Traffic Differentiation Support in Vehicular Delay-Tolerant Networks

Vasco N. G. J. Soares[1,2,3], Farid Farahmand[4] , and Joel J. P. C. Rodrigues[1,2]

[1]*Instituto de Telecomunicações, Portugal*

[2]*Department of Informatics, University of Beira Interior, Covilhã, Portugal*

[3]*Superior School of Technology, Polytechnic Institute of Castelo Branco, Castelo Branco, Portugal*

[4]*Department of Engineering Science, Sonoma State University, CA, USA*

vasco.g.soares@ieee.org; farid.farahmand@sonoma.edu; joeljr@ieee.org

Abstract — Vehicular Delay-Tolerant Networking (VDTN) is a Delay-Tolerant Network (DTN) based architecture concept for transit networks, where vehicles movement and their bundle relaying service is opportunistically exploited to enable non-real time applications, under environments prone to connectivity disruptions, network partitions and potentially long delays. In VDTNs, network resources may be limited, for instance due to physical constraints of the network nodes. In order to be able to prioritize applications traffic according to its requirements in such constrained scenarios, traffic differentiation mechanisms must be introduced at the VDTN architecture. This work considers a priority classes of service (CoS) model and investigates how different buffer management strategies can be combined with drop and scheduling policies, to provide strict priority based services, or to provide custom allocation of network resources. The efficiency and tradeoffs of these proposals is evaluated through extensive simulation.

Keywords* — *Vehicular Delay-Tolerant Networks; Traffic Differentiation; Resource Management; Scheduling and Drop Policies

1. Introduction

Vehicular delay-tolerant networks (VDTNs) [1] are a promising technology for vehicular communications, based on the delay-tolerant networking (DTN) paradigm [2]. Nonetheless, VDTN is a new proposal with a layered architecture that assumes the separation between control and data planes and places the bundle layer below the network layer.

The control plane is responsible for exchanging signaling information between nodes at a contact opportunity. This information is used to setup a data plane connection to transmit data between network nodes. Bundles are defined as the protocol data unit at the VDTN bundle layer, and represent aggregates of Internet protocol (IP) packets with common characteristics, such as the same destination node.

In VDTNs, end-to-end connectivity does not require a continuous end-to-end path between source and destination nodes. Vehicle mobility and the store-carry-and-forward paradigm are exploited to extend the range of the network. Vehicles store bundles on behalf of the sender and carry them while moving along roads. When a node is in range with other network nodes, bundles are forwarded to their final destination or to intermediate nodes that can take the data closer to its destination. This paradigm allows that vehicles may carry data over time, from source (eventually, if possible) to the destination.

Opportunistic bundle replication is performed at contact opportunities. It contributes to the delivery probability improvement and minimizes the delivery delay. However, on the other hand, it increases the contention for network resources (e.g., bandwidth and storage), leading to poor overall network performance [3, 4].

Figure 1 depicts a VDTN scenario. Mobile nodes (e.g., vehicles) physically carry data exchanging bundles with one another. They move along the roads randomly (e.g., cars), or following predefined routes (e.g., buses). Stationary relay nodes are fixed devices located at road intersections with store-and-forward capabilities. They allow mobile nodes passing by to pickup and deposit data on them, thus increasing contact opportunities, and contributing to increase bundles delivery ratio while decreasing bundles average delay [5, 6].

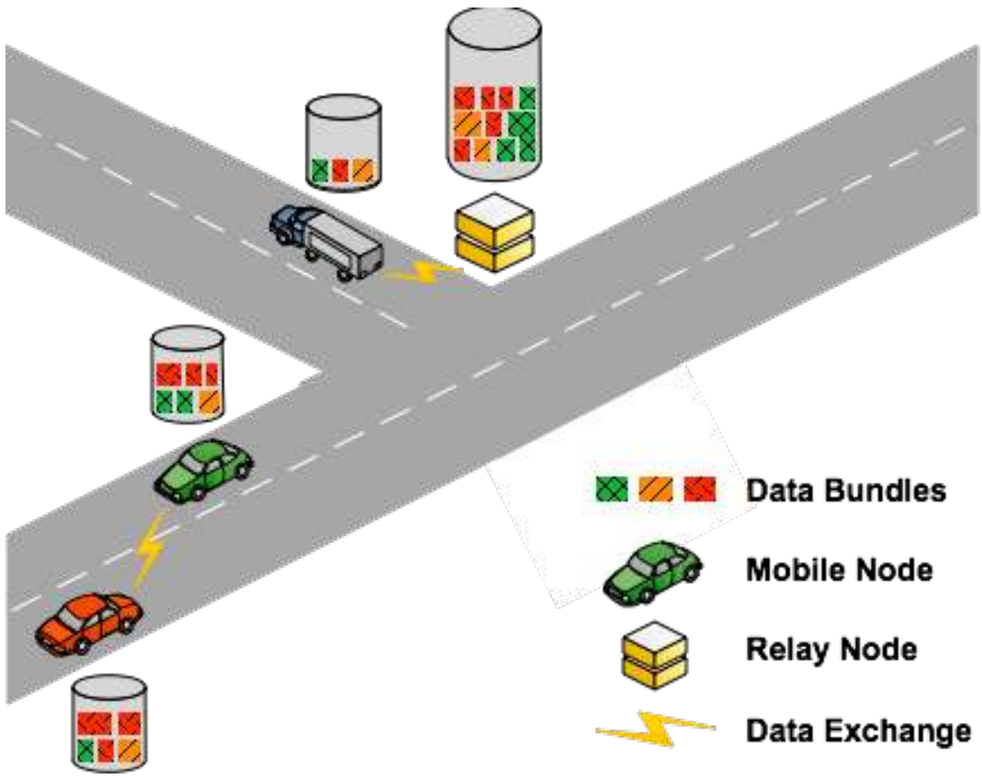

Figure 1 - Illustration of vehicular delay-tolerant network nodes.

VDTNs enable non-real time applications in scenarios where a conventional telecommunications infrastructure is not available or is destroyed. Examples of these networks include networks to disseminate information advertisements (e.g., marketing data) or safety related information (e.g., emergency notification, traffic condition and collision avoidance) [7], monitoring networks to collect data (e.g., pollution data, road pavement defects) [8], transient networks to benefit developing communities in remote rural regions [9, 10], and disaster recovery networks to restore communications following a natural disaster [11].

In fact, multiple of those applications can be supported simultaneously on a single vehicular delay tolerant network. For instance, one can envision a scenario where a VDTN is opportunistically exploited to transport data from an emergency dissemination information application and from a monitoring pollution data collection application.

Each of these applications generates data bundles with different requirements. An application for emergency dissemination information is better served by minimizing delivery delay (since the information becomes quickly outdated), whereas an application for monitoring pollution data collection is better served by maximizing delivery ratio.

The use of a traditional best-effort store-carry-and-forward service is inadequate in such scenario, since bundles from both applications would be treated equally. Without implementing traffic prioritization, the VDTN network is not able to distinguish bundles with different priorities and to provide preferential treatment to higher priority bundles.

This paper addresses this problem, focusing on the proposal of traffic differentiation support on vehicular delay-tolerant networks. In order to classify data bundles, a priority class service model is considered. Different buffer management strategies and drop policies with distinct approaches to buffer space allocation and contention resolution are evaluated. These mechanisms are combined with scheduling policies with different solutions to the traffic prioritization problem.

This work extends a preliminary contribution about the impact of scheduling and drop policies for traffic differentiation on VDTNs [12]. The paper has been extended in two directions: *i*) introducing different buffer management schemes and correspondent drop policies; and *ii*) proposing a scheduling policy that explores contact duration information for traffic prioritization.

The remainder of the paper is organized as follows. Section 2 presents the problem definition and the motivation for traffic differentiation. Section 3 presents an approach proposed for prioritizing network traffic, describing in detail the buffer management strategies and the scheduling and drop policies proposed in the context of this work. Section 4 focuses on the performance assessment of the proposed approaches. Section 5 concludes the paper and points further research directions.

2. Problem Definition and Motivation

Data communications in vehicular delay-tolerant networks (VDTNs) present new challenges when compared with other kinds of networks. VDTN networks can be sparse and partitioned, due to the large distances usually involved and low node density. This results in a few transmission opportunities and high and unpredictable delays.

Taking into account the high speed of vehicles, VDTNs register short contact durations and experience rapid changes in topology. The vehicles mobility pattern directly influences inter-contact time distributions. At the same time, limited transmission ranges, physical obstacles, and interferences, contribute to intermittent connectivity and high error rates commonly observed in these networks. All these characteristics, together with limited data transfer rates, restrict the number of data bundles exchanged between network nodes during encounters.

To enable data delivery in such environments long-term storage is combined with routing replication schemes. These techniques seek to improve reliability and reduce the latency, at the cost of increased storage on nodes buffers and communication overhead. Nevertheless, in resource-limited networks, these techniques cause the rapid depletion of buffer space, and the depletion of available bandwidth. This results in contention for network resources and in large performance variation [9].

The traditional “best-effort” store-carry-and-forward approach is not convenient in a scenario where multiple non-real time applications, with different performance requirements (e.g. delivery ratio, delivery urgency), compete for scarce network resources. In a best-effort model, all traffic is treated in the same manner, regardless of its type. Bundles are handled according to a first-in, first-out (FIFO) policy, as represented in Figure 2. Thus, bundle scheduling and drop policies are only based on the criteria of bundle arrival time with no guarantee of service quality.

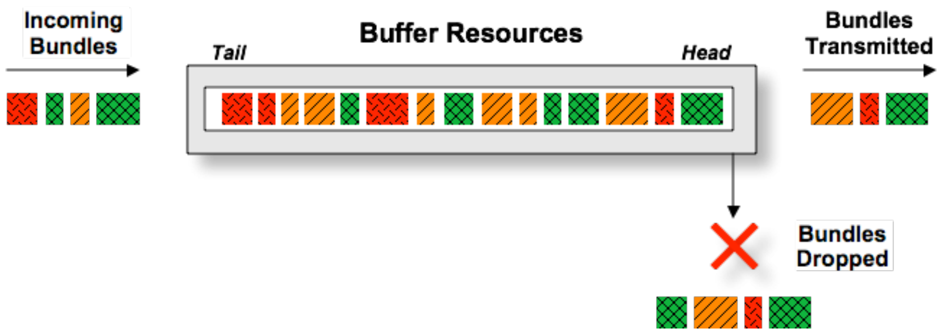

Figure 2 – Illustration of FIFO policy.

In this sense, the main objective of this work is the integration of traffic differentiation mechanisms on VDTNs, as illustrated in Figure 3. Implementation is based on network traffic classification and marking, according to a priority classes-of-service scheme. Moreover, different buffer management schemes, and priority-based drop and scheduling policies are evaluated. Next section describes these proposals in detail.

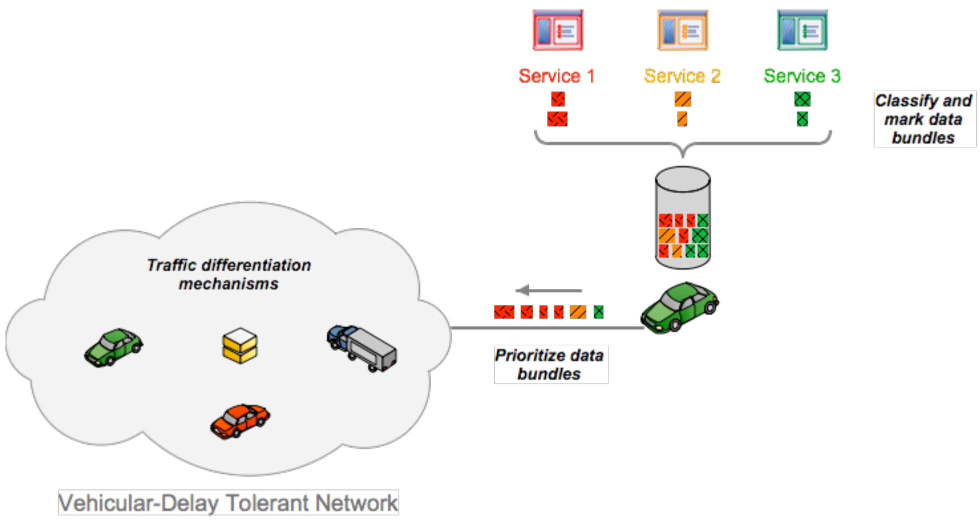

Figure 3 – Traffic differentiation in a vehicular delay-tolerant network.

3. Traffic Differentiation Mechanisms

In order to provide traffic differentiation at the bundle layer, network traffic must be classified and marked according to a scheme that defines priority classes of traffic. In addition, buffer management strategies, and scheduling and drop policies with support to traffic prioritization must be enforced across all network nodes. Next subsections will discus these concepts in detail.

3.1 Data Bundles Classification and Marking

Source nodes classify and mark data bundles. Classification is the first stage to implement differentiated services. Several criterions can be used to classify data, such as source application, delivery urgency, IP destination addresses, IP precedence, among others. Each of these criteria can be used separately or in conjunction with one another. Classification identifies traffic that will map to each priority class and, according to VDTN architecture proposal, traffic that belongs to the same class is aggregated in a large data packets, called data bundles [1]. Following the classification criteria, data bundles that belong to priority classes are marked accordingly.

This work considers a priority classes' scheme presented in the DTN architecture [13]. Therefore, data bundles can be marked as bulk (lowest priority), normal or expedited (highest priority), based on their delivery urgency. In addition, it is assumed that bundles priorities are time invariant [14], and that bundles' (initial) priority class cannot be classified again by any network node.

3.2 Buffer Management Strategies

Network nodes provide traffic differentiation by processing incoming and outgoing data based on the bundles' priority class marking. This processing involves performing per-hop actions like buffering, dropping, and scheduling. This subsection discusses the both strategies for buffer space management considered in this work.

The first approach, illustrated at Figure 4, considers that all bundles share the same buffer space. Since preference is given to high priority classes, in cases of buffer congestion, the drop policy selects lower priority bundles to be discarded first. The buffer space occupied by these bundles is used to store higher priority ones.

In a scenario with stringent storage constraints where network applications generate high rates of expedited bundles, these bundles may monopolize all the network storage resources. Thus, preventing that bulk and even normal priority bundles of being stored, carried and forwarded between nodes.

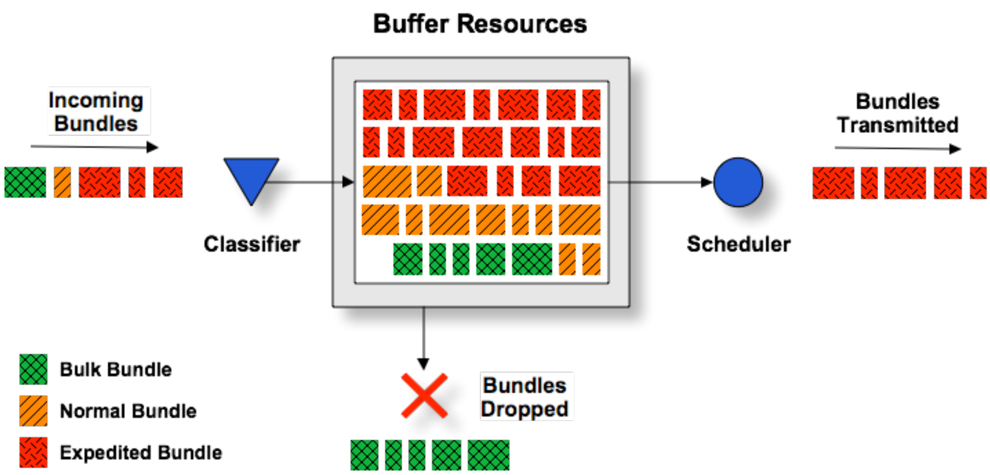

Figure 4 – Operation of a common buffer for all priority classes.

Another approach for buffer management based on priority classes, is presented in Figure 5. This second strategy proposes the creation of a separate queue for each priority class. The length allocated in each queue for bundles is related to each priority class. The queue for expedited bundles is great than the queue for normal bundles and this queue is also great than the queue for bulk bundles. Network nodes indentify and classify the incoming data bundles and store them in the corresponding queue. When there are no space available in a certain queue of a given priority class to store an incoming data bundle, the drop policy only discards bundles from that queue (until there is enough space available). This approach guarantees that network nodes can store and carry bundles of all priority classes at all times, independently of the storage constraints, and the expedited and normal bundles generation rates.

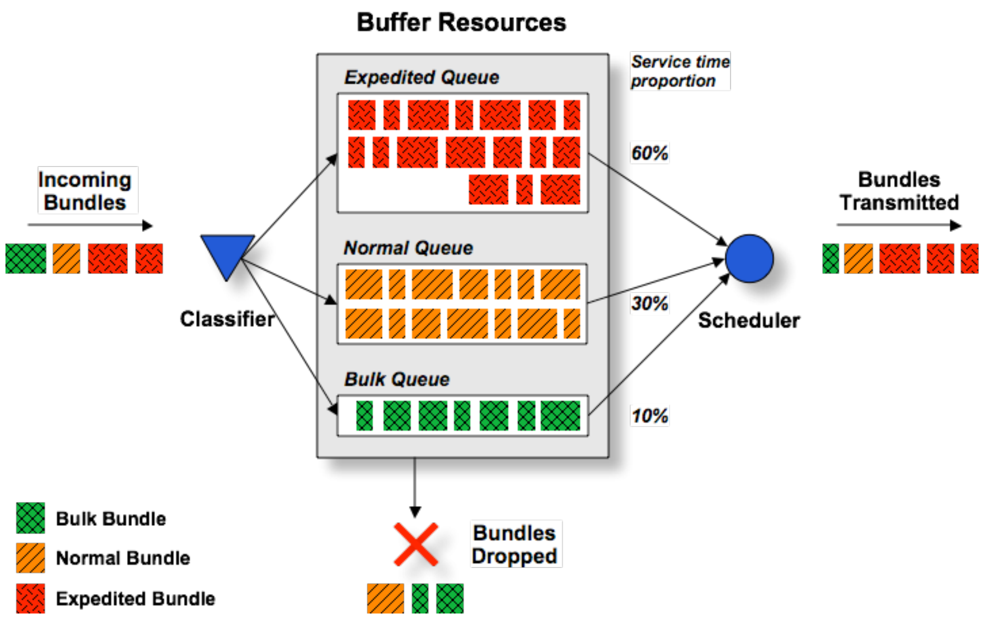

Figure 5 – Separate queues for each priority class.

3.3 Scheduling Policies

In order to achieve traffic differentiation, the above-mentioned buffer management strategies and drop policies must work together with scheduling policies specifically designed to support traffic prioritization. This paper analyzes the performance of the following priority class scheduling policies: Priority Greedy and Custom Service Time.

Priority Greedy (PG) scheduling policy strictly complies with the priority class sequence from high (expedited) to low (bulk). At a contact opportunity, higher priority class bundles are always scheduled before the lower priority class. Hence, higher priority bundles have the ability to monopolize the network resources (e.g., bandwidth and storage), and lower priority bundles may be severely delayed. These bundles may never get served in scenarios with limited network resources and short contact duration times. This scheduling policy is illustrated in Figure 4. As may be seen, due to a short contact duration between nodes, only expedited bundles were serviced.

Custom Service Time (CST) scheduling policy uses the estimation about contact time duration provided by the VDTN control plane [1, 15]. CST assigns service time percentages to each of the priority classes, as illustrated in Figure 5. At a contact opportunity, the contact duration estimation is used in conjunction with the service time percentages to calculate the periods of time during which bundles from each priority class are transmitted.

When there are no bundles of a certain priority class available at the node's buffer, the service time assigned to this priority class is used by the next one with lower priority. Moreover, while dispatching bundles of a certain priority class, if the remaining service time is insufficient to transmit any bundle stored in this queue, this time is used for transmitting bundles from the next lower priority queue. The Custom Service Time operating principle not only ensures expedited bundles can get more service time but also prevents normal and bulk bundles from not being served at all (Figure 5).

Our previous research efforts on the effect of scheduling and drop policies in the performance of vehicular delay-tolerant networks have shown that scheduling bundles with longer remaining lifetimes to be sent first, results in decreasing the bundles average delay significantly and increasing the overall bundles delivery ratio [12, 16]. Based on those results, in each of the above-described buffer management strategies, bundles are sorted based on their remaining lifetimes per each priority class. The same criterion is also applied on drop policies, that will discard bundles whose remaining TTL expires sooner and, therefore, have less time left to reach destination.

4. Performance Evaluation

This section studies the impact of the above-described buffer management strategies, and scheduling and drop policies on the performance of VDTNs in an urban scenario. This performance analysis considers scenarios with different node densities, and under distinctive constraints in terms of contact opportunities, contact durations, and buffer sizes. The study was conducted by simulation using a modified version of the Opportunistic Network Environment (ONE) simulator [17]. ONE was modified to implement the VDTN layered architecture model proposed in [1]. Additional modules were developed to implement the traffic differentiation mechanisms proposed in this work.

The performance metrics considered are the number of successfully delivered bundles and the number of dropped bundles, per priority class. Next subsections describe the two simulation scenarios and the corresponding performance analysis.

4.1 Simulation Setup

Two simulation scenarios with different node densities are evaluated. The first scenario considers a network with 25 vehicles while the second scenario assumes a network with 50 vehicles. For each scenario, a time period of 12 hours (e.g., from 8:00 to 20:00) is simulated. During this period, vehicles move on the roads of a map-based model shown in Figure 6, between random locations, and with random stop times between 5 and 15 minutes.

To change the duration of contact opportunities, vehicles move at a speed of 30 or 50 kilometers per hour (km/h). Different storage constraints are also introduced by changing the vehicles buffer size between 25, 50, and 100 Megabytes, across the simulations.

Vehicles exchange data between themselves and with the five stationary relay nodes positioned at the road intersections, as identified in Figure 6. All network nodes use a wireless communication link with a data transmission rate of 6 Mbps and a transmission range of 30 meters.

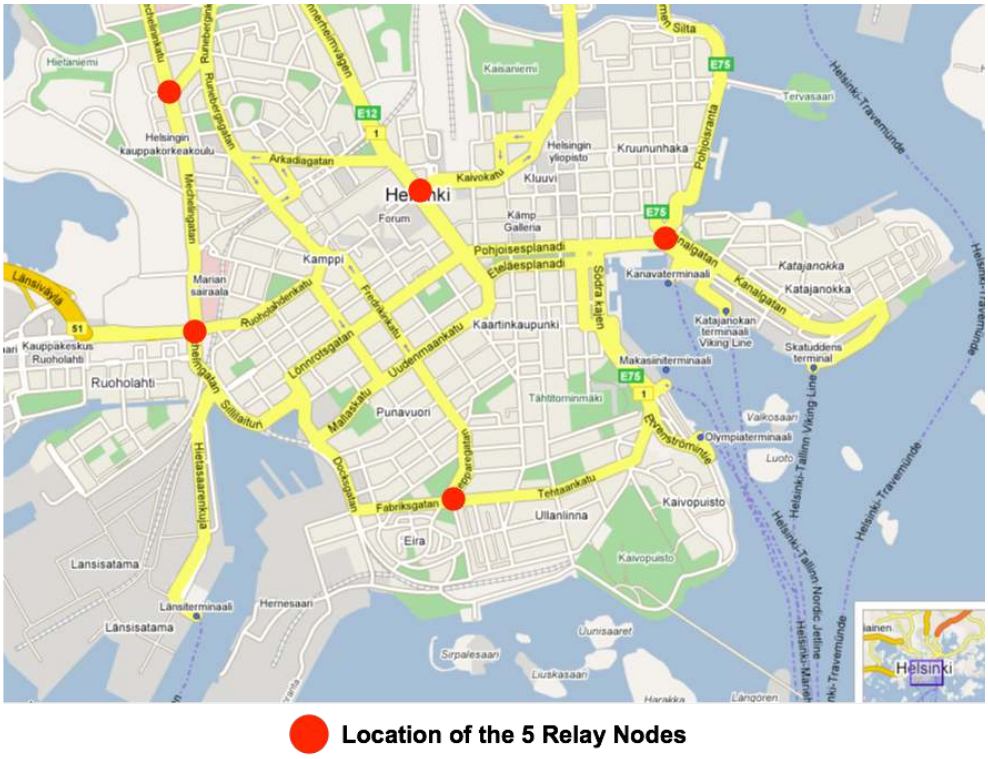

Figure 6 – Simulation scenario: Helsinki downtown area, with a dimension of 4500×3400 meters.

The volume of network traffic is equal on both scenarios. Three bundle event generators are responsible for generating data bundles that correspond to data aggregations with different performance requirements and sizes. In the context of this study, it is assumed that high demanding applications generate larger volumes of traffic. Thus, bundles are generated with sizes uniformly distributed in the ranges of [100KB, 250KB] for bulk bundles, [250KB, 750KB] for normal bundles, and [750KB, 1.5MB] for expedited bundles.

All data bundles of each priority class are generated using an inter-bundle creation interval that is uniformly distributed in the range of [15, 30] seconds. In addition, all data bundles have random source and destination vehicles and a time-to-live (TTL) of 120 minutes.

Spray and Wait [18] (binary variant) is used as the underlying DTN bundle routing scheme. Spray and Wait creates a number of copies N to be transmitted ("sprayed") per bundle (assuming N=12, in this study). A given node A that has more than 1 bundle copies and encounters any other node B that does not have a copy, forwards to B $N/2$ bundle copies and keeps the rest of the bundles. A node with 1 copy left, only forwards it to the final destination.

The difference of performance resulting from the combination of the above-mentioned buffer management strategies and scheduling policies is evaluated for both scenarios. The common buffer strategy is enforced in conjunction with the Priority Greedy scheduling policy.

It is assumed that a buffer management strategy providing separate storage space for each priority class is used in conjunction with a Custom Service Time scheduling policy. For this case, it is also assumed that 10% of the full buffer space is reserved for bulk bundles, 30% for normal bundles, and 60% for expedited bundles. In addition, service time percentages assigned to each priority class are also 10% for bulk bundles, 30% for normal bundles, and 60% for expedited bundles.

In both simulated scenarios, it is assumed a cooperative opportunistic environment without knowledge of the traffic matrix and contact opportunities. In order to get representative and meaningful result values, each simulation configuration is executed 30 times, using different random seeds. The results present the mean values of those 30 simulations.

4.2 Performance Analysis for the Scenario with 25 Vehicles

The performance analysis starts with the scenario where only 25 vehicles move across the map roads at a speed of 30km/h. As may be observed in Figure 7, Priority Greedy (PG) policy presents results with the greatest differences between the delivery ratios for each priority class. These ratios are represented as percentages inside the stacked columns. When buffer resources are stringent (25MB), PG prevents normal and bulk bundles of being stored and relayed between network nodes, since expedited bundles monopolize the existing resources. On the contrary, Custom Service Time (CST) policy guarantees that bundles from all priority classes can be transmitted at a contact opportunity. Although a lower number of expedited bundles were successfully delivered for CST, the delivery ratio of bulk and normal bundles is greatly enhanced. This behavior is verified across all simulations for this policy.

As expected, duplicating the buffer size of vehicles to 50MB, it increases the number of bundles successfully delivered across all priority classes, for both scheduling policies. In the case of PG policy, the additional buffer space attenuates the resource contention problem caused by its operating principle. Also, it is worth noticing that CST with a 25MB buffer size presents a sum of delivered messages great than the one presented by PG with a 50MB buffer. Increasing the buffer size to 100MB the delivery ratio of bulk and normal bundles in PG also increase. Nevertheless, CST policy only increases expedited bundles ratio slightly.

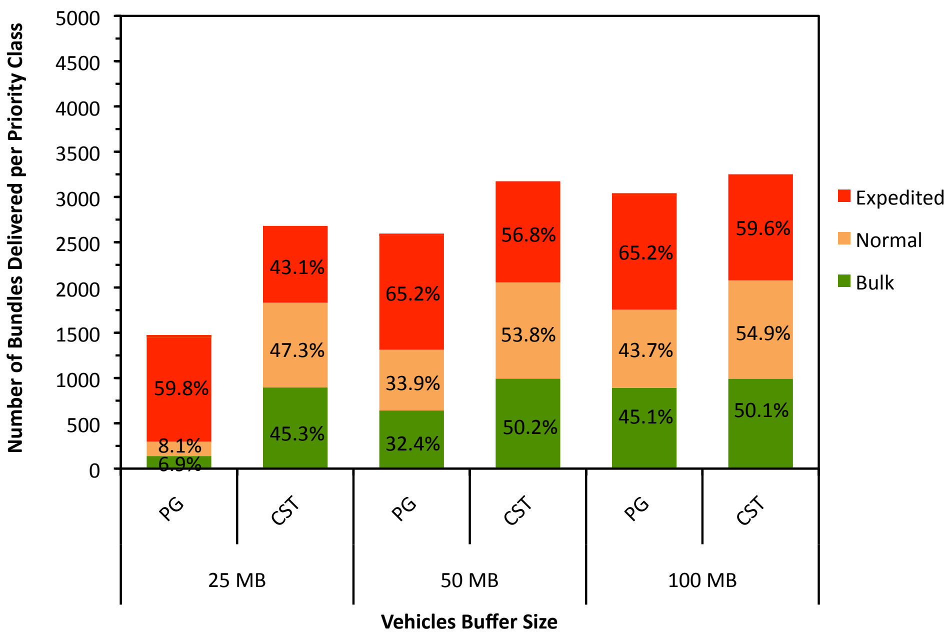

Figure 7 – Effect of vehicles buffer size on the delivery of bundles per priority class for PG and CST scheduling policies with 25 vehicles moving at a speed of 30km/h.

Increasing the vehicles speed to 50km/h, the contact durations decrease and also decreases the number of bundles exchanged during a contact opportunity. As may be seen through the comparison between Figures 7 and 8, this results in lower delivery ratios for all priority classes across all simulations. This analysis also shows a common trend on the policies performance for both cases.

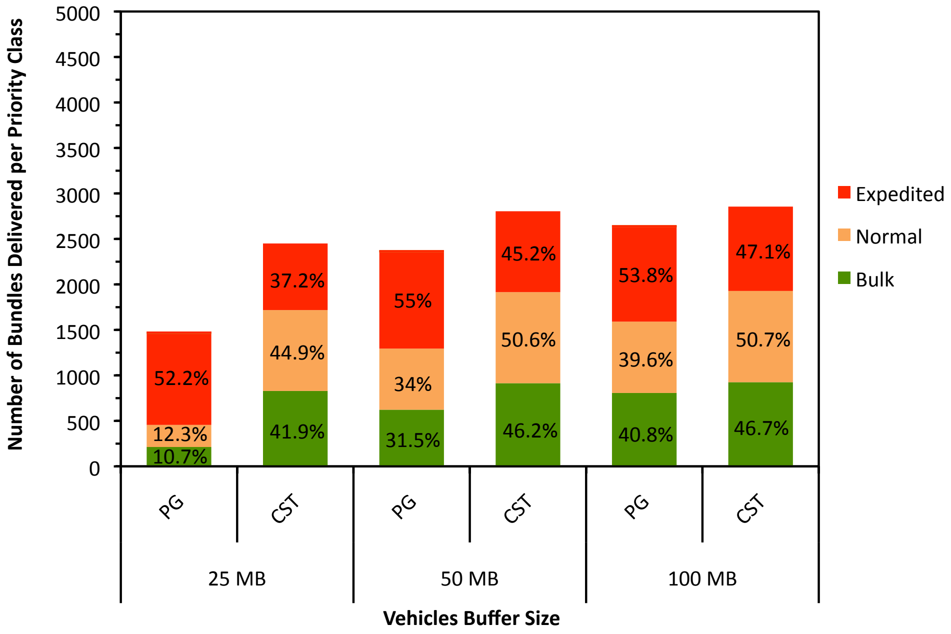

Figure 8 – Effect of vehicles buffer size on the delivery of bundles per priority class for PG and CST scheduling policies with 25 vehicles moving at a speed of 50km/h.

As expected, Figure 9 shows that the number of bundles dropped depends on the available buffer size. When the results shown in this figure are analyzed, it is important to mention that it was assumed that bundles from different priority classes have different sizes, with expedited bundles being the largest ones. At a contact opportunity, CST policy guarantees that bundles from all priority classes are served. Since normal and bulk bundles have smaller sizes, this means that larger numbers of these bundles are possibly exchanged during an encounter between two network nodes. In conjunction with limited lower storage resources assigned to these priority classes, this results in contention. Consequently, CST presents the largest sums of dropped bundles across all simulation scenarios. Likewise, the large size of expedited bundles constrains their relaying and reflects in the observed lower numbers of delivered and drop bundles of this kind. Finally, when vehicles move at a speed of 50km/h, it was observed that number of dropped bundles was not significantly changed. Hence, these results are not shown.

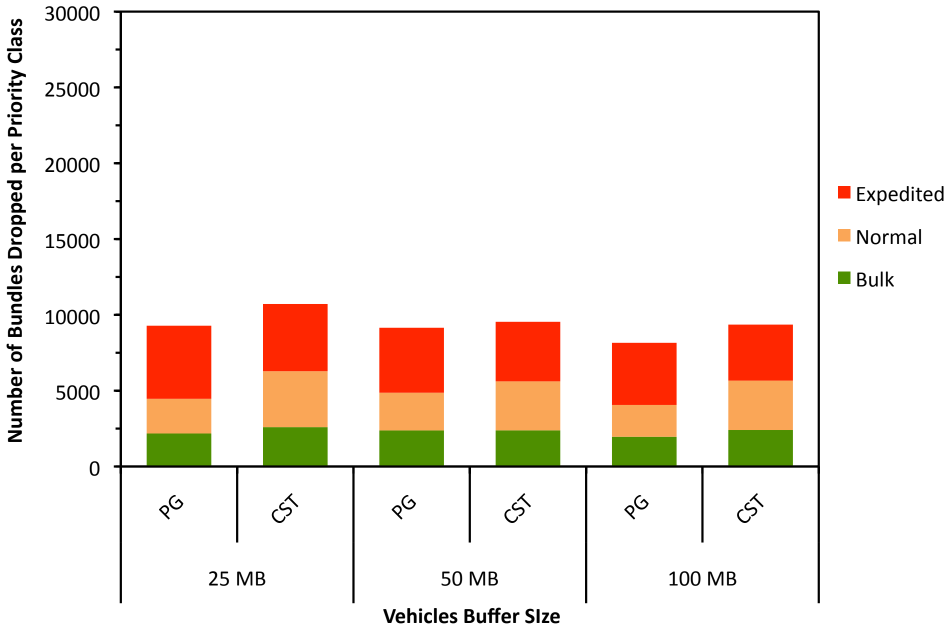

Figure 9 – Effect of vehicles buffer size on the number of dropped bundles per priority class for PG and CST scheduling policies with 25 vehicles moving at a speed of 30 km/h.

4.3 Performance Analysis for the Scenario with 50 Vehicles

The second scenario considers 50 vehicles moving across the map (Figure 6). Increasing node density, contact opportunities also increase. Therefore, network nodes take the opportunity to exchange more bundles. First, this increases the probability for bundles to be successfully delivered and, second, more relayed bundles imply more contention for network resources (e.g., storage, bandwidth).

Figure 10 shows that number of delivered bundles per priority class increases for both policies across all simulations. Recall that the traffic generated is equal on both scenarios. When compared to the results observed in the first scenario (Figure 7), Custom Service Time (CST) scheduling policy registers gains of approximately 20%, in the delivery ratios of all priority classes, independently of the vehicles buffer size. Priority Greedy (PG) also improves the delivery ratio of expedited bundles in 20%. On the other hand, normal and bulk bundles delivery ratios only improve considerably when vehicles carry a 100 MB buffer.

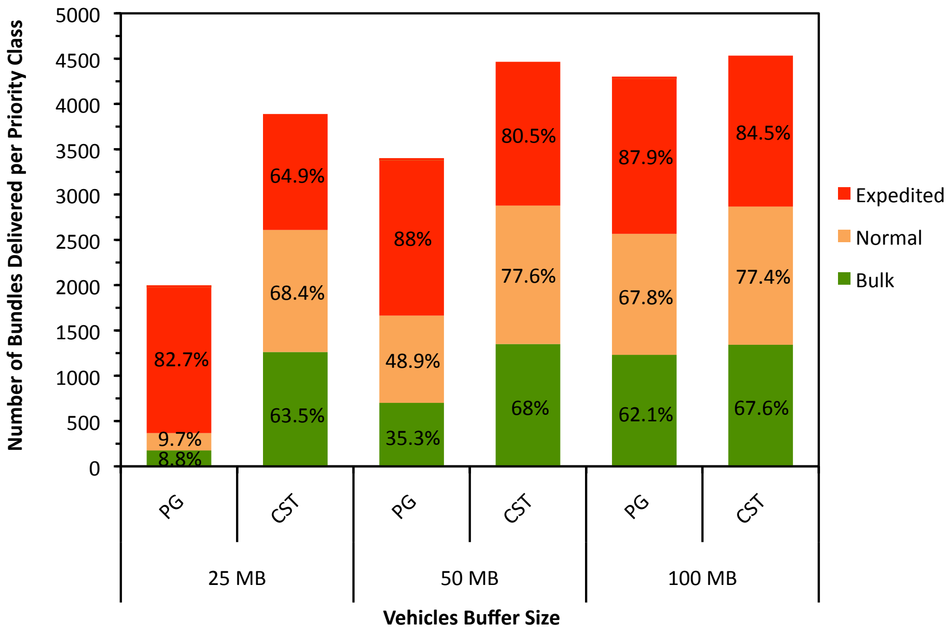

Figure 10 – Effect of vehicles buffer size on the delivery of bundles per priority class for PG and CST scheduling policies with 50 vehicles moving at a speed of 30km/h.

As expected, and following the results shown in the previous scenario (Figure 8), increasing the vehicles speed to 50km/h lowers the number of successfully delivered bundles per priority class (Figure 11). Nevertheless, in this scenario, the differences observed are attenuated by the larger number of contact opportunities.

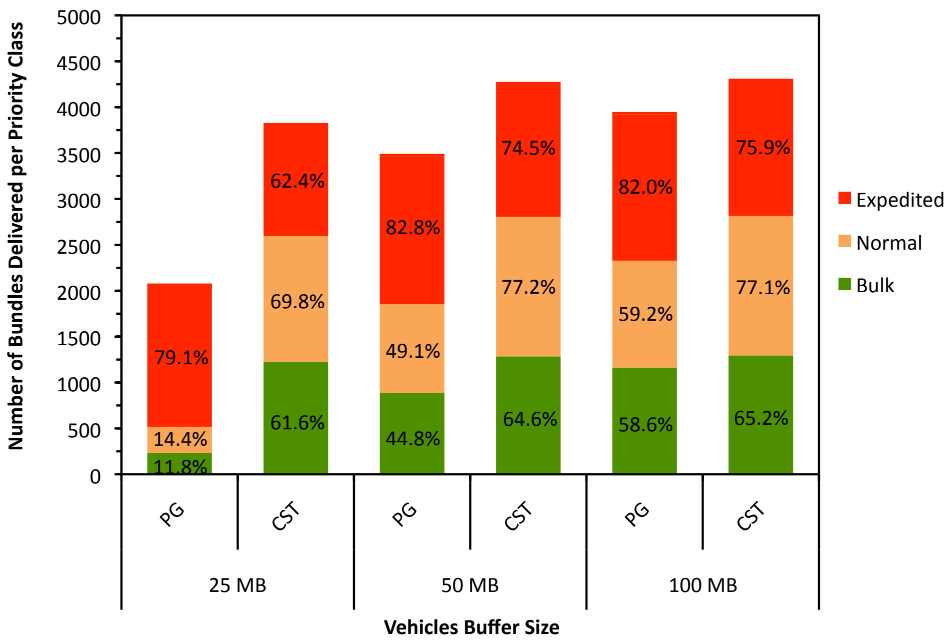

Figure 11 – Effect of vehicles buffer size on the delivery of bundles per priority class for PG and CST scheduling policies with 50 vehicles moving at a speed of 50km/h.

Considering the number of bundles dropped per priority class, Figure 12 shows that introduction of 50 vehicles increased the competition for network resources severely. When compared to the values observed in the first scenario (Figure 9), PG and CST policies register significantly larger values of dropped bundles.

The conclusions presented in the first scenario, in respect to the low number of dropped expedited bundles, may also be applied here. Although both PG and CST prefer the treatment of expedited bundles, the large size of bundles limits their relaying between network nodes. Thus, diminishing the number of delivered and dropped bundles of this priority class.

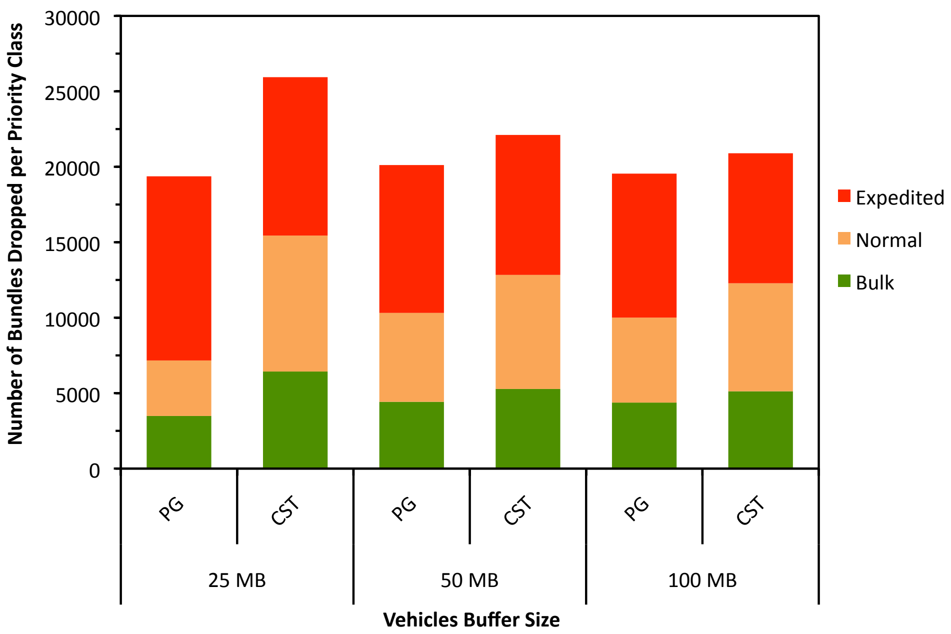

Figure 12 – Effect of vehicles buffer size on the number of dropped bundles per priority class for PG and CST scheduling policies with 50 vehicles moving at a speed of 30km/h.

Finally, and on contrary to the first scenario, increasing the vehicles speed to 50 km/h, it affects the number of dropped bundles, as may be seen in Figure 13. The sum of dropped bundles decrease in 5000 bundles approximately, for all evaluated cases.

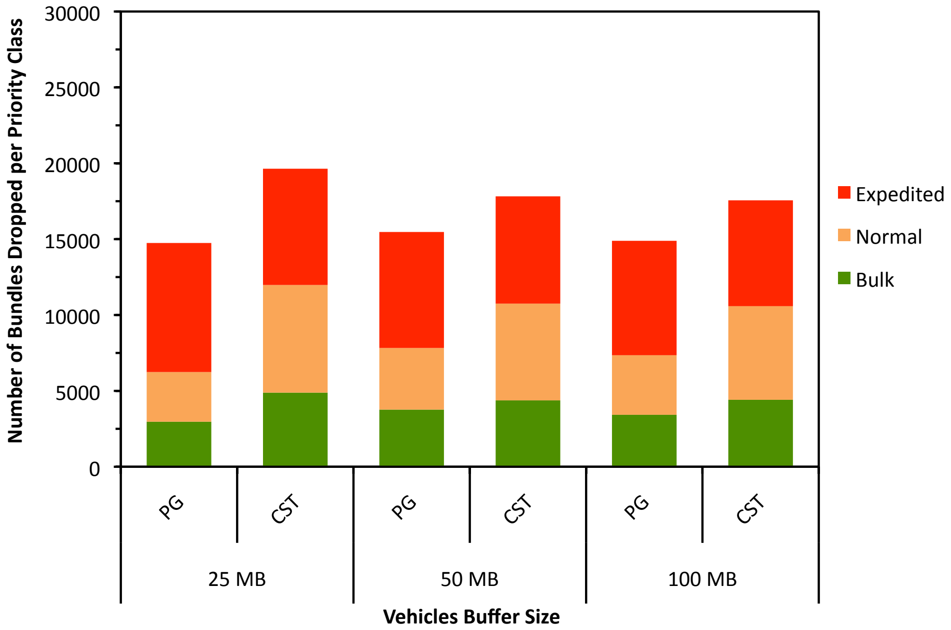

Figure 13 – Effect of vehicles buffer size on the number of dropped bundles per priority class for PG and CST scheduling policies with 50 vehicles moving at a speed of 50km/h.

5. Conclusions and Future Work

In a vehicular delay-tolerant network, traffic prioritization can be used to selectively allocate network resources to services and applications, according to their performance requirements. Traffic differentiation is particularly important when network resources are scarce. In such scenarios, it may be necessary to accommodate and give preference to higher priority traffic, while delaying the processing of lower priority traffic.

This paper focused on the proposal of traffic differentiation mechanisms for a VDTN. Different buffer management strategies with corresponding drop policies, and scheduling policies were proposed and evaluated. In order to compare their performance under an opportunistic network environment, two simulated urban scenarios with different node densities were considered. In each scenario, storage constraints were changed, as well as the frequency and duration of contact opportunities.

Results confirm the importance of supporting traffic differentiation on a VDTN, and motivate further research in this domain to develop new proposals for prioritization scheduling policies. Furthermore, introducing VDTN "quality of service" routing capabilities and studying its effect over the network traffic and the network utilization are also open research issues that may be addressed in future works.

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Vasco N. G. J. Soares is a PhD student on Informatics Engineering at the University of Beira Interior under supervision of Professor Joel José P. C. Rodrigues. He received his 5-year B.S. degree (licentiate) in 2002 in Informatics Engineering from University of Coimbra, Portugal. He also teaches in the Informatics Engineering Department at the Superior School of Technology of the Polytechnic Institute of Castelo Branco, Portugal. He is a PhD student member of the Instituto de Telecomunicações, Portugal. His current research areas are Delay Tolerant Networks, and Vehicular Networks. He authors or co-authors more than 12 international conference papers, participates on several Technical Program Committees, and also has one accepted journal publication, and one accepted book chapter publication.

Farid Farahmand received his PhD in 2005 and is currently an Assistant Professor in the Department of Engineering Science at Sonoma State University. He is also the director of Advanced Internet Technology in the Interests of Society Laboratory. Prior to this position, Dr. Farahmand worked as the research scientist at Alcatel-Lucent Corporate Research and was involved in development of terabit optical routers. Dr. Farahmand holds multiple international patents, numerous reference conference articles and journal publications, and several book chapters, on the subject of wireless communications, optical networking, and delay tolerant networks. He has also authored many educational papers focusing on eLearning and Active Learning in classroom. He is a member of IEEE, ASEE, and Engineers Without Borders-USA.

Joel José P. C. Rodrigues is a Professor at the Department of Informatics of the University of Beira Interior, Covilhã, Portugal, and researcher at the Instituto de Telecomunicações, Portugal. He received a PhD degree in Informatics Engineering, MSc degree from the University of Beira Interior, Portugal, and a 5-year B.S. degree (licentiate) in Informatics Engineering from University of Coimbra, Portugal. His main research interests include delay-tolerant networks, sensor networks, high-speed networks, and mobile and ubiquitous computing. He is the Editor-in-Chief of the International Journal on E-Health and Medical Communications. He is the general Chair of the MAN 2009 and MAN 2010 (in conjunction with IEEE ICC 2009 and 2010), N&G 2010 (with IEEE AINA 2010), Chair of the Communications Software, Services and Multimedia Applications Symposium at IEEE Globecom 2010, Chair of the Symposium on Ad-Hoc and Sensor Networks of the SoftCom Conference, TPC Chair of IEEE CAMAD 2010, and chaired many other technical committees. He is or was member of many international program committees (IEEE ICC, IEEE Globecom, IEEE WCNC, IEEE CCNC, IEEE ISCC, IEEE ICCCN, ICTTA, SoftCOM, etc.) and several editorial review boards (IEEE Communications Magazine, Journal of Communications Software and Systems, International Journal of Communications Systems, International Journal of Business Data Communications and Networking, etc.), and he has served as a guest editor for a number of journals including the Journal of Communications Software and System. He chaired many technical sessions and gave tutorials at major international conferences. He has authored or co-authored over 100 papers in refereed international journals and conferences, a book and a patent pending. He is a licensed Professional Engineer and he is member of the ACM SIGCOMM, a member of the Internet Society, IARIA Fellow, and a Senior Member of the IEEE.