Traffic Shaping for Enabling Less-than-Best Effort Services at the Edges of Broadband Connections

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ABSTRACT

Broadband connection sharing constitutes a network resource pooling technique that could evolve toward supporting the establishment of the “Free Internet for All” notion. This technique could be implemented through the User-Provided Network model in which any end-user device (e.g. ADSL Access Points) could behave as supplier of Internet connectivity. In this paper, the behavior of such a system is investigated from a queue-management perspective. A numerical analysis that takes into consideration both the high variability of broadband link speeds and different packet-size distributions is presented. Based on the results, we propose a hybrid packet-scheduling scheme that enables the application of Less-than-Best Effort services at the connection edges.

Categories and Subject Descriptors

C.2.3.a [Network Operations]: Network Management

Keywords

Broadband Resource Sharing, User-Provided Networks, Less-than-Best Effort Service, Delay Tolerant Networking.

1. INTRODUCTION

“Free Internet for All” is a notion introduced by Vint Cerf [1] that has not been realized yet although it could have a huge social impact. Recently, LCD-Net: Lowest Cost Denominator Networking [2] was proposed to realize this concept. It approaches the issue from various angles investigating possible infrastructural, networking and economic barriers. From a networking perspective, it proposes the exploitation of several existing resource pooling Internet technologies to enable free Internet. A basic prerequisite though to make such a scheme successful and sustainable is for the system to ensure zero impact on the users or network operators who share their resources and at the same time incentivised them for doing so. The work proposed here is towards this direction.

Our work departs from broadband connection sharing; a network resource pooling technique whose implementation can be based on User-Provided Networks (UPN). The philosophy behind this idea is well-developed in [1, 3], where the authors also present possible incentives for its use. The concept of UPNs comprises two main entities: i) the micro-provider, which is the home-user or group of home-users that own the broadband connection and ii) the group of guest-users. Guest-users are often considered to be wireless connected users that need to freely access the Internet by exploiting the available unused capacity. Such a type of access could be implemented by mandating Less-than-Best Effort (LBE) services, which provide lower access priority to the available resources compared to the standard Internet Best Effort (BE) services offered to typical subscribers. In the current study, we are investigating the behavior of such systems from a queue-management perspective.

Unlike other type of services such as guaranteed and Better-than-Best Effort, LBE service determines in its own right the target level of service. That is, LBE service, or simply Less Effort (LE) service, clearly correspond to low-expected quality, which however cannot be that low to violate the notion of service itself. Service in this case is the reason for the system to exist: no user, even free, would punish himself by attempting to access a system repeatedly that will, likely, not work. This last argument constitutes the main philosophy in the present work. In particular, we are seeking technically feasible approaches that could be used to design network tools that allow for BE- and LE-traffic to coexist harmonically. However, prior to designing such tools, we study here the feasibility of such systems along with their potential to guarantee the corresponding level of services. Clearly therefore, we assume that even LE service requires to guarantee some level of service.

In this context, we assess numerically the impact of LE-traffic on BE-traffic in association with different packet-size distributions and varying network speeds. To the best of our knowledge our study is the first one to report results in this topic for different packet-size distributions; a rather important network parameter that largely affects both the average service time of the system, as well as its modeling and analysis methodology. Based on our findings, we show that i) the approach followed by other proposed methods for LE-traffic regulation is not optimal in several cases and ii) there is a certain bandwidth availability point over which the trade-off between exclusively allocating resources to serve LE-traffic and increasing the impact on queuing delay for BE-traffic is efficiently balanced.

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This fact allows Priority Queuing-type schemes (PQ-schemes) to be replaced by Weighted Fair Queuing-type schemes (WFQ) in order to guarantee a certain level of service. Along these lines, we also propose a transition towards Hybrid Packet Scheduling.

The rest of the paper is structured as follows: In Section 2, we present the related work. In Section 3, we elaborate on the potential applicability of Delay Tolerant Networking (DTN) technology in UPNs. In Section 4, we discuss the modeling of the system, outline the applied numerical analysis and present the results. In Section 5, we describe the design principles of Hybrid Packet Scheduling Scheme, and sketch its implementation. Finally, our study is concluded in Section 6.

2. RELATED WORK

During the last few years, broadband connection sharing has earned a central role in the international research agenda of mobile networking due to high demand for seamless network connectivity anytime, anywhere. Several commercial and non-commercial efforts trying to address that issue have emerged, focusing primarily on broadband connection sharing through Wi-Fi technology. Hotspot, social-networking, mesh-based, mobile-based and provider-based UPN models are among the most common architectures of UPN. FON [4], OpenSpark [5], Wifi.com [6], Open-Mesh [7], and Netsukuku [8] are few of the most active communities currently operating across the globe. Despite the fact that each one of them presents different advantages and disadvantages (e.g. limited maximum speeds, manual configuration etc.), their common characteristic is that none of them is able to support the "Free Internet for All" notion. Their design and deployment philosophy of extending user's paid services hinders their deployment under such broadband connection sharing schemes. Unlike the aforementioned efforts, Public Access Wifi (PAWS) [9] is a recent innovative research project that seeks to develop technology for enabling the "Free Internet for All" notion. It aims to achieve that target by providing LE access to guest-users, enabling them to exploit the spare capacity in existing broadband connections in homes and public buildings. The key idea of this effort is that the LE service could act as the foundation of a network architecture that implements the "Free Internet for All".

Several research studies and technical reports have been published on the deployment and configuration of the LE service on ISPs' core network. In [10], Carlberg K. et al. present the design and implementation of a novel architecture that supports LE traffic and propose the Persistent Class Based Queueing system (P-CBQ) as the preferred scheduling mechanism that determines the rate of service between BE- and LE-traffic classes. P-CBQ degrades the service of a class at some specified rate according to a penalizing algorithm. After the incorporation of LE service in well-known educational networks such as GEANT and Internet-2, authors in [11] and [12] have studied several possible packet scheduling configurations based on Weighted Round-Robin (WRR), Modified Deficit Round-Robin (MDRR) and Weighted Fair Queueing (WFQ) schemes. In most cases, they conclude in assigning a fixed weight (e.g. 1% of the total available bandwidth) on the service of the LE traffic. In practical terms, scavenger flag has been defined in the DiffServ architecture for marking the LE-traffic and networking companies, such as Juniper Networks and Cisco have already integrate it in their routers.

While there is a substantial number of studies for the deployment of LE service and its related issues on ISPs' core network routers there is a lack of collaborative deployment studies for the APs of broadband ADSL connections. The proposed approaches so far are either based on specialized transport protocols [13] or on queue-management techniques for packet scheduling [14]. Based on the topic of our work, we focus on the second category. In [3, 14] the authors present UPNQ, a packet scheduling mechanism based on the non-preemptive priority queuing scheme (PQ). The $\Sigma M/D/1$ queueing model is used to analyse the behavior of the system, as a result of assuming fixed packet sizes. By applying an algorithm that regulates the rate in which LE-traffic is served, they show that a small rate of LE-traffic packets can be served with statistically zero impact on the performance of the BE-traffic.

In this paper, our modeling philosophy adopts most arguments stated in [14]; we cancel, however, the fixed packet-size assumption by studying the impact of different packet-size distributions on the performance of the system. Furthermore, we propose a new algorithm for regulating LE-traffic.

3. COMMENTS ON THE POTENTIAL APPLICABILITY OF DELAY TOLERANT NETWORKING IN UPNs

Due to the network-management benefits associated with the Delay Tolerant Networking technology, the incorporation of storage into APs' architecture will be considered in a context similar to the philosophy of LCD-Net. This will allow for APs to have the additional ability of storing large amounts of data for long time intervals in contrast to the short buffering time provided by current AP architectures.

We strongly support this idea due to its great potential for exploitation in a number of useful applications. In the context of this study, we argue that DTN mechanisms could be utilized not only by simple traffic offloading techniques but also as advanced traffic shaping mechanisms.

4. SYSTEM MODELING

In a user-provided network, traffic can be classified into two major categories: home- and guest-traffic. For both groups we assume the following: i) traffic is generated by a large number of flows[1] , ii) flow arrivals follow a Poisson distribution, iii) packet-size varies from 40-1500 bytes and iv) same packet-size distribution.

Traffic differentiation in an AP that implements a network resource sharing scheme can be aligned to a queue-management perspective by assigning each group of traffic to a different class of service. We consider the following traffic-classes: i) BE-class and ii) LE-class. Packets of the home-traffic are assigned to the BE-class while guest-traffic packets are assigned to the LE-class.

We expect that each micro-provider will share a single broadband link, so it is reasonable to assume that our system is supported by a single server. Since we are dealing here with packets produced by common Internet applications and due to the abundance in

[1] Several studies suggest that the packet arrival process for highly multiplexed environments tends to follow a Poisson distribution [15, 16].

storage space that the new architecture will provide, we can safely assume that the buffering space of the AP is infinite. In this context, ΣM/G/1 is selected for our analysis.

4.1 Numerical Analysis

Through the present analysis, we aim at evaluating the impact of guest-traffic on home-traffic in terms of queueing delay and average system time. Bandwidth availability on the transmission link and packet-size distribution of the flows are two critical factors for the overall behavior of the system, since their respective values have a direct impact on the average system service time. In general, service time is proportional to the size of a packet. Based on the assumptions presented in the previous section, we expect from both classes to present equal average service times.

In particular, we are interested primarily in drawing conclusions for the upstream link, since its allocated bandwidth is usually low and highly variable. Typical values of the allocated bandwidth for the upstream link range from hundred Kbps to a few Mbps. Unlike upstream, the downstream link is significantly faster, with typical bandwidth values in the order of tens of Mbps.

As far as packet-size distribution is concerned, the particular choice of queueing model allows for investigating the behavior of queueing delay under general distribution service times. That said, we analyze the impact of different packet-size distributions on the queueing delay of the system. We consider several bimodal and trimodal packet-size distributions found in the literature [17, 18]. A list of the examined packet-size distributions is presented in Table 1.

Table 1. List of the examined packet-size distributions

Model Descriptions (in bytes)	Distribution
40-576-1500 (tri-m)	58% - 33% - 9% [17]
40-576-1500 (tri-m)	40% - 20% - 40% [18]
64-1300-1500 (tri-m)	60% - 20% - 20% [18]
64-1500 (bi-m)	60% - 40% [17]

Our numerical analysis is carried out in steady-state condition (ρ<1) and is completed in two stages. We start by analyzing the behavior of the system when it operates under a First Come First Served policy (FCFS) with no priorities. This part of the analysis allows for a rough estimation of the average global system time. In case the range of average global system time values exceeds an acceptable level the AP should apply proper scheduling mechanisms in order to guarantee that the impact in terms of additional queueing delay is statistically zero for the home-group users. Furthermore, the applied scheduling mechanism should also allow guest-users to fully exploit the capacity of the broadband link in case of zero home-traffic. In that context, the second stage of our analysis includes the investigation of system's behavior under a non-preemptive priority queueing policy with BE-class traffic having full priority over LE-class traffic.

Finally, also note that, for convenience, BE-class and LE-class are denoted as classes 1 and 2, respectively, throughout the analysis. Our notation is summarized in Table 2.

Table 2. Notation table

Symbol	Description
λ_i	Arrival Rate of Class-i
$\lambda = \lambda_1 + \lambda_2$	Total Arrival Rate
$E(S_i)$	Average Class-i Service Time
$E(S)$	Average System Service Time
$\rho_i = \lambda_i * E(S_i)$	Utilization of Class i
P	Cumulative Utilization
$Cv(S_i)$	Coefficient Variation of Service Times
$V(S_i)$	Variance of Service Times
$E(W_i)$	Average Class-i Waiting Time
$E(R_i)$	Average Class-i System Time
$E(W)$	Average Global Waiting Time
$E(R)$	Average Global System Time
$E(RS)$	Mean Residual Service Time
K	Percentage Impact of Traffic Class-2 on Traffic Class-1
I	Temporal Impact of Traffic. Class-2 on Traffic Class-1

4.1.1 FCFS Policy (no priorities)

The total arrival rate of the system equals to $\lambda = \lambda_1 + \lambda_2$, therefore, the average global waiting time equals to:

$$E(W) = \frac{E(RS)}{(1-\rho)} \tag{1}$$

Mean residual time for ΣM/G/1 systems is given by:

$$E(RS) = \frac{\lambda * E(S^2)}{2} \tag{2}$$

Since $Cv^2(S) = \frac{V(S)}{E^2(S)}$ and $E(S^2) = V(s) + E^2(S)$, we proceed in substituting $E(S^2)$ with $E^2(S) * (1 + Cv^2(S))$ and based on Eqs. (1) and (2), we get the average global waiting time:

$$E(W) = \frac{\lambda * E^2(S) * (1 + Cv^2(S))}{2 * (1 - \lambda * E(S))} \tag{3}$$

The average global system time is given by:

$$E(R) = E(W) + E(S) \tag{4}$$

4.1.2 Strict Non-Preemptive Priority Scheduling

The average waiting time for traffic classes 1 and 2, respectively, equals to:

$$E(W_1) = \frac{E(RS)}{(1-\rho_1)} \tag{5}$$

$$E(W_2) = \frac{E(RS)}{(1-\rho_1)(1-\rho_1-\rho_2)} \tag{6}$$

Then, the mean residual time is given by:

$$E(RS) = \sum_{i=1}^{I} \frac{\lambda_i * E(S_i^2)}{2} \tag{7}$$

Since packet-size distribution is the same for both classes we get:

$$E(S) = E(S_1) = E(S_2) \quad (8)$$

$$Cv^2(S) = Cv^2(S_1) = Cv^2(S_2) \quad (9)$$

Based on Eqs. (5), (6), (7), (8) and (9) we calculate the average waiting time for both classes as follows:

$$E(W_1) = \frac{(\lambda_1+\lambda_2)*E^2(S)*(1+Cv^2(S))}{2*(1-\lambda_1*E(S))} \quad (10)$$

$$E(W_2) = \frac{(\lambda_1+\lambda_2)*E^2(S)*(1+Cv^2(S))}{2*(1-\lambda_1*E(S))(1-\lambda_1*E(S)-\lambda_2*E(S))} \quad (11)$$

Average service times for each class and the average global system time, respectively, are given by:

$$E(R_1) = E(W_1) + E(S) \quad (12)$$

$$E(R_2) = E(W_2) + E(S) \quad (13)$$

$$E(R) = \frac{\lambda_1}{\lambda}E(R_1) + \frac{\lambda_2}{\lambda}E(R_2) \quad (14)$$

In order to calculate the impact of traffic class-2 on traffic class-1, we calculate the average system time of class-1 in case of zero traffic:

$$E'(R_1) = E'(W_1) + E(S), \text{ where } \lambda 2=0$$

Based on Eq. (10) we get:

$$E'(R_1) = \frac{\lambda_1*E^2(S)*(1+Cv^2(S))}{2*(1-\lambda_1*E(S))} + E(S) \quad (15)$$

Therefore, the average impact in milliseconds (I) equals to:

$$\mathrm{I} = E(R_1) - E'(R_1) \quad (16)$$

Percentage-wise the impact can be calculated as:

$$\frac{\mathrm{E(R_1)}}{\mathrm{E'(R_1)}} = 1 + \frac{\lambda_2*\mathrm{E(S)}*(1+\mathrm{Cv}^2(\mathrm{S}))}{\lambda_1*\mathrm{E(S)}*(\mathrm{Cv}^2(\mathrm{S})-1)+2} \quad (17)$$

From Eq. (17), we observe a K percentage increase on the average system time of class-1, equal to:

$$\mathrm{K} = \frac{\lambda_2*\mathrm{E(S)}*(1+\mathrm{Cv}^2(\mathrm{S}))}{\lambda_1*\mathrm{E(S)}*(\mathrm{Cv}^2(\mathrm{S})-1)+2} \quad (18)$$

4.2 Results

4.2.1 Impact of different packet-size distributions and bandwidth capacities on avg. global system time

Based on Eq. (4), we obtain the results presented in Figure 1. It is clear that the longest queueing delays are produced by the bimodal packet-size distribution while the 58-33-9 trimodal packet-size distribution produces the shortest queueing delays.

The other two packet-size distribution models present statistically similar behavior, exhibiting performance close to that of the bimodal distribution. As expected, bandwidth capacity significantly affects queueing delays, especially under high channel utilization. An interesting observation is that even in high-bandwidth configurations, average global system time remains close to the bound of 1 second; a rather significant delay especially for delay-sensitive applications. This fact constitutes a strong indication that time-sensitive applications ran by the home-group users might suffer intolerable delays. This calls for a queuing scheme with priorities to classify packets according to some predefined level of service.

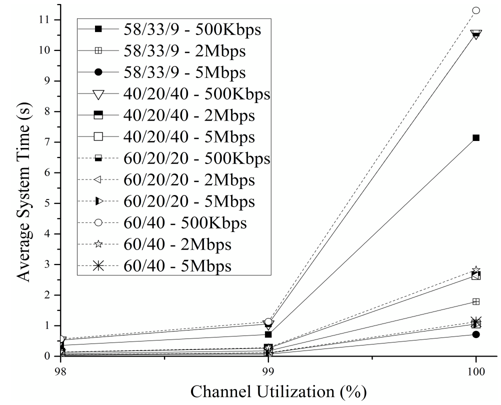


Figure 1. Avg. system time for various packet-size distributions and bandwidth capacities.

4.2.2 Impact of guest traffic on home-users' traffic

Due to limited space, we present in this section only a small portion of our results on bimodal distribution, in which the system exhibited worst performance. Figure 2 presents the average system time for both classes under several combinations of channel utilization, in a system with 500Kbps available bandwidth. Priority queueing reduces significantly the average system time of traffic class-1 (under 50ms in most cases), even for high channel utilizations. Note that in any case, maximum class-1 delay is equal or less than average global system time (see in Figure 2, case"Class-1, λ2=0, λ1=λ"), which reaches here up to 11 seconds for high channel utilizations.

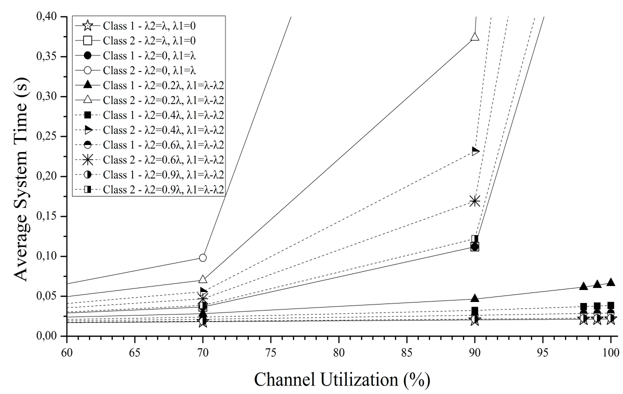


Figure 2. Avg. system time for both classes under several combinations of channel utilization.

Both the percentage and temporal impact of traffic class-2 on the average system time of traffic class-1 are depicted in Figures 3 and 4, respectively.

In particular, Figure 3 captures the pace in which the impact of traffic class-2 on traffic class-1 increases. Furthermore, Figure 4 shows that the additional average delay imposed to traffic class-1 can reach, in the worst case, up to 11ms; a rather significant delay considering that typical propagation delays between home-users' ADSL APs and popular websites are ranging between 40 and 70ms. However, we also note that even for low-bandwidth links there is a specific area, in which proper regulation of traffic class-2 can lead to significantly shorter delays (see Figure 4, x-axis 0-10%). Therefore, packet scheduling appears in such cases to be a powerful tool to control the impact on traffic class-1. In the following, we present two potential options for regulating λ2: i)

Based on Eq. (18) and setting K appropriately to confine λ2 (this is the method used in [14]) and ii) Based on Eq. (16) where λ2 is regulated by its actual impact on class-1 in milliseconds. A careful comparison of Figures 3 and 4 though, reveals that the percentage values of impact do not correspond to the respective milliseconds values. Consider for example the “99.9% Load” case with 500Kbps bandwidth availability (see the respective graphs in Figures 3 and 4). The linear increase of the percentage impact does not correspond to a similar temporal behavior, which remains constant for most values of class-2 channel utilization. Having said that, we argue that Eq. (16) is more efficient for regulating λ2.

Finally, our results indicate that a bandwidth availability point exists over which the impact on average system time for class-1 remains under a specific target value. This point for 1ms is estimated at 6Mbps and constitutes a clear indication that over that bound a certain amount of bandwidth could be exclusively allocated to traffic class-2.

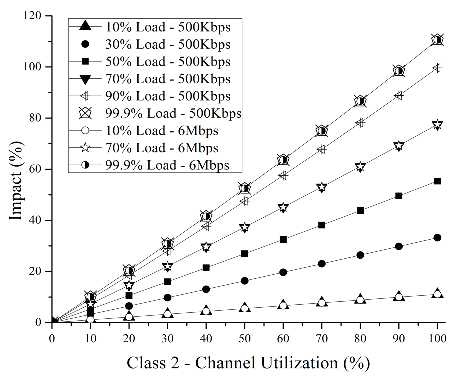


Figure 3. Percentage impact of traffic class-2 over traffic class-1.

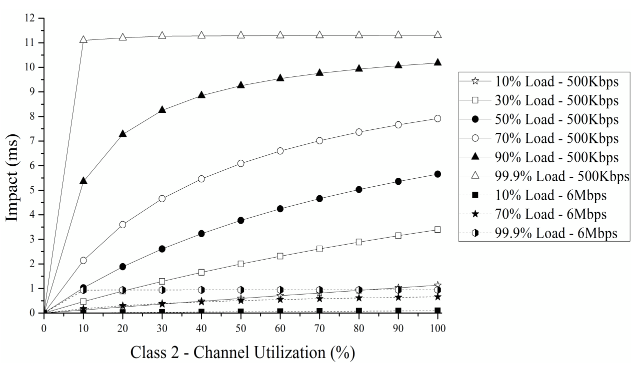
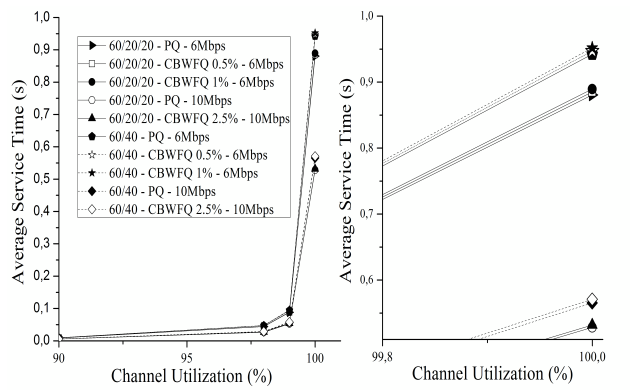


Figure 4. Temporal impact of traffic class-2 over traffic class-1.

5. TOWARDS A HYBRID PACKET SCHEDULING SCHEME (HPSS)

Departing from these observations, we propose a hybrid queueing scheme for enabling LE service in the APs of UPNs. It applies service differentiation on a per-packet basis and its hybrid nature comes from the fact that it has two modes of operation. In the first mode, which is active when link speed is below 6Mbps, the scheme applies a non-preemptive PQ policy between BE- and LE-traffic. Unlike [14], our packet scheduling algorithm confines the maximum additional imposed delay on traffic class-1 under the specific limit of 1ms, which we consider here as insignificant compared to the typical propagation delays mentioned in 4.2.2. The second mode of operation is activated for link speeds over 6Mbps. It applies a class-based WFQ policy, which allocates specific resources per class in order to guarantee a minimum service rate. The allocated resources for LE-class are increased by 0.5% for each Mbps over the 6Mbps limit (e.g. 6Mbps: BW2 = 0.005*BW, 10Mbps: BW2 = 0.025*BW etc.) and allocates the remaining to the BE-class. The analysis of the M/G/WFQ model is presented at [19] from which we use the lower-bound mean delay limit equation to calculate the average system delay of each class.

In Figure 5, we show that the analogy of 0.5% per Mbps and the 6Mbps limit guarantees that BE-traffic will experience almost zero impact on its average system time compared with the active PQ policy case. (see Figure 5 – PQ and CBWFQ 0.5% cases). Beyond this level, the statistical impact is significant. (see Figure 5 - CBWFQ 1% cases).



(a) Class-1 Avg. Service Time (b) Class-1 Avg. Service Time Zoom In

Figure 5. Average system time of traffic class-1 for various policies, and bandwidth capacities.

6. CONCLUSIONS AND FUTURE WORK

In this study, we assessed the behavior of a queueing system that administers the resource sharing process of an AP between home and guest users. We highlighted several aspects of the examined model such as the various packet-size distribution and link speeds. We concluded that for low link speeds the application of a priority-queueing system alone is not sufficient: an additional mechanism for regulating the arrival rate of the low-priority traffic is required to guarantee non-significant impact on high-priority traffic. We also identified a traffic pattern for high link speeds that permits a hybrid packet-scheduling scheme. HPSS entails low complexity, efficiency and high scalability.

Some of our future plans include the development of traffic shaping techniques based on DTN technology, which may not be appropriately modeled based on Poisson arrivals when traffic is regulated, and the experimental evaluation of HPSS in order to investigate its interaction with common congestion avoidance (e.g. TCP), active queue management (e.g. RED) and QoS mechanisms on specific buffering conditions of the customer-premises equipment. Furthermore, we intend to incorporate the developed shaping tactics and the corresponding mechanisms into our DTN testbed.

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