Routing protocols in Vehicular Delay Tolerant Networks: A comprehensive survey

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This article presents a comprehensive survey of routing protocols proposed for routing in Vehicular Delay Tolerant Networks (VDTN) in vehicular environment. DTNs are utilized in various operational environments, including those subject to disruption and disconnection and those with high-delay, such as Vehicular Ad-Hoc Networks (VANET). We focus on a special type of VANET, where the vehicular traffic is sparse and direct end-to-end paths between communicating parties do not always exist. Thus, communication in this context falls into the category of Vehicular Delay Tolerant Network (VDTN). Due to the limited transmission range of an RSU (Road Side Unit), remote vehicles, in VDTN, may not connect to the RSU directly and thus have to rely on intermediate vehicles to relay the packets. During the message relay process, complete end-to-end paths may not exist in highly partitioned VANETs. Therefore, the intermediate vehicles must buffer and forward messages opportunistically. Through buffer, carry and forward, the message can eventually be delivered to the destination even if an end-to-end connection never exists between source and destination. The main objective of routing protocols in DTN is to maximize the probability of delivery to the destination while minimizing the end-to-end delay. Also, vehicular traffic models are important for DTN routing in vehicle networks because the performance of DTN routing protocols is closely related to population and mobility models of the network.

1. Introduction

Intelligent Transportation Systems (ITS), are advanced applications aiming to provide innovative services related to different modes of transport and traffic management, through vehicular communication, to improve road safety and to provide more comfort for conductors. Cars equipped with wireless devices can exchange traffic and road safety information with nearby cars and/or roadside units. Vehicular Networks have become a popular research topic during the last years, due to the important applications that can be realized in such an environment. In [1], the authors have divided such applications into two major categories: safety applications that increase vehicle safety on the roads, and user applications that provide value added services, such as entertainment. Inter-vehicle communication (IVC) can increase the safety, efficiency, and convenience of transportation systems involving planes, trains, automobiles, and robots [2]. In vehicular networks, messages between vehicles can be used to detect different levels of traffic jams [3], and thus traffic congestion can be reduced with the help of vehicle-to-vehicle communication [4]. Recently, the authors in [5] presented how IVC can reduce the number of secondary collisions caused by an accident, through dissemination of warning messages. A more recent survey of other applications and use cases can be found in [6], where the authors classified them into three categories: (1) Active road safety applications, (2) Traffic efficiency and management applications, and (3) Infotainment applications.

Direct communication between vehicles may be established via mobile ad hoc networks (MANETs), which do not rely on fixed infrastructure. Research on MANETs covers application requirements and communication protocols for everything from sensor networks to hand-held computers and vehicular systems [2]. Vehicular Ad-Hoc Networks (VANET) is a technology that uses vehicles as nodes. Thus, MANETs that span airplanes, trains, cars, and robots are called VANETs. However, VANETs exhibit bipolar behavior depending on network topology: fully connected topology with high traffic volume or sparsely connected topology when traffic volume is low [7]. Thus, one can distinguish between two different categories of vehicular networks: VANETs as presented

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above and Vehicular Delay Tolerant Networks (VDTNs) which are vehicular networks in sparse traffic (Fig. 1), and where Delay Tolerant Network (DTN) protocols can be applied. In order to guarantee the feasibility of many applications through vehicular networks, it is imperative to design networking protocols that can overcome relevant problems that arise from vehicular environments.

Furthermore, Internet protocols do not work well for some environments [8], due to some fundamental assumptions built into the Internet architecture such as the existence of an end-to-end path between source and destination for the duration of a communication session, short end-to-end round-trip delay time [9], and the perception that packet switching is the most appropriate abstraction for interoperability and performance.

The high mobility and speed of nodes in vehicular environments is responsible for a highly dynamic network topology that is different from the traditional concept of the Internet. These nodes can exhibit short contact durations, or move in an unpredictable way [10]. The links may be short lived, with high link error rates, and the absence of an end-to-end path from source to destination. As a result, networks in such environments can be partitioned, due to the large distances involved and to variable node densities and sparse traffic, resulting in discontinuities along the path from source to destination [11].

Many conventional routing protocols were designed for VANETs in the case of a fully interconnected environment, aiming to establish end-to-end connectivity among network nodes [12]. However, these protocols cannot be used when the traffic quiets down. End-to-end connections via intermediate nodes cannot be established any more [13]. Thus, this category of routing protocols fails to deliver data in sparse traffic, partitioned networks, and opportunistic vehicular networks.

In an attempt to address this problem, vehicular networks may deliver data using the store-carry-and-forward (SCF) paradigm of DTNs [8] rather than a simple carry-and-forward method. Consequently, asynchronous, long and variable length messages, called bundles, can be opportunistically routed towards the destinations through intermittent connections, assuming that end-to-end network path is not necessarily currently available, but rather that such a path exists over time. Thus, DTNs in vehicular environment are called Vehicular Delay Tolerant Networks (VDTNs) [14]. In vehicular DTNs, contacts between nodes appear without any previous knowledge [13], and therefore the challenges that DTNs need to overcome have led to significant research focused on routing.

We particularly acknowledge some related and excellent surveys on DTN [15], [16]. For example, the survey in [15] covers the literature until mid 2010. In this paper, we update these surveys by providing the advances in VDTN forwarding algorithms from mid 2010 to February 2013, the date used in writing this paper. Some previous algorithms are provided as background for better readability.

Fig. 1. VDTN-scenario.

The remainder of this paper is organized as follows. Section 2 is an overview of DTNs focusing on routing protocols used in such networks. Section 3 deals with the unsuitability of VANET routing protocols for VDTNs. Section 4 provides a detailed description of VDTNs, related routing protocols and discusses challenges and open issues. Finally Section 5 concludes the paper and suggests further research works.

2. Background on delay-and disruption-tolerant networking

DTN [17–19] concepts were initially designed with a substantial focus on interplanetary networks [20]. Such networks may suffer from frequent disruptions and long delays. However, gradually, the DTN field has grown to include other types of networks, such as opportunistic mobile ad hoc networks, wireless sensor networks, sparse vehicular networks (the focus of this paper) and so on. Some of these terrestrial networks also suffer from extreme conditions, due to the nature of the hostile environments where they are deployed such as battlegrounds, volcanoes or some other forms of disaster response, deep sea, under developed areas, etc. Such conditions, with intermittent connections, low bandwidth, high error rates and high delays have attracted the attention of researchers towards DTN. However, already existing current Internet protocols were designed after bearing in mind certain assumptions that make them inefficient or at worst ill suited for such kinds of networks [15]. As during design and modeling, it was assumed that most of the time, and if a delay is affordable, a route can be found from a given source to a given destination. The Internet was designed to even survive a nuclear attack, but it may not work optimally in such extreme scenarios. For example, TCP, which is the popular transport protocol used in the Internet, and more generally connection-oriented protocols, will not function if there are long disruptions or their efficiency will significantly deteriorate, as delays become longer.

The Delay-Tolerant Networking Research Group (DTNRG) [21], a research group chartered as part of the Internet Research Task Force (IRTF), was formed in 2002 to address the architectural and protocol design principles for the aforementioned extreme environments. The research group proposed a DTN architecture [8], and a communication protocol called bundle protocol [22]. In this section, we provide an overview of the principles related to DTN architecture, bundle protocol, DTN addressing, routing and security.

2.1. Naming, addressing and late binding

Originally, in the DTN architecture, hierarchical identifiers were considered to identify end nodes as well as applications [16]. For identification, 3-tuple identifiers of the following form (region, node, application) were used. Thus it was possible to route data, based on first the name of the region, then the node and finally the application.

However, as the concept of DTN evolved, it was realized that more flexibility was required to include several dynamic, extreme as well as heterogeneous environments. Nodes were seen to have multiple network interfaces and nodes were mobile, changing the point of attachment. A naming system consisting of multiple naming spaces was sought. Already existing work in IETF, RFC 3986 [106], related to generalized naming system was used: Uniform Resource Identifiers (URI). URIs in DTN are called as Endpoint identifiers (EIDs). The URI scheme has some useful properties for naming in DTN scenarios. For instance, a host can be referred to using multiple naming spaces.

Each URI begins with a scheme name, which in turn refers to the specification that defines how the current URI will be interpreted. Some examples of well-known schemes are http, ftp, etc. Let us consider the following example with a machine called "mymachine". Then:

ether: <mac address of mymachine> may refer to mymachine and its ethernet interface

http:mymachine.com may refer to http access to mymachine
dtn:∗.mymachine.com may refer to any dtn application on mymachine using the wildcard "∗".

More proposals, such as in [23], can be used to aid routing by using a destination address that is a function of its content.

DTN also uses a concept called late binding. Traditionally, when data is transmitted to lets say mymachine.com then early binding is used so that the name mymachine.com is immediately converted into its IP address at the source itself using DNS. However DTN supports early as well as late binding. This is required because some DTN nodes are capable of routing data using just names, and thus not addresses, and are more efficient. Thus, data is routed using names and when it is closer to its destination then, with late binding, its name is converted into the destination address.

2.2. Bundle protocol

The data in DTN is transmitted in the form of variable length messages called bundles. It is called a bundle because it not only contains the data for the destination, but it also contains all the information such as protocol data, authentication data, etc that is required for the completion of a transaction in one go. This is useful in scenarios with high delays, as several round trips are needed to exchange protocol messages or authentication data may not be feasible at all.

A bundle is formed of several blocks. The first block is called the primary block and it contains version, source, destination EIDs, length, and other fields required for the processing of the message. For example, a dictionary is included in the bundle to decompress the message.

There is also a fragmentation field that is used to manage the fragmentation of the bundle in case only a smaller bundle size can be transmitted. For example, consider the case of VANETs. As mentioned before, a contact opportunity with another vehicle may be small and the whole bundle may not be transmitted. Thus, fragmentation becomes useful.

Finally, it should be noted that bundle protocol does not provide any error detection or correction capabilities. It is assumed that the application or underlying protocols (in some cases TCP or UDP) will handle it. The authors of [24] argue in their work that bundle protocol has some shortcomings and absence of any error detection or correction capability is one of them. They argue that for example, the corruption of headers can lead to mis-delivery and mishandling.

2.3. Store carry and forward (SCF)

Internet routing operates in a store and forward manner. Incoming packets are stored in the buffer till the packets ahead are served and then the packets are forwarded to the next hop, according to the routing decision. If the next hop is down, then the packets may be dropped. The size of the buffers is not very large, as packets are not supposed to stay in the buffer for a long time.

However, the nodes in DTN operate in a store, carry and forward (SCF) manner. A DTN node needs to take custody of a bundle until it is either delivered to the destination or another DTN node has taken custody of it after coming into contact. The concept of contact is used to define a window of opportunity when it is possible to establish a connection with another DTN node. It should be noted that such a window of opportunity may be short, as is the case of VANETs when a car comes closer to another car and has to transmit the bundle, before the other car goes away. In any case, due to intermittent connectivity, the bundle can take long time to travel from a source or destination and persistent storage is needed in the DTN nodes.

2.4. From DTN to VDTN

VDTNs have some unique characteristics borrowed from both DTNs and VANETs which should be taken into account when designing protocols for them. Moreover it has been identified that DTN concepts *need* further improvements before they can be applied to VDTNs, thus, motivating further research. A survey on routing protocols for VANETs [12], published in 2007, discusses some unique characteristics related to vehicular networks. Some of the application requirements and challenges faced by varied environments and other specific characteristics are discussed below.

2.4.1. Vehicular applications

Some safety related applications in vehicular networks could have hard delay constraints, for example, to warn other drivers in the event of an emergency brake. Moreover, the information does not need to travel to faraway vehicles. For such kinds of applications DTN concepts may *not* be optimal and some of them are not even applicable to the VDTN scenario.

Other applications, for example, a car maintenance application that can capture the data from car sensors and transmit it to a garage, an application that can help a car find a parking lot, an email application, weather update, etc., do not have such stringent requirements and DTN principles can be applied.

2.4.2. High mobility and frequent disconnections

Due to the high speed and mobility of vehicles the topology is very dynamic and the short range of inter vehicular communication results in frequent disconnections. For example, imagine two cars coming from opposite directions and meeting each other at 100 kmph: the window of communication opportunity is just a few seconds and after that there will be disconnection. This disconnection duration increases when traffic density is low, as in the case of VDTNs. This property makes the DTN concepts attractive, as they were designed to deal with such network conditions.

Operating environments also vary, ranging from highly dense highways, where ad hoc networking concepts can be applied, to urban areas with sparse traffic. Road infrastructure or cellular networks may also be used depending on cost trade-off. Thus, a possibility could be to design hybrid solutions that explore synergies between different technologies such as cellular networks, ad hoc networking and DTNs.

2.4.3. Geographical awareness

GPS devices are increasingly becoming common in the vehicles. Thus, the geographical location of vehicles can be determined and, in some cases, even the trajectory can be predicted very well, for example, in the case of public transportation trains and buses. This information can be exploited by the algorithms for message delivery and routing.

Different message delivery paradigms such as unicast, multicast, broadcast and anycast exist in computer networking. In vehicular networks, another form of message delivery called Geocast is useful, in which messages are delivered to a group of destination nodes limited by their geographical location. Geocast can be useful for many vehicular applications for example, the delivery of weather information such as the presence of ice on the road, safety information related to accident location, the location of traffic jams, etc to the vehicles located near and moving towards that point.

Thus, an addressing and naming scheme that should be flexible enough to consider geographical routing is needed. Naming and addressing concepts of DTN as discussed in Section 2.1 prove relevant, as they provide better flexibility. Moreover, the DTN concept of late binding is also useful. With late binding and naming flexibility, messages can first be routed based on the destination geographical address and can be converted, late, into the node address near the point of delivery.

2.4.4. Mobility prediction

With GPS capabilities it is possible to locate different vehicles. In addition given the speed and the fixed trajectories enforced by highways and street maps, it is possible to predict the future location of a vehicle. Thus, mobility models that can predict the future position of smarter nodes can help in making optimal routing decisions. Mobility models need to take into account several things such as street conditions, vehicle speed and statistics such as density of vehicles and obstacles such as buildings.

2.4.5. Storage and computation capabilities

It can be assumed that nodes have sufficient capabilities in terms of storage, computation as well as energy. This is because nodes will either be a car, bus or train or other vehicles and not sensors or hand-held devices.

3. From VANETs to VDTNs

Vehicular Delay-Tolerant Networks are a special case of VANETs when DTN paradigm is used to address the problems such as frequent disconnections, network partitioning, etc. DTN approach can be applied to a broad types of networks where there is no guarantee of end-to-end connectivity such as interplanetary communications [18]. VANETs can suffer from similar problems due to high mobility of vehicles, which communicate with each other or with infrastructure, with conditions characterized by: intermittent connectivity, long-variable delays and latencies, end-to-end route may never exist at certain time and there may be high error rates. Such conditions are found for example, in scenarios with sparse vehicular density.

In VDTN, the nodes (vehicles) store and carry network data while waiting for opportunities to forward it. Thus, in VDTN, the vehicles are also used to carry the data towards the destination, which is unlike the other non-VDTN approaches for VANETs. Storing and carrying data can also be done through the use of special nodes, namely relay node and terminal node as we can see in Fig 2. Terminal nodes can be located in isolated regions and they can provide Internet access for the VDTN [14]. Relay nodes are mainly fixed devices, which allow mobile nodes to upload and download bundles when there is no other alternative.

Conventional routing and forwarding protocols used in the case of fully connected vehicular networks (VANETs), fail to deliver data in VDTN environments. VANET routing protocols are appropriate for dense and non-intermittent networks [16]. In this section, we present some VANET protocols to discuss their unsuitability for VDTNs. We will also present some VANET protocols that are evolving towards VDTNs by including some notions of store-carry and forward and thus are moving towards a hybrid approach that

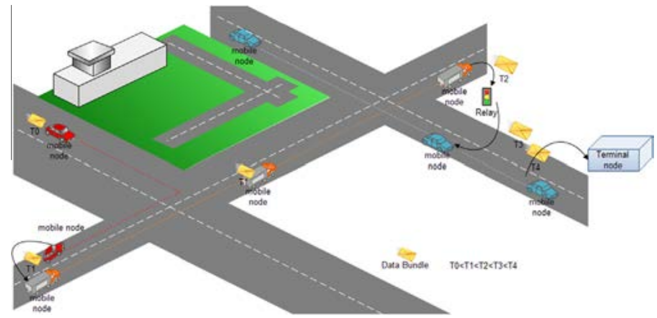

Fig. 2. Store-carry-and-forward paradigm in DTN.

may be suitable for both scenarios. One of the main challenging research fields in VDTNs is routing problem in such environments. Conventional routing and forwarding protocols used in the case of fully connected vehicular networks (VANETs), fail to deliver data in sparse and opportunistic environment. These routing protocols support vehicle traffic on a large scale, intense mobility of vehicles and connections without link breakage [25]. Routing protocols in VANETs aim to establish end-to-end connectivity among network nodes through some path, which is not the case of Delay Tolerant environment. Hence, routing protocols in VDTNs use the store-carry-and-forward paradigm of DTNs to deliver data. This paradigm is based on the concept that the end-to-end network path exists over time. However, the bundle protocol, which is the basis of DTN, does not solve routing problems. It does not establish routes between nodes. The following section presents routing protocols in VANETs and discusses their suitability or not for VDTNs.

3.1. VANET routing protocols

Many routing protocols in VANETs [26], belonging to different categories such as: Geocast routing, position-based, broadcast, cluster based and ad hoc [12] have been proposed and studied recently.

Greedy Perimeter Stateless Routing (GPSR) [27] is one of the popular location-based routing protocols. It forwards packets using location information. GPSR is scalable and can be applied to highly dynamic networks. This has made it a major research interest in vehicular networks and many versions of GPSR were developed for VANET environments [12].

With GPSR [27], every node maintains a routing table listing all neighbors by name and position. The entry is soft so that it is updated after a timer expires or if the presence of a new neighbor, using beacon broadcasts, is known. In addition, for routing, it is assumed that the location of the destination is known with the help of the location service. For routing, GPSR uses two modes:

- Greedy forwarding mode: the packets are forwarded to a node geographically closer to the destination
- Perimeter mode: when there are voids or obstacles to reach the destination, GPSR uses perimeter mode to traverse the obstacle and as soon as the obstacle is traversed, GPSR returns to Greedy mode.

Thus, it can be noted that greedy mode may not always work and perimeter mode may make GPSR go through loops, as it lacks information about topology [12], when disconnections are there in the topology.

In [28], the authors present a protocol based on forwarding data packets using the optimal path model: JARR (Junction-based Adaptive Reactive Routing). Due to high mobility in the VANET scenario, routing is done reactively in JARR by taking into account the velocity (including direction) of traveling nodes as well as other network conditions. JARR considers the estimated density of paths to be taken and implements a packet routing scheme with different modes that can adapt to different sparse and dense vehicular density conditions. The carry and forward strategy [29] which was shown in [30] produced reasonable results. JARR uses a modified carry and forward strategy [25] to connect vehicles that are out of transmission range for short intervals only. It uses an adaptive beaconing mechanism, so that the next forwarding nodes can be identified more quickly, reducing the delay. Even if nodes move at low velocities in a sparse network, JARR still produces good results [28].

To reduce the hop count, and thus the reduction of the end to-end delay, another protocol called BAHG (Back-Bone-Assisted Hop Greedy) was designed in [31]. This protocol tries to find a routing path consisting of a minimum number of intermediate intersections. It is designed considering certain features in a city map, such as intersections and road segments. To address the problem of opportunistic networks, maintaining connectivity at the intersections and detection of sparse and void regions, authors rely on a method that consists of a group of nodes called backbone nodes. If any part of a road segment longer than the transmission range, is devoid of nodes, it can be noted by the nodes present at the periphery of the void region. Nodes closest to the void region from both directions declare themselves as back-bone nodes and they are appointed "void-guard". Their goal is to inform the presence of a void region to the neighbouring back-bone nodes stationed at intersections of the presence of a void region.

The stable back-bone nodes take the responsibility of packet buffering. The packet is stored in a stable back-bone node in the absence of an adequate forwarding node. On availability of a forwarding node in the desired direction, packet is retrieved and forwarded. A back-bone node is always preferred when there is a need to choose a forwarding node from an intersection. This is because back-bone nodes can maintain communication history and store packets in the absence of a forwarder at the intersection. Furthermore, BAHG ensures successful delivery of data packets to destinations. The "hop greedy" algorithm, proposed by BAHG, finds the best possible path in terms of both hop count and connectivity. It also includes the concept of backbone node to address connectivity issues such as void regions and unavailability of forwarders.

IGRP (Intersection-Based Geographical Routing Protocol) [32] is another protocol that performs a selection of road intersections through which a packet must pass to reach the gateway to the Internet. This selection must guarantee network connectivity among the road intersections, while satisfying quality of service constraints on error rate, tolerable delay and bandwidth usage. To overcome the limitations (route instability) of certain protocols, such as OLSR (optimized link-state routing), DSR (dynamic source routing) [33], and AODV (ad-hoc on demand distance vector routing) [34] in VANET, the authors in [32] proposed IGRP consisting of successions of road intersections that have network connectivity among them. The use of geographical forwarding is efficient for transferring packets between any two intersections within the path, reducing the path's sensitivity to individual node movements. The selection of the road intersections is made in a way that maximizes the connectivity probability of the selected path, while satisfying quality of service constraints on the tolerable delay within the network, bandwidth usage, and error rate. Authors consider different scenarios like nighttime with low density (sparse network). To do so, they use different numbers of vehicles, given that the area of the simulated network is fixed. Numerical results show that the proposed protocol IGRP achieves an optimal or a near-optimal solution, particularly in sparse network [32].

There is no routing protocol suitable for all scenarios and contexts. No protocol performs well in all conditions. Thus, a hybrid approach is likely to be more successful. HLAR (hybrid location-based ad hoc routing) [35] was proposed because in all scenarios no single routing protocol will excel in VANETs. Therefore, the authors in [35] adopt a hybrid design approach, where they combine features of reactive routing AODV [34], which has the best performance and lowest routing overhead of all topology, based routing protocols [36–38], with geographic routing. The main point of the protocol is not to compete or replace current AODV type protocols, but to enhance and complement existing AODV protocols, as location information is made available to the nodes.

HLAR initiates route discovery in an on-demand fashion. If the source vehicle has no route to the destination vehicle, then it creates a route request (RREQ) packet containing the location coordinates of both itself and the destination vehicle. Then, it looks up its own neighbor table to find if it has any closer neighbor vehicle toward the destination vehicle. If a closer neighbor vehicle is available, the RREQ packet is forwarded to that vehicle. If no closer neighbor vehicle is available (void region or neighbor vehicles) have no location information, the RREQ packet is flooded to all neighbor vehicles. In either case, the procedure is repeated until the RREQ packet reaches the destination vehicle.

Despite the fact that HLAR treats the case of a sparse network with a flooding mechanism, it is mainly a technique that increases the probability of message delivery to the destination. It does not use the store carry and forward paradigm to store messages. Thus, if the network is disconnected at the time of flooding, nodes will not broadcast when new connections appear. Hence, the HLAR protocol may not be suitable for VDTNs.

VADD (Vehicle-Assisted Data Delivery) [30] is a multi-hop routing protocol that is used in VANETs. It aims to improve routing in disconnected vehicular networks by the concept of carry-and-forward based on the use of predictable vehicle mobility. At a junction, a vehicle makes a decision and selects the next forwarding path with the smallest packet delivery delay. The data delivery delay depends on each road's vehicular density, and the routing path would be the shortest delay path to the destination. A path is simply a branched road from an intersection. The expected packet delivery delay of a path can be modeled and expressed by parameters such as road distance, road density and average vehicle velocity

VADD proposes three packet transition modes:

1. Intersection Mode: the VADD routing protocol knows the priority list of outgoing directions, and checks the available vehicles in the list that could make sure packets are routed to the preferred directions.
2. StraightWay Mode: geographical greedy forwarding that selects the routing path with the lowest packet delivery delay. Data forwarding in the StraightWay Mode is much simpler than the Intersection Mode, since the traffic is at most bidirectional
3. Destination Mode: a packet switches to the Destination Mode when its distance to the destination is below a predefined threshold. The location of the destination becomes the target location, and GPSR is used to deliver the packet to the final destination.

Using the carry-and-forward strategy, VADD algorithm allows packets to be carried by vehicles in sparse networks and, eventually, it relays it to an appropriate node when it enters in broadcasting range. Each node in VADD knows its own position and also requires an external street map that includes traffic statistics. Selection of the candidate node, to which messages need to be forwarded, is encountered through different selection criteria.

However such criteria are either not scalable or consume more bandwidth through duplication of packets. The authors of [30] have observed while using VADD, network becomes unstable as vehicle density decreases. This is because the optimal paths are not available and because the algorithm relies on probabilistic traffic density information.

Finally, to summarize, in this section, we have presented some VANET protocols that can also be used in an opportunistic network. They have some characteristics suitable for VDTNs, but some feature or other is missing making them unsuitable in general. Moreover, they also need to be compared with VDTN protocols during simulations. Table 1 summarizes the characteristics of these routing protocols. Column 2 gives the type of the protocol how they use position information, how they are evaluated (simulators, simulation scenarios, velocity...), and whether they use the store-carry-forward paradigm, and finally the last column shows the aptitude of each protocol to manage the network disconnections. If a routing protocol fails to maintain connection between nodes when traffic density is reduced, we deduce that it is not suitable for VDTNs.

4. Routing in Vehicular Delay-Tolerant Networks

VTDNs is one of the newest research fields related to Delay Tolerant Networks, aiming to present an architecture suitable for non-real time applications where long delays can be tolerated at low costs. There are many potential applications of VDTNs, which have been cited in the literature. Examples of such applications are: road safety, traffic flow optimization, providing Internet access provision for rural and mountainous regions, telemedicine and marketing advertising. A classification of inter-vehicular communication protocols and their applications to intelligent vehicles was made in [39], and a more recent survey on the subject is provided in [2].

There have been many projects concerning VDTNs. A project related to very low-cost Internet access has been done using KioskNet [40]. This consists of a set of kiosks using mechanical backhaul (vehicles) as the primary means of communication to the Internet. As the kiosk has no permanent Internet access, vehicles carry data to and from a kiosk to a set of gateways which communicate with a proxy on the Internet. Hence, ferries upload and download bundles opportunistically to and from an Internet gateway using DTN protocols. The authors in [14] propose a layered architecture for VDTNs, where the bundle layer is placed below the network layer instead of above the transport layer (Fig. 3), in order to aggregate incoming IP data packets into bundle messages. The bundle in this model aggregates several IP packets with several common properties, like the same destination node [11]. This VDTN architecture is based on three node types, including terminal nodes (access points), mobile nodes (vehicles), and relay nodes (fixed devices located at crossroads). Mobile nodes can exchange information with one another or collect and leave data in relay nodes. The architecture is based also on the separation of data planes and control plane in order to improve the overall performance of the VDTN, by routing large size messages instead of small size IP packets. A survey of further VDTN projects has been presented in [16].

Furthermore, as discussed earlier, one of the main challenging research fields in VDTNs, is the problem of routing in such environments. Conventional routing and forwarding protocols used in the case of fully connected vehicular networks (VANETs), fail to deliver data in sparse and opportunistic environments. These routing protocols support vehicle traffic on a large scale, assuming intense mobility of vehicles and connections without link breakage [41]. Routing protocols in VANETs aim to establish end-to-end connectivity among network nodes such that an end-to-end path is assumed to be available. This is not the case of the Delay Tolerant environment. Hence, routing protocols in VDTNs use the store-carry-and-forward paradigm of DTNs to deliver data. This paradigm is based on the premise of that the end-to-end network path exists over time. However, the bundle protocol, which is the basis of DTN, does not solve routing problems. It does not establish routes between nodes. The following section presents routing protocols in VANETs suitable for VDTNs and summarizes DTN routing protocols applicable in vehicular environment.

In the following text, we present forwarding algorithms for VDTNs according to different categories.

4.1. Primary algorithms for forwarding

There are some forwarding algorithms that have become well known and are used as a reference by researchers to compare their proposals or to propose their developments based on them. We describe them here and some of them will be repeatedly referred to in the later subsections for comparison and reference.

Different classifications have been made by researchers for routing protocols in DTNs. Based on the methodology used to find destinations, and whether replication of messages is used or not, routing in DTN can be classified into several categories: Single copy vs Multiple copies forwarding, flooding [42], Random forwarding, forwarding based on different types of available information, etc. Note that these categories can have significant overlapping.

Fig. 4 shows a general taxonomy of VDTN forwarding algorithms. The figure shows several categories and some of them, with their details, will be described in later sections. We did not draw Single copy vs Multiple copy and Multicast strategies in the taxonomy figure because they overlap a lot with other categories. In this section, we discuss only those categories that are relevant to the primary algorithms.

4.1.1. Single copy vs Multiple copies

DTN-based routing strategies can be classified based on the number of copies of bundles disseminated through the network [43]. The single-copy category maintains a single copy of a bundle in the network that is forwarded between network nodes. The multiple-copy category replicates bundles at contact opportunities.

An example of single copy routing protocol, is Direct Delivery [44] where there is no need of knowledge about the network to make forwarding decisions. The source node carries a message until it meets its final destination. The example of multiple copies forwarding protocols include several flooding and controlled flooding algorithms that will be described in the following text.

Table 1
Comparison of some VANET routing protocols.

Protocol	Type	Simulation scenario	Vehicle density estimation	Store carry and forward	Network disconnections management
GPSR	Geolocation	Street map	No	No	No
IGRP	Geolocation	Street map	Yes	Yes	No
JARR	Packet forward	3x3 km map	Yes	Yes	Yes
BAHG	Packet forward	3x3 km map	No	Yes	Yes
HLAR	Hybrid	Highway & grid	Yes	No	No
VADD	Hybrid	4x3 km map	Yes	Yes	Yes

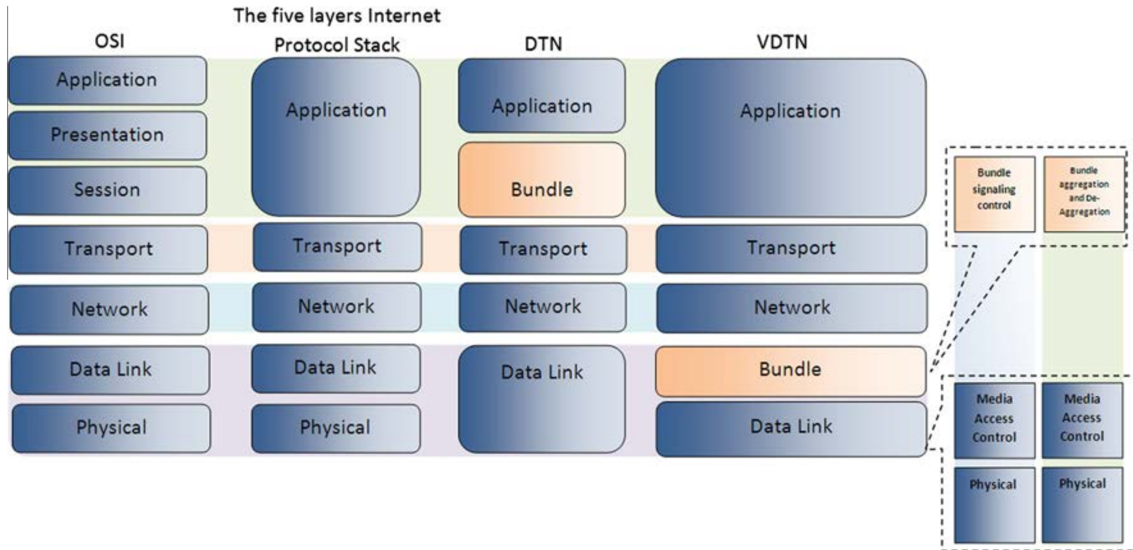

Fig. 3. OSI, five layers internet protocol stack, DTN and VDTN network architecture.

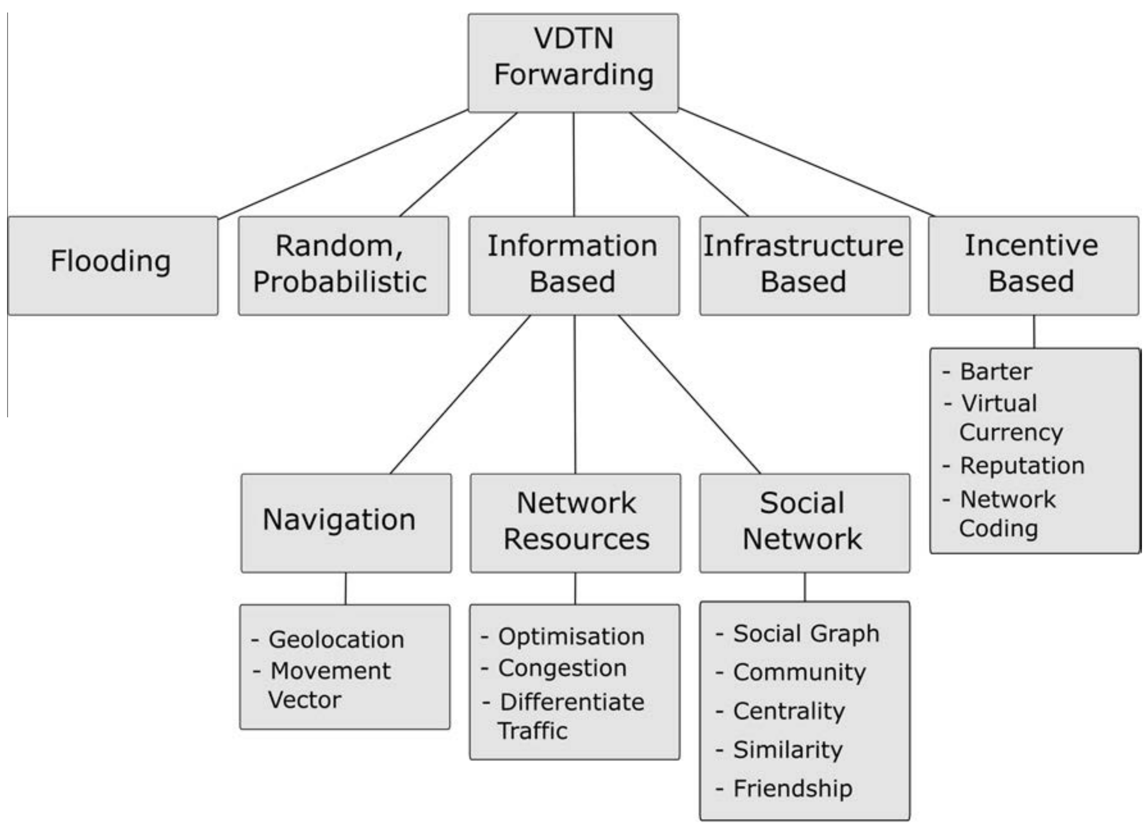

Fig. 4. Taxonomy of VDTN forwarding protocols.

4.1.2. Random forwarding

Other classifications of routing protocols in DTN, have been made in [45] where the authors differentiated between deterministic DTN routing and stochastic DTN routing. Deterministic routing is characterized by knowledge of the current topology such that future changes can be predicted. On the other hand, stochastic DTN routing is applied when node movement is random or unknown and nodes know very little or nothing about the future evolution of the topology. Message forwarding in this case is done randomly hop by hop with the expectation of eventual delivery. No pre-scheduling of transmissions can be done, and hence there are no guarantees of delivery.

A simple random forwarding protocol is First Contact [46] where nodes forward bundles randomly to the first node they meet. This results in a random search for the destination node. However, bundles may oscillate among a set of nodes, or be delivered to a dead end.

4.1.3. Flooding

In flooding strategy, messages are replicated to enough nodes so that destination nodes must receive them, while in forwarding strategy, knowledge about the network is used to select best path to the destination Fig 5.

When replication is used, it allows for better message delivery ratios than in forwarding-based protocols. Each node maintains a number of copies of each message and transmits them opportunistically to other contacts. These flooding based protocols increase the probability of message delivery to the destination. However the flooding based approach increases the contention for network resources like bandwidth and storage, and thus cannot cope with network congestions and does not scale well [42]. It has been mentioned in [15] that some link state routing protocols, such as Open Shortest Path First, system to Intermediate system and Optimized Link state Routing avoid routing loops by flooding any change of the topology to all nodes of the routing area. This behavior is practically impossible in DTN based routing protocols, because of the absence of any prior knowledge of an end-to-end. This approach can also be extended to vector distant protocols.

The authors in [47] added another category to flooding and forwarding, which is based on coding. Routing protocols under this category utilize different kinds of coding techniques to encrypt data packets and the nodes only need to receive enough packets to decrypt the data. This may improve the overall delivery rate.

In [48], the authors proposed the Epidemic Routing protocol in a mostly sparse network with mobile nodes. The context of the protocol has encouraged many authors to consider it for VDTNs [14,16,43,45]. The Epidemic protocol is a multi-copy protocol that implements flooding in a DTN, and does not need any prior knowledge of the network. Messages in epidemic routing are flooded in the whole network to reach just one destination. At a *contact opportunity,* the nodes exchange their bundles, which they do not have in common. This can be considered the optimal solution in an environment with no buffer space/bandwidth limits. Consequently, the epidemic routing protocol minimizes the delivery delay and maximizes the delivery ratio as messages may reach the destination on multiple paths, but spoils storage and bandwidth in comparison with other protocols [16]. Also, when new messages are received, the older messages in the buffers will be dropped which will reduce the delivery probability for destination nodes that have a low contact rate [45].

Another flooding based routing protocols dedicated to VDTNs is MaxProp [49]. MaxProp also floods the messages but explicitly clears them once a copy gets delivered to the destination. This

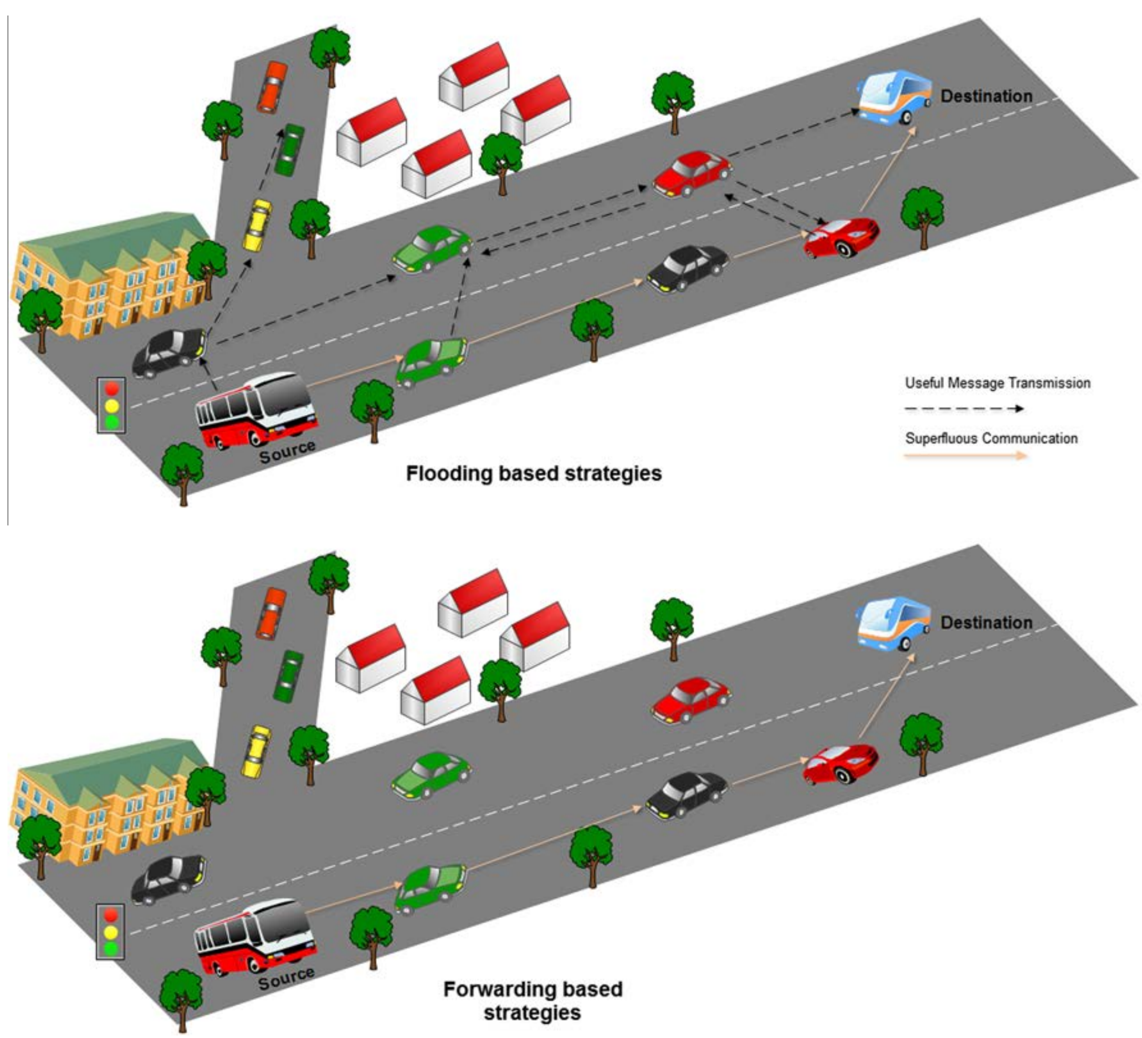

Fig. 5. Comparison between flooding based and forwarding based strategies.

protocol addresses scenarios in which either transfer duration or storage is a limited resource in the network. Nodes do not have a priori knowledge of network connectivity, or their futures coordinates, nor are there always-on stationary peers in the environment. The MaxProp protocol principle is based on a ranked list of the peer's stored packets. The list is build through a cost (an estimate of delivery likelihood) assigned to each destination. MaxProp deals with the problem of scheduling packets for transmission to other peers and deleting packets when buffers are low on space. In addition, MaxProp sends messages to other hosts in specific order that takes into account message hop counts and message delivery probabilities based on previous encounters.

To control flooding, another protocol, called Spray and Wait [50], limits the number (N) of bundle copies created per bundle. The Spray and Wait protocol is composed of two phases: the spray phase and the wait phase. It sprays Bundle copies to intermediate nodes and waits until one of them meets the destination node. This is a zero-knowledge routing protocol that reduces flooding of redundant messages in a DTN, which is not the case in epidemic routing. Two spraying modes are proposed in [50]. In the normal spray mode, the source node forwards one of the copies to each encountered node. In the binary spray mode, (N/2) of the bundle copies are forwarded to each (N−1) encountered node until there is only one copy left on the node that will only be forwarded to the final destination. During this "spray phase", if the destination node is not found, direct transmission will be performed at the "wait phase".

4.1.4. Information based forwarding

In this forwarding category, some routing protocols use knowledge about the network to select the best path to the destination. This category is also known as knowledge-based [51]. One of the main differences between these routing protocols is the type of information used: prior knowledge of the network, history of node encounters, location information. However, there is no VDTN routing protocol that can be considered perfect and suitable for all kinds of vehicular networks.

The PRoPHET (Probabilistic Routing Protocol using History of Encounters and Transitivity) [52] protocol transfers a message only if it estimates that the contacted node/neighbor has higher chances to deliver the message to the final destination. The estimation is based on past node encounter history. However, the PRoPHET protocol necessitates additional overheads to maintaining the estimates of meeting probabilities [16].

In another instance of using different types of information, Geographic routing is one of the most promising approaches for VDTNs. It is based on the use and availability of vehicle navigation systems which tend to become a standard in today's vehicles. Geographical Opportunistic Routing for Vehicular Networks (GeOpps) is a VDTN forwarding protocol based on geographic information. It exploits the geographical information present in navigator systems of vehicles to forward the geographical bundle opportunistically to a certain geographical location closer to the final destination [53]. Thus, the vehicle that is able to deliver the bundle packet quicker/closer to its destination becomes the next bundle carrier. More details on GeOpps are provided in the next section. Table 2, summarizes characteristics of forwarding protocols discussed in this section.

4.2. Geographic based forwarding

From this section onwards, we discuss several categories of VDTN forwarding algorithms. Geographic routing is one of the most promising approaches for routing efficiency. It is based on the use and availability of vehicle navigation systems that are becoming common in today's vehicles. Geographical Opportunistic Routing for Vehicular Networks (GeOpps) [53], a single copy forwarding protocol based on a geographical delay tolerant routing algorithm, aims to enhance the single-copy routing performance in VDTNs. It exploits the navigation information present in navigator systems of vehicles to forward the geographical bundle opportunistically to a certain geographical location closer to the final destination [53]. Thus, the vehicle that is able to deliver the bundle packet quicker/closer to its destination becomes the next bundle carrier.

A moving vehicle carrying a bundle may never get to the bundle's destination, but will eventually get closest to the destination at some point. This point called the nearest point is used to calculate the minimum estimated time of delivery (METD). The expected time required from that nearest point to the destination is then added to it using the distance left divided by the average vehicle speed thus:

$$\text{METD} = \text{time to nearest point} + (\text{remaining distance}/\text{average speed})$$

METD is then used in forwarding decisions and the bundles are forwarded the vehicle having the lowest value of METD.

GeOpps assumes that the bundle carrier will always find another vehicle when arriving at the nearest point. In some cases, it might be practical to hand over the packet that is going slowly but is very close to the destination, rather than giving it to a vehicle reaching a given nearest point faster. To do this, GeOpps can vary the average vehicle speed, acting as a weight, used to divide the remaining distance to give more weightage to vehicles moving closer to the destination. However, it does not provide a method to optimally calculate this weight.

The single copy approach of GeOpps limits the benefits of finding diverse paths to the destination as some of them might be faster. Thus, GeoSpray [11] uses the principles of GeOpps and combines the multicopy approach. Multi-copy routing schemes are noted for high delivery ratios, low bundle delivery delays, but high overheads due to duplicated copies. Thus, GeoSpray combines the replication approach of the Spray and Wait protocol [50] to

Table 2
State of the Art forwarding algorithms.

Algorithms	Type	Single/multiple copy	Replication rate	Functions, objectives
Direct delivery	Direct	S	None	Source moves and delivers the bundle directly
First contact	Probabilistic	S	Very low	Random walk search is used to deliver the bundle to its destination
Epidemic (ER)	Flooding	M	Very high	Rapid propagation of data
Spray & wait	Controlled flooding	M & S	Medium	Sets a limit on the number of copies
PRoPHET	Probabilistic	M	Medium	Forwards packets based on past node encounter history
MaxProp	Flooding	M	High	Use of the delivery likelihood as a cost assigned to each destination
Delegation forwarding	Intelligent forwarding	S	Low	Versatile forwarding based on quality (flexibly defined) of encountered node.

limit the amount of duplicated copies. It initially uses a multiple-copy scheme, which spreads a limited number of L bundle copies to exploit diverse paths. After that, it switches to a single-copy forwarding scheme. GeoSpray also uses a scheme to clear the already delivered bundles from node storage by propagating the delivery information. GeoSpray shows better delivery ratio than GeOpps at the cost of increased overhead due to replication, but those overheads are less than the Epidemic protocol and are similar to Spray and Wait.

For the above protocols, note that the calculation of the nearest point is made during contact. Sometimes, the contact opportunities are short and, if the nearest point calculation involves calculating the route from multiple intersections then it can be very slow and can waste a significant percentage of contact opportunity. Another approach suggested by GeOpps to take the forwarding decision uses straight line distance. That approach is faster but less accurate because actual routes to the destination are not considered.

One limitation of the above work is that they assume the destination is static and will suffer when the destination node is mobile. To tackle this problem, Location Aware Routing for Delay-Tolerant Networks (LAROD) [54] uses a location dissemination service. The moving destination disseminates its new location using LAROD. The algorithms are evaluated under a realistic application, namely unmanned aerial vehicles and road networks are not considered. Moreover the comparison is made only with a non geographic scheme, Spray and Wait.

Another approach, Converge and Diverge (CAD) [55], uses delegation replication, which is similar to delegation forwarding [55]. This uses two phases to route bundles to the mobile destination. The authors of CAD improve upon their previous work, Come-Stop-Leave (CSL) [56], by considering destination mobility. CSL assumes a fixed destination and reduces the number of replications using geographic information by not replicating to the nodes leaving the area of stationary destination. For mobile destinations, CAD estimates the movement radius of the destination using its historical location, speed and time elapsed. This estimate is updated with time and during the converge phase, the node carrying the bundle replicates it to the encountered node only if that node is moving faster towards the movement area of destination, considering its distance from the area, its speed and angle of its direction to the area. The diverge phase is started once the node is within the destination movement area. During the diverge phase, the angle of the moving node is not taken into account and a replication candidate is chosen based on how fast it can diverge to cover the area of estimated movement of the destination node.

A parallel proposal, called Delay Tolerant Firework Routing DTFR [57] follows a similar approach with a few differences. During the first phase, called homing, the bundles are forwarded using geographic information, like a piece of firework, homing in to the destination towards a point called the firework center. During this phase, the bundles are forwarded in a single copy manner. After the bundle reaches the firework center, the explosion and spread phases take place, so that L bundle copies are spread to symmetric points chosen on the circumference of the circle covering the destination area. The authors of DTFR propose their own simulator and are able to simulate large number of nodes. Comparison studies are not available, but there are some points where CAD and DTFR differ. In comparison with CAD, DTFR should produce lower overhead as initially DTFR uses single copy forwarding compared to delegation replication which is used in CAD. At the same time DTFR cannot take the advantage of multiple-copy forwarding and the benefits of diverse paths. Moreover, DTFR is evaluated for simplistic maps and results may not correlate with realistic city maps.

Finally, a hybrid geographic based algorithms GeoDTN+nav [58] has mutiple modes so that it can switch from GPSR like mode during dense traffic to DTN mode when vehicle traffic is sparse.

4.3. Multicast algorithms

During transfer situations in the Internet or in MANETs, it is often assumed that multicast group membership changes rarely. This is essentially due to the short data transmission delay on this type of network. However, this is not the case when it comes to DTNs, because of the long connection delays and disruptions, which result in frequent changes to multicast group membership. There are many potential DTN applications where it is important to operate in a group-based manner, such as information dissemination about victims in the case of a disaster recovery. The authors in [59] suggested another scenario, where multicast communications is relevant. For example, one can consider a network of city buses, where a transportation agency wants to provide passengers with personalized news related to their position. In this case, a given bus can obtain news updates by the cellular network and share the information among various buses via radio communication, which is less costly.

As a consequence, it becomes necessary to define new multicast models as a solution to this kind of challenging problems. The authors in [60] focus on three models related to multicast DTNs: (a) single node model, where a unique node holds all destinations and delivers to each destination at contacts; (b) multiple copies model based on replication if the encountered node satisfies a certain quality condition; (c) single copy model, in which destinations can be scattered at different nodes through by maintaining of a single copy of each destination.

A survey covering multicast routing for DTN, up to 2010 is presented in [61]. The authors classify the multicast routing protocols into four categories: flooding, Tree based, probabilistic and Intelligent, which combines flooding and forwarding for a better use of available resources.

A recently proposed multicast routing protocol, named NewVDTN [62], uses features from geographic routing, PRoPHET and Spray and Wait protocols. The idea proposed by the authors is to test the performance of protocol in cases that are similar to a rural area where usually the vehicle density is low and a city where the traffic is dense, differentiation between the dense and sparse scenario is based on an estimation of the number of nodes encountered. If a dense scenario is detected, a careful selection of MULE nodes is made. Taking into account aspects such as the network general storage level estimation and their movement directions, the sources assign a TTL to the created message, according to the message priority, to reduce congestion. Messages are scheduled according to priority and general buffer occupancy estimation. In sparse scenarios, the goal is to forward messages to as many vehicles as possible, in order to get better deliver possibilities to final destinations. The network node density is estimated by each node using an Exponentially Weighted Moving Average (EWMA), which gives an importance weight to each network node. The list of nodes contacted is always sorted according to their estimate of the density of vehicles. It is possible to transmit messages first to the contacts with highest contact probabilities. Another feature implementation has been the choice of MULE vehicles according to their direction of movement which has to be at least 45 degrees different from the direction of movement of the node that carries the bundles, which helps to better distribute the bundles.

The authors compared NewVDTN to the Epidemic protocol that disseminates a very high number of messages copies inside the network. The same message generation period for all sources forces higher message traffic and a larger number of transmissions. It also notes that the mechanisms used contribute to an enormous overhead reduction better network congestion control, giving a better delivery ratio. Using the WFQ scheduling method together with the implemented features, a better delivery ratio for the new routing protocol was achieved.

4.4. Optimisation based algorithms

Some of the resources in VDTNs are limited such as link capacity, due to interference from other nodes, encounter duration and storage space. Thus, allocating resources can be formulated as an optimisation problem, subject to these constraints, if one can build a mathematical model for VDTNs. Given the complexity of such mathematical models and the much lower amount of network information available, many heuristic algorithms have been popular, even if they are not based on theoretical formulation. Importantly, some of them do not even take resource limitations into account or do not consider all resource constraints.

Note that theoretical modeling can provide important insights that can help in further designing of forwarding protocols. Thus, some algorithms based on theoretical models have been proposed recently. The notion of per packet/bundle utility is used by RAPID (Resource Allocation Protocol for Intentional DTN) [107] to allocate bandwidth resources to a set of bundles, with an aim to optimize a given routing metric such as average delay, worst case delay or delivery ratio. The resource constraints considered are transfer bandwidth and storage capacity. Information about the network is obtained through a control plane by exchanging information among nodes. The exact solution is proven to be NP-Hard. Nonetheless, based on the insights obtained after the formulation as an optimisation problem, a heuristic algorithm is derived.

RAPID requires global information on which node carries which bundle and this could be a significant overhead. Thus, Lee et al [65] propose Max-contribution that considers further approximation by considering only local knowledge, using a technique called fusion to reduce the control plane data exchanges. They formulate their optimization problem based on a snapshot of current information available about the network. The solution being NP-hard, they derive a heuristic algorithm that solves the optimization problem. Another difference with RAPID is that a greedy link scheduling is used, unlike random link scheduling in RAPID.

4.5. Mobility and movement prediction

With navigation devices becoming standard and trajectories being quasi-known, it is possible to make predictions about node mobility and trajectory. This information can be useful for bundle delivery to find an optimal route or to locate the destination etc. Based on data mining, [66] found a spatio-temporal correlation in vehicle mobility and noted that a future trajectory of a vehicle is correlated with its past trajectory. Nonetheless, prediction is non trivial in an environment that is dynamic and intermittent as in the case of VDTNs.

Different levels of prediction are made starting from just using the vector of node movement as in vector based routing [67]. This work proposes that the nodes exchange their direction of movement and their velocity. With this information, nodes decide whether the bundles be replicated or not depending on the proposed function that takes into account the angle of movement as well as velocity of their neighbor. A node replicates most bundles to a neighbor moving orthogonal to itself. Bundles are not replicated to the neighbors moving in the same or opposite direction, the rationale being that a node moving in the opposite direction may pass through the nodes already met in the past by the carrier node. Similarly, a node moving in the same direction and at the same speed has similar chances of bundle delivery to that of the carrier and bundles are not replicated. However, as discussed previously, the velocity of the neighbors is also considered and hence bundles are replicated to a neighbor moving with higher velocity. Similarly the work in [108] proposes a simple data dissemination protocol considering only two directions: tail and non tail, to suppress excessive replicated bundles.

History based vector routing (HVR) [68] is an extension of the approach in [67] so that each node maintains its own location history as well as the location history of previously encountered nodes. When two nodes meet then they exchange information vectors. They also estimate a rendezvous probability for a given bundle. This depends on the node's transmission area and the area of destination node's possible location, which in turn depends on the destination's past known location and velocity. A bundle is replicated to its neighbor node with the highest rendezvous probability regarding its destination node.

An approach based on real statistics of inter-contact times is proposed in [69]. The authors use real vehicular traces, from two metropolis cities of China, and characterize the mobility patterns of thousands of public vehicles using higher order Markov chains. A vehicle carrying a bundle estimates the average bundle delivery delay between its encountered neighbour and the bundle's destination. If the estimated delay is smaller than its own delivery delay then the bundle is forwarded to the neighbour. The authors compare their scheme with alternative approaches [46][52], which use similar metrics such as bundle delivery delay and contact frequency. The results show that their approach performs better in terms of bundle delivery delay and delivery ratio.

Note that most of the previous works focus on the prediction of whether two nodes would have a contact, without considering the point in time of the contact or a regularly visited region. To improve this, Predict and Relay (PER) [70] uses two observations: first that nodes usually move around a set of well-visited landmarks, such as schools, office, etc, instead of moving randomly and second that mobility behavior can be semi-predicted using mobility history. PER employs a time-homogeneous semi-Markov process model that describes node mobility as transitions between landmarks. This model is further employed to design data forwarding rules that improve the delivery ratio as well as delivery latency. A similar work, [71] proposes REgioN bAsed (RENA) forwarding algorithms that uses regional movement history and model the probability of a node being found in a particular region. Moreover, it uses staying time, hitting time and return time from that region. Unlike PER that is tested through simulations of pocket switched networks, RENA is tested for VDTN scenarios through simulations. Pocket Switched Networking (PSN) [72] is a communication paradigm that relies on both occasional transmission opportunities and human mobility to carry data to its destination. PSN falls under Delay Tolerant Networking (DTN) umbrella. It assumes the following: mobile networking users carry one or more devices having significant storage capacity. Their mobility may be useful as a data carrying mechanism. Though PSN is different from VDTNs, both of them have highly dynamic network topologies due to mobile users.

4.6. Congestion control and traffic differentiation

Nodes may have to carry bundles for a long period of time and combining that with bundle replications can lead to congestion in VDTNs. Bundles have an expiry time, but even then the network can become congested. Thus, congested nodes will have to drop the incoming bundles that in turn will deteriorate the performance of routing algorithms and result in bandwidth wastage. Note that some replication schemes such as Spray and Wait, already put a limit on the total number of replications. However these approaches are proactive and cannot react to varying network congestion. Moreover, as VDTNs are intermittently connected, the closed loop congestion control strategies such as those used in Internet cannot be used.

One of the causes of excessive bundles in the network is when some bundles are stored in some nodes even after being successfully delivered. To solve this problem some proposals [73] use the acknowledgement method to disseminate the information that a particular bundle has been delivered. On receiving the acknowledgement the corresponding bundles are dropped from the storage.

Solis et al. [63] tackle the problem of malicious resource hogs that can cause congestion. Resource hogs are those who take lot of resources without contributing to the resource pools and are equivalent to free riders in peer to peer networks. A buffer management strategy is proposed such that trusted users are given priority over unknown users. With this approach, resource hogs will not be able to impact trusted users.

In order to gain some general insights on congestion, Thomson et al. [64] model the effect of changing network conditions and limited buffer space using Markov chains. A congestion control approach is proposed so that every node tries to gauge the level of network congestion based on local observations. This information is used to compute a metric named congestion value (*CV*) that is an exponential weighted moving average of drops/replication ratio. *CV* is used to determine the level of congestion and the replication limit of bundles is adapted using an additive increase and multiplicative decrease based on the current value of *CV*. This approach, combined with the acknowledgement approach is able to significantly improve the performance in terms of delivery ratio. Note that it can be difficult to fine tune the adaptation mechanism for the replication limit and it is not clear what the optimal values of adaptation factors and threshold values for *CV* are.

None of the approaches above take into account that even if VDTNs consider non real time applications, they still can have different performance requirements. It could be effective to give some bundles priority over others when the network is congested; storage is limited or when all the bundles cannot be transmitted during the short contact duration of an encounter. Soares et al. [74] propose a differentiated service approach so that a classifier is used to mark different bundles according to their application class: Expedited, Normal or Bulk as shown in Fig. 6. Different scheduling algorithms are studied which show the benefits in terms of better delivery ratios for priority bundles at the cost of lower priority ones. This work motivates further study on differentiated services and scheduling algorithms based on priority classes. A similar study for traffic differentiation was carried out by Shin et al. [75].

4.7. Incentive based cooperative forwarding

Most of the previous forwarding algorithms are designed assuming cooperation from the intermediate nodes so that the intermediate nodes will unselfishly forward the bundles to the next node. However, if they turn out to be selfish and if they do not forward the bundles, then it will significantly impact the performance of these algorithms. Please see some examples on modeling and analyses of the impact of selfish nodes in [76–78]. As pointed out in [79], when DTN nodes are controlled by rational entities such as people then they may behave selfishly. Without any incentive, they may not participate in forwarding of the bundles in order to save computational, storage and energy resources.

The existing incentive based approaches can be classified into three main categories [80]. Many of them use game theory for design and analysis: The first category is barter based algorithms based on direct reciprocation so that two nodes will reciprocate by doing favors for each other. This scheme is simple to implement as any long-term state information does not need to be maintained and leads to no overheads. However, when the service and its rewards are not simultaneous, or there is no way of knowing whether the other node had done some useful favor before doing a service for that node, then the barter approach can easily fail. The second category is virtual-currency based on which nodes would earn some credits by serving others. This approach however incurs implementation overheads in the form of billing, centralized agents to maintain the records, etc. In the third category, reputation based approaches give a reputation score based on the services received. Highly reputed nodes receive preferential treatment. This category is similar to a credit based approach and hence similar advantages and disadvantages.

Tit for tat strategy is proposed in [79], which can be classified as a barter strategy. The intermediate nodes are paid some credit based on forwarded bundles. They will then be able to forward their own bundles using the same credit. This scheme can improve the overall performance in terms of delivery ratio and low average delay as it can stimulate selfish nodes to cooperate using tit-for-tat (TFT) [79]. However, in order to work properly in practical scenarios, any credit based scheme needs some security mechanisms. Thus, a secure multilayer credit-based incentive (SMART) scheme, which uses multi-layered coins, is proposed in [81]. A multi-layered coin consists of a base layer added and signed by the source and other endorsement layers added by the intermediary nodes that forward the bundle. SMART also proposed some countermeasures against some attacks, such as credit forgery, submission refusal etc.

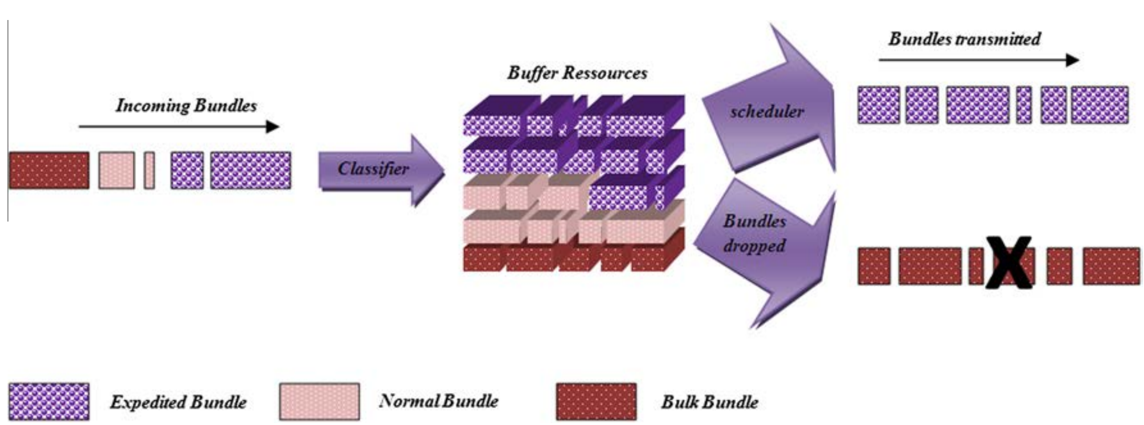

Fig. 6. Differentiation and classification of bundles in terms of application class.

Another credit based protocol, Practical incentive (Pi), which also tackles fairness issues, using credits as well as a reputation system, is proposed in [76]. To achieve fairness, the intermediate nodes can receive credit from the source if and only if the bundles arrive at the destination node. If the bundle fails to arrive at the destination then the intermediate nodes can still acquire some good reputation values.

With the above protocol, still a few more security issues need to be addressed, such as when a node having good reputation is compromised by a malicious node as pointed out by [82]. Also, Pi considers only single hop forwarding and it would be interesting to see how credit based mechanisms are applied to multi-copy protocols. One proposal applied to algorithms such as Spray and Wait is proposed in [83]. This uses game theory to compute the payoff allocation for cooperating nodes.

Some approaches use a local reputation system to avoid the overheads of communicating and maintaining a global reputation system. Reputation based context aware routing (RCAR) [84] and Trust based PRoPHET tackle the problem of malicious nodes called black holes, which deliberately attract many bundles, only to discard them later or to only forward them selectively. By using a reputation system, the nodes with a bad reputation will not be trusted as they are highly likely to discard the received bundle. The reputation of all nodes that participated in a bundle's delivery is increased using an ACK mechanism from the destination as a list is maintained in the bundle to record the identities of the nodes participating in forwarding. However, one issue is that if the bundle is not delivered, then the source cannot know which node misbehaved in the path of delivery or what the cause of the problem was. To tackle this problem, an aging mechanism is used and reputation of different nodes is decremented periodically and the interval for decrement is predicted round trip value. This value is predicted using history and ACK arrivals.

A new type of incentive paradigm is proposed in [80], called C4, where the authors use the help of infrastructure-based nodes such as infostations to forward the packets. The infostation combines all the received packets into network coded packets and then forwards them. After that the coded packets provide a forwarding incentive for everyone, as their data is also encoded within. It could be interesting to see how this approach can be developed and studied further and it can be extended to an infrastructure less scenario.

4.8. Social-based forwarding

Social-based forwarding is an evolution of algorithms for Delay tolerant Networks. This new angle of looking at DTN routing has attracted lot of attention. Many researchers look at ways to exploit social behaviors and properties in order to optimize routing performance. Some excellent surveys on social based routing can be found here [85], [86]. We provide an update on recent advances and also recapitulate the general background for readability.

In order to use social characteristics, social network analysis is important and some key aspects are [85]: community detection, information propagation, recommendation system, and security and privacy. Community detection is important as detecting clusters and communities among social networks can be exploited for example, by routing algorithms, as users belonging to the same cluster or community tend to have good connectivity. Study of information propagation can help us model the spread of information and can provide some insights on spread efficiency and time with respect to other social properties. Recommendation systems provide an idea on user behavior, for example, when a recommendation comes from someone known as compared to it coming from an unknown correspondence.

Some of the social based properties that are useful in the analysis and design of DTN routing algorithms are summarized here [85]:

- Social graph or contact graph: a social graph is a popular as well as an intuitive way of obtaining some social metrics, such as communality, centrality, similarity, etc that in turn are used in designing social based approaches. In order to build a social graph, some DTN approaches [72,87,88] use history of contacts and the sum of contacts among nodes over time is aggregated to form an aggregate contact graph. The aggregate contact graph is then used in place of a social graph with the argument that both are statistically similar.
- Community: the concept of community is useful because once the community or social clustering can be detected in a social graph it can be used for bundle forwarding. A user of a given community is more likely to meet another user of the same community as compared to some other user chosen randomly. Thus forwarding a bundle to a user from the destination's community can result in better performance.
- Centrality: centrality is related to a node's capability to relay bundles to others. Different metrics and definitions can be used ranging from simply how many edges are incident on that particular node, its capability of bridging different communities or a measurement of how close it is to all other nodes.
- Similarity: similarity of two nodes can be defined for example, similarity in terms of common neighbors, common interests or common location.
- Friendship: in DTNs, it defines the strength of connection between two nodes using contact history or common interests in the contents of bundles for example.
- Selfishness: as we discussed in the previous subsection, selfishness can be detrimental to the performance of VDTN routing algorithms as they are based on the assumption of cooperation. Thus, this is one social property that should be considered for forwarding and as discussed before some incentives can used to discourage selfishness. Incentive based approaches disregard the social ties among nodes. In one approach called Social selfishness aware routing (SSAR) [89] users are allowed to be socially selfish by considering user willingness (between 0 and 1). Willingness indicates whether a user is willing to forward the packet to another user or not, in combination with DTN constraints.

Now let us see how some of the above social based concepts are used. Grant [90] uses ant colony optimization considering the social metrics degree centrality, betweenness centrality and social proximity. Another approach, Simbet routing [87] uses betweenness centrality and similarity metrics to take forwarding decisions. Let us take the example of a source node sending a bundle to a destination node of a different community. Betweenness centrality is the measurement of a node's bridging capabilities between different communities. This metric can help in performing efficient forwarding between two different communities and thus node A can forward the bundle to another node with better betweenness centrality. Similarity metric is useful for example, in the later stages of forwarding as high value of similarity means two nodes belong to same community and are more likely to meet each other. Thus, forwarding the bundle to a node having better similarity with the destination node has a better chance of quick delivery. Thus Simbet uses a utility that is a weighted combination of these two metrics: betweenness centrality and similarity.

Bubble-rap [88] is another algorithm that uses social based metrics: centrality and community to forward packets. It is proposed for pocket switched networks, but it is equally interesting and can be applied to social based VDTNs. Two types of centrality metrics are calculated for different nodes: global and local. When a source sends a packet to a destination then a global bubble forwarding takes place so that the packet is hierarchically forwarding using global centrality until it reaches a node belonging to the community of the destination. After that the second phase, where local instead of global centrality is used to forward the packet inside the community until it reaches the destination, is started.

One drawback of the above approaches is that network wide global information is needed for forwarding decisions. Social group based routing (SGBR) [91] is a recent proposal that proposes forwarding using only local information for VDTNs. It looks only at the connectivity between two meeting nodes that is based on the history of previous meetings. When a node encounters another node, it forwards the bundle only if the other node's connectivity is below a threshold. Thus, the bundle is forwarded only to a node that is unlikely to belong to the same community as the forwarder. Moreover, a multiple replication approach, with a limit on the number of replications, similar to Spray and Wait, is used. SGBR shows improved performance as compared to traditional VDTN forwarding algorithms such as PRoPHET, Spray and Wait. However this is not the case compared with other recent approaches, especially the social based ones.

Contact frequency and duration is the key to many social based approaches. However, this can present some difficulties, as the information is dynamic, it is further complicated by the need to obtain this information globally. Recently, Wu et al. [92] proposed the use of social features, that are more static, such as gender, social status, language, region of origin, etc for forwarding in pocket switched networking. Two nodes are connected if they share at least one feature. A hypercube is formed using different social features as its dimensions and a feature matching step by step process is used for forwarding the packet to its destination. It will be interesting to see how this feature based approach can be translated to VDTNs.

CAF [93] considers a combination of geolocation as well as social characteristics for forwarding. Note that most of the algorithms discussed above are Push type of algorithms where a sender pushes a bundle towards a destination. In contrast, Delque [94] is a receiver oriented approach that is called query and response. The chosen relays take charge of both querying the relevant interest data and returning it to the demander. Delque uses geo-community and mobility prediction in its algorithm. The Geo-community concept is used for locating information from a community based on its geolocation and mobility prediction is used when the source can be mobile. Spatio-temporal prediction is used, in order to exploit the information that some nodes are usually present at a given location, such as offices, only during certain time ranges.

4.9. Other approaches

For the case of highway environments, authors in [95] developed a V2 V (vehicule-to-vehicule) model for information propagation in bidirectional Vehicular Delay Tolerant Networks (DTNs). They showed the existence of a threshold concerning vehicle density, above which the information speed increases in a remarkable way over the vehicle speed, and below which the information propagation speed is on average equal to the vehicle speed. The study showed that, under the threshold, even though the average propagation speed equals the vehicle speed, DTN routing that uses cars moving in both directions, provides a gain in the propagation distance, with respect to the elapsed time. This gain follows a sublinear power law, in the referential of the moving cars.

The authors characterize information propagation speed as increasing quasi-exponentially with the vehicle density when the latter is well above the threshold. They analyzed how information propagates under the threshold, and showed that DTN routing using bidirectional traffic provides a gain in the propagation distance, following a sub linear power law with respect to the expired time.

Obtaining a complete image of the way information propagates in vehicular networks on roads and highways, which is useful in determining the performance limits and designing appropriate routing protocols for VANETs, the authors have not:

- Dealt with other models of vehicle traffic and radio propagation.
- Given a detailed expression of this threshold in specific VANET models.

Network coding (NC) is a novel technique introduced at the turn of the millennium to improve performance of network as well as throughput. In DTNs, the emergence of a routing protocol that uses a batch of messages might be an interesting problem. These routing protocols are mainly driven by limited resources and transmission opportunities, as well as, the long delivery delays.

To combat network overheads, the authors in [96] exploit the principles of network coding and its advantage of reducing the number of transmissions in a DTN context. They proposed a Network Coding-based Epidemic Routing (NCER) protocol which enhances ER with the network coding efficiency. Furthermore, the authors in [97] proposed Efficient Network Coding-based Protocol (ENCP) as an extension to Coding-based Epidemic Routing. This aims to increase the efficiency of the protocol and reduce its incurred message delivery delay.

The Message Ferrying (MF) scheme is a proactive approach for data delivery in sparse networks [98]. As network partitioning occurs, MFs are injected into the network. In an MF scheme, the network devices are classified as message ferries nodes based on their roles in communication. Ferries are devices which take the responsibility for carrying messages to other nodes, while regular nodes are devices without such responsibility. MF movements span the entire network area with each one of them mainly responsible for carrying bundles from nodes in one partition to nodes in another partition. The challenge is to determine the number of required MFs and determine the route of each, so as to reach a certain optimal objective.

In this article, we mostly considered approaches that do not rely on the infrastructure. Deploying infrastructure nodes, such as Road Side Units (RSUs), can always help improve the performance of bundle delivery protocols. The authors of [99] show that deploying RSUs can improve the performance up to 5 times in some cases. However, with numerous vehicles, the buffering capacity of RSUs becomes a limiting factor. Thus, they propose an algorithm to do joint optimization of bundle forwarding and buffer allocation.

5. Discussion and open issues

In the beginning of this paper, we discussed some VANET protocols. Some initial VANET protocols do not manage disconnections, making them unsuitable for VDTNs, or when vehicular density becomes sparse. Recently there have been some proposals such as VADD [30], JARR [28], etc, that incorporate some mechanisms that allow them to be applicable for VDTNs. However, such protocols need to be evaluated in comparison with existing VDTN protocols, in order to obtain more insights on their performance.

In the context of VDTNs, the protocols have evolved from using random forwarding or flooding to more intelligent forwarding, such as using geolocation, mobility prediction, etc. Currently, the trend is to exploit social behavior prediction. The behavior and movements of people can be used to predict optimal forwarding opportunities, because people's daily routines follow certain patterns in many cases. For example, many people take the same

Table 3
Routing proposals for VDTN.

Forwarding algorithm	Type	Single/ multi copies	Replicate rate	Information needed	Objectives/comments
GeoSpray	Geo	M & S	Medium	Navigation	Does not tackle mobile dest
LAROD	Geo	M	Medium	Navigation	Tackles mobile dest.
CAD, DTFR	Geo, delegation	M & S	Medium	Navigation, dest. trajectory	Replicate at end to reach the destination
New VDTN	Multicast, geo, prob.	M	Medium	Previous encounters, geolocation	Estimates congestion and density to limit the number of copies
RAPID	Optimisation	M	Medium	Global knowledge on nodes, transfers	Powerful approach but needs global information
Max-Contribution	Optimisation	M	Medium	Local knowledge	Needs a local snapshot of information
Vector based (VR), HVR	Movement prediction	M	High-Medium	Movement vector, velocity	Unlike VR, HVR uses historical vectors of encounter nodes
PER, RENA	Mobility Prediction	S	Low	Spatio-temporal mobility history	Nodes visiting particular regions at particular time
Solis et al. [63]	Tackling free riders	NA	NA	Trusted/untrusted users information	Complementary to forwarding schemes
Thomson et al. [64]	Congestion control	M	Adaptive, medium	Local levels of congestion	Adapts replication level to congestion
Soares et al. [74], Shin et al. [75]	Differentiate traffic	NA	NA	Type of application	Marks different bundles, differential packet scheduling
TFT	Incentive	NA	NA	Credits	Lacks security schemes
SMART, Pi	Incentive	NA	NA	Credits, Reputation	Use multilayer credits, Pi uses reputation too
RECAR	Incentive	NA	NA	Reputation	Est. reputations from dest. ACKs or history when non-delivery
C4	Incentive	M	Medium	Network coding	Coded packets are valuable to all
SimBet, Bubble-rap	Social	M	Medium	Global contact info	Bubble rap uses 2 phases: global & local forwarding
SGBR	Social	M	Medium	Local contact info	Forward to a node unlikely to be in the same community
CAF	Social	M	Medium	Geolocation,	Combines geolocation with social characteristics
Wu et al. [92]	Social	M	Medium	Social features	No need of global contact info
Delque	Social	M	Medium	Spatio-temp mobility, social	Receiver driven approach

vehicular route at approximately the same time when going from their homes to offices on weekdays. These prediction based approaches show that if we are able to predict a node's movement or behavior, or are able to find patterns, then we can improve the performance of opportunistic forwarding in the context of VDTNs.

Table 3, summarizes routing proposals for VDTNs discussed in this article. Different columns show the type of the protocol (geographic, social, etc.), whether it uses single or multi copies, replicate rate, type of information exploited and the last column provides some comments on the algorithm used. It can be noted that several VDTN protocols exist in the literature. Now we have several protocols with varied forwarding metrics suitable to different scenarios. Thus, one of the current directions in DTNRG group is to design a global routing framework that is flexible enough to incorporate several such metrics. Apart from the need to design such a global framework, there are other open issues that need attention from the research community. In the following, we discuss some of the challenges and open issues that deserve to be addressed. Starting from some theoretical aspects we move on to some practical as well as global issues.

5.1. Mathematical modeling, simulation and real test beds

Mathematical modeling of VDTNs is complicated, due to intermittent connectivity and dynamic temporal notions. Some future directions would be to refine existing models or to design new ones. Such models will be useful for analytical studies and for simulating a high number of nodes. Moreover they will be highly useful in providing some intuitive insights that in turn will be invaluable in designing heuristic algorithms for optimal forwarding.

For simulations, there are many options to simulate mobile nodes in a realistic way. First, mobility traces are generated and then they are injected into a network simulator to study the performance of forwarding algorithms. However, this is like an open loop simulation and the use of these traces does not allow us to study the impact of network performance on the behaviour of nodes and their mobility. Thus, integral closed loop simulation is one way forward. Different simulators have been used in the field of DTN, like the well known NS2 or NS3, however there is another simulator which is dedicated to this kind of networks: The opportunistic network environment (ONE). It is a JAVA based simulator, which allows node movement modelling, opportunistic contact between nodes using different interface types. The ONE implement many DTN routing protocols cited above and permits graphical visualization of mobile nodes [100] [101].

Finally, many of the algorithms presented in this paper do not evaluate their performance on real testbeds. Relying only on simulations may not help us to find some issues that will easily appear when tested on real test beds.

5.2. Addressing and naming problem

Addressing and naming of VDTN nodes also need to evolve further to have more and more flexibility. Sometimes geographic notions are assumed for addressing in VDTNs, however for dynamic nodes, which may not be tied to a particular geographic location, it will be difficult to find with an addressing scheme that can make things easier for forwarding.

Moreover, it is useful to provide Internet connectivity to the nodes at some point, thus addressing should be able to consider the case of collecting information from the sensors, relaying and passing it to the Internet and vice versa.

5.3. Improvement of bundle protocol

Some of the problems such as time synchronization, no error correction, etc, with bundle protocol were identified in [24].

Forwarding algorithms have attracted lot of attention of the researchers, but some of the problems of bundle protocol also need to be addressed.

5.4. Considering fairness while forwarding

Fairness is one issue that needs to be addressed as nodes can have different levels of reachability and less reachable nodes might be unfairly treated. One initial approach is to design forwarding strategies so that they also consider fairness and not only other parameters like delivery probabilities etc are taken into account. One such initial approach is presented in [102].

5.5. Algorithms considering multiple forwarding metrics

Many algorithms look at a certain metric such as contact probability or some social based metric in order to take decisions on bundle forwarding. However, there exist multiple interesting metrics especially in social based approaches. One future exploration could be to look at multiple metrics together for example, with different weightage or depending on the situation or type of application. This approach could be difficult, but it can provide interesting angles to tackle the problem of bundle forwarding.

5.6. Towards smart cities

In this paper, we focused only on forwarding protocols in VDTNs. Nonetheless; the big picture is to design smart cities with networked sensors, intelligent vehicles and people with portable devices. This would automatically mean nodes with heterogeneous capabilities and varied functions. Sensors would sense the environment before sending the data to relay nodes. Relay nodes will relay the information to some destination or some other point with Internet connectivity. Our recent studies [103,104], focus on the assessment of the performance of some well-known VDTN routing protocols for collecting sensor data in cities. In order to have transparent connectivity, protocol design should be able to consider and tackle the heterogeneous capabilities of different nodes. Multi-disciplinary technological advances are needed, considering different technologies together. A recent survey [105] on wireless sensor networks (WSNs) explores synergies between different technologies.

Some cross layer solutions are also needed. For example, some of the algorithms presented already assume that Geo-localisation information is readily available to be used by the forwarding layer. However, for that to function a cross-layer interface is needed. Moreover, the use of other cross-layer information, such as radio maps and available radio spectrum, like in cognitive radio, needs to be explored for optimizing forwarding in VDTNs [109].

Different applications need to be considered and hence traffic differentiation or a notion of "Quality of Service" needs to be developed. Most of the VDTN applications will not be real time. However, if we consider a general use case, then there will still be different applications with different priorities and different requirements. Moreover, all of them will need to be either virtually or physically separated from real time ITS data traffic.

Finally, vehicles will not remain in a VDTN scenario all the time. In a real scenario, apart from crossing a region with sparse vehicle density, they may go through cities with dense traffic and may cross some Internet access points. Thus, solutions are needed that can deal with general cases. For example, either by making different applications for different scenarios or by looking for hybrid solutions, which are able to treat different types of scenarios. Thus, hybrid solutions are one future direction so that these solutions can switch from one mode to another. Some of these were already presented in this paper and further exploration is needed.

6. Conclusion

In this paper we provided a survey on the advances of opportunistic forwarding for Vehicular Delay Tolerant Networks. First, a background on DTN was given and then different forwarding algorithms were covered. We discussed some state of the art algorithms that have become popular and are used by researchers for reference and for performance comparison. Then some recent proposals were presented after classifying them into different categories such as geographical forwarding, mobility prediction, social based forwarding etc. We also presented some solutions such as incentive based and congestion control that are complimentary to the forwarding algorithms. Some background information was also provided in some subsections. Before concluding the paper, we discussed some of the relevant challenges and open issues that deserve some attention from the research community. There are several challenging issues that need to be tackled, in addition, deployment of real test beds and standardization of VDTNs need to be carried out in future.

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