Tornell, SM.; Tavares De Araujo Cesariny Calafate, CM.; Cano Escribá, JC.; Manzoni, P. (2015). DTN Protocols for Vehicular Networks: An Application Oriented Overview. Communications Surveys and Tutorials, IEEE Communications Society. 17(2):868-887. doi:10.1109/COMST.2014.2375340.

DTN Protocols for Vehicular Networks: an Application Oriented Overview

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Abstract

This survey provides an in-depth analysis of the different proposals for Vehicular Delay Tolerant Networks (VDTNs). We introduce the DTN architecture and classify VDTN proposals according to the type of knowledge needed to route messages. This classification also includes some Delay Tolerant Network (DTN) protocols originally designed for Opportunistic Networks to illustrate the evolution from Opportunistic DTN protocols to VDTN protocols. We also identify a set of common mechanisms that can be applied to almost all the VDTN protocols, heavily influencing their performance. Finally, we present some applications where VDTNs can be applicable and evaluate the suitability of the different proposals for each specific application. Moreover, this survey is not only limited to describing the different protocols but also focuses on the reproducibility and repeatability of experiments. With this in mind, we also review the evaluation methods used by VDTN researchers. We identify a lack of realism in most of the simulation models used by the VDTN research community, providing certain guidelines to address this issue.

Index Terms

Delay tolerant networks, Vehicular networks, VANET, survey

I. INTRODUCTION

Wireless networks have evolved at a very fast rate and are applicable to several contexts and different communication solutions. In the automobile industry, many wireless solutions have been proposed to improve safety-related and data communication among vehicles and between vehicles and infrastructure. These proposals form the Intelligent Transport Systems (ITSs) field, which aims to improve the efficiency and security of transportation using Vehicular Networks (VNs).

Although, VNs make use of Vehicular Ad-Hoc Networks (VANETs) for Vehicle to Vehicle (V2V) communication, the concept of VN expands VANETs by adding Vehicle to Infrastructure (V2I) as well as cellular communication. Sometimes, VANETs are considered a subset of Mobile Ad-hoc NETworks (MANETs). However, the high speed of the nodes in a VANET, and the presence of obstacles like buildings, produce a highly variable network topology, as well as more frequent partitions in the network. Therefore, typical MANET protocols [1] do not adapt very well to VANETs since a complete connected path between sender and receiver is usually missing. Under these conditions, Delay Tolerant Networks (DTNs) [2] are an alternative able to deal with VANET characteristics, and are applicable to VN for ITS.

DTNs originated as a proposal for InterPlanetary Networks (IPNs) to provide communication between satellites, and base stations. DTNs allow for information to be shared between nodes even in the presence of high delays, which are typical in spatial communications. In DTNs, when a message cannot be routed to its destination, it is not immediately dropped but is instead, stored and carried until a new route becomes available. Messages are removed from the buffer when their lifetime expires or for buffer management reasons. This mechanism cannot only be applied to IPNs but also to VNs, taking advantage of their high degrees of mobility [3][4]. DTNs have been standardized by the Delay Tolerant Network Research Group (DTNRG) [5] to ensure network interoperability.

The research community has been very active over recent years, proposing new protocols and applications for Vehicular Delay Tolerant Networks (VDTNs). This diversity may overwhelm the inexperienced researcher. Our aim in this survey is to provide the reader with a broad view of the different proposals for VDTNs. We classify them according to their main routing metric, showing their relationships and evolution. We also present the applications where VDTNs can be applied, and evaluate the suitability of different protocols for each application.

There have been other works to survey DTN routing proposals and opportunistic routing for VNs, but, as far as we know, this is the first survey to specifically focus on VDTNs and how Opportunistic DTN protocols have evolved into VDTN protocols.

Before VDTN became a hot research topic, in [6], the authors developed a framework to classify DTN routing algorithms and protocols. Their framework described routing protocols based on *i)* routing objective, *ii)* proactive routing vs reactive routing, *iii)* source routing vs per-hop routing, and *iv)* message splitting. To classify routing algorithms they defined several knowledge oracles, called *Contacts summary Oracle, Contacts Oracle, Queuing Oracle and Traffic Demand Oracle*, which gradually increase the knowledge available at the nodes. Based on the knowledge of the nodes they mathematically formulated the DTN routing problem as several resource management problems and proposed mathematical algorithms to solve them.

In [7], the authors presented a survey of the most representative DTN protocols for MANETs to date (2006). They distinguished between *i)* deterministic routing, *ii)* epidemic and random routing, *iii)* link forwarding probability estimation, and *iv)* the model based approach. Most of the modern routing VDTN protocols we survey in this paper may have been included in the last category. They also included “node movement control based” algorithms, which allow the routing protocol to control the movement of certain nodes, and “network coding” methods. The earlier types of algorithm clearly do not apply to vehicular networks where vehicles move freely.

In a more recent work [8], the authors presented a survey on VANET routing protocols that included a small section devoted to DTN protocols. This section was insufficient and only summarized some of the characteristics of VAAD [9] and GeOpps [10].

In [11], the authors performed an extensive survey of DTN architectures, analyzing the bundle protocols and its advantages and disadvantages. They did not classify DTN routing protocols, but instead presented some mechanisms generally applicable to any DTN routing protocol and listed several protocols that use them. Their work provides a broad view of the DTN routing problem, without considering the special characteristics of VDTNs.

Position-based routing surveys have been previously published [12]. Although some works referred to in this paper match the definition of “position-based routing”, our analysis focuses on the DTN characteristics of the protocol, while previous papers focused mainly on their pure geographic characteristics.

In [13], the authors performed an analysis of certain DTN routing protocols in vehicular networks. We consider the scope of their work to be limited, as they consider only a dozen protocols while in this survey we consider 41 different contributions.

More recently, in [14], the authors presented a detailed DTN survey with more than 140 referred papers. However, their impressive work focused solely on Opportunistic DTN protocols and, therefore they did not cover most of the protocols we analyze in this survey. Their classification of DTN routing protocols was one of the bases of this work and we really encourage the reader to read their article in order to obtain a broader perspective of the DTN routing protocols universe.

As far as we know, this is the first survey to have focused on VDTNs and their applications. Moreover, this survey is not limited to protocol descriptions, focusing on reproducibility and repeatability of experiments, we include a review of the evaluation methods used by VDTN researchers.

The rest of this article is organized as follows: Section II introduces the DTN paradigm and its standards, discussing their suitability to VNs. Section IIIanalyzes and classifies VDTN protocols. Section IV surveys the methods used by researchers to evaluate VDTN protocols. Later, Section V introduces applications proposed by the research community which depend on the use of VDTNs and, finally, Section VI concludes the paper and provides some insights on future trends.

II. OVERVIEW OF DELAY TOLERANT NETWORKS

The DTN paradigm was initially proposed to enable communication between satellites, surface rovers, and other devices within the IPN [16] [17]. Space communication may suffer high delays and frequent disconnections. The DTN concept was also adapted for wildlife monitoring [18] and remote village communication [19], [20]. However, DTN solutions used their own protocols and were unable to intercommunicate. To enable intercommunication between different DTNs, regardless of the network technology, the DTNRG [5] started to work towards its standardization [3]. Figure 1 represents a heterogeneous DTN, which interconnects the IPN with terrestrial DTN nodes. As a result of these efforts, in 2007 two RFCs were published in 2007 that defined the DTN architecture [2] and the Bundle protocol [21]. The following subsection describes the DTN architecture.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2014.2375340, IEEE Communications Surveys & Tutorials
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A. Architecture and Standards

To support the heterogeneity of different networks the DTN architecture is designed to run as an overlay network over the network layer (IP in the case of the Internet). To do so, two new layers are added: The bundle layer, and the convergence layer [21]. The bundle layer encapsulates application data units into bundles, which are then forwarded by DTN nodes following the bundle protocol. The convergence layer abstracts the characteristics of lower layers to the bundle layer. The convergence layer does not need to run over the internet protocol stack, thus allowing for the implementation of DTNs over any type of network.

1) The Bundle Protocol: The Bundle Protocol stores and forwards bundles between DTN nodes. Instead of end-to-end forwarding, the Bundle Protocol performs hop-by-hop forwarding. To deal with network disruption, the Bundle Protocol can store bundles in permanent storage devices until a new transmission opportunity appears. The concept of reliable custody transfer ensures that a DTN node will not remove a bundle from its buffer until another node has taken **custody** of it.

The Bundle Protocol operation depends on contacts. A **contact** occurs when a connection between two DTN nodes can be established. The contact type depends on the type of operating network: it may be deterministic, as in Interplanetary networks, opportunistic, as in VN, or persistent, as in the Internet.

Where the size of a bundle exceeds the maximum transferred data of contacts, the bundle protocol must perform fragmentation. Fragmentation is supported in two different schemes: proactive, where a DTN node may fragment an application message into different bundles and forwards every bundle independently, and reactive, where bundles are fragmented during transmissions between nodes.

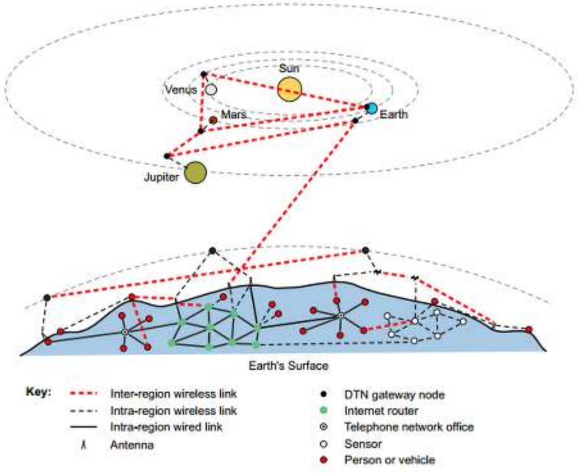


Fig. 1. Heterogeneous Delay Tolerant Network Example [15].

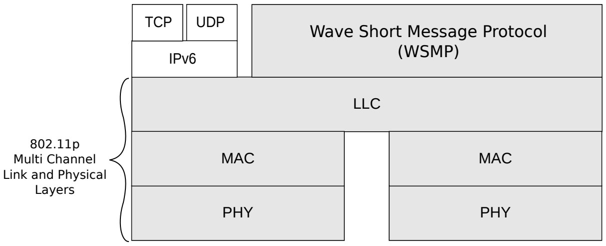


Fig. 2. WAVE Architecture.

2) The Convergence Layer: The convergence layer abstracts the characteristics of lower layers to the bundle protocol and is in charge of sending and receiving bundles on behalf of the bundle protocol. The convergence layer allows for any set of lower protocols to be used to reliably transfer a bundle between two DTN nodes. For example the TCP/IP convergence layer [22] uses a TCP connection between two DTN nodes to transfer bundles. That TCP connection can be established via the Internet. To implement a DTN over other technologies, new convergence layers are needed. Convergence layers must provide the bundle protocol with a reliable delivery and reception mechanism.

3) The Generic Opportunistic Routing Framework (GORF): After the standardization of DTN architecture, the DTNRG focused on the routing protocols, releasing GORF [23]. GORF architecture specifies all necessary basic functionalities common for utility-based routing protocols, and provides a framework to easily define and implement any opportunistic routing protocol for DTNs. To date, only the Epidemic protocol [24] and the PRoPHET protocol [25] have been standardized [26] [27].

The GORF assumes that nodes are able to detect their neighbors using a service running independently. When a neighbor has been detected the protocol sets up a link between the current carrying node, called **custodian**, and the detected neighbor, called **candidate**. Once a link is established, nodes exchange routing information on other nodes in the network. Afterwards, the custodian sends a *bundle offer* that contains a list of the bundles in its buffer. Then, the candidate responds with a list of requested bundles, that will be forwarded to it.

B. Does the Standard Apply to Vehicular Networks?

Before evaluating the suitability of DTN standards to VN, it is worth briefly introducing the currently approved standard in the USA for ITS: the Wireless Access for Vehicular Environment (WAVE) standard [28]. This standard uses the 5.9 GHz band by relying on the 802.11p protocol for medium access [29]. Figure 2 shows its architecture. WAVE architecture includes two different transport/network layers: one compatible with IPv6 and its own network/transport layer based on the WAVE Short Message Protocol (WSMP), which reduces the overhead.

The standard DTN protocol stack can be used directly in VDTNs through the IPv6 compatible stack. To implement a pure VDTN directly over the WSMP, which introduces less overhead and more flexibility, the only requirement

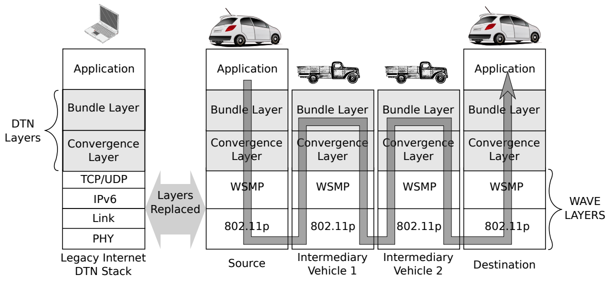


Fig. 3. Comparison between Internet DTN stack and VDTN stack. Scheme of a message transmission in a VDTN

is the implementation of a convergence layer between the bundle layer and the WSMP. Figure 3 compares the pure VDTN stack against the legacy internet DTN stack. Few researchers have tried to adopt the standard DTN stack for VDTNs. Among the papers reviewed in this survey, only those proposals which were tested on the UMassDieselNet testbed [30] implemented the standard DTN stack.

With regards to GORF architecture as it is proposed at present it may be applicable to all of the unicast protocols surveyed in this article. However, due to its newness, none of the protocols exactly match the functions and phases defined by the GORF. The main difference arises in the node that performs the routing decision process. Most proposals consider that the custodian node must decide whether or not to forward a bundle, according to its neighbors' characteristics; whereas GORF architecture assigns the routing decision process to the candidate node, which requests bundles stored in the custodian buffer. Since the candidate node may have a different local view of the network status, decisions may be different, and the routing information exchange phase should be appropriately adapted.

III. DTN PROTOCOLS FOR VANETS: TAXONOMY

In this section, DTN protocols are classified according to different parameters. Firstly, they must be grouped together according to the objective of the protocol: *a)* protocols whose objective is to disseminate messages to all the nodes in the network (**Dissemination**) and *b)* protocols whose messages have a specific destination that can either be a vehicle or an Road Side Unit (RSU) (**Unicast**). Secondly, they are grouped together according to the amount of control information required by each protocol. Inside the dissemination protocols group, we distinguish between the epidemic approach and a group of protocols that uses geographic information to estimate connectivity of nodes (**geo-connectivity**). Inside the unicast group, we distinguish between **zero knowledge** protocols, those that do not require any knowledge about the vehicles status or the environment and **utility based** protocols. Utility based protocols try to estimate the benefit of each transmission (*i.e.* how a transmission improves the probability of reaching the destination) to determine the best forwarding node among neighbors. Each protocol estimates this utility using a pre-defined metric. We have divided these utility-based proposals into five different categories, according to the type of knowledge they need: *i)* **contact history & social relationships**, *ii)* **geographic location**, *iii)* **road map**, *iv)* **hybrid** protocols and *v)* **online** protocols. The "online" subcategory includes protocols that, besides combining several simpler protocols, require information on the current state of the road network or use sophisticated metrics that do not fit into any other category. Figure 4 summarizes this classification, while Figure 5 orders and classifies the protocols collected in this survey chronologically. For each category, we first list the different protocols forming part of it before describing those protocols and, finally, explaining their advantages and disadvantages.

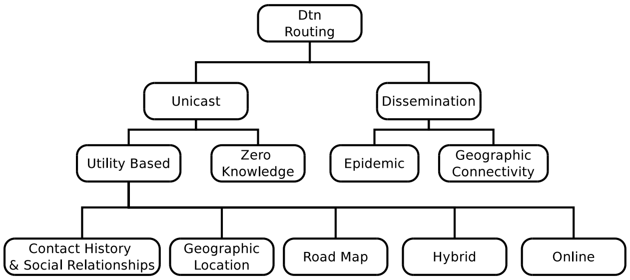


Fig. 4. DTN Protocol Taxonomy.

Table I summarizes the characteristics of the different proposals. The second column indicates whether the protocols were originally proposed for VN or not. The third column contains the objective application of each protocol as it is stated in its original publication. The fourth column classifies protocols according to the classification explained previously. The fifth column offers a quick and simple description of the routing metric used by each proposal. Finally, the columns under the "Optimizations" label indicate whether the mechanisms described in Subsection III-D are considered in the proposal.

A. Dissemination Protocols

The objective of the dissemination protocols is to inform as many nodes as possible of an event. The most obvious solution is the simple flooding scheme, where nodes rebroadcast every message received [31]. However, this scheme generates some well-known problems, such as the broadcast storm [32], or infinite rebroadcasting loops that waste resources. To limit the impact of these problems, some modifications to the simple flooding scheme have been proposed [33]. Simple flooding and its modifications are limited by the connectivity of the network: they will only propagate messages as long as the network is connected. In this section we present proposals that add DTN support to dissemination protocols. Since DTN dissemination protocols are not limited by the connectivity of the network, the dissemination process must be limited in time or space to avoid collapsing the network.

TABLE I

CHARACTERISTICS OF DIFFERENT PROTOCOLS.

Protocol	Year	VN specific	Application	Group	Routing Metric	Optimizations		
						Reliability	Redundancy	Messages Priority
Epidemic Vahdat2000	2000	No	Dissemination	Zero Knowledge	–	–	Multicopy	No
ProPHET Lindgren2003	2003	No	P2P	Contact History	Contact Rate	No	Open	No
MoVe Lebrun2005	2005	Yes	Collect	Geographic Loc.	Direction	No	No	No
Spawn Nandan2005	2005	Yes	Cooperative Download	Geographic Loc.	Distance	No	Fragment Multicoy	Neighbor Dist
Spray&Wait Spyropoulos2005a	2005	No	P2P	Zero Knowledge	–	No	Multicopy	No
MaxProp Burgess2006	2006	Yes	P2P	Zero Knowledge	Conctac Rate	End-End ACK	Multicopy	PRoPHET
RAPID Belasubramanian2007	2007	No	P2P	Zero Knowledge	Contact Rate	No	Multicopy	Contact Rate
SimBet Daly2007	2007	No	P2P	Social	Social Graph	No	No	No
GeOpps Leontiadis2007	2007	Yes	P2P/V2I	Road Map	Nearest Point, ETA	No	No	No
Gil-Castineira2008	2008	Yes	Collect	Zero Knowledge	Direct	No	No	No
POR Li2008d	2008	No	P2P	Zero Knowledge	Distance	No	Multicopy	Distance
DAER Luo2008	2008	Yes	P2P/V2I	Zero Knowledge	Distance	No	Multicopy	Distance
VADD Zhao2008	2008	Yes	P2P/V2I	Online	Loc+Density+Speed	No	No	No
DSCF Kuribayashi2009	2009	Yes	Dissemination	Geographic Loc.	Loc+Connectivity	No	No	No
FFRDV Yu2009	2009	Yes	Dissemination	Geographic Loc.	Speed	Hop ACK	No	No
Infocast Sardari2009	2009	Yes	Dissemination	Zero Knowledge	–	–	Rateless Coding	No
ADPBSW Xue2009a	2009	No	P2P	Contact History	Contact Rate	No	No	No
Adv. ProPHET Xue2009	2009	No	P2P	Contact History	Contact Rate	No	No	No
Extended GeOpps Leontiadis2010	2010	Yes	Cooperative Download	Road Map	GeOpps+Estimated Route	No	No	No
C-DTN Chen2010a	2010	Yes	Dissemination	No Data	No Data	Open	Open	–
DvCast Tonguz2010	2010	Yes	Dissemination	Connectivity	Loc+Connectivity	No	No	No
ROD Cherif2010	2010	Yes	Dissemination	Connectivity	Loc+Connectivity	No	No	No
Uv-Cast Viriyasitavat2010	2010	Yes	Dissemination	Connectivity	Loc+Connectivity	No	No	No
ProPHET+ Huang2010	2010	No	P2P	Contact History	Buffer+Power+Contact Rate	No	No	No
DRTAR Wang2010	2010	Yes	P2P/V2I	Road Map	Loc+Density+Speed	No	No	No
GeoDTN+NAV Cheng2010	2010	Yes	P2P/V2I	Geographic Loc.	GPCR+GeOpps	No	No	No
Nakamura2010	2010	Yes	P2P/V2I	Road Map	Nearest Point	No	No	No
SADV Ding2010	2010	Yes	P2P/V2I	Online	Loc+Density+Speed	No	No	No
D-Greedy D-MinCost Skordylis2011	2011	Yes	Collect	Online	Nearest Point/VADD like	Hop ACK	No	No
SERVUS Gotcitz2011	2011	Yes	Dissemination	Geographic Loc.	Loc+Connectivity	Hop ACK	Multicopy	No
DTFR Sidera2011	2011	Yes	P2P	Hybrid	S&W+Location	No	Multicopy	No
Orion Medjiah2011	2011	No	P2P	Hybrid	Distance+Contact Rate	No	No	No
RENA Wen2011	2011	Yes	P2P	Hybrid	Contact rate+S&W	No	No	No
GeoSpray Soares2011	2011	Yes	P2P/V2I	Hybrid	S&W+GeOpps	No	Multicopy	No
DSRelay	2012	Yes	Cooperative Download	Distance	Direction on Highway	No	No	No
Trullols-Cruces2012	2012	Yes	Cooperative Download	Online	Predicted Contacts	No	Fragment Multicoy	No
CAN DELIVER Mershad2012	2012	Yes	P2P	Online	Nearest Point	End-End ACK	Multicopy	No
RWR Zhu2012	2012	No	P2P	Hybrid	Distance+RSU	No	No	No
CSM Wang2013	2013	Yes	Collect	Data Agregation	Geographic Location	No	Yes	No
MSDP Tornell2013c	2013	Yes	Collect	Road Map	Nearest Point+Buffer	Hop ACK	Fragment Redundancy	No
ZOOM Zhu2013	2013	Yes	P2P	Social	Social Graph + Contact Rate	No	No	No

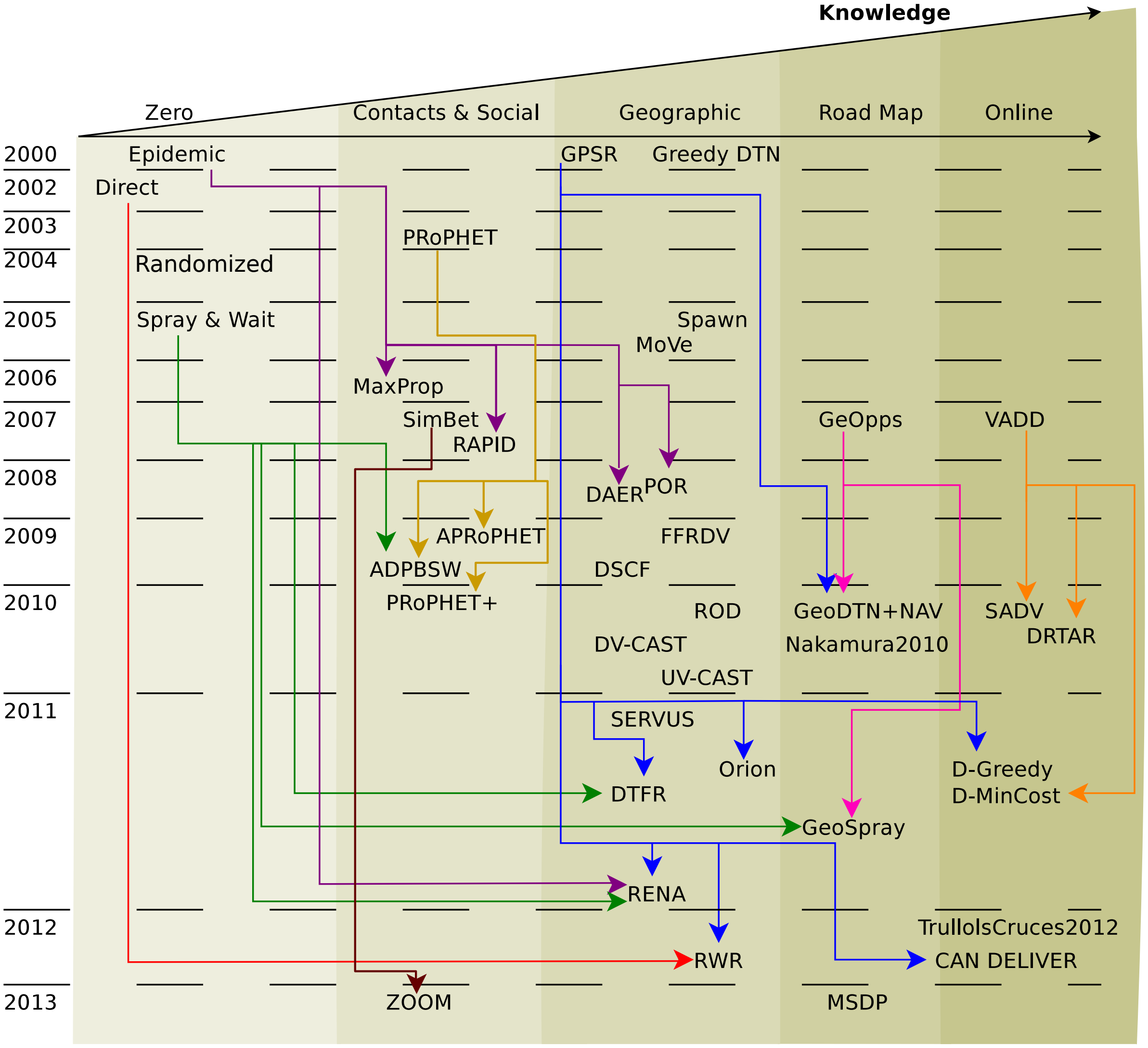
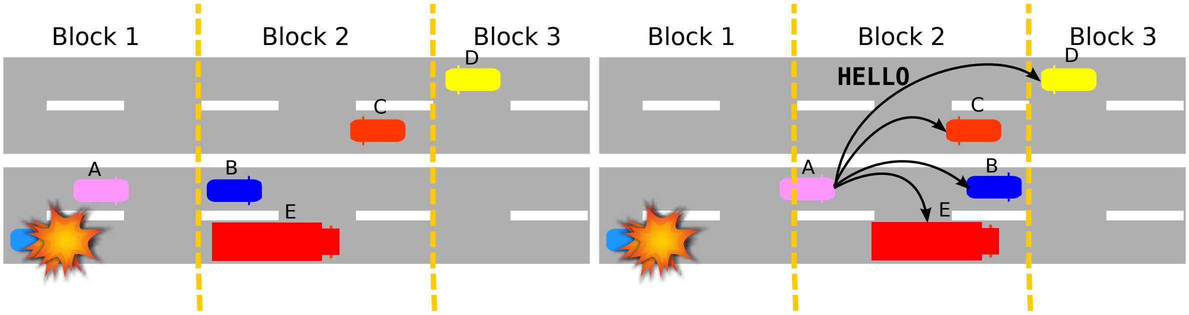


Fig. 5. Protocols ordered chronologically, grouped by knowledge required. Protocols at the end of the arrows are an evolution of the protocol at the beginning of the arrow.

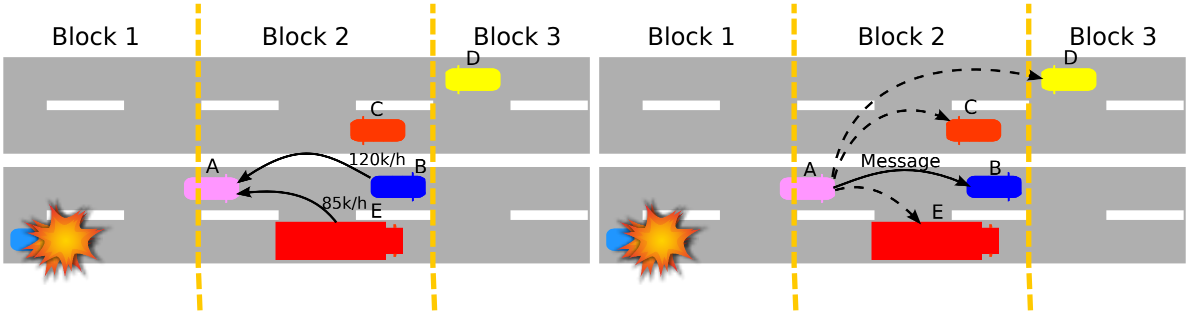
1) Epidemic Protocol: The simplest DTN dissemination protocol is the Epidemic protocol [24], which consists of sharing all the messages in the nodes' buffers every time a contact occurs. The Epidemic protocol needs a *negotiation phase* to determine which messages to share, increasing the delay and generating more overhead than the non-DTN proposals. In dense networks this *negotiation* traffic may be even bigger than data traffic. Moreover, the Epidemic protocol neglects the opportunity of a node *overhearing* a message from broadcast transmissions between neighbors. The Infocast protocol [34] extends the Epidemic protocol with fragmentation and coding, to give better performance.

2) Geographic & Connectivity Protocols: Within this category we include DTN dissemination protocols that need information on node location. This information can be used to limit the number of messages exchanged by nodes and to estimate the connectivity of the network in order to choose the best possible candidate as the new carrier. This carrier will bring the message to the next cluster. The protocols matching this definition are: Directional Store-Carry-Forward (DSCF) [35], Fastest Ferry Routing in DTN-enabled Vehicular Ad-Hoc (FFRDV) [36], Road Oriented Dissemination (ROD) [37], Urban Vehicular BroadCast (UV-CAST) [38], Distributed Vehicular BroadCast (DV-CAST) [39], and SERVUS [40].

- The **DSCF** protocol [35] requires every node to have 2 different antennas. It works by following three simple rules; *i)* messages received from one direction are transmitted in the opposite direction, *ii)* if there are no vehicles in the propagation direction, the message is stored in the buffer until a new neighbor appears, and *iii)* any duplicated message is ignored. Apart from the requirement of having two interfaces, which is not considered in the WAVE standard, when several nodes rebroadcast they will probably collide when accessing the channel. Moreover, it is limited to highways, where the propagation direction is clearly defined.



(a) T1: An event is detected and node A becomes a carrier. (b) T2: Node A enters a new block and broadcasts a beacon.



(c) T3: Only nodes moving away from the event answer the beacon.

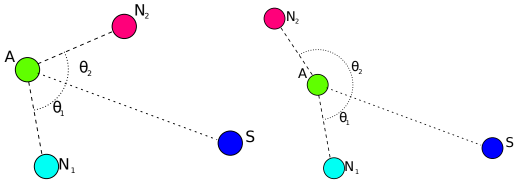
(d) T4: Node B is chosen as the new carrier, it will broadcast a beacon as soon as it enters block 3.

Fig. 6. FFRDV example

- The **FFRDV** protocol [36] assumes that vehicles are moving on a highway. It divides the road into small blocks, and, when an event occurs, the first vehicle passing by generates a message and becomes its carrier. The carrier broadcasts a beacon message every time it enters a new block. Neighbors inside the same block answer the beacon message with information on their speed and moving direction. Then, the fastest vehicle moving towards the propagation direction is chosen to become the new carrier, while the remaining nodes overhear the message. If no neighbor answers to the beacon, the carrier keeps it in its buffer until the next block. It is clear that, besides the connectivity of the network, the propagation delay depends on the size of the blocks. Moreover, since the FFRDV is invalid for city environments, it must be complemented by other dissemination protocols. Figure 6 depicts the behavior of this protocol.

As long as the network is connected, multi-hop forwarding protocols disseminate information faster than store and carry protocols. To take advantage of this characteristic, several protocols use the multi-hop forwarding scheme until they detect a disconnected network. Then, they use geographic information to choose several carriers that will carry the message further.

- The **ROD** protocol [37] does not need nodes to periodically send beacon messages. When a node receives a message from another node, it decides whether to retransmit it according to its relative position with respect to the sender. This phase of the protocol is similar to the Distance Defer Transmission (DDT) protocol [41]. If a node detects that none of its neighbors rebroadcasted a message, it switches to *store-carry and forward* mode. In this mode, the node periodically rebroadcasts the message until it detects that another node has also received and rebroadcasted the message.



(a) (b)

Fig. 7. UV-CAST example: in a) node A switch to SCF mode while in b) does not.

- The **UV-CAST** protocol [38] defines a Region of Interest (ROI) where the message must be disseminated. The main difference between UV-CAST and ROD lies in how they choose the carrier nodes. While in ROD the selection is only based on overhearing messages from neighbors, UV-CAST nodes use their geographic location information to determine wheter they are boundary nodes for the source node's connected region. To determine if a node must switch to *store-carry and forward* mode UV-CAST follows this process. Suppose node A receives a message from the source (S), with N neighbors (N_i) (Fig. 7): *i)* it calculates the angle θ_i between $\overrightarrow{AS}$ and $\overrightarrow{AN_i}$, *ii)* if the sum of the smallest and largest angles is less than π, A must switch to *store-carry and forward* mode. Once in *store-carry and forward* mode, the node will rebroadcast the message and switch to normal mode as soon as a beacon from a new neighbor is received.
- The **DV-CAST** protocol [39] is another example of a highway-limited protocol. As in ROD, nodes are grouped into clusters, and they switch between *normal* and *store-carry and forward* modes according to

the estimated connectivity. DV-CAST defines three different operation modes, *well connected neighborhood*, *sparsely connected neighborhood*, and *totally disconnected neighborhood*. In the first mode, nodes work in *normal* mode; in the second mode, nodes switch to *store-carry and forward* when they move contrarily to the message source and, finally, in the third mode, nodes always switch to *store-carry and forward* mode.

- The **SERVUS** protocol [40] follows a similar approach, where nodes modify their behavior according to the location of their neighbors. In SERVUS, nodes detect whether they are the last node of a group of connected nodes, called a cluster, and then rebroadcast previous messages when they contact a new node from outside the cluster. In SERVUS, cluster detection is only based on the geographic location of neighbors obtained from periodic beacons.

To conclude, in all these protocols, to choose the next carrier node the algorithms assume that all the nodes in the neighborhood have the same information and, therefore, they depend greatly on the correctness of the neighbors list, which can be easily compromised by a high loaded channel and high mobility. Moreover, the calculation of angles and relative locations may be affected by the variability of heterogeneous Global Positioning System (GPS) devices.

B. Unicast Protocols

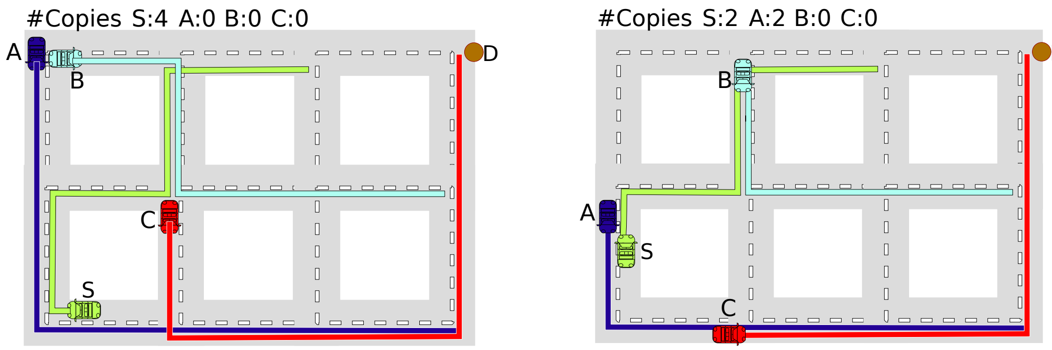
Besides pure unicast protocols, we have included in this category those anycast protocols where the destination is any of the RSUs present in the VN, since they are reduced to unicast by choosing the closest RSU as the destination.

The first subgroup inside the unicast protocols category is formed of protocols that do not need any external source of information; we call these **Zero Knowledge** protocols. A much larger group includes protocols that estimate the utility of each transmission, *i.e.* how a transmission improves the probability of reaching the destination to determine the best forwarding node among neighbors. For the sake of clarity, we will discuss the **Utility Based Protocols** in a separate subsection (III-C).

Under the Zero Knowledge category we have included protocols that do not need any external source of information, or to collect information while they are running. As a result of this limitation, their performance is usually surpassed by utility based protocols. Most of them were designed for intermittently connected MANETs [1], but are usually used as a reference for comparison with VDTN protocols. The protocols included in this category are: *Direct* [42], *Randomized Routing* [43], Epidemic [24], and Spray&Wait [44].

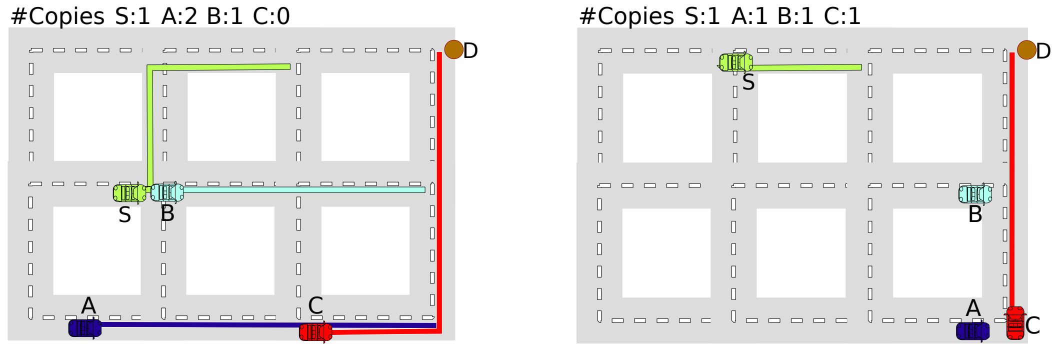
- The **Direct** is the simplest possible protocol [42]. It works as follows: a node A forwards a message to a node B only if B is the destination. This case presents an unbounded delay but it has the advantage of performing only a single transmission per message. It represents an upper bound for delay and a lower bound for delivery ratio.
- The **Randomized Routing** protocol was presented in [43]. It works as follows; node A forwards a message to another node B, which A finds with a given probability p. In its work, authors showed that random routing behaves better than direct routing.

- The **Epidemic** protocol [24] has also been applied to the unicast problem. As long as enough resources are available, the Epidemic protocol guarantees that messages will eventually arrive at their destination along the shortest path. Therefore, under ideal conditions, the Epidemic protocol provides a lower bound for delay and an upper bound for delivery probability. The main problem of the epidemic protocol is that it wastes resources by propagating copies of messages that have already been delivered, and along paths that will never reach the destination. In order to limit this resource wastage, researchers have proposed several modifications to the original Epidemic protocol. In [45], authors presented four different mechanisms to block the propagation of already-delivered messages. In [46], nodes exchange a copy of the messages with a probability smaller than 1, which reduces the number of copies in the network. Protocols such as MaxProp [30], RAPID [47], POR [48], and DAER [49] add message priority management techniques to make the most of every contact. We will go into detail about these techniques in Section III-D.



(a) T1: S generates a message for D.

(b) T2: S sends a copy to A.



(c) T3: S sends a copy to B.

(d) T4: A sends a copy to C, which will finally deliver it to D.

Fig. 8. Binary Spray and Wait example

- The **Spray&Wait** protocol [44] divides the propagation of messages into two different phases. Initially it disseminates a certain number of copies of a message to neighbor nodes and then it waits until any of the carrier nodes moves and reaches the destination of the message. Several spraying mechanisms were presented and studied in [44], where the Binary Spray & Wait (BS&W) protocol offered the best results. In the BS&W

protocol, the source of a message initially starts with L copies. Any node A that has $n > 1$ message copies (source or carrier) and encounters another node B (with no copies) hands $\lfloor n/2 \rfloor$ copies over to B and keeps $\lceil n/2 \rceil$ for itself. When only one copy is left, it switches to direct transmission. Figure 8 shows this behavior.

In the following subsections we will go into detail as to how some authors adapted these *zero knowledge* protocols to turn them into utility based protocols, as seen for example in [50] and [51].

Since the protocols included in this category do not consider any type of external information, they are suitable for environments where we cannot make any assumption about mobility models, road maps, or social relationships. However, in VDTNs we typically find better alternatives because mobility is restricted to the road network, vehicles are driven following certain rules and people usually live in communities.

C. *Utility Based Protocols*

We define the utility function as a function that combines several parameters to obtain an index that estimates how a transmission would increase the probability of reaching the destination of a message (hereafter called the Utility Index). In some protocols the utility function can be as simple as the distance to the destination, while in others it may combine several parameters from different sources of information. In this section we classify utility-based protocols into five different categories according to the type of knowledge they need to obtain the required parameters to calculate the utility index: *i)* **contact history & social relationships**, *ii)* **geographic location**, *iii)* **road map**, *iv)* **hybrid** protocols and *v)* **online** protocols.

1) Contact History & Social Relationship Protocols: The protocols included in this category work under the assumption that the probability of a node meeting the destination node of a message can be estimated based on the history of previous contacts. Although most of them were developed for MANETs, and are mainly applicable to wildlife tracking systems [18] or pedestrian communities [52] (where this *frequent contacts* paradigm seems to clearly apply), these protocols have been extensively used for comparison with VDTN protocols. In this category, we find the following protocols: PRoPHET [25], APRoPHET [53], PRoPHET+ [52], ZOOM [54], and SimBet [55].

- **PRoPHET**, which was the first *contact history based* protocol, was presented in [25]. This protocol relies on a self-defined *delivery predictability metric*, $P \in [0, 1]$, which is updated according to Equation 1, where $P_{(a,b)}$ is the *delivery predictability* that node a has for node b, and P_{init} is an initialization constant. Note that, nodes experiencing frequent encounters have a higher *delivery predictability*.

$$P_{(a,b)} = P_{(a,b)_{old}} + (1 - P_{(a,b)_{old}}) \times P_{init} \tag{1}$$

  The defined *delivery predictability* ages (decreases its value) when two vehicles do not meet for a while. PRoPHET also defined the transitivity property for the *delivery predictability*, *i.e.* if node a frequently encounters node b, and node b often encounters node c, node a is a *good* node to forward messages to c. To grasp this behavior, the *delivery predictability* metric is updated in line with Equation 2, where β is a constant that quantifies the impact of the transitivity on the *delivery predictability* metric.

$$P_{(a,c)} = P_{(a,c)_{old}} + (1 - P_{(a,b)_{old}}) \times P_{(a,b)} \times P_{(b,c)} \times \beta \tag{2}$$

- The **Advanced PRoPHET** protocol was presented in [53]. It modifies the PRoPHET protocol's metric to smooth its variability. The main effect of the smoothed variability is that the protocol needs more time to react to changes in the network.
- In [52], authors presented **PRoPHET+**, another improved version of the PRoPHET protocol that adds four new parameters related to *i)* buffer (V_B), *ii)* power (V_P), *iii)* popularity (V_O), and *iv)* bandwidth (V_A). Using Simple Additive Weighting, the utility function is defined as follows:

$$V_d = W_B(V_B) + W_P(V_P) + W_A(V_A) + W_O(V_O) + W_{PRoPHET}(V_{PRoPHET}) \tag{3}$$

Where W_i refers to weight factors that must be configured by the users and whose optimal value depends on the scenario. Their results showed that, by considering more variables and not only the contacts history, the performance of PRoPHET is improved. They also proved that a misconfiguration of weight factors may degrade the performance of the protocol.

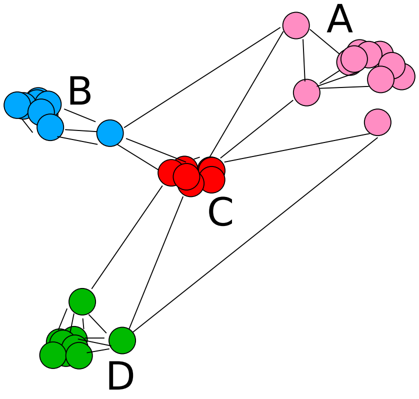


Fig. 9. Social graph: nodes inside cluster C are connected better than nodes in others clusters.

- In [54] and [55], authors presented **ZOOM** and **SimBet**, which use *social metrics*, such as 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. Figure 9 shows an example of the relationships inside a community. Nodes from cluster C are better connected than nodes from other clusters, meaning that, those nodes are better carriers.

These routing schemes require a nearly-closed community to be effective: new nodes, which do not have previous contacts, seem to be isolated, and nodes that left the network, which had a long contacts-history, seem to still

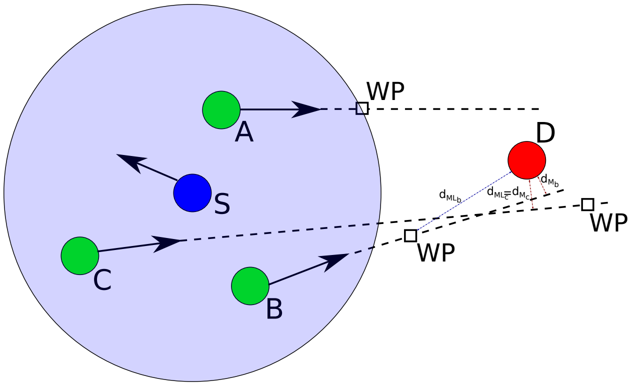


Fig. 10. In MoVe, only the direction is taken into account to choose the next forwarding node, while in MoVe-Lookahead the way-points are also considered. Therefore, when using MoVe, node S will choose node B to forward a message to D, while it will choose node C when using MoVe-Lookahead.

belong to it for a long time after leaving. Since a high mobility and a highly changing membership are among of the main characteristics of VNs, the protocols studied in this section may tend to select old routes. Moreover, several authors have shown that the average inter-contact time, when applied to VNs, is in the order of several hours or even days [54], [56]. Since the inter-contact time is closely correlated to the *expected delay to destination*, the applications running on top of one of these protocols should expect an end-to-end delay in the order of hours. Finally, when using *social metrics*, the relationships between the nodes need to be carefully analyzed before full deployment, which presents scalability and privacy issues.

2) Geographic Location Protocols: Protocols included in this subsection assume that each node is aware of its location and its moving direction. Although we found only two examples of protocols related to VNs that match this exact definition, we decided to create a new category since these can be considered the ancestors of more advanced protocols that, beside location and direction, use other sources of information. Those protocols are Greedy-DTN and MoVe [57].

- The **Greedy-DTN** protocol is closely related to the most referenced geo-assisted routing protocols in literature, GPSR [58] and GPCR [59], which are not delay-tolerant protocols. In GPCR/GPSR messages are forwarded greedily towards the destination, *i.e.*, the best forwarding neighbor is the one closest to the destination. When a message reaches a local minimum, where no neighbor is closer to the destination, it is routed in *perimeter mode* in an attempt to find a new route. GPSR is generally adapted to DTN omitting the *perimeter mode* and carrying the message inside the buffer until a better forwarding node to forward the messages appears. From now on we will refer to this adapted version of GPSR as **Greedy-DTN**. Greedy-DTN has been widely used as a reference for comparison with more sophisticated DTN protocols [10][60].
- **MoVe** [57] is a protocol that estimates the future location of the nodes using their current direction of movement. In MoVe, the node whose estimated trajectory is the closest to destination becomes the best forwarding node.

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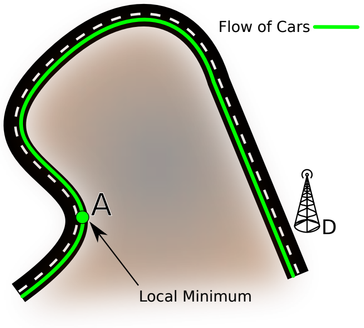

Fig. 11. When using geo-routing, if a constant flow of vehicles exists, messages for D could get stuck in A because there is a permanent local minimum.

> A modification of MoVe, called *MoVe-Lookahead*, uses the location of the next *waypoint* (authors assumed the random waypoint mobility model) to predict the mobility of the nodes and avoid forwarding messages to nodes that will change their direction before arriving at the closest point to destination. Figure 10 shows an example where node B is the best forwarding node when using MoVe, while C would be the best forwarding node when using MoVe-Lookahead.

These approaches are suitable for unrestricted mobility models, but ignore the fact that mobility in vehicular networks, despite its high variability, is constrained to roads. Therefore, these proposals are prone to inducing suboptimal routing decisions. For example, the Greedy-DTN protocol may get blocked when a constant flow of vehicles generates a permanent local minimum, as illustrated in Fig. 11. Besides, loops occur when two vehicles moving in opposite directions meet. In the case of MoVe, it assumes a random-waypoint model for node movements, ignoring the fact that the current direction of vehicles, especially in downtown or rough rural areas, may change frequently and that it may not match the *long term direction of movement*.

Another problem of geo-assisted protocols is that they require a location service to obtain the destination's location. However, authors usually ignore this requirement. Without a location service, protocols are limited to V2I communication. This problem also affects Road-Map protocols, which are covered in the next subsection. The design of a location service is far from trivial and is outside the scope of this survey.

3) Road Map Protocols: Since vehicular mobility is always restricted to roads, the use of pure geographic protocols, such as Greedy-DTN or MoVe, can lead to messages being forwarded to vehicles whose *long term destination* is far from the destination of the message. The *long term destination* is important in the case of sparse networks, where vehicles rarely meet. Protocols included in this section assume that vehicles have a Navigation System (NS) that provides information on the road layout and the vehicle's future route, besides an accurate geographic location. The protocols included in this category are: GeOpps [10], and its extension [61], the protocol presented in [62] and the Map-based Sensor-data Delivery Protocol (MSDP) [60].

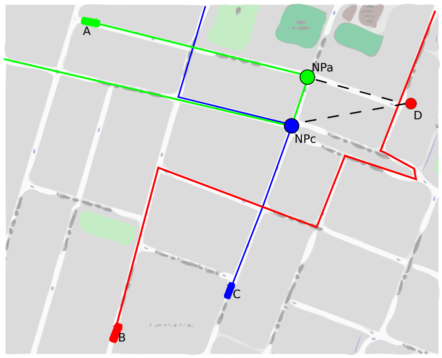

Fig. 12. Calculation of the NP in GeOpps. Although NP_B is closer to the destination than NP_A and NP_C, A and C nodes are probably better forwarding nodes, since they will reach their NPs faster than B.

- The **GeOpps** protocol chooses the next-forwarding nodes based on the Minimum Estimated Time of Delivery (METD) metric, which is the sum of: *i)* the estimated time that a vehicle would need to reach the nearest point (NP) of its route to the destination, plus *ii)* the time a vehicle would need to travel from the NP to the final destination. If the latter factor cannot be calculated, an estimation based on the straight distance can be used [10]. Fig. 12 shows an example of the NP calculation.

  GeOpps was extended to support traffic from RSU to vehicles [61] by routing the reply message to a point inside the vehicle's route, and then backwards on the vehicle's path until the destination is reached.
- The protocol presented in [62] simplifies GeOpps by ignoring the speed of the vehicle, and selecting the vehicle whose route passes closest to the destination as next carrier.
- **MSDP** is another protocol that uses the programmed route and the road layout to estimate the time required to reach the destination [60]. It also takes into account the reliability of the programmed route, giving priority to reliable nodes with fixed routes like buses or taxis over private vehicles which might modify their routes.

These protocols emphasize the store-carry phase, missing multi-hop communication opportunities, which increases the delay. Moreover, they depend heavily on the reliability of programmed routes, which may present vulnerability.

4) Hybrid Protocols: In this category we include protocols that combine the behavior of several protocols from those expounded previously. The protocols we find are: Average Delivery Probability Binary Spray and Wait (ADPBSW) [50], GeoDTN+Nav [63], Orion [64], GeoSpray [51], Delay Tolerant Firework Routing (DTFR) [65], REgioN-bAsed (RENA) [66], and RWR [67].

- **ADPBSW** [50] combines the PRoPHET protocol with the BS&W protocol. It was originally designed for MANETs and is the first proposed hybrid protocol for DTNs. It complements the Spray & Wait protocol by using the *delivery probability* calculated by PRoPHET to propagate copies only to vehicles experiencing a *delivery probability* higher than the current carrier.
- **GeoDTN+Nav** is a protocol that divides the process of delivering a message into two different phases [63].

During the first phase it uses GPCR to forward the message near to the destination. Once a local maximum is reached, the protocol switches to perimeter mode. Contrarily to GPCR, in GeoDTN+Nav, after a certain number of hops in perimeter mode, the protocol switches to DTN mode, and the message is delivered using the GeOpps protocol. The vehicle switchs back to GPCR phase if it finds a neighbor closer to the destination than the previous local maximum that triggered the switch to DTN mode.

- Similar to GeoDTN+Nav, the **Orion** routing protocol [64] combines the Greedy-DTN protocol with a contact history based protocol. Therefore, messages are forwarded greedily until a local maximum is reached. Afterwards, the message is scheduled to be forwarded to the vehicle with the highest delivery probability.
- The **GeoSpray** routing protocol [51] combines the S&W multi-copy scheme with the GeOpps protocol. Similarly to S&W, L copies of every message are distributed through the network. Then, instead of waiting until carriers arrive to the destination, the copies are propagated using GeOpps.
- The **DTFR** protocol [65] forwards a message to the destination greedily. However, the *target destination* differs from the actual destination of the message. The *target destination* depends on the phase of the protocol and changes step-by-step, combining phases similar to S&W with pure Greedy-DTN phases. If, at any time during any of the phases, a vehicle finds a path to the destination, it uses that path to deliver the message.

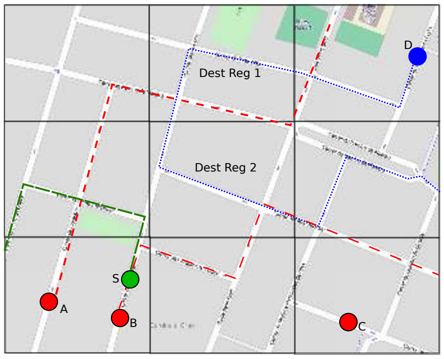

Fig. 13. RENA: To send a message from S to D, two copies will be sent to A and B, which will later distribute them in the destination regions.

- The **RENA** protocol [66] combines the Spray & Wait and Epidemic protocols. It divides the map into regions and calculates the probability of moving between them for every vehicle. Additionally, it estimates the probability of being inside a given region for every node. Then, the routing process is divided in four phases. When a message is generated, *i)* it distributes n copies to vehicles that will probably travel to regions where the destination vehicle is likely to be located, *ii)* those copies are forwarded to vehicles that have a better probability of reaching the destination region than the current carrier, *iii)* once the message has arrived at the destination regions, m copies are distributed to vehicles with a low probability of leaving the region, and *iv)* these copies are forwarded to vehicles with a smaller return time to the destination region until the destination is found. The main advantage of RENA, when compared with other replication mechanisms, is that RENA limits the replication of the messages to the destination regions. Figure 13 illustrates this behavior.

- Finally, **RWR** [67] combines pure multi-hop geo-routing with an alternative where messages are delegated to an RSU. It estimates the expected delay of a message using GPCR and using RSU delegation to choose between these two alternatives.

The protocols included in this section have the advantages and some of the disadvantages of the combined protocols. For example, GeoDTN+Nav benefits from the typical low delay of GPCR for multi-hop routing and the low message loss ratio of DTN, but consumes more resources than GeOpps; GeoSpray, probably performs better than its predecessors, the original GeOpps protocol and BS&W, at the cost of consuming more resources; and RENA is clearly expected to waste fewer resources than epidemic routing. However, their implementation is complicated and depends on many user-defined parameters, which may lead to incompatibilities.

5) Online Protocols: Under the name of *Online Protocols* we have included protocols that need information on the current state of the road network, for example, number of nodes, average speed of the nodes, and congestion of every road. Some of them are also hybrid protocols that combine these new metrics with modifications of protocols we have previously reviewed. The list of protocols included in this section is: Vehicle-Assisted Data Delivery (VADD) [9], Static-Node-Assisted Adaptive Data Dissemination in Vehicular Networks (SADV) [68], Distributed Real-time Data Traffic Statistics Assisted Routing (DRTAR) [69], D-Greedy and D-MinCost [70], the protocol presented in [71], and CAN DELIVER [72].

- In [9], authors presented **VADD**, which allows vehicles to send messages to an RSU. The routing process in VADD is divided in four steps; *i)* it estimates the travel time of a message for each road taking into account the vehicles density of the road, its length and the duration of traffic lights. Then *ii)* it calculates the shortest path to the destination using Dijkstra, *iii)* it routes messages between road intersections using the Greedy DTN protocol and finally *iv)*, when a threshold distance to the destination is reached, it routes messages using GPSR [58]. Every node traversed by the message recalculates steps i and ii. To obtain information on road density, duration of traffic lights, maximum speed of roads, etc, required in step i, a database containing this information is preloaded. The authors presented three variations of VADD that differ on how they route messages inside crossroads. L-VADD routes messages based on location, while D-VADD uses the direction of the vehicles. H-VADD combines L-VADD and D-VADD, switching from the first to the second when a loop is detected. The main problem of VADD is that it clearly tends to use the most heavily populated roads, which may congest the network.
- The **SADV** protocol [68] complements the VADD protocol by installing static nodes at intersections. It routes packets like VADD, although inside intersections, when no vehicle in the shortest path is found, the message is stored in static nodes until a vehicle in the shortest path appears. A more general, but similar, architecture, where the routing protocol between static nodes is not specified, was proposed in [73]. From our point of

view, inside cities, the increase in cost from backbone-disconnected static nodes to fully-connected RSUs is negligible compared with the deployment cost. Therefore, we believe that once static nodes are deployed, it is a better option to connect them to the backbone than to simply use them as static relays.

- The **DRTAR** protocol [69] is similar to VADD, but it uses a distributed data traffic statistics service to obtain information on road status. In addition, in DRTAR, the shortest path is only calculated by the first node, which attaches it to the message. The shortest path is then only recalculated when the current carrier cannot find a neighbor inside the attached shortest path. Other authors have also proposed different distributed data traffic statistics services [74], which show the feasibility of this approach.
- In [70], authors presented **D-Greedy** and **D-MinCost**, two DTN protocols for traffic-monitoring in vehicular networks. As far as we know, this is the first paper to introduce a routing protocol that does not try to minimize the delay from source to destination, but minimizes the consumed resources while ensuring that the collected information meets certain maximum delay requirements. Authors defined two operation modes, multi-hop forwarding (MF) mode and the DTN mode (DM). During MF mode messages are forwarded using Greedy-DTN through the shortest path to destination, while in DM mode messages are only forwarded at intersections to keep them inside the shortest path when the current carrier moves away. The only difference between D-Greedy and D-MinCost is that, in the former, only local and map layout information is available, while in the latter the current road status information is also available. Therefore, D-Greedy calculates the shortest path to destination based solely on road lengths, while D-MinCost also takes into account the road's vehicle density, like VADD. Once the shortest path is calculated, both protocols estimate the delay of the message using MF, as well as DM. Afterwards, it uses the DM as long as its estimated delay is less than the Time To Live (TTL), switching to MF in all other cases. Since MF mode is much faster than DM, both modes tend to alternate, thereby minimizing the number of hops to the destination.
- In [71], authors presented a routing protocol for delivering data from RSUs to vehicles. In their protocol vehicles make requests while they are connected to an RSU. The answers are usually larger than the requests and, therefore, cannot be downloaded during the period while they are connected. Authors proposed the use of other vehicles to deliver the answers to the destination vehicles. They assumed that all RSUs are connected via a backbone network, and that, based on empirical data, contacts between vehicles can be predicted. With this information, their protocol uses other vehicles as carriers for answers.
- The **CAN DELIVER** [72] protocol allows for the routing of messages from vehicles to 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 own route and speed to the message. Then, the message is forwarded between the intersections using the Greedy DTN protocol. In the latter case, RSUs try to estimates the vehicle's location using the information from the vehicle previously attached to the message. Once the future location is estimated, an area around it is defined, and the reply message is forwarded to it using a scheme that combines the S&W

multi-copy scheme with the Greedy-DTN forwarding metric. When the message reaches the estimated area, vehicles switch to a limited epidemic mode and broadcast the message inside that area. To avoid broadcast storms, vehicles only broadcast each message once. If a vehicle outside the estimated area receives a message from inside it, it must be dropped.

These protocols require a complex platform formed by RSUs, information servers, databases, etc., increasing the implementation and deployment cost. Moreover, they depend on real-time information, which is easily available in simulations but can be difficult to obtain in real implementations.

D. Common Basic Mechanisms

Our DTN protocol taxonomy is based on the criteria used to select the next forwarding node, also called the routing metric. However, this is not the only element that can make a difference in the performance of different protocols. A set of mechanisms that define the hop-by-hop and the end-to-end communication schemes can heavily influence the delivery ratio, the delay or other performance metrics. Generally, these mechanisms can be applied to any utility based protocol. In this section we cover the most representative mechanisms available in the bibliography addressing: reliability, redundancy, path diversity and message priority. We introduce these concepts, provide some examples of protocols that use them and measure their impact on performance.

1) Reliability: The reliability of a protocol is the degree of guarantee that the protocol provides to the sender with respect to the delivery of messages. The typical mechanism used to provide *end-to-end* reliability in non-DTN networks is the use of ACK messages to confirm that messages are correctly received. VDTN protocols use *hop-by-hop* reliable mechanisms. By using *hop-by-hop* ACK messages, the protocols ensure that a message will be kept in the buffer of the vehicle until another vehicle confirms its reception. This mechanism does not explicitly ensure the reception of the message by its destination, but it does ensure that a message will eventually reach its destination if no node failure occurs (node shutdown or buffer overflow). Most of the protocols covered in this survey simply ignore the impact of reliability. Those that consider and use it are: DTFR [65], D-Greedy and D-MinCost [70], CAN DELIVER [72] and MSDP [60].

The impact of *hop-by-hop* ACKs increases with the number of hops. For example, if a message traverses 6 hops and the Packet Error Rate (PER) is 10^{-1} (quite optimistic in wireless communications [75]), the *end-to-end* PER would be $1-(1-10^{-1})^6 = 0.46$, which is an unacceptable value. Since the PER increases with the distance between transmitters, protocols that tend to select the furthest node as the forwarding node, face higher transmission losses and can heavily benefit from the use of *hop-by-hop* ACKs. Obviously, the use of ACKs increases both the load of the channel and the delay experienced by the messages but, from our point of view, it is a small price to pay compared with its advantages.

Since there is not a specific *destination* in dissemination protocols, the concept of *reliability* changes. In dissemination protocols we consider reliability as the capability of the protocol to guarantee that at least one of the nodes inside the ROI will disseminate the message until it expires. This feature is usually implemented as follows: *i)* the current carrier broadcasts the message, *ii)* after broadcasting the carrier keeps sniffing the channel to check if a neighbor has rebroadcasted it, *iii)* the transmission confirmation is implicit when a neighbor has rebroadcasted the message. All of the dissemination protocols included in this survey implement this mechanism.

2) Fragmentation and Redundancy: The objective of fragmentation is to provide flexibility to routing. In VDTN, the duration of the contacts limits the amount of data that two nodes can exchange. When a connection between two nodes breaks, the message being transmitted has to be discarded by the receiver and enqueued again by the transmitter, thus wasting the resources used for that transmission to date. In the case of messages of a large size, the amount of wasted resources can be high.

The use of fragmentation allows for redundancy fragments to be added using Forward Error Correction (FEC) techniques. This means that, if a message needs N fragments, $N * \alpha$ fragments will be sent, where the redundancy factor alpha is greater than 1 and depends on the configuration. At the destination, only N fragments are needed to reassemble the original message. This type of redundancy is usually called *coding*, and it reduces the impact of possible losses. The cost of coding depends on the amount of extra fragments sent. Fragmentation and coding only appear in two of the protocols we have reviewed, which are CAN DELIVER [72] and MSDP [60].

A more aggressive type of redundancy consists of sending multiple copies of the same message. This mechanism is much simpler than coding, but it also consumes more resources. Moreover, it does not solve the problems arising from large-sized messages. This redundancy mechanism is much more common and is used in the following protocols: Epidemic [24], PRoPHET [25], Spray&Wait [44], MaxProp [30], RAPID [47], DAER [49], POR [48], ADPBSW [50], DTFR [65], GeoSpray [51], RENA [66] and CAN DELIVER [72].

3) Message Priority: By message priority we refer to the order in which messages are forwarded to another node when a contact occurs. This is important, as the duration of contacts is limited. In the bibliography, some protocols have extended the Epidemic protocol to consider message priority: MaxProp [30] and RAPID [47] prioritize those messages with a better transmission delivery probability according to PRoPHET, while POR [48] and DAER [49] prioritize those messages that will get closer to their destination. Although we were unable to find more examples of this mechanism, it may be implemented to complement and improve the performance of any protocol.

IV. EVALUATING DTN PROTOCOL PERFORMANCE IN VANETS

Since developing and conducting real implementation and tests for VNs is an expensive task in terms of time, personnel and money, researchers have focused on simulations to evaluate and compare the performance of different protocols. However, on analizing the reviewed articles, we have found a balanced mix of different simulation models that complicates the comparison of results. Moreover, very rarely do works evaluate the same metrics under the same scenarios, which totally invalidates any comparison among results from different papers.

Table II summarizes the contents of this section. The second column shows the different metrics measured during the evaluation of each proposal. The third column specifies the simulator used for this evaluation. The fourth and fifth columns contain the MAC and radio channel models they used. The sixth column briefly describes the

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simulated scenario. Finally, the last column shows the number of DTN protocols compared to justify every new proposal. As stated in Table II, we found that most researchers did not compare their proposal against any other DTN protocol (14 out of 41 papers) and that a large group of researchers compared their proposal against only one previously proposed protocol (12 out of 41 papers). This unfortunate situation is a consequence of the mix of available simulation models, as well as the commonly vague description on low-level protocol details, as already explained in Section III-D. Moreover, researchers do not usually offer the source code of their proposals, which complicates the replication and validation of their experiments.

In this section, we first list the metrics evaluated by researchers discussing their relevance. Second, we provide an overview of the models and tools used by the research community to evaluate VDTN protocols and identify the most advanced solutions.

A. *Evaluated Metrics*

When introducing a new proposal, researchers need to justify the performance improvement by comparing metrics among different protocols. We have found that the most commonly evaluated metrics are:

- The Delivery Ratio (DR), which is given by the ratio of the number of successfully received messages and the number of sent messages. Since delivering messages to their destination is the task of a routing protocol, the DR is the most important metric when evaluating such a protocol. However, researchers must find a trade-off between resource consumption and effectiveness.
- The Average Delay (AD), which is given by the average time needed to deliver a message. In DTNs, this metric may be heavily influenced by a small number of high delay measurements and, therefore, its value is not representative of the general behavior of a protocol.
- The Delay Cumulative Distribution Function (DC), which illustrates the distribution of the delay experienced by messages. Since the average delay is heavily influenced by messages experiencing long delays, this measurement gives a better idea of the performance of a protocol.
- The Overhead (O), which measures the amount of extra bytes needed per delivered byte. This is a very important metric when evaluating VDTN protocols because part of the network may become easily saturated.
- The Average Number of Hops (H) traversed by a message. This measurement provides an idea of resource consumption. As a general rule, more hops means more consumed resources. However, fewer hops usually implies longer carrying phases, increasing the average delay of the messages.

Table II includes a column that shows the different metrics evaluated in each paper.

B. *Simulators and Models*

The choice of a certain simulator does not influence the results of simulation studies, but it commonly implies the use of a certain set of models and default values. Through the reviewed papers, we clearly identify a worrying

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TABLE II

EVALUATION OF DIFFERENT PROTOCOLS.

	Measurements	Simulator	Medium Access	Radio & Channel	Simulation Scenario	#Compared
Epidemic [24]	DR AD DC	Ns2	No, only contacts	Fix Distance	Random	0
ProPHET [25]	No evaluation					
MoVe [57]	DR AC DC O	Custom	No Data	No Data	Limited random in city map and traces	1
Spawn [76]	O H	Nab	CSMA/CA Model	No Data	One Direction Highway	0
Spray&Wait [44]	DR AD O	Custom	Sloted Collision Detection	No Data	Random Way Point	2
MaxProp [30]	DR AC H	Custom	No, only contacts	No Data	Real & Synthetic Traces	0
RAPID [47]	DR AD O	Custom	No, only contacts	Fix Distance	Real Traces, Contact Model	1
SimBet [55]	DR DC O H	Custom	No, only contacts	Contacts Traces	Real Traces	2
GeOpps [10]	DR AD DC O H	Omnet++, MF	CSMA/CA Model	Nakagami, No Obst, Interferences	Synthetic Realistic Traces	2
Direct [77]	DR AD DC	Custom	No Data	Fix Distance	RandomWay Point in Grid & Implemented	0
POR [48]	DR AD DC	Custom	No, only contacts	Fix Distance	Real Traces	4
DAER [49]	DR DC H	Custom	No, only contacts	Fix Distance	Real Traces, SUMO	0
VADD [9]	DR AD O	Ns2	CSMA/CA Model	Fix Distance, Interferences	Limited Random in city map	1
DSCF [35]	DC	Custom	No, only contacts	Fix Distance	Grid Map, Random mobility	0
FFRDV [36]	DC	Ns2	No, Only contacts	Fix Distance	Highway, Car Following Model	1
Infocast [34]	DR	Ns2	No Data	Fix Distance	Only 1 road	0
ADPBSW [50]	DR AD	ONE	No, Only contacts	Fix Distance	Limited random in city map	1
Adv. ProPHET [53]	DR AD	ONE	No, Only contacts	Fix Distance	Limited random in city map	1
Extended GeOpps [61]	No Evaluation					
C-DTN [78]	DR AD	QualNet	CSMA/CA Model	Fix Distance, Interferences	Car Following Model in a Grid	0
DvCast [39]	DR DC O	Ns2	No Data	Ricean Fading	Circular High Way	0
ROD [37]	DR	Airplug-ns	CSMA/CA Model	Fix Distance, Interferences	VehicleMobiGen	2
Uv-Cast [38]	DR O	Ns2	CSMA/CA Model	Fix Distance, Interferences	Real City, SUMO	0
ProPHET+ [52]	DR DC	ONE	No, Only contacts	Contacts Traces	Real Traces	1
DRTAR [69]	AD	Custom	CSMA/CA Model	Fix Distance, Interferences	Limited random in city map	0
GeoDTN+NAV [63]	DR AD H	QualNet	CSMA/CA Model	Fix Distance, Interferences	VanetMobiSim	0
[62]	DR O	Custom	CSMA/CA Model	Nakagami, No Obst, Interferences	NETSTREAM	1
SADV [68]	AD O	MatLab	No, Only contacts	Fix Distance	Limited random in city map	1
D-Greedy D-MinCost [70]	DR AD DC O	Custom	No, Only contacts	Fix Distance	Synthetic Realistic Traces	2
SERVUS [40]	DR O	Ns2	CSMA/CA Model	Fix Distance, Interferences	Grid, Random	0
DTFR [65]	DR AD	Custom	Slotted mac	Fix Distance, Interferences	Limited random in city map and traces	3
Orion [64]	DR AD H	Omnet++	No Data	No Data	Random	1
RENA [66]	DR AD	ONE	No, Only contacts	Fix Distance	Limited random in city map and traces	4
GeoSpray [51]	DR AD O	ONE*	No, Only contacts	Fix Distance	Limited random in city map	4
DSRelay [79]	DR	Custom	No, Only contacts	Fix Distance	Highway, Random Speed	1
[71]	DR OM	Custom	Slotted mac	Fix Distance	Synthetic Realistic Traces	0
CAN DELIVER [72]	DR AD DC O	Ns2	CSMA/CA Model	Nakagami, No Obst, Interferences	Real Map, SUMO	3
RWR [67]	DR AD DC	Custom	No, Only contacts	Fix Distance	Real Traces	2
CSM [80]	Error Estimation	Custom	No, Only contacts	Fix Distance	Real Traces	1
MSDP [60]	DR AD DC O	Omnet++,INET	CSMA/CA Model	Nakagami, W. Obst, Interferences	Real Map, SUMO	2
ZOOM [54]	DR AD O	Custom	No, Only contacts	Contacts Traces	Real Traces	3

DR=Delivery Ratio; AD=Average Delay; DC=DelayCDF; O=Overhead; H=Number of Hops trend: 18 works out of 41 used a custom simulator. The use of a custom simulator complicates or almost prevents proper comparison among different proposals. Moreover, it also complicates the peer reviewing system and code reutilization, slowing the developing pace. On the other hand, we have found four different event-driven simulators that have been previously validated and are long-established in the networking community: Ns2 (8 times), The ONE (5 times), OMNeT++ (3 times) and Qualnet (2 times). Below we briefly describe the characteristics of different simulators.

- The Ns2 simulator integrates advanced propagation and channel models (Nakagami fading and shared channel), medium access (CSMA/CA) and mobility models (traces generated using SUMO) [81]. However, only one of the reviewed proposals used the most advanced features of Ns2 [72]. Three of the articles that used Ns2 neglect the effects of propagation and interferences, while remaining articles used a deterministic propagation model combined with an interference model.
- *The ONE* is a contact-oriented simulator[82]. As far as we know, it is the only simulator specifically designed for DTN, speeding up the development and implementation of new protocols. At present, it does not support propagation or channel models and the mobility model is limited to map-constrained random mobility or real traces, although it is easily extendable. Due to its simplicity, *The ONE* is significantly faster than other simulators. We would recommend it for early research stages, to evaluate the logic of different proposals and to test whether they have major drawbacks, such as local minimums where messages get stuck. We believe that *The ONE* may be easily extended to implement car following mobility models and a non-deterministic propagation model.
- Veins [84], for OMNeT++ [83], is currently the most advanced simulation framework for VN simulation. It implements a complex propagation and interference model and a fully featured medium-access model based on the 802.11p standard, with support for advanced driving models provided by SUMO. However, none of the reviewed works used this framework. In [60], authors used the INET framework [85], whose medium access model is limited to 802.11a/b/g. In [10], authors used a framework that was later integrated in the Inet framework. Because of the fine-grain simulation provided by OMNeT++ and Veins, it consumes a lot of resources in terms of memory, CPU and time, making unaffordable simulations with thousands of nodes.
- QualNet is a non-opensource simulator. Therefore, the correctness of its models cannot be verified. It implements a 802.11 medium-access model and a complex propagation model, as well as an interference channel model. It supports the use of trace-based mobility models, which can be obtained from mobility generators such as SUMO or VanetMobiSim. The models implemented in QualNet are less advanced than the ones implemented in Veins.

When simulating network protocols, models are more important than the simulators [86], [87], [49]. In the following subsections, we go through the models used by researchers to evaluate their proposals. The following subsections does not seek to be a survey on Inter-Vehicle Communication (IVC) simulation models, which can be found in [88].

C. Low level models

Radio propagation models for VN must reflect the effects of path loss, shadowing, and multipath fading. The path loss defines the average received power at certain distance from the transmitter, while shadowing and multipath fading add a random component related to obstacles between the transmitter and the receiver, and the multiple delayed replicas of the signal received. A more extended discussion of these effects is not included in the scope of this survey, and can be found in [89].

Only considering the effects of path loss results in a deterministic propagation distance, which is far from a realistic scenario, we have found that 26 out of 41 reviewed papers use a deterministic propagation model. Considering a deterministic communication range between neighbors has overly optimistic effects on the performance evaluation of the protocols.

More recent works have incorporated the effects of fading into their propagation models [10], [39], [62], [72], which is closer to propagation behavior in real environments. However, only one of the reviewed papers [60] considers the effects of buildings and obstacles when simulating urban scenarios.

In terms of interference models, we have found that only 8 works considered the effects of interference between neighbor nodes.

In this survey we have found that some papers (5 out of 41) ignore or do not specify the radio propagation and channel models used. We firmly believe that the VDTN research community should make an effort to improve the quality of the propagation and channel model used to evaluate protocols.

Besides the propagation and channel model, as shown in [90], it is also important to use a fully featured IEEE 802.11p model. However, none of the reviewed papers used such an advanced model. The most advanced models were limited to a CSMA/CA model, used in 12 out of 41 papers, while 3 papers used a simplified slotted MAC. As a negative trend, 19 of the 41 reviewed papers ignore the necessity of a medium-access model, and assume that nodes within the communication range can always communicate. This assumption only holds true in very sparse networks, where the probability of interfering neighbors is negligible. Moreover, 5 papers did not define the MAC model they used, which clearly compromises the reproducibility of their simulations.

Although the medium-access model may seem less important than the propagation and channel models, from our point of view, the minimum required medium-access model is a slotted mac, where only a connection between 2 nodes in a certain area can be established. It is clear that researchers must improve the average detail of medium-access models used in VDTNs.

D. Mobility Model and Simulated Scenario

Authors such as Joerer et al. [88] have shown their concerns about mobility model specifications in VN. Fortunately, only two of the reviewed papers used the *Random Way Point* mobility model [91]. The majority of the papers used a *limited random* mobility model, *i.e.* nodes move randomly but their movements are limited by the road network topology. This model is better than pure random mobility, but it does not capture the characteristics of vehicular mobility; for example, two vehicles may occupy the same location at the same time. We also found a group of papers that implemented their own *car following* mobility model [36], [78]. Given the complexity of the models, a self-implemented car following model also compromises the reproducibility of the experiments. Finally, in only 8 papers, we found what we consider the best practice: the use of a validated micro mobility simulator. In the papers we reviewed, researchers used VanetMobiSim [92], SUMO [93] and NETSTREAM [94] as the mobility generator. SUMO is the most advanced mobility simulator, implementing a car following model and real maps and enabling researchers to run mobility and network simulation concurrently, thus allowing events in the network to influence the mobility of the nodes. It is also worth noticing that 11 of the reviewed articles used traces obtained from real vehicles to simulate the mobility of the nodes. Real traces are a good option but they lack flexibility when varying network parameters such as number of nodes, road topology, etc.

Concerning the simulated scenario, it is important to evaluate VDTN protocols in both city and highway scenarios. We found that only 3 papers considered the highway scenario, while 22 used the city scenario. Inside the city scenario there is a huge variety of configurations ranging from urban grids to low-building-density suburban areas. Once again, this diversity complicates the comparison of different proposals. The mobility model and the simulated scenario can significally affect the performance of protocols, especially VDTN protocols, where nodes tend to carry information in buffers and protocols tend to make decisions based on node mobility.

Table II summarizes our findings when analyzing the tools and models used by researchers. As previously explained, the diversity of models and simulators makes it impossible to compare different proposals without re-implementing every proposal.

E. Testbeds and Implementations

Over recent years, some researchers have pointed out the need for real tests prior to VN deployment [95]. Within the set of papers reviewed in this survey only [96], [77] and [30] test their proposals in a real environment. In [96], authors run a test of the Cartorrent system, which is based on the Spawn protocol. In [77], authors extended the Controller Area Network (CAN) bus of vehicles to send its data to a base station using the DTN reference implementation [97]. In [30], authors used a testbed formed by buses inside the University of Massachusetts called UMassDieselNet.

Others authors have presented their testbed for VNs where VDTN protocols could easily be tested. In [98], authors presented Cabernet, a VN deployed over 10 taxis of Boston area. In 2010, researchers from UCLA presented C-VeT, an advanced testbed for vehicular networking and urban sensing, which combined a VANET formed by management vehicles and buses with a mesh network based on Open-WRT. In [99], an implementation of a warning protocol for VDTNs was presented and tested. In [100], authors presented a *Creative Testbed* that combines simulations with testbed results to maximize flexibility while minimizing deployment cost.

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TABLE III

GRADE OF SUITABILITY OF PROTOCOLS TO DIFFERENT APLICATIONS

Group Application	Zero Knowledge	Contacts History & Social	Geographic Location	Road Map	Online
P2P & I2V	1	5	2	3	4
V2I & Sensors Collecting	1	2	3	4	5
Cooperative Downloads	1	5	4	3	5
Dissemination	3	5	4	5	3

less suitable 1-5 more suitable

We clearly identify a positive trend towards more advanced testbeds, closer to real deployment. We would like to support and encourage researchers to use these new testbeds whenever possible, since such initiatives are vital for promoting the full deployment of VDTNs.

V. DTN BASED APPLICATIONS IN VEHICULAR NETWORKS

In this section we introduce applications proposed by the research community that depend on the use of DTNs. We describe them presenting some of the problems and challenges they must face. We start this classification with the most frequent application in the reviewed articles, Peer-to-Peer (P2P) communication. Secondly we present what we call **environment-sensing applications**, which consider the use of DTN protocols in order to collect information using vehicles as sensors. The third group includes **dissemination applications**; beside broadcast dissemination, we also consider context-based dissemination. Finally, we explore **collaborative content-downloading applications** and new proposals such as cellular offloading. Table I classifies each of the protocols analyzed previously in each of these categories. For each application described, we provide some examples of its utilization and discuss which group of protocols best adapts to it.

Table III quantifies the suitability of each group of protocols for each application according to the criteria explained in this section.

A. P2P Applications

The most obvious application of any communications system involves allowing users to exchange messages and information between them. Hence, it is not surprising that the majority of the analyzed articles focus on “P2P” communication.

As stated in previous sections, when using geographic protocols for P2P communication we need a Location Service to obtain the location of the destination of a message. Table I shows that 22 of 41 works are labeled as “P2P” or “P2P/V2I”. The second label includes protocols that are presented as a “P2P” protocol, but obviate the complexity of the required location service, which makes the communication between vehicles impossible, thereby reducing

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them to V2I communication protocols. We have grouped V2I applications with environment-sensing applications, due to their similarities.

The typical example of a P2P application is a kind of e-mail system, where users can exchange personal messages. Obviously, this scenario application assumes that the sender and the receiver have met previously. We can also assume that the number of users of this application is relatively small (dozens of individuals), compared to the number of vehicles that typically form a VN (thousands of nodes). Given these assumptions, we believe that contact rate and social relationship-based protocols are the best alternative for this application.

If the cost of infrastructure deployment is affordable, it is probably a better option to deploy a set of RSUs connected by a backbone network and then use them to slice the source-to-destination routing problem into two smaller problems: routing from source to an RSU, and routing from another RSU to the destination. This scheme is similar to the one described in [72].

B. V2I and Sensing Applications

In V2I applications the objective is to send information from a vehicle to an RSU. In environment-sensing applications, the main objective is the same, but it can be assumed that the information is typically correlated to the geographic location of the source.

An example of a V2I application is the scenario where a user wants to order a large number of goods in a shop. Using VDTNs, the user can send a message to the shop, which will be able to prepare the order in advance. In the second case, we envision a scenario where traffic management and road security authorities collect information on speed, road status or weather from vehicles. This information can be used to optimize emergency vehicle routes, monitor pollution inside cities, plan taxi routes, etc.

Since RSUs have a fixed location that can be stored in a quasi-static database, geographic, road map, and online protocols do not require a location service to route messages to its destination. This feature is used in protocols such as GeOpps [10], GeoDTN+Nav [63] or MSDP [60]. In [80], authors introduce a new scheme where messages from different nearby sources are combined to compress their information and reduce the channel load. As stated before, one of the key issues of zero knowledge protocols is that node mobility increases the probability of reaching the destination of a message. Since RSUs are static, zero knowledge protocols are not suitable for these applications. A similar problem applies to contact history and social based protocols. Since they require nearly-closed communities, they tend to ignore nodes that pass by a region.

C. Dissemination

Dissemination applications aim to quickly deliver information to as many nodes as possible. In this scope, the adoption of delay-tolerant protocols may seem counter-intuitive since the expectable delay is rather high. Nevertheless, in sparse networks where the degree of node connectivity is low, the store-carry-and-forwarding paradigm may be the only method capable of guaranteeing a high message delivery ratio.

Accidents occurring on highways represent a typical scenario where quick message dissemination may be useful, for example by notifying drivers approaching the accident area and thereby avoiding cascading car crashes.

When disseminating information, an ROI where a message must be disseminated is typically defined. The ROI is usually related to geographic or road network restrictions, being mostly useful to vehicles moving towards an accident, vehicles moving on streets adjacent to a traffic jam or vehicles ahead of an ambulance route, for example. The strong relationship between the ROI and the actual characteristics of the road environment makes geographic and map based protocols the most suitable alternatives for this application.

Other cases, for example when disseminating non-geographically correlated information (e.g. advertisements), the best socially-connected nodes would probably be the best carriers.

D. Cooperative Download

In cooperative download applications, the main data flow occurs from RSUs to vehicles. Typically, a user requests data that is too large to be transferred during a single contact with an RSU. To solve this problem RSUs which are connected to a backbone inject fragments of the responses into the network. Once fragments are injected, there are two main alternatives: to distribute these fragments between every interested node [76] or to deliver them only to its specific destination [71], [61], [79].

When distributing fragments to every interested node, it is usually easy to identify social relationships between interested nodes and this information can be used to maximize the protocol performance. On the other hand, geographic information can also be useful to select the best contact, as in [76].

When delivering a message to its specific destination, it can be seen as a P2P communication between an RSU and a mobile node and, therefore, we can apply the same methods as for P2P applications.

VI. CONCLUSIONS

In this survey, we provided the reader with a broad view of the different proposals for VDTNs. We classified them according to their utility index, showing the relationships between different protocols and their evolution. We identified a set of common mechanisms that can be applicable to almost all VDTN protocols, and that may heavily influence their performance. We also presented some applications where VDTNs can be used and evaluated the suitability of the different proposals for each application.

Moreover, this survey is not limited to a mere description of protocols, since it also addresses critical issues such as the reproducibility and repeatability of experiments and reviews the evaluation methods used by the different VDTN researchers. We pointed out a lack of realism in most of the simulation models used by the VDTN research community.

Tables I and II summarize the contents of this survey, and offer important information at a glance.

Based on the extensive survey presented in this paper, we can conclude that no VDTN protocol is suitable for all possible target applications. From our point of view, researchers must focus on providing services/applications, and VDTN protocols should be flexible enough to adapt their behavior to the characteristics of the running application. We also believe that routing metrics should adapt to current network characteristics by making the most of opportunistic contacts or taking advantage of vehicular mobility according to available resources.

ACKNOWLEDGMENTS

This work was partially supported by the *Ministerio de Economía y Competitividad*, Spain, under Grants TIN2011-27543-C03-01 and BES-2012-052673.

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ACRONYMS

ADPBSW	Average Delivery Probability Binary Spray and Wait
BS&W	Binary Spray & Wait
CAN	Controller Area Network
CDF	Cumulative Distribution Function
DDT	Distance Defer Transmission
DRTAR	Distributed Real-time Data Traffic Statistics Assisted Routing
DSCF	Directional Store-Carry-Forward
DTFR	Delay Tolerant Firework Routing
DTN	Delay Tolerant Network
DTNRG	Delay Tolerant Network Research Group
DV-CAST	Distributed Vehicular BroadCast
FEC	Forward Error Correction
FFRDV	Fastest Ferry Routing in DTN-enabled Vehicular Ad-Hoc
GORF	Generic Opportunistic Routing Framework
GPS	Global Positioning System
IPN	InterPlanetary Network
ITS	Intelligent Transport System
IVC	Inter-Vehicle Communication
MANET	Mobile Ad-hoc NETwork
METD	Minimum Estimated Time of Delivery
MSDP	Map-based Sensor-data Delivery Protocol
NS	Navigation System
P2P	Peer-to-Peer
PER	Packet Error Rate
RENA	REgioN-bAsed
ROD	Road Oriented Dissemination
ROI	Region of Interest
RSU	Road Side Unit
SADV	Static-Node-Assisted Adaptive Data Dissemination in Vehicular Networks
TTL	Time To Live
UV-CAST	Urban Vehicular BroadCast
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication. The final version of record is available at http://dx.doi.org/10.1109/COMST.2014.2375340

VADD	Vehicle-Assisted Data Delivery
VANET	Vehicular Ad-Hoc Network
VDTN	Vehicular Delay Tolerant Network
VN	Vehicular Network
WAVE	Wireless Access for Vehicular Environment
WSMP	WAVE Short Message Protocol

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