MANAGEMENT OF VoIP AND MISSION CRITICAL DATA TRAFFIC OVER HETEROGENEOUS MILITARY NETWORKS

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ABSTRACT

A Quality of Service (QoS) mapping problem arises when different encapsulation formats are employed to support the QoS over different transport technologies. For example when IP packets are transferred over ATM or MPLS core networks. The paper faces this problem in terms of bandwidth management, by investigating the sensitivity of bandwidth needs due to the change of encapsulation format. We study a novel control algorithm to estimate the bandwidth shift required to keep the same performance guarantees, independently of the technology change. The proposed algorithm is based on the Infinitesimal Perturbation Analysis, which is a sensitivity estimation technique for Discrete Event Systems. Simulation results concern a comparison with an heuristic much used in industrial applications as well as some experimental tests concerning Voice over IP to highlight the fast convergence of the algorithm in variable system conditions.

INTRODUCTION

Some studies report that a possible evolution of the next few year will include a core network composed of ATM (or MPLS) technology connecting border IP portions. It is a widespread perspective that "[…] *capital expediture constraints in both service providers and enterprises will mean that MPLS will evolve in the carrier core network first, with ATM remaining for some time to come as the primary technology for multiservice delivery in bandwidth-limited edge and access networks*" [Bocci03]. In such situation, *Quality of Service* (QoS) internetworking issues, namely the maintenance of an end-to-end communication between users attached to access networks supported by different QoS technologies reveals to be a hot topic of research. This problem is enforced by the fact that the traffic flows that interconnect users located in different localities of the world are routed throughout different proprietary networks, often called *Autonomous Systems* (ASes), managed by different *Service Providers* (SPs) [Gao01].

If the overall network is composed of portions implementing different technologies, the key point is measuring the bandwidth shift imposed by the different encapsulation formats. Concerning a network scenario composed of an ATM core fed by IP edge flows, it is topical to know the amount of bandwidth that needs to be offered by the core to support the QoS required by the IP flows. The main idea is to have a control algorithm that can dimension correctly the necessary bandwidth shift, but does not need any closed-form formula of the performance metric and is able to react to traffic changes.

The paper is organized as follows. Section II states the interworking environment where the bandwidth allocation algorithm is applied. Section III focuses on the main problems of QoS mapping. Section IV contains the definition of the algorithm proposed and provides details about estimation performance metric, the optimization problem and the conditions for convergence. Section V contains the results and Section VI the conclusions.

THE QOS INTERWORKING ENVIRONMENT

The Application Framework

A possible application framework is depicted in Figs 1 and 2, which show the IP-ATM interworking scenario, where a *QoS-Relay Node* (QoS-RN) is used to "map" the QoS among the network portions. IP packets originated by an edge IP network are transported over an ATM core. The identification of the technology (IP and ATM) is just an example; each of them may be substituted by alternative technologies.

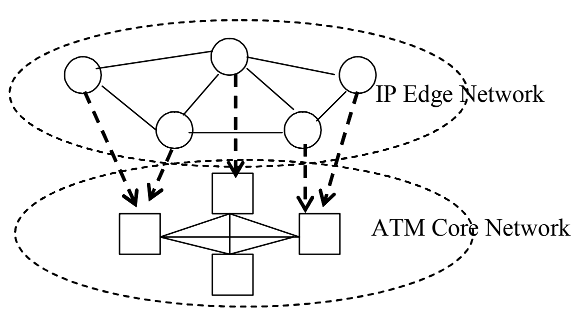

Fig. 1. IP over ATM architecture.

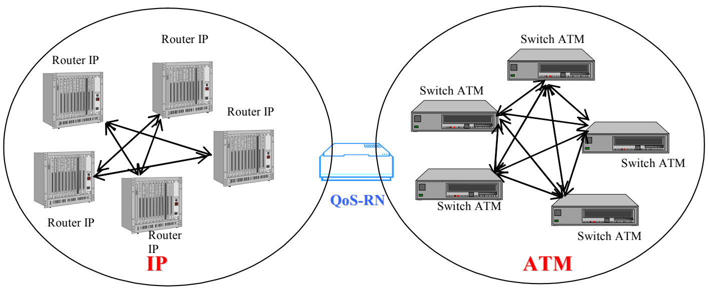

Fig. 2. The QoS-RN.

The ATM over IP environment, still relevant and timely due to the widespread diffusion of ATM backbones may be extended to other encapsulation formats.

IP is typically mapped onto ATM using AAL 5 frames. Both the ATM Forum ([ATM01]) and the Internet Engineering Task Force (IETF) ([Fischer02, Martini02]) are currently developing several techniques in order to manage the interworking between ATM and MPLS flows. The Pseudo Wire Emulation Edge-to-Edge (PWE3) working group of IETF is working on protocols for transporting layer 2 services (which, in PWE3 view, includes also ATM) over IP-based network. This includes not only the transport of ATM over MPLS ([Fischer02]), but frame relay, circuit emulation, synchronous optical network (SONET), and Ethernet over MPLS, too. Our control algorithm is suitable for managing the aforementioned interworking scenarios. However, without loss of generality, we take the IP over ATM interworking framework as a reference.

THE QOS MAPPING PROBLEM

References [IETF99, Garret98] of IETF and [ATM00] of the ATM Forum are the most important proposed standards for the mapping of QoS declarations between different QoS technologies. They investigate which ATM service categories must be chosen to support different QoS IP service classes. In reference [Giac99] the mapping of IntServ over ATM is investigated, showing that the ATM nrt-VBR service class gives more bandwidth saving than the CBR service class. Reference [Cobley98] shows by simulations analysis that the IntServ-ATM mapping of [Garret98] causes an excessive cell loss rate. These works have in common the investigation of the change of the QoS parameters at the QoS-RN when a flow changes its transport layer, namely the QoS parameters change their specification units from cell to packet and viceversa. Actually, one of the topical problems is the effect of the basic information unit length over the bandwidth requirements of a traffic flow [Schmitt03]. The topic is extremely complex even because it heavily depends on the traffic statistical behavior, but it is fundamental for a proper design of QoS interworking.

THE BANDWIDTH SHIFT AT THE QOS-RN

Definition of the problem

We suppose that the bandwidth pipe assigned to the flow in the IP portion has been correctly dimensioned to guarantee the required QoS. The problem here is to find the new bandwidth assignment when such IP flow changes the transfer mode and a new encapsulation format (e.g., the LLC-SNAP encapsulation of the AAL5) is applied at the QoS-RN, by tunneling IP packets along the ATM portion of the network.

Fig. 3 shows the protocol stack within the QoS-RN. The layer identified as QoS-RN is virtual and represents the control algorithm introduced in this work. Its role is to assign the necessary bandwidth to the ATM portion, thus maintaining the same level of quality guaranteed by IP.

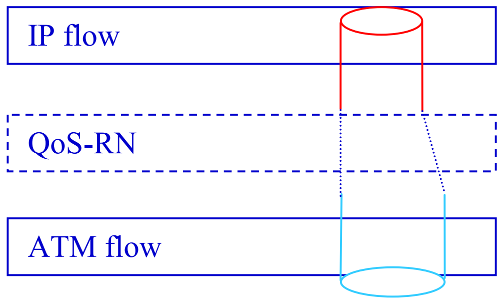

Fig. 3. The bandwidth shift at the QoS-RN.

We adopt a *Service Level Agreement* (SLA) based on a protection over the loss of the information carried by the IP flow. Such SLA is expressed in terms of IP *Packet Loss Probability* (PLP), which is the performance metric used in this paper, both within the IP and the ATM portion. An IP packet is lost if at least one of the ATM cells of its encapsulation is lost along the ATM tunnel. In this scenario, two issues arise: the first one concerns how the ATM *Cell Loss Probability* (CLP) can influence, in the ATM subnetwork, the IP PLP. The second one concerns how much bandwidth must be reserved in the ATM tunnel to preserve the SLA guaranteed in the QoS IP subnetwork.

Some more words are necessary concerning the notion of *equivalent bandwidth* and its application in the framework of this work. Equivalent bandwidth is the minimum amount of network resources to be allocated to guarantee a fixed degree of performance. It can have a local switching element value and concern only the interworking node but its scope may be also extended including end-to-end communication. It may be representative of an IP tunnel within an IP portion, of a *Virtual Path* (VP) [Schwartz96] in

ATM, of a *Label Switched Path* (LSP) in MPLS, of a bundle of circuits in ISDN.

Fig. 4 reports the interworking scenario along with the buffer model used to get the results reported in this paper.

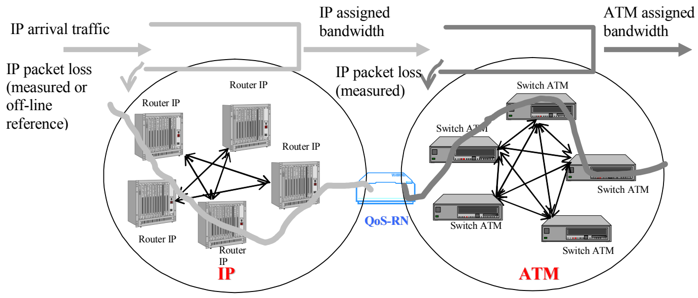

Fig. 4. Interworking scenario and used model.

As said before, we suppose to measure the IP PLP volume within ATM portion and within the IP portion (or, in this last case, to have an off-line reference value) by monitoring IP and ATM traffic performance. The same scheme may be applied with different metrics as delay and jitter. According to such on-line measurements, the algorithm proposed adapts the bandwidth assigned to the ATM portion so to keep the same loss volume obtained within the IP network so that the same QoS is guaranteed, independently of the change in the transfer mode. Operatively, if applied along a VP, after the computation, a signal of bandwidth reservation will be propagated along the ATM subnetwork in order to perform the actual bandwidth assignment along the VP.

The derivative estimation of the loss performance metric

To do this, we firstly need a derivative estimate of the performance index (the packet loss) defined in the SLA. With a notation that slightly differs from [Wardi02], we adopt a *Stochastic Fluid Model* (SFM) for each of the modeling buffers, shown in Fig. 4. Each buffer has a finite-capacity buffer of fixed size c and a single server with service rate θ. Fig. 5 reports the formal model of a buffer.

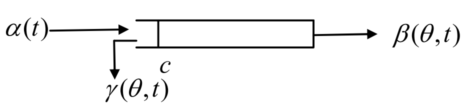

Fig. 5. Model of the traffic buffers.

The stochastic processes associated with this model and essential for the optimization procedure are: $\alpha(t)$: the input flow rate (*inflow*) process into the SFM; $\gamma(\theta,t)$: the loss rate (*overflow*) process due to a full buffer and $\beta(\theta,t)$: the *outflow* rate process of the buffer.

Since our aim is to exploit a control scheme for the loss probabilities of the IP packets on the ATM portion of the network, we adopt the following IPA performance measure: the *loss volume* $L_V(\cdot)$ over a time interval [0,*T*]. It is defined as:

$$L_V(\theta) = \int_0^T \gamma(\theta,t)\, dt \qquad (1)$$

Now, our first purpose is to obtain a derivative estimate of performance metric, $L_V(\theta)$, with respect to the service rate $\theta \in \Re$. Let B_k be an "active" period of the buffer between two times of bandwidth reallocation, namely, a period of time in which the buffer is non-empty. Let ξ_k be the starting point of B_k. Let ν_k be the instant of time when the last loss occurs during B_k. Then, for every θ, it can be shown ([Wardi02]) that:

$$\frac{\partial L_V^k(\theta)}{\partial\theta} = -(\nu_k(\theta) - \xi_k(\theta)) \qquad (2)$$

The contribution to the derivative of each active period B_k, during which some losses occurred, is the length of the time interval from the start of B_k until the last time point in B_k at which the buffer is full. Denoting by N_B the number of active periods during an observation window (for instance, between two consecutive service rate reallocations of the buffer), an estimation of the derivative performance can be obtained as (Fig. 6):

$$\frac{\partial L_V(\theta)}{\partial\theta} = \sum_{k=1}^{N_B} \frac{\partial L_V^k(\theta)}{\partial\theta} \qquad (3)$$

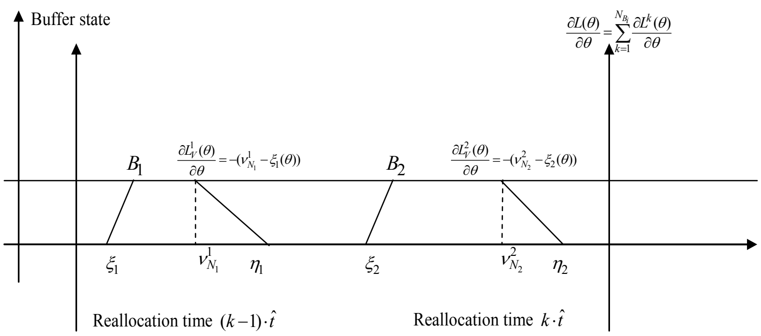

Fig. 6. IPA derivative estimation (3), looking at the busy periods of the buffer.

The Optimization Problem at the QoS-Relay Node

Let $L_V^{IP}(\theta^{IP})$ be the loss volume measured (or imposed) at the IP buffer according to the IP bandwidth allocation θ^{IP} guaranteed on the IP subnetwork. Let $L_V^{IPoATM}(\theta^{ATM})$ be the loss volume of the IP packets measured at the ATM buffer according to the ATM bandwidth allocation θ^{ATM}. The problem is to find the optimal bandwidth allocation, ${}^{Opt}\theta^{ATM}$, in order to minimize a proper penalty cost function $J(\theta^{ATM})$:

$$
{}^{Opt}\theta^{ATM} = \arg \min_{\theta^{ATM} \in \Re} J(\theta^{ATM});
$$

$$
J(\theta^{ATM}) = \underset{\omega \in \Theta}{E} [L_V^{IP}(\theta^{IP}) - L_V^{IPoATM}(\theta^{ATM})]^2 \quad (4)
$$

Let $L_{\Delta V}^{IPoATM} = [L_V^{IP}(\theta^{IP}) - L_V^{IPoATM}(\theta^{ATM})]^2$ be the functional cost whose derivative estimation is needed to establish an optimization procedure aimed at approximating the optimal solution ${}^{Opt}\theta^{ATM}$ of (4). The control variable is the θ^{ATM} and such derivative estimation can be obtained according to $\frac{\partial L_{\Delta V}^{IPoATM}(\theta^{ATM})}{\partial \theta^{ATM}} =$

$$
2 \cdot \frac{\partial L_V^{IPoATM}(\theta^{ATM})}{\partial \theta^{ATM}} [L_V^{IPoATM}(\theta^{ATM}) - L_V^{IP}(\theta^{IP})] \quad (5)
$$

$\frac{\partial L_V^{IPoATM}(\theta^{ATM})}{\partial \theta^{ATM}}$ is computed according to the IPA formulas (2) and (3). The proposed optimization algorithm is based on the gradient method ruled by (6).

$$
\theta_{k+1}^{ATM} = \theta_k^{ATM} - \eta_k \left. \frac{\partial L_{\Delta V}^{IPoATM}(\theta^{ATM})}{\partial \theta^{ATM}} \right|_{\theta_k^{ATM}} \quad (6)
$$

where η_k is the gradient stepsize.

PERFORMANCE EVALUATION

The Heuristic Allocation

We compare the proposed control algorithm with a heuristic strategy much used in industry. It disposes of a perfect knowledge about the bandwidth assignment on the IP portion of the network and about the IP packet size distribution. The increase in the bandwidth allocation necessary for the ATM tunnel can be foreseen by mean of the well-known "Cell-Tax" effect of the AAL5 with LLC-SNAP encapsulation. Since, during the generation of the ATM frame, at each IP packet, two octets need to be added for the LLC-SNAP overhead, the number of ATM cells for each IP packet is:

$$
\# ATMCells = \left\lceil \frac{DimIPPacket + 2}{48} \right\rceil \quad (7)
$$

where $DimIPPacket$ denotes the IP packet's size in bytes and 48 is the payload of an ATM cell in bytes. Hence, it is possible to compute the overall overhead due to the encapsulation format on the ATM frame and then the percentage bandwidth increase on the ATM side of the network, denoted in the following by $CellTax\%$:

$$
CellTax\% = \frac{\# ATMCells \cdot 53 - DimIPPacket}{DimIPPacket} \cdot 100 \quad (8)
$$

where 53 is the overall size (payload and overhead) of an ATM cell in bytes.

If the IP source has its own packet's size distribution, the CellTax must take into account the mean number of ATM cells in the ATM frame as:

$$
CellTax\% = \frac{\overline{\# ATMCells} \cdot 53 - \overline{DimIPPacket}}{\overline{DimIPPacket}} \cdot 100 \quad (9)
$$

where $\overline{DimIPPacket}$ is the mean size of the IP packets and $\overline{\# ATMCells}$ is the mean number of ATM cells generated by an IP source that produces n different packet's size $DimIPPacket_i$, $i = 1,...,n$, each of which with probability p_i, ($\sum_{i=1}^{n} p_i = 1$):

$$
\overline{\# ATMCells} = \sum_{i=1}^{n} \frac{DimIPPacket_i + 16}{48} \cdot p_i \quad (10)
$$

A good forecast concerning the ATM bandwidth allocation is then:

$$
{}^{CellTax}\theta^{ATM} = (1 + CellTax\%) \cdot \theta^{IP} \quad (11)
$$

Tunnelling Voice over IP through ATM

We now consider the case of a *Voice over IP* (VoIP) traffic, originated in an IP-based network, and carried along an ATM-based portion. Taking [Byungsuk02] as a reference, each VoIP source is modeled as an exponentially modulated on-off process, with the mean on and off times, as for the ITU P.59 ([ITU P.59]) recommendation, being 1.008 s and 1.587 s, respectively. All VoIP connections are modeled as 16.0 Kbps flows voice over RTP/UDP/IP. The packet size is 80 bytes. The required end-to-end performance objectives of a VoIP flow (shown in Table 1) are less than 2% of IP PLP and 150 ms of end-to-end delay.

Service Level Agreement	***Range***
Premium VBR for *Voice over IP*	Variable Bit Rate (VBR)
Traffic description and conformance testing of VoIP	Peak Rate: 16 kbps; Mean Rate: 14.87 kbps; Packet Size: 80 bytes; Maximum Burst Size: 1.0 s.
Performance guarantees	**Packet Loss Rate: 2 %**.

Table 1. VoIP Service Level Agreement [ITU P.59].

The proposed control algorithm is adopted in order to manage the equivalent bandwidth shift due to the LLC-SNAP encapsulation of the VoIP packets. For now, it concerns only the loss, but as should be clear from the results, the allocation performed allows also getting satisfying performance concerning the delay.

We compare the aforementioned *CellTaxAllocation* strategy with the proposed control algorithm with the same size of the IP and ATM buffers (fixed at 20 VoIP packets corresponding to 31 ATM cells) and by progressively increasing, from 70 to 110, the number of VoIP sources in the flow. The step is of 10 sources each 3000 s. Each time the number of VoIP source changes (every 3000 seconds) the ATM bandwidth allocation of the control algorithm is initialized with the *CellTaxAllocation* strategy (i.e., $\theta^{ATM}(0) = (1 + CellTax\%) \cdot \theta^{IP}$), then, every 30 seconds a new derivative estimation of the penalty cost function (4) is computed according to (5) and a new ATM bandwidth allocation is performed through the gradient descent (6). The gradient stepsize is fixed to 8.0 $\forall k$, which is the best value (found by simulation inspection) to maximize the convergence speed.

The IP bandwidth allocation guarantees the required IP PLP along the IP portion. Fig. 7 shows the failure of the *CellTaxAllocation* strategy at guaranteeing the required IP PLP along the ATM tunnel, while the proposed control algorithm (Fig. 8) is able to achieve the required QoS performance.

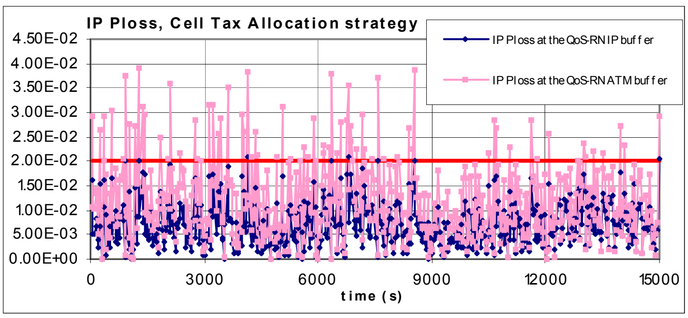

Fig. 7. VoIP over ATM simulation scenario.

IP PLP CellTaxAllocation strategy.

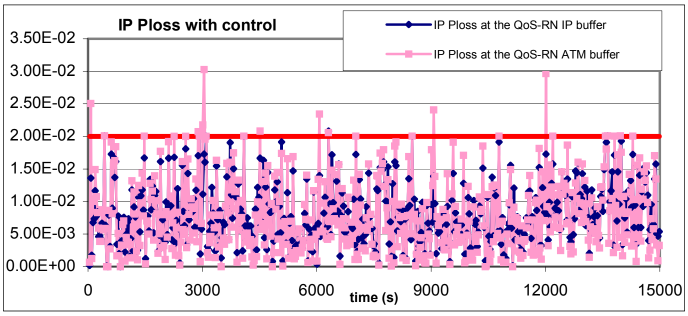

Fig. 8. VoIP over ATM simulation scenario.

IP PLP with control.

In Fig. 9 the two types of ATM bandwidth allocation techniques are compared showing that, even if the buffers are of equal size, the *CellTaxAllocation* strategy underestimates the required ATM equivalent bandwidth to correctly carry the VoIP flows. In Fig. 10 the equivalent bandwidth shift between the IP and ATM is shown. In Fig. 11 the CellTax measured by our control algorithm as

$$SimulatedCellTax(k) = \frac{\theta^{ATM}(k) - \theta^{IP}}{\theta^{IP}} \qquad (12)$$

is compared with the one ruled by (9), for each reallocation step.

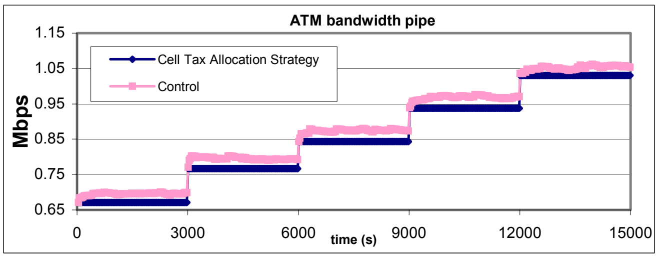

Fig. 9. VoIP over ATM simulation scenario. ATM pipe.

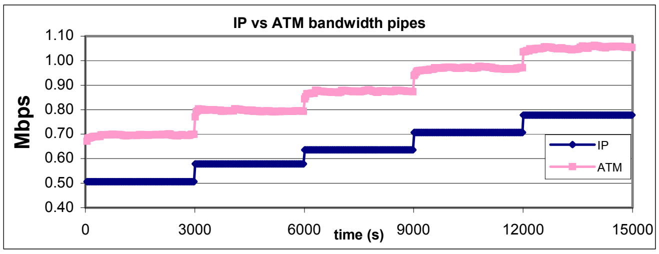

Fig. 10. VoIP over ATM simulation scenario.

IP versus ATM bandwidth pipes.

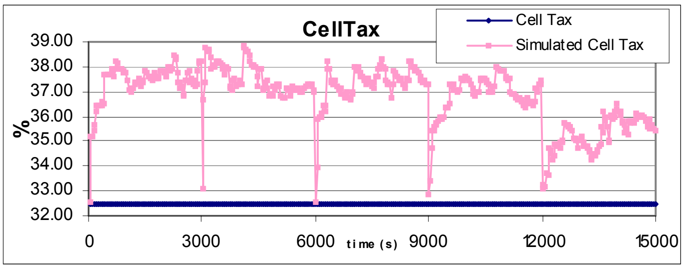

Fig. 11. VoIP over ATM simulation scenario. CellTax.

As far as the end-to-end delay of the VoIP SLA is concerned, it should be noted that even with the lowest bandwidth allocation (0.50 Mbps of the 70 VoIP sources case, see Fig. 10), the maximum delay of a full buffer is around 25 ms. Therefore, along a route of no more than 6 nodes the required 150 ms end-to-end delay is guaranteed.

Tunnelling IP Mission Critical Data over ATM

We consider now the case of mission critical data characterized by the *trimodal* distribution in the packet size. According to it, the packet size can assume three different values: a with probability p_a, b with probability p_b and c with probability $1-p_a-p_b$. The trimodal distribution is widely used to accurately describe the packet size distribution of the current Internet traffic. A Pareto distributed iterarrival time between the IP packets has been introduced. The mean interarrival time used are 10 ms and 100 ms and the number of connections in the IP flow is 1, 20, 100. The IP buffer size is set to 150,000 bytes and the IP bandwidth allocation θ^{IP} guarantees a IP PLP $\le 1\cdot 10^{-2}$.

A comparison between the *CellTaxAllocation* strategy and the proposed control scheme is shown in Table 2 (ATM buffer size = IP buffer size = 2830 ATM cells) and Table 3 (ATM buffer size = 200 ATM cells), where, from left to right, the mean interarrival times of the IP packets (*Arr-Time*), the number of connection in the flow (*#Conn*), the IP bandwidth allocation (θ^{IP}), the ATM bandwidth allocation computed by the *CellTaxAllocation* strategy (${}^{CellTax}\theta^{ATM}$), the ATM bandwidth allocation computed by the proposed control algorithm (${}^{Opt}\theta^{ATM}$), the "real" *CellTax* computed by the proposed control algorithm (i.e., $SimulatedCellTax\% = \frac{{}^{Opt}\theta^{ATM} - \theta^{IP}}{\theta^{IP}} \cdot 100$), and the difference between the *Simulated CellTax%* and the *CellTax%* computed by the *CellTaxAllocation* strategy (*CellTax%* difference) are visualized. As shown above, the ${}^{Opt}\theta^{ATM}$ is the optimal value for dimensioning of the bandwidth pipe assigned to the IP flow in the ATM subnetwork and it should be taken as the target value for the following comparison.

From these results, it is clear that the *CellTaxAllocation* strategy produces good results only if the buffers of the QoS-RN have the same size. In such a situation, the difference between the *CellTax* computed by the *CellTaxAllocation* strategy and the real *CellTax*, is below the 5% (see last column of Table 2).

On the contrary, if the ATM buffer has only 200 cells (Table 3), such difference reaches values up to 30% (4th row of Table 3). It is worth noting that, if the mean interarrival time is 0.01 (first 3 rows of Table 3) such difference is around 20% with a minimum of 18% for 1 connection in the flow (first row of Table 3), while, if the mean interarrival time is 0.1 (last 3 rows of Table 3), such difference is much higher and it has a maximum of 31% for 1 connection in the aggregated flow (4th row of Table 3).

The rationale of this behaviour comes from the fact that at the increase of the mean interarrival time and with a small number of connections in the flow, the rate variability of the flow increases and this has stronger impact on the error produced by the *CellTax* computed by the *CellTaxAllocation* strategy.

Arr-Time	***#Conn***	θ^{IP} ***Mbps***	***CellTax%***	${}^{CellTax}\theta^{ATM}$ ***Mbps***	${}^{Opt}\theta^{ATM}$ ***Mbps***	***Simul. Cell-Tax%***	***CellTax% diff.***
0.01	1	0.28	20.44%	0.337	**0.352**	25.82%	**4.38%**
0.01	20	5.700	20.44%	6.865	**7.024**	23.22%	**2.31%**
0.01	100	28.50	20.44%	34.325	**34.944**	22.61%	**1.80%**
0.1	1	0.039	20.44%	0.047	**0.048**	23.66%	**2.19%**
0.1	20	0.78	20.44%	0.939	**0.964**	23.61%	**2.62%**
0.1	100	4.100	20.44%	4.938	**4.870**	18.79%	**-1.38%**

Table 2. ATM buffer size = 2830 ATM cells.

Arr-Time	***#Conn***	θ^{IP} ***Mbps***	***CellTax%***	${}^{CellTax}\theta^{ATM}$ ***Mbps***	${}^{Opt}\theta^{ATM}$ ***Mbps***	***Simul. Cell-Tax%***	***CellTax% diff.***
0.01	1	0.29	20.44%	0.349	**0.413**	42.56%	**18.37%**
0.01	20	5.750	20.44%	6.925	**8.075**	40.44%	**16.60%**
0.01	100	28.75	20.44%	34.627	**41.657**	44.89%	**20.30%**
0.1	1	0.038	20.44%	0.046	**0.06**	57.64%	**30.89%**
0.1	20	0.78	20.44%	0.939	**1.130**	44.93%	**20.33%**
0.1	100	3.900	20.44%	4.697	**5.556**	42.45%	**18.28%**

Table 3. ATM buffer size = 200 ATM cells.

CONCLUSIONS

A novel control algorithm has been proposed in order to manage the mapping of the QoS among heterogeneous networks. Showing a promising "self-learning" property, it is able to react to traffic changes, always guaranteeing the minimal bandwidth allocation necessary for the maintenance of the Service Level Agreement when a traffic flow is routed along subnetworks supported by different transport technologies.

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