

# Evaluating the Impact of Storage Capacity Constraints on Vehicular Delay-Tolerant Networks

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## Abstract

*Vehicular Delay-Tolerant Network (VDTN) was proposed as a particular application of a mobile Delay-Tolerant Network (DTN), where vehicles act as the communication infrastructure for the network, relaying messages between the network nodes. In this paper, we consider the use of a VDTN to provide low-cost asynchronous communication between sparse populations spread over a remote vast region. We analyze the influence of the VDTN network node's storage capacity (buffer size), on the efficiency of four DTN routing protocols, in terms of message delivery probability. Our scenarios show that the routing protocols message replication strategies react differently to the increase of buffer size in specific network nodes. Epidemic and MaxProp protocols benefit from the increase of the storage capacity on all network nodes. Spray and Wait protocol only takes advantage on the increase of the vehicle's buffer capacity. We expect that this paper will provide a deep understanding of the implications of storage constraints over the performance of a VDTN, leading to insights for future routing algorithm and buffer management theoretic studies and protocol design.*

## 1. Introduction

The Delay-Tolerant Networking (DTN) [1] paradigm was proposed to address communication issues in challenged environments with sparse intermittent connectivity, long or variable delays, asymmetric data rates, high loss rates, and even when no end-to-end connectivity exist. The DTN concept has been applied to various areas including interplanetary networks [2], underwater networks [3], wildlife tracking sensor networks [4], and networks to benefit developing communities [5].

Vehicular Delay-Tolerant Network (VDTN) is a particular application of a mobile DTN, where vehicles are opportunistically exploited to offer a message relaying service [6]. In this paper, we consider the use of a VDTN to provide a low cost solution to connect villages located in a vast geographical area with a sparse population density, and where a telecommunications infrastructure is not available. In such a scenario incurred delays are high and unpredictable, intermittent connectivity is common and data paths exist over time.

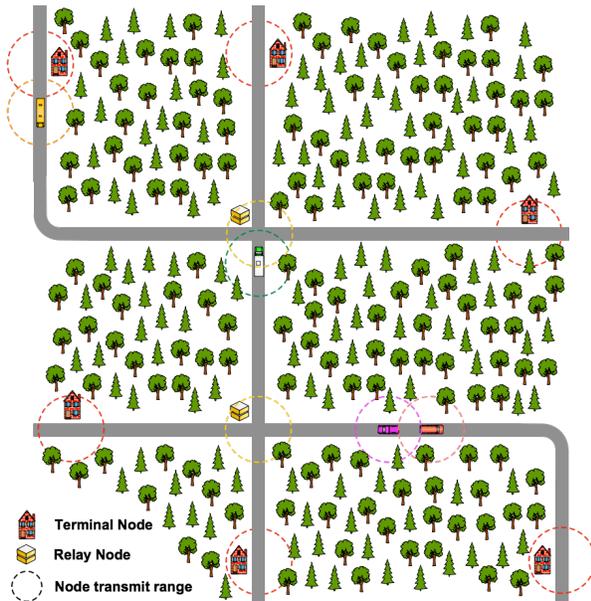
To cope with disconnection, fixed or mobile network nodes store data on their buffers for long periods of time, while waiting for new opportunities to forward data to intermediate nodes or to the final destination. Therefore, intuitively, the storage capacity of the network nodes may affect the end-to-end-performance of the network. Using a map-based model of a Portuguese rural dispersed region, we analyze by simulation the efficiency of buffer resource utilization on four DTN routing protocols applied to a VDTN, comparing their performances in terms of overall message delivery probability.

The remainder of this paper is organized as follows. Section 2 describes the VDTN architecture and identifies our contribution. Section 3 presents the simulation scenarios and analyzes the obtained results. Section 4 concludes the paper and provides guidelines for future work.

## 2. Vehicular Delay-Tolerant Network

VDTN architecture model is based on the three node types presented on figure 1: *terminal nodes*, *mobile nodes*, and *relay nodes*. *Terminal nodes* are located in isolated villages and provide network connection to end-users. *Mobile nodes* (e.g., vehicles) act as the communication infrastructure for the network, collecting and disseminating data. They move

on roads and carry data between *terminal nodes* (figure 2). *Relay nodes* are store-and-forward stationary devices located at crossroads. They allow *mobile nodes* that pass by to collect and leave data on them, thus improving the overall message delivery probability [7]. When *mobile nodes* meet, they can exchange data with one another.



**Figure 1. Example of Vehicular Delay-Tolerant Network nodes**

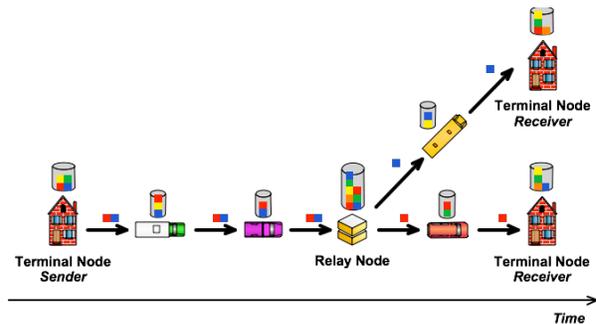
Vehicular Delay-Tolerant Networking store-carry-forward paradigm is used to deal with intermittent connectivity. In these networks the same message can be spread to multiple nodes in order to increase message delivery probability and reduce message average delay. However, messages can be dropped in cases of buffer overflow.

Several network parameters have an impact on the end-to-end performance of a VDTN. The number of mobile nodes, their mobility pattern and speed can influence the overall performance of the network. Furthermore, network nodes interactions, cooperation, and their design characteristics, such as, power, storage capacity, transmit range, and physical link rate should also be considered.

Whereas the size of the nodes buffers, it is also important study how nodes use their buffers. Large buffer capacities may not be sufficient to increase the probability of messages to arrive at their destinations, and buffer management schemes may be necessary.

Thus, this paper studies the impact of varying the buffer size of *terminal nodes* and *mobile nodes*, on four multiple copy DTN routing protocols applied to a VDTN. The motivation to introduce different values to the *terminal node's* buffer size comes from the fact that besides being *traffic sources* and *traffic sinks*, if sufficient storage is available, they can also implement the functionality of *relay nodes*. Therefore, a *terminal node* can store data destined for any other *terminal node(s)*, which was leaved there by a *mobile node*. This process is illustrated in figure 2. Intuitively, this will improve the overall message delivery ratio.

We consider three different scenarios, where the number of *mobile nodes* is increased and, therefore, the number of transmission opportunities is augmented (and the overall network load). The objective is to determine if increasing the node's buffer size has a direct effect on augmenting the overall message delivery ratio.



**Figure 2. Mobile nodes carrying data between terminal nodes**

### 3. Performance Assessment

In order to evaluate how the *terminal nodes* and *mobile nodes* buffer sizes affect the VDTN performance, a simulation study is performed using the Opportunistic Network Environment (ONE) Simulator [8]. We are interested on the performance evaluation of the overall message delivery ratio (measured as the relation between the number of unique delivered messages and the number of sent messages). The following four widely applicable multiple copy DTN routing protocols are considered: Epidemic [9], MaxProp [6], PRoPHET [10], and Spray and Wait [11].

Epidemic is a flooding-based routing protocol where nodes exchange the messages they don't have. In an environment with infinite buffer space and bandwidth, this protocol performs better than the other ones in terms of message delivery ratio and latency,

providing an optimal solution. MaxProp prioritizes the schedule of messages transmitted to other nodes and also the schedule of messages to be dropped.

PRoPHET is a probabilistic routing protocol that considers a history of encounters and transitivity. It considers that nodes move in a non-random pattern, and applies “probabilistic routing”. Spray and Wait protocol creates a number of copies  $N$  to be transmitted (“sprayed”) per message. In its normal mode, a source node  $A$  forwards the  $N$  copies to the first  $M$  different nodes encountered. In the binary mode, any node  $A$  that has more than  $l$  message copies and encounters any other node  $B$  that does not have a copy, forwards to  $B$  the number of  $N/2$  message copies and keeps the rest of the messages. A node with  $l$  copy left, only forwards it to the final destination. We evaluate both the normal and binary modes, with  $l2$  message copies.

Next, subsection 3.1 presents the simulation settings. The experimental results of each scenario are discussed on subsections 3.2 to 3.4.

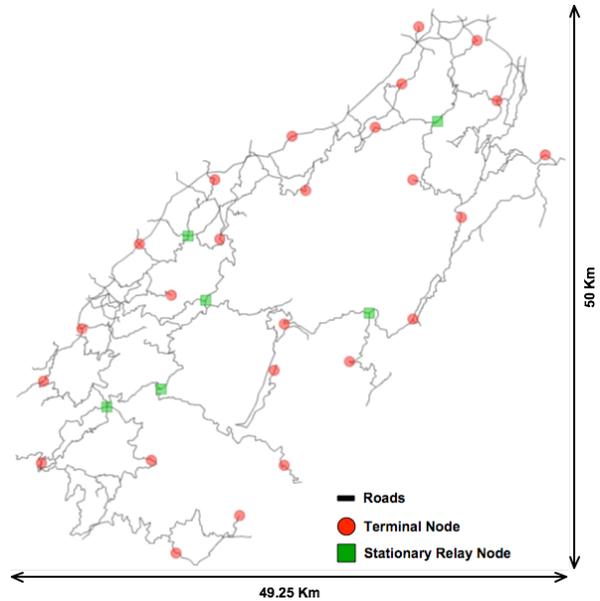
### 3.1. Simulation Settings

Using Google™ Maps [12] and OpenJUMP Geographic Information System [13], we have modelled a real-world map of the *Serra da Estrela Region*, a Portuguese Mountain Region that covers a dispersed area with approximately 2500 Km<sup>2</sup>. This map-based model is shown on figure 3.

We analyze three different scenarios with 6, 12, or 18 *mobile nodes* moving between *terminal nodes*. For each of those scenarios we change the buffer size of the *terminal nodes* and the *mobile nodes*.

The study assumes 25 real-world sparse village locations to place the *terminal nodes* (Figure 3). Each *terminal node* is simultaneously a *traffic source* and a *traffic sink*. It also generates messages using an inter-message creation interval in the range [5, 15] minutes of uniformly distributed random values. Each message has a size in the range [500 KB, 2 MB] of uniformly distributed random values. All the messages have an infinite time to live (TTL). *Terminal nodes* have a FIFO message buffer whose size changes between 100, 200, 300, 400 and 500 Mbytes across the simulations, for each scenario.

Six *relay nodes* with 1 Gbyte FIFO message buffer were placed at the crossroads, as shown in Figure 3. The results collected during the simulations guarantee that this amount of storage is large enough, and does not bias the results presented on next subsections.



**Figure 3. Serra da Estrela Region simulation area with the locations of the terminal nodes and the relay nodes**

*Mobile nodes* only move between *terminal nodes*. When a *mobile node* reaches a *terminal node*, it randomly waits 15 to 30 minutes. Then, selects a random *terminal node* (different from the previous one) as its next destination. Afterwards, a random speed between 30 and 80 km/h is selected, and the *mobile node* moves over there using the shortest path. Every *terminal node* has equal probability for being selected.

*Mobile nodes* have a FIFO message buffer whose size changes between 200 and 400 Mbytes across the simulations, for each scenario. When *mobile nodes* are in contact with *terminal nodes* they try to deliver the messages stored in their buffers. Each of the messages successfully delivered is removed from the buffer, freeing essential storage space.

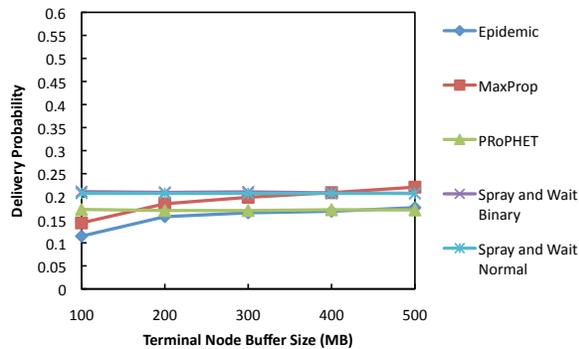
All the network nodes connect to each other using 802.11b with a data rate of 6 Mbit/s [14], and a transmission range of 350 meters using omni-directional antennas. *Terminal nodes* and *relay nodes* only exchange data with *mobile nodes*. In addition, *mobile nodes* can communicate between themselves.

For each scenario, the network nodes will exchange messages during twelve real time hours (simulated). The traffic matrix is not provided in advance, and the network behavior is non-deterministic. We run series of simulations using different random seeds, and report the mean values.

### 3.2. Results with 6 Mobile Nodes

In order to evaluate the impact of the nodes storage constraints on the overall message delivery probability, we first consider a scenario where 6 vehicles (*mobile nodes*) with a 200 MB buffer, carry data (messages) between *terminal nodes*. The results collected during simulation, shown that 100 MB are enough to store all messages created by a *terminal node* during the twelve (simulated) hours. This is due to the messages creation interval, and their possible sizes. The *terminal node's* buffer size changed between 100 MB and 500 MB.

Figure 4 shows the message delivery probability for six mobile nodes with 200 MB buffer. As may be seen, the Epidemic flooding approach benefits from the increase on the *terminal node* buffer size, augmenting its delivery probability. This effect is more evident when the buffer size increases from 100 MB to 200 MB. Furthermore, increasing the buffer size only slightly augments the delivery ratio. This is caused by the limitation introduced by the number of *mobile nodes* and their buffer size that restricts the dissemination of messages. MaxProp protocol also floods, but after delivering messages explicitly clears them. It performs better than the other protocols when buffers with 400 MB or 500 MB are deployed. PRoPHET registers similar delivery ratios across the simulations. Spray and Wait binary and normal variants limit the number of copies of each message (for twelve, in our case). Both variants register similar values across the simulations. When *terminal nodes* have buffer size smaller than 300 MB, they perform better than the other protocols.

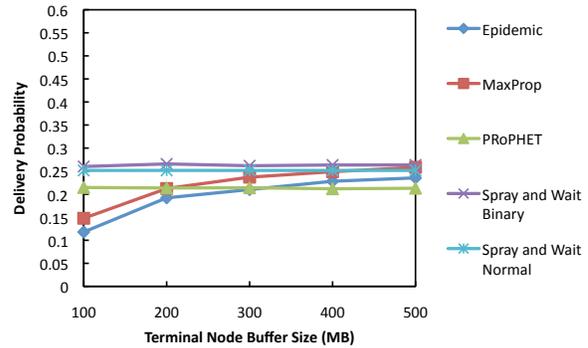


**Figure 4. Message delivery probability using 6 mobile nodes with 200 MB buffer**

Even though, increasing *terminal node's* buffer size augments the delivery probabilities for two of the routing protocols, all routing protocols still register low delivery ratios. Since *mobile nodes* are responsible for physically carry data, their buffer size was increased to

400 MB, allowing them to store and transport a larger number of messages. The effect of this modification is shown on figure 5.

As it can be observed, all routing protocols increase their delivery probabilities. Like previously, PRoPHET and Spray and Wait present a behavior where no significant effect is registered by changing the *terminal node's* buffer size. In this case, the Spray and Wait binary variant performs better than the other protocols. As expected, increasing the *mobile nodes* and *terminal nodes* buffers sizes reduces the effect of Epidemic poor utilization of the network storage resources. Its performance approximates to MaxProp and Spray and Wait.



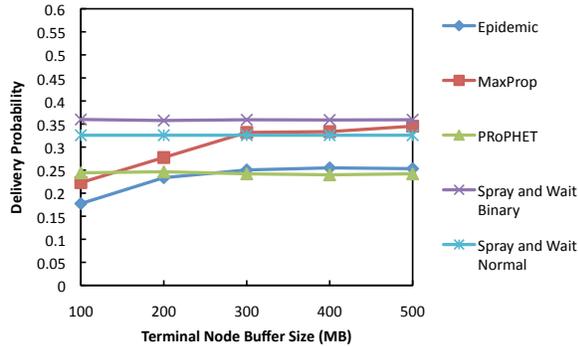
**Figure 5. Message delivery probability using 6 mobile nodes with 400 MB buffer**

PRoPHET behavior is caused by its “probabilistic routing” approach. When buffers over 400 MB are deployed it performs worse than the other protocols. Therefore, in this scenario, it does not take any advantage of large buffers. Finally, comparing Figures 4 and 5, it is observed that Epidemic and MaxProp register similar values when *terminal nodes* have 100 MB buffer, independently of the *mobile node's* buffer size. This demonstrates the importance of *terminal node's* storage capacity, to increase the overall message delivery ratio on these protocols.

### 3.3. Results with 12 Mobile Nodes

In the second scenario, instead of having 6 *mobile nodes* we have 12 (with a 200 MB buffer). This increases the number of transmission opportunities, and improves the message delivery probability, as it can be observed on Figure 6. As observed on the previous scenario, and because of the same reasons, PRoPHET and Spray and Wait variants register similar values across the simulations, which mean that their performance does not depend on the *terminal node's* buffer size.

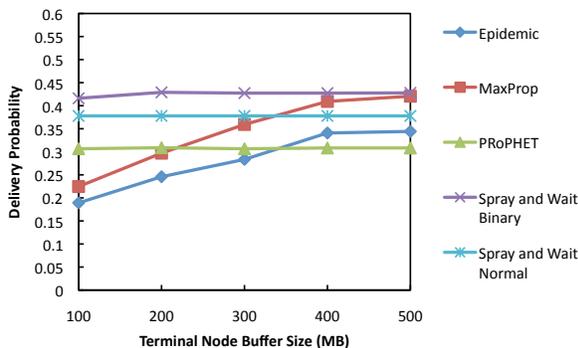
Spray and Wait binary variant performs better than other protocols. However, with the increase of the buffer size, MaxProp performance approximates from Spray and Wait binary. The Epidemic protocol origins poor network resources utilization, caused by its flooding technique, prevents it from increasing the delivery probability when *terminal node's* buffer size is greater than 300 MB.



**Figure 6. Message delivery probability using 12 mobile nodes with 200 MB buffer**

When *mobile node's* buffer size is increased to 400 MB (shown in figure 7), the overall message delivery ratio of all routing protocols increases. As it can be observed, comparing results of figure 4 to figure 7, the performance difference between the two variants of Spray and Wait has increased. The binary variant is more efficient, and when twelve *mobile nodes* with 400 MB buffer are deployed, it achieves better delivery probabilities than the other routing protocols.

Figure 7 also shows that Epidemic and MaxProp take advantage of larger buffers. In this case, the network load produced by Epidemic has less effect on the delivery ratio because of the larger storage capacity available on the *mobile nodes*.



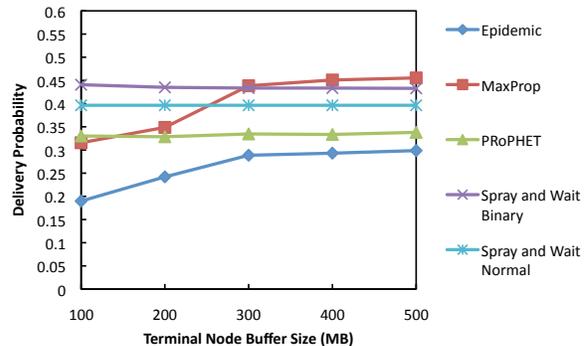
**Figure 7. Message delivery probability using 12 mobile nodes with 400 MB buffer**

### 3.4. Results with 18 Mobile Nodes

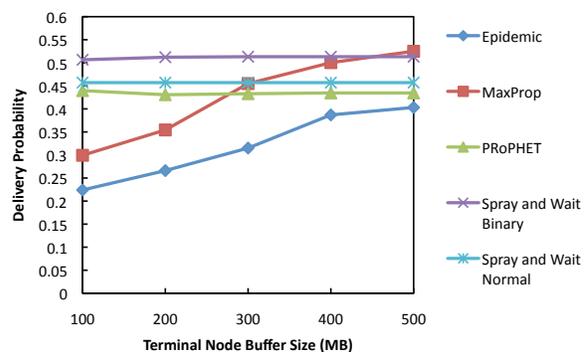
In the third scenario we increase the number of *mobile nodes* to 18 (also with a 200 MB buffer). This also increases the number of opportunistic contacts, reducing the inter-contact times, and improving the overall connectivity. Hence, this has a positive impact on the overall message delivery probability of all routing protocols, as shown in figure 8.

An analysis of these results reinforces that Epidemic flooding scheme is limited by the available storage at *mobile nodes*. Eighteen *mobile nodes* create more transmission opportunities. Therefore more messages will be exchanged, and buffer congestion will occur often. MaxProp protocol explicit message clearing after delivery, allows it to make a better use of the network node's storage resources.

When *terminal node's* buffers are equal or greater than 300 MB, MaxProp registers better delivery probabilities than the other protocols. Because of the fixed/limited number of copies created per message, Spray and Wait protocol does not benefit from the increase in the *terminal node's* buffer capacity.



**Figure 8. Message delivery probability using 18 mobile nodes with 200 MB buffer**



**Figure 9. Message delivery probability using 18 mobile nodes with 400 MB buffer**

Figure 9 also reinforces the importance of the storage capacity on *mobile nodes*. Since vehicles are opportunistically exploited to offer a message relaying service, increasing their buffer size augments the probability of messages to be successfully delivered. Even Spray and Wait routing protocol, takes advantage from the possibility of *mobile nodes* to store and transport more messages between terminal nodes, increasing its performance in comparison with results presented in figure 8.

#### 4. Conclusions and Future Work

In this paper we considered a VDTN network to provide connectivity on an isolated and dispersed region without network infrastructure. We evaluated how storage constraints of VDTN network nodes affect the overall network performance in terms of message delivery probability.

Several experiments were performed in three different scenarios with different number of *mobile nodes*. In addition, on each scenario, we changed the buffer size of *mobile nodes* and *terminal nodes*. It was assumed a fully cooperative opportunistic environment without knowledge of the traffic matrix and contact opportunities.

The DTN routing protocols considered in this study, require different buffer sizes to be distributed on different network nodes, in order to improve their message delivery rate. This is due to their different message replication strategies.

The study and protocol design of specific VDTN routing algorithms and buffer management techniques, are our interests for future work.

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