weighted graph, based on the minimum traverse time of roads. Therefore, upon request, the *NP* and the *METD* metrics are computed at an affordable cost, then, they are returned to Veins via socket communication, as depicted in Fig. 6.

## 6. Evaluation and simulation results

The main goal of this work is to provide a global overview of protocol performance for on-field researchers. To that end, a quan-

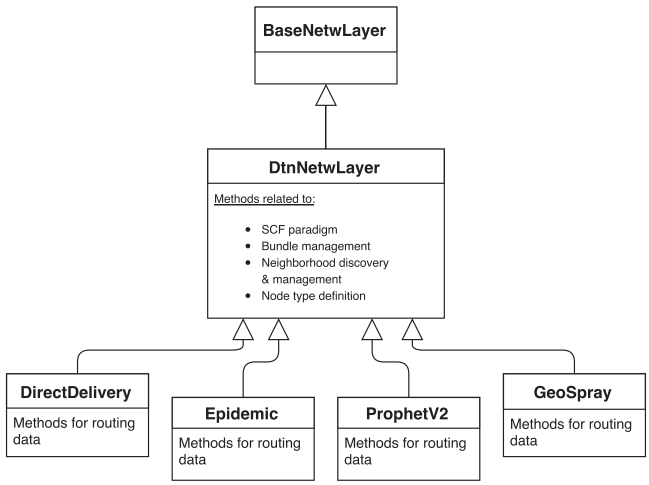


**Fig. 5.** UML class diagram describing the developed architecture for implementing protocols under the Veins Simulation Framework.

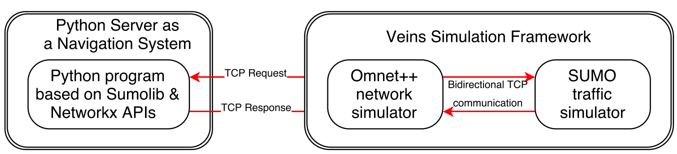


**Fig. 6.** The veins simulation framework interacting with the self-developed python server.

titative evaluation of selected protocols under small- and large-scale scenarios is conducted, based on synthetic as well as realistic vehicle mobility. In fact, while an evaluation under a small and synthetic scenario is what is usually done, the need for a realistic and large-scale scenario makes sense since the main use case of studied protocols is routing data under real-world conditions in terms of the scalability or the vehicle motion. Furthermore, by evaluating protocols under a small-scale scenario, we attempt to determine to what extent it is possible to reflect and simulate their behaviour under a large and realistic scenario and, most importantly, predict their relative performance along with the protocol hierarchy. Besides, we test the proposed settings of Prophet and estimate the impact of some parameters and mechanisms on GeoSpray. Lastly, we present the three (03) distinct considered scenarios:

- Scenario A: a small-scale scenario with synthetic vehicle mobility.
- Scenario B: a small-scale scenario with synthetic vehicle mobility plus special vehicles called looping vehicles that are continuously rerouted.
- Scenario C: a large-scale scenario with a realistic road map and vehicle mobility according to the TAPAS Cologne project.

Regarding the working environment, the simulations are done by means of the High-Performance Computing Grid MAGI of Paris XIII University [60], while the study relies, as cited before, on the Veins framework (v2.0-rc1) which is based on the network simulator Omnet++ (v4.2) and the traffic simulator Sumo (v0.13). The latter is responsible for vehicle mobility and provides many mobility models like the Dynamic User Assignment (DUA) which is considered in Scenario A & B. It provides a user equilibrium for all considered vehicles instead of optimal paths, therefore reflecting much more realistic driver behaviour [50]. Regarding radio propagation models, Veins implements various models, including the Two Ray Interference model [61,62] and the Simple Obstacle Shadowing [63] whose uses are highly advised by the Veins authors. The first one is an enhanced version of the Two Ray Ground model and succeeds in modelling signal fading at short distances which is an expected phenomenon. The model has been tested through real-world experimentation thus confirming its accuracy and superiority to the Two Ray Ground model. The latter succeeds in modelling through a simplistic approach, building shadowing as frequently happens in urban environments. It has been experimentally validated and yields a good trade-off between complexity and accuracy which allows simulation scalability. Finally, Veins implements specifications of IEEE 802.11p, limited to Broadcast mode only, since recent research works highlight the unsuitability of Unicast transmissions due mainly to head of line blocking effects [64].

The implementation of the four (04) protocols was done using the Omnet++ programming language (C++/NED) since no reference implementation was available. Meanwhile, the Python Server was implemented with the help of the Python language (v2.7), SumoLib API embedded in Sumo (v0.13) and Networkx API (v1.11). The latter allows the translation of the road map into a weighted graph.

For data traffic modelling, we make use of a Car to X communication scheme (C2X) where vehicles through their network devices, commonly named On Board Units (OBU), periodically generate bundles addressed to fixed entities of the network, commonly called Road Side Units (RSU). For that purpose, vehicles may collaborate between them and act as a relay by taking advantage of the SCF paradigm and their mobility.

Finally, regarding the performance metrics, we selected three (03) of them, in addition to an optional one. They are described below and arranged in decreasing order of importance:

- Delivery Ratio (DR): the main target of this work being routing protocols for a vehicular delay tolerant network, we are interested at first in the ratio of the delivered bundles that corresponds to the number of unique received bundles divided by the number of total unique emitted bundles.
- Overhead (O): this reflects the cost of the protocol and allows the evaluation of a good trade-off between bundle delivery and network overload. It corresponds to the total number of bundle replica divided by the total number of emitted bundles.
- Average Delay (AD): regarding the delay tolerant context, this metric is less important than those cited before. It corresponds to the average delay needed to deliver the first replica of any bundle.
- Hop Count (H): this is the average number of hop counts needed by the first replica of any bundle to arrive at its final destination.

In the remainder of this section, each scenario along with its characteristics and a comparative study of protocol performances are presented.

### *6.1. Scenario A: evaluation under a small-scale scenario*

This first scenario reflects an urban scenario of a Manhattan type. In fact, the evaluations of protocols are done under a road map of a limited/small size, more precisely, a grid of 1.65 km × 1.65 km with multiple intersections spaced by 150 m as depicted in Fig. 7. Vehicles periodically send bundles to a single Road Side Unit (RSU) placed at an intersection at the centre of the road map, after being inserted from its edges. Finally, simulations are done within the Veins framework, as stated before, over two (02) h. Other simulation parameters can be found in Table 3 and the considered performance metrics are, respectively: Delivery Ratio (DR), Overhead (O), Average Delay (AD) and, optionally, Hop Count (H).

**Table 3**
Simulation parameters for small and large scale scenarios.

| Global Parameters | | Values for | | |
|---|---|---|---|---|
| | | Scenario A | Scenario B | Scenario C |
| Simulation | Duration | **7200 s** | **7200 s** | **3600 s** |
| | Nbr. Run Per TTL value | 20 | 20 | 20 |
| Bundle | Size | 1500 bits | 1500 bits | 1500 bits |
| | Generation period | 150 s | 150 s | 150 s |
| | TTL values | 300 s, 600 s, 900 s, 7200 s | 300 s, 600 s, 900 s, 7200 s | 300 s, 600 s, 900 s, 7200 s |
| Neighborhood Discovery | $Period_B$ | 0.4 s | 0.4 s | 0.4 s |
| | $Timer_{Pend}$ | 1.2 s | 1.2 s | 1.2 s |
| | $Timer_{Exp}$ | 2 s | 2 s | 2 s |
| Wi-Fi | Technology & mode | 802.11p Broadcast | 802.11p Broadcast | 802.11p Broadcast |
| | Transmission rate | 18 Mbits/s | 18 Mbits/s | 18 Mbits/s |
| | Maximum range | 127 m | 127 m | 127 m |
| | Propagation model | Two Ray Interference & Simple Obstacle Shadowing | Two Ray Interference & Simple Obstacle Shadowing | Two Ray Interference & Simple Obstacle Shadowing |
| RSU | Nbr. of | **1** | **1** | **957** |
| | Transmission mode | Reception only | Reception only | Reception only |
| Vehicle | Nbr. of | **2280** | **2280** | **9920** |
| | Transmission mode | Emission only | Emission only | Emission only |
| | Mobility | **SUMO DUA** | **SUMO DUA** | **Real Traces (TAPAS Cologne)** |
| | Nbr. of rerouted | – | **5** | – |

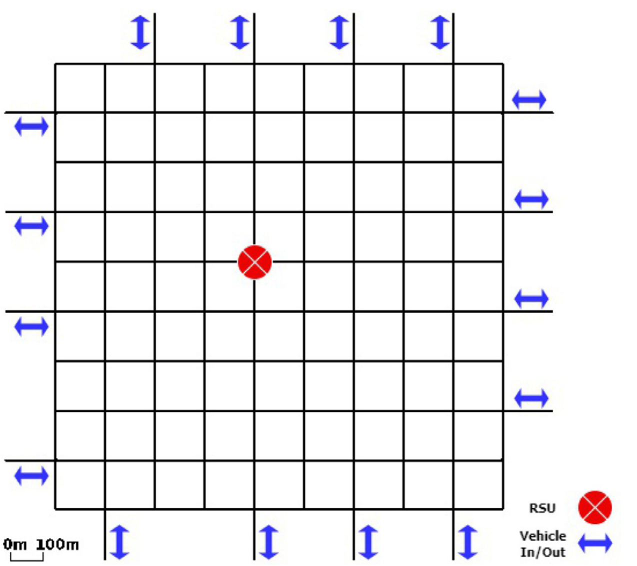


**Fig. 7.** Road network with a single RSU used in small scale scenario .

**Table 4**
Protocol parameters when evaluating performances of Direct Delivery, Epidemic, Prophet and GeoSpray.

| Protocols parameters | | Values |
|---|---|---|
| All | With bundle ACK | Yes |
| Prophet only | $P_{max}$ | 0.7 |
| | $P_{first_contact}$ | 0.5 |
| | $I_{typ}$ | 1800 |
| | $\beta$ | 0.9 |
| | $T_{unit}$ | 30 |
| | $\gamma$ | 0.999 |
| GeoSpray only | Maximum Number of Replica $R$ | 20 |

#### 6.1.1. Global performance evaluation for all protocols

This evaluation has the task of providing field researchers with a first overview of a protocol hierarchy through a comparative analysis of the performances of the four (04) considered protocols, under their default or simplified (as for GeoSpray) settings. Also, note that all protocols make use of acknowledgements (ACKs) to clear already delivered bundles. Lastly, their respective settings can be reviewed in Table 4.

*Evaluation of delivery ratio:* Fig. 8 A highlights the good performances for Epidemic which delivers up to 80% of bundles, followed successively by GeoSpray and Prophet, whereas Direct Delivery performs poorly by delivering only 5% of them. The performances of Epidemic and Direct Delivery were expected due to their specific approach, with unrestricted bundle spreading for the former and bundle transfer restricted to the final recipient for the latter. However, the performances of GeoSpray and Prophet were less predictable, with the first performing much better than the latter, achieving up to 40% against only 15%. These behaviours are explained by the fact that GeoSpray selects forwarders based on their planned future mobility, while Prophet tries to predict future contacts between vehicles based on their history. Therefore, with the lack of correlation between old and future contacts as in this scenario, vehicles are misled when choosing the next forwarder and Prophet performs poorly. Furthermore, its settings must be fine-tuned and adapted to the considered scenario, otherwise vehicles may experience a very slow prediction aging and thus hold bundles for a long period. Finally, regarding Bundle TTL, Direct Delivery and Prophet are not impacted upon by its variation because they deliver a limited number of bundles prior to TTL expiry, in contrast with other protocols where a TTL value of 300 s results in a limited delivery ratio and higher values of TTL ( $\geqslant$ 600 s) show a stabilised delivery ratio.

*Evaluation of overhead:* As expected, simulation results reveal, through Fig. 8(B), a large overhead for Epidemic, which is due to its flooding approach. GeoSpray generates a controlled number of replicas due to its bounded replication scheme whereas Prophet produces a limited number of copies. These results are explained mainly by the long period of bundle holds observed for Prophet, but are also partially due to its poor performance. Direct Delivery has no overhead because the protocol follows a single copy approach. Finally, it is interesting to note that the unlimited replication scheme of Prophet generates fewer replicas than GeoSpray's limited one, while varying TTL has no impact on the overhead produced by protocols apart from Epidemic that shows a drop when considering a shorter TTL (300 s).

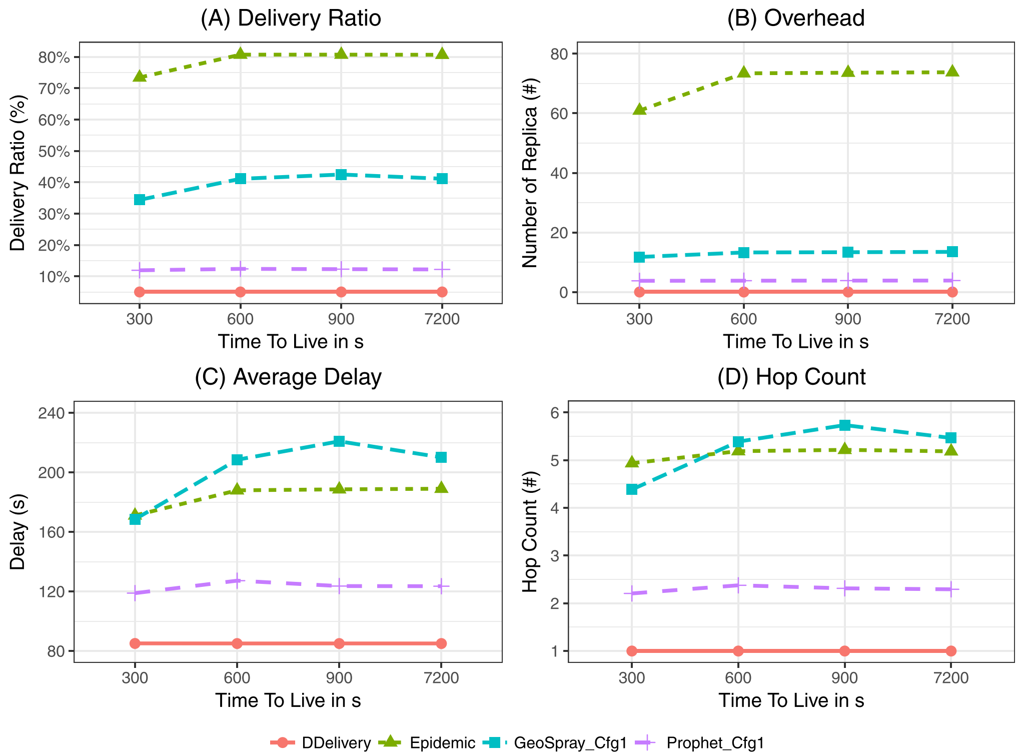


**Fig. 8.** Simulations results for Direct Delivery (abbreviated in DDelivery), Epidemic, Prophet and GeoSpray protocols as function of bundles TTL under Scenario A.

*Evaluation of average delay:* The results illustrated in Fig. 8(C) show the highest average delay for GeoSpray followed successively by Epidemic, Prophet and finally Direct Delivery. This contrasts substantially with assertions found in the literature that Direct Delivery & Epidemic are expected to achieve the highest and shortest delays respectively. However, these delays are due to global protocol performance. In fact, Epidemic delivers a great number of bundles and therefore experiences a higher average delay, whereas the few bundles that are delivered with Direct Delivery are the successful result of fast encounters between the RSU and vehicles.

*Evaluation of Hop Count:* An observation made from Fig. 8(D) shows the lowest hop counts for Direct Delivery, while Prophet scores lower than both Epidemic and GeoSpray, with a slight increase for the latter. These results are not surprising and may be explained as follows. The stable hop count of Direct Delivery equal to 1 is due to its own approach that restricts bundle transfer to the final recipient without relying on any other relay. For Prophet, the conjunction of its inadequate settings with the considered scenario and its own misleading approach, as explained before, leads to a long period of bundle holdings by vehicles and poor overall performance, which explain the low and stable hop counts. Regarding Epidemic, its uncontrolled data dissemination allows it to explore all paths and deliver data through an average of 5 hops, which translates into a similar average for RSU reachability, starting from any vehicle in the network. In contrast, GeoSpray needs, in general, more hops, because it does not explore all paths and consequently requires more forwarding to deliver data. Finally, analysis of the results shows that observable increase for higher TTL values ($\geqslant$ 600 s) in Epidemic & GeoSpray is related to their performance increase.

### 6.1.2. Evaluating prophet under default and proposed settings

As presented in Section 4.2.3, the Prophet protocol makes use of various parameters to compute delivery predictions, their default values being already fixed in the RFC standard 6693 RFC6693. Previous simulations were conducted according to the latter; however, as stated by the protocol authors, they must be adapted to the considered scenario. Indeed, the current standard provides some guidance and recommendations in that sense, but unfortunately, it is poorly documented, unclear and not concise enough. Furthermore, no mechanism has been proposed for that purpose and consequently, researchers must do it through experimentation. To this end, first we looked for a suitable value for these parameters, then we compared both versions of Prophet, one with default settings which means default parameter values, denoted by $Prophet\_Cfg_1$, while the other made use of the proposed values for $I_{typ}$, $T_{unit}$ and $\gamma$, denoted by $Prophet\_Cfg_2$.

The setup of these parameters is not a random process and complies with straightforward observations. In fact, the first parameter $I_{typ}$ involved in the computation of predictions according to Eq. (1) is set by default to 1800 s. This is not consistent with our scenario where the typical mean interval between two successive vehicle encounters is around 60 s; therefore, $I_{typ}$ for $Prophet\_Cfg_2$ is set to 60 s. Regarding $T_{unit}$ and $\gamma$, they are involved in Eq. (3) which is related to the prediction aging process. The former parameter reflects the smallest unit of time and is set by default to 30 s. Consequently, and following its re-compute, its new value is set to 1 s in accordance with the relationship between $I_{typ}$ and $T_{unit}$ presented in Eq. (5). Concerning $\gamma$, it is set to a lower value of 0.986 as shown in Eq. (6), with the purpose of accelerating the aging of predictions. Indeed, by doing so, misleading vehicles should be avoided when selecting the next forwarder. Therefore, it is possible to lower a given value of prediction from 0.5 to 0.1 in a typical delay of 120 s which corresponds to the maximum observed interval of time between two successive encounters for a specific pair of vehicles. All parameters can be reviewed in Table 5.

$$\left(\frac{Intvl_y}{T_{unit}}\right) = \left(\frac{1800s}{30s}\right) = 60 \Rightarrow \text{if } Intvl_y = 60s \text{ then } T_{unit} = 1s \quad (5)$$

$$0.1 = 0.5 \times \gamma^{120} \Rightarrow \gamma = 0.986 \quad (6)$$

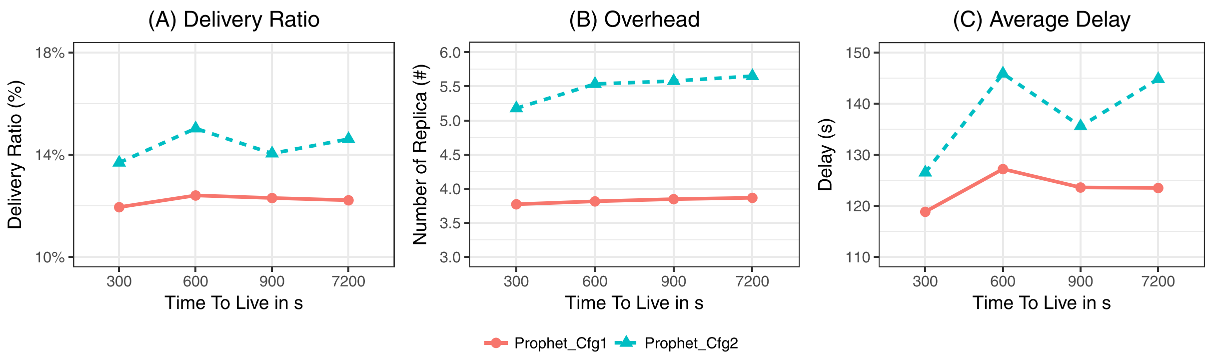


**Fig. 9.** Simulation results for Prophet with defaults ($Prophet\_Cfg_1$) and optimized ($Prophet\_Cfg_2$) parameters as function of bundles TTL under Scenario A.

**Table 5**
Protocol parameters when evaluating performances of different Prophet Configurations: Cfg1 & Cfg2.

| Prophet parameters | Values for Cfg1 | Values for Cfg2 |
|---|---|---|
| $P_{max}$ | 0.7 | 0.7 |
| $P_{first_contact}$ | 0.5 | 0.5 |
| $I_{typ}$ | **1800** | **60** |
| $\beta$ | 0.9 | 0.9 |
| $T_{unit}$ | **30** | **1** |
| $\gamma$ | **0.999** | **0.986** |

**Table 6**
Protocol parameters when evaluating performance of various GeoSpray configurations.

| Configuration name | Value of R | Use of H2H Ack |
|---|---|---|
| GeoSpray_Cfg1 | 20 | No |
| GeoSpray_Cfg2 | 60 | No |
| GeoSpray_Cfg3 | 20 | Yes |
| GeoSpray_Cfg4 | 60 | Yes |

*Evaluation of Delivery Ratio:* A comparative analysis of each configuration reveals a small performance gain for Cfg2, up to 2–3% as illustrated in Fig. 9(A), whereas the Cfg1 results are more stable. This limited gain is explained by the introduced settings that are better adapted to the considered scenario and vehicle motion. Thus, the proposed settings partially avoid the bad forwarder selection since the computed predictions increase and decay quickly, but not totally, because the approach advocated by Prophet tries to predict future contacts based on their history, with no guarantee regarding a possible correlation between the two. Moreover, this latter factor may explain the unstable performances of Cfg2 for any considered TTL, as highlighted by the results.

*Evaluation of overhead:* As demonstrated in Fig. 9(B), Cfg2 achieves better overall performance at the price of a minimal increase in overhead compared to Cfg1. This is due to the considered settings that allow a quick increase/decay of predictions, leading to more bundle forwarding and consequently to the generation of more replica.

*Evaluation of average delay:* As shown in Fig. 9(C), Cfg1 offers a stable delay around 125 s, while Cfg2 shows a delay varying between 130 s and 145 s. This behaviour originates from two factors that delay bundle delivery. In fact, the quickly evolving predictions more often replicate bundles but do not necessarily select suited forwarders. Moreover, the replication process results in a more overloaded network bandwidth. Finally, it is noticeable through Fig. 9 that bundle TTL has a limited impact on the results, with a slight under performance when considering the TTL value of 300 s.

#### *6.1.3. Evaluating the impact of increasing R and guaranteeing the handover of the replication quota on GeoSpray*

The GeoSpray protocol makes use of a limited replication scheme, brought to it from the Spray&Wait protocol, which implies fixing, prior to bundle transmission, the maximum number of replica that can be generated, denoted by *R*. According to the authors of Spray&Wait, it must be set to a certain percentage of mobile vehicles (by default 15%). However, in the real world, it is very unlikely to estimate correctly the total number of vehicles, or at least, when it is possible, the resulting *R* is very important. Consequently, it is generally accepted that researchers set it to a fixed value.

Another important facet of GeoSpray is the handover of replica after each vehicle encounter. Unfortunately, the protocol does not provide any mechanism to ensure that, even if it targets networks with unreliable communication and frequent disconnection. This results, basically, in the loss of some replicas, but more dramatically, in an important drop in global performance. To fix this problem, we try to ensure the handover of replicas by implementing a two-step acknowledgement mechanism called *H2HAck*, which confirms the transfer and updates the remaining replicas. Accordingly with these protocol aspects, namely the considered value of *R* and the use of the *H2HAck* mechanism, we evaluate, in this section, their respective impacts on performance and thus consider four distinct configurations of GeoSpray summed up in Table 6. It should be noted here that the previously considered parameters for GeoSpray are identical to those of the first configuration denoted by $GeoSpray\_Cfg_1$.

*Evaluation of Delivery Ratio:* The simulation results shown in Fig. 10 A reveal a positive impact on the delivery ratio for both the *H2HAck* mechanism and the increased value of *R*. However, while the latter increases the performance by 5–10% as demonstrated by Cfg1 and Cfg2, the former has a more important impact and results in an increased delivery ratio by up to 10% and 20% when comparing Cfg2 with Cfg4 and Cfg1 with Cfg3. Therefore, it is concluded that GeoSpray must ensure the handover of replicas to perform well. Regarding Bundle TTL, the observations show a net increase when considering a TTL higher than 300s. This is an expected behaviour since the bundles experience a longer lifetime and thus are delivered more often before expiring.

*Evaluation of overhead:* As presented in Fig. 10(B), it is clear that the previous performances of Cfg3 & Cfg4 are achieved at the expense of a higher overhead which exceeds even the maximum number of replicas. This indicates that the *H2HAck* mechanism partially fails to contain the number of replicas to its maximum value *R*, and needs more synchronisation between vehicles to do it. Nevertheless, the proposed mechanism reveals that a great performance improvement can be made at the price of a slight bun-

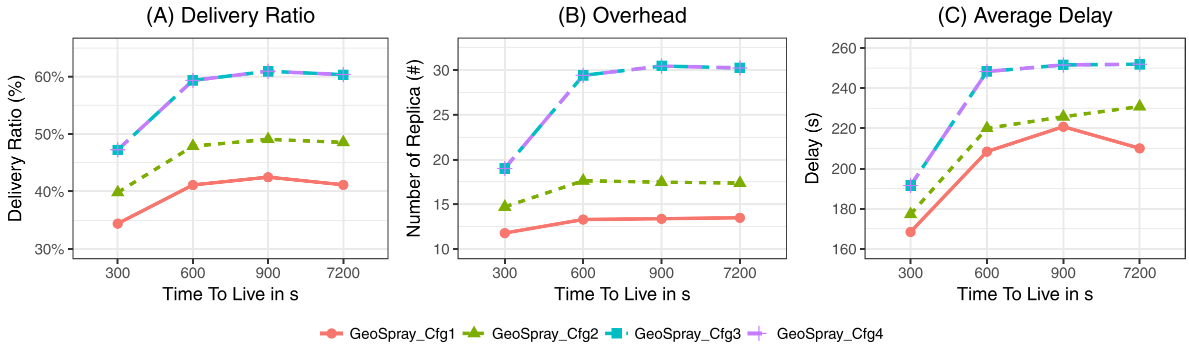


**Fig. 10.** Simulation results for GeoSpray with default parameters ($GeoSpray\_Cfg_1$) and others evaluated configuration: $GeoSpray\_Cfg_2$, $GeoSpray\_Cfg_3$ and $GeoSpray\_Cfg_4$, as function of bundles TTL under Scenario A.

dle over-replication. Regarding Cfg1 & Cfg2 overheads, they are low and affordable, especially for the latter configuration. This demonstrates that the overhead does not increase linearly with $R$ since the ratio between the overheads of Cfg2 & Cfg1 ($\approx$ 1.x) is less than that between their considered $R$ ($=$ 3). Ultimately, the minimal considered TTL shows the smallest overhead, meanwhile higher TTLs ($\geqslant$ 600 s) show greater but stable values.

*Evaluation of Average Delay:* Cfg3 and Cfg4 deliver bundles after a high delay as illustrated in Fig. 10(C), followed successively by Cfg2 and Cfg1. The higher delays observed for Cfg3 and Cfg4 are explained by their overall good performances that imply a more loaded network bandwidth. Therefore, they experience a higher delay in delivering bundles.

### *6.2. Scenario B: evaluation under a small-scale scenario with looping vehicles*

In this section, we evaluate the protocol performances under the same scenario as in the preceding section (see Fig. 7) but with a major difference that consists of the introduction of continuously rerouted vehicles, called looping vehicles, which try to reproduce the motion of buses and public transportation characterised by their cyclical nature. In this regard, the use of a bi-directionally coupled simulator such as Veins is crucial, since it allows vehicles to be continuously redirected to a new destination (at run-time) after they have reached the current one by means of a very minimalist code alteration.

The main purpose in evaluating protocols under such a scenario is to assess to what extent it is possible to predict protocol performances and behaviours in a large-scale scenario, like C and its anycast scheme, through the use of a small-scale scenario that introduces looping vehicles. The latter try somewhat to mimic the anycast scheme. Furthermore, they allow an evaluation of the potential performance gain in Prophet since the scenario is more suited to its own approach and consequently its performance may be positioned against other protocols. As a reminder, Prophet operates optimally when the vehicle mobility follows a community-based model, reflected in this scenario by the looping vehicles. Concerning the simulation parameters and metrics, they are similar to those considered in the previous scenario A, in addition to a total of five (05) looping vehicles. They can be reviewed in Table 3.

#### *6.2.1. Global performance evaluation for all protocols*

The purpose of the current evaluation is to provide a primary overview of the protocol performances and hierarchy, when assuming similar conditions and parameters as in Section 6.1.1 and introducing looping vehicles. These latter mimic buses and public transportation motion. All simulation parameters are summed up in Table 4.

*Evaluation of delivery ratio:* Through the analysis of the results in Fig. 11(A), it appears clearly that the protocol hierarchy is similar to that observed in Fig. 8(A), with Epidemic outperforming all protocols, followed successively by GeoSpray, Prophet and lastly Direct Delivery. However, compared to the case in the previous scenario, these performances are improved because of the introduction here of the looping vehicles which are able to carry and deliver much more data before bundle expiry. This is especially true for Prophet which experiences substantial gains gradually with an increasing bundle TTL and ultimately achieves a delivery ratio of twice the TTL value of 7200 s compared to 300 s. Despite this huge improvement, it is important to note that GeoSpray still outperforms Prophet for all the considered TTLs.

*Evaluation of overhead:* As shown in Fig. 11(B), Epidemic generates a large overhead, followed successively by GeoSpray, Prophet and lastly Direct Delivery. In general, similar identified factors and observations made from Fig. 8(B) are involved here, with a slight overhead increase due to the introduced looping vehicles which hold bundles for a longer period and lead to more important bundle replications.

*Evaluation of average delay:* Similarly to the previous results and due to the same factors, Fig. 11(C) shows a medium and stable average bundle delivery delay for Epidemic and GeoSpray, with the latter requiring more time for delivery. Regarding Direct Delivery and Prophet, the results differ ostensibly: the average delay increases in function of TTL, starting with a low and medium delay when TTL is set to 300 s and reaching up to 450 s and 750 s respectively when considering the highest TTL. These surprising results are explained by the introduction of the looping vehicles that carry more and more bundles when the TTL value increases and take more time to deliver, because encountering RSU will occur only after an interval of time on the one hand, and on the other, network bandwidth is more loaded.

*Evaluation of Hop Count:* The simulation results represented in Fig. 11(D) are quite similar to those observed in Fig. 8(D) and can be explained in the same way, especially for Direct Delivery. Regarding the other protocols, Epidemic delivers data in fewer hops than previously because the introduction of looping vehicles decreases the average number of hops needed. In the meantime, Prophet and GeoSpray show an increase in hop counts whenever considering a higher TTL. This is due to their enhanced global performance when introducing looping vehicles and allowing bundles to live longer. However, Prophet still needs fewer hop counts compared to GeoSpray since its advocated approach and slow prediction aging foster the holding of bundles by vehicles, whereas GeoSpray tends to forward bundles very often, in fact whenever it meets a vehicle that minimises the *METD* metric, which means that this vehicle will converge quickly or be closer to the final recipient.

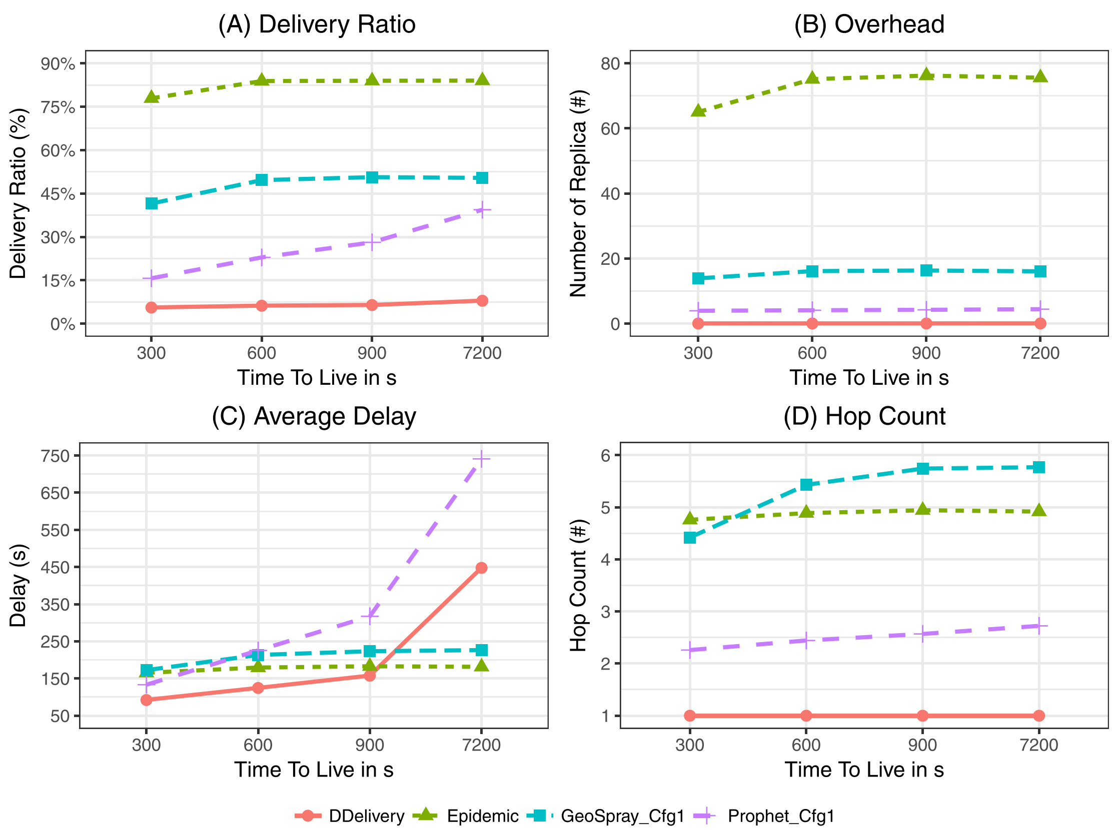


**Fig. 11.** Simulations results for Direct Delivery (abbreviated in DDelivery), Epidemic, Prophet and GeoSpray protocols as function of bundles TTL under Scenario B.

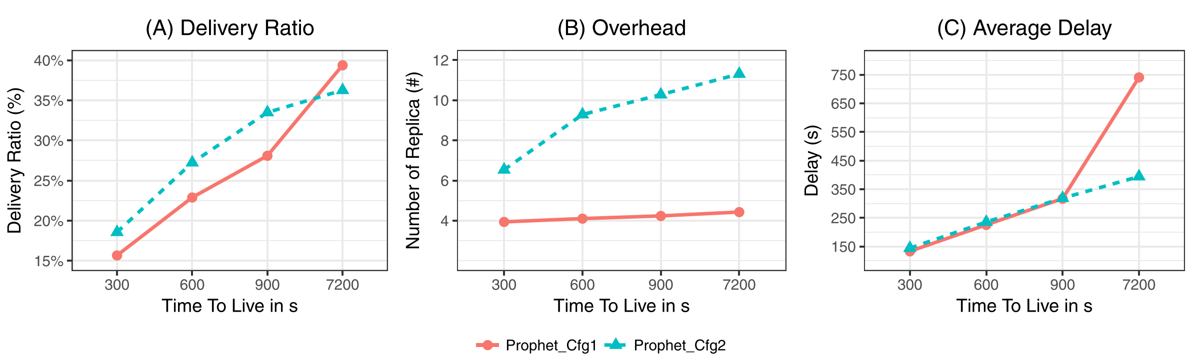


**Fig. 12.** Simulation results for Prophet with defaults ($Prophet\_Cfg_1$) and optimized ($Prophet\_Cfg_2$) parameters as function of bundles TTL under Scenario B.

*6.2.2. Evaluating prophet under default and proposed settings*

Similarly to the study conducted in Section 6.1.2, we evaluate the performances of the Prophet protocol when introducing looping vehicles under two different settings: the default one (Cfg1) and proposed one (Cfg2), in terms of following parameters: $I_{typ}$, $T_{unit}$ and $\gamma$. For the sake of a fair comparison with the previous study, similar simulation parameters and metrics are considered and can be reviewed in Table 5.

*Evaluation of delivery ratio:* Through the results in Fig. 12(A), the positive impact of the looping vehicles on the Prophet delivery ratio is demonstrated. It increases drastically with an increasing bundle TTL that ultimately doubles the results, from 16% to 39% for Cfg1 and 18% to 36% for Cfg2, when considering the lowest and highest TTL values respectively. Also, the results show that Cfg2 outperforms Cfg1, until there is a TTL of 7200 s. Generally, these results are due to an adapted scenario to the protocol approach with the looping vehicles reflecting a community-based mobility model and carrying bundles during a longer period whenever increasing TTL and thus delivering them more often. This observation is accentuated by the proposed settings that are also better adapted to the considered scenario, except for a TTL of 7200s where the default settings perform better, because they allow a slow aging of predictions, in line with a high TTL. This leads to better forwarder selection for older bundles.

*Evaluation of overhead:* As shown in Fig. 12(B), both versions of Prophet require few replicas to deliver data, within an average of 4 replicas for Cfg1 and a slowly increasing overhead in the function of TTL for Cfg2, starting at 7 copies for a TTL value of 300 s and going up to 11 copies when TTL is set to 7200 s. These results are explained by the different behaviour of Prophet when changing its settings. In fact, under Cfg2, a previous encounter of the RSU will experience a quick decay in its predictions leading to an ear-

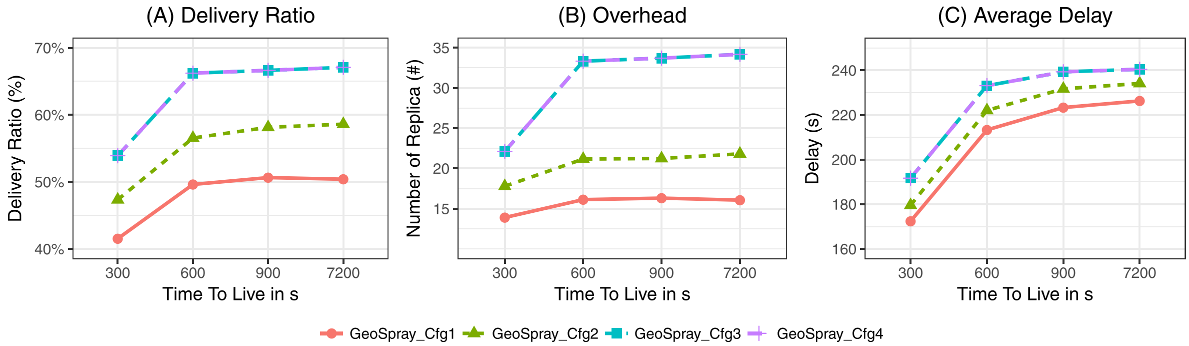


**Fig. 13.** Simulation results for GeoSpray with default parameters ($GeoSpray\_Cfg_1$) and others evaluated configuration: $GeoSpray\_Cfg_2$, $GeoSpray\_Cfg_3$ and $GeoSpray\_Cfg_4$, as function of bundles TTL under Scenario B.

lier and more frequent bundle forwarding compared to Cfg1. In the latter case, bundles are kept for a long time without being largely replicated since its predictions decay very slowly.

*Evaluation of average delay:* Fig. 12(C) shows an increasing average delay in the function of Bundle TTL for both versions of Prophet, starting at an affordable delay of 140 s up to 750 s and 395 s for Cfg1 & Cfg2, respectively. These results are due to the introduced looping vehicles. Indeed, they successfully capture a large fringe of bundles since their predictions for meeting RSU are higher. However, these encounters are time spaced and therefore a higher TTL allows the delivery of older bundles. Regarding the peak of Cfg1, it is explained by the default settings of Prophet that tend to keep bundles instead of replicating them since the predictions decay very slowly, whilst the looping vehicles are their main carriers and should encounter RSU only after a long delay.

#### 6.2.3. Evaluating the impact of increasing R and guaranteeing the handover of the replication quota on GeoSpray

As previously undertaken in Section 6.1.3, this study tries to evaluate the impact of both an increased maximum number of replicas $R$ and the use of the *H2HAck* mechanism, when considering similar simulation parameters and metrics but introducing looping vehicles. As a reminder, the *H2HAck* mechanism is a proposition that aims to ensure and grant the handover of replication quota, in disruptive and unreliable networks. Simulation parameters are resumed in Table 6.

*Evaluation of delivery ratio:* Compared to those in the previous scenario, the results in Fig. 13(A) show an average improvement of 10% in the delivery ratio for all the considered configurations, with Cfg3 & Cfg4 performing equally and outperforming both Cfg2 and Cfg1. The Introduction of the looping vehicles coupled to an increasing TTL is involved with this improvement since these vehicles are able to deliver more bundles before their expiry progressively to a longer bundle lifetime. Finally and as concluded previously, the use of the *H2HAck* mechanism enhances performance in a significant manner, far more than increasing the maximum number of replicas $R$.

*Evaluation of overhead:* In comparison with the general performance improvement, Fig. 13(B) brings to light a small and hopefully affordable drawback that consists of an increased overhead for all the considered configurations, especially for Cfg3 & Cfg4. The relative controlled overhead of Cfg1 & Cfg2 is due mainly to the protocol approach, jointly, with the lack of any mechanism to ensure the handover of replication quota. Therefore, some replicas are lost and the generated overhead is low. This behaviour contrasts with that observed for Cfg3 & Cfg4, where the use of the *H2HAck* mechanism increases the overhead. The reasons are its avoidance of the loss of some replicas and the fact that it exceeds even the fixed $R$ because, as explained before, it needs more synchronisation between vehicles to avoid exceeding this threshold.

*Evaluation of average delay:* The results in Fig. 13(C) reveal an average delay consistent with the previous scenario: a short delay for a TTL of 300 s and a high but stable delay for the others. The bundles delivered by Cfg3 & Cfg4 experience the longest delays, followed by Cfg2 and then Cfg1. This is due to the overall improvement in performance for all the configurations. Indeed, it comes with a higher overhead and results, ultimately, in a more congested network.

### 6.3. Scenario C: evaluation under a large-scale scenario with TAPAS Cologne

In the current section, we aim to establish a clear overview of the protocol hierarchy and evaluate the performances of the four considered protocols under a large-scale scenario based on realistic vehicle mobility. Furthermore, after achieving similar studies, with and without looping vehicles, in scenarios A & B, we are especially interested in the ability to predict current results based on small and synthetic scenarios and therefore, to offer appropriate responses to some crucial questions raised by researchers such as:

- Is it possible to correctly predict the protocol performances deployed in the real world, since it is their main target, from evaluations done under small and not-realistic scenarios?
- Should the protocol evaluations be done more often under large-scale and realistic scenarios?

In this regard, we rely here on the TAPAS testbed that provides a large-scale road map and realistic vehicle mobility, all at once. Indeed, it includes mobility traces from 38,592 vehicles from the town of Cologne, Germany, over a 2-h period, from 06.00 to 08.00, while these vehicles evolve in a very large road map including downtown Cologne and its peripheral zone, constituting an area of 29 km × 33 km.

For the purpose of our case studies and due to computational constraints, we made some adjustments to the data provided by TAPAS. Firstly, the traffic demand modelling was limited to 1 h only and the total number of simulated vehicles was shrunk to one third, which is roundly equal to 9920 vehicles, as indicated in Table 3. Furthermore, the map was divided into sectors of 1 $km^2$ size (1 km × 1 km) as illustrated in Fig. 14, with a single (01) RSU placed at the main intersection of the considered sector. Therefore, a total of 957 sectors were created for as many RSUs. Concerning data traffic and unlike previous analyses, the vehicles made use of an anycast scheme to send periodical bundles to any RSU; by addressing them first to the RSU of the current sector and then fol-

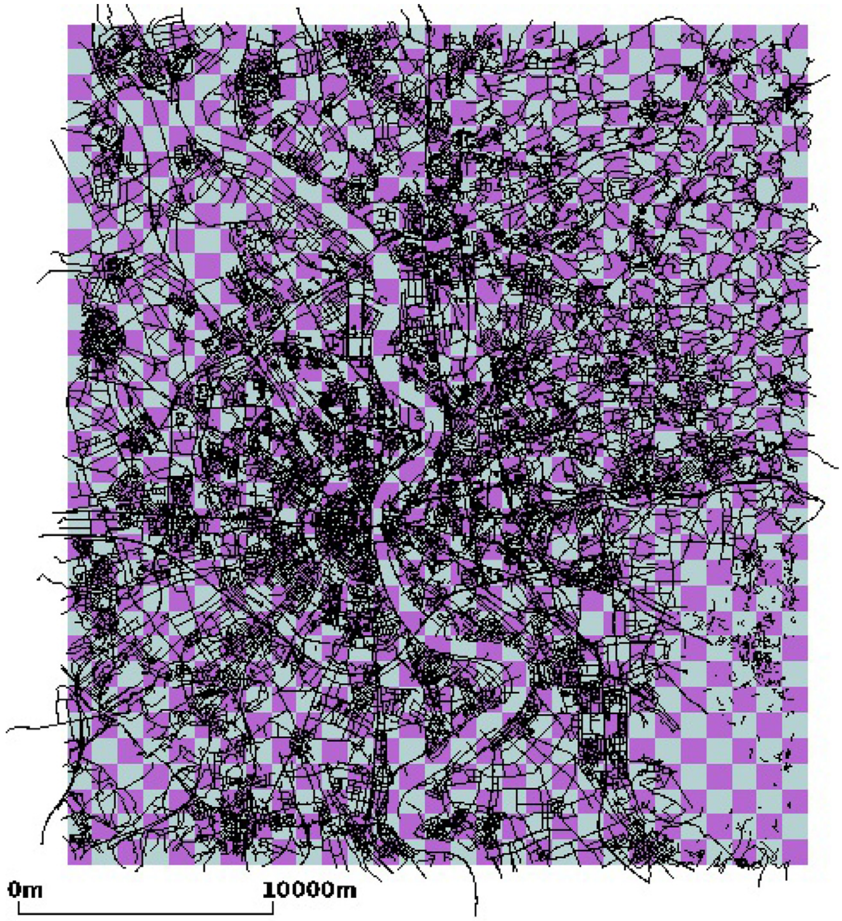


**Fig. 14.** Road network city of Cologne divided in 957 sectors used in large scale scenario.

lowing to a sector change, they were readdressed to the RSU of the current traversed sector.

Also, we deliberately restricted our evaluations to two analyses. The first one is dedicated to the four considered protocols and the second targets only Prophet and its default & proposed settings. Indeed, running such simulations involves huge computational costs and previous studies have already demonstrated the positive impact of increasing *R* and even more of using the *H2HAck* mechanism in the GeoSpray protocol. Finally, the considered performance metrics are, successively: Delivery Ratio (DR), Overhead (O), Average Delay (AD) and, optionally, Hop Count (H).

#### 6.3.1. Global performance evaluation for all protocols

As stated before, the main focus of this study is to evaluate the performances of Epidemic, GeoSpray, Prophet and Direct Delivery, but also to bring to light the protocol hierarchy and its possible differences with previous observations when they are tested in a large-scale scenario with realistic vehicle mobility. To ensure a fair comparison, the protocol settings and simulations parameters are similar to those considered previously and are resumed in Table 4.

*Evaluation of delivery ratio:* The results in Fig. 15(A) show overall good performance for all protocols. Epidemic outperforms the others by delivering up to 80% of bundles, followed surprisingly by Direct Delivery, then GeoSpray and lastly Prophet that achieves a delivery ratio of 70%. Regarding the bundle TTL, increasing its value enhances the delivery ratio of all protocols, but to a limited extent. These results were not expected nor predicted by previous studies since they fail to predict the good performance of Direct Delivery and more importantly, the protocol hierarchy. Nevertheless, these results are explained by multiple factors. The first one lies in the use of an anycast communication scheme, in parallel with the large dissemination and the great number of RSUs. In fact, by adopting such a communication scheme, the vehicle increases its probability of encountering and reaching 1 of the 957 identified RSUs; therefore, it clearly appears that under a realistic urban mobility scenario, and when using VDTN anycast transmission the probability of finding a relaying vehicle that will pass nearby any anycast destination node is very high, which increases the deliverability of carried bundles. Secondly, the approach advocated by Direct Delivery simply resorts to waiting for a possible encounter between the current vehicle and a single RSU, which may happen very often as explained above. All of that occurs without generating any bundle replicas or overloading network bandwidth, which explains its better performance against both GeoSpray and Prophet. This also brings to light a possible use case for this protocol under some specific network and road map conditions. Finally, as demonstrated, the TTL has little impact on performance; this can only be explained by successful delivery of bundles before they expire and in a far shorter period than previously.

*Evaluation of overhead:* Unusually compared to previous scenarios, the results in Fig. 15(B) reveal a low overhead for all protocols. However, the protocol hierarchy is somewhat respected here since Epidemic is the one that generates the most overhead, followed by Prophet and GeoSpray and then Direct Delivery with its near null overhead. Also through the results, it is noticeable that the Epidemic overhead increases slightly with an increasing TTL, unlike the other protocols for which the overhead is relatively stable. The main explanation for these results lies in the approach advo-

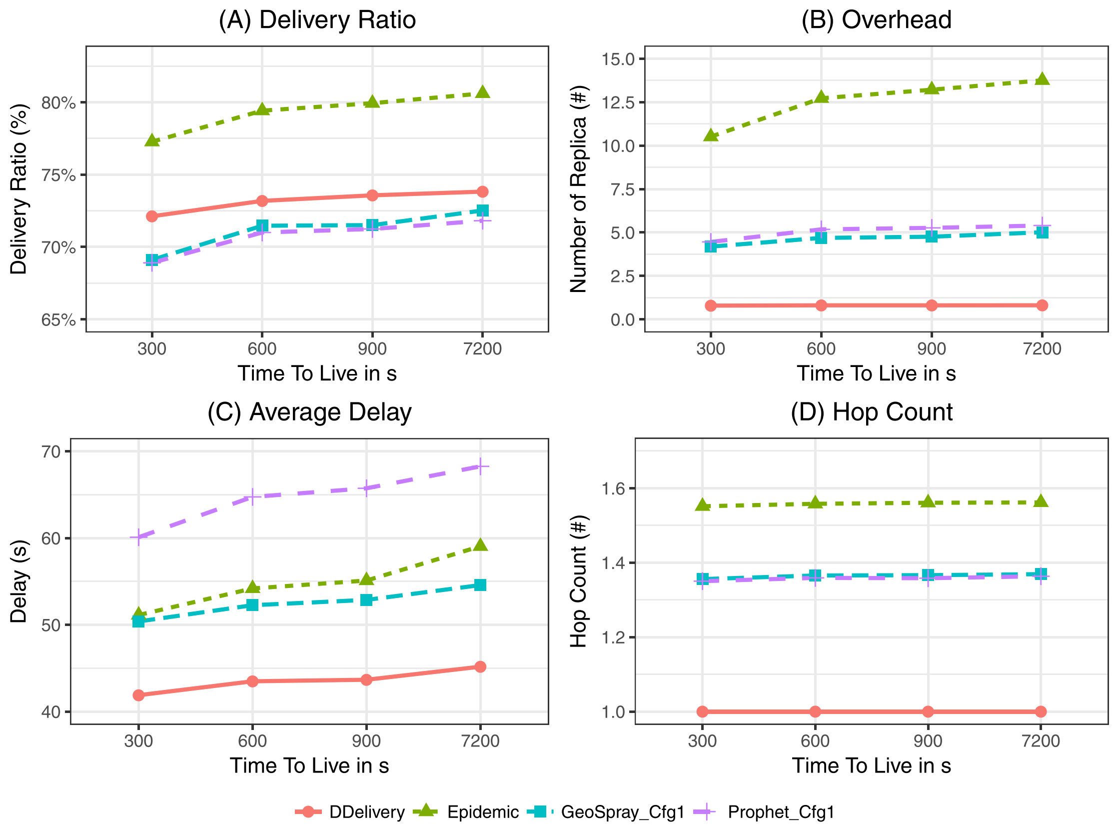


**Fig. 15.** Simulations results for Direct Delivery (abbreviated in DDelivery), Epidemic, Prophet and GeoSpray protocols as function of bundles TTL under the large scale Scenario C (TAPAS Cologne).

cated by each protocol. Indeed, Epidemic spreads bundles in the network without any constraint, coupled with an increasing TTL. This results in a longer lifetime for bundles which are more often replicated. Concerning Prophet and GeoSpray, as stated before, their approaches do not generate a lot of replicas or are limited. Finally, the Direct Delivery overhead is a side effect of delivering bundles without successfully acknowledging them; therefore, some replicas may exist.

*Evaluation of average delay:* While readers should note that the presented delays are averaged and the bundles may be delivered after a much longer time, the simulation results in Fig. 15(C) reveal shorter and low delays compared with previous scenarios for all protocols. Prophet requires the most time, followed by Epidemic, GeoSpray and finally Direct Delivery. Further observations also show a continuously small increase in delay in parallel with an increasing TTL, which may be due to the overall enhanced performances. Regarding Epidemic and GeoSpray, they generate more replicas which result in a more loaded network and ultimately in delays higher than those observed for Direct Delivery. Finally, Prophet achieves the worst delay whose potential explanation lies in its predictive approach which is not suited to the current scenario and to its anycast communication scheme. Consequently, predicting future contacts based on their history can be harmful and leads to a bad forwarder selection and a significant increase in bundle delivery delay.

*Evaluation of Hop Count:* Observations made based on Fig. 15(D) depict small and quite close hop counts for all the protocols, with a stable performance in function with an increasing TTL. The results here are partially expected since the anycast scheme fosters more direct forwarding to the final recipient instead of relying on multiple intermediate relays, this being especially true for Direct Delivery and Prophet. However, the overall lower performance of GeoSpray against Epidemic is less expected and can be explained only by the relative closeness of the RSU and its good reachability (through 2 hop counts on average, according to Epidemic performance) in this scenario and when considering an anycast scheme. Consequently, under such conditions, a large fringe of vehicles minimises the corresponding *METD* metrics which results in less bundle forwarding.

### 6.3.2. Evaluating prophet under default and proposed settings

In a similar way to research undertaken previously, we are interested in this current study in evaluating the performances of Prophet. More precisely, it is about evaluating the potential gain following the proposal of adapted settings to the considered scenario, especially since the previous studies did not allow any recommendations to be established or reach a solid conclusion. Once again, the simulation parameters and metrics are analogue to previous ones, while the default and proposed settings for Prophet are resumed in Table 5.

*Evaluation of delivery ratio:* The simulation results in Fig. 16(A) show good performances for both Cfg2 & Cfg1, with a small advantage for the former, that does not exceed 2–3%. The overall good results are not surprising and are explained by the anycast communication scheme which facilitates the delivery of bundles for any considered protocol as demonstrated before. However, the relatively small gain of Cfg2 with respect to Cfg1 is disappointing. Indeed, it highlights the challenging task which consists of successfully adapting the Prophet parameters to the considered scenario. Finally, as previously observed, the delivery ratio increases linearly with bundle TTL because more bundles can be delivered before expiry.

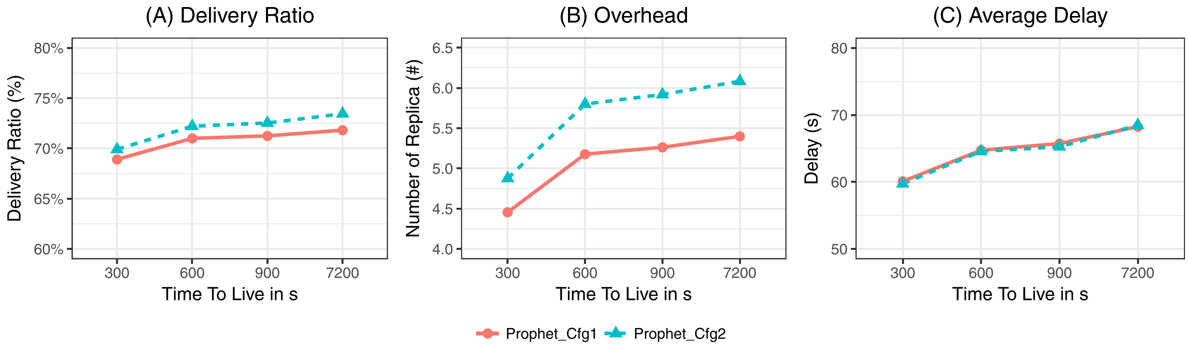


**Fig. 16.** Simulation results for Prophet with defaults ($Prophet\_Cfg_1$) and optimized ($Prophet\_Cfg_2$) parameters as function of bundles TTL under the large scale Scenario C (TAPAS Cologne).

*Evaluation of overhead:* As expected , the Prophet protocol generates few replicas only. This applies to both evaluated configurations, particularly to Cfg1 and its default settings as illustrated in Fig. 16(B). The low overhead of Prophet is due to the protocol approach as explained before, whereas the higher overhead of Cfg2 compared to Cfg1 lies in the considered settings which foster a quick decay of predictions and result in more important bundle replication.

*Evaluation of average delay:* As shown in Fig. 16(C), both Prophet configurations achieve a similar average delay for bundle delivery, with a stable increase in function with an increasing TTL. This behaviour is due to the growing number of bundle replicas that live longer, overload the network and consequently increase the delays. Regarding the similar results of Cfg1 & Cfg2, they were not expected since the use of adapted settings should avoid bad forwarder selection; however, this is not the case. An explanation of this may lie in the incapacity to correctly adapt the Prophet settings combined with the anycast scheme and the approach advocated by the protocol which tries to predict future contacts based on their history, without any certitude about a possible correlation between past and future vehicle contacts.

## 7. Conclusion and perspectives

In this paper, we focus on Vehicular Delay Tolerant Networks (VDTNs) and, in particular, routing protocols dedicated to them. Therefore, extensive work was conducted that covers various relevant aspects. Firstly, the origins & historical background of VDTNs in parallel with the taxonomy of their routing protocols were covered. Then, related works and comparative studies found in the literature were analysed. Following that, four (04) main protocols were selected according to multiple criteria such as the followed replication strategy, the knowledge used to make forwarding decisions or the generally advocated routing approach. Thereafter, these protocols, namely Epidemic, Direct Delivery, Prophet, and GeoSpray, were studied in depth and detail. Subsequently, the last two (02) appeared to be the most promising ones since they foster interesting approaches, i.e. predictive/social on the one hand and geographically-based on the other and are particularly competitive. Moreover, through this work, tools and simulators dedicated to vehicular networks were studied and compared.

Finally, we conducted an extensive comparative study and a performance evaluation of the considered routing protocols under small- and large-scale scenarios with synthetic as well as realistic vehicle mobility. This was done by successfully implementing all the protocols under the Veins simulation framework and with the help of the TAPAS Cologne testbed which provides a large and realistic scenario. Besides, two distinct settings of Prophet and two main factors that impact on the performance of GeoSpray were evaluated. As a result of this overall work, multiple findings leading to recommendations listed below could be made:

- Considering road map and network conditions, in parallel with a selected communication scheme, greatly influences protocol performances; therefore, predicting the performances of protocols when deployed in real environments, on the basis of a small-scale scenario and synthetic vehicle mobility, is not feasible. For instance, Direct Delivery performs poorly under a small-scale scenario and a unicast communication scheme, which contrasts highly with its own performance when considering a realistic scenario and an anycast communication scheme.
- Simulations results for the large-scale scenario highlight the potential benefits of adopting an anycast communication, which enhances all protocol performances. Furthermore, among all the protocols, Direct Delivery and its straightforward approach is the one which benefits the most from the anycast and the large number of RSUs, by delivering more bundles than complex solutions like GeoSpray and Prophet, while cutting the overhead by more than 90% compared to Epidemic, and achieving, consequently, an ideal trade-off between a good delivery ratio and an affordable overhead. Thus, these unexpected results stress the potential use of Direct Delivery and its routing approach under ideal conditions regarding the considered scenario and the adopted communication scheme.
- Correctly predicting the performance of protocols on the basis of a small-scale scenario and synthetic vehicle mobility is not feasible. Therefore, if routing protocols were to be deployed in the real-world by researchers, they should be evaluated under conditions as close as possible to it, which means large-scale scenarios and realistic vehicle mobility.
- A geographical approach as advocated by GeoSpray outperforms the predictive one of Prophet under all considered scenarios. Consequently, future proposals for VDTNs routing protocols should focus more on this promising approach.
- Adapting the settings of Prophet to the considered scenario is a challenging task. Indeed, when it is not done correctly, the performances of Prophet are improved to a very limited extent. Conversely, introducing looping vehicles greatly enhances performance since they reflect a community-based mobility model, which is much better suited. Thus, future research on Prophet should focus on proposing a mechanism to automatically adapt protocol settings.
- The GeoSpray performance can be enhanced greatly by adopting a mechanism to ensure the handover of replication quota, as for the proposed *H2HAck* mechanism, while increasing the maximum number of replica *R* slightly enhances the performance. Hence, future works on GeoSpray should address the

proposal for a mechanism to ensure the handover of the replicas.

- In general, the optimal Time To Live (TTL) of bundles varies between 300 and 600 s. Therefore, considering a higher TTL has a limited impact on results.
- In work found in the literature, many authors attribute to the Epidemic and Direct Delivery protocols, maximal or minimal boundaries regarding specific performance metrics such as Delivery Rate, Overhead or Average Delay. Our results tend to invalidate these statements except for Overhead, for which Epidemic is a maximal boundary and Direct Delivery is a minimal one.
- The need for realistic simulators & tools combined with real word mobility traces is a key aspect when evaluating the VDTN routing protocols, but unfortunately, it is too often neglected. This is especially true for the selected protocols for which quite large performance deviations can be observed between their original evaluations under not-realistic simulations or favourable scenarios and our evaluations. The GeoSpray protocol is a good example of this trend.

For future research, we intend, firstly, to enhance and mature the common architecture which forms the basis of our implementation of the considered protocols under the Veins simulation framework, and which is already publicly available on the software development platform GitHub [65]. Also, in our opinion, the interesting findings related to the good performance of Direct Delivery in the large-scale scenario and the positive impact of the proposed *H2HAck* mechanism both deserve to be considered further. At last and over the long term, it would be very interesting to conduct similar comparative studies, relying on various large-scale scenarios and realistic vehicle mobility traces, to evaluate various radio technologies including cellular networks or to expand the comparison to other routing protocols.

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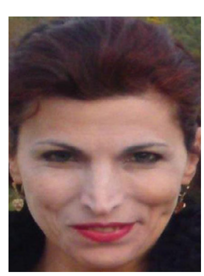
**Arslane Hamza-Cherif** is a Ph.D. Candidate, since December 2012, at the University of Abou Bakr Belkaïd, Tlemcen, Algeria. He received a License degree in Computer Sciences from the University of Ahmed Ben Bella, Oran, Algeria in 2010 and a Master degree in Computer Sciences, specialized in Networking & Distributed Systems, in 2012 from the same University. His research interests cover Computer Networks, Wireless Networks, P2P. Currently, his research focuses on Intelligent Transportation Systems, Vehicular Networks, Delay Tolerant Networks and lastly on the design and the development of routing protocols for Vehicular Networks, more specifically Vehicular Delay Tolerant Networks.

**Khaled Boussetta** is associate professor at L2TI laboratory of the Institut Galilée, University Paris 13, since September 2004. He received an M.S. degree in Computer Science from University Paris 6 in 1996 and in 2003 a Ph.D. degree in Computer Science, with the highest honors, from the University of Versailles. In 2001, he worked as a visiting researcher at the Network Research Lab at UCLA. In 2003 he joined the Networks and Performances Analysis team within the LIP6 laboratory, University Paris 6, as a postdoc researcher. Since 2012, he is external collaborator of the INRIA AGORA (former Urbanet) team located in Lyon. His research interests cover designing, modeling and performance evaluation of wireless networks. Currently, his research focuses on IoT, vehicular networks, Edge/Fog/Cloud, infrastructures dimensioning and network mechanisms to support delay sensitive applications. He is actively involved in the community as a TPC member, and a reviewer for many top-tier conferences and journals.

**Gladys Diaz** is associated professor, since 2001, at the University of Paris 13, France. She is member of the Network team at L2TI laboratory (Laboratory of Information Processing and Transmission). She received her Ph.D. degree in 2000 from INPL (Institut National Polytechnique de Lorraine), Nancy, France. She has obtained her HDR degree (Habilitation Diriger les Recherches) in 2016 from the UPMC University (Université Pierre et Marie Curie, Paris 6), Paris, France.
Her research interests are network and service architectures (SOA, Cloud Networking and Virtual networks), QoS and information modeling, ITS architectures and network management. More recent works are currently focused on the convergence between architectural and informational dimensions of the Services/Networks of the future, in special with the architectures and platforms in the Cloud, the dynamic orchestration and deployment of network services in virtualized environments (SDN/NFV). This work is concerning different uses cases: 5G network slicing, ITS routing, IoT platforms.



**Fedoua Lahfa** received her Master in Telecommunications from the University of Tlemcen, Algeria in 1990. Since 1991, she has been assistant professor in computer engineering. She has served on the scientific council and other Committees of Computer Department of the University of Tlemcen. Her research interest now is mobile networks and services, QoS service provisioning, Performance evaluation, modeling and security of large scale distributed system.

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**UNIVERSITE ABOU-BEKR BELKAID – TLEMCEN**

# THÈSE LMD

Présentée à :

FACULTE DES SCIENCES – DEPARTEMENT D'INFORMATIQUE

Pour l'obtention du diplôme de :

DOCTORAT

Spécialité : *Réseaux et Services*

Par :

**M. Arslane HAMZA-CHERIF**

Sur le thème

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# Design and Assessment of Routing Protocols For Vehicular Delay Tolerant Networks

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| | | | |
|---|---|---|---|
| M. CHIKH Azeddine | Professeur | Université de Tlemcen | Président |
| M^me LAHFA Fedoua | Professeur | Université de Tlemcen | Directrice de Thèse |
| M. BOUSSETTA Khaled | Maître de Conférences | Université de Paris 13 | Co-Directeur de Thèse |
| M. BENMAMMAR Badr | Maître de Conférences | Université de Tlemcen | Examinateur |
| M. KADDOUR Mejdi | Professeur | Université d'Oran 1 | Examinateur |
| M. KECHAR Bouabdellah | Professeur | Université d'Oran 1 | Examinateur |
| M^me DIAZ Gladys | Maître de Conférences | Université de Paris 13 | Invitée |

*Laboratoire de Recherche en Informatique de Tlemcen (LRIT)*
*BP 119, 13000 Tlemcen - Algérie*

UNIVERSITY OF ABOU BAKR BELKAÏD TLEMCEN

Faculty of Sciences

Department of Computer Sciences

# DOCTORAL THESIS

*Presented by:*
ARSLANE HAMZA-CHERIF

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# Design and Assessment of Routing Protocols for Vehicular Delay-Tolerant Networks

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*A thesis submitted in fulfilment of the requirements for the degree of Doctor in:*

*Computer Sciences: Networks & Services*

**Committee**

| | | |
|---|---|---|
| Prof. CHIKH Azeddine | University of Tlemcen | *President* |
| Prof. LAHFA Fedoua | University of Tlemcen | *Supervisor* |
| Assoc.Prof. BOUSSETTA Khaled | University of Paris 13 | *Co-supervisor* |
| Assoc.Prof. BENMAMMAR Badr | University of Tlemcen | *Examiner* |
| Prof. KADDOUR Mejdi | University of Oran 1 | *Examiner* |
| Prof. KECHAR Bouabdellah | University of Oran 1 | *Examiner* |
| Assoc.Prof. DIAZ Gladys | University of Paris 13 | *Invited* |

December 23, 2018

# Declaration of Authorship

I, Arslane HAMZA-CHERIF, declare that this thesis titled, “Design and Assessment of Routing Protocols for Vehicular Delay-Tolerant Networks” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

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Date:

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English: "*Demand much from yourself, little from others, and you will prevent discontent.*"

French: "*Exige beaucoup de toi-même et attends peu des autres. Ainsi beaucoup d'ennuis te seront épargnés.* "

Confucius

# *Abstract*

Doctor

**Design and Assessment of Routing Protocols for Vehicular Delay-Tolerant Networks**

by Arslane HAMZA-CHERIF

In the context of an increasing adoption of Intelligent Transportation Systems to increase the safety and optimise the management of road traffic, Vehicular Delay-Tolerant Networks (VDTNs) emerged as a hot research topic that will revolutionise the daily-life of drivers and passengers. Nevertheless, there is still a long journey before the adoption of VDTNs due mainly to the lack of a consensus regarding the routing protocol to adopt. Therefore, the sole focus of this Thesis is data routing in VDTNs, through the study of well-known routing protocols, the design of newer ones, and lastly their assessment. The latter may be achieved via realistic computer simulation that obey to specific requirements regarding the involved network simulator & vehicle mobility or the considered scenario. Indeed, through the long-journey that was this Thesis, we proposed first the predictive VDTN routing protocols ProCC based on a converge-cast approach and the Prophet protocol. The proposal achieved mixed results due to multiple factors including the unpredictability nature of vehicle mobility, but ultimately allowed us to switch our efforts to the proposal and development of one of our main contributions, namely the GeoDTC protocol. The promising GeoDTC is inspired in well-known geographic-based VDTN routing protocols, and able to achieve impressive results by relying on its multiple mechanisms & features. Besides that, the lack of an up to date, realistic and large-scale assessment of main VDTN routing protocols definitely convinced us of the necessity of achieving such large and important work. This lead us to the performance evaluation of four well-known protocols via a large-scale scenario based on the TAPASCologne mobility dataset, and consequently brought to light many interesting findings, whereas the persistent difficulties to successfully apply a predictive approach to VDTNs were further confirmed. Finally, to achieve these works, we developed an architecture for the implementation of VDTN routing protocols based on the VEINS simulation framework, and which is publicly available on the software development platform GitHub, in the hope that this will reduce the development gap and enrich the research community.

**Keywords:** Intelligent Transportation Systems, Vehicular Ad hoc Networks (VANETs), Vehicular Delay-Tolerant Networks (VDTNs), routing protocols, VDTN routing protocols

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# Contents

# List of Figures

# List of Tables

# List of Acronyms

**5GAA** 5th Generation Automotive Association.

**ACO** Ant Colony Optimization.

**AIFS** Arbitration Inter-Frame Space.

**ARC-IT** Architecture Reference for Cooperative and Intelligent Transportation.

**ASTM** American Society for Testing Materials.

**BSS** Basic Service Set.

**BSSID** Basic Service Set Identifier.

**C-ITS** Cooperative Intelligent Transportation System.

**C2X** Car To X.

**CALM** Communications Access for Land Mobiles.

**CAM** Cooperative Awareness Message.

**CCH** Control Channel.

**CH** Channel.

**CSMA/CA** Carrier Sense Multiple Access with Collision Avoidance.

**CVRIA** Connected Vehicle Reference Implementation Architecture.

**CW** Contention Window.

**DCC** Decentralized Congestion Control.

**DCF** Distributed Coordination Function.

**DENM** Decentralized Environmental Notification Message.

**DOT** Department of Transportation.

**DSRC** Dedicated Short Range Communication.

**DTN** Delay-Tolerant Network.

**DTNRG** Delay-Tolerant Network Research Group.

**EDCA** Enhanced Distributed Coordination Access.

**ETSI** European Telecommunications Standards Institute.

**FCC** Federal Communications Commission.

**GeoDTC** Geographic routing protocol based on Distance, Time and Custody transfer.

**GPS** Global Positioning System.

**IDM** Intelligent Driver Model.

**IPN** InterPlanetary Networking.

**IRTF** Internet Research Task Force.

**ITS** Intelligent Transportation System.

**IVC** Inter-Vehicle Communication.

**JPO** Joint Program Office.

**LTE** Long Term Evolution.

**LTE-V2X** LTE Vehicle To Everything.

**MANET** Mobile Ad-Hoc Network.

**METD** Minimum Estimated Time of Delivery.

**MIB** management information base.

**MMTS** Multi-agent Microscopic Traffic Simulator.

**NHDP** NeighbourHood Discovery Protocol.

**NP** Nearest Point.

**OCB** Outside the Context of a BSS.

**OFDM** Orthogonal Frequency-Division Multiplexing.

**OSM** Open Street Map.

**ProCC** Probabilist ConvergeCast.

**RFC** Request For Comment.

**RSU** Road Side Unit.

**RVC** Roadside-to-Vehicle Communication.

**SAE** Society of Automotive Engineers.

**SCF** Store, Carry & Forward.

**SCH** Service Channel.

**TIS** Traffic Information System.

**V2I** Vehicle To Infrastructure.

**V2V** Vehicle To Vehicle.

**VANET** Vehicular Ad-Hoc Network.

**VDTN** Vehicular Delay-Tolerant Network.

**VN** Vehicular Network.

**WAVE** Wireless Access in Vehicular Environments.

**WSMP** WAVE Short Message Protocol.

**WSN** Wireless Sensor Network.

*To all those who are dead but are still living in my head. . .*

*To all PhD candidates that felt, feel or will feel depressed one day during the long journey which is a thesis. . .*

*To my fiancee, my family and my friends for their sacrifice, support and patience during these years. . .*

# Chapter 1

# Introduction



This first chapter intends to provide the readers with a clear overview of the context that leads to the advent of Intelligent Transportation Systems in general, and to Vehicular Networks more particularly. Furthermore, the primary purpose of this thesis is to study routing protocols dedicated to Vehicular Delay-Tolerant Networks, and to design, implement and evaluate newer protocols able to cope with the requirements of such networks while achieving higher performances. Consequently, we present first the motivations behind this work, then we establish a summary of what we believe are the main contributions of this thesis. Finally, this introductory chapter is the right opportunity for us, to detail the organisation of the manuscript, before any further readings.

## 1.1 Context

From the launch of the Benz-Patent-Motorwagen by Karl & Bertha Benz more than 130 years, which is widely recognised as the first vehicle powered by an internal combustion engine, and the mass production of the Ford Model T via a moving assembly-line imagined by Henry Ford in 1913, to nowadays, where more than 97 million vehicles have been produced over the world in 2017 [OIC17]. The automotive industry became in more than a century one of the most successful economic sectors. Furthermore, it has greatly impacted our modern society, by shaping our daily lifestyle and routines, participating to the birth or growth of other economic branches and last but not least facilitating the transport of goods and persons. However, the increase in the number of cars combined to rapid population growth and a large expanse of urban areas, as it happened during the second half of the 20th century, has led to the multiplication of real-life transportation problems like; accidents, traffic jams. This resulted through a domino effect in economic and ecologic concerns such as a notable increase in goods delivery delays, waste of precious resources, especially motor fuel and a rise in pollution.

In such a context, road safety remains a crucial topic even with the improvements made during the last decades. Indeed, previous efforts in the area have mostly been focused on improving and creating safety systems inside the vehicles (e.g. security belt, anti-lock braking system, airbag, and so on) and seem to have reached their goal with a substantial decrease in the number of fatalities due to motor vehicle accidents. Despite this, the World Health Organisation reported in 2015 that more than 1.2 million people die each year due to road injuries, making it the leading cause of death among people aged between 15 and 29 years [WHO15]. Moreover, in 2017, the number of death due to car crashes topped 40.000 in the USA, while reaching more than 3.600 in both France and Algeria, in parallel to a more significant number of injured people as highlighted in Table 1.1.

Meanwhile, many solutions were experimented to manage road traffic efficiently and to address congestion, but with little success. Indeed, early solutions focused mainly on the development of road infrastructure to sustain increasing traffic but neglected the human behaviour, which turns out to be a key factor as brought to light by the German mathematician Dietrich Braess and the paradox that bears his name (The Braess's Paradox) [Bra68]. In addition to the occurrence of fake traffic jams called ghost jams or traffic waves. Therefore, further solutions tried to alter and change drivers behaviours, first by creating national road information centres particularly in western countries, to estimate and prevent future congestions. Secondly, by adopting tolls with prohibitive prices in many cities like in London, Milan or Singapour for smoothing downtown traffic flow, or by lowering the maximum allowed speed on highways from 130km/h to 110km/h to avoid ghost jams, as experienced recently in France highways A7 and A9.

Despite the experiments of previous solutions, the traffic congestion is steadily increasing over the World, in parallel to its various drawbacks summarised above. For instance, the Texas Transportation Institute has estimated the cost of congestion to be up to 160 billions dollars with an extra delay of 42h per commuter and 11.7 billions litres of fuel wasted across the 471 major urban areas of the United-States in 2014 only [Sch+15]. In France, accordingly, to the 2014 report of INRIX, the extra delay per commuter has risen to more than 28h, while the direct and indirect costs of congestion are estimated to more than 18.7 billion dollars. Finally, due to a lack of officials statistics in Algeria, it is difficult to estimate its costs correctly, however studies conducted by Professor Chems Eddine Chitour of the National Polytechnic School put forward the figure of 182 millions litres of wasted fuel across the country

| Country | Algeria | France | USA |
|---|---|---|---|
| **Total Death** | 3,639 | 3,684 | 40,100 |
| **Total Injured** | 36,287 | 76,840 | 4,57 millions |
| **Year** | 2017 | 2017 | 2017 |
| **Source** | [CNP17] | [ONI17] | [NSC17] |

TABLE 1.1: Road accident victims reported in Algeria, France & USA for 2017

and more than 150 millions dollars economic loss for the 3 major urban areas for 2014 only. All these statistics are summarised in Table 1.2.

Therefore, to make road traffic safer and reduce congestion, on-field stakeholders started to shape the future of road traffic management, where Traffic Information Systems are augmented with further capabilities to sense the traffic flow efficiently and prevent crashes, by relying both on global sensors disseminate across the network and in-vehicle ones to collect information on the state of road traffic. Research works in that sense were further encouraged by a global context characterised by the emergence of Intelligent Transportation Systems (ITSs) pilots developed through national & regional programs, in addition to the continuous integration of electronic components & Global Positioning System (GPS) navigation systems, and the advent of affordable information technology as cellular networks and Wi-Fi. Consequently, these systems are commonly identified by ITSs, and can turn vehicles from a passive to an active component of the system, by allowing them to gather information, cooperate with others and finally report information to the central system. To that end, ITSs introduce the concept of Inter-Vehicle Communication (IVC), which regroup a wide range of technology and standards dedicated to communication from a car to any other entity of the network (often designated by Car To X (C2X) communication), like the IEEE 802.11p Wi-Fi standard or the IEEE 1609 standards family.

Consequently, on-field stakeholders and automakers have realised that such Intelligent Transportation Systems can be extended to provide value-added services, in addition to their initial purpose which covers both road safety and traffic optimisation. Moreover, the adoption of Inter-Vehicle Communication technologies led to the emergence of networks constituted by vehicles, commonly named Vehicular Networks (VNs) or Vehicular Ad-Hoc Networks (VANETs), which are at the core of any Intelligent Transportation System, because they are envisioned to be the main mean of providing ITS applications presented before to the drivers of the road network.

| Country | Algeria | France | USA |
|---|---|---|---|
| **Extra Delay Per Commuter (hours per year)** | — | 28h | 42h |
| **Congestion Costs (million dollars)** | 150 | 18,700 | 160,000 |
| **Wasted Fuel (million liters)** | 182 | — | 11,734 |
| **Year** | 2014 | 2013 | 2014 |
| **Source** | [Chi14] | [IC13] | [Sch+15] |

TABLE 1.2: Road congestion costs in Algeria & USA for 2014, in France for 2013

## 1.2 Motivations

In nowadays, VANETs emerged as a hot research topic among the global research field of ITS, fostered by public policies that aim to increase the safety of road passengers and to minimise the various sides effects of traffic congestions, as stated previously. While VANETs are described too often as the promising land that will revolutionise the relationship between humans and cars; there is still a long journey before it will happen. Indeed, VANETs are facing many challenges that will delay their broad adoption and one of their primary challenges consist in the design and the wide implementation of a dedicated routing protocol.

In the early stages of VANETs, researchers tried to deliver data by relying on some well-known Mobile Ad-Hoc Network (MANET) routing protocols, due to the relative closeness of context application and because a vehicle can be considered as a mobile node. However, due to the highly changing topology and the cost associated with the maintenance of topology information, these protocols failed to perform correctly. Therefore, researchers shifted to the proposal of routing protocols dedicated to VANETs. These latter faced a new challenge very quickly, that limits their scope of application. Indeed, driven by an Internet protocol overview, these protocols try each time to find and establish a route of an affordable delay, for a given couple of source & destination, which is near impossible in such dynamic networks that are VANETs. Consequently, researchers started to pay close attention to Delay-Tolerant Networks (DTNs), and to their alternative routing approach, that can relay data in a hop by hop manner until the destination, while being apt to be deployed over networks that experience high delays or frequent disruptions.

To successfully operate under such network conditions, DTNs advocate a set of critical concepts and principles, that have been standardised through multiple Request For Comments (RFCs), and most notably allow a permanent storage until resuming the packet forwarding, instead of dropping it, due to a high delay or a missing forwarder, as usually done in Internet routing. Therefore, the adoption of DTN concepts by VANETs, paved the way for the advent of Vehicular Delay-Tolerant Networks (VDTNs) and to routing protocols dedicated to them, able to successfully deliver data, despite the challenging network conditions.

Since then, many VDTN routing protocols were proposed, following various approaches. However, in practice, there is still few operational use cases and almost no full implementations. Several reasons lurk behind such a situation; the first one is the lack of a consensus among the research community about the approach to follow. Furthermore, many proposed protocols make assumptions and simplifications that are hard to accept, to envision in a vehicular environment. Lastly, a primary reason being, the low level of confidence in global observed results, which is closely tied to the difficulties to conduct on field experimentations or realistic simulations, under a sufficiently large scenario able to precisely assess protocol performances.

In this sense, this thesis fits into the continuous effort of providing the research community with general guidance regarding the most suitable VDTN routing approach. Moreover, a recurrent barrier faced by researchers and which this thesis tries to address is the unavailability of baseline implementation of well-known routing protocols, under a realistic simulator, to evaluate newly proposed protocols. Finally and most significantly, the primary motivation behind this thesis is the search for a VDTN routing protocol able to achieve better performances compared to well-known protocols, while taking into consideration its feasibility, degree of realism and lastly its capacity to be successfully deployed over a large-scale scenario.

## 1.3 Summary of Contributions

The main contributions of this thesis are summarised as follows

- **A State of the art on ITSs, VANETs and VDTNs** This work was done in order to provide a global overview on the current state of the art on Intelligent Transportation Systems, Vehicular Ad-Hoc Networks, Vehicular Delay-Tolerant Networks, and more specifically routing protocols dedicated to such vehicular networks. Therefore, we studied the main proposed ITS proposed across the world, in addition to their key characteristics and differences. Furthermore, we also investigate closely VDTN routing protocols and their taxonomy, as well as the recent advances in this research field.
- **Performance evaluation of the main VDTN routing protocols under small- and large-scale scenarios** Through this major contribution, we aimed to provide the research community with general guidance for the development of

future VDTN routing protocol, by comparing and evaluating well-known protocols and their respective routing approaches, under both of small- and large-scale scenario, with the use of a realistic simulator. Moreover, this work allowed us to make a quick tour of the main tools dedicated to the simulations of vehicular networks.

- **Proposal of a predictive VDTN routing protocol** The purpose of this work was to adapt and evaluate well-known predictive routing protocols to the vehicular environment. Moreover, it was a first attempt to provide an alternative VDTN routing protocol, based on a hybrid approach.
- **Proposal of a geographic VDTN routing protocol** In this major contribution, we conducted a detailed study of main geographic VDTN routing protocols, then we switched to the proposal of a new geographic VDTN routing protocol. The proposal was able to achieve better performances when compared to other well-known protocols, and most significantly brought to light neglected aspects capable of greatly increasing the performance of any routing protocol.
- **Development of a common implementation platform for VDTN routing protocols** As stated before, one of the key motivation behind this thesis was the unavailability of baseline implementation of well-known routing protocols, under a common and realistic simulation environment. Therefore, We tried to address it in this contribution, notably by proposing and developing a common implementation platform for VDTN routing protocols, which also facilitate the comparison of protocols under similar considered parameters and environments. Furthermore, we developed and made available baseline implementation for some well-known protocols.

## 1.4 Thesis Outline

The remainder of this thesis is organised as follows:

- **Chapter 2** presents the main ITS projects across the world, their recent advances, and the various standards related to IVC technologies. Besides, it also depicts a brief background related to the evolution of VANETs into VDTNs, in addition to a taxonomy of routing protocols dedicated to the latter.
- **Chapter 3** initiate the readers to the key factors needed for a realistic evaluation of a VDTN routing protocol, as well as the various simulation tools and available mobility datasets. The second facet of this chapter describes the proposed implementation platform for the development of future protocols succinctly.
- **Chapter 4** details one of our main contribution, namely the performances evaluation and comparative study of well-known protocols under a small- and large-scale scenario, based on a realistic simulator. It also highlights the key

findings that emerged from this work, including how the performances of a specific protocol can be improved with a minor change.

- **Chapter 5** is dedicated to the presentation and the evaluation of the first proposed routing protocol, namely the Probabilist ConvergeCast (ProCC) protocol. First, a quick review of similar works is provided then the protocol along with its operation mode are detailed. Finally, the main results and conclusions drawn from the evaluation of ProCC under a small-scale scenario are presented.
- **Chapter 6** is devoted to the presentation and evaluation of the second proposed routing protocol, namely the Geographic routing protocol based on Distance, Time and Custody transfer (GeoDTC). The chapter covers various aspects related to this major contribution, by providing first a concise review of main geographic-based VDTN routing protocols. Subsequently, GeoDTC is presented, and its key features & mechanisms behind its good performances are detailed. Lastly, the main results and conclusions of the large-scale and realistic evaluation of the protocol are discussed, notably because these latter brought to light aspects capable of greatly increasing the performance of any routing protocol.
- **Chapter 7** points out the interest of this thesis, compiles its contributions and the result of the current research, provides several perspectives for future works, and lastly briefly summarises the publications related to this thesis.

The bibliography is given at last.

# Chapter 2

# Intelligent Transportation Systems & Vehicular Networks

---

Through this chapter, we provide readers with a brief and concise literature review regarding Intelligent Transportation Systems (ITSs) and their development in two major research poles, namely: the United States of America (USA) and the European Union (EU). Furthermore, involved Inter-Vehicle Communication (IVC) technologies are presented, in parallel with the advocated protocol stack for future ITS in the USA and Europe. Following this first part, we will introduce Vehicular Networks (VNs), their historical background and moreover the reason behind the emergence of Vehicular Delay-Tolerant Networks (VDTNs). Finally, an overview of existing VDTN routing protocols is given, which allow us to put in context the works conducted in this thesis, and presented in the following chapters.

## 2.1 Intelligent Transportation Systems (ITS)

Although providing a unique and clear definition of ITS is merely possible, because organisations and countries involved in the process of their development tend to define them accordingly to their objectives and constraints. It is possible by now to provide a clear overview of what should be an ITS since all involved entities share a common vision and future in this regard.

In this sense, it is generally assumed that an Intelligent Transportation System (ITS) is a system designed to provide innovative and sustainable solutions for modern means of transport (including terrestrial, maritime or aerial transport, with the former being their principal target and the sole focus of this thesis). All this, to address public issues of steadily increasing negative impacts on daily life and economy, as well as to take part of the growing worldwide efforts to reduce the pollution and its side effects or to develop new services and applications centred on user needs [AG12].

Such a definition fits partially with the one of Traffic Information Systems (TISs), which were developed in many countries since the 60's with the sole goal of successfully manage road traffic to avoid congestions. However, ITSs should not be resumed to TISs, but rather to enhanced and augmented ones with two majors difference, the first consists in the application scope of ITSs, which incorporate road traffic management, as well as road traffic safety and infotainment applications or services. Thus, an ITS is a one-stop system that covers all aspects related to transportation. Secondly, unlike TISs which collect data on their own before generating statistic and valuable information to notify drivers and passengers about the state of the traffic, ITSs rely on several means to collect data, by using their sensors or those embedded on cars. Moreover, they tend to close the communication loop between vehicles and traffic management centres, by empowering vehicles with nowadays affordable information technology such as cellular networks and Wi-Fi. Therefore,

| Applications category | Latency tolerance | Range | Example (delay requirements) |
|---|---|---|---|
| **Road traffic safety** | Low latency | Local range | Pre-crash sensing/warning (50 ms) Collision risk warning (100 ms) |
| **Road traffic management** | Some latency is acceptable | Medium range | Traffic information - Recommended itinerary (500 ms) |
| **Third-party applications & services** | Long latency is accepted | Medium range | Map download update - Point of interest notification (500 ms) |

TABLE 2.1: ITS Applications: use-cases & requirements [MCF10]

this ultimately turns the vehicle from a passive component of the system fed by external data to an active component that generates data, cooperate with other vehicles and last but not least report to the system any event that occurred in its immediate vicinity.

This latter aspect of ITS corresponds to the concept of IVC which is a wide range of technology and standards dedicated to communication from a car to any entity of the network C2X. Furthermore, it allows the emergence of networks constituted mainly of vehicles, commonly named Vehicular Networks VNs or Vehicular Ad-Hoc Networks VANETs. Both will be discussed later in this chapter.

### 2.1.1 ITS Applications

As aforementioned, ITS applications are categorised into three main categories:

- Road traffic safety: The primary goal of this set of applications is to reduce road fatalities by assisting and warning the driver about the potential risks. This category covers applications like pre-crash sensing and collision risk warning.
- Road traffic management/efficiency: this category is intended to relieve traffic congestion by helping to monitor the traffic flow and by providing alternative itineraries to drivers. These applications make the transportation systems not only more efficient but also more environmentally friendly by optimising routes and decreasing gas emissions.
- Third-party applications & services: they include on-demand services related to infotainment, comfort or vehicle management like for instance notifying a point of interest (e.g. parking lots or restaurants). Finally, even though the previous categories are the top priority, those applications and services will capture the interest of automakers and stakeholders because they constitute an emerging business opportunity, and ultimately an undoubted source of profits, which could help to finance the deployment of ITSs.

One thing concerning the categories above of ITS applications is their different requirements, especially regarding the tolerated latency or the deployment range, which imply generally different solutions to provide them to the end user. In fact, road traffic safety applications obey to hard deadlines, in order to prevent a crash, for instance; therefore such applications tolerate only low latencies that do not exceed 100 ms. In contrast, road traffic management applications can tolerate higher latencies, while third-party applications & services have no deadlines; thus they tolerate higher latencies. Table 2.1 sums up these different requirements and provide some examples [MCF10].

### 2.1.2 ITS in the USA and Europe

In the past twenty years, ITS emerged as a hot research topic due to the growing interest of automakers and transportation agencies of official authorities. Consequently, many programs were funded to research, develop, evaluate and test various aspects & technologies related to ITSs, mainly in the three dominant research pole of the world, namely the USA, the European Union and the Japan, then in other countries like in Brazil, China, South Korea, Russia, Canada, Mexico and so on.

Within this context, it is hard to keep track of the recent progress of all these projects that aim to develop an ITS. Moreover, covering all of them is out of the scope of this thesis; Therefore, interested readers should pay attention to other works like in [AG12] which depicts a clear overview of existing projects in countries mentioned above. Regarding this thesis, we will present the recent advances of ITSs in USA and Europe only, which are well-documented and reached a sufficient level of maturation to envision their partial deployment in the near future.

#### 2.1.2.1 ITS in USA

In December 2014, The Joint Program Office (JPO) of the US Department of Transportation (DOT) unveiled the ITS Strategic Plan 2015-2019 [DOT14], which is in line with previous projects for the management of road traffic, and furthermore crowns 2 decades of intensive research works triggered by the decision of the Federal Communications Commission (FCC) to allocate 75Mhz of spectrum in the 5.9 GHz band for ITS, specifically for Vehicular Communication under the name of Dedicated Short Range Communication (DSRC) [FCC99].

Through this research plan, the JPO which coordinates the effort of all stakeholders, namely federal agencies of the DOT, automakers and standard organisations is launching its final stage for the development and the test of significant involved technologies before the advent and the deployment of the envisioned ITS America, which is an harmonised system that will operates at a national level. In fact, the plan is built around two key priorities, namely realising connected vehicle implementation by relying on the substantial progress made in recent years and advancing automation by shaping programs around the research, development and adoption of emerging automation-related technologies. Therefore to achieve these priorities, it defines six broad research program areas which include research, development and future deployment activities related to all necessary technologies. The defined program areas are as follow:

- Connected Vehicles: After more than 8 years since the publication of the wireless standard dedicated to vehicular communication, namely the IEEE 802.11p [IEE10], [IEE16a] and many years of a maturation process for other related-standards, like the IEEE Wireless Access in Vehicular Environments (WAVE) [IEE13] or Society of Automotive Engineers (SAE) J2735 [SAE16a]; The research works is entering a new stage with a primary focus on the adoption and eventual deployment of connected vehicles based on these standards.
- Automation: Nowadays, many automakers or big technology company are involved in a research program to develop automated road-vehicle which are expected to make road-traffic safer. In this regard, this program area focuses on automated road-vehicle systems and related technologies that transfer some amount of vehicle control from the driver to the vehicle.
- Emerging Capabilities: Automakers have realised the potential benefit of interconnecting their vehicles, to provide value-added services, including infotainment and commercial applications. Therefore, this program area focuses on the future generation of transportation systems which will include such applications.
- Enterprise Data: Continues existing efforts in operational data capture from stationary sensors, mobile devices, and connected vehicles and expands into research activities involving the development of mechanisms for housing, sharing, analysing, transporting, and applying those data for improved safety and mobility across all modes of travel.
- Interoperability: Focuses on how to ensure effective connectivity among devices and systems, mainly by developing a common framework/architecture for the interoperability between all involved entities in the envisioned ITS.
- Accelerating Deployment: Advances the work from adoption to wider-scale deployment in coordination with several other DOT agencies.

One of the major works related to the interoperability area is the development of the Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT), which provides a framework for planning, programming and implementing intelligent transportation systems [AI17c]. The last version of this framework (v8.1) is by now considered as the official architecture for ITS America, since it supersedes the National ITS Architecture (v7.1), by taking up most of its bases that was developed during more than 20 years, and merging them with the recent progress made

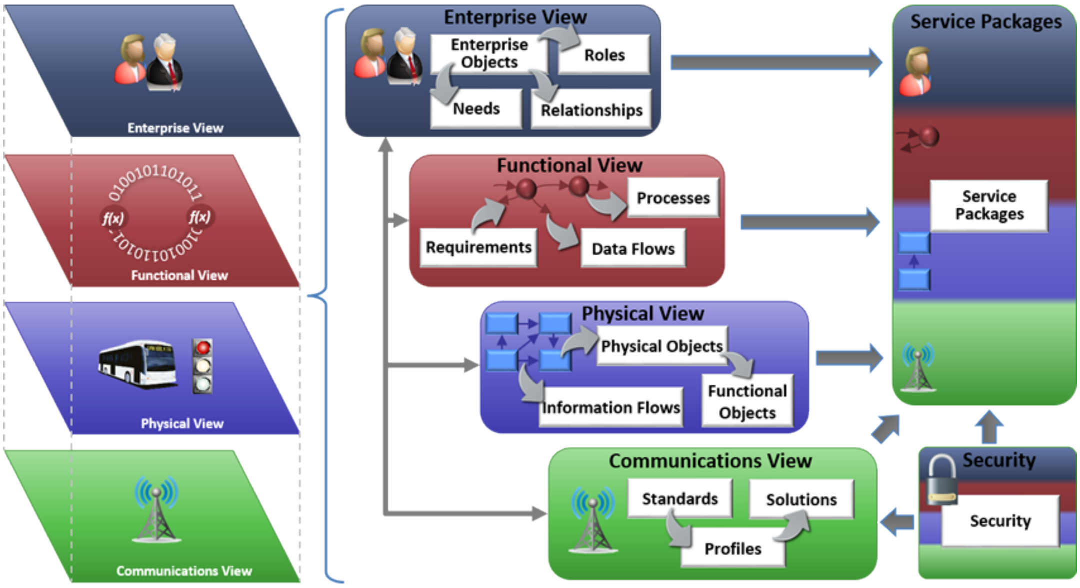


FIGURE 2.1: ITS America architecture v8.1 as defined by ARC-IT [AI17b]

on shaping the future of connected vehicles through the Connected Vehicle Reference Implementation Architecture (CVRIA) [AI17a]. Consequently, ARC-IT is built around a set of interconnected components that are organised into four views that focus on four different architecture perspectives. Moreover, ARC-IT defines the concept of service packages which are a set of atomic services dispatched across the different views and that work together to provide one of the many envisioned services provided by ITS America [AI17b]. An overview of the whole architecture is depicted in 2.1.

A brief description of the four views defined by ARC-IT is provided below:

- Enterprise: Describes the relationships between organisations and the roles those organisations play within the connected vehicle environment.
- Functional: Describes abstract functional elements (processes) and their logical interactions (data flows) that satisfy the system requirements.
- Physical: Describes physical objects (systems and devices) and their functional objects as well as the high-level interfaces between those physical objects.
- Communications: Describes the layered sets of communications protocols that are required to support communications among the physical objects that participate in the connected vehicle environment.

Regarding the critical priority consisting in realising connected vehicle implementation and its achievement. It is starting to materialise, especially after the decision of the JPO to launch the Connected Vehicle Pilot Deployment Program, which aims to design, deploy and test them across three pilots sites, in New York City (NYCDOT pilot), Tampa (THEA pilot) and Wyoming (WYDOT pilot). The three pilots programs are deployed with different settings regarding the road network environment, the vehicle fleet size or the device manufacturer. More interestingly, while the pilots are built around a shared vision, their goals differ sensibly. Indeed, the NYCDOT pilot focuses on improving the safety & mobility of travellers, and testing a large-scale deployment of Vehicle To Vehicle (V2V) & Vehicle To Infrastructure (V2I) technologies, over more than 8,000 vehicles. Regarding the THEA pilot, its primary focus consists in improving the road traffic management to avoid congestion during the peak hours, in the vicinity and major arterials of Tampa. Lastly, the WYDOT pilot tries to address the needs of commercial vehicle operators in the state, while reducing the number and severity of adverse weather-related incidents in the Interstate 80.

#### 2.1.2.2 ITS in Europe

The main entry point to the ITSs program of the European Union consists in the ERTICO-ITS Europe (ERTICO) organisation, which coordinates efforts of all stakeholders, through a public-private partnership of 120 companies and organisations. The purpose of ERTICO is to develop, promote and deploy technology solution for safer, smarter and cleaner mobility; mainly by co-founding or managing several projects and platforms that fit into four identified areas for smart mobility, namely: connected and automated driving, urban mobility, clean mobility and lastly transport and logistics.

The most notable projects or platforms sponsored by ERTICO are presented below [ERT18]:

- Advanced Driver Assistance Systems Interface Specifications (ADASIS): The purpose of this project is to define an appropriate interface and data model to exchange information between in-vehicle map database, ADAS (Advanced Driver Assistance Systems) and automated driving applications.
- MaaS Alliance: The Mobility as a Service (MaaS) Alliance is a public-private partnership, whose members work towards achieving a truly seamless and effortless ecosystem for new mobility services highly centred on user need, and which will combine multiple transport services into a single mobility service accessible on demand, for both travellers and goods.
- I_HeERO: The Harmonised eCall European Deployment project aimed to set the basis for the introduction of the Europe wide eCall system, which became mandatory in April 2018. As a reminder, the eCall system is envisioned to reduce road causalities and injuries, by cutting emergency response times by 40% in urban areas and by 50% in rural areas, through embedded devices that will automatically dial 112 and send Galileo coordinates to local emergency agencies, in the event of a serious road accident.

- Traveller Information Services Association (TISA): Coordinates the effort of multiple organisations and companies to successfully develop and implement valuable traffic and travel information services and products. Moreover, it ensures the relevance of these services vis-a-vis of the current policies and practices that emerged from other ERTICO projects or standards.
- Traffic Management (TM) 2.0: Is an innovation platform which brings together 36 members around a single goal, agreeing on common interfaces, principles and business models for facilitating data exchange between road vehicles and Traffic Management & Control Centres. Recently, this platform shifted from innovation to deployment in order to evaluate the proposed solutions, which are expected to be part of further ERTICO projects.

All these projects paved the way for the setting up of the Cooperative Intelligent Transportation System (C-ITS) Deployment Platform by the European Commission in early 2014. The Platform is conceived as a cooperative framework including national authorities, C-ITS stakeholders and the Commission, in view to develop a shared vision on the interoperable deployment of C-ITS in the EU [EC14]. Therefore, the Phase I of C-ITS which was conducted between 2014 and 2016, focused on providing policy recommendations for the development of a deployment strategy in the EU, identifying potential solutions to some critical cross-cutting issues and lastly initiating multiple pilot projects to create new ITS services for all European road users [EC16]. Regarding the Phase II initiated in 2016, it further develops a shared vision on the interoperable deployment of C-ITS towards cooperative, connected and automated mobility (CCAM) in the European Union, mainly by making tangible progress towards the definition of implementation conditions for topics already discussed during the first phase, especially those related to Security, Data Protection, Compliance Assessment and Hybrid Communication[EC17].

## 2.2 Inter-Vehicle Communication (IVC)

As stated before, Inter-Vehicle Communication IVC refers to any technology or standard that allows vehicles to communicate directly with other entities of the network without the need for any third party. This vehicle capability was made possible thanks to the technological prowess made in radio and wireless communications by the beginning of the 21st century, and moreover due to their constant enhancement and popularisation, like for instance Wi-Fi, cellular networks or Bluetooth.

### 2.2.1 IEEE 802.11p

Nowadays, one of the major technology upon which connected vehicles will be built consists of Wi-Fi, more specifically the IEEE 802.11p standard. This standard differs in many aspects with the traditional Wi-Fi, even if it shares with it many specifications.

#### 2.2.1.1 IEEE 802.11p specifications

Following to the decision of the FCC in 1999, to release a 75Mhz of spectrum in the 5.9 GHz band for Vehicular Communication under the name of DSRC [FCC99], the American Society for Testing Materials (ASTM) took up the task of developing a dedicated communication protocol which resulted by 2003, in the publication of the ASTM E2213-03 [AST03] that included the specifications and requirements of a first standard for vehicular communication. The ASTM standard was based on the already popular family of IEEE 802.11 protocols, more specifically on IEEE 802.11a [IEE99], and in 2004 the IEEE established the Task Group p (TGp ), in order to improve ASTM E2213-03 and include it to IEEE 802.11 family. TGp reached its goal in July 2010, when the IEEE 802.11p amendment was published [IEE10], and furthermore when it was superseded and enrolled into the new version of IEEE 802.11 [IEE16a].

The IEEE 802.11p standard was developed to support new emerging applications based on Inter-Vehicle Communication (IVC) and Roadside-to-Vehicle Communication (RVC), to decrease road traffic accidents and improve road traffic efficiency. Most importantly, to correctly perform this standard must cope with short connection times and highly changing topology, which differs from usual wireless communications requirements of other IEEE 802.11 standards. Consequently, it introduces a novel operation mode called Outside the Context of a BSS (OCB) mode, which can be activated by setting to true the new management information base (MIB) variable **dot11OCBActivated**, and allows nodes to operate without being part of a Basic Service Set (BSS), which implicitly translate into the removal of the time-consuming procedures that are authentication and association. Furthermore, instead of relying on a lengthy procedure for negotiating network parameters like the modulation and coding scheme, these nodes are invited to use well-known parameters for accessing the channel. Ultimately, all these simplifications allow the IEEE 802.11p standard to drastically shorten the latency of communication and cope with the requirements of VNs [R.S11].

Within this context, an OCB communication can be thought of as a regular Ad-Hoc/Infrastructure-less communication, based on an Independent BSS as commonly known. However, it should not be confused with it, given the differences between them. Therefore, to distinguish between communication within a BSS and outside of a BSS, the network identification ID Basic Service Set Identifier (BSSID)) is set to a wildcard in every frame transmitted in an 802.11p communications [ETS13a]. Regarding defined specifications and requirements, this standards details those that

| Transfer rate (Mbit/s) | Modulation scheme | Coding rate | Data bits per OFDM symbol | Coded bits per OFDM symbol |
|---|---|---|---|---|
| 3* | BPSK | 1/2 | 24 | 48 |
| 4.5 | BPSK | 3/4 | 36 | 48 |
| 6* | QPSK | 1/2 | 48 | 96 |
| 9 | QPSK | 3/4 | 72 | 96 |
| 12* | 16-QAM | 1/2 | 96 | 192 |
| 18 | 16-QAM | 3/4 | 144 | 192 |
| 24 | 64-QAM | 2/3 | 192 | 288 |
| 27 | 64-QAM | 3/4 | 216 | 288 |

* Mandatory transfer rate for IEEE 802.11p

TABLE 2.2: Physical layer specifications of an IEEE 802.11p 10 Mhz channel bandwidth [ETS13a]

rule the two first layers of the OSI model [ISO89], namely the Physical and MAC layers, as usually do other standards of IEEE 802.11 family, and are presented below:

- **Physical layer:** It is mainly based on the specifications of IEEE 802.11a and its Orthogonal Frequency-Division Multiplexing (OFDM) encoding method, with 52 sub-carriers, where 48 are used for data, and 4 are pilot carriers. Regarding the radio channel bandwidth, OFDM supports both of 5 MHz, 10 MHz and 20 MHz. However, it is commonly assumed that a channel bandwidth of 10 Mhz is the one used for the vehicular environment. Finally, the Physical (PHY) layer support eight different transfer rates, through different modulation schemes and coding rates, as highlighted in Table 2.2, with three of them being mandatory, whereas the maximum transmission range is up to 1000m [N.M16].

- **MAC layer:** The MAC layer of IEEE 802.11p uses the Enhanced Distributed Coordination Access (EDCA) which is an improvement of the former Distributed Coordination Function (DCF) introduced in the IEEE 802.11e amendment [IEE05]. Indeed, to ensure more chance for safety messages to be transmitted within a reasonable time, the EDCA introduces the management of Quality of Services (QoS) concept through the notion of Access category (AC). In fine, the standard defines four access categories according to the type of traffic: Background traffic (AC0 or BK), Best Effort traffic (AC1 or BE), Video traffic (AC3 or VI) and Voice traffic (AC3 or VO), with the Access category AC3 being the highest, whereas the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is the method used by EDCA to access the channel.

  In an effort to prioritise data traffic further, the standards also assigns to each AC a distinct data queue, and defines a specific value per AC for both of the

| Priority | AC | $CW_{min}$ | $CW_{max}$ | AIFS |
|---|---|---|---|---|
| Highest | AC_VO | 3 | 7 | 58us |
| — | AC_VI | 7 | 15 | 71us |
| — | AC_BE | 15 | 1023 | 110us |
| Lowest | AC_BK | 15 | 1023 | 149us |

TABLE 2.3: Mac layer specifications of IEEE 802.11p EDCA access categories [ETS13a]

minimal and maximal Contention Window (CW), denoted respectively $CW_{min}$ and $CW_{max}$ and commonly used to defer the access to the channel according to a randomized time period; additionally to the listening period called Arbitration Inter-Frame Space (AIFS), and during which a node can check the channel occupancy and consequently performs a back-off procedure. The defined values can be reviewed in Table 2.3 [IEE10] & [ETS13a].

#### 2.2.1.2 is the IEEE 802.11p the de-facto standard for IVC?

The IEEE 802.11p is considered by now as the de-facto standard for vehicular networks, especially after more than a decade of standardisation, testing, evaluation and implementation that demonstrate its feasibility and moreover its ability to address all the envisaged use-cases, which may range from road safety to traffic management and third-party application. Nevertheless, during the several stages of the development of IVC several technologies were or are considered even now.

Indeed, before the official release of the standard in 2010, the WiMax radio communication technology also known as IEEE 802.16e [IEE11] was sometimes considered for vehicular communication. However, this technology has proven its incapacity to meet some of the vehicular communication requirements, especially in safety scenario where it is unable to cope with the hard deadlines enforced by safety applications [TK15]. Moreover, while it offers a higher transmission rate combined to a large coverage zone which makes it eligible to non-safety scenario [MCF10], the high vehicle mobility deteriorates the performances significantly, contrary to the IEEE 802.11p [MB13].

More recently, the continuous improvements made on cellular networks to further increase their speed, like for instance the broad deployment of the 4th generation network across the world and which is based on the Long Term Evolution (LTE) standard, or the ongoing development of the 5th generation network that is envisioned to provide a high-speed network, has convinced several automakers and technology companies to fund the 5th Generation Automotive Association (5GAA). The primary purpose of this latter is to call for the adoption of cellular networks based on the LTE standard and the newly developed technology LTE Vehicle To Everything (LTE-V2X) [3GP16] to connect vehicles, rather than using the traditional

IEEE 802.11p. In this context, several studies have been initiated to compare the performances of both technologies, with contrasting results and conclusions. In fact, for the technology company Siemens and NXP Semiconductors the LTE-V2X is far from being operational compared to the IEEE 802.11p, the technology needs further maturation and several stages of standardisation before supporting safety related use-cases. Despite this, its capacity to support non-safety related use cases is an attractive perspective which can lead to the development of heterogeneous vehicular networking system that leverages the best of both technology [AF16]. [AT18] concludes to similar results, after demonstrating that the 802.11p outperforms the LTE-V2X regarding packet reception ratio in function of an increased transmission distance. Authors of [Xu+17] conducted on Field Experiments to compare performances of both, the results showed that the Doppler effect [Dop42] deteriorates the performances of LTE-V2X, and does not allow it to cope with the requirements of safety applications. Conversely, both technologies are acceptable for traffic management applications, whereas infotainment applications can take advantage of the long coverage range of LTE compared to 802.11p. Lastly, the study conducted in [5GA17] contrasts with previous work. In fact, through the modelling of various scenarios related to safety and non-safety use-cases, the study highlights better benefits for adopting the LTE-V2X instead of 802.11p, by reducing the road causalities and injuries on the one hand, and saving more than 60 billion US dollars on the other.

In conclusion, the IEEE 802.11p is a ready to go technology, that could save thousands of lives per year, and moreover, its adoption will reshape the manner that we think our modern transportation means. However, the joint use of this standard with the 4th & 5th generation of cellular networks that need further maturation can make alive Connected Vehicles, which can sense their environment, to avoid a collision, better manage traffic and much more.

### 2.2.2 IVC Technologies for the USA and Europe

Through the recent process of developing ITS and connecting vehicles based on IVC, several approaches emerged among the different research poles, leading ultimately to the design of different standards, technologies and more importantly network stacks. Fortunately, these different approaches to realise connected vehicles are based on the well established standard IEEE 802.11p, as it will be highlighted regarding the advocate IVC standards in Europe and the USA.

Before presenting these standards, it should be noted that the term DSRC is very confusing, and may be interpreted differently from one region to another. For instance, in the USA, the term DSRC points to both of the 75 Mhz radio band allocated

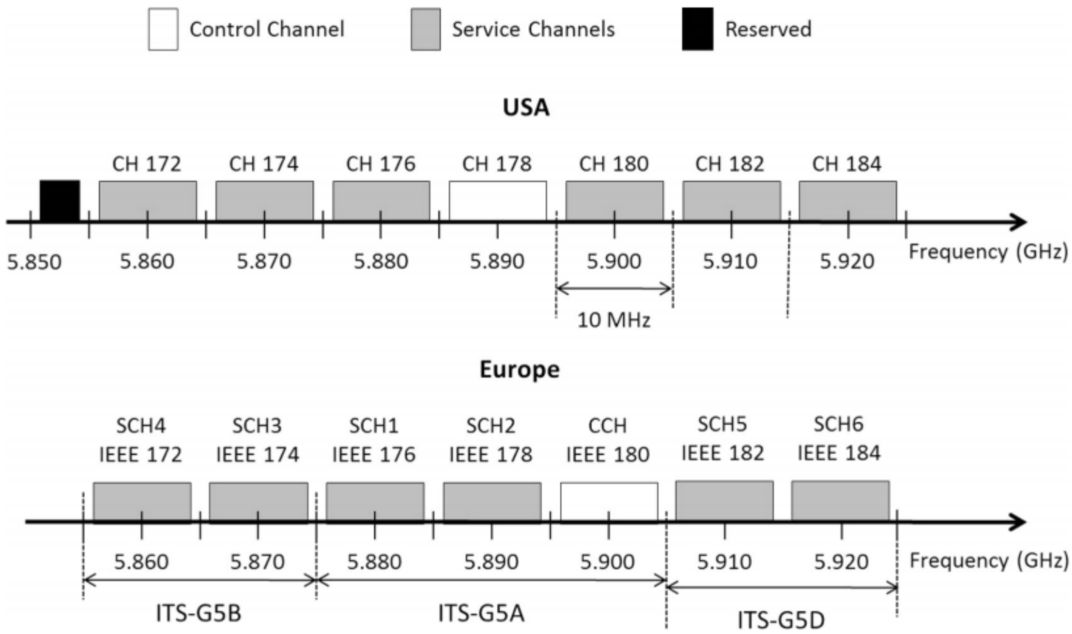


FIGURE 2.2: Spectrum and channels allocation for IVC in USA and Europe [CMS15]

to vehicular networks and the whole technologies involved in the process of connecting vehicles (often known as US DSRC). However, in Europe, the term DSRC refers only to the allocated radio spectrum.

#### 2.2.2.1 IVC For USA: IEEE WAVE

In United States, the whole architecture and set of standards & technologies behind enabling is commonly known as US.DSRC, which IVC is based on three major components: the 75 Mhz radio band between 5.850-5.925 GHz, allocated by the FCC under the name of DSRC as depicted in Fig 2.2; the radio communication technology IEEE 802.11p presented previously; and finally the architecture of an ITS sub-system, also known as the WAVE architecture [IEE13].

The latter component is a set of standards that define the network layers of the stack, apart from the physical and lower mac layer defined by IEEE 802.11p. Furthermore, it splits its upper layers into two branches: a first one based on traditional Internet protocols (IPv6, TCP, UDP) and designed to support non-safety applications, a second one designed to support a fast single-hop reliable broadcast of safety messages, by relying on the WAVE Short Message Protocol (WSMP). The overall network stack is shown in Fig 2.3, whereas its various standards are presented below:

- SAE J2735 Dedicated Short Range Communications (DSRC) Message Set Dictionary: This standard will assure that future applications are interoperable. Applications, including collision avoidance, emergency vehicle warnings, and signage, require this standard to be effective [SAE16a].

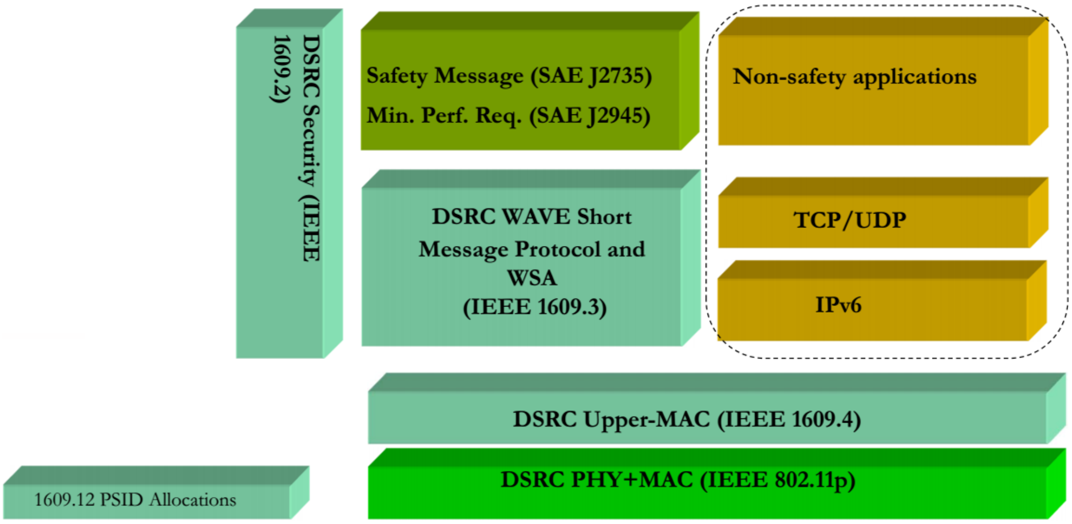


FIGURE 2.3: US.DSRC stack & main standards [J.K16]

- SAE J2945/1 Onboard Minimum Performance Requirements for V2V Safety Communications: This standard sets the minimum performance requirements and the interface standard features that are required to establish interoperability between onboard units for V2V safety systems [SAE16b].
- IEEE 1609.2-2016 Standard for Wireless Access in Vehicular Environments (WAVE) – Security Services for Applications and Management Messages: This standard defines secure message formats and processing within the WAVE architecture [IEE16b].
- IEEE 1609.3-2016 Standard for WAVE – Networking Services: This standard defines network and transport layer services, including addressing and routing, in support of secure WAVE data exchange. It also defines the WSMP and WAVE short messages which provide an efficient WAVE-specific alternative to Internet Protocol version 6 that can be directly supported by applications, in addition to the MIB for the WAVE protocol stack [IEE16d].
- IEEE 1609.4-2016 Standard for WAVE – Multi-Channel Operations: This standard provides enhancements of the IEEE 802.11p MAC layer to support WAVE operations and describes various standard message formats for supported applications [IEE16c].
- IEEE 1609.12-2016 Standard for WAVE – Identifier Allocations: This standard specifies allocations of WAVE identifiers defined in the IEEE 1609 series of standards [IEE16e].

#### 2.2.2.2 IVC For Europe: ETSI ITS-G5

The first major milestone on the ongoing process of enabling connected vehicles and establishing ITS in Europe, was the publication of a reference architecture that describes the network stack for an ITS station, specified in the European Telecommunications Standards Institute (ETSI) EN 302 665 [ETS10] and the ISO 21217 Communications Access for Land Mobiles (CALM) – Architecture [ISO14] standards. As it can be noticed from Fig 2.4, this architecture includes various standards which cover a broader scope than the IEEE WAVE architecture, integrating multiple communication technologies [R.S11].

However, many concepts are shared between the two designs, like the allocation of a similar radio spectrum for vehicular communication, or the use of the IEEE 802.11p as the primary communication technology, but without integrating the IEEE 1609 standards. Moreover, in a similar manner to the IEEE WAVE architecture, the ITS-G5 architecture splits the Network & Transport layers into two branches: a first one based on traditional Internet protocols (IPv6, TCP, UDP), designed to ensure network interoperability and facilitate remote communications; a second one designed to support specific ITS protocols, based on GeoNetworking, which is a multi-hop routing protocol oriented to the geo-dissemination of information in vehicular environments and standardised in [ETS11] & [ETS13b].

Regarding the higher layers, the most notable aspect is the definition of a facilities layer, motivated by the profile of safety services. In fact, the newly introduced layer is a basis for applications with the sole purpose of gathering and storing the relevant data from other vehicles and from the onboard sensors to make them available to all the applications, without the need of application-to-application communication. Besides, the architecture introduces the Cooperative Awareness Message (CAM) protocol which sends beacons at a frequency between 1 Hz and 10 Hz, containing critical vehicle state information like positions and movement used by safety and traffic efficiency applications [ETS18a]. In addition to, the Decentralized Environmental Notification Message (DENM) protocol which is in charge of disseminating safety information within a specific geographical region after the detection of traffic or a road hazard event [ETS18b].

#### 2.2.2.3 IEEE WAVE versus ETSI ITS-G5

Even though the two designs namely the IEEE WAVE and the ETSI ITS-G5 have many concepts in common, there are many substantial differences. Indeed, while both rely on the same radio band to enable vehicular communication, they allocate different channels to the Control Channel (CCH), with the Channel (CH) 178 for the former and the CH 180 for the latter, as highlighted in Fig 2.2. Furthermore, the envisioned usage of the six Service Channels (SCHs) is different, the IEEE WAVE

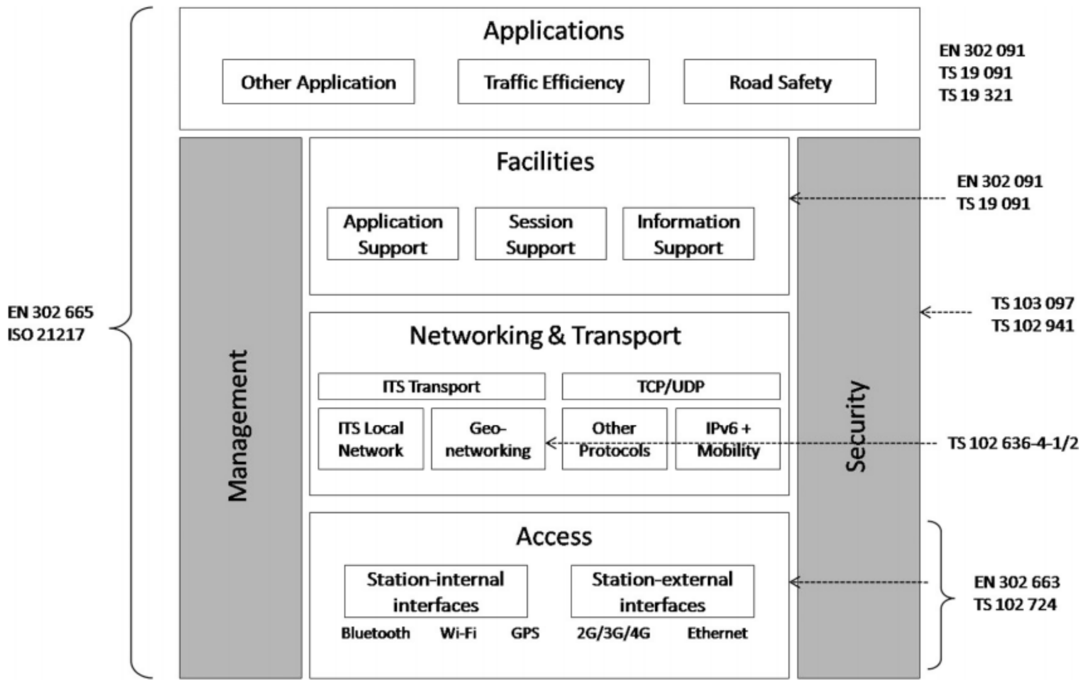


FIGURE 2.4: European ITS-G5 reference architecture & main standards [CMS15]

reserves the CH 172 & 184 respectively to critical safety of life & high power public safety applications, whereas remaining SCHs may be used to support any ITS applications. On the other hand, the ETSI ITS-G5 regroups the channels into three categories denoted by ITS G5-B/A/D, which are dedicated respectively to ITS non-safety applications, ITS safety applications and Future ITS applications.

Another significant difference consists in the channel switching imposed by the IEEE WAVE and which limits the available bandwidth considerably due to the switch between CCH & SCH each 50 ms and the add of a guard interval of 4 ms. This behaviour contrasts with the one of the ETSI ITS-G5, since this latter identifies the network congestion as the critical issue to the communication in the network, and therefore avoids the limitation of the bandwidth through a continuous channel switching. Moreover, it tries to ensure the reliability of both control and services channels in low and highly congested networks, by introducing the Decentralized Congestion Control (DCC) mechanism, which adapts communication parameters in function of the state of the network [ETS18c].

## 2.3 Vehicular Networks (VNs)

With the development of IVC technologies, Vehicular Networks (VNs) which are also known as Vehicular Ad-hoc Networks (VANETs) are now tangible and will be deployed in the next decades to realise Intelligent Transportation Systems (ITSs). Consequently, researchers started to design and develop dedicated routing protocols, while considering the various characteristics of such networks. However, while trying to achieve such primordial task, researchers faced many challenges which ultimately lead to the split of VANETs into two distinct networks, namely traditional VANETs (known simply as VANETs) and Vehicular Delay-Tolerant Networks (VDTNs). The following section provides a step-by-step historical background behind the advent of VDTNs, which are the main subject of this thesis.

### 2.3.1 The origin: Vehicular Ad-Hoc Networks (VANETs)

#### 2.3.1.1 Definition & Context

In essence, VANETs are nothing more and nothing less than MANETs, in which the nodes that manage the whole network in an Ad-hoc manner are vehicles. However, VANETs have many characteristics that highly differ them from MANETs; moreover, whereas the latter can be used to support various applications, the aims of the former are clearly oriented on providing applications and services dedicated to drivers & passengers of road transportation, which are similar to ITS applications and include generally: road safety, traffic management or Internet accessibility [Fil+16].

One of the main issues faced by VANETs is data routing. Indeed, early research works tried to apply some well-known MANET routing protocols, like AODV [PBRD03] and DSR [JHM07], because as explained above VANETs are derived from MANETs. However, these protocols failed to cope with the characteristics of VANETs and consequently to perform correctly. So, researchers shifted to the proposal of dedicated VANETs routing protocols like GPSR [KK00], GPCR [Loc+05] and so on. However, their design was still driven by an Internet protocol overview where strong assumptions are made about the network, as it assumes that most of the time, and if a delay is affordable, a route can be found from a given source to a given destination.

Consequently, these protocols cannot function if there are long disruptions or their efficiency can significantly deteriorate as delays become longer. Such extreme network conditions are far from being strange to vehicular networking and may occur very often. In this context, Delay-Tolerant Networking appears to be a promising approach to address such requirements [HC+18].

#### 2.3.1.2 Features & Characteristics

Despite VANETs inherited characteristics of MANETs, they have their own inherent features. Furthermore, they have a new set of issues, challenges and advantages/disadvantages which are summarised by authors of [Fil+16] as follow:

- Predictable mobility: Unlike MANETs, in VANETs the mobility of a node which turns out to be a vehicle, is restricted by the constructs and limits of the roads, making the future pathways of the network nodes much more predictable.

- No power constraints: in general, MANETs have an inherent power restriction, which obliges applications & network protocols running on top of them to recognise the best use of the battery in order to conserve energy. This contrast with VANETs, where applications can always rely on available energy thanks to the energy supply system of the vehicle. This characteristic avoids concerns regarding power saving issues for VANET applications and protocols.
- Variable density of the network: the density of the network may vary considerably through the day, depending on the rush and off-peak hours, traffic patterns or the current state of the traffic. Thus, there may be times when the network is either sparse or dense, or simply overcrowded. In the sparse case, it is hard to establish an end-to-end connection because of the absence of vehicles. In the dense case may exist excessive packet retransmissions producing packet collisions and significant delays.
- Rapid changes in topology: due to the dynamism and high speeds of the nodes of VANETs, the network topology is constantly changing in addition to the extremely short contacts between any two communicating nodes. These characteristics complicate the operation of the traditional TCP/IP in this environment. This difficulty is due to the incapacity to differentiate between congestion and link failure, which can cause unnecessary reductions in the parameter settings related to the congestion window size, leading ultimately to severe degradation of performances in VANETs, especially in heavily dense or overcrowded situations.
- High computational processing and information power possibility: since the nodes of VANETs are vehicles; there is the ease of installing many resources that can assist in the operations of these networks. For instance, it is possible to embed a GPS device or a navigation system into the vehicles, which while further assist the driver in many situations, like for handling traffic or when making a route decision.

### 2.3.2 The promising approach: Delay-Tolerant Networks (DTNs)

#### 2.3.2.1 Definition & Context

Initially, the concept of DTN was designed with a substantial focus on interplanetary networks. Indeed, during the late 90s, the InterPlanetary Networking (IPN) project was initiated with the express aim of defining and developing the architecture for interoperability of terrestrial and interplanetary Internet, based on communication between satellites, surface rovers and other devices, while coping with the many issues raised by such network, like for instance high delays and intermittent connectivity. However, the initial analysis of the adopted solution turned out to be an elegant one which could be successfully applied to some terrestrial networks with harsh network conditions.

In this context, researchers of the Internet Research Task Force (IRTF) expanded its application field by creating a research group on Delay-Tolerant Networks, known as the Delay-Tolerant Network Research Group (DTNRG). Moreover, they designed the DTN architecture, which relies on the Store, Carry & Forward (SCF) paradigm to cope with intermittent connectivity and long delays. This latter differs from the advocated approach in TCP/IP networks, where the received packets are stored in intermediate nodes for a duration of a few milliseconds and are systematically lost or discarded from further forwarding in case of a missing route, which may happen with intermittent connectivity. In fact, the advocated approach here is first to receive the packets by an intermediate node, then to permanently store it until resuming the forwarding process when finding the next node along the transmission path. The process is then repeated until the packet reaches its targeted destination.

All these research works lead ultimately to expanding the DTN field to include regular networks, such as the Wireless Sensor Networks (WSNs), MANETs or VNs under the name of VDTNs which are the sole focus of this thesis, in parallel with some specific terrestrial networks like disaster networks or those deployed on battlegrounds or in remote/underdeveloped areas, for instance.

#### 2.3.2.2 Key Principles & Concepts

The DTNRG have formalised under the RFC4838 standard related to the DTN architecture [Cer+07], the key concepts and principles for ensuring the Internet or network connectivity to isolated nodes in an opportunistic manner. These concepts are presented below [Ben+14], [HC+18]:

1. The Bundle Protocol: standardised in the RFC5050 [SB07], it defines the basic data transmitted across DTN nodes in the form of messages of varying lengths called bundles, containing all the information needed by the destination for the completion of a transaction in one go, including protocol and authentication data. This is useful since several round trips between nodes may not be feasible at all. The bundle protocol also defines a new network layer called bundle layer as shown in Fig 2.5. This layer permanently allows the storage of bundles and is in charge of the bundle forwarding in a hop-by-hop scheme instead of an end-to-end one, whenever a new transmission opportunity appears, which happens when two DTN nodes enter into contact and establish a connection between them. Finally, it is important to note that this protocol does not provide any error detection or correction capabilities and so they must be assumed by upper layers.

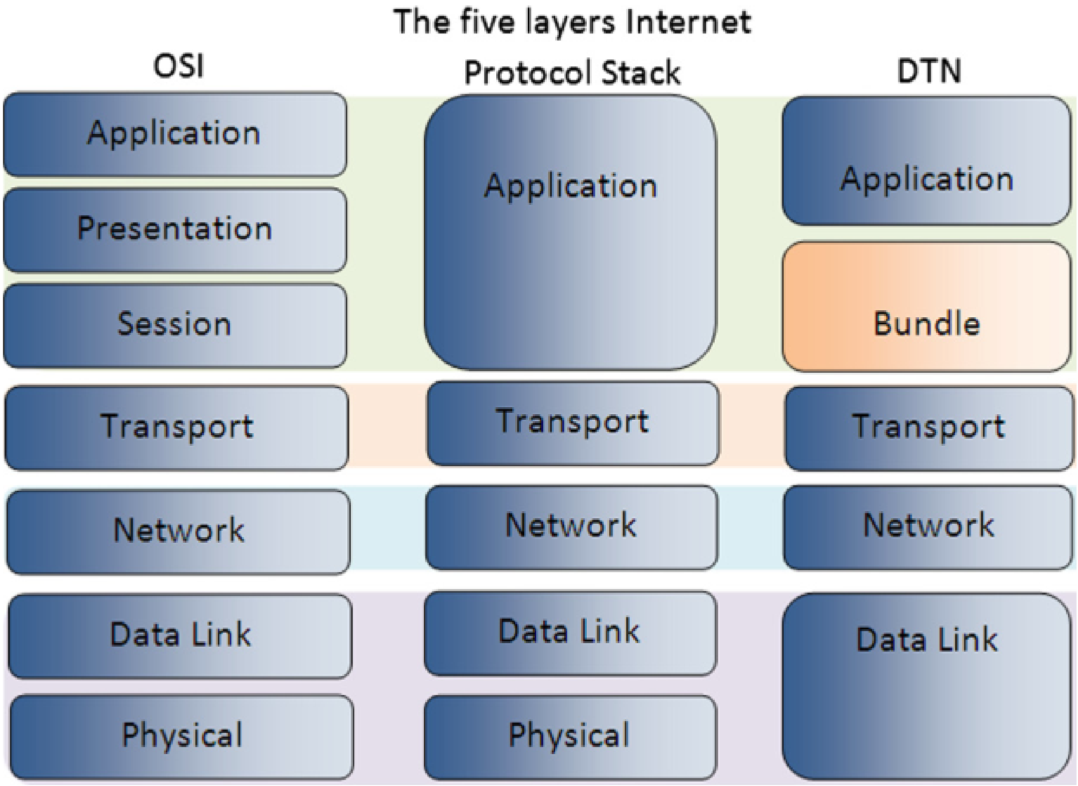


FIGURE 2.5: OSI, TCP/IP & DTN network stacks [Ben+14]

2. The Store, Carry and Forward (SCF): this transmission paradigm is the most notable aspect since it contrasts highly with the store and forward operation mode used by Internet routing where incoming packets are stored in the buffer temporarily upon receipt and then forwarded to the next hop. Indeed, SCF allows a DTN node to store a bundle permanently, due to the Bundle protocol, then carry it until resuming the bundle forwarding whenever the carrier node finds a suitable relay/forwarder.

3. The Custody mechanism: by default, a DTN node is responsible for the bundles that it carries until their delivery or transmission to another DTN node. Sometimes, it is interesting for a DTN node to transfer to another node the responsibility for the replication, modification or deletion of its carried bundles. This may happen, for instance, when the current bundle carrier is no longer a suitable forwarder, and only one replica of the bundle remains.

4. The Addressing and Late Binding: to ensure maximum flexibility, DTNs introduce the late binding concept which allows the routing of data based on an identifier instead of an address until the data arrives at the final region where the address resolver convert the identifier to the corresponding address. This behaviour differs from the early binding in vigour in TCP/IP networks, where the address pointing to a domain name is resolved before any routing.

#### 2.3.2.3 Raised issues and current challenges

Due to the inherent nature, DTN may face issues and challenges that traditional networks based on TCP/IP do not face generally. These latter are described and summed up by authors of [Fil+16] as follow:

- Buffer problem: the strategy used by DTN requires that the bundle be stored in the nodes. Therefore, the routing protocols must know how to deal with buffer usage in order not to have a high number of unnecessary bundle copies circulating at intermediate nodes in the network.
- Unpredictability of contacts: in a DTN, there is a possibility that a node may be ignorant about the network. Therefore, there is great unpredictability concerning new contactable nodes. Thus, a DTN routing protocol should look for other means of trying to estimate when new contacts will happen.
- Notification of a received bundle at its target: when a bundle reaches its target there are still other copies of it in the network. They were stored in intermediate nodes, which causes a waste of buffer storage and computing time required to maintain them. Establishing a reasonable estimation time to predict when the bundle will arrive at its destination is a difficult task. The complication is caused by those nodes which are still busy storing the bundle, rather than estimating the transmission transfer times.
- Lifetime for a bundle: a lifetime is defined for every bundle. The period that the bundle stays stored in a buffer must be lower than the lifetime. When this storage time expires, the bundle must be discarded from the buffer. This fact raises the following question: for how long will the bundle be stored? As there is a limited time span for the bundle to achieve or reach a contact along its communication path, the bundle may be discarded before it can even reach its destination.

### 2.3.3 The current trend: Vehicular Delay-Tolerant Networks (VDTNs)

#### 2.3.3.1 Definition & Context

Recently, and in an attempt to assess the potential benefits of using DTN principles, multiple works have conducted in-depth studies of VANETs, in parallel with a thorough analysis of their topology and its temporal evolution, or their behaviour when introducing a Store-Carry and Forward paradigm. Some of the major works that fall within this context are those in [QSC17] and [GFG15]. In [QSC17], the authors show that under real conditions, VANETs are partitioned into thousands of small vehicle platoons; thus routing data can be achieved only by taking advantage of the temporal connectivity of VANETs and by adopting the store-carry & forward paradigm.

Moreover, the authors of [GFG15] conclude that the adoption of this paradigm increases the overall network reachability, by a factor of up to 90% in sparse networks, while facilitating the implementation of some features such as the local dissemination of data at road junctions.

These research works fostered the emergence of a hot research topic, namely Vehicular Delay-Tolerant Networks, at the crossroads of DTNs and VANETs. These new networks target a class of vehicular applications characterised by delay-tolerant and asynchronous data traffic. At the time of decision-making, these applications can tolerate some data loss and do not need end-to-end connectivity. Instead, they may continue to operate efficiently by relying on DTN principles.

#### 2.3.3.2 Main Characteristics

Through the various conducted studies, researchers noticed that VDTNs share some unique characteristics inherited from DTNs and VANETs which should be taken into account when designing protocols for them. Authors in [Ben+14] summarised these unique characteristics as follows:

1. Vehicular applications: VDTNs are far from being suited for all vehicular applications since some of them may have some hard delay constraints like crash awareness and emergency braking, for which DTN concepts are not optimal or not applicable at all. Aside from previous applications, VDTNs can support various other ones that do not have such stringent requirements like road traffic information or third-party application, which may range from Internet connectivity and multimedia contents to non-real-time services such as a file transfer, email application or more unexpectedly, applications for localising parking lots and repair garages.

2. High mobility and frequent disruptions: high speed and mobility of vehicles induce a very quick changing topology whereby the relatively short contact duration and limited communication range of IVC result in frequent disruption. To put that in perspective, the contact duration between two vehicles on opposite sides of a highway, moving towards each other at a speed of 100 km/h, with a maximum range of up to 100m is less than 3.6 seconds. Therefore, VDTNs have to take advantage of this opportunity before the disconnection occurs. Readers should also note that vehicles may evolve in dense as well as sparse traffic regions; thus ideal VDTN routing protocols must perform correctly in both conditions.

3. Geographical awareness & Mobility predictions: a growing trend in modern transportation is the use of embedded GPS devices, a trend that is also fostered with GPS capable Smartphones. As a consequence, the current location of vehicles can be easily determined. Furthermore, the future trajectory can be

predicted given the speed or the fixed trajectories as it is for buses and public transportation. Finally, VDTNs can exploit these mobility patterns for message delivery by taking the optimal decisions. This characteristic facilitates the development of applications dedicated to the dissemination of information within a specific region, following a geocast communication scheme.

4. Storage and computation capabilities: in contrast with other DTN environments, VDTNs do not suffer from storage, computation or energy limitations, since the de-facto nodes will be cars, buses or any other types of road transportation which have sufficient capabilities.

## 2.4 Routing Protocols for Vehicular Delay-Tolerant Networks

Across the diverse literature, numerous DTN routing protocols have been proposed. Although some of them were designed to suit specific application environments or scenarios, others were aimed at generic application scenarios. Therefore, they can be easily applied in the vehicular context and consequently, the taxonomy of VDTN routing protocols may include these DTN protocols. Moreover, due to the effervescence of research related to VDTNs, researchers proposed numerous dedicated routing protocols, based on various approaches, which further enrich the taxonomy of these specific vehicular routing protocols.

Beyond that, researchers used to classify VDTN routing protocols on the basis of different criteria: the replication strategy of the protocol (if it uses single or multiple copies of a unique bundle in order to route it), the transmission scheme (unicast, multicast, broadcast or geocast), or in rare cases, the number of dimensions considered in the use case scenario of the protocol (1D, 2D, 3D). However, most researchers agree to classify them based on the existence or not of a forwarding metric and its nature, whereas the replication strategy constitutes a secondary criterion. This is mainly due to a global consensus about the crucial importance of the considered forwarding metric in each VDTN routing protocol.

Despite this, readers should note that providing a concise taxonomy of VDTN routing protocols is a hard task because some protocols make use of multiple approaches to operate and forward data. In fact, although the presented routing protocol families differ from one another, they are mutually influenced by each other, which lead to the development of new protocols based on various approach or by introducing new metrics and considering geographical information such as position, speed or direction. This situation is perfectly depicted in Fig 2.6 which demonstrates that the development of new routing protocols arises from the mutual influences between the different routing families. The figure also covers a partial chronology of VDTN routing protocols between the 2000 - 2013 period, while classifying them accordingly to their respective routing family.

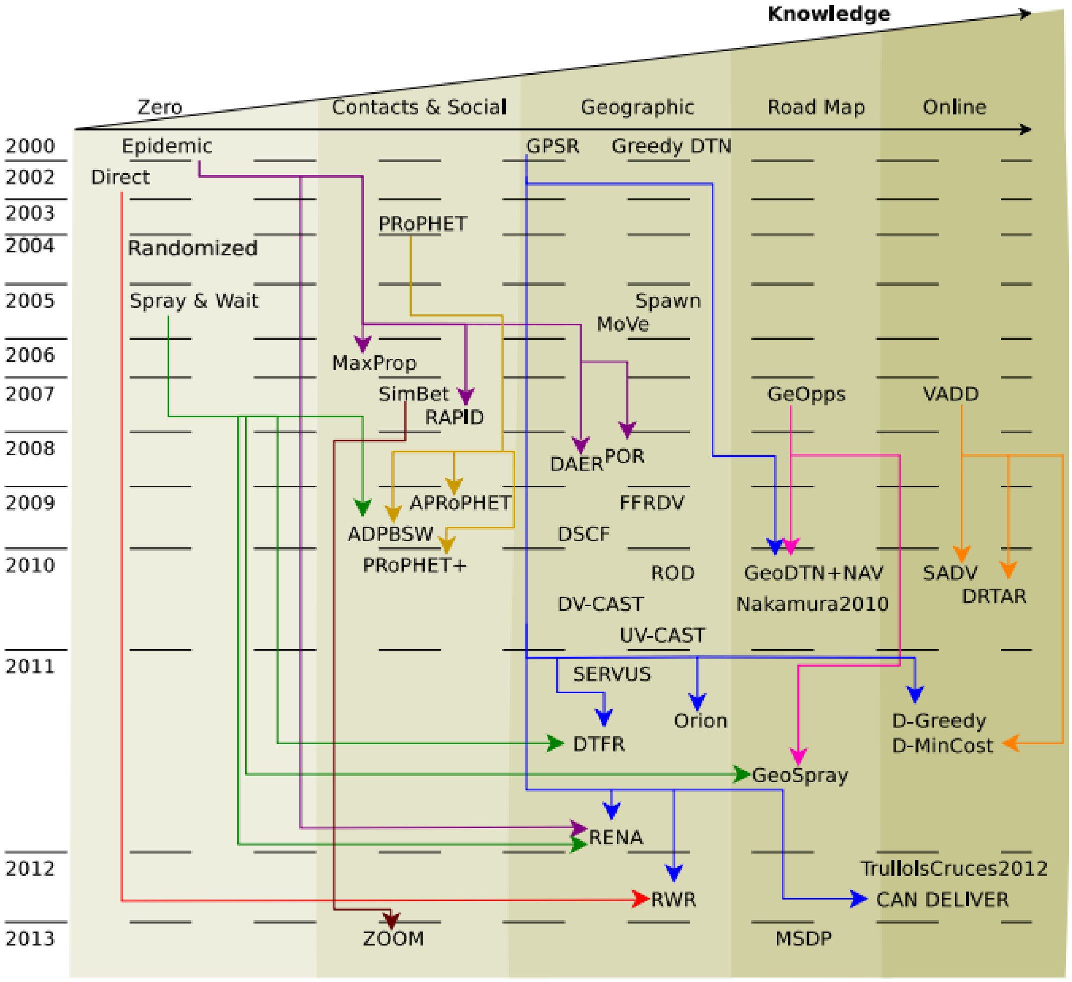


FIGURE 2.6: Partial chronology of main VDTN routing protocols [Tor+15]

Finally, far from being exhaustive, the following section presents the commonly assumed taxonomy of VDTN routing protocols, based on the existence or not of a forwarding metric and its nature, by cross-checking the works of multiple surveys, [Che+15], [Ben+14] and [Tor+15]. This taxonomy is summarised in Fig 2.7.

### 2.4.1 Zero knowledge-based protocols

This family regroups protocols that do not need or collect any information, while they are running. As a result of this limitation, their performance is generally surpassed by other families. Most of these protocols were designed in the early stage of DTN and thus regroups first developed protocols like:

- Direct-Delivery (also abbreviated as DDelivery) [SPR04]: follows a straightforward and simple approach consisting in carrying the bundle until meeting the final recipient. Further details related to this protocol are presented in Section 4.2.1.

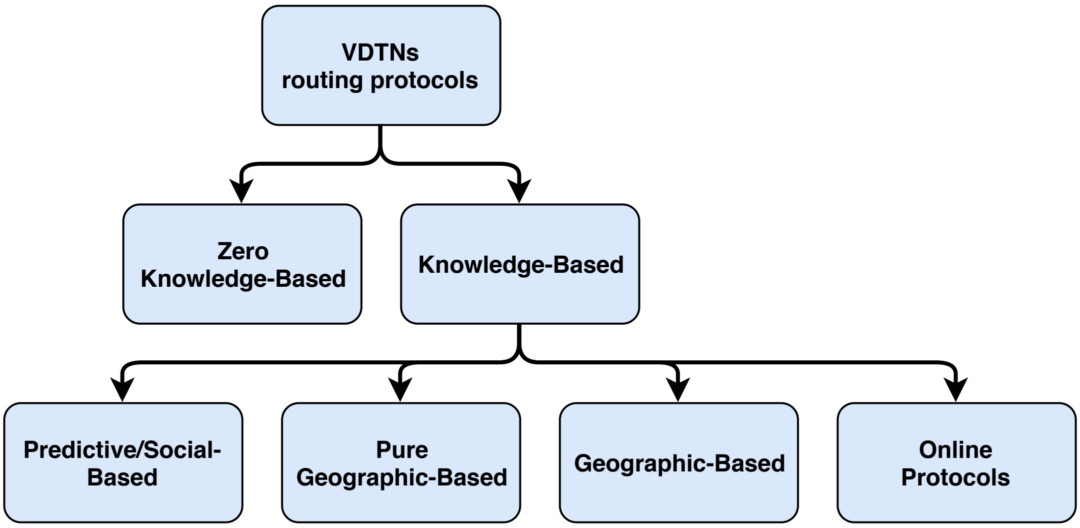


FIGURE 2.7: Taxonomy of VDTN routing protocols based on knowledge

- Epidemic [VB00]: is based on a simple but greedy approach consisting of the dissemination of bundles in the whole network without any restriction. A detailed description of its operation mode is provided in Section 4.2.2.
- Spray&Wait (also abbreviated as S&W) [SPR05]: is a well-known DTN protocol which splits the forwarding process into two distinct phases, first a controlled and contained bundle spreading over the network is achieved, where a varying number of copies of a bundle are handed over to the encountered node, accordingly to the adopted spraying approach. Subsequently, the protocol enters a waiting phase whenever the current node possesses only a single copy of the bundle, therefore it carries it and waits for possible contact with the final recipient. Regarding the spraying approaches, the binary approach (often abbreviated as Binary S&W) hands over the half of remaining copies to the encountered node, whereas the vanilla approach hands over only one copy.

### 2.4.2 Knowledge-based protocols

Since a flooding or a random approach advocated by previous protocols is less prone to success in vehicular environments, a majority of protocols rely on a utility function (also known as forwarding metric) which combines several parameters to estimates how a transmission would increase the probability of reaching the final destination. The forwarding metric can be as simple as the distance to the destination, while in others it may combine several parameters from different sources of information. Therefore, the protocols belonging to this family are further classified into several families accordingly to the type or nature of needed knowledge/information, as described below:

1. Contact predictions & social relationship: this subcategory includes protocols which work under the assumption that the probability for a node to meet the final destination of a bundle can be estimated based on the history of previous contacts, or those which make the forwarding decision thanks to newly introduced social concepts such as community, centrality, similarity, friendship and selfishness. Although most of them were intended to be deployed over pure DTNs, where the frequent contacts paradigm and social concepts brought from social networks seem to apply clearly, these protocols have been extensively used for comparison with VDTN protocols. The following protocols fall into this class:

   - Prophet [Gra+11]: The Routing Protocol using History of Encounters and Transitivity was the first contact history based protocol, it relies on a self-defined delivery predictability metric P, to deliver bundles to the final destination. This metric is computed based on several calculations that reflect its transitivity or ageing and was enhanced recently through a major update of the protocol. Therefore, works based on the first version of Prophet are considered as outdated, whereas its second version (ProphetV2) is the only one that has been considered during this thesis. The protocol and its operation modes are detailed in Section 4.2.3
   - SimBet [DH07] & ZOOM [Zhu+13]: these protocols use social metrics, like for instance the node's number of links in the social graph or their centrality, to choose the next forwarding node. They complement the delivery predictability by estimating the centrality of the node within the social graph formed by the nodes inside the network.

   These routing protocols have many drawbacks which limit their usage in vehicular context severely. In fact, they generally require a nearly-closed community to be effective because, in case of a highly changing topology as for VDTNs, new nodes which do not have previous contacts seem to be isolated, and nodes that left the network but had a long contacts-history, seem to still belong to it for a long time after leaving. Therefore such protocols tend to select an old or broken route. Furthermore, protocols based on social metrics require a deep analysis of the relationship among the nodes which rise many concerns regarding the scalability and more especially privacy [Tor+15].

2. Pure Geographic-based: protocols included in this subcategory use geographic data to make the forwarding decision while assuming that the nodes are aware of their position and direction. Earlier protocols inherited or inspired by MANETs fall under this category like, for instance:

   - Greedy-DTN [Loc+03]: is an adaptation of the GPSR [KK00], where the perimeter mode is replaced by a DTN mode, that allow the the carrying of bundles until finding a more suitable forwarder. Consequently, the protocol relies exclusively on two modes only, the former is the greedy mode, whereas the latter is the DTN mode.

- MoVe [LeB+05]: is a protocol that estimates the future location of the nodes using their current direction of movement. Thus, the node whose likely trajectory is the closest to destination becomes the best forwarding node.

3. Geographic-based: such protocols also use geographic data to make the forwarding decision but with a practical difference compared to the previous subcategory. In fact, they assume that nodes which are vehicles evolve in a roadmap network, and thus they are not constraint-free and move according to routes and intersections, which avoid them including suboptimal routing decisions. This approach shows good performance and is amongst the most promising ones. In the rest of this thesis, this routing protocol family will be referred to as a geographic-based one, since the pure geographic-based family, as presented previously, is no longer considered a viable approach. Some of the most well-known routing protocols belonging to this family are presented below:

   - GeoDTN+Nav[Che+10]: introduces a DTN mode, in addition to the greedy and perimeter modes frequently used by the GPSR [KK00] & GPCR [Loc+05] protocols, in order to successfully deliver the bundles. Therefore, this protocol differs from the Greedy-DTN protocol, since it relies on three distinct modes that are respectively the greedy, the perimeter and lastly the DTN mode, whereas Greedy-DTN relies only on two of them as highlighted previously.

   - GeOpps [LM07]: forwards data through a single-copy replication scheme and the forwarding time metric Minimum Estimated Time of Delivery (METD), which is computed based on a vehicle trajectory.

   - GeoSpray [SRF14]: is based on a multiple-copy replication scheme and a forwarding strategy that combines the two-forwarding phases of Spray&Wait with the time metric METD of GeOpps. The protocol is further detailed in Section 4.2.4.

4. Online protocols: under this subcategory fall protocols that require a fully connected approach with high knowledge of the current state of the road network, notably the number of nodes, average speed and road congestion. Therefore, these protocols require a complex platform and a large network of sensors to efficiently gather and disseminate such information, which limits their scalability drastically. Moreover, they depend on real-time information, which is easily available in simulations but can be difficult to obtain in real implementations. The main protocols included in such category are: VADD [ZC08] and Can Deliver [MAG12].

- VADD [ZC08]: divides the forwarding process to the final destination into four steps. First, it estimates the travel time of a bundle for each road taking into account the vehicles density of the road, its length and the duration of traffic lights. Subsequently, it calculates the shortest path to the destination using Dijkstra, and then it routes bundles between road intersections using the Greedy-DTN protocol. Finally, when a threshold distance to the destination is reached, it routes messages using the GPSR protocol.
- Can Deliver [MAG12]: is designed to provide a routing solution from vehicles to fixed access points usually referred to as Road Side Units (RSUs), and vice-versa. In the former case, the vehicle calculates the shortest road-path to the RSU and attaches it, together with information on its route and speed to the bundle. Then, the message is forwarded between the intersections using the Greedy-DTN protocol. In the latter case, RSUs try to estimates the future location of a vehicle based on information previously attached to the bundle. Then, an area around the possible future position is defined, this latter is used to reply within it to the vehicle by combining the S&W multi-copy scheme with the Greedy-DTN forwarding metric.

# Chapter 3

# Evaluation of VDTN routing protocols



With the advent of vehicular networks and their specificities, newer IVC technologies emerged like the IEEE 802.11p wireless standard or the IEEE 1609 standards, whereas new tools where developed with the purpose of correctly evaluating such networks and the potential protocols and applications envisioned to operate over these networks, in addition to the existing tools dedicated to the evaluation of traditional networks. Despite this, and as it will be highlighted in this chapter only a few tools fulfil the requirements needed to perform a right evaluation of vehicular routing protocols. Moreover, when it comes to conducting a comparative study of existing VDTN routing protocols, the lack of base implementations in parallel to a common ground for evaluation are majors issues. Therefore, the rest of this chapter tackles these recurrent barriers by presenting the proposed architecture for the implementation of VDTN routing protocols, which served as a common implementation and evaluation platform through this thesis.

## 3.1 How to evaluate a VDTN routing protocol

Many VDTN routing protocols are proposed in the literature following various forwarding approaches and replication strategies which differ ostensibly regarding the information needed to make the forwarding decision. Nevertheless, in practice, there are still few operational use cases and almost no wide-ranging implementations.

In fact, whilst studying VDTNs and their topology or behaviour can be achieved through theoretical approaches and mathematical modelling, to extract critical facts which are able to provide general guidance for researchers; the evaluation of VDTN routing protocols requires a more concrete and straightforward approach, by relying for instance, on practical experimentations or realistic and sufficient large-scale simulation scenarios. However, within a context where practical experiments are hard to set-up (because they are expensive and require large test-fields & fleet of vehicles), and where existing test-beds are not mostly accessible to the research community; Computer simulations remain the de-facto and primary tool for the assessment of VDTN routing protocols, especially when multiple simulation tools exist and are widely available.

Moreover, in many cases, the proposed protocols are envisioned to provide data routing for a specific range of applications/services. Therefore, their evaluation scenarios are limited to the targeted use cases. It is then difficult to extend and reproduce the obtained results to other scenarios, protocols, and applications. In some cases, a simplification of the simulation scenario is introduced with the aim of reducing the processing time, which can be prohibitive when simulating realistic VDTN environments. While such an approach can help to quickly allow observation of general trends in the performance of some protocols, the obtained results have limited and contextual validation, since the evaluation context is not reflective of the characteristics of a realistic vehicular environment.

Within this context, authors of several studies as in [JSD12], [Che+15] and [Tor+15], identified different factors and parameters to take into consideration when evaluating VDTN routing protocols, and in order to ensure the validity, compatibility and reproducibility of assessed results. Furthermore, these studies highlighted the importance of selecting adequate simulation tools. Consequently, future research works should fulfil or comply at least partially with these recommendations, that must be viewed as a set of minimal requirements which can be categorized into three main categories, namely:

- Those related to the considered network simulator;
- Those inherent to the specificities of vehicular environments as:
  - The vehicle mobility.
  - The considered scenario & road topology.

### 3.1.1 Requirements regarding the network simulator

As stated before, the primary mean for evaluating VDTN routing protocols consists in simulations. Therefore, it is evident that a network simulator is at the core of any evaluation process, whereas its choice may obey to different criteria and implies the use of a specific set of models and default values, but ultimately shall not influence the results of simulation studies.

Despite this and the existence of many well-established network simulators, the previous studies identify a worrying trend consisting in the use of custom and self-developed simulator, which prevents proper comparison among different proposals, complicates the peer reviewing system and code re-utilisation, and lastly slows down the developing pace. In parallel to that, some network simulators focus solely on the behaviour of routing and others protocols operating respectively at the network and upper layers; thus they make a partial or total abstraction of other components in the communication stack, or regarding the underlying transmission conditions. Such simplifications are useful for understanding the behaviour of a VDTN routing protocol in an isolated manner but are far from being realistic and cannot be considered to offer a valid overall evaluation.

Furthermore, adequate network simulators should provide realistic models for the physical and mac layers. Indeed, a significant factor that influences the realism of simulation results is the considered radio propagation model of the physical layer. In the real world, the propagation of radio signals is influenced by six main factors; namely, free-space path loss, shadowing, reflection, diffraction, fading and Doppler shift. Consequently, researchers have developed different models to simulate such phenomena as unit disc, free space, two-ray ground, log-normal shadowing, Rayleigh, Longley-Rice, Nakagami or those based on straightforward ray-tracing.

Therefore, it is very attempting to rely on sophisticated models, but modelling the propagation of radio signals can be prohibitively time-consuming, and relying on the most advanced models as those based on straightforward ray-tracing do not scale due to a large number of simulated vehicles and transmission. On the other hand, models like the unit disc and free space can be considered for starting due to their light-weight and simplicity, and since they provide a first approximation, but in general it advised to rely on more sophisticated and time-consuming models with a better approximation. Finally, the usage of some models should be avoided as highlighted by authors of [SJD12], and which reveal that the commonly used simplified Two-Ray Ground model is of no benefit in comparison with the basic Free Space. Thus, the former should be replaced by the new Two-Ray Interference model which substantially improves the quality of the predicted path loss.

Regarding the mac layer, it is clear that the considered model is another major factor. Thus, while it is understandable that early research work was conducted under various mac layer specifications or protocols due to a higher degree of specification freedom, newer research work must be built upon the 802.11p standard which is, nowadays, the de facto standard for vehicular networking as highlighted in 2.2.1. In fact, this standard has many benefits which perfectly suits the specificities of vehicular environment, comparatively to other standards of the IEEE 802.11 family, since it increases the Wi-Fi radio coverage up to 1 km, speeds up communication by allowing it without the need for association or authentication thanks to the OCB mode, and lastly integrates QoS settings based on the IEEE 802.11e amendment.

As a consequence, and to sum up the general guidelines regarding the network simulator, future research works are invited to rely on well-established network simulators to consolidate confidence in results and facilitate the comparison of protocols. Furthermore, these network simulators should not make abstraction of lower layers of the network stack; instead they must be transparent regarding the employed radio propagation model, this latter should provide an ideal trade-off between simplicity and complexity like the Two-Ray Interference, log-normal shadowing and Nakagami, whereas the only acceptable mac protocols among the IEEE 802.11 family is the IEEE 802.11p.

### 3.1.2 Requirements regarding the vehicle mobility

A critical aspect in a simulation study of vehicular networks is the need for a mobility model reflecting the real behaviour of vehicular traffic. During the early stages of VANETs, researchers relied on mobility models inspired by MANETs like the limited random mobility model, which allows vehicles to move randomly while being limited to the road topology. However it has been shown that such models are far from being able to capture the complexity of vehicular mobility; and more dramatically, they lack consistency since they allow two vehicles to occupy the same location at the same time.

This situation substantiates a clear trend towards using a specific road traffic simulator in addition to the network simulator, which provides many benefits. At first, it should be noted that the capacity of bidirectionally coupling some road traffic simulators with network ones facilitates greatly the study of protocols and mechanisms that influence the behaviour of vehicles. Moreover, road traffic simulators offer different approaches to model the behaviour of vehicles, like the macroscopic approach which treats the traffic flow like a fluid and focuses heavily on traffic flow patterns as density or speed of vehicles; whereas the microscopic one, analyses each vehicle individually and consequently is the advised one for simulating vehicular networks. Also, the road traffic simulators are established generally on top of either car-following models or cellular automaton models, which mimic the behaviour of vehicular traffic with a higher degree of realism. It is especially true, for the former who derive future acceleration/deceleration decisions based on the velocity and the distance of the vehicle and those ahead of it, and thus are more convenient with the advocated microscopic approach. Some major car-following models regularly employed by road traffic simulators are the Wieldemann model which is the first one to be published, has been developed further to consider physical and psychological aspects of drivers; the Gipps model and the Intelligent Driver Model (IDM) which augments the Gipps model with further effects like traffic instabilities.

Finally, during the recent years, researchers started to develop mobility datasets by collecting real vehicle mobility traces based on GPS sensors, and by extracting road topology from real street maps. These datasets that are built generally upon road traffic simulators provide detailed representations of the vehicular traffic both at a microscopic level (individual vehicle physical characteristics and behaviour) as well as macroscopic level (flow patterns based on diurnal cycles, population synthesis and activities) and therefore their use should be considered whenever possible.

In the light of the preceding and accordingly to previous statements, it is clear that researchers are invited to reject the usage of simplistic MANETs mobility models, for the benefits of realistic ones like those based on cellular automaton or more interestingly on car-following approach. These models are generally provided by road traffic simulators which will be employed jointly with network simulators, more often in the near future due to their many benefits; and free researchers from the difficulty and complexity of developing a mobility model. Lastly, whatever they are built upon a traffic simulator or feeding a network simulator, mobility datasets provide an elegant solution to correctly reflect the complexity of vehicular traffic and consequently should be used whenever possible.

### 3.1.3 Requirements regarding the scenario & road topology

In the real world, vehicles evolve in a continuously changing environment switching from dense urban areas surrounded by building blocks to sparse areas or highways where only a few obstacles may exist. Therefore, assessing the validity and more importantly, the reproducibility of vehicular simulations require a proper scenario description.

This situation applies even more since the impact of the right network simulator and model for vehicle mobility strongly depends on the chosen scenario. In general terms, the scenarios employed in vehicular network simulations are divided into two main types, highway and city, which are further divided into subcategories. This distinction is made because as explained above the experienced network conditions may change from one type to another. Besides, some research works rely on small and self-proposed road topologies to evaluate the proposed protocols and get a quick insight into the performances. However, these self-proposed topologies are far from reflecting a realistic road topology, and their usage should be avoided to the benefits of road topologies extracted from real-world street maps, by relying on the various existing tools dedicated to such purpose like the public Open Street Map (OSM) project [OSM].

Consequently, researchers are strongly advised to evaluate their protocols under both city and highways scenarios, while considering realistic road topology based for instance on road streets extracted real maps. Such requirements can be easily fulfilled by relying on mobility datasets which include as explained above mobility traces for vehicles evolving into the real world.

## 3.2 Overview of simulation tools

As previously explained, the performance evaluation of VDTN routing protocols is commonly built upon simulations and therefore based on a single or a set of tools and simulators. This includes for sure a network simulator which is in charge of correctly simulating the multiple communications that may exist between vehicles. Besides, the need for realistic mobility models has pushed more researchers towards employing road traffic simulators in order of reflecting the behaviour of drivers. These dedicated simulators have many benefits which encourage their usage. Moreover, some of them can be coupled with network simulators, which ultimately lead to the development of a simulation framework dedicated to vehicular networks able to synchronise and establish communication with both simulators. The following section provides a global overview of both historically and commonly employed tools for simulating vehicular networks based on various surveys like[SAK12], [Che+15], [Tor+15] and [SCB11].

### 3.2.1 Network simulators

During recent years, many network simulators are regularly employed to study Vehicular Networks or VDTN routing protocols. These well-known simulators are described below, whereas the Table 3.1 resumes their main characteristics:

| Network Simulator | ONE | NS-2 | NS-3 | Omnet++ | QualNet |
|---|---|---|---|---|---|
| **License** | GNU GPLv3 | GNU GPLv2 | GNU GPLv3 | Academic | Commercial |
| **Simulator Written in** | Java | C++ | C++ | C++ | C/C++ |
| **Simulation Language** | Java | C++/OTcl | C++/Python | C++/NED | C/C++ |
| **GUI IDE** | Yes | No | No | Yes | Yes |
| **Officialy Supported Wireless Technology** | None[1] | Wi-Fi/Satellite/ Cellular | Wi-Fi/WiMax/ LTE | Through Omnet++ libraries only[2] | Wi-Fi/WiMax/ GSM/UMTS/ LTE/Zigbee |
| **Scalability** | Small | Medium | Large | Large | Large |

[1] The simulator makes a total abstraction of lower layers of the network stack.
[2] The simulator supports various technologies like Wi-Fi, LTE or IEEE 802.11p via Omnet++ libraires.

TABLE 3.1: Main network simulators used in the vehicular research field [Che+15]

- Opportunistic Network Environment (ONE): this is one of the rare simulators specifically designed for DTN. It is written in Java language which limits its capacity to scale. Moreover, it makes a total abstraction of network lower layers, and the mobility models are limited to random mobility or some real traces. However, its major benefit is its great simplicity combined with its high-speed execution which fosters the proposal and development of newer protocols. This is why ONE is recommended for early research stages when evaluating different proposals, their logic and behaviours [KOK09].
- NS-2: is one of the most popular network simulators. It integrates advanced propagation & channel models and supports various wireless technologies like Wi-Fi, satellite communication or cellular networks, while mobility models can be obtained from the most advanced traffic simulator SUMO. However, it does not support the 802.11p standard, and furthermore, its design combined with the use of C++/OTcl language complicates and slows down the development of network simulations [MFF].
- NS-3: is the successor of the popular NS-2 simulator. The simulator provides many benefits compared to its ancestor, since it is built upon a complete redesign which eliminates some public issues/bugs, and replaces the complex OTcl language commonly used for the definition of the simulated network with Python. Moreover, it provides an upgrade of some technologies and supports more recent ones, especially those related to later advancements on the field of cellular networks [RH10].
- Omnet++: is a network simulator and a development environment at the same time, providing different tools for that purpose as a UI, a language for network definition, tools for result collection and visualisation. Furthermore, it is built around a modular component approach with a solid programming base, which facilitates the development of dedicated simulators greatly. Finally, the

simulator is in continuous development, well-documented and supported by a large community [VH08].

- QualNet: this is a non-open source simulator, and consequently its correctness cannot be verified. It implements various wireless technologies such as Wi-Fi, WiMAX, GSM, UMTS, LTE, and ZigBee, along with complex propagation models and interference channels. Regarding mobility models, it supports the use of traces obtained from different road traffic simulators [Tec].

### 3.2.2 Traffic simulators

The growing interest of researchers, traffic solution providers and public authorities in order to efficiently manage road traffic have fostered the development of many road traffic simulators. However, these simulators have met varying degrees of success due to multiple factors, as the degree of realism, complexity, licence type or adoption by the community. Such a situation ultimately leads to halt their maintenance and discard them in favour of more evolved and successful simulators. Below are presented the two main simulators currently in use by the research community:

- Vissim: or PTV Vissim was first developed in 1992 by PTV AG and is today the global leader on the market of commercial traffic simulators. The simulator incorporates a car-following model based on the psycho-physical model published by Wiedemann in 1974 and has been continuously enhanced since then. Besides, it includes a pedestrian mobility model and supports multi-modal transportation. Moreover, it is part of the PTV Vision Traffic Suite which also includes PTV Visum (traffic analysis and forecasting) and PTV Vistro (signal optimisation and traffic impact). Consequently, Vissim has the necessary means and tools to simulate complex transportation systems correctly, and their behaviour in continuous time, sampled time, or a combination of both; whereas its advanced UI offers a simple method for constructing a personalised road topology and defining its maps and scenarios. Lastly, it should be noted that Vissim is only available for Microsoft Windows operating systems [Gro].

- SUMO (Simulation of Urban MObility): is an advanced open source microscopic simulator, mainly developed by employees of the Institute of Transportation Systems at the German Aerospace Center. It can be used on most operating systems and has a large community of users which developed further the simulator capabilities, providing many interesting extensions and features. This includes, for instance, the possibility to generate real-time GPS traces from dump output; to run it concurrently to a network simulation, thus allowing events in the network to influence the mobility of vehicles, or to conduct realistic studies based on the many mobility datasets compatible with it. Regarding the supported car-following mobility models, it supports both of the Gipps and IDM models, which translates in a higher simulation speed but fewer details in the mobility model compared to Vissim. Finally, due to its many features like the possibility to simulate multi-modal transportation and pedestrians, additionally to its high portability and its GNU General Public License, SUMO has become the most used traffic simulator for vehicular networks [Kra+12], [SCB11].

### 3.2.3 Vehicular simulation Frameworks

During the recent years, the approach aiming to couple the network and traffic simulator together meets a growing success, despite its implementation complexity, and slow execution time. Indeed, as stated before such an approach provides many benefits, at first it facilitates the study of protocols that influence the mobility of vehicles. Moreover, it provides a higher degree of realism. Lastly, the continuous development of the tools and frameworks dedicated to such purpose has facilitated the usage of this approach, and more interestingly has provided the support for various IVC standards and technologies. Far from being exhaustive, these binding tools, often called VANETs frameworks or vehicular simulation frameworks, are presented below:

- TraNS: Traffic and Network Simulation Environment (TraNS) was the first open-source project aiming to link a network with a road traffic simulator. This pioneering work was motivated by avoiding the diverging results observed between simulations and real-world experiments experienced by researchers when studying some networks like MANETs. Therefore, the main purpose of this tool was to offer a more realistic simulation environment that brings together the network and traffic simulators, like NS-2 & SUMO, and allows the study of protocols and mechanisms which influence the behaviour of vehicles and drivers. TraNS offers two distinct modes to combine the two simulators: the network-centric mode which feeds NS-2 with vehicular traces from SUMO; and the application-centric mode which synchronises both simulators through a specific interface that sends commands, and consequently allowing the study of applications influencing the mobility. Finally, due to its low-performances, the maintenance of TraNS has been shut-down which restricts it to the support of older versions of SUMO. Nevertheless, it has the merit of paving the way for further frameworks which supplanted it [Pió+08].
- iTetris: The Integrated Wireless and Traffic Platform for RealTime Road Traffic Management Solutions (iTetris) is a European Union Framework Program 7 funded project. It provides a bi-directional coupling between NS-3 and SUMO through a central control block named iTetris Control System (iCS), and it is seen as the successor of TraNS. The Platform aims to develop an open simulation environment dedicated to the study and the development of intelligent

transportation systems and vehicular networking, by fostering the collaboration between engineering companies, road authorities, and communications experts, accordingly to European specifications originating from ETSI. iTetris also supports the 802.11p standard and the ETSI ITS-G5 architecture. Moreover, it has contributed to the development of several communication models for NS-3 (WiMAX, UMTS, DVB-H). Finally, it provides various optimisations solutions of the network simulator which increase the speed and scalability of the simulation, and allow for instance the execution of a 20.000 vehicles one-hour scenario in about a week, while preserving the high accuracy of simulation provided by NS-3 [Ron+13].

- Veins: The VEhicle In Network Simulation (Veins) is one of the most advanced simulation frameworks for vehicular networking, built upon a bi-directionally coupling of Omnet++ & SUMO through the TraCI Python based module, which sends commands to both simulators via a TCP connection. During the recent years, a clear trend toward using this simulator emerged due to its numerous advantages, like the support of multiple standards like the 802.11p, WAVE and LTE-V2X, in parallel to the implementation of different radio propagations models like the two ray interference, nakagami, vehicle obstacle shadowing. Furthermore, Veins is in continuous development to incorporate the recent features and advances made on both simulators, and to reflect the state of the art of research on the field of vehicular networks like those related to the platooning or the security of vehicles. As a consequence, Veins is adopted by a growing community of users and contributors since the project is licensed under a GNU General Public License v2.0 [SGD11].
- MOVE: The MObility model generator for VEhicular networks (MOVE) is build on top of SUMO and produces traces files that can be directly used in NS-2 and QualNet network simulators. The primary goal of MOVE is to facilitate the creation of user-defined scenarios including the traffic flow and the roadmap, through a very user-friendly, but complete interface. The creation of a roadmap is simplified since MOVE proposes some pre-defined topologies as a grid, spider or random network. Regarding the traffic flow, it is generated automatically or manually through a Vehicle Movement Editor. By now, the project seems to be abandoned, and the URL to the project is broken [KML07].

## 3.3 Summary of mobility datasets

As stated previously, mobility datasets enhance the realism of vehicular simulation greatly since they include traffic flow & patterns based on data collected from real vehicles and via GPS sensors and road topology extracted from the roadmap of a city, town or region. This has lead to the proposals of several mobility datasets which are presented below:

- Bologna: it is a small-scale dataset based on the city of Bologna in Italy, developed as part of the iTetris project. It includes three distinct scenarios with a sufficient number of simulated vehicles, based on traces collected during the peak hour running between 8:00 and 9:00 AM. Due to its smallness and simplicity, this dataset constitutes a good way to familiarise itself with realistic vehicular simulation. It is freely available and supports recent versions of SUMO [Bie+15].

- Luxembourg SUMO Traffic (LuST): This dataset covers the downtown and peripherals zones of the city of Luxembourg with a total area of 155 $km^2$. Regarding the traffic demand, the dataset simulates the traffic flow of 24 hours for 200.000 to 300.000 vehicles depending on the set configuration and includes the traces of 38 bus lines for a total of 563 bus stops and 2.336 buses. The dataset supports traffic light systems and also defines the position for more than 14.171 buildings and parking lots which allows the study of protocols behaviour in urban areas where buildings regularly obstruct the wireless connectivity. The dataset is freely available under the MIT license on GitHub [CFE15].

- TAPASCologne: To date, it is the largest scale freely available vehicular mobility traces, comprising more than 700.000 individual car trips simulated during 24 hours, in an area up to 900 $km^2$ around the city of Cologne in Germany. The dataset was built upon the TAPAS system which computes mobility wishes based on travelling habits. Despite the existence of some bugs which were fixed partially by further releases, the dataset defines existing buildings, combines a real-world road topology with accurate microscopic mobility modelling and realistic traffic demand. Lastly, it supports later version of SUMO which in overall encourages its usage highly, to assess protocol performances [UF11].

- Realistic Vehicular Traces for Zurich: Authors of this dataset relied on the Multi-agent Microscopic Traffic Simulator (MMTS) developed at ETH Zurich to generate 24 hours detailed traffic traces for more than 260.000 vehicles. Regarding the road topology, it is extracted from the Canton of Zurich, which includes main country highways and covers an area of around 250 km x 260 km. The dataset is intended to be used directly by a network simulator like NS-2 or Omnet++ without the need for a traffic simulator, is available online for free use [NBG06].

- Shanghai Urban Vehicular network (SUVnet): This dataset has been built by gathering three-month GPS data from over 4000 taxis in the downtown area of Shanghai, China and then reconstructing the traces by mapping the data onto a digital map. The resulting dataset, called SUVnet, simulates more than 1.170

vehicles with an average speed of 25 km/h, during 20 minutes into an area covering a surface of 102 $km^2$ [Hua+07].

## 3.4 Common architecture for the implementation of VDTN routing protocols

Another important practical issue that arises when evaluating VDTN routing protocols is related to the availability of base implementation codes for the considered protocols in the same simulation environment. Indeed, several VDTN routing protocols were evaluated; however, it is generally achieved by relying on different simulation frameworks, where each one has its degree of realism and parameter setting. Moreover, from the reported implementation codes cited in the literature, only a limited set of them are made publicly available to the research community.

Consequently, a significant research gap that must be addressed and which we try to address through the work conducted during this thesis consists in the availability of base implementations codes for well-known VDTN routing protocols, in parallel to the proposed protocol GeoDTC. The implementation of those protocols is built upon a state of the art Vehicular Simulation Framework, and a proposal of an architecture that facilitates the development of future VDTN routing protocols.

### 3.4.1 Simulation environment

Based on the aforementioned presentation of network simulators commonly used for the evaluation of vehicular networks, and in accordance with sections 3.2.2 & 3.2.3 which covers respectively road traffic simulators and vehicular simulation framework, we selected the Veins simulation framework [SGD11] as a basis for the development of our proposed architecture, further detailed in the following sections.

As a reminder, Veins is one of the most advanced simulation frameworks dedicated to vehicular networks, it is built upon state of the art advancements on the research field, and supports consequently new standards like the 802.11p, WAVE and LTE-V2X. Moreover, it includes a concise implementation of different radio propagations models and Wireless technologies, by relying partially on the Omnet++ library INET [INE04]. Besides, Veins bidirectionally couples the Omnet++ network simulator with the SUMO traffic simulator, through a TCP communication ensured by the Python-based TraCI server [Weg+08], which ultimately allows the usage of real-world mobility traces compliant with SUMO like TAPASCologne and LuST, while facilitating the study of the reversible influence between mobility on one hand, and network protocols and mechanisms on the other. Finally, the considered version of Veins is the v2.0-rc1, which incorporates the version v4.2 of Omnet++ and the v0.13 of SUMO.

### 3.4.2 Proposed architecture for the implementation of VDTN routing protocols

After presenting the primary requirements needed for the evaluation of VDTN routing protocols, detailing the various simulation tools involved into this process and finally selecting the right simulation environment for our work, we discuss in the following section the details behind the proposed architecture for the implementation of VDTN routing protocols under the Veins framework.

More specifically, we begin by presenting the general specifications for the proposed architecture, this latter serves as a common ground for the implementation of any routing protocol, by relying on different components that are dedicated to different tasks as ensuring the storage of bundles, scheduling their transmission, or discovering neighbouring vehicles. Subsequently, we introduce specifications related to geographic-based routing protocols like the well-known protocol GeoSpray [SRF14], or the proposed protocol GeoDTC.

#### 3.4.2.1 General specifications for the proposed architecture

The proposed architecture was developed based on the official development language of Omnet++, namely the C++ language. Therefore, it includes several C++ classes that can be organised into packages or modules of a dedicated purpose like routing, storage or mobility; and as illustrated in the Fig 3.1 which is a UML class diagram. This latter highlights the interaction occurring between a large number of classes and dissociates between previously existing and newly developed classes. Finally, the figure is far from being exhaustive and does not cover some specific packages which will be briefly described below, along with those already depicted.

**Routing:** This package is at the core of the proposed architecture since it includes the *DtnNetwLayer* class which is at the base of the implementation of any routing protocol. More specifically, this class extends the basic network layer implementation of the existing *BaseNetwLayer* class, with primary methods related to the implementation of core mechanisms and features that ensure the correct behaviour of VDTN routing protocols, and the fair comparison between them. These core mechanisms and features provided by the *DtnNetwLayer* class are briefly described below:

- **Neighbourhood discovery:** the discovery of neighbouring vehicles is essential for the functioning of a VDTN routing protocol. However, it is often neglected by researchers and to the best of our knowledge, authors of TGRP [Bág+14] are the only ones to consider it, relying in particular on the NeighbourHood Discovery Protocol (NHDP) standardised in the RFC 6130 [CDD11], even though this latter is not suited for such networks. Consequently, the *DtnNetwLayer*

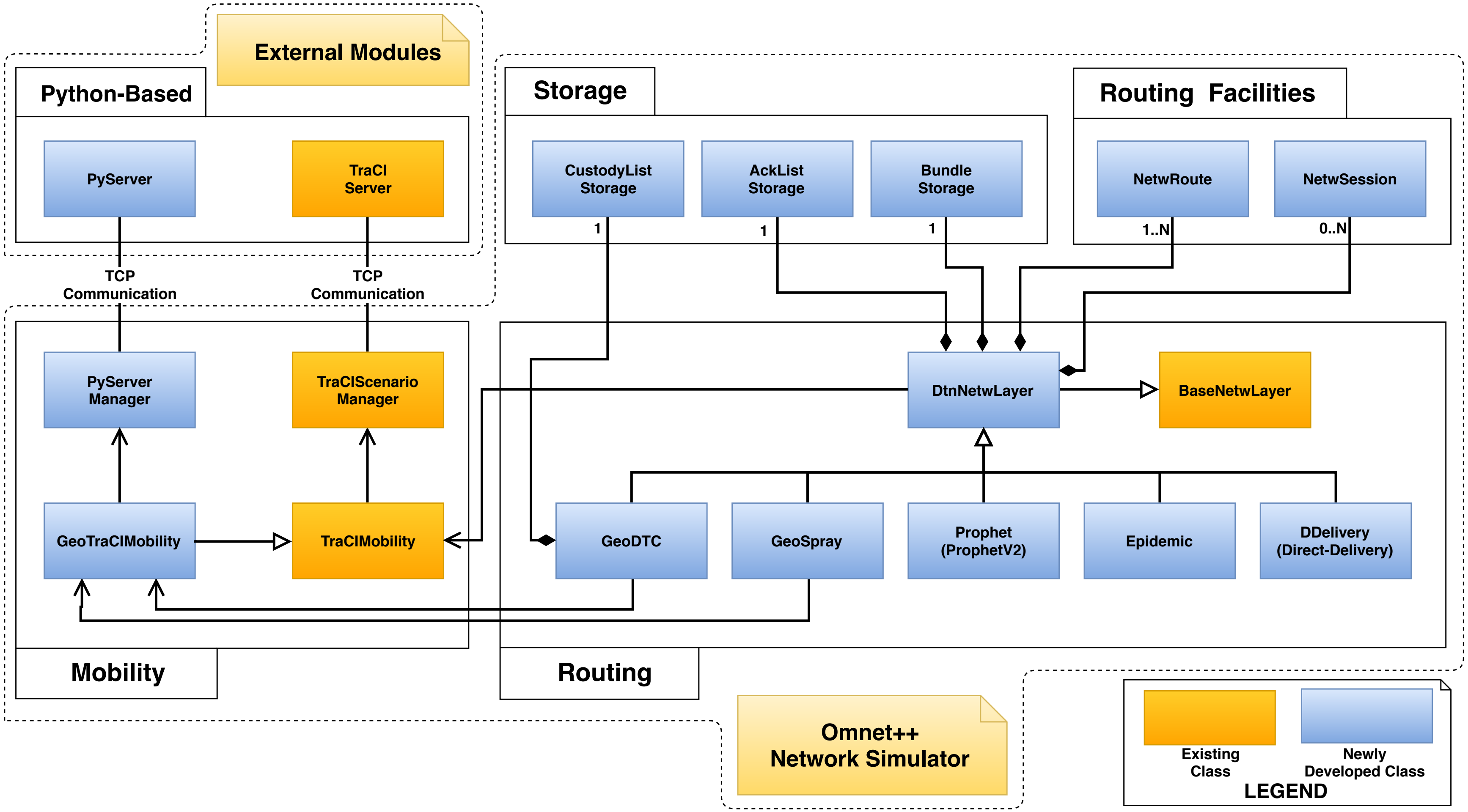


FIGURE 3.1: UML class diagram of the proposed architecture

class includes a minimalist neighbourhood discovery process based on periodic beaconing and timers triggering. Thus, a vehicle periodically broadcasts beacons according to a beacon period denoted by $Period_B$; upon their receipt, a receiver vehicle adds the sender to its known neighbours then triggers two distinct timers that are the pending and the expire one denoted respectively by $Timer_{Pend}$ and $Timer_{Exp}$. The last timer is used to delete a previously known neighbour after missing several beacons, whereas the former is used to mark the vehicle in pending mode which is a transient state where the vehicle is not connected, nor already disconnected after missing a few beacons. Such behaviour may occur due to micro-disconnection and connectivity may be re-established or not after the receipt or the miss of following beacons. Finally, it should be noted that both timers are multiples of $Period_B$ and $Timer_{Pend} < Timer_{Exp}$.

- **Store, carry & forward:** to implement this key DTN principle, the *DtnNetwLayer* class intercepts any bundles generated by upper layers of the network, by first proceeding to their storage then by resuming their transmission whenever a vehicle is encountered, and a forwarding decision is made.
- **Storage facilities:** the *DtnNetwLayer* class provides storage facilities for bundles, list of acknowledgements and custodian bundles, by relying mainly on classes defined in the **Storage** package.
- **Scheduling and dropping policies:** to efficiently prioritise the transmission and manage the lifetime of bundles, a routing protocol must define scheduling and dropping policies related respectively to the transmission and the deletion of bundles. Regarding the proposed architecture, the *DtnNetwLayer* class implements policies defined by the notable works conducted in [SFR10] & [Dia+11], and follows their recommendation.

Finally, the package includes the implementation of multiple VDTN routing protocols through the extending of the *DtnNetwLayer* class. This covers for now, the four well-known protocols Direct-Delivery (abbreviated as DDelivery), Epidemic, GeoSpray and Prophet (as mentioned previously ProphetV1 is outdated, thus ProphetV2 is the only one to be considered in this thesis), additionally to the proposed protocol GeoDTC, but could be extended easily to the implementation of other VDTN routing protocols.

**Storage:** This package regroups three distinct classes, namely *BundleStorage*, *AckListStorage* and *CustodyListStorage*, which are respectively in charge of the storage of bundles and list of acknowledgements in general, and of list of custodian bundles for the GeoDTC protocol. The main benefits of these classes consist in their ability to provide statistics related to stored and deletes items along with the reason behind (for instance: a bundle may be deleted upon the receipt of an ack or due to its expiry).

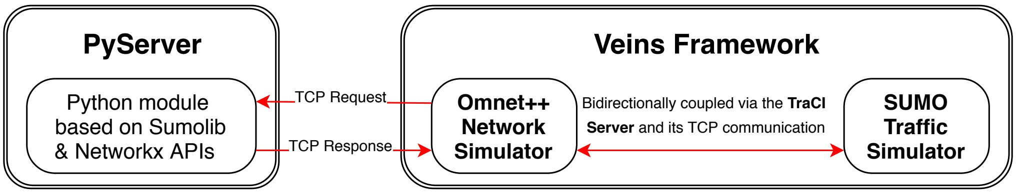


FIGURE 3.2: TCP communication between The Veins Framework & PyServer

Furthermore, they guarantee the storage consistency through regular integrity check of storing indexes.

**Routing facilities:** This package includes the *NetwRoute* and *NetwSession* classes. The former is involved into the process of neighbourhood discovery; in fact, it includes information related to the network address, current forwarding metrics and coordinates (if needed), and node type (vehicle or RSU), which are sent to other entities of the network through periodic beacons. The latter allows the current node to keep track of data sent by a specific node during the current session, likes, for instance, sent bundles and acknowledgements, which ultimately avoids their retransmission or request.

**Mobility and Python-based:** These packages includes several classes that may be categorised into three different categories, those who reflect the mobility within the network simulator like for *TraCIMobility* and *GeoTraCIMobility* classes, the managers as *TraCIScenarioManager* and *PyServerManager* which retrieve data from external modules and serve as an interface for them with Omnet++. Finally, the Python-based module *TraCIServer* allows the bidirectional coupling of both simulators through a TCP-based communication, whereas the *PyServer* is a Python server dedicated to geographic-based protocols, which are in need for a navigation system able to compute the shortest path and the Nearest Point (NP), as it will be highlighted in the next section.

**Application:** This package which is not involved into the routing process and consequently not represented in the UML class diagram, is in charge of defining settings related to the application running on top of the vehicular network. The main class of this package is the *DtnApplLayer* which extends the existing *BaseWaveApplLayer* class, with methods for the generation of bundles (periodic or after entering a specific zone or sector), the definition of the sender and receiver nodes (vehicles only, RSUs only or both), and the collect of statistics and other tasks. Moreover, it serves as a base implementation for the derived classes *VehicleAppl* and *RSUAppl* which control the behaviour of the application layer for vehicles and RSUs and could be easily derived/adapted to define other applications.

#### 3.4.2.2 Specifications related to geographic-based VDTN routing protocols

Geographic-based VDTN routing protocols like the implemented GeoSpray and GeoDTC, or those not extensively studied, nor implemented during this thesis, require in general terms a navigation system able to return the current position and compute the shortest path. While the current position can be easily retrieved from the SUMO traffic simulator, some limitations exist regarding the computing of the shortest path between two random points on the map by the considered version of SUMO (v0.13). Moreover, the on-demand handling of such repeated requests is expensive in terms of computational costs and ultimately may slow down the whole simulation.

To avoid such scenario, the proposed architecture includes the Python module *PyServer*, which acts like an embedded navigation system able to provide the geographic-based VDTN routing protocols GeoSpray and GeoDTC with the information needed like the shortest path, the Nearest Point (NP), or the minimum traverse time for a specific road. Furthermore, to speed up the computing or the retrieval of such information, a pre-processing step occurs prior to the beginning of the simulation, where the *PyServer* module loads the considered map, and then translates it into a weighted graph of minimum traverse time for all roads, by relying jointly on SumoLib (embedded into SUMO v0.13) [Kra+12] and NetworkX (v1.11) [HSS08] Python libraries. Besides, the shortest paths between any two random points are computed and stored for future reuse.

Starting from there, the forwarding metrics used by the network classes of GeoSpray and GeoDTC, are computed by the mobility class *GeoTraCIMobility*. This latter achieves this task by relying jointly on both managers. Indeed, the *PyServerManager* sends a request to the *PyServer* module for the computing of the shortest path and the NP, via a TCP communication illustrated by Fig 3.2. Then, the current position and the maximum allowed speed for a specific road are retrieved from the SUMO traffic simulator, via the bidirectional TCP communication established by the *TraCIServer* and the TraCI requests sent by the *TraCIScenarioManager*. Finally, all these information are combined by the *GeoTraCIMobility* to estimate with accuracy forwarding metrics as the METD metric or the distance between the NP and the final destination.

# Chapter 4

# Comparison of main VDTN routing protocols



After covering various aspects in the precedent chapter, like defining the minimum requirements for the evaluation of VDTN routing protocols through simulation, presenting an overview of existing simulation tools, and finally selecting the right simulation environment for the development of the proposed architecture. This chapter presents one of the major contributions of this thesis, namely the comparison of the main VDTN routing protocols under small- and large-scale scenario. The selected protocols are considered in general as the main flag-carriers of the different routing families presented in Section 2.4. Regarding the considered scenario, and accordingly to the recommendations made in Section 3.3, the large-scale and realistic scenario was conducted based on the TAPASCologne [UF11] mobility dataset, as it will be highlighted in this chapter.

## 4.1 Related comparative works

Performance evaluation of multiple VDTN routing protocols is an active research topic with numerous pieces of related work. It is possible to classify these works easily into two distinct categories: those who propose a new routing protocol and therefore run a performance evaluation of their proposal against other well-known routing protocols, and those who conduct a performance evaluation of already established routing protocols without proposing a new one. The contribution falls into this latter category.

However, good performance evaluations must meet some criteria as highlighted in Section 3.1 namely: realistic network simulator, road topology that reflects the real-world map and mobility patterns that mimic daily life routines of drivers, without omitting another critical aspect which is the evaluation of the protocol scalability. Therefore, it appears that only a few works meet these requirements, as for GeOpps [LM07] or the DAER routing protocol [Hua+07], and more recently in [LPD12]. These statements are supported by Table 4.1, which compares the performance evaluations done by the cited research studies.

In order to correctly evaluate GeOpps, the authors run it against two other protocols by using real-world traffic traces of the ETH Zurich mobility dataset previously presented, within an area of 15 km x 15 km and more than 21,500 simulated cars [NBG06]. On the other hand, the DAER authors evaluated their proposal against the Epidemic protocol, based on the SUVNet mobility datasets and the traces of more than 4,000 Shanghainese taxis. Finally, the authors in [LPD12] performed simulations of multiple routing protocols such as Louvre [Lee+08], VADD [ZC08] and GPCR [Loc+05] under the NS-3 network simulator [RH10] and TAPASCologne mobility dataset with approximatively 4,670 nodes.

Another interesting study was conducted by the authors in [Mon+15], where the Static, Epidemic, and Prophet protocols were evaluated first under a small-scale simulation, then via a real testbed in the harbour of Porto city, Portugal, by means of the IBR-DTN software [Sch+11]

Apart from the works cited before, other ones fail to fulfil the requirements by omitting one or more criteria. Even major works presenting well-known DTN routing protocols deployed on vehicular environments or pure VDTN routing protocols suffer from this lapse. The above statement is true for Prophet which has been evaluated through the Opportunistic Network Environment (ONE) simulator [KOK09] which allows a good understanding of the routing protocol behaviour but at the expense of a total abstraction of lower layers, making it inconsistent with a high degree of network simulation realism. The same goes for GeoSpray and comparative works achieved in [Spa+16], [Ben+13] and [Cuk+17], with a notable difference for this latter work whereby efforts were made regarding the realism of vehicle mobility by relying on the SUMO traffic simulator [Kra+12].

Finally, the respective authors of the GeoDTN+Nav routing protocol [Che+10] and the VADD protocol [ZC08] make use of the TIGER dataset [Peu90] without explaining the underlying mobility of vehicles. Besides, the evaluation is done under a limited number of nodes. Whereas those involved in the TGRP routing protocol are insufficiently clear about compared protocols, by choosing pseudo protocols to represent different approaches such as DTN routing or Geo-routing [Bág+14].

## 4.2 Presentation of compared protocols

For the purpose of evaluating the performance of VDTN routing protocols under both realistic network simulators and scenarios, we selected four well-known protocols, namely: Direct-Delivery (abbreviated as DDelivery), Epidemic, Prophet, and GeoSpray. This selection was not undertaken lightly since it relates to different criteria and is somewhat dictated by a global consensus across the research community.

Basically, we tried to pick the most representative, or the best routing protocols for some routing approaches as highlighted in Section 2.4 related to the VDTN routing protocol taxonomy. Other approaches were deliberately excluded as their inaccuracies or assumptions make them less suited to the vehicular context, especially when the delay/disruptive tolerance constitutes a requirement.

As confirmed by different works such as [Ben+14] and [Tor+15], the pure geographical approach which is not constrained by road topology, along with on-line protocols, fall into this last category, and consequently, they have been excluded. Therefore, we selected both DDelivery and Epidemic protocols as representative of the zero-knowledge routing family, in parallel with Prophet and GeoSpray protocols, representative of the predictive/social and geographic-based routing family respectively.

The selection of the two former protocols responds to different criteria. First, DDelivery and Epidemic make use of single versus multiple copy replication schemes respectively, which allows us to compare the pros and cons of each replication scheme. Secondly, due to their protocol design, they may constitute an ideal benchmark for

| | [SRF14] | [Che+10] | [LM07] | [ZC08] | [Hua+07] | [LPD12] | [Mon+15] | [Spa+16] | [Ben+13] | [Cuk+17] |
|---|---|---|---|---|---|---|---|---|---|---|
| **Proposal of a new protocol** | Yes | Yes | Yes | Yes | Yes | No | No | No | No | No |
| **Network Simulator** | VDTNsim[1] | QualNet | Omnet++/MF[2] | NS-2 | Self-Developed | NS-3 | IBR-DTN[3] | ONE | ONE | ONE |
| **Realistic Mobility (Dataset Name)** | No | Tiger | ETH Zurich | Tiger | SUVNet | TAPAS Cologne | Yes[3] | No | No | No |
| **Considered Topology** | Helsinki City | ND[4] | Zurich Canton | ND | Shangai City | Cologne City | Porto City | Tirana City | Helsinki City | Fukuoka City |
| **Simulation Area (km)** | 4,5 x 3,4 | ND | 15 x 15 | ND | 100 km$^2$ | 20 x 20 | ND | 5 x 3.5 | 4,5 x 3,4 | ND |
| **Simulation Duration** | 6H | ND | 24H | ND | 1200s | 1000s | ND | 4H | 12H | 660s |
| **Maximum Vehicles** | 115 | 50 | 21500 | 210 | 1000 | 4670 | 30 | 200 | 100 | 220 |
| **Comparison with VANETs/VDTNs protocols** | Yes/Yes | Yes/No | Yes/No | Yes/Yes | Yes/Yes | Yes/Yes | Yes/Yes | Yes/Yes | Yes/Yes | Yes/Yes |

[1] Self developed network simulator based mainly on ONE.
[2] MF for Mobility Framework is a framework for Omnet++ with a great focus on low layers and radio transmission technologies (Ancestor of Mixim).
[3] Software for conducting on field experimentations under live conditions with support of 802.11p.
[4] ND: Not Defined

TABLE 4.1: Performance evaluation parameters of related works routing protocols

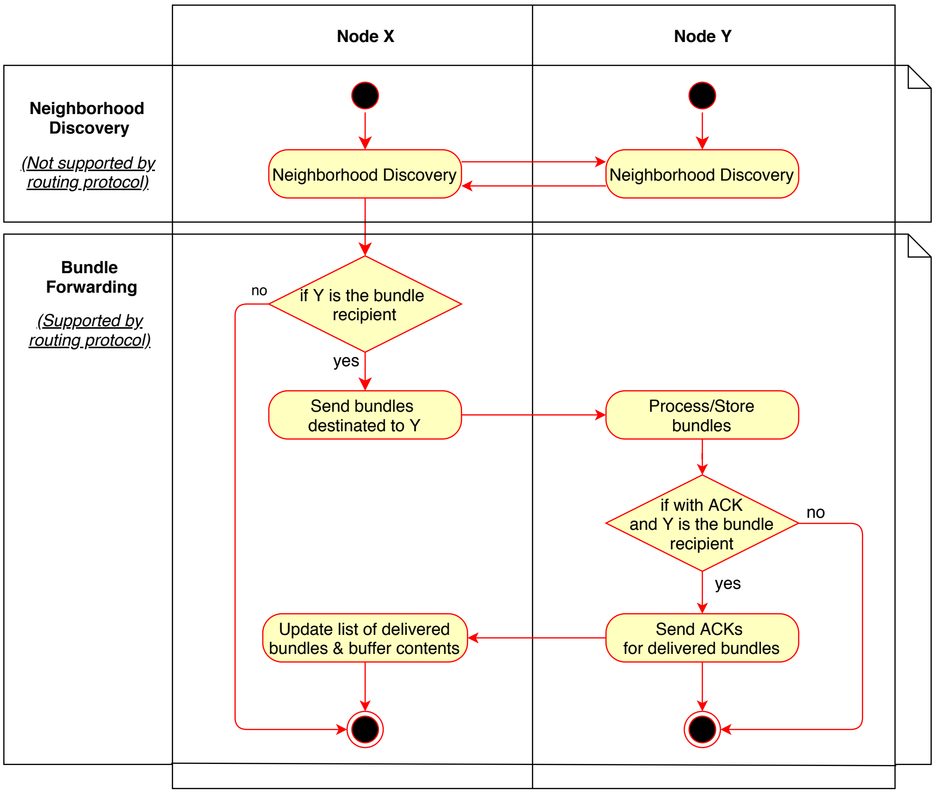


FIGURE 4.1: UML activity diagram of DDelivery operations for data routing

VDTN routing protocols since they potentially provide the lower and upper bounds for critical networking metrics such as delivery rate or delay [Tor+15]. Finally, the zero-knowledge family is historically the first one from which all others derive, so it is an opportunity for us to measure the progress made in this research field.

When shifting to the remaining approaches, namely predictive/social-based and geographic-based, it is evident through the literature review that they are competing to provide the best routing protocol. When the first one tries to extract a pattern from the vehicle mobility that is induced by a daily routine, the last one is fostered by the large availability and easy use of GPS devices.

Prophet is a well-established predictive/social-based routing protocol, with a solid background and good documentation, standardised in the RFC6693 [Lin+12]. Since its proposal, the research community conducts different works aimed at enhancing its performances, leading to the release of a second version that grants better performance and resolves some issues.

GeoSpray is a promising geographic-based routing protocol since it is one of the newest protocols with a good presentation of protocol routines, clear attention to making use of the best schedule/dropping bundle policies and finally, a good trade-off between performance and replication overhead. Therefore, it succeeds in capturing the interest of researchers.

### 4.2.1 Direct-Delivery

Among the multitude of VDTN routing protocols, Direct-Delivery or DDelivery is the simplest one, proposing a very minimalist forwarding scheme that does not require any prior knowledge. In fact, the authors of [SPR04] proposed in 2004 the use of the sender node mobility as a key factor for data delivery to the final recipient instead of building an end-to-end path between them. Hence, the sender node X carries data until it meets the recipient node Y and finally delivers data.

Such a protocol design implies the use of a single replication scheme and the need to wait for a possible encounter between the sender and the recipient in order to deliver data as illustrated in Fig 4.1, which may or may not happen after a very long delay, making this last point the major drawback of the routing protocol. Consequently, and as stated by the authors, this routing protocol may represent a lower bound for the delivery ratio and an upper bound for the delay.

### 4.2.2 Epidemic

Proposed by Vahdat & Becker in [VB00], the Epidemic routing protocol is one of the oldest DTN routing protocols upon which many other DTN routing protocols have been based or inspired by such as MaxProp [Bur+06] and RAPID [BLV07].

The protocol is based on a simple design that does not require any prior knowledge to route data, but it floods the network with multiple replicas of data and, along the way, explores all possible paths to reach the destination, until the optimal path is found. Therefore, under ideal conditions such as when there are no resource constraints or network congestion, Epidemic may find the shortest path to reach the destination and provide an upper bound for the delivery ratio and a lower bound for the delay as claimed by the authors and many researchers. However, the creation of a large amount of data replication along with the exploration of all possible paths have some critical drawbacks regarding the waste of resources or more drastically and disastrously, congestion of the network by saturating the bandwidth with unnecessary replica transmission.

The Epidemic protocol operations are based on a three-step information exchange process, starting with an exchange between each part of the offered and the requested bundle lists which contain the corresponding meta-data and are referred to as Summary Vectors (SVs). This process is concluded by the forwarding of requested bundles and, optionally, their acknowledgements. In other words, if node X is the current bundle carrier and node Y is a possible relay or the final recipient, X starts by sending a summary vector of offered/proposed bundles that it holds, denoted by $SV_X$, then Y replays to it by sending a summary vector denoted by $SV_Y$ and including required bundles not already held, excluding those which are stored by both X & Y. Upon the receipt of $SV_Y$, X starts forwarding the requested bundles. Finally, if Y

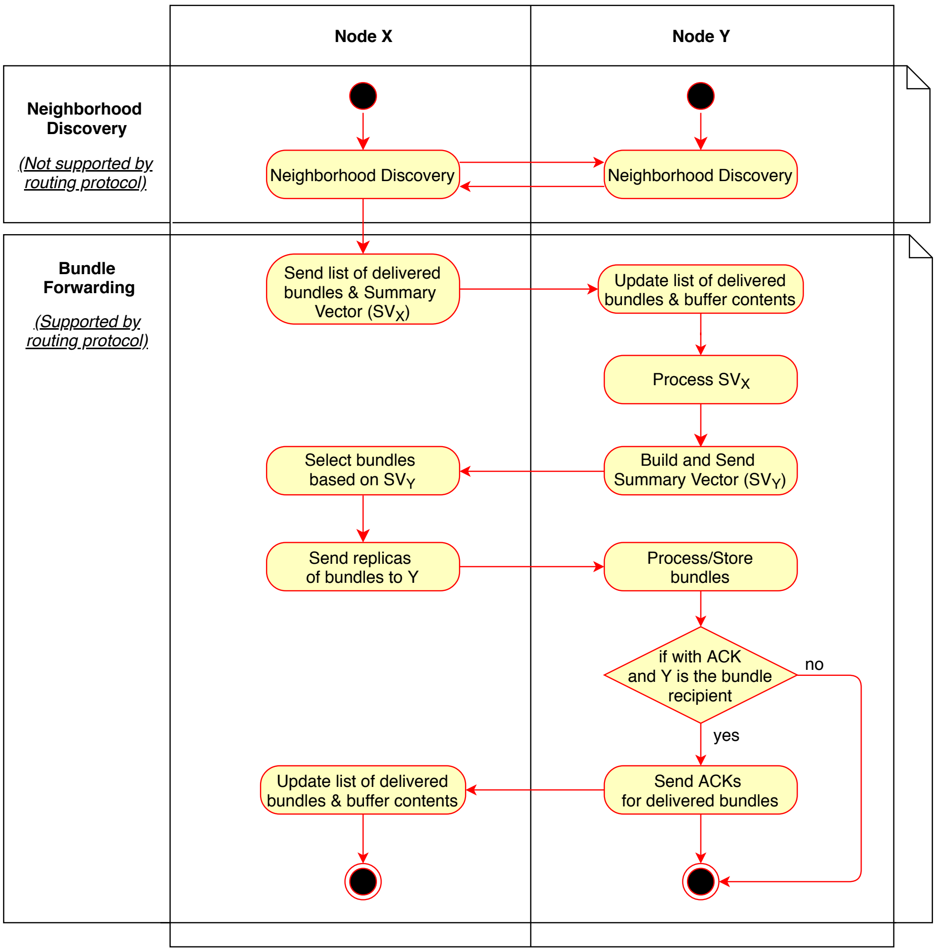


FIGURE 4.2: UML activity diagram of Epidemic operations for data routing

is the final recipient for some bundles, it can optionally generate acknowledgements (ACKs) for those bundles, then send them back to X and consequently allow the whole system to release more resources for the remaining ones. This overall process of information and data exchange is illustrated in Fig 4.2.

### 4.2.3 Prophet

Prophet, which stands for Probabilistic Routing Protocol using History of Encounters and Transitivity, is the first contact history-based routing protocol. It was first presented in [LDS03], then enhanced in the second version in [Gra+11] and later standardised through the RFC6693 [Lin+12]. Consequently, this last version (ProphetV2) is the only one that has been considered in this work.

To route data and so making a forwarding decision after a node encounter, Prophet follows a multiple copy replication scheme and relies on a self-defined delivery predictability metric denoted by $P$ with $P \in [0, 1]$. This metric reflects the probability of encountering a specific node and thus delivering its associated data. The higher this value is, the more likely becomes the encounter of this node. Consequently, a

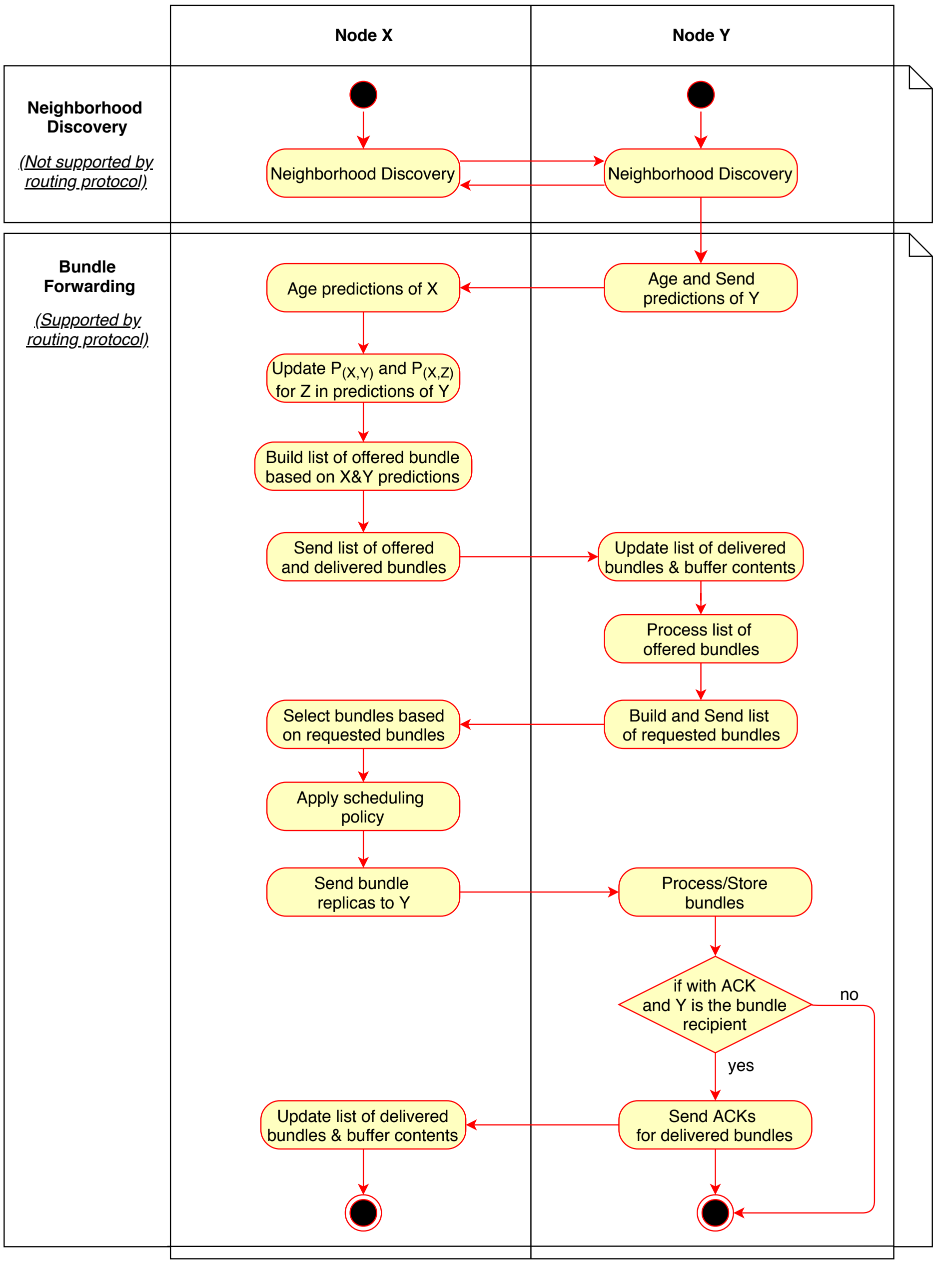


FIGURE 4.3: UML activity diagram of Prophet operations for data routing

suitable forwarder is one with a higher predictability of encountering the bundle recipient, whereas multiple encounters between a specific pair of nodes lead to a higher predictability of encountering each other.

Concretely, the RFC6693 defines the computation and the management of the delivery predictability for each known node Y by the current node X, denoted by $P_{(X,Y)}$, according to three mathematical formulas/equations. The Equation (Eq.) 4.1 updates the delivery predictability $P_{(X,Y)}$ after each encounter between X and Y based on the previous predictability, denoted by $P_{(X,Y)old}$, and the encountering factor, denoted by $P_{enc}$. The latter is computed according to different criteria, mainly, the maximum delivery predictability, denoted by $P_{max}$, the interval of time since the last encounter between the node pair, denoted by $Intvl_Y$, and lastly the typical interval time between two successive encounters of a node pair, denoted by $I_{typ}$. Readers should note that $P_{(X,X)}$ is always equal to 1, whilst $P_{enc}$ is set to the first contact delivery predictability, denoted by $P_{first\_contact}$, instead of $P_{max}$, in the absence of any prediction $P_{(X,Y)}$ for Y.

$$P_{(X,Y)} = P_{(X,Y)old} + (1 - P_{(X,Y)old}) \times P_{enc} \tag{4.1}$$

$$\text{With } P_{enc} = \begin{cases} P_{max} \times (Intvl_Y / I_{typ}), & \text{if } 0 \leq Intvl_Y \leq I_{typ} \\ P_{max}, & \text{otherwise} \end{cases}$$

Meanwhile, Prophet defines the transitivity property for the delivery predictability. Indeed, if X frequently encounters Y and this latter often encounters Z, then X is a potential good forwarder of bundles to Z. Eq.4.2 reflects this behaviour by allowing the update of $P_{(X,Z)}$, where $\beta$ is a constant that quantifies the impact of the transitivity.

$$P_{(X,Z)} = max(P_{(X,Z)old}, P_{(X,Y)} \times P_{(Y,Z)} \times \beta) \tag{4.2}$$

Finally, in contrast with previous equations that allow delivery predictability to be updated and consequently increased, the latter equation does the reverse process by ageing delivery predictability and decreasing it after a period without node encounters. This is done according to Eq.4.3 that makes use of the ageing constant $\gamma$ with $\gamma \in [0,1]$ and the number of time units $K$ that have elapsed since the last ageing. The time unit used, denoted by $T_{unit}$, should be defined based on the considered scenario/application where $K$ should be a multiple of it.

$$P_{(X,Y)} = P_{(X,Y)old} \times \gamma^k \tag{4.3}$$

Furthermore, the standard describes the whole process needed to deliver data between a sender X and a relay or final recipient Y, as illustrated in Fig 4.3. Y starts the process by successively ageing then sending predictions to X for all known nodes according to Eq.4.3. Upon the reception of such a message, X also ages its predictions for all known nodes according to Eq.4.3. Then it updates $P_{(X,Y)}$ according to Eq.4.1 and at last updates $P_{(X,Z)}$ according to Eq.4.2 for each node known by Y and contained in the predictions sent to X. Upon the completion of prediction updates, X selects bundles for which Y is a good forwarder. This is done according to the selected forwarding strategy and generally means that $P_{(Y,bundle\_dest)}$ is higher than the bundle final destination $P_{(X,bundle\_dest)}$. Based on selected bundles, X and Y exchange between them bundle offers and bundle responses that contain meta-data related to those offered by X to Y respectively and, inversely, those requested by Y from X. Finally, the bundle forwarding from X to Y is triggered after the receipt of bundle responses and may engender an additional message to acknowledge the

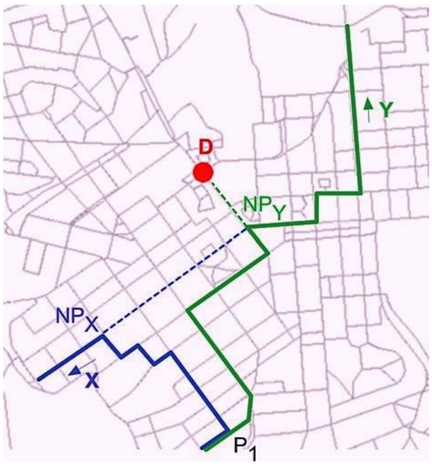


FIGURE 4.4: Calculation of nearest points for vehicles X & Y and destination D [SRF14]

bundle receipt if Y is the final recipient. It should be noted that these processes occur in parallel without any interference in both directions from X to Y and Y to X, while offered bundles from X to Y may incorporate the list of already delivered bundles.

### 4.2.4 GeoSpray

GeoSpray is one of the most recent and promising routing protocols belonging to the geographic-based family [SRF14]. It assumes that vehicles navigate by means of GPS-based navigation systems and follow a hybrid approach by taking advantage of both GeOpps [LM07] and Spray&Wait (S&W) [SPR05] routing protocols. So, GeoSpray makes use of a limited multiple copy replication scheme by fixing at the start the maximum number of replicas that can exist through the network, denoted by $R$, as defined by S&W, and it relies on a position-based forwarding metric as introduced by GeOpps.

This forwarding metric is called the Minimum Estimated Time of Delivery and abbreviated to $METD$. It can be summarised as follows: a vehicle moving along a suggested route (determined by 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, as depicted in Fig 4.4. Then, the navigation system is used to calculate the estimated time to arrive at $NP$, denoted by $ETA_{\text{to NP}}$, and to determine the similar time needed to go from $NP$ to $D$, denoted by $ETA_{\text{NP to D}}$, based on the length and maximum speed of each considered road for both paths. Therefore $METD$ is the sum of these values as shown in Eq.4.4, while the choice of a suitable forwarder can be explained in the following manner: forwarding bundles to the vehicle that is converging more quickly or is closer to the final destination means selecting the vehicle that minimises $METD$.

$$METD = ETA_{\text{to NP}} + ETA_{\text{NP to D}} \tag{4.4}$$

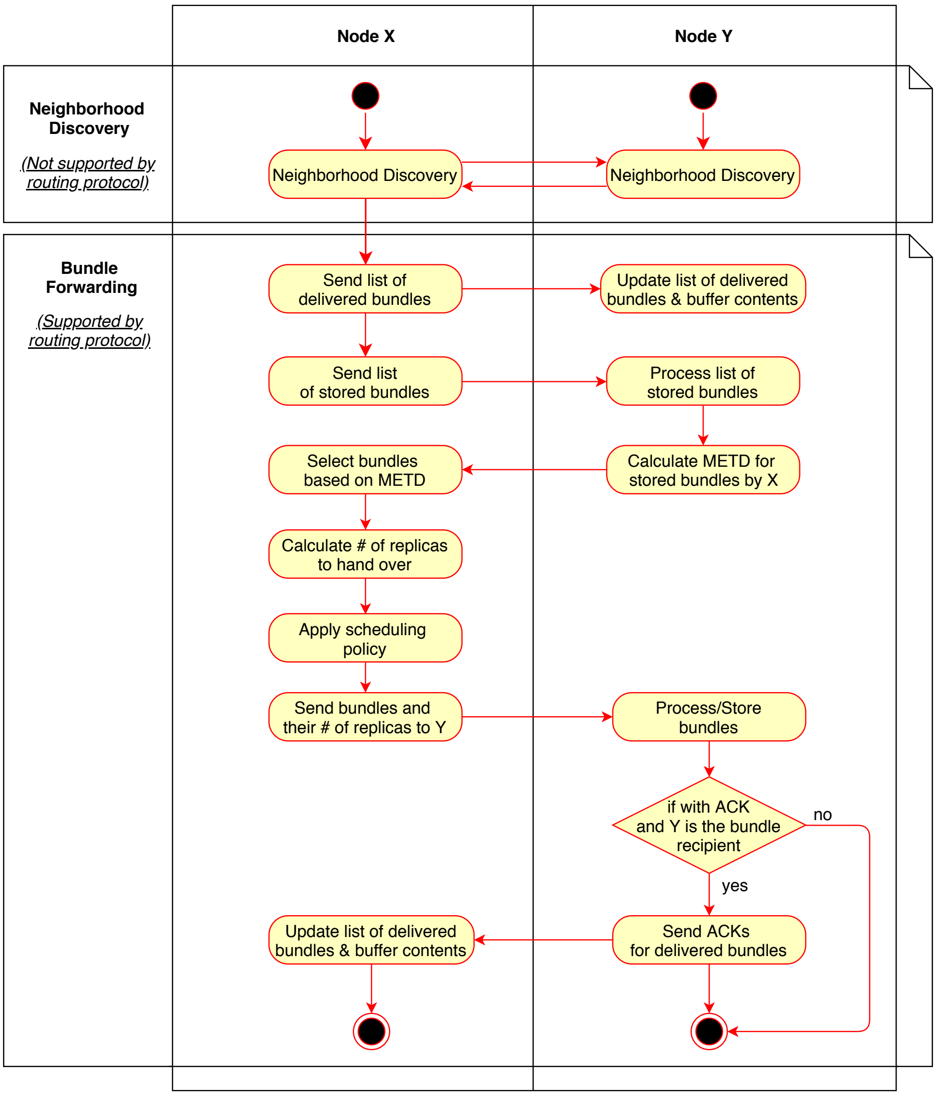


FIGURE 4.5: UML activity diagram of GeoSpray operations for data routing

For clarity about the GeoSpray behaviour, operations performed by it whenever two nodes meet each other are illustrated in Fig 4.5. Note that operations are mirrored between both nodes. As expected, bundle forwarding occurs at the final stage, preceded by information exchange between a bundle carrier X and a bundle relay/recipient Y, which is organised as follows: The former node starts by sending the list of already delivered bundles, with the aim of updating the acknowledgement list of Y and purging the network through the release of more resources for bundles still waiting to be delivered. This operation is followed by the sending of stored bundle lists of X which allows Y to calculate $METD$ for those bundles, subsequently returning this critical information to X. Upon their receipt, X selects bundles for which Y minimises the $METD$ metric and is therefore considered as a suitable forwarder. Also, X must set the amount of replica to handover to Y in order to stay consistent with the limited replica scheme of GeoSpray. This last operation is done with respect to the Spray&Wait strategy and then results in a handover of $L/2$ copies

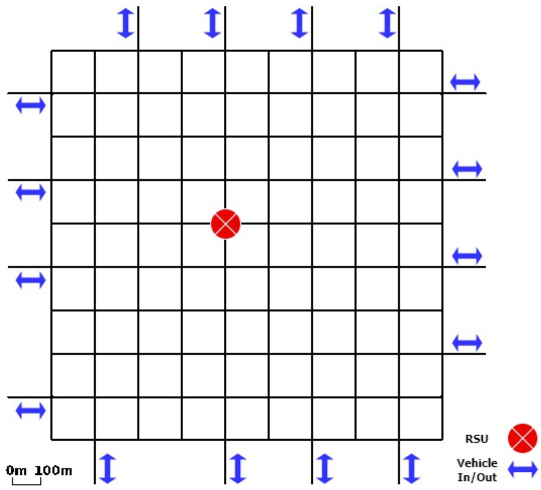


FIGURE 4.6: Road network with a single RSU used in small-scale scenarios

to Y whenever $L > 1$ or 1 copy if $L = 1$, with $L$ being the remaining number of replicas whose value is equal to $R$ at the bundle generation. Finally, X reorders bundles that must be forwarded to Y according to its scheduling policy before sending them.

## 4.3 Evaluation of compared protocols

The main goal of this work is to provide a global overview of protocol performance for on-field researchers. To that end, a quantitative evaluation of selected protocols under small- and large-scale scenarios is conducted, based on synthetic as well as realistic vehicle mobility. In fact, while an evaluation under a small and synthetic scenario is what is usually done, the need for a realistic and large-scale scenario makes sense since the main use case of studied protocols is routing data under real-world conditions regarding the scalability or the vehicle motion. Furthermore, by evaluating protocols under a small-scale scenario, we attempt to determine to what extent it is possible to reflect and simulate their behaviour under a large and realistic scenario and, most importantly, predict their relative performance along with the protocol hierarchy. Besides, we test the proposed settings of Prophet (ProphetV2) and estimate the impact of some parameters and mechanisms on GeoSpray. Lastly, we present the three (03) distinct considered scenarios:

- Scenario A: a small-scale scenario with synthetic vehicle mobility.
- Scenario B: a small-scale scenario with synthetic vehicle mobility plus special vehicles called looping vehicles that are continuously rerouted.
- Scenario C: a large-scale scenario with a realistic roadmap and vehicle mobility according to the TAPASCologne dataset.

Regarding the working environment, the simulations are done by means of the High-Performance Computing Grid MAGI of Paris XIII University[SPCU], while the study relies, as cited in Section 3.4.1, on the Veins framework (v2.0-rc1) which is based on the network simulator Omnet++ (v4.2) and the traffic simulator Sumo (v0.13). The latter is responsible for vehicle mobility and provides many mobility models like the Dynamic User Assignment (DUA) which is considered in Scenario A & B. It provides a user equilibrium for all considered vehicles instead of optimal paths, therefore reflecting much more realistic driver behaviour [Kra+12]. Regarding radio propagation models, Veins implements various models, including the Two Ray Interference model [SD11] & [SJD12] and the Simple Obstacle Shadowing [Som+11] whose uses are highly advised by the Veins authors. The first one is an enhanced version of the Two Ray Ground model and succeeds in modelling signal fading at short distances which is an expected phenomenon. The model has been tested through real-world experimentation thus confirming its accuracy and superiority to the Two Ray Ground model. The latter succeeds in modelling through a simplistic approach, building shadowing as frequently happens in urban environments. It has been experimentally validated and yields a good trade-off between complexity and accuracy which allows simulation scalability. Finally, Veins implements specifications of IEEE 802.11p, limited to Broadcast mode only, since recent research works highlighted the unsuitability of Unicast transmissions due mainly to head of line blocking effects [KDS15].

The implementation of the four selected protocols was achieved via the Omnet++ programming language (C++/NED) and the proposed architecture detailed in Section 3.4.2, since no reference implementation was available. Whereas for data traffic modelling, we make use of a Car to X communication scheme (C2X) where vehicles through their network devices, commonly named On Board Units (OBU), periodically generate bundles addressed to the fixed entities of the network, called Road Side Units (RSU). For that purpose, vehicles may collaborate between them and act as a relay by taking advantage of the SCF paradigm and their mobility.

Finally, regarding the performance metrics, we selected three (03) of them, in addition to an optional one. They are described below and arranged in decreasing order of importance:

- Delivery Ratio (DR): the main target of this work being routing protocols for VDTNs, we are interested at first in the ratio of the delivered bundles that corresponds to the number of unique received bundles divided by the number of total unique emitted bundles.

- Overhead (O): this reflects the cost of the protocol and allows the evaluation of a good trade-off between bundle delivery and network overload. It corresponds to the total number of bundle replica divided by the total number of emitted bundles.

| **Global Parameters** | | **Values for** | | |
|---|---|---|---|---|
| | | **Scenario A** | **Scenario B** | **Scenario C** |
| **Simulation** | Duration | **7200s** | **7200s** | **3600s** |
| | Nbr. Run Per TTL Value | 20 | 20 | 20 |
| **Bundle** | Size | 1500 bits | 1500 bits | 1500 bits |
| | Generation Period | 150s | 150s | 150s |
| | TTL Values | 300s, 600s, 900s, 7200s | 300s, 600s, 900s, 7200s | 300s, 600s, 900s, 7200s |
| **Neighborhood Discovery** | $Period_B$ | 0.4s | 0.4s | 0.4s |
| | $Timer_{Pend}$ | 1.2s | 1.2s | 1.2s |
| | $Timer_{Exp}$ | 2s | 2s | 2s |
| **Wi-Fi** | Technology & Mode | 802.11p Broadcast | 802.11p Broadcast | 802.11p Broadcast |
| | Transmission Rate | 18 Mbits/s | 18 Mbits/s | 18 Mbits/s |
| | Maximum Range | 127m | 127m | 127m |
| | Propagation Model | Two Ray Interference & Simple Obstacle Shadowing | Two Ray Interference & Simple Obstacle Shadowing | Two Ray Interference & Simple Obstacle Shadowing |
| **RSU** | Nbr. of | **1** | **1** | **957** |
| | Transmission Mode | Reception only | Reception only | Reception only |
| **Vehicle** | Nbr. of | **2280** | **2280** | **9920** |
| | Transmission Mode | Emission only | Emission only | Emission only |
| | Mobility | **SUMO DUA** | **SUMO DUA** | **Real Traces (TAPAS Cologne)** |
| | Nbr. of Rerouted | **-** | **5** | **-** |

TABLE 4.2: Simulation parameters for scenarios A, B & C

| Protocols Parameters | | Values |
|---|---|---|
| All | With Bundle ACK | Yes |
| Prophet Only | $P_{max}$ | 0.7 |
| | $P_{first_{c}ontact}$ | 0.5 |
| | $I_{typ}$ | 1800 |
| | $\beta$ | 0.9 |
| | $T_{unit}$ | 30 |
| | $\gamma$ | 0.999 |
| GeoSpray Only | Maximum Number of Replica $R$ | 20 |

TABLE 4.3: Parameters for all considered protocols in scenarios A, B & C

- Average Delay (AD): regarding the delay-tolerant context, this metric is less important than those cited before. It corresponds to the average delay needed to deliver the first replica of any bundle.
- Hop Count (H): this is the average number of hop counts needed by the first replica of any bundle to arrive at its final destination.

In the remainder of this work, each scenario along with its characteristics and the comparative study of protocol performances are presented.

### 4.3.1 Scenario A: Evaluation under a small-scale scenario

This first scenario reflects an urban scenario of a Manhattan type. In fact, the evaluations of protocols are done under a roadmap of a limited/small size, more precisely, a grid of 1.65 km x 1.65 km with multiple intersections spaced by 150 m as depicted in Fig 4.6. Vehicles periodically send bundles to a single Road Side Unit (RSU) placed at an intersection at the centre of the roadmap, after being inserted from its edges. Finally, simulations are done within the Veins framework, as stated before, over two (02) hours. Other simulation parameters can be found in Table 4.2, and the considered performance metrics are, respectively: Delivery Ratio (DR), Overhead (O), Average Delay (AD) and, optionally, Hop Count (H).

#### 4.3.1.1 Global performance evaluation of considered protocols

This evaluation has the task of providing field researchers with a first overview of a protocol hierarchy through a comparative analysis of the performances of the four (04) considered protocols, under their default or simplified (as for GeoSpray) settings. Also, note that all protocols make use of acknowledgements (ACKs) to clear already delivered bundles. Lastly, their respective settings can be reviewed in Table 4.3.

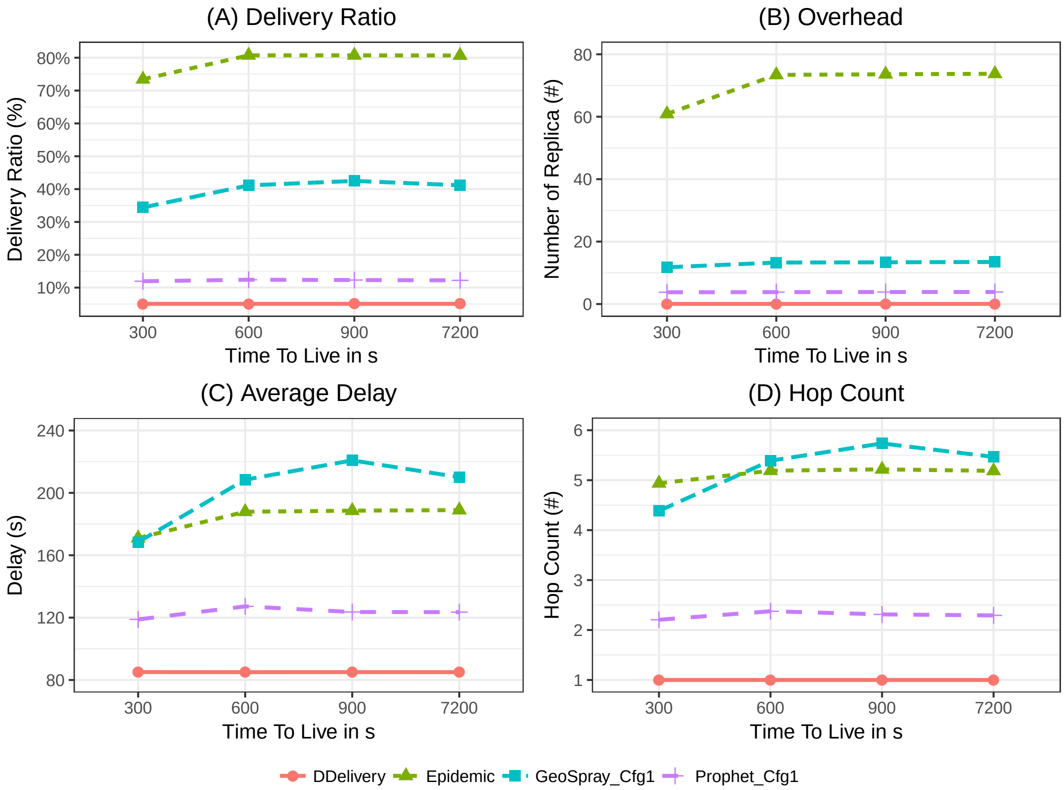


FIGURE 4.7: Simulations results for all considered protocols under scenario A

**Evaluation of Delivery Ratio:** Fig 4.7A highlights the good performances for Epidemic which delivers up to 80% of bundles, followed successively by GeoSpray and Prophet, whereas DDelivery performs poorly by delivering only 5% of them. The performances of Epidemic and DDelivery were expected due to their specific approach, with an unbounded bundle spreading for the former and bundle transfer restricted to the final recipient for the latter. However, the performances of GeoSpray and Prophet were less predictable, with the first performing much better than the latter, achieving up to 40% against only 15%. These behaviours are explained by the fact that GeoSpray selects forwarders based on their planned future mobility, while Prophet tries to predict future contacts between vehicles based on their history. Therefore, with the lack of correlation between old and future contacts as in this scenario, vehicles are misled when choosing the next forwarder and Prophet performs poorly. Furthermore, its settings must be fine-tuned and adapted to the considered scenario; otherwise, vehicles may experience a very slow prediction ageing and thus hold bundles for a long period. Finally, regarding Bundle TTL, DDelivery and Prophet are not impacted upon by its variation because they deliver a limited number of bundles prior to TTL expiry, in contrast with other protocols where a TTL value of 300s results in a limited delivery ratio and higher values of TTL ($\geqslant$ 600s) show a stabilised delivery ratio.

**Evaluation of Overhead:** As expected, simulation results reveal, through Fig 4.7B, a large overhead for Epidemic, which is due to its flooding approach. GeoSpray generates a controlled number of replicas due to its bounded replication scheme whereas Prophet produces a limited number of copies. These results are explained mainly by the long period of bundle holds observed for Prophet, but are also partially due to its poor performance. DDelivery has no overhead because the protocol follows a single copy approach. Finally, it is interesting to note that the unlimited replication scheme of Prophet generates fewer replicas than GeoSpray's limited one while varying TTL has no impact on the overhead produced by protocols apart from Epidemic that shows a drop when considering a shorter TTL (300s).

**Evaluation of Average Delay:** The results illustrated in Fig 4.7C show the highest average delay for GeoSpray followed successively by Epidemic, Prophet and finally DDelivery. This contrasts substantially with assertions found in the literature that DDelivery & Epidemic are expected to achieve the highest and shortest delays respectively. However, these delays are due to global protocol performance. In fact, Epidemic delivers a great number of bundles and therefore experiences a higher average delay, whereas the few bundles that are delivered with DDelivery are the successful result of fast encounters between the RSU and vehicles.

**Evaluation of Hop Count:** An observation made from Fig 4.7D shows the lowest hop counts for DDelivery, while Prophet scores lower than both Epidemic and GeoSpray, with a slight increase for the latter. These results are not surprising and may be explained as follows. The stable hop count of DDelivery equal to 1 is due to its approach that restricts bundle transfer to the final recipient without relying on any other relay. For Prophet, the conjunction of its inadequate settings with the considered scenario and its misleading approach, as explained before, leads to a long period of bundle holdings by vehicles and poor overall performance, which explain the low and stable hop counts. Regarding Epidemic, its uncontrolled data dissemination allows it to explore all paths and deliver data through an average of 5 hops, which translates into a similar average for RSU reachability, starting from any vehicle in the network. In contrast, GeoSpray needs, in general, more hops, because it does not explore all paths and consequently requires more forwarding to deliver data. Finally, analysis of the results shows that the observable increase for higher TTL values ($\geqslant$ 600s) in Epidemic & GeoSpray is related to their performance increase.

#### 4.3.1.2 Performance evaluation of Prophet configurations

As presented in Section 4.2.3, the Prophet protocol makes use of various parameters to compute delivery predictions, their default values being already fixed in the

| **Prophet Parameters** | **Values for Cfg$_1$** | **Values for Cfg$_2$** |
|---|---|---|
| $P_{max}$ | 0.7 | 0.7 |
| $P_{first_contact}$ | 0.5 | 0.5 |
| $I_{typ}$ | **1800** | **60** |
| $\beta$ | 0.9 | 0.9 |
| $T_{unit}$ | **30** | **1** |
| $\gamma$ | **0.999** | **0.986** |

TABLE 4.4: Parameters for Prophet configurations under scenarios A, B & C

RFC6693 [Lin+12]. Previous simulations were conducted according to the latter; however, as stated by the protocol authors, they must be adapted to the considered scenario. Indeed, the current standard provides some guidance and recommendations in that sense, but unfortunately, it is poorly documented, unclear and not concise enough. Furthermore, no mechanism has been proposed for that purpose, and consequently, researchers must do it through experimentation. To this end, first we looked for a suitable value for these parameters, then we compared both versions of Prophet, one with default settings which means default parameter values, denoted by $Prophet_{Cfg_1}$ or simply $Cfg_1$, while the other made use of the proposed values for $I_{typ}$, $T_{unit}$ and $\gamma$, denoted by $Prophet_{Cfg_2}$ or $Cfg_2$.

The setup of these parameters is not a random process and complies with straightforward observations. In fact, the first parameter $I_{typ}$ involved in the computation of predictions according to Eq.4.1 is set by default to 1800s. This is not consistent with our scenario where the typical mean interval between two successive vehicle encounters is around 60s; therefore, $I_{typ}$ for $Cfg_2$ is set to 60s. Regarding $T_{unit}$ and $\gamma$, they are involved in Eq.4.3 which is related to the prediction ageing process. The former parameter reflects the smallest unit of time and is set by default to 30s. Consequently, and following its re-compute, its new value is set to 1s in accordance with the relationship between $I_{typ}$ and $T_{unit}$ presented in Eq.4.5. Concerning $\gamma$, it is set to a lower value of 0.986 as shown in Eq.4.6, with the purpose of accelerating the ageing of predictions. Indeed, by doing so, misleading vehicles should be avoided when selecting the next forwarder. Therefore, it is possible to lower a given value of prediction from 0.5 to 0.1 in a typical delay of 120s which corresponds to the maximum observed interval of time between two successive encounters for a specific pair of vehicles. All parameters can be reviewed in Table 4.4.

$$(\frac{Intvl_y}{T_{unit}}) = (\frac{1800s}{30s}) = 60 \implies \text{if } Intvl_y = 60s \text{ then } T_{unit} = 1s \tag{4.5}$$

$$0.1 = 0.5 \times \gamma^{120} \implies \gamma = 0.986 \tag{4.6}$$

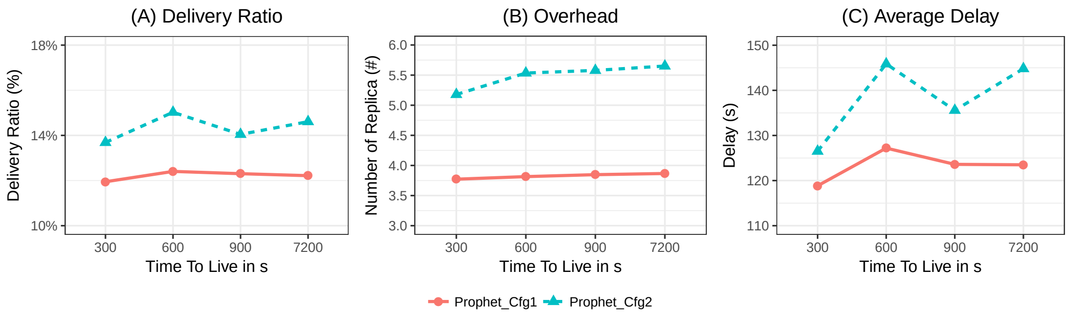


FIGURE 4.8: Simulation results for Prophet configurations under scenario A

**Evaluation of Delivery Ratio:** A comparative analysis of each configuration reveals a small performance gain for $Cfg_2$ up to 2-3% as illustrated in Fig 4.8A, whereas the $Cfg_1$ results are more stable. This limited gain is explained by the introduced settings that are better adapted to the considered scenario and vehicle motion. Thus, the proposed settings partially avoid the bad forwarder selection since the computed predictions increase and decay quickly, but not totally, because the approach advocated by Prophet tries to predict future contacts based on their history, with no guarantee regarding a possible correlation between the two. Moreover, this latter factor may explain the unstable performances of $Cfg_2$ for any considered TTL, as highlighted by the results.

**Evaluation of Overhead:** As demonstrated in Fig 4.8B, $Cfg_2$ achieves better overall performance at the price of a minimal increase in overhead compared to $Cfg_1$. This is due to the considered settings that allow a quick increase/decay of predictions, leading to more bundle forwarding and consequently to the generation of more replica.

**Evaluation of Average Delay:** As shown in Fig 4.8C, $Cfg_1$ offers a stable delay around 125s, while $Cfg_2$ shows a delay varying between 130s and 145s. This behaviour originates from two factors that delay bundle delivery. In fact, the quickly evolving predictions more often replicate bundles but do not necessarily select suited forwarders. Moreover, the replication process results in more overloaded network bandwidth. Finally, it is noticeable through the figure that bundle TTL has a limited impact on the results, with a slight underperformance when considering the TTL value of 300s.

#### 4.3.1.3 Performance evaluation of GeoSpray configurations

The GeoSpray protocol makes use of a limited replication scheme, brought to it from the Spray&Wait protocol, which implies fixing before bundle transmission, the maximum number of replica that can be generated, denoted by $R$. According to the

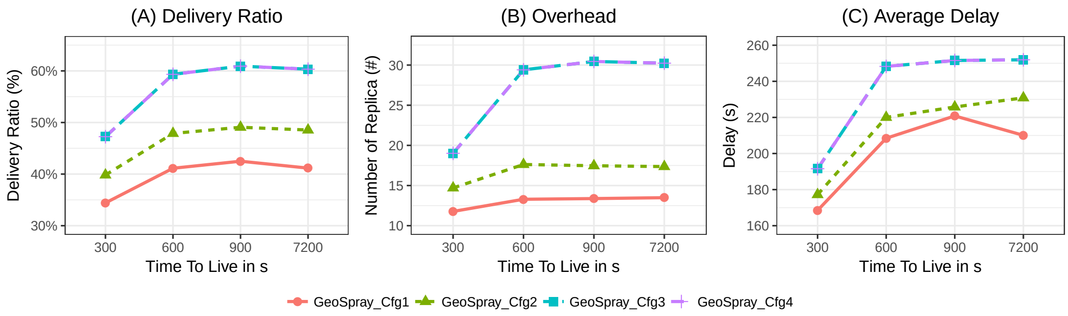


FIGURE 4.9: Simulation results for GeoSpray configurations under scenario A

| Configuration Name | Value of R | Use of H2H Ack |
|---|---|---|
| $GeoSpray_{Cfg_1}$ or $Cfg_1$ | 20 | No |
| $GeoSpray_{Cfg_2}$ or $Cfg_2$ | 60 | No |
| $GeoSpray_{Cfg_3}$ or $Cfg_3$ | 20 | Yes |
| $GeoSpray_{Cfg_4}$ or $Cfg_4$ | 60 | Yes |

TABLE 4.5: Parameters for GeoSpray configurations under scenarios A, B & C

authors of Spray&Wait, it must be set to a certain percentage of mobile vehicles (by default 15%). However, in the real world, it is improbable to estimate the total number of vehicles correctly, or at least, when it is possible, the resulting $R$ is very important. Consequently, it is generally accepted that researchers set it to a fixed value.

Another essential facet of GeoSpray is the handover of replica after each vehicle encounter. Unfortunately, the protocol does not provide any mechanism to ensure that, even if it targets networks with unreliable communication and frequent disconnection. This results in the loss of some replicas, but more dramatically, in an important drop in global performance. To fix this problem, we try to ensure the handover of replicas by implementing a two-step acknowledgement mechanism called $H2HAck$, which confirms the transfer and updates the remaining replicas. Accordingly with these protocol aspects, namely the considered value of $R$ and the use of the $H2HAck$ mechanism, we evaluate, in this section, their respective impacts on performance and thus consider four distinct configurations of GeoSpray summed up in Table 4.5. It should be noted here that the previously considered parameters for GeoSpray are identical to those of the first configuration denoted by $GeoSpray_{Cfg_1}$ or simply $Cfg_1$.

**Evaluation of Delivery Ratio:** The simulation results shown in Fig 4.9A reveal a positive impact on the delivery ratio for both the $H2HAck$ mechanism and the increased value of $R$. However, while the latter increases the performance by 5-10% as demonstrated by $Cfg_1$ and $Cfg_2$, the former has a more critical impact and results in an increased delivery ratio by up to 10% and 20% when comparing $Cfg_2$ with $Cfg_4$

and $Cfg_1$ with $Cfg_3$. Therefore, it is concluded that GeoSpray must ensure the handover of replicas to perform well. Regarding Bundle TTL, the observations show a net increase when considering a TTL higher than 300s. This is an expected behaviour since the bundles experience a longer lifetime and thus are delivered more often before expiring.

**Evaluation of Overhead:** As presented in Fig 4.9B, it is clear that the previous performances of $Cfg_3$ & $Cfg_4$ are achieved at the expense of a higher overhead which exceeds even the maximum number of replicas. This indicates that the $H2HAck$ mechanism partially fails to contain the number of replicas to its maximum value $R$, and needs more synchronisation between vehicles to do it. Nevertheless, the proposed mechanism reveals that significant performance improvement can be made at the price of a slight bundle over-replication. Regarding $Cfg_1$ & $Cfg_2$ overheads, they are low and affordable, especially for the latter configuration. This demonstrates that the overhead does not increase linearly with $R$ since the ratio between the overheads of $Cfg_2$ & $Cfg_1$ ($\approx$ 1.x) is less than that between their considered $R$ ($= 3$). Ultimately, the minimal considered TTL shows the smallest overhead, meanwhile higher TTLs ($\geqslant$ 600s) show greater but stable values.

**Evaluation of Average Delay:** $Cfg_3$ and $Cfg_4$ deliver bundles after a high delay as illustrated in Fig 4.9C, followed successively by $Cfg_2$ and $Cfg_1$. The higher delays observed for $Cfg_3$ and $Cfg_4$ are explained by their overall good performances that imply a more loaded network bandwidth. Therefore, they experience a higher delay in delivering bundles.

### 4.3.2 Scenario B: Evaluation under a small-scale scenario with looping vehicles

In this section, we evaluate the protocol performances under the same scenario as in the preceding section (see Fig 4.6) but with a major difference that consists of the introduction of continuously rerouted vehicles, called looping vehicles, which try to reproduce the motion of buses and public transportation characterised by their cyclical nature. In this regard, the use of a bi-directionally coupled simulator such as Veins is crucial, since it allows vehicles to be continuously redirected to a new destination (at run-time) after they have reached the current one via a very minimalist code alteration.

The main purpose in evaluating protocols under such a scenario is to assess to what extent it is possible to predict protocol performances and behaviours in a large-scale scenario, like C and its anycast scheme, through the use of a small-scale scenario that introduces looping vehicles. The latter try somewhat to mimic the anycast scheme. Furthermore, they allow an evaluation of the potential performance gain in Prophet

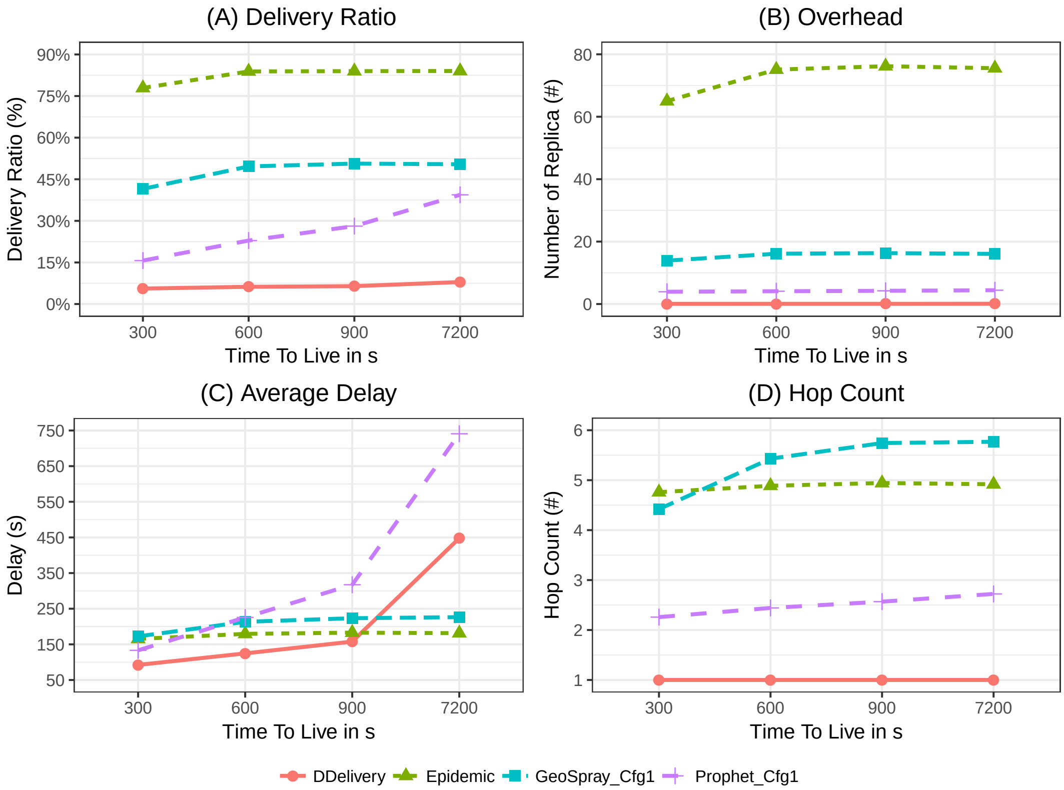


FIGURE 4.10: Simulations results for all considered protocols under scenario B

since the scenario is more suited to its approach and consequently its performance may be positioned against other protocols. As a reminder, Prophet operates optimally when the vehicle mobility follows a community-based model, reflected in this scenario by the looping vehicles. Concerning the simulation parameters and metrics, they are similar to those considered in the previous scenario A, in addition to a total of five (05) looping vehicles. They can be reviewed in Table 4.2.

#### 4.3.2.1 Global performance evaluation of considered protocols

The purpose of the current evaluation is to provide a first overview of the protocol performances and hierarchy, when assuming similar conditions and parameters as in Section 4.3.1.1 and introducing looping vehicles. These latter mimic buses and public transportation motion. All simulation parameters are summed up in Table 4.2.

**Evaluation of Delivery Ratio:** Through the analysis of the results in Fig 4.10A, it appears clearly that the protocol hierarchy is similar to that observed in Fig 4.7A, with Epidemic outperforming all protocols, followed successively by GeoSpray, Prophet and lastly DDelivery. However, compared to the case in the previous scenario, these performances are improved because of the introduction here of the looping vehicles which can carry and deliver much more data before bundle expiry. This is especially true for Prophet which experiences substantial gains gradually with an increasing bundle TTL and ultimately achieves a delivery ratio of twice the TTL value of 7200s compared to 300s. Despite this considerable improvement, it is important to note that GeoSpray still outperforms Prophet for all the considered TTLs.

**Evaluation of Overhead:** As shown in Fig 4.10B, Epidemic generates a large overhead, followed successively by GeoSpray, Prophet and lastly DDelivery. In general, similar identified factors and observations made from Fig 4.7B are involved here, with a slight overhead increase due to the introduced looping vehicles which hold bundles for a longer period and lead to more important bundle replications.

**Evaluation of Average Delay:** Similarly to the previous results and due to the same factors, Fig 4.10C shows a medium and stable average bundle delivery delay for Epidemic and GeoSpray, with the latter requiring more time for delivery. Regarding DDelivery and Prophet, the results differ ostensibly: the average delay increases in function of TTL, starting with a low and medium delay when TTL is set to 300s and reaching up to 450s and 750s respectively when considering the highest TTL. These surprising results are explained by the introduction of the looping vehicles that carry more and more bundles when the TTL value increases and take more time to deliver, because encountering RSU will occur only after an interval of time on the one hand, and on the other, network bandwidth is more loaded.

**Evaluation of Hop Count:** The simulation results represented in Fig 4.10D are quite similar to those observed in Fig 4.7D and can be explained in the same way, especially for DDelivery. Regarding the other protocols, Epidemic delivers data in fewer hops than previously because the introduction of looping vehicles decreases the average number of hops needed. In the meantime, Prophet and GeoSpray show an increase in hop counts whenever considering a higher TTL. This is due to their enhanced global performance when introducing looping vehicles and allowing bundles to live longer. However, Prophet still needs fewer hop counts compared to GeoSpray since its advocated approach and slow prediction ageing foster the holding of bundles by vehicles, whereas GeoSpray tends to forward bundles very often, in fact whenever it meets a vehicle that minimises the $METD$ metric, which means that this vehicle will converge quickly or be closer to the final recipient.

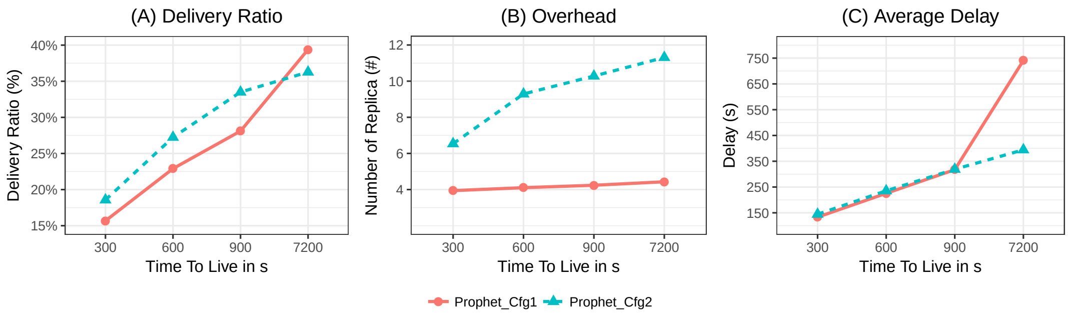


FIGURE 4.11: Simulation results for Prophet configurations under scenario B

#### 4.3.2.2 Performance evaluation of Prophet configurations

Similarly to the study conducted in Section 4.3.1.2, we evaluate the performances of the Prophet protocol when introducing looping vehicles under two different settings: the default one $Cfg_1$ and proposed one $Cfg_2$, in terms of following parameters: $I_{typ}$, $T_{unit}$ and $\gamma$. For the sake of a fair comparison with the previous study, similar simulation parameters and metrics are considered and can be reviewed in Table 4.4.

**Evaluation of Delivery Ratio:** Through the results in Fig 4.11A, the positive impact of the looping vehicles on the Prophet delivery ratio is demonstrated. It increases drastically with an increasing bundle TTL that ultimately doubles the results, from 16% to 39% for $Cfg_1$ and 18% to 36% for $Cfg_2$, when considering the lowest and highest TTL values respectively. Also, the results show that $Cfg_2$ outperforms $Cfg_1$ until there is a TTL of 7200s. Generally, these results are due to an adapted scenario to the protocol approach with the looping vehicles reflecting a community-based mobility model and carrying bundles during a more prolonged period whenever increasing TTL and thus delivering them more often. This observation is accentuated by the proposed settings that are also better adapted to the considered scenario, except for a TTL of 7200s where the default settings perform better, because they allow slow ageing of predictions, in line with a high TTL. This leads to better forwarder selection for older bundles.

**Evaluation of Overhead:** As shown in Fig 4.11B, both versions of Prophet require few replicas to deliver data, within an average of 4 replicas for $Cfg_1$ and a slowly increasing overhead in the function of TTL for $Cfg_2$, starting at 7 copies for a TTL value of 300s and going up to 11 copies when TTL is set to 7200s. These results are explained by the different behaviour of Prophet when changing its settings. In fact, under $Cfg_2$, a previous encounter of the RSU will experience a quick decay in its predictions leading to an earlier and more frequent bundle forwarding compared

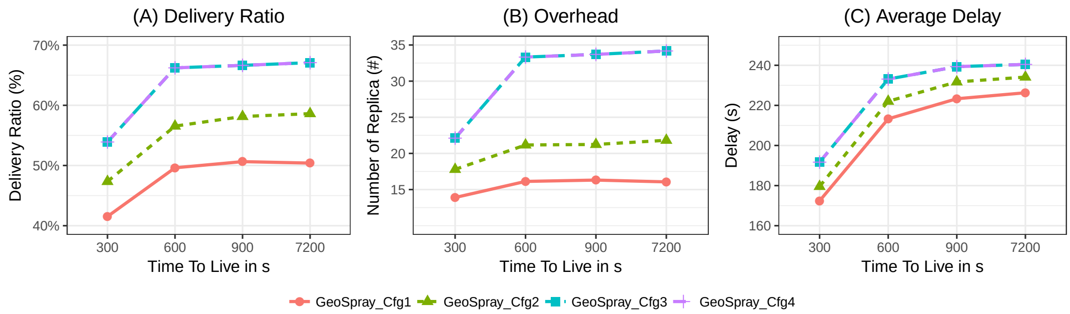


FIGURE 4.12: Simulation results for GeoSpray configurations under scenario B

to $Cfg_1$. In the latter case, bundles are kept for a long time without being largely replicated since its predictions decay very slowly.

**Evaluation of Average Delay:** Fig 4.11C shows an increasing average delay in the function of Bundle TTL for both versions of Prophet, starting at an affordable delay of 140s up to 750s and 395s for $Cfg_1$ & $Cfg_2$, respectively. These results are due to the introduced looping vehicles. Indeed, they successfully capture a large fringe of bundles since their predictions for meeting RSU are higher. However, these encounters are time spaced, and therefore a higher TTL allows the delivery of older bundles. Regarding the peak of $Cfg_1$, it is explained by the default settings of Prophet that tend to keep bundles instead of replicating them since the predictions decay very slowly, while the looping vehicles are their main carriers and should encounter RSU only after a long delay.

#### 4.3.2.3 Performance evaluation of GeoSpray configurations

As previously undertaken in section 4.3.1.3, this study tries to evaluate the impact of both an increased maximum number of replicas $R$ and the use of the $H2HAck$ mechanism, when considering similar simulation parameters and metrics but introducing looping vehicles. As a reminder, the $H2HAck$ mechanism is a proposition that aims to ensure and grant the handover of replication quota, in disruptive and unreliable networks. Simulation parameters are resumed in Table 4.5.

**Evaluation of Delivery Ratio:** Compared to those in the previous scenario, the results in Fig 4.12A show an average improvement of 10% in the delivery ratio for all the considered configurations, with $Cfg_3$ & $Cfg_4$ performing equally and outperforming both $Cfg_2$ and $Cfg_1$. The Introduction of the looping vehicles coupled to an increasing TTL is involved with this improvement since these vehicles can deliver more bundles before their expiry progressively to a longer bundle lifetime. Finally and as concluded previously, the use of the *H2HAck* mechanism enhances performance in a significant manner, far more than increasing the maximum number of replicas $R$.

**Evaluation of Overhead:** In comparison with the general performance improvement, Fig 4.12B brings to light a small and hopefully affordable drawback that consists of increased overhead for all the considered configurations, especially for $Cfg_3$ & $Cfg_4$. The relative controlled overhead of $Cfg_1$ & $Cfg_2$ is due mainly to the protocol approach, jointly, with the lack of any mechanism to ensure the handover of replication quota. Therefore, some replicas are lost, and the generated overhead is low. This behaviour contrasts with that observed for $Cfg_3$ & $Cfg_4$, where the use of the *H2HAck* mechanism increases the overhead. The reasons are its avoidance of the loss of some replicas and the fact that it exceeds even the fixed $R$ because, as explained before, it needs more synchronisation between vehicles to avoid exceeding this threshold.

**Evaluation of Average Delay:** The results in Fig 4.12C reveal an average delay consistent with the previous scenario: a short delay for a TTL of 300s and a high but stable delay for the others. The bundles delivered by $Cfg_3$ & $Cfg_4$ experience the longest delays, followed by $Cfg_2$ and then $Cfg_1$. This is due to the overall improvement in performance for all the configurations. Indeed, it comes with higher overhead and results, ultimately, in a more congested network.

### 4.3.3 Scenario C: Evaluation under a realistic & large-scale scenario

In the current section, we aim to establish a clear overview of the protocol hierarchy and evaluate the performances of the four considered protocols under a large-scale scenario based on realistic vehicle mobility. Furthermore, after achieving similar studies, with and without looping vehicles, in scenarios A & B, we are especially interested in the ability to predict current results based on small and synthetic scenarios and therefore, to offer appropriate responses to some crucial questions raised by researchers such as:

- Is it possible to correctly predict the protocol performances deployed in the real world, since it is their main target, from evaluations done under small and not-realistic scenarios?
- Should the protocol evaluations be done more often under large-scale and realistic scenarios?

In this regard, we rely here on the TAPASCologne mobility dataset that provides a large-scale roadmap and realistic vehicle mobility, all at once. Indeed, it includes mobility traces from 38,592 vehicles from the town of Cologne, Germany, over a

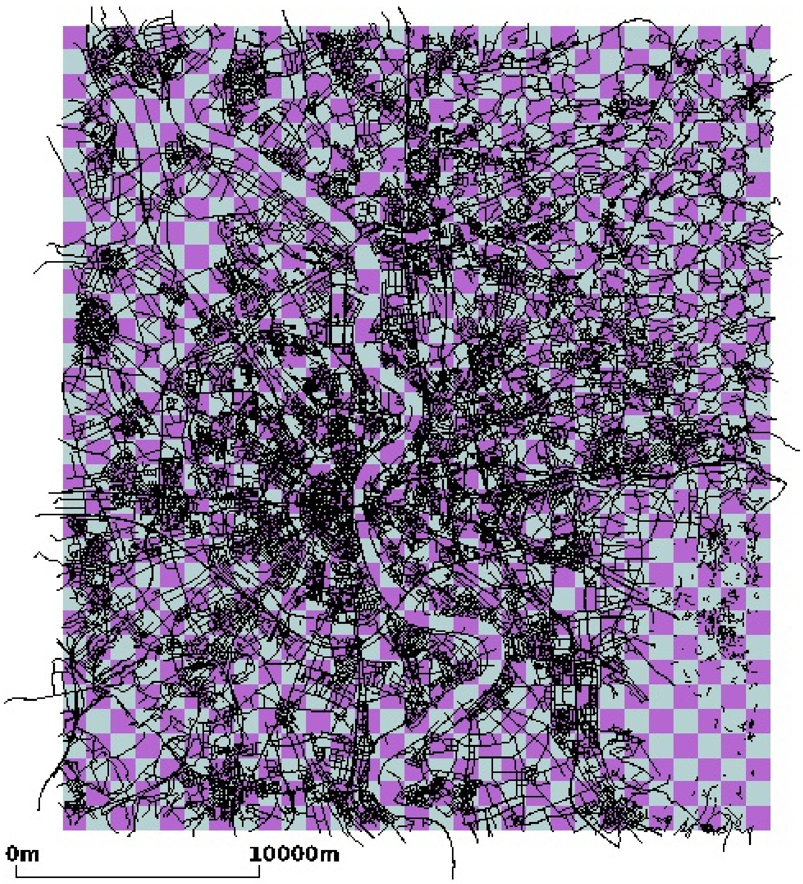


FIGURE 4.13: Road network of Cologne with 957 RSUs used in large-scale scenarios

2-hour period, from 06.00 to 08.00, while these vehicles evolve in a huge roadmap including downtown Cologne and its peripheral zone, constituting an area of 29 km x 33 km.

For our case studies and due to computational constraints, we made some adjustments to the data provided by TAPASCologne. Firstly, the traffic demand modelling was limited to 1 hour only, and the total number of simulated vehicles was shrunk to one third, which is roundly equal to 9,920 vehicles, as indicated in Table4.2. Furthermore, the map was divided into sectors of 1 $km^2$ size (1 km x 1 km) as illustrated in Fig 4.13, with a single (01) RSU placed at the main intersection of the considered sector. Therefore, a total of 957 sectors were created for as many RSUs. Concerning data traffic and unlike previous analyses, the vehicles made use of an anycast scheme to send periodical bundles to any RSU; by addressing them first to the RSU of the current sector and then following to a sector change, they were readdressed to the RSU of the current traversed sector.

Also, we deliberately restricted our evaluations to two analyses. The first one is dedicated to the four considered protocols and the second targets only Prophet and its default & proposed settings. Indeed, running such simulations involves huge computational costs, and previous studies have already demonstrated the positive

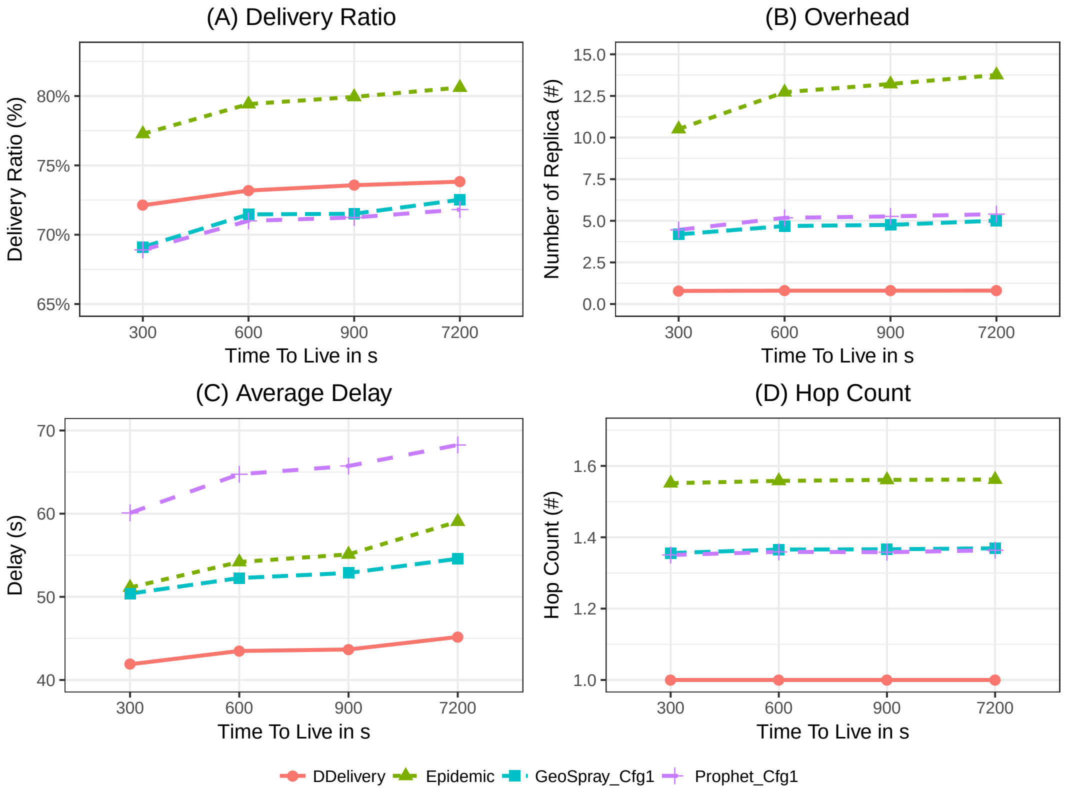


FIGURE 4.14: Simulations results for all considered protocols under scenario C

impact of increasing *R* and even more of using the *H2HAck* mechanism in the GeoSpray protocol. Finally, the considered performance metrics are, successively: Delivery Ratio (DR), Overhead (O), Average Delay (AD) and, optionally, Hop Count (H).

#### 4.3.3.1 Global performance evaluation of considered protocols

As stated before, the main focus of this study is to evaluate the performances of Epidemic, GeoSpray, Prophet and DDelivery, but also to bring to light the protocol hierarchy and its possible differences with previous observations when they are tested in a large-scale scenario with realistic vehicle mobility. To ensure a fair comparison, the protocol settings and simulations parameters are similar to those considered previously and are resumed in Table 4.3.

**Evaluation of Delivery Ratio:** The results in Fig 4.14A show overall good performance for all protocols. Epidemic outperforms the others by delivering up to 80% of bundles, followed surprisingly by DDelivery, then GeoSpray and lastly Prophet that achieves a delivery ratio of 70%. Regarding the bundle TTL, increasing its value enhances the delivery ratio of all protocols, but to a limited extent. These results were not expected nor predicted by previous studies since they fail to predict the good performance of DDelivery and more importantly, the protocol hierarchy. Nevertheless, these results are explained by multiple factors. The first one lies in the use of an anycast communication scheme, in parallel with the broad dissemination and the high number of RSUs. In fact, by adopting such a communication scheme, the vehicle increases its probability of encountering and reaching 1 of the 957 identified RSUs. Therefore, it clearly appears that under a realistic urban mobility scenario, and when using VDTN anycast transmission the probability of finding a relaying vehicle that will pass nearby any anycast destination node is very high, which increases the deliverability of carried bundles. Secondly, the approach advocated by DDelivery consists in waiting for a possible encounter between the current vehicle and a single RSU, which may happen very often as explained above. All of that occurs without generating any bundle replicas or overloading network bandwidth, which explains its better performance against both GeoSpray and Prophet. This also brings to light a possible use case for this protocol under some specific network and roadmap conditions. Finally, as demonstrated, the TTL has little impact on performance. This can only be explained by successful delivery of bundles before they expire and in a far shorter period than previously.

**Evaluation of Overhead:** Unusually compared to previous scenarios, the results in Fig 4.14B reveal a low overhead for all protocols. However, the protocol hierarchy is somewhat respected here since Epidemic is the one that generates the most overhead, followed by Prophet and GeoSpray and then DDelivery with its near null overhead. Also through the results, it is noticeable that the Epidemic overhead increases slightly with an increasing TTL, unlike the other protocols for which the overhead is relatively stable. The main explanation for these results lies in the approach advocated by each protocol. Indeed, Epidemic spreads bundles in the network without any constraint, coupled with an increasing TTL. This results in a longer lifetime for bundles which are more often replicated. Concerning Prophet and GeoSpray, as stated before, their approaches do not generate many replicas or are limited. Finally, the DDelivery overhead is a side effect of delivering bundles without successfully acknowledging them; therefore, some replicas may exist.

**Evaluation of Average Delay:** While readers should note that the presented delays are averaged, and the bundles may be delivered after a much longer time, the simulation results in Fig 4.14C reveal shorter and low delays compared with previous scenarios for all protocols. Prophet requires the most time, followed by Epidemic, GeoSpray and finally DDelivery. Further observations also show a continuously small increase in delay in parallel with an increasing TTL, which may be due to the overall enhanced performances. Regarding Epidemic and GeoSpray, they generate more replicas which result in a more loaded network and ultimately in delays higher than those observed for DDelivery. Finally, Prophet achieves the worst delay

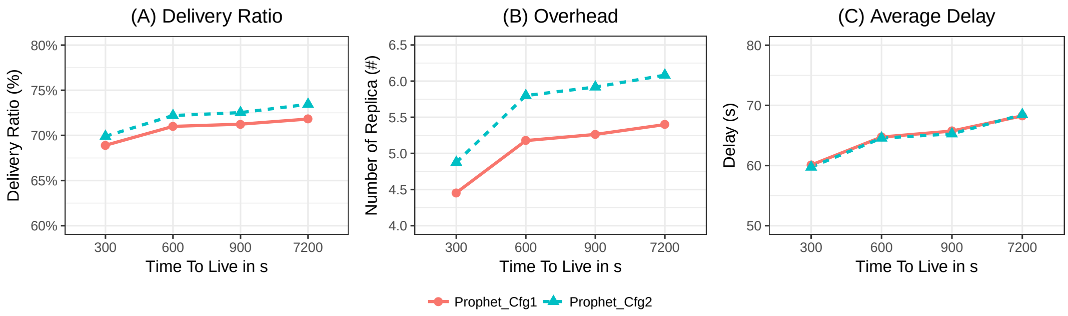


FIGURE 4.15: Simulation results for Prophet configurations under scenario C

whose potential explanation lies in its predictive approach which is not suited to the current scenario and its anycast communication scheme. Consequently, predicting future contacts based on their history can be harmful and leads to a bad forwarder selection and a significant increase in bundle delivery delay.

**Evaluation of Hop Count:** Observations made based on Fig 4.14D depict small and quite close hop counts for all the protocols, with stable performance in function of an increasing TTL. The results here are partially expected since the anycast scheme fosters more direct forwarding to the final recipient instead of relying on multiple intermediate relays, this being especially true for DDelivery and Prophet. However, the overall lower performance of GeoSpray against Epidemic is less expected and can be explained only by the relative closeness of the RSU and its good reachability (through 2 hop counts on average, according to Epidemic performance) in this scenario and when considering an anycast scheme. Consequently, under such conditions, a large fringe of vehicles minimises the corresponding $METD$ metrics which results in less bundle forwarding.

#### 4.3.3.2 Performance evaluation of Prophet configurations

In a similar way to research undertaken previously, we are interested in this current study in evaluating the performances of Prophet. More precisely, it is about evaluating the potential gain following the proposal of adapted settings to the considered scenario, especially since the previous studies did not allow any recommendations to be established or reach a solid conclusion. Once again, the simulation parameters and metrics are analogue to previous ones, while the default and proposed settings for Prophet are resumed in Table 4.4.

**Evaluation of Delivery Ratio:** The simulation results in Fig 4.15A show good performances for both $Cfg_2$ & $Cfg_1$, with a small advantage for the former, that does not exceed 2-3%. The overall good results are not surprising and are explained by the anycast communication scheme which facilitates the delivery of bundles for any considered protocol as demonstrated before. However, the relatively small gain of $Cfg_2$ with respect to $Cfg_1$ is disappointing. Indeed, it highlights the challenging task which consists of successfully adapting the Prophet parameters to the considered scenario. Finally, as previously observed, the delivery ratio increases linearly with bundle TTL because more bundles can be delivered before expiry.

**Evaluation of Overhead:** As expected, the Prophet protocol generates few replicas only. This applies to both evaluated configurations, particularly to $Cfg_1$ and its default settings as illustrated in Fig 4.15B. The low overhead of Prophet is due to the protocol approach as explained before, whereas the higher overhead of $Cfg_2$ compared to $Cfg_1$ lies in the considered settings which foster a quick decay of predictions and result in more important bundle replication.

**Evaluation of Average Delay:** As shown in Fig 4.15C, both Prophet configurations achieve a similar average delay for bundle delivery, with a stable increase in function with an increasing TTL. This behaviour is due to the growing number of bundle replicas that live longer, overload the network and consequently increase the delays. Regarding the similar results of $Cfg_1$ & $Cfg_2$, they were not expected since the use of adapted settings should avoid bad forwarder selection; however, this is not the case. An explanation of this may lie in the incapacity to correctly adapt the Prophet settings combined with the anycast scheme and the approach advocated by the protocol which tries to predict future contacts based on their history, without any certitude about a possible correlation between past and future vehicle contacts.

## 4.4 Main conclusions

In this chapter, we focus on Vehicular Delay-Tolerant Networks (VDTNs) and, in particular, routing protocols dedicated to the challenging networks that are VDTNs. Indeed, after covering the origins & historical background of VDTNs in Section 2.3, additionally to the taxonomy of their routing protocols in Section 2.4, related works and comparative studies found in the literature were first analysed. Subsequently, four (04) main protocols were selected according to multiple criteria such as the followed replication strategy, the knowledge used to make forwarding decisions or the generally advocated routing approach. Thereafter, these protocols, namely Epidemic, Direct-Delivery (abbreviated as DDelivery), Prophet (more precisely ProphetV2), and GeoSpray, were studied in depth and detail, especially the last two (02) protocols which appeared to be the most promising ones since they foster interesting approaches, i.e. predictive/social on the one hand and geographically-based on the other and are particularly competitive.

Finally, we conducted an extensive comparative study and a performance evaluation of the considered routing protocols under small- and large-scale scenarios with synthetic as well as realistic vehicle mobility. This was done by successfully implementing all the protocols under the Veins simulation framework and with the help of the TAPAS Cologne dataset which provides a large and realistic scenario. Besides, two distinct settings of Prophet and two main factors that impact on the performance of GeoSpray were evaluated. As a result of this overall work, many findings leading to recommendations listed below could be made:

- Considering roadmap and network conditions, in parallel with a selected communication scheme, greatly influences protocol performances; therefore, predicting the performances of protocols when deployed in real environments, on the basis of a small-scale scenario and synthetic vehicle mobility, is not feasible. For instance, DDelivery performs poorly under a small-scale scenario and a unicast communication scheme, which contrasts highly with its performance when considering a realistic scenario and an anycast communication scheme.
- Simulations results for the large-scale scenario highlight the potential benefits of adopting an anycast communication, which enhances all protocol performances. Furthermore, among all the protocols, DDelivery and its straightforward approach is the one which benefits the most from the anycast and the large number of RSUs, by delivering more bundles than complex solutions like GeoSpray and Prophet. In the meantime, it successfully cuts the overhead by more than 90% compared to Epidemic, and consequently, achieves an ideal trade-off between a good delivery ratio and an affordable overhead. Thus, these unexpected results stress the potential use of DDelivery and its routing approach under ideal conditions regarding the considered scenario and the adopted communication scheme.
- Correctly predicting the performance of protocols on the basis of a small-scale scenario and synthetic vehicle mobility is not feasible. Therefore, if routing protocols were to be deployed in the real-world by researchers, they should be evaluated under conditions as close as possible to it, which means large-scale scenarios and realistic vehicle mobility.
- A geographical approach as advocated by GeoSpray outperforms the predictive one of Prophet under all considered scenarios. Consequently, future proposals for VDTNs routing protocols should focus more on this promising approach.
- Adapting the settings of Prophet to the considered scenario is a challenging task. Indeed, when it is not done correctly, the performances of Prophet are improved to a very limited extent. Conversely, introducing looping vehicles enhances performance greatly since they reflect a community-based mobility

model, which is much better suited. Thus, future research on Prophet should focus on proposing a mechanism to adapt its settings automatically.

- The GeoSpray performance can be enhanced greatly by adopting a mechanism to ensure the handover of replication quota, as for the proposed $H2HAck$ mechanism, while increasing the maximum number of replica $R$ enhances the performance slightly. Hence, future works on GeoSpray should address the proposal for a mechanism to ensure the handover of the replicas.

- In general, the optimal Time To Live (TTL) of bundles varies between 300 and 600 seconds. Therefore, considering a higher TTL has a limited impact on results.

- In work found in the literature, many authors attribute to the Epidemic and DDelivery protocols, maximal or minimal boundaries regarding specific performance metrics such as Delivery Rate, Overhead or Average Delay. Our results tend to invalidate these statements except for Overhead, for which Epidemic is a maximal boundary and DDelivery is a minimal one.

- The need for realistic simulators & tools combined with real word mobility traces is a key aspect when evaluating the VDTN routing protocols, but unfortunately, it is too often neglected. This is especially true for the selected protocols for which quite large performance deviations can be observed between their original evaluations under not-realistic simulations or favourable scenarios and our evaluations. The GeoSpray protocol is a good example of this trend.

For future research, we intend, firstly, to enhance and mature the common architecture which forms the basis of our implementation of the considered protocols under the Veins simulation framework, and which is already publicly available on the software development platform GitHub [Ars18b]. Also, in our opinion, the interesting findings related to the good performance of DDelivery in the large-scale scenario and the positive impact of the proposed $H2HAck$ mechanism both deserve to be considered further. At last and over the long term, it would be very interesting to conduct similar comparative studies, relying on various large-scale scenarios and realistic vehicle mobility traces, to evaluate various radio technologies including cellular networks or to expand the comparison to other routing protocols.

# Chapter 5

# First proposal: The ProCC Protocol



This chapter covers works achieved during the early stage of this thesis, where substantial efforts were made to develop a new VDTN routing protocol based on a predictive approach, able to achieve better performances especially in terms of delivery ratio, and lastly inspired in the well-known Prophet protocol in one hand, and in convergecast based protocols on the other one. This ultimately leads to the development of the Probabilist convergecast protocol abbreviated in ProCC, which is one of the contributions of this thesis and has been evaluated against Prophet through minimal and small-scale scenarios, with synthetic vehicle mobility. Despite the novelty of the advocated approach, and being inspired in convergecast based protocols, the overall evaluation results of ProCC were able to achieve only similar performances compared to Prophet, but not to outperform it. These mixed results and the difficulty in predicting future contacts between vehicles based on their history paved the way for future research works on another VDTN routing approach, namely, the geographic-based one.

## 5.1 Related Works

During the past years, many attempts have been made by researchers to develop a new predictive-based protocol for DTNs and VDTNs data routing. One of the most notable works that fit into this context is the Prophet protocol, that has paved the way for the advent of many other predictive protocols, that combines, in general, the principals advocated by Prophet with newer and original approaches. For instance, authors of [Aba+14] have developed the AntProphet which successfully combines the predictive approach of Prophet, with prediction calculations based on the social behaviour of ants and the Ant Colony Optimization (ACO) algorithm. Preliminary findings when comparing AntProphet to Prophet are encouraging and therefore, deserve further evaluations to correctly assess the performances of the proposal.

Besides, the GreedyAnt (GrAnt) is another interesting protocol where authors have relied also on the ACO algorithm [Ven+11] to route data in delay-tolerant environment. The elegant but greedy solution proposed by the authors tries to find a path to an unknown destination. However, unlike traditional approach where the search of the best path is the main objective, GrAnt focuses on the search and discovery of multiple paths to the destination to allow the delivery of data through redundant paths, which is more adapted to an environment with frequent disconnection and highly changing topology. For its evaluation, GrAnt has been compared against Epidemic and Prophet protocols and has performed better than both, nevertheless, its evaluation based on a more realistic and complex network simulator is mandatory to further increase confidence in observed results.

In addition to these works, many proposals have been made to increase the performances of Prophet, like for instance the Prophet+ protocol which relies on a weighted utility routing metric to make the forwarding decision. This latter is computed by combining the prediction based on history with various parameters as the buffer size, power, bandwidth and popularity [HLC10]. Another example is the DiProphet protocol which takes into consideration the history of contacts as well the distance between vehicles, to forward and deliver data [SK13].

Regarding the convergecast communication scheme in use by ProCC, it should be noted at first that this refers initially to network routing in tree topology where all data sent by children nodes converge to the root node. Such a definition implies that this scheme is the opposite of a broadcast, where data are propagated from a single node to all nodes. One of the most well-known use-case for convergecast is the data routing in WSNs. Nevertheless, to the best of our knowledge, convergecast has been rarely used for data routing in delay-tolerant environments. Among these specific works, it is possible to cite the Convergent Hybrid-replication Approach to Routing in Opportunistic Networks (CHARON) protocol, which combines the convergecast communication scheme with a metric function to make its forwarding decisions, simulations results show honourable performances when compared to other DTN protocols [SFR10]. Otherwise, authors in [Tak+14] have attempted to set the basics of a novel routing scheme for convergecast message delivery in DTNs.

## 5.2 Presentation of the ProCC protocol

ProCC is a new VDTN routing protocol based on an unlimited multiple-copy replication scheme, with the intent of successfully delivering bundles from the mobile sender nodes that are vehicles to the fixed receiver nodes commonly known as Road Side Units (RSUs). Consequently, its design focuses mainly on Vehicle-To-Infrastructure communication, denoted by V2I. Furthermore, the protocol is biologically inspired in the cooperative work achieved by an ant colony. Indeed, ants leave the nest and start to search for food randomly. Then whenever a food source is found, they get back to the nest while spraying pheromones down a trail from the food to the colony, the latter will be used by others to retrieve the remaining food.

Therefore, ProCC combines a hybrid approach that relies on the predictive-based protocol Prophet and the convergacast communication scheme. Indeed, the vehicles that send multiple bundles to a single RSU receiver, whose address is already known, reflect a convergecast communication scheme similar to the behaviour of ants that converge to the food source. Meanwhile, the frequent encounters between vehicles and RSUs translate in a high contact prediction, which is sprayed and exchanged between vehicles, in a similar way to the spray and exchange of pheromones that occur down the route from the food to the nest.

Regarding the assumptions made by ProCC, the proposal assume that the roadmap is divided into multiple sectors of a specific dimension and layout, with each sector hosting a single RSU whose address is already known by vehicles via other means (e.g. preloaded digital map with a fixed RSU address for a given sector). Besides, the protocol relies on the Store, Carry & Forward (SCF) paradigm to be resilient to frequent disconnections and long delays.

Finally, readers should note that the envisioned supported applications by ProCC are those able to be deployed over VDTNs and their inherent specificities. Such applications may include road traffic information and third-party services like web access, email service or multimedia content download. Therefore this routing protocol is not suited to the hard deadlines for road safety applications, like emergency braking or collision avoidance.

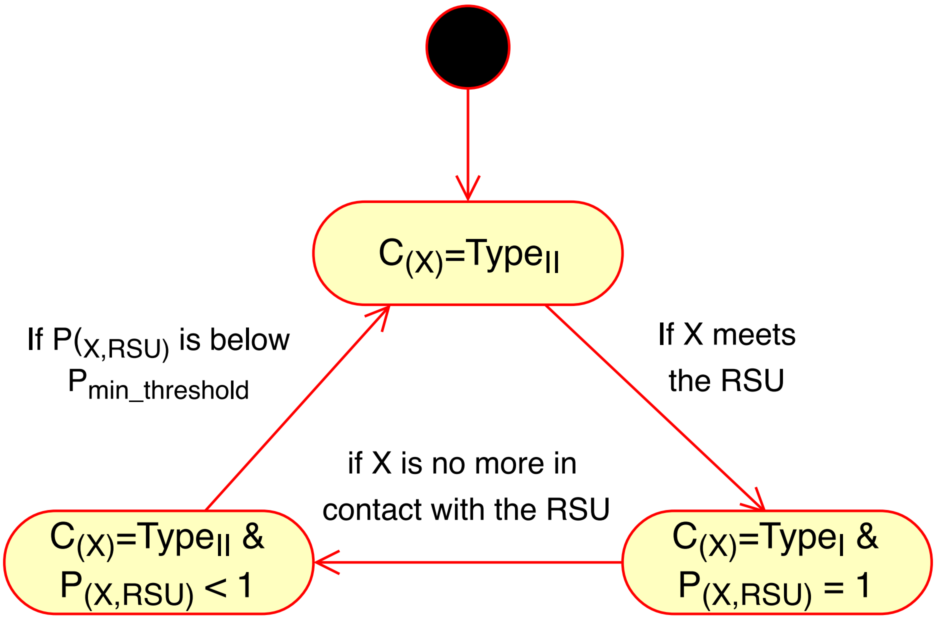


FIGURE 5.1: UML state machine diagram of ProCC vehicle classes switch

## 5.3 Main Characteristics and Keys Features

### 5.3.1 Vehicles Classes

To reproduce the desired behaviour described above, the proposal must distinguish between two categories of vehicles which play a different role, namely, those that spray a high contact prediction after a recent contact with the RSU, and those that have not yet met with it. Therefore, ProCC introduces the notion of the class denoted by $C_{(x)}$ for the Vehicle X, that takes two distinct values, namely $Type_I$ which is associated with the former group of vehicles, and $Type_{II}$ which is associated with the latter group.

Consequently, vehicles evolving into the network, start their journey as $Type_{II}$ and may switch back and forth from this class to $Type_I$ based on two factors: the meeting with an RSU and the ageing of contact prediction. In fact, even when meeting other vehicles (whatever they are $Type_I$ or $Type_{II}$) and exchanging with them predictions, vehicles keep their classes unchanged until meeting the RSU, upon it, they become $Type_I$ and set their predictions of contact with RSU denoted by $P_{(X,RSU)}$ to 1. After leaving the coverage zone of the RSU, these vehicles start to experience rapid ageing of their predictions, similar to the decay over time of ants pheromones sprayed down the route from the food to the nest. This ageing process is continued until $P_{(X,RSU)}$ is below a minimal threshold for predictions denoted by $P_{min\_threshold}$, thus $P_{(X,RSU)}$ is setted to 0, whereas $C_{(X)}$ is reverted back to its initial value $Type_{II}$. These changes in vehicle classes are reflected in the UML state machine diagram illustrated in Fig 5.1.

### 5.3.2 Prediction Calculations

Regarding the compute of ProCC predictions, it follows a similar process to the one in effect for the Prophet protocol (more precisely ProphetV2, since ProphetV1 is outdated), with few differences. Indeed, unlike Prophet, vehicles that rely on ProCC to route data maintain only a single prediction related to the prediction of contact between the current vehicle X, and the RSU that is in charge of the visited sector, denoted by $P_{(X,RSU)}$. Thus, vehicles do not maintain predictions of contact related to other vehicles.

Moreover, if the prediction $P_{(X,RSU)}$ is set to 1 whenever meeting the RSU as mentioned earlier, it is also exchanged between vehicles independently of their respective class, after each meeting between the current vehicle X and the encountered vehicle Y, accordingly to the Eq.5.1 and the factor $\alpha$ which controls the impact of $P_{(Y,RSU)}$. Finally, it should be noted that the maintained predictions are also aged before any exchange or update, based on the ageing equation Eq.4.3 of Prophet, until satisfying the following condition $P_{(X,RSU)} < P_{min\_threshold}$, and thus set to 0.

$$P_{(X,RSU)} = \alpha \times P_{(X,RSU)old} + (1 - \alpha) \times P_{(Y,RSU)} \tag{5.1}$$

### 5.3.3 Forwarding Metric and Strategies

Due to the difficulty of extracting a general pattern for vehicle mobility, and by classifying vehicles into two distinct classes, namely, $Type_I$ and $Type_{II}$, the ProCC protocol assumes that in general, $Type_{II}$ vehicles are more likely to meet the RSU compared to $Type_I$ which have already met with it. This applies even more for $Type_{II}$ vehicles that are receiving higher and higher predictions, which suggests that they are approaching the position of the RSU. Therefore, the proposal relies on different factor to decide whether or not forward a bundle from the current vehicle X to the encountered vehicle Y, including, the highest prediction between $P_{(X,RSU)}$ & $P_{(Y,RSU)}$, their classes or the $\delta$ threshold. The latter is used to permit bundle forwarding when the prediction of Y is less but very close to the one of X. This ultimately leads to the definition of multiple forwarding strategies advocated by the ProCC protocol, that are depicted in Table 5.1. Finally, it should be noted that each vehicle stores the ten (10) last computed predictions, which are needed to determine how many times the RSU has been encountered, and what was the value of $P_{(X,RSU)}$ when it happened.

## 5.4 Protocol Operations

As illustrated in Fig 5.2, the ProCC protocol forwards a bundle $M_D$ from a carrier vehicle $X$ to a candidate vehicle $Y$ in a similar way to the Prophet protocol. Indeed,

| $C_{(X)}$ | $C_{(Y)}$ | Forward bundle from X to Y if |
|---|---|---|
| $Type_I$ | $Type_I$ | $P_{(Y,RSU)}$ >0 AND<br>Y has encountered the RSU more then 1 |
| $Type_I$ | $Type_{II}$ | Always TRUE |
| $Type_{II}$ | $Type_I$ | $P_{(Y,RSU)}$ >0 AND<br>Y has encountered the RSU more then 1 |
| $Type_{II}$ | $Type_{II}$ | $P_{(Y,RSU)} > P_{(X,RSU)}$ OR<br>( ($P_{(Y,RSU)}$ >0) AND ( $\mid P_{(Y,RSU)} - P_{(X,RSU)} \mid < \delta$)) ) |

TABLE 5.1: Forwarding strategies of ProCC protocol

the vehicle $Y$ starts the exchange of information by successively ageing its prediction $P_{(Y,RSU)}$ according to Eq.4.3, updating its class $C_{(Y)}$ if needed, and lastly sending to $X$ both of its predictions & class, additionally to the ten last computed predictions. Following this initial phase, $X$ updates its prediction accordingly to Eq.5.1, and its class if $Y$ is an RSU rather than a vehicle. Moreover, $X$ makes a forwarding decision based on the received data and forwarding strategies of ProCC illustrated in Table 5.1. Thus, if $X$ must forward replicas of its bundles, then it builds and sends a list of offered & already delivered bundles. Upon the receipt of such list, $Y$ updates its list of delivered bundles and deletes any unnecessary replicas, then it replies to $X$ by sending back a bundle responses list, containing offered bundles that were not discarded but instead retained (e.g. $Y$ may receive a bundle from multiple vehicles and during the communication with one of them). Finally, the forward of a bundle replica from $X$ to $Y$ is triggered after the receipt of bundle responses and may engender an additional message to acknowledge the bundle receipt if Y is the final recipient. It should be noted that these processes occur in parallel without any interference in both directions from X to Y and Y to X, while offered bundles from X to Y may incorporate the list of already delivered bundles.

## 5.5 Evaluation of ProCC

To assess the performance of ProCC, a quantitative evaluation of the protocol against the Prophet routing protocol is performed. Indeed, the proposal is inspired in Prophet, which is one of the most prominent protocols among the predictive-based routing family, therefore this latter must be considered for the quantitative evaluation. Regarding its considered version, ProphetV2 is the only one to be considered in this work and more generally during this thesis, since the former version (ProphetV1) is outdated and contains many flaws that have been fixed afterwards.

Besides, two distinct scenarios with different settings regarding the size of the road topology or vehicle fleet are considered for the need of theses performances evaluations, as detailed below:

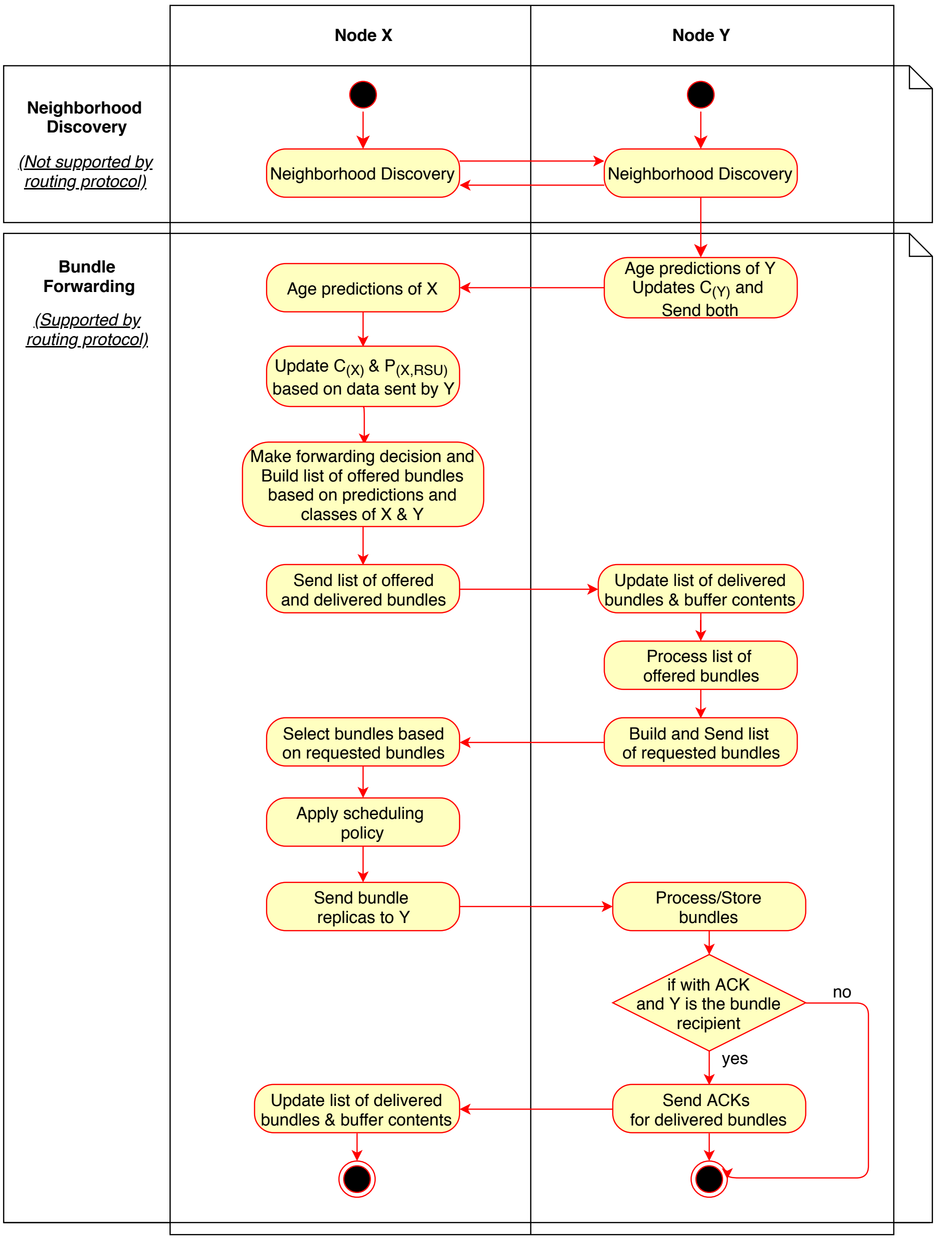


FIGURE 5.2: UML activity diagram of ProCC operations for data routing

- Scenario E: a tiny scenario with synthetic vehicle mobility. The scenario must be viewed as a minimal proof of concept regarding the proposal, and able to give acceptable preliminary results.
- Scenario F: a small-scale scenario with synthetic vehicle mobility. The scenario will further assess the performance of the proposal, following the assessment made based on the scenario E.

Regarding the working environment, the Veins simulation framework [SGD11] was selected for the implementation of both protocols, including Prophet since no reference implementation is available for it. Veins is a well established by now since it is one of the most advanced simulation framework dedicated to vehicular networks.

| Global Parameters | | Values for Scenario E | Values for Scenario F |
|---|---|---|---|
| **Simulation** | Duration | **7200s** | **7200s** |
| | Nbr. Run Per TTL Value | 5 | 20 |
| **Bundle** | Generation Period | 300s | 300s |
| | TTL Values | 7200s | 7200s |
| **Wi-Fi** | Technology & Mode | 802.11p Broadcast | 802.11p Broadcast |
| | Transmission Rate | 18 Mbits/s | 18 Mbits/s |
| | Maximum Range | 127m | 200m, 250m, 300m, 350m |
| | Propagation Model | Two Ray Interference & Simple Obstacle Shadowing | Two Ray Interference & Simple Obstacle Shadowing |
| **RSU** | Nbr. of | **1** | **1** |
| | Transmission Mode | Reception only | Reception only |
| **Vehicle** | Nbr. of | **400** | **2280** |
| | Transmission Mode | Emission only | Emission only |
| | Mobility | **SUMO JTRRouter** | **SUMO DUA** |

TABLE 5.2: Simulation parameters for scenarios E & F

| Protocols Parameters | | Values | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| All | **Parameters/Values for all protocols configurations** | | | | | | | | | |
| | $\gamma$ | 0.98 | | | | | | | | |
| | $P_{min\_thresold}$ | 0.05 | | | | | | | | |
| ProCC only | **Parameters/Values for all ProCC configurations** | | | | | | | | | |
| | $\delta$ | 0.1 | | | | | | | | |
| | With Bundle ACK | Yes | | | | | | | | |
| | **Parameters/Values for each ProCC configurations** | | | | | | | | | |
| | **ProCC Configuration** | **A1** | **A2** | **A3** | **B1** | **B2** | **B3** | **C1** | **C2** | **C3** |
| | $\alpha$ | 0.25 | 0.25 | 0.25 | 0.5 | 0.5 | 0.5 | 0.75 | 0.75 | 0.75 |
| | $T_{unit}$ | 6 | 12 | 24 | 6 | 12 | 24 | 6 | 12 | 24 |
| Prophet only | **Parameters/Values for all Prophet configurations** | | | | | | | | | |
| | $P_{max}$ | 0.75 | | | | | | | | |
| | $P_{first\_contact}$ | 0.5 | | | | | | | | |
| | $I_{typ}$ | 1800 | | | | | | | | |
| | $\beta$ | 0.9 | | | | | | | | |
| | $T_{unit}$ | 12 | | | | | | | | |
| | **Parameters/Values for each Prophet configurations** | | | | | | | | | |
| | **Prophet Configuration** | **G** | | | | **H** | | | | |
| | With Bundle ACK | Yes | | | | No | | | | |

TABLE 5.3: Parameters for Prophet and ProCC configurations under scenario E

It is built upon the network simulator Omnet++ [VH08] and the traffic simulator Sumo, which is responsible for vehicle mobility [Kra+12]. Moreover, the framework implements the de facto Wi-Fi standard for vehicular networks, namely, the IEEE 802.11p; additionally to several realistic radio propagation models, including the Two Ray Interference model [SJD12] and the Simple Obstacle Shadowing [Som+11] whose uses are highly advised by the authors.

Finally, global simulation parameters regarding both scenarios are summarised in Table 5.2, whereas four (04) performances metrics are considered. These latter are described below and arranged in decreasing order of importance:

- Delivery Ratio (DR): since the main target of this work is VDTN routing protocol, this metric is considered as being the main performance metric. It is the ratio between the unique received bundles and the whole unique emitted bundles.
- Overhead (O): this reflects the cost of the protocol and allows the evaluation of a good trade-off between bundle delivery and network overload. It corresponds to the total number of bundle replica divided by the total number of emitted bundles.
- Average Delay (AD): regarding the delay-tolerant context, this metric is less important than those cited before. It corresponds to the average delay needed to deliver the first replica of any bundle.
- Hop Count (H): this is the average number of hop counts needed by the first replica of any bundle to arrive at its final destination.

### 5.5.1 Scenario E: Evaluation under a tiny scenario

The intent of relying on a tiny scenario for the completion of this first study is to provide researchers with preliminary results regarding the performances of the proposal ProCC. In fact, this minimal scenario reflects an urban scenario, which includes a single (01) Road Side Unite (RSU), placed at the middle of a major road among the small road network of 0.2 km x 0.52 km, depicted in Fig 5.3. Vehicles enter it from its edge and send periodically bundles addressed to the RSU during the two (02) hours of simulation. Remaining simulation parameters are summarised in Table 5.2, whereas considered performance metrics are those presented in Section 5.5.

Regarding the considered protocols, multiple configurations of both ProCC and Prophet are considered, with a total of nine (09) and two (02) configurations respectively for each one, and as illustrated in Table 5.3. The aim of evaluating multiple configurations for ProCC is to define the right settings regarding the two main factors involved in the process of predictions calculations, namely, the factor $\alpha$ and ageing time unit $T_{unit}$. Meanwhile, the two configurations of Prophet try to evaluate the

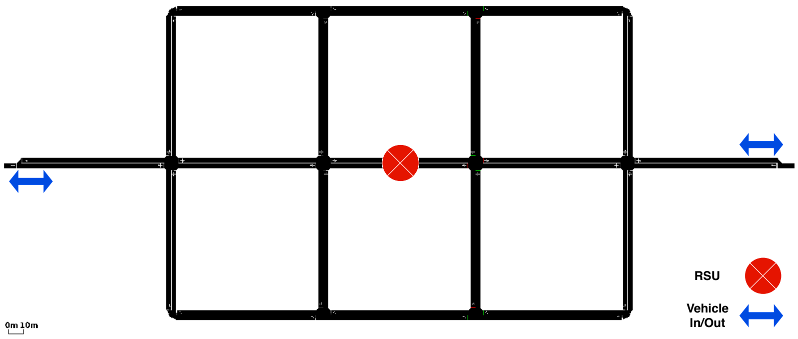


FIGURE 5.3: Road network with a single RSU used in tiny scenarios

impact of bundle acknowledgements upon their final receipt on globally observed performances.

**Evaluation of Delivery Ratio:** The results in Fig 5.4A show high performances for all configurations, with slightly better results for ProCC compared to Prophet. The overall good performances are explained by the relatively small size of the scenario combined to the good placement of the RSU which facilitates the bundle delivery. Regarding the small gap between ProCC and Prophet, it may be due to the lack of correlation between past and future contacts between vehicles, however, the difference is minimal. Besides, there is no a clear winner among the evaluated settings of ProCC, therefore further simulations based on a larger and more realistic scenario are needed to identify the best configuration for ProCC, which will also help to clarify the reason behind the small gap between both protocols.

**Evaluation of Overhead:** Observations made from Fig 5.4B highlight a low overhead for Prophet-G, followed respectively by the various configurations of ProCC and lastly Prophet-H. Such results were partially expected, especially regarding the very high overhead generated by Prophet-H compared to Prophet-G, which is related to the use of ACKs that delete unnecessary replicas from the network. This observation brings to light the positive impact of ACKs in reducing the generated overhead and generally observed performances. Regarding the various configurations of ProCC, they achieve a higher overhead compared to Prophet, which may be correlated to the ProCC approach that forward more often bundles and thus generates more replicas. Finally, further evaluations are needed to identify the most suitable configuration for ProCC.

**Evaluation of Average Delay:** As shown in Fig 5.4C, the considered configurations of ProCC deliver bundles in an acceptable average delay, with a slight difference among the considered configurations. On the other hand, Prophet-G requires more time to deliver bundles, but it is still acceptable, especially when compared with

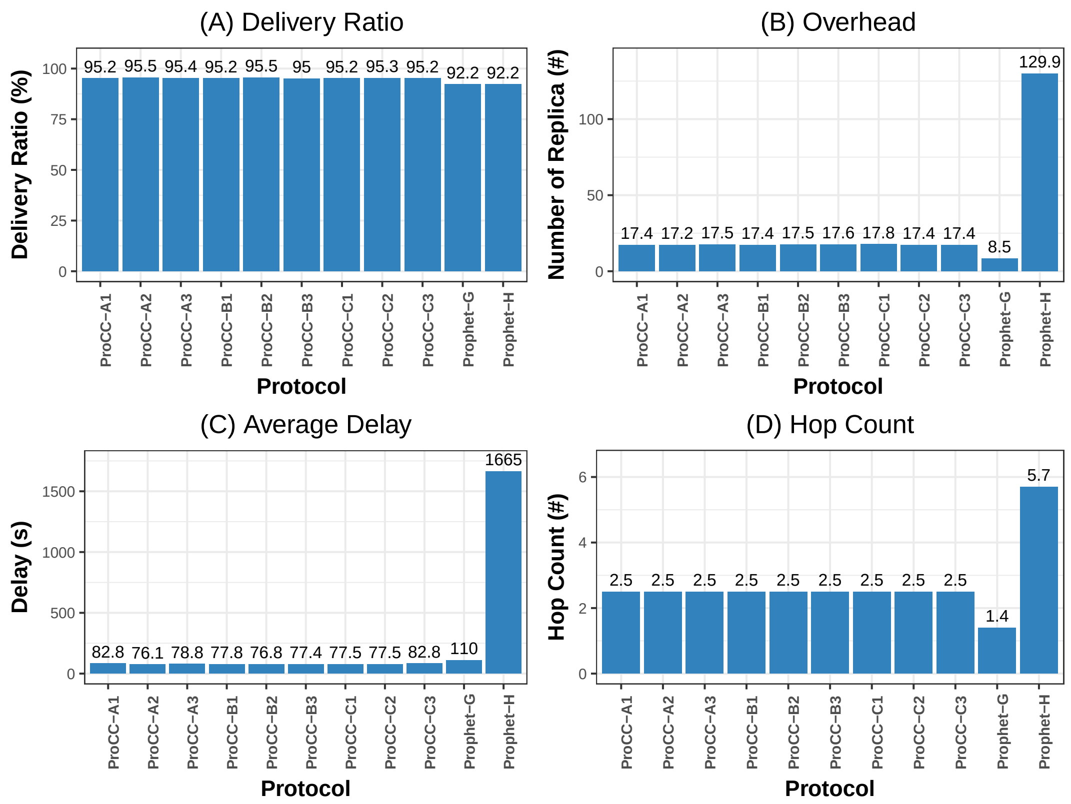


FIGURE 5.4: Simulations results for ProCC and Prophet protocols under scenario E

Prophet-H that requires a very long delay. These results were partially expected and are be explained by the straightforward approach of ProCC, whereas Prophet tries to predict future contacts based on the history of contacts, but due to the use of default configuration and since the non-existence of vehicle patterns, it selects bad forwarders which delays the delivery. Finally, the delay observed for Prophet-H is largely due to the absence of bundle acknowledgements.

**Evaluation of Hop Count:** Through the analysis of the results in Fig 5.4D, it appears clearly that the Prophet-G is the one that requires the fewer hop counts, followed by the various configuration of ProCC that perform similarly, and finally, Prophet-H which delivers bundles through a higher number of hop counts. These results are not surprising, in fact, the default configuration of Prophet proceeds to a slow ageing of predictions which misleads vehicles that tend to holder during a long time bundles. However, when there are no acknowledgements, bundles are delivered through multiple paths, whereas the bandwidth is congested thus, it substantially increases the hop counts. Lastly, ProCC delivers bundles through 2 or 3 hops, which is partially due to the convergecast approach but requires more realistic simulations to be correctly understood.

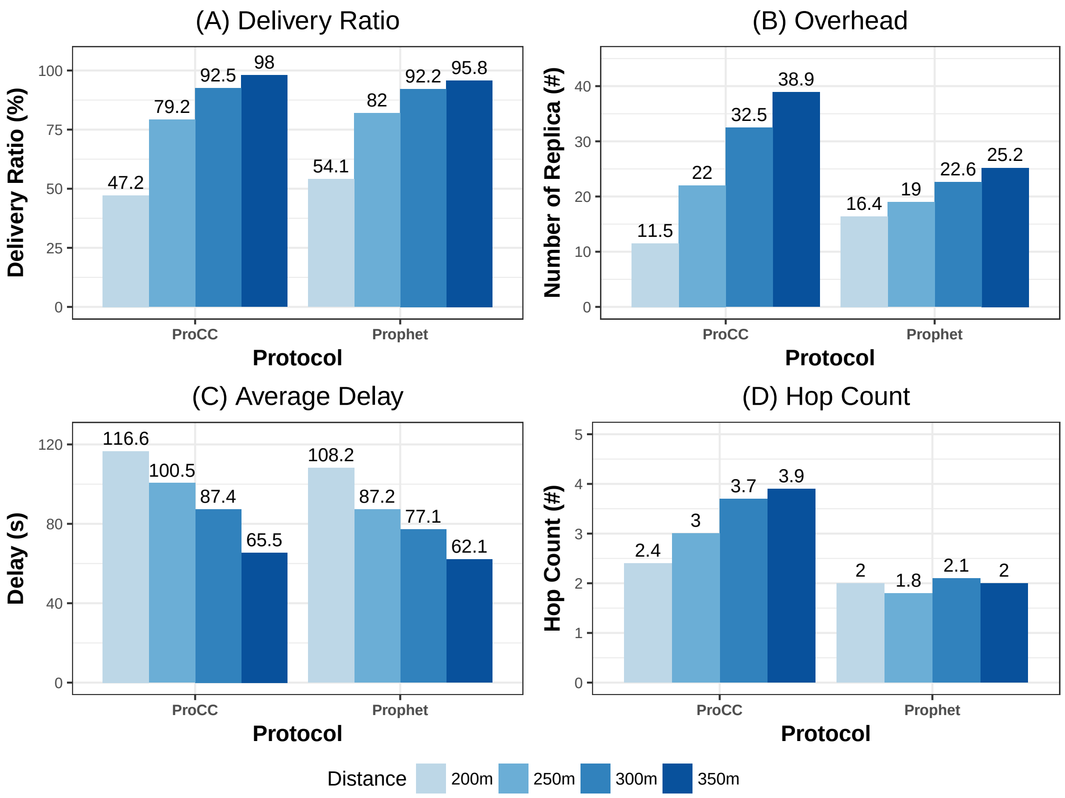


FIGURE 5.5: Simulations results for ProCC and Prophet protocols under scenario F

### 5.5.2 Scenario F: Evaluation under a small-scale scenario

The evaluation of ProCC based on a tiny scenario was encouraging and had revealed its capacity to compete with Prophet, especially in terms of Delivery Ratio. However, the scale of the scenario was far from being realistic and thus further evaluations are needed to assess the performances of ProCC. This is the main purpose of this study, where ProCC and Prophet are evaluated based on a larger road network of 1.65 km x 1.65 km, depicted in Fig 4.6. More specifically, the interest of this study is to compare the performances of ProCC and Prophet based on different transmission range, consequently, four (04) distance has been considered (200m, 250m, 300m and 350m), meanwhile, both protocols rely on ACKs and their settings are highlighted by Table 5.4. Finally, the simulation parameters are summarised in Table 5.2, whereas performance metrics are the same as those considered in the previous study.

**Evaluation of Delivery Ratio:** The results of simulation illustrated in Fig 5.5A highlight a steadily increasing delivery ratio in function of a longer transmission range, that allows vehicles to communicate between each other more frequently and thus increase the delivery ratio. Regarding the performances of each protocol, they are quite similar with a slightly better performance for Prophet compared to ProCC, until considering a transmission range of 300m or more, where ProCC performs equally or better than Prophet.

| Protocols Parameters | Values for Prophet | Values for ProCC |
|---|---|---|
| $P_{max}$ | 0.75 | - |
| $P_{first\ contact}$ | 0.5 | - |
| $I_{typ}$ | 1800 | - |
| $\beta$ | 0.9 | - |
| $\alpha$ | - | 0.5 |
| $\delta$ | - | 0.1 |
| $T_{unit}$ | 30 | 30 |
| $\gamma$ | 0.96 | 0.96 |
| $P_{min}$ | 0.05 | 0.05 |
| With Bundle ACK | Yes | Yes |

TABLE 5.4: Parameters for Prophet and ProCC configurations under scenario F

**Evaluation of Overhead:** As highlighted by results in Fig 5.5B, the generated overhead by both protocol increases proportionally to the increase in transmission range until reaching its maximum when the transmission range is set to 350m. Despite this, the overhead of Prophet is relatively low and stable compared with ProCC, which triples its overhead between the lowest and highest overhead. This behaviour is far from being unexpected, indeed, the ProCC protocol is more prone to forward and replicate bundles compared to Prophet, because this latter relies exclusively on the predictions of future contacts based on history of contacts, and in absence of a clear mobility patterns that allow it, vehicles tend to hold bundles during a longer period which limits the overhead.

**Evaluation of Average Delay:** The performances of both protocol are quite similar as shown in Fig 5.5C, with a slightly higher delay for ProCC. Moreover, and conversely to previous metrics, the average delay reduces in function of a longer transmission range. In general terms, the constantly reduced average delay observed here is due to the higher transmission range which advocates the quick relay of bundles, instead of their carrying during longer period, whereas the higher delay observed for ProCC compared to Prophet, may be due to the a more congested network since the approach advocated by the former protocol generates more replicas.

**Evaluation of Hop Count:** As expected the results in 5.5D show a low and stable hop counts for Prophet, and a high and steadily increasing hops in function of increasing transmission range for ProCC. These results are explained by the approaches advocated by both protocols, indeed, the former tries to predict future contacts based on history. However, when there is no real pattern behind vehicle mobility and with a slow ageing process, vehicles tend to hold bundles instead of forwarding them, this is why hop counts for Prophet is stable even when the transmission range is increased. This behaviour is very different from the one of ProCC where hop counts increase with higher transmission range, mainly due to its specific forwarding strategy which relays more often bundles and generates therefore replicas.

## 5.6 Main conclusions

This chapter presents the Probabilist Convergecast (ProCC) protocol, which is a new unlimited multiple-copy and predictive-based routing protocol dedicated to VDTNs, with the intent of successfully delivering bundles from the mobile sender nodes that are vehicles to the fixed receiver nodes commonly known as Road Side Units (RSUs). The protocol combines a predictive approach inspired by the well-known protocol Prophet, with a convergecast communication scheme biologically inspired in the cooperative work achieved by an ant colony. Regarding the performance evaluation of ProCC, it has been conducted against Prophet based on a tiny scenario and while considering various configurations to identify its best settings, and on a small-scale scenario with different transmission range to evaluate the behaviour of both protocols. The results show acceptable performances for ProCC. However, the identification of its most suitable settings via the tiny scenario has failed. Moreover, the proposal performs somewhat similarly to Prophet and does not provide cutting-edge results. Therefore, further developments are needed to improve the performances of ProCC, whereas its evaluation based on a more realistic and large-scale scenario will increase sensibly the confidence in results and facilitate the identification of its right configuration.

# Chapter 6

# Second proposal: The GeoDTC protocol



Through this thesis, the geographic-based routing family has turned out to be the most suitable approach to route data in vehicular environments. Indeed, the better performances observed for such approach compared to the predictive-based in Chapter 4, in addition to the mixed results that have emerged from the performance evaluation of the proposed protocol ProCC in Chapter 5, highlight the great difficulty to adapt correctly, fine-tune settings and apply predictive-based protocols. Meanwhile, this demonstrates that geographic-based are less dependable from the history of contacts, and more adaptable due to their capacity to understand the underlying topology and take the most of it to route data. Consequently, this chapter is devoted to the study of geographic-based VDTN routing protocols, and more importantly to the description and the evaluation of the core contribution of this thesis, namely The Geographic VDTN routing protocol based on Delay, Time and Custody transfer, commonly known as the GeoDTC protocol.

## 6.1 State of the Art for geographic protocols

Through the last decade, routing protocols based on geographical approach, emerged as a natural way, for the delivery of packets/bundles in Vehicular Delay-Tolerant Networks and their harsh conditions. This is due to multiple factors: First, the advocated approach is the most appropriate for capturing the highly changing network topology and vehicles motion. Furthermore, the increasing number of vehicles that embed GPS devices and On-Board Navigation Systems facilitate the application of such protocols. Finally, through various studies and comparative works, it has been demonstrated that other approaches fail to deliver data correctly, due to multiple reasons like network congestion for flooding based routing protocols; or lake of correlation between past and future mobility patterns for predictive ones.

In this context, researchers proposed numerous geographic protocols, that rely on various replication strategies and differ regarding the considered metric used to make the forwarding decision, as highlighted in Table 6.1, which resumes some major works, in parallel to their characteristics, and considered simulation environments & evaluation scenarios.

For instance, authors of [LM07] proposed the single copy routing protocol GeOpps, which forwards data based on the vehicle trajectory and the computed forwarding time metric $METD$ (which stands for Minimum Estimated Time of Delivery). The proposal was evaluated via a realistic network simulator and real-world traffic traces, extracted from the canton of Zurich, Switzerland [NBG06]. While the first results showed good performances and confirmed the applicability of the advocated protocol design, further works highlighted the limited performances due to the use of the single replication scheme.

In[Hua+07], the authors proposed an enhanced Epidemic routing protocol, called DAER. This protocol is characterised by the newly introduced geographic information, like the moving direction and the distance which are used to limit the bundle replication and consequently the generated overhead too. DAER protocol showed good performances when evaluated against Epidemic, under a large-scale scenario, based on real-world traffic traces extracted from taxi mobility of Shanghai city, China; with more than 4000 cars.

Regarding the VADD protocol [ZC08], it first calculates the shortest path to the destination accordingly to the Dijkstra Algorithm; then it routes data by selecting each time the next intersection by which data must be routed. To correctly select the next junction, it continuously alternates between two modes, based on different geographic information as the current location, or the heading direction of vehicles. One of its central issues is its tendency to use the most densely populated roads, which may congest the network.

Other works, as in [Che+10] and [FYG15], are highly inspired from non-tolerant to delay MANETs & VANETs routing protocols like the GPSR protocol [KK00] and its greedy forwarding approach. However, to correctly performs under spare networks, these protocols rely on additional forwarding mode, as for the GeoDtn+Nav protocol that uses a DTN forwarding mode in the third and last possible instance, if the greedy and the perimeter modes successively fail to deliver data. The RobustGeo protocol follows a similar behaviour while attempting to maximise the probability of delivering bundles that fall back to DTN mode, by periodically broadcasting them to neighbouring nodes, in order to deliver them through the greedy and the perimeter modes.

Whereas other works propose novel approaches, like the CMGR protocol [SL11] which use a new route selection logic, aware of vehicle density and adaptive to its measurement into the network. Consequently, data delivery goes through an on-demand process of route discovery and selection, triggered each time a bundle is sent, and by relying on multiple intermediate nodes to forward data from the initial sender to the final recipient.

In parallel to works cited above, many protocols as those presented in [SRF14], [Cao+15] and [Cao+18a], follow a hybrid approach, based on the limited replication scheme advocated by Spray & Wait [SPR05]. For instance, GeoSpray relies jointly on GeOpps [LM07] and its forwarding metric $METD$, and on the binary version of S&W to diffuse and deliver remaining bundle replicas. When only one replica remains, it stops its replication and switches instead to its transfer whenever encountering a better forwarder. This behaviour is justified by the need to comply with the limited replication scheme. Regarding GSAR, it aims to deliver data to both fixed and mobile destination, by diffusing replicas to the broadest extent possible during the spray phase, until only a single replica remains. Then, it switches to a second phase, where it focuses solely on the delivery of its unique replica, based on historical records of nodes mobility, and their best potential moves towards the estimated movement range of the final destination. TBHGR protocol delivers data also through two distinct steps. However, it makes the forwarding decision by computing a newly introduced metric, based on various geographic information of the current vehicle, like direction, speed, distance and time towards the destination.

Last but not least, the authors of [Cao+18b] present a unique trajectory driven protocol called TDOR. This work differs sensibly from other works because it considers the trajectory of bundles rather than vehicles as the critical factor to successfully deliver data. Consequently, it computes and embeds an optimal delivery path into the bundle, then it tries to deliver the bundle accordingly to the computed path, by forcing them to follow it and selecting each time a forwarder, which follows a similar path or can bring the bundle closer to its destination.

As highlighted in Section 3.1, one of the major concerns regarding any routing protocol, and especially proposals presented above, is the realism of their evaluation scenario. In fact, only some works as those presented in [LM07] (GeOpps), [ZC08] (VADD), [Che+10] (GeoDtn+Nav) or [FYG15] (RobustGeo), are evaluated through the use of realistic simulation tools like the QualNet simulator [Tec], the Omnet++ simulation framework[VH08] or lastly NS-2 [MFF] and its later successor NS-3 [RH10]. Moreover, in 2010, a Wi-Fi radio standard dedicated to vehicular networking was introduced, namely the 802.11p standard [IEE10], and by now, it is considered as the de facto standard. However, all presented works avoided the use of this standard. Finally, some parameters regarding protocols evaluation are frequently missing like the simulation duration in [ZC08] and [Che+10], or set to minimalist values like the number of simulated vehicles. All these factors limit the reproducibility and the degree of confidence in results greatly.

## 6.2 Presentation of the GeoDTC protocol

GeoDTC is a new geographic routing protocol based on two distinct forwarding metrics, and intensive use of the Custody transfer (or simply Custody) mechanism. Furthermore, it follows an unlimited multiple-copy replication scheme, while being highly inspired by the general guidelines of well-known geographic VDTN routing protocols, namely GeOpps [LM07] & GeoSpray [SRF14]. Consequently, this protocol assumes that vehicles which are at the core of the networks, embed a GPS navigation system able to provide a set of basic functionalities like geographic awareness, geo-localisation, or shortest route calculation between two map points. Such assumptions are mostly acceptable by now, due to the broad democratisation and continuously increasing adoption of GPS navigation systems. Moreover, readers should note that GeoDTC focuses mainly on Vehicle-To-Infrastructure communication denoted V2I, from mobile sender nodes that are vehicles to fixed receiver nodes that correspond to Road Side Units (RSUs), while bundles can be addressed to a single RSU (Unicast) or any RSU (Anycast). Therefore, the protocol does not take into consideration parked vehicles, and assumes that vehicles are aware of their current route, whereas the positions of the terminal nodes (RSUs) are known and already loaded in their digital map. Regarding targeted applications, GeoDTC is intended to deliver data for applications able to be deployed over networks prone to frequent disconnections & reconnections and long delays, like VDTNs. Such applications range from road traffic information to third-party services, including email service, web access, multimedia content download or geographic services discovery. Thus, this routing protocol is not adapted to the hard deadlines of road safety applications, like emergency braking or collision avoidance.

| Protocol | Year | Protocol Design | | Simulation | | Evaluation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Replication Scheme | #Replica Sent[1] | Simulation Tool | Medium Access | Mobility Dataset | RoadMap (Size) | Duration | #Nodes | #Compared Protocols |
| GeOpps [LM07] | 2007 | Single | 0 | Omnet++ (MF)[2] | 802.11b | ETH Zurich | Zurich (15x15km) | 24h | 21500 | 2 |
| DAER [Hua+07] | 2007 | Multiple Unlimited | 0,1 | ND | 802.11g+n | SUVNet | Shanghai (10x10km) | 1200s | 1000 | 1, Including: - Epidemic |
| VADD [ZC08] | 2007 | Single | 0 | NS-2[3] | 802.11 with DCF | Tiger | ND (4x3,2km) | ND | 210 | 2, Including: - Epidemic |
| GeoDtn + Nav[Che+10] | 2010 | Single | 0 | QualNet[2] Vanet-Mobisim[3] | 802.11b | Tiger | Oakland (1,5x4km) | ND | 90 | 2 |
| CMGR [SL11] | 2010 | Single | 0 | NS-2[2] Move[4] SUMO[3] | 802.11 with DCF | Tiger | ND (2,5x2,5km) | 20000s | 400 | 2, Including: - VADD |
| GeoSpray [SRF14] | 2011 | Multiple Limited | 0,N | ONE (VDTN-Sim)[2] | No | No | Helsinky (4,5x3,4km) | 6h | 115 | 4, Including: - Epidemic - S&W - Prophet - GeOpps |
| GSAR [Cao+15] | 2014 | Multiple Limited | 0,1,N | ONE[2] | No | No | Helsinky (4,5x3,4km) | 9h | 100 | 4, Including: - Prophet |
| TBHGR [Cao+18a] | 2016 | Multiple Limited | 0,N | ONE[2] | No | No | Helsinky (4,5x3,4km) | 12h | 100 | 4, Including: - GeoSpray - S&W |
| TDOR [Cao+18b] | 2018 | Multiple Unlimited | 0,1 | ONE[2] | No | No | Helsinky (4,5x3,4km) | 6h | 120 | 3, Including: - Epidemic - TBHGR |

[1] Replica Sent & Replication Type: 0 - No replica is sent instead the same copy is forwarded; 1 - One replica is sent only; N - N copies are sent following the replication scheme of the S&W protocol.
[2] Network Simulator + (optionally an Extension or a dedicated Library).
[3] VANET Simulation Framework.
[4] Road Traffic Simulator.
* ND: Not Defined.

TABLE 6.1: Review of recent geographic-based VDTN routing protocols

## 6.3 Main Characteristics and Keys Features

### 6.3.1 Forwarding metrics

Based on its GPS navigation system, a vehicle carrying a message $M_D$ that must be delivered to the destination $D$, can determine along its proposed route, the nearest point to the location of the same destination $D$, denoted $NP$. Such concept that has been first defined by GeOpps then taken up by GeoSpray allows the computing of the time based metric $METD$, already used by GeOpps and GeoSpray, in addition to the alternative, newly introduced, distance-based metric $Dist$. Therefore, these two metrics are at the base of the forwarding decision made by GeoDTC.

In practical terms, a vehicle can estimate the required travel time from its current position to its $NP$, denoted $ETA_{\ to\ NP}$ (for Estimated Time of Arrival to $NP$), and moreover the required travel time of the message between the $NP$ and the position of the final destination $D$, denoted $ETA_{\ from\ NP\ to\ D}$, based on the topological shortest path between these two geographic positions and by considering the maximum allowed speed on streets, known to the GPS navigation system. Thus, and accordingly to Eq.6.1, the sum of these two measurements constitute the Minimum Estimated Time of Delivery metric, denoted $METD$.

$$METD = ETA_{\ to\ NP} + ETA_{\ from\ NP\ to\ D} \tag{6.1}$$

However, one of the major drawbacks of the $METD$ metric is its incapacity to determine if a candidate vehicle will pass by the destination, which can substantially increase the likelihood of successfully delivering the message $M_D$. In fact, this time-based metric don't distinguish between a vehicle that is converging quicker or closer to the final destination, while sometimes it might be interesting to choose one that is moving slowly but will get close, or even better pass-by the destination $D$, and consequently deliver $M_D$ directly under acceptable network conditions (No storm broadcast or similar phenomena). To address this issue, GeoDTC introduces the topological distance of the shortest path between the $NP$ and the destination $D$ as a second metric denoted $Dist$. Therefore, the protocol can determine if the candidate vehicle will pass-by the destination $D$ (if $Dist = 0$ ), which makes it an ideal forwarder while potentially limiting the induced overhead, as it will be highlighted later.

$$Dist = Distance_{\ from\ NP\ to\ D} \tag{6.2}$$

### 6.3.2 Custody transfer & BRAC mechanism

Under a DTN environment, each node is intrinsically a custodian node, because it is responsible for its carried bundles until their delivery or forwarding. Therefore, the Custody transfer referees to the transfer of responsibility from one node to another over the management, the replication and the deletion of a single or a set of bundles, called also custodian bundles. In practical terms, this interesting mechanism allows a protocol to differentiate custodian bundles from others, or to assign them to specific nodes; like for instance delegating a bundle and its final delivery to a node which is supposed to increase the likelihood of successfully delivering the bundle, since its current carrier is no longer a suitable forwarder.

Regarding GeoDTC, if a carrier vehicle will not pass-by the destination $D$ (if $Dist_{carrier} \neq 0$ ), and it meets a candidate vehicle that will (if $Dist_{candidate} = 0$ ), then this vehicle must proceed to a Custody transfer of $M_D$, by transferring it to the candidate node which is now in charge of the bundle delivery instead of replicating it. By doing so, the protocol achieves a twofold goal, by first increasing the likelihood of successfully delivering $M_D$, and secondly preventing any further and unnecessary replication of $M_D$ by the initial carrier, which limits the protocol overhead. Lastly, it should be noted that the Custody as employed by GeoDTC also implies an acknowledgement (ACK) upon a successful Custody transfer, sent to the previous custodian vehicle by the new one. It is done to avoid the deletion of a custodian bundle that has not yet been transferred to the new custodian vehicle.

In parallel to the Custody transfer, GeoDTC introduces the Bundle Replication Avoidance based on Custody (BRAC) mechanism. The basic idea here lies on whether or not use the Custody and more interestingly how to use it. Indeed, instead of simply processing to a Custody transfer whenever needed, it is possible to notify the existence of custodian bundles and diffuse the list of these bundles among other vehicles, to prevent any further replication. Moreover, it is possible to take a specific action upon the receipt of such list, like deleting custodian bundles from any no-custodian vehicles. Therefore, the BRAC mechanism can be viewed as a set of strategies regarding the usage and the implementation of the Custody transfer, with the goal of preventing the replication of custodian bundles, and that range from the laziest and the most reactive strategy to the most restrictive and proactive one, as highlighted in Table 6.2.

### 6.3.3 Time To Live for Control Messages

It is well established by now that the use of acknowledgements (ACKs) upon a successful bundle delivery, enhance the overall performances of any considered protocol. Indeed, the use of ACKs has many benefits like avoiding misuse of bandwidth and any unnecessary replication of delivered bundles, which in turn free-up buffers

| Strategy N° | Strategy Name | Make use of Custody transfer? | Diffuse list of custodian bundles? | Required action upon the receipt of the list |
|---|---|---|---|---|
| 0 | $BRAC_0$ | No | No | None |
| 1 | $BRAC_1$ | Yes | No | None |
| 2 | $BRAC_2$ | Yes | Yes | None |
| 3 | $BRAC_3$ | Yes | Yes | Delete Custodian Bundles |

TABLE 6.2: BRAC mechanism & strategies of GeoDTC protocol

and network resources for remaining bundles, and therefore increase their likelihood to be successfully delivered.

Furthermore, by nowadays many routing protocols like Epidemic, Prophet, and GeoSpray advocate a pro-active strategy to take the most from acknowledgements, by diffusing for instance lists of ACKs among other nodes to purge the whole network from delivered bundles. However, such a strategy has a significant drawback. Indeed, while it is commonly assumed that bundles will be deleted upon the expiry of their assigned Time To Live (TTL), there is no such TTL for Control Messages as for ACKs. Consequently, the use of an ACK list can be even harmful if its size continues to grow until reaching its maximum, which results in increased usage of bandwidth to diffuse ACKs rather than deliver bundles.

$$TCM_{ACK} = \begin{cases} FTCM_{ACK} = TTL_{BundleM_D} \\ ATCM_{ACK} = TTL_{BundleM_D} - \mathit{Delay\ Of\ Delivery}_{BundleM_D} \end{cases} \tag{6.3}$$

$$TCM_{Custody} = \begin{cases} FTCM_{Custody} = TTL_{BundleM_D} \\ ATCM_{Custody} = METD_{BundleM_D} + \mathit{Guard\ Interval} \end{cases} \tag{6.4}$$

To address this drawback, GeoDTC introduces a TTL for Control Messages denoted $TCM$, which includes lists of ACKs and Custodians Bundles like those used by the BRAC mechanism, denoted respectively $TCM_{Ack}$ and $TCM_{Custody}$. Moreover, it introduces two types of $TCM$, namely Fixed and Adaptive denoted respectively $FTCM$ and $ATCM$. The $FTCM$ aims to reduce the size of control messages lists, based on a fixed value, aligned with the current bundle TTL. The $ATCM$ is based on a more evolved approach, where the computed value of the $TCM$ depends on the type of control messages (ACKs vs Custodian Bundles) and the purpose of using it. For instance, a $ATCM_{Ack}$ must expire at the same time as bundle expiry. Regarding a $ATCM_{Custody}$, it must last only during the short period needed by the custodian vehicle to deliver the carried custodian bundles, majored by a regular guard interval of 10%. If it lasts more, it can be harmful because it will prevent the replication of any undelivered custodian bundles by custodian vehicles, which may happen in real conditions. Therefore, $TCM_{Ack}$ and $TCM_{Custody}$ are computed accordingly to Eq. 6.3

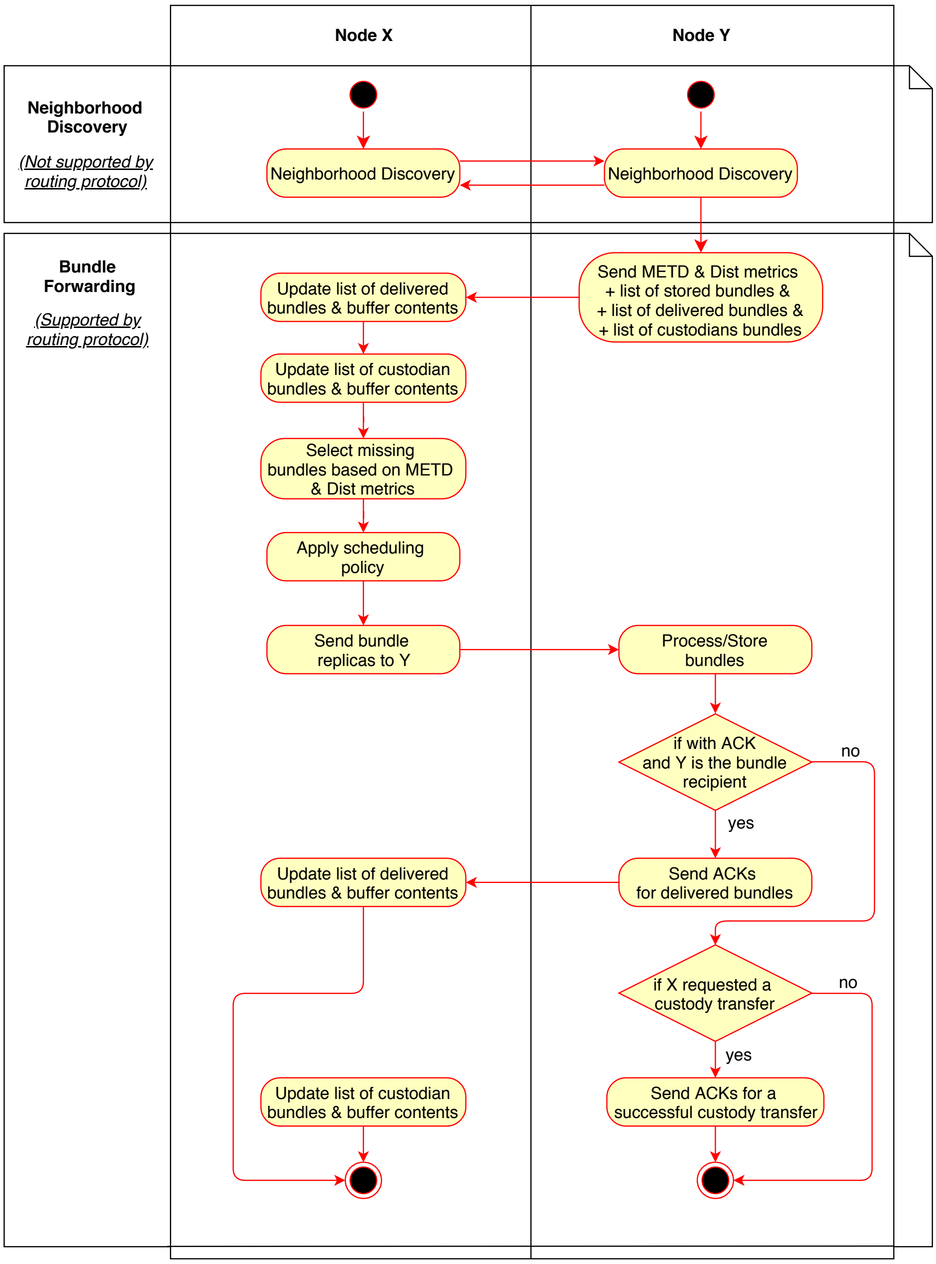


FIGURE 6.1: UML activity diagram of GeoDTC operations for data routing

& Eq. 6.4

## 6.4 Protocol Operations

The GeoDTC protocol forwards a bundle $M_D$ from a carrier vehicle $X$ to a candidate vehicle $Y$, through a three-step process. The vehicle $Y$ starts the exchange of information by sending to $X$, its current $METD$ and $Dist$ metrics, in addition to the list of ACKs and Custodian Bundles, accordingly to the considered BRAC strategy (e.g. If the current strategy is $BRAC_0$, then there is no Custody and therefore no need for a list of Custodian Bundles, which contrasts with other BRAC strategies). Following this first step, $X$ updates its lists of ACKs and Custodians Bundles, deletes any unnecessary bundles identified by those lists, according to the considered BRAC strategy (e.g. if the current strategy is $BRAC_2$, and $X$ is not a Custodian Vehicle, then it must deletes any possessed Custodian Bundles), and lastly computes and compares its metrics to those of $Y$, and if $Y$ enhances one of them (If $METD_X \geq METD_Y$ or $Dist_X \geq Dist_Y$) then $X$ must sent a replica of $M_D$ to $Y$. Except if $Y$ will encounter the destination $D$ (if $Dist_Y = 0$) then $X$ must proceed to a Custody Transfer of $M_D$, instead of its replication. Finally, $Y$ receive the bundle and process to its storage, and if it is the final recipient of $M_D$, or $X$ requested a Custody Transfer, then it must reply to $X$, by sending respectively the generated ACK upon the receipt of $M_D$ or an acknowledgement for a successful Custody Transfer, which in both cases allows $X$ to delete $M_D$ from its storage. The overall process is described through the UML activity diagram illustrated in Fig 6.1

## 6.5 Evaluation of GeoDTC protocol

To correctly assess the performance of GeoDTC, a quantitative evaluation of the protocol against well-known routing protocols, namely Epidemic, Direct-Delivery (abbreviated as DDelivery), Prophet (as mentioned before ProphetV1 is outdated, thus ProphetV2 is the only one to be considered in this work) and GeoSpray is performed. The choice of these routing protocols obeys to different criteria. Indeed, Epidemic offers a high delivery ratio at the price of high overhead and greedy approach. Conversely, DDelivery is a lightweight protocol with poor performances. Prophet is the main protocol among the predictive/social-based major routing family. Lastly, GeoSpray is one of the greatest routing protocol among those advocating a geographic-based approach. Furthermore, since GeoDTC is inspired in the general guidelines of GeOpps and GeoSpray, this latter must be considered.

Regarding the working environment, the Veins simulation framework [SGD11] was selected for the implementation of all considered protocols, including the proposal, since no reference implementation is available for them. Veins is a well established by now since it is one of the most advanced simulation framework dedicated to vehicular networks. It is built upon the network simulator Omnet++ [VH08] and the traffic simulator Sumo, which is responsible for vehicle mobility [Kra+12]. Finally, the High-Performance Computing Grid MAGI of the University of Paris XIII [SPCU] was used to simulate this large scenario successfully.

### 6.5.1 Scenario I: Evaluation under a realistic & large-scale scenario

To evaluate the performances of GeoDTC without any overestimation, simulations are built upon a large-scale scenario based on the TAPAS Cologne dataset [UF11].

| Global Parameters | | Values | Global Parameters | | Values |
|---|---|---|---|---|---|
| **Simulation** | Duration | 3600s | **Bundle** | Size | 1Kbit |
| | Nbr. Run Per TTL Value | 20 | | Generation Period | 150s |
| **Wi-Fi** | Technology & Mode | 802.11p Broadcast | | Bundle TTL | 600s |
| | Transmission Rate | 18Mbits/s | **Transmission** | # Vehicles | 9920 |
| | Maximum Range | 127m | | # RSUs | 957 |
| | Propagation Model | Two Ray Interference & Simple Obstacle Shadowing | | Mode | From Vehicles To RSUs only |

TABLE 6.3: Simulation parameters for scenario I

| Configuration Name | Configuration Parameters | Configuration Name | Configuration Parameters |
|---|---|---|---|
| GeoDTC-A1 | $BRAC_0 + FTCM$ | GeoDTC-A2 | $BRAC_0 + ATCM$ |
| GeoDTC-B1 | $BRAC_1 + FTCM$ | GeoDTC-B2 | $BRAC_1 + ATCM$ |
| GeoDTC-C1 | $BRAC_2 + FTCM$ | GeoDTC-C2 | $BRAC_2 + ATCM$ |
| GeoDTC-D1 | $BRAC_3 + FTCM$ | GeoDTC-D2 | $BRAC_3 + ATCM$ |
| GeoSpray-E | Parameters: $R$=20 | GeoSpray-F | Parameters: $R$=60 |
| Prophet | Parameters: $P_{max}$=0.7; $P_{first_contact}$=0.5; $I_{typ}$=1800; $\beta$=0.9; $T_{unit}$=30; $\gamma$=0.999 | | |

TABLE 6.4: Parameters for GeoDTC, GeoSpray & Prophet configurations under scenario I

The dataset which is known to be the largest freely available to researchers, includes mobility traces of 38 592 vehicles during 2 hours, from 6h00 to 8h00 AM (due to computational constraints, the road traffic is limited to 1 hour and 9920 vehicles only), from the town of Cologne-Germany and its peripheral zone, for a total roadmap size of 29 km x 33 km. Over this map, 957 Road Side Units (RSUs) are deployed over 957 sectors of 1 $km^2$ area.

Regarding the considered radio specifications, Veins implements the de facto Wi-Fi standard for vehicular networks, namely, the IEEE 802.11p, limited to broadcast mode only, since recent research works highlighted the unsuitability of Unicast transmissions due mainly to head of line blocking effects [KDS15]. Moreover, the framework implements various radio propagations models, including the Two Ray Interference model [SJD12] and the Simple Obstacle Shadowing [Som+11] whose uses are highly advised by the authors. For data traffic modelling, since GeoDTC is envisioned to provide a routing service from mobile vehicles to fixed RSUs, this communication scheme is the only one considered, and vehicles generate periodically bundles addressed to the RSU of the current sector, through a unicast communication. Remaining simulation parameters can be reviewed in Table 6.3.

Finally, three (03) performances metrics are considered. They are described below and arranged in decreasing order of importance:

- Delivery Ratio (DR): since the main target of this work is VDTN routing protocol, this metric is considered as being the main performance metric. It is the ratio between the unique received bundles and the whole unique emitted bundles.

- Overhead (O): this reflects the cost of the protocol and allows the evaluation of a good trade-off between bundle delivery and network overload. It corresponds to the total number of bundle replica divided by the total number of emitted bundles.
- Average Delay (AD): regarding the delay-tolerant context, this metric is less important than those cited before. It corresponds to the average delay needed to deliver the first replica of any bundle.

#### 6.5.1.1 Global performance evaluation of considered protocols

The main goal of this study is to provide researchers with a first overview regarding the performance evaluation of the proposal GeoDTC under its basic configuration when ran against DDelivery, Epidemic, Prophet and GeoSpray. More significantly, this first study attempts to address the recurrent answer that rises when a proposal of a new VDTN routing protocol is made, namely:

- Is the proposal able to achieve an ideal trade-off between a high delivery ratio similar to Epidemic, and a low or at least an affordable overhead like those generated by GeoSpray or Prophet?

Indeed, due to the inherent constraints and specificities of the vehicular environment, the loss of a packet or bundle is frequent which implies addressing such phenomena by designing routing protocol that maximises first the delivery ratio, and after that the generated overhead or the average delivery delay. Therefore, such protocols tend to generate multiple replicas of a single bundle, which in turn can severely deteriorate the network performances if the replication is uncontrolled. Consequently, an ideal trade-off between the two is sought, whereas a suitable routing protocol is one who achieves it successfully.

To this end, the performances of a basic configuration of GeoDTC, denoted by $GeoDTC-A1$ are compared against those of DDelivery, Epidemic, Prophet and GeoSpray protocols. The latter is evaluated under two distinct settings regarding the maximum number of replica parameter $R$, whereas other protocols are evaluated under their default configurations. Besides, readers should note that all protocols make use of ACKs upon the final receipt of bundles. Finally, the parameters related to the considered configurations of Prophet, GeoSpray and GeoDTC are summarised in Table 6.4.

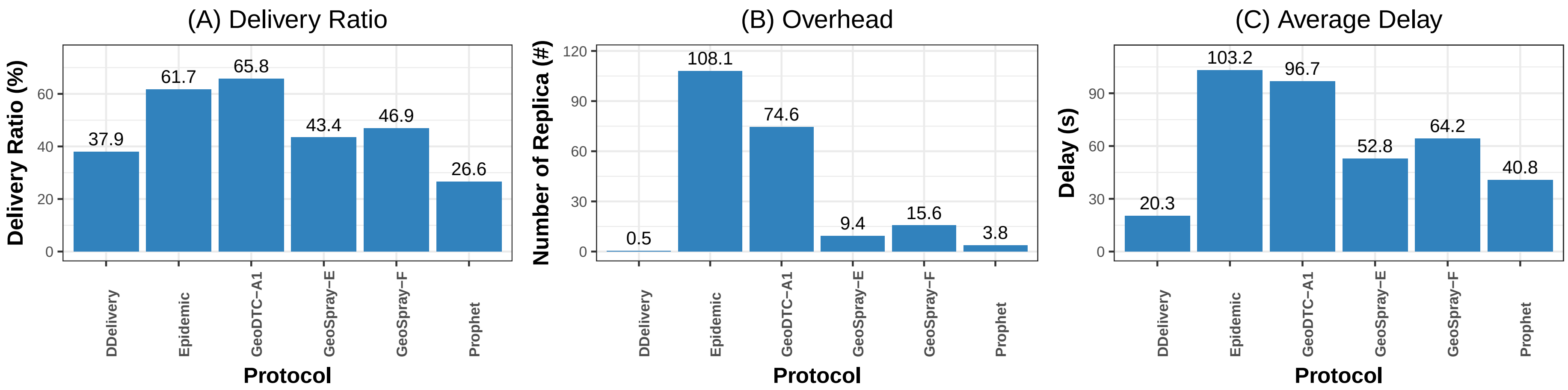


FIGURE 6.2: Simulation results for all considered protocols under scenario I

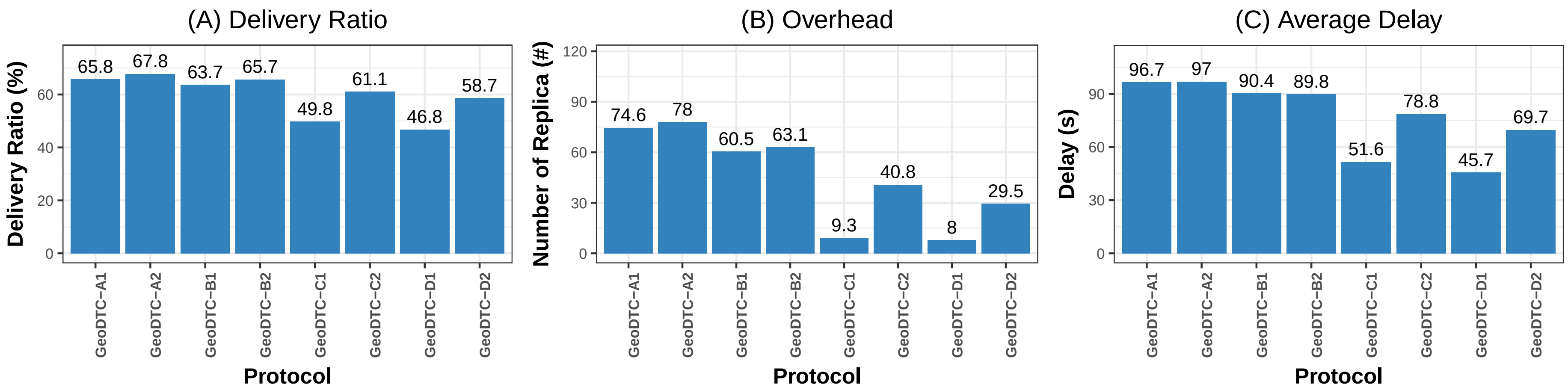


FIGURE 6.3: Simulation results for GeoDTC configurations under scenario I

**Evaluation of Delivery Ratio:** The results in Fig 6.2A show acceptable performances for all protocols, especially for a large-scale scenario with an anycast communication and a large fleet of simulated vehicles. Surprisingly, GeoDTC-A1 outperforms all other protocols by delivering more than 65.8% of bundles, followed by Epidemic, GeoSpray-F, GeoSpray-E and lastly by an unusual DDelivery protocol which ranks ahead of Prophet. The better performances of GeoDTC compared to Epidemic are explained by the use of accurate forwarding metrics which restrict the bundle replication to vehicles with better metrics, instead of flooding the network with replicas. Moreover, GeoDTC outperforms GeoSpray, because this latter restricts the bundle replication to the current value of the parameter $R$, and more significantly, the binary spray in use leads to slow diffusion of replica among the network and a lower delivery ratio. Therefore, the combined effects of both explain why GeoSpray-F achieves a slightly higher delivery ratio compared to GeoSpray-E, even if the parameter $R$ is tripled. Regarding DDelivery, its acceptable performances are due to its zero-overhead, and its approach which does not require any control information jointly to proper placement of RSUs. Lastly, the poor results of Prophet are explained by the difficulty to fine-tune its settings and to its inadequate routing approach, especially in such networks where future vehicle contacts cannot be predicted based on the history of past vehicle contacts and patterns.

**Evaluation of Overhead:** Observations made based on Fig 6.2B reveal a very high overhead for Epidemic, followed respectively by GeoDTC-A1, GeoSpray-F, GeoSpray-E, Prophet and lastly DDelivery. These overall results were widely expected. Indeed, Epidemic and its network flooding approach generate a very high overhead, whereas the near-zero overhead of DDelivery is due to its approach where the sender carries a bundle until meeting the final recipient, without the need for any intermediate relays. Regarding Prophet, its low overhead is due to its poor performances and the unsuitability of its routing approach, based on community-based mobility. For GeoSpray, the low and affordable overhead compared to its overall performance is due to its limited replication and slow bundle diffusion that is confirmed by the relatively small difference between GeoSpray-E and GeoSpray-F even if the parameter $R$ has tripled. Finally, GeoDTC generates a significant overhead compared to GeoSpray, but it is still lower than the one of Epidemic. A less restrictive approach explains such results compared to GeoSpray, which generates more replicas in order to achieve higher performances, and ultimately can be acceptable since the primary goal is to maximise the bundle delivery while achieving a trade-off between the high delivery rate of Epidemic and the low overhead of GeoSpray.

**Evaluation of Average Delay:** Surprisingly, the results in Fig 6.2C highlight the higher average delay (for the delivery of the 1st copy) for Epidemic, compared to all other protocols, followed by GeoDTC-A1, GeoSpray-F, GeoSpray-E, Prophet and

DDelivery. Far from being expected, the high delay of Epidemic is due to the network congestion that arises due to the excessive use of bandwidth by the uncontrolled bundle replication, additionally to an increasing competition between vehicles to access the communication channel. A similar phenomenon is also observed for GeoDTC-A1 but with a limited extent due to a higher but controlled bundle replication. Meanwhile, GeoSpray achieves an average delay that confirms the slow diffusion of bundles in the network, due to the binary S&W adopted by the protocol, whereas Prophet achieves a low delay that comes to the expense of poor performances. Lastly, DDelivery can deliver bundles in a very short delay, which confirms the excellent placement of a fringe of RSUs, and the possibility to relay some bundles through a simple and straightforward protocol as DDelivery.

#### 6.5.1.2 Performance evaluation of GeoDTC configurations

After revealing the potential benefits of using the proposal GeoDTC to route data from vehicles to RSUs, and showing encouraging results toward an ideal trade-off between a high delivery ratio and a low overhead previously, this study aims to improve the overall performances of GeoDTC, by evaluating different configurations of the proposal based on the four BRAC strategies and the two distinct TCM detailed in Sections 6.3.2 & 6.3.3 respectively. Therefore, eight configurations of GeoDTC are considered, the first one is $GeoDTC - A1$, whereas other configurations can be reviewed in Table 6.4. Finally, regarding the considered simulation parameters and scenario, they are similar in all respects to those of the previous study.

**Evaluation of Delivery Ratio:** The results in Fig 6.3A show a clear hierarchy among the different configurations of GeoDTC with, GeoDTC-A2 outperforming all considered configurations followed respectively by A1, B2, B1, C2, D2, C1 and lastly D1. Such hierarchy highlights the existence of several trends. At first, this stresses the benefit of using an Adaptive TCM ($ATCM$) like in A2, B2,C2 & D2 instead of a fixed one ($FTCM$) like in A1, B1, C1 & D1, which increases the delivery ratio, due to a more adapted expiry delay for control messages that frees the bandwidth and ultimately allows the delivery of more bundles. This applies even more for configurations C & D, because these latter send list of custodian bundles, and therefore correctly adapting the $TCM_{Custody}$ increases the likelihood of successfully delivering undelivered custodian bundles, whereas a long and fixed $TCM_{Custody}$ prevents their replication. Regarding the BRAC strategies, observations show that a basic one increases the delivery ratio, whereas a more intelligent and complex one slightly lowers it. This is explained by the fact that the latter tends to prevent the bundle replication by exchanging a list of custodian bundles (e.g. $BRAC_2$ ) or deleting them from non-custodian vehicles upon the receipt of such list (e.g. $BRAC_3$ ), which in turn translates in a lower delivery ratio.

**Evaluation of Overhead:** As shown in Fig 6.3B, GeoDTC-A2 generates the highest overhead followed respectively by A1, B2, B1, C2, D2, C1 and lastly D1. In general terms, these reflect the good performances observed previously, which explain why the best configuration in term of delivery ratio achieves the highest overhead and vice versa. Furthermore, through results, it is clear that the Adaptive TCM ($ATCM$) generates a higher overhead compared to the fixed one ($FTCM$) which is directly related to its capacity to release more bandwidth by correctly adapting the expiry of entries included in the lists of ACKs and custodian bundles. Regarding the considered BRAC strategies, it is interesting to note that the Custody transfer can reduce the overhead on its own, by up to 20% (e.g. when comparing A1 with B1 and A2 with B2), while offering near comparable overall performances. Moreover, further strategies like $BRAC_2$ reduces more the overhead, by up to 45% (e.g. when comparing A2 with C2) which comes with a reduced but still good overall performances, whereas $BRAC_3$ reduces the overhead sensibly but at the price of lower performances. Therefore, the results of the eight considered configurations of GeoDTC highlight the positive impact of the often neglected use of the Custody transfer, additionally to the more evolved BRAC strategies that can sensibly reduce the overhead.

**Evaluation of Average Delay:** the high average delay depicted in Fig 6.3C was partially expected. Indeed, the overall good performances of the different configurations of GeoDTC are made at the price of a longer delivery delay which is two main factors: the existence of a significant number of replicas and the use of the Custody transfer. These statements are supported by the high average delay observed for configurations based on $BRAC_0$ & $BRAC_1$, which are known to generate a high number of replicas; whereas remaining configurations rely intensively on Custody transfer which slows the delivery process but offers a more robust delivery solution. However, the side effect of Custody transfer is counterbalanced by the better usage of the bandwidth thanks to the list of ACKs and custodian bundles that avoid unnecessary bundle replication and forwarding. Therefore, even if the average delay is high, it is sensibly reduced compared to former BRAC strategies.

## 6.6 Main conclusions

This chapter presents an unlimited multiple-copy and geographic-based routing protocol dedicated to VDTNs, inspired by the general guidelines of previous major works like GeOpps and GeoSpray, called GeoDTC. To route data, GeoDTC relies on the joint use of two (02) forwarding metrics, namely the Distance-based metric $Dist$ and the Time based metric $METD$. Moreover, to the best of authors knowledge, GeoDTC is the first routing protocol to extend the application scope of the Custody transfer mechanism, by introducing the Bundle Replication Avoidance based on Custody (BRAC) mechanism with the goal of limiting the overhead induced by the protocol replication strategy. Furthermore, GeoDTC introduces the Time To Live For Control messages ($TCM$), for ACKs and list of Custody Bundles to optimise the usage of the network bandwidth. Lastly, readers should note that GeoDTC can operate with a single forwarding metric ($Dist$ or $METD$), however preliminary studies showed better results when combining the use of both metrics.

Regarding the performance evaluation of GeoDTC, it was conducted against well-known VDTN routing protocols, namely, Direct-Delivery (abbreviated as DDelivery), Epidemic, Prophet (more precisely ProphetV2) and GeoSpray; under a large-scale and realistic scenario based on the TAPAS Cologne dataset. Moreover, multiple configurations of GeoDTC were considered with the sole purpose of improving its performance. The overall results reveal the capacity of GeoDTC to achieve an excellent trade-off between a high delivery ratio and an acceptable overhead or average delay, mainly by extending the usage scope of the Custody transfer, which contrasts with the performances of the flooding based Epidemic and the geographic-based GeoSpray protocols. Moreover, the various evaluated configurations of GeoDTC demonstrate the ability of the protocol to cope with different needs as maximising the delivery ratio (e.g. GeoDTC-A2), minimising the overhead and average delay (e.g. GeoDTC-D1), or achieving an ideal trade-off between the formers (e.g. GeoDTC-B2 or GeoDTC-C2). Therefore, the recommended configuration may depend heavily on the intended objective, even if authors recommend the use of GeoDTC-B2 or GeoDTC-C2 because they offer similar or better delivery ratio than Epidemic while drastically reducing the overhead of the average delay. Besides, the results demonstrate also the potential benefits of adopting a $ATCM$, which increase the delivery ratio at the expense of a slight increase of overhead and average delay, which ultimately must not prevent its use.

Finally, to contribute and enrich the research community, the base implementation codes related to considered routing protocols in this work, are made publicly available by authors on the software development platform GitHub [Ars18a] & [Ars18c].

# Chapter 7

# Conclusion and perspectives



This closing chapter provides the readers with a clear and concise summary of this thesis, its specific context, intents and main contributions. Moreover, the chapter describes the envisioned future research works, emerging from this thesis, where substantial efforts were made to develop newer protocols and implementation platforms, and which require continuous works and further maturation to be fully usable by the research community. Lastly, the Journals & Conferences articles published during this thesis are listed.

## 7.1 Summary

In a constantly evolving world characterised by a steadily growing population and galloping urbanisation, current Information Technologies (IT) demonstrate their ability and capacity to address nowadays challenges faced by humanity. This is the case for instance with the various challenges that emerge from modern transportation habits and increasing number of vehicles sold across the world, which lead to the development of Intelligent Transportation Systems (ITS) and more concretely of Vehicular Networks.

Vehicular Networks or Vehicular Ad-hoc Networks (VANETs) are networks, constitute of vehicles that are able to communicate between them or with other entities of the network, in an Ad-hoc manner and via wireless communication technologies based on standards dedicated to such purpose like the de-facto IEEE 802.11p Wi-Fi standard or the newly coming cellular network standard LTE-V2X. During the recent years, where substantial efforts were made to develop VANETs, such networks were subdivided into two different categories: traditional VANETs that are not tolerant to delay and mostly dedicated to vehicular applications with hard deadlines and short latencies; and Vehicular Delay-Tolerant Networks (VDTNs) which are tolerant to delays & high latencies, and more importantly dedicated to applications with soft or no deadline at all.

This thesis fits into the context of growing research interest on VDTNs and more especially on VDTN routing protocols. Therefore the primary purpose of this thesis is to provide this research field with breakthroughs and majors contributions as the proposal of an architecture for the implementation of VDTN routing protocols, the performance evaluation of main VDTN routing protocols, and lastly the proposal of the geographic-based VDTN routing protocol GeoDTC. Additionally, to some minor contributions like the presentation of state of the art regarding ITS, VANETs and VDTNs and the proposal of the predictive-based VDTN routing protocol ProCC.

Indeed, through the works presented in Chapter 3, 4 & 6, we presented what we believe are the main contributions of this thesis. Chapter 3 is constituted of two distinct parts, the former presents a pressing topic regarding the evaluation of VANETs and VDTNs through simulations, but unfortunately too often neglected, namely the critical requirements needed for realistic evaluation regarding the network simulator, vehicle mobility and scenario description. Moreover, it presents a summary of currently available simulations tools and mobility datasets. The latter describes with a higher degree of details the proposed architecture for the implementation of VDTN routing protocol, based on the Veins simulation framework, and which was used to conduct our works.

In Chapter 4, the main existing VDTN routing protocols were first detailed, then extensively compared via a performance evaluation under a small- and large-scale scenarios, with the latter being based on the TAPASCologne dataset. The overall results showed a clear trend toward the use of geographic-based routing protocols instead of predictive ones, due to their ability to understand the underlying topology and take the most of it, which lead us to say that such routing protocols are more suitable to the vehicular environment. Lastly, we proposed in Chapter 6 a new geographic-based VDTN routing protocol called GeoDTC, which outperforms the GeoSpray protocol and provides an ideal trade-off between a high delivery ratio, and an affordable generated overhead. Its overall good performances are due to multiple factors, like the introduction of the more reliable $Dist$ metric, the intensive use of the Custody transfer, without omitting the rely on the multiple proposed $BRAC$ strategies, in parallel to the fixed & adaptive $TCM$.

Besides, Chapter 2 & 5 cover the minor contributions of this thesis. The former presents the main ITS projects in progress over the world, namely in Europe and USA, in addition to the main involved technologies and standards. Furthermore, it traces the evolution of Vehicular Networks from pure VANETs to VDTNs, based on the fundamental principles and mechanisms of DTNs, in addition to a concise description of the various approaches existing for data routing in VDTNs, and the commonly recognised taxonomy for such routing protocols. Whereas the latter covers works achieved during the early stages of this thesis, where our main focus was to develop a new predictive-based VDTN routing protocol called ProCC, inspired by the Prophet protocol and convergecast approaches. However, the mixed results of ProCC, in parallel to the observations made in Chapter 4 have definitively convinced us of the difficulty to apply such approach and successfully route data based on predictive protocols. This finding ultimately allows us to shift our focus to geographic-based protocols and propose the GeoDTC protocol in Chapter 6 and which is at the core of the thesis contributions.

## 7.2 Future Works

Because Research is a continuous work in progress, and a Thesis is first and foremost a set, a bunch, a collection of research works, we have identified multiple rooms for improvements, which can be completed through an incremental and continuous research work spread out over the time-scale.

In the short-term, we ambition first to enhance and maturate the common implementation platform developed during this thesis to take the most from later developments of the Veins simulation framework, Omnet++ network simulator and SUMO road traffic simulator, which further increase the realism of the simulation and fix previously known bugs. After that, we will shift our focus to the improvement of the proposed geographic-based routing protocol GeoDTC, more precisely to the reduction of its overhead and to the achievement of a better trade-off between a high delivery ratio and an acceptable overhead.

Beyond that, works related to different aspects as enhancing well-known VDTN routing protocols or testing and experiencing the overall performances of the proposal GeoDTC should be considered in the medium-term. This may include:

- Evaluating the impact of bundle scheduling and dropping policies on global performances of VDTN routing protocols.
- Testing and experiencing the performances of VDTN routing protocols based on Unicast & Anycast communication scheme, or different mobility datasets and IVC technologies (e.g. IEEE 802.11p vs LTE-V2X, IEEE WAVE vs ETSI ITS-G5).
- Deepening the interesting findings related to the good performance of Direct-Delivery under the large-scale scenario and the positive impact of the proposed *H2HAck* mechanism dedicated to GeoSpray.

- Proposing a mechanism to adapt Prophet protocol settings to the considered scenario automatically.

Finally, our long-term commitment is to enrich the implementation platform with more VDTN routing protocols like Spray&Wait or GeOpps, and more fundamentally address other major topics related to the improvements of Intelligent Transportation Systems like an ideal, cost-effective deployment of Road Side Units or an efficient traffic-flow based on recent advances in the field of Traffic engineering.

## 7.3 Publications

- International Journal Articles
  - Arslane HAMZA-CHERIF, Khaled BOUSSETTA, Gladys DIAZ, Fedoua LAHFA *"Performance evaluation and comparative study of main VDTN routing protocols under small- and large-scale scenarios"* in: Ad Hoc Networks Journal, Volume 81, December 2018 https://doi.org/10.1016/j.adhoc.2018.07.008
- International Conferences Articles
  - Arslane HAMZA-CHERIF, Khaled BOUSSETTA, Gladys DIAZ, Fedoua LAHFA *"A probabilistic convergecast protocol for vehicle to infrastructure communication in ITS architecture"* in: 13th IEEE Annual Consumer Communications & Networking Conference (CCNC), 9-12 January 2016, Las Vegas, NV, USA https://doi.org/10.1109/CCNC.2016.7444877
  - Arslane HAMZA-CHERIF, Khaled BOUSSETTA, Gladys DIAZ, Fedoua LAHFA *"Improving the performances of geographic VDTN routing protocols"* in: 16th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net), 28-30 June 2017, Budva, Montenegro https://doi.org/10.1109/MedHocNet.2017.8001641
  - Arslane HAMZA-CHERIF, Khaled BOUSSETTA, Gladys DIAZ, Fedoua LAHFA *"GeoDTC: A New Geographic Routing Protocol based on Distance, Time and Custody Transfer"* in: Proceedings of the 5th International Conference on Internet of Vehicles (IOV), 19-22 November 2018, Paris, France https://doi.org/10.1007/978-3-030-05081-8_3
- National Conferences Articles
  - Arslane HAMZA-CHERIF, Fedoua LAHFA, Khaled BOUSSETTA, Gladys DIAZ *"A State of Art of Modern Intelligent Transport Systems"* in: Proceedings of the 2015 International Conference on Advanced Communication Systems and Signal Processing (ICOSIP), 8-9 November 2015, Tlemcen, Algeria.

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## Abstract:

Through this thesis, we aimed to contribute to the research field of Vehicular Delay Tolerant Networks (VDTNs), and more importantly to the subfield of VDTN routing protocols. Indeed, our research works brought to light multiples findings related to this hot research topic; at first we gave a reminder about the minimal requirements needed to correctly assess the performances of VDTN routing protocols, especially regarding the considered network simulator & vehicle mobility, additionally to the realism of the scenario. Subsequently, our comparative study of main protocols demonstrated the suitability of geographic-based routing protocols compared to predictive ones. Consequently, we proposed the new geographic-based protocol GeoDTC based on Distance, Time and Custody transfer, which demonstrated its ability to outperform well-known geographic-based protocols, while achieving an ideal trade-off between a high delivery ratio and an acceptable overhead. Last but not least, we developed through this thesis a common architecture for the implementation of such routing protocols, which was largely used to achieve our works and was made publicly available online, in the hope that this will reduce the development gap and enrich the research community.



**Keywords:** Intelligent Transportation Systems, Vehicular Ad hoc Networks (VANETs), Vehicular Delay Tolerant Networks (VDTNs), routing protocols, VDTN routing protocols.



## Résumé:

À travers cette thèse, notre objectif était de contribuer au domaine de recherche des réseaux véhiculaires tolérants aux délais (VDTNs), et plus important encore, au sous-domaine des protocoles de routage VDTN. En effet, nos travaux de recherche ont mis en lumière plusieurs découvertes liées à ce sujet de recherche d'actualité ; En premier lieu, nous avons rappelé les exigences minimales requises pour évaluer correctement les performances des protocoles de routage VDTN, en particulier en ce qui concerne le simulateur réseau et la mobilité des véhicules, ainsi que le réalisme du scénario. Par la suite, notre étude comparative des principaux protocoles a démontré la pertinence des protocoles de routage basés sur l'approche géographique par rapport à ceux basés sur une approche prédictive. Par conséquent, nous avons proposé un nouveau protocole géographique GeoDTC basé sur la distance, le temps et le Custody transfer, qui a démontré sa capacité à surpasser les protocoles géographiques connus, tout en réalisant un compromis idéal entre un taux de livraison élevé et un surcout acceptable. Enfin, nous avons développé à travers cette thèse une architecture commune pour l'implémentation de ces protocoles de routage, qui a été largement utilisée pour la réalisation de nos travaux de recherche et rendue publique en ligne, dans l'espoir que cela puisse réduire les écarts de développement et enrichir la communauté scientifique.



**Mots-Clés:** Systèmes de Transport Intelligents, Réseaux Ad-Hoc de Véhicules (VANETs), Réseaux Véhiculaires Tolérants aux Délais (VDTNs), Protocoles de routage, Protocoles de routage VDTN.



## ملخص:

من خلال هذه الأطروحة، كان هدفنا هو المساهمة في مجال البحث المتعلق بشبكات السيارات المتسامحة للتأخير(VDTNs)، وبالخصوص، المجال الفرعي لبروتوكولات التوجيه VDTN. لقد سلطت أبحاثنا الضوء على العديد من الاكتشافات المتعلقة بهذا الموضوع الساخن. أولاً، لقد ذكرنا بالمتطلبات الأدنى اللتي نحتاجها لتقييم كفائة بروتوكولات التوجيه بشكل صحيح، خاصة فيما يتعلق بمحاكي الشبكة وحركة السيارات، بالإضافة إلى واقعية السيناريو. بعد ذلك أدلت دراستنا المقارنة لأبرز البروتوكولات على ميزة بروتوكول التوجيه ذو الطابع الجغرافي مقارنة بالبروتوكول المستند إلى الجانب التنبئي. ولذلك، اقترحنا البروتوكول الجغرافي الجديد GeoDTC بناء على المسافة، الفترة و Custody transfer، والذي أثبت قدرته على التفوق على أبرز البروتوكولات الجغرافية، ويتوصل إلى نتائج مثالية تمكننا في نفس الوقت تحقيق نسب إرسال قياسية بتكلفة إضافية مقبولة. أخيرًا، لقد طورنا من خلال هذه الأطروحة بنية مشتركة لتنفيذ بروتوكولات التوجيه هذه، والتي تم استخدامها على نطاق واسع لتحقيق أبحاثنا ثم نشرها على الإنترنت، أملا أن هذا سيمكن من تقليص الثغرات في تطوير بروتوكولات التوجيه VDTN وإثراء المجتمع العلمي.



**الكلمات المفتاحية:** نظام نقل ذكي، فانيت، شبكات السيارات المتسامحة للتأخير، بروتوكولات التوجيه، بروتوكولات التوجيه VDTN.