Equivalent Bandwidth Control for the Mapping of Quality of Service in Heterogeneous Networks

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***Abstract* - There are several QoS technologies available for an *Internet Service Provider* to manage *Guaranteed Performance* Services in a telecommunication network. The study of the possible interactions between different QoS technologies is currently an open area of research often called, in the literature, *QoS mapping*. A QoS mapping problem arises when different encapsulation formats are employed to support a fixed QoS with different transport technologies (e.g., ATM, IP). We face this problem in terms of bandwidth management. We adopt a novel control scheme that does not need any closed-form formula for the performance metric and that is able to react to traffic changes.**

Keywords – Quality of Service, QoS Interworking, Equivalent Bandwidth Control, Infinitesimal Perturbation Analysis.

I. INTRODUCTION

Several QoS technologies are now available to support *Guaranteed Performance* (GP) services in a telecommunication network. ATM technology and the QoS IP technologies (the *Integrated* and the *Differentiated Services* techniques) adopt different approaches to support QoS. *Multi Protocol Label Switching* (MPLS), has been recently developed from the convergence between IP world and ATM ([1]). As of today, the QoS offered by QoS IP solutions may not be as mature as in the ATM environment but the IP community is currently working to fill the gap (see, e.g., [2-5]). It is a widespread perspective that *"…capital expenditure 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"* [6]. In such a situation, QoS internetworking issues, namely the problem regarding the maintenance of an end-to-end communication between users attached to access networks supported by different QoS technologies, is a hot topic of research for the telecommunication community ([6-17]). A control mechanism to manage the *equivalent bandwidth* shift, due to the possible changes in the transport protocol, is investigated in this paper, supposing that an ATM network supports IP traffic. The paper is structured as follows: the next section describes the QoS interworking environment. Section III focuses on equivalent bandwidth shift control. Section IV contains the results and section V the conclusions.

II. THE QOS INTERWORKING ENVIRONMENT

A possible QoS interworking scenario is shown in Fig. 1. The identification of the technology (IP and ATM) is just an example. The scope of the paper is not limited to ATM and IP even if the tests reported concern the IP over ATM environment. The interconnection implies the definition of a special communication node, defined as *Quality of Service - Relay Node* (QoS-RN).

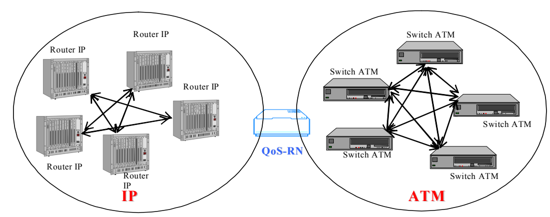

Fig. 1. Possible application framework.

The change in the information transport unit has a strong impact on the bandwidth requirements to keep the same level of QoS while traversing the QoS-RN [7, 11-14].

III. BANDWIDTH CONTROL AT THE QOS-RN

A GP user subscribes a proper SLA (*Service Level Agreement*) with strict QoS requirements, such as with constraints over the end-to-end mean delay or delay jitter or in terms of loss probability of the packets. It is possible, at the time of a GP call setup, to translate these requirements in terms of the *equivalent bandwidth*. There are several methods to calculate the equivalent bandwidth, based on analytical models or by means of simulation analysis, possibly also on the basis of on-line measurements (see, e.g., [1, 19]).

We are going to investigate the equivalent bandwidth necessary to satisfy the SLA of an IP DiffServ traffic flow that is routed along an ATM network. We suppose that the employment of one of the aforementioned equivalent bandwidth methods has guaranteed a correct dimensioning of the bandwidth pipe assigned to the IP flow in the IP portion of the network. The problem, in the context of QoS mapping, 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, to forward the flow through the ATM portion of the network. We shall adopt a SLA based on a protection over the loss of information carried by the IP DiffServ flow. Such SLA is expressed in terms of IP *Packet Loss Probability* (IP-PLP). In this scenario, two issues arise: the first one concerns how the ATM *Cell Loss Probability* (ATM-CLP) can influence, in the ATM subnetwork, the IP-PLP, the second one regards how much bandwidth must be reserved in the ATM tunnel to preserve the SLA guaranteed in the QoS IP subnetwork. An example may help understand. If the DiffServ flow receives, in the QoS IP subnetwork, a bandwidth allocation of, e.g., 1.0 Mbps in order to guarantee an IP-PLP of, e.g., $1 \cdot 10^{-2}$, when such flow is mapped over the ATM subnetwork, we have to answer the following questions:

- *what ATM-CLP must be guaranteed, in the ATM tunnel, to maintain the same IP-PLP of* $1 \cdot 10^{-2}$ *?*
- *how much bandwidth must be reserved to the ATM tunnel ?*

Even if a "map function" between the ATM-CLP and the IP-PLP is available, we do not know the equivalent bandwidth that must be assigned to the ATM tunnel just because it strongly depends on the IP traffic statistics (IP sources' rate, IP packet size distribution). As we will show in the simulation results, even if such IP traffic statistics are perfectly known (or perfectly estimated), only heuristics can be applied to establish the ATM bandwidth allocation because, in the literature, there are no closed-form formulas for the planning of an IP over ATM flow in terms of QoS maintenance. In order to manage such a difficult situation (unknown IP traffic statistics and bandwidth allocation and unavailable closed form formulas for the mapping of the IP-PLP to the ATM-CLP), we proceed by formulating a control scheme based on the so-called *Infinitesimal Perturbation Analysis* (IPA). IPA is a sensitivity estimation technique for *Discrete Event Systems* (DESes). It is based on the observation of the sample paths followed by the stochastic processes of a DES and it gives an estimation of the derivative of the performance index, with mild a-priori assumptions about the statistical properties of the DES under investigation [20].

A. *The equivalent bandwidth shift at the QoS-RN*

We suppose that the QoS-RN is endowed with two buffers in order to store the incoming IP traffic flow and forward it into the ATM subnetwork. A monitoring action of the IP and ATM traffic performance over the two buffers (in terms of losses) is established. The measures performed at the ATM buffer of the QoS-RN are representative of the QoS received by the traffic flow in the ATM portion of the network. According to such on-line measurements, we generate a signal of bandwidth reservation that must be propagated through the ATM subnetwork in order to equal the values of IP losses (measured at the IP buffer of the QoS-RN) to the values of the IP losses over ATM (measured at the ATM buffer of the QoS-RN), so that the same QoS is guaranteed, despite the change in the transfer mode. It is important to highlight that the performance metric is always the "IP packet loss", which is measured both over the IP portion ("IP buffer") and over the ATM portion ("ATM buffer").

B. *Derivative estimation of the loss performance metric*

To do this, we firstly need a derivative estimate of the performance index defined in the SLA. With a notation that slightly differs from [20], we adopt a *Stochastic Fluid Model* (SFM) for both the buffers of the QoS-RN. Each of them has its finite-capacity c and a single server with service rate θ. The stochastic processes (Fig. 2) associated with this model and useful for our control algorithm are:

$$\beta(\theta,t) = \begin{cases} \theta \text{ if the buffer is not empty at time } t \\ 0 \text{ otherwise} \end{cases}$$

the "instantaneous" service rate process;

$\alpha(t)$,the input flow rate process into the SFM)

$\gamma(\theta,t)$, the loss rate process due to a full buffer).

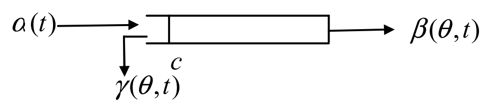

Fig. 2. Stochastic Fluid Model of the buffers at the QoS-RN.

The *loss volume* $L_V(\theta)$ over a time interval *[0,T]* is:

$$L_V(\theta) = \int_0^T \gamma(\theta,t)\, dt \tag{1}$$

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 that:

$$\frac{\partial \hat{L}_V^k(\theta)}{\partial \theta} = -(\nu_k(\theta) - \xi_k(\theta)) \tag{2}$$

The contribution to the derivative estimation 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 instant in B_k at which the buffer is full. Denoting with 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:

$$\frac{\partial \hat{L}_V(\theta)}{\partial \theta} = \sum_{k=1}^{N_B} \frac{\partial \hat{L}_V^k(\theta)}{\partial \theta} \tag{3}$$

C. The Optimization Problem at the QoS-Relay Node

Since our aim is to apply the estimator for the derivative of the performance index, formulated in the previous subsection, in order to find out the amount of bandwidth that must be reserved in the ATM portion of the network, it is necessary to identify a proper penalty cost function whose values can be interpreted as an indication about the current inability of the ATM subnetwork to guarantee the required IP-PLP.

Let $L_V^{IP}(\theta^{IP})$ be the loss volume measured at the IP buffer of the QoS-RN according to the IP bandwidth allocation θ^{IP} guaranteed through the IP subnetwork. Let $L_V^{IPoATM}(\theta^{ATM})$ be the loss volume of the IP packets measured at the ATM buffer of the QoS-RN according to the ATM bandwidth allocation θ^{ATM}. The problem is to find the optimal bandwidth allocation, ${}^{Opt}\theta^{ATM}$, in order to minimize the following cost function:

$$\begin{aligned} {}^{Opt}\theta^{ATM} &= \arg\min_{\theta^{ATM}\in\Re^+}\{\underset{\omega\in\Omega}{E}[L_{\Delta V}^{IPoATM}]\}; \\ L_{\Delta V}^{IPoATM} &= [L_V^{IP}(\theta^{IP}) - L_V^{IPoATM}(\theta^{ATM})]^2 \end{aligned} \quad (4)$$

$\underset{\omega\in\Omega}{E}[\cdot]$ represents the mean value over all possible sample paths Ω followed by the two buffers, according to the statistical behaviour of the IP sources. The control variable is the θ^{ATM} and the functional cost derivative estimation is:

$$\frac{\partial\hat{L}_{\Delta V}^{IPoATM}(\theta^{ATM})}{\partial\theta^{ATM}} = 2\cdot\frac{\partial\hat{L}_V^{IPoATM}}{\partial\theta^{ATM}}[L_V^{IPoATM}(\theta^{ATM}) - L_V^{IP}(\theta^{IP})] \quad (5)$$

$\frac{\partial\hat{L}_V^{IPoATM}}{\partial\theta^{ATM}}$ is computed according to the IPA formulas (2) and (3), where the ν_k variable denotes the time instant when the first ATM cell is lost, belonging to the last IP packet lost during the busy period B_k. All of the variables of (5) can be computed by monitoring the buffers of the QoS-RN. The optimization algorithm is based on the gradient method:

$$\theta_{k+1}^{ATM} = \theta_k^{ATM} - \eta_k\frac{\partial\hat{L}_{\Delta V}^{IPoATM}(\theta_k^{ATM})}{\partial\theta_k^{ATM}} \quad (6)$$

where η_k is the gradient step size. A sequence of bandwidth reallocations, $k = 1,2,\ldots$, is performed according to (6), and, after a steady state has been reached, the correct bandwidth requirement for the ATM tunnel, ${}^{Opt}\theta^{ATM}$, is obtained. The best combination of η_k and of the dimension of the time intervals between two consecutive ATM bandwidth reallocations, ($\Delta T_{\theta^{ATM}}$), has to be evaluated through simulation inspection.

IV. SIMULATION RESULTS

The simulation scenario under investigation deals with the previously mentioned example of an IP DiffServ flow carried over an ATM subnetwork. We have developed a C++ simulator for the QoS-RN in which the AAL5, based on the LLC-SNAP encapsulation, is employed to establish the ATM tunnel. The statistical behaviour of the IP flow is characterized by the Internet IP packet size variability, based on a *trimodal* probability distribution. 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 describe the packet size distribution for Internet traffic. Measurements collected by the *Politecnico di Torino* telecommunication research group have shown that a trimodal distribution with $a = 48$ bytes, $b = 576$ bytes, $c = 1500$ bytes, $p_a = 0.559$, $p_b = 0.2$ (denoted in the following with *Trimodal(48, 576, 1500, 0.559, 0.2)*) well approximates the traffic traces collected during the first 13 days of the year 2001 ([21]).

A. Convergence behaviour of the control algorithm

In the following simulation scenario, the IP traffic flow is composed by the aggregation of 10 sources, each of them characterized by the above mentioned *Trimodal(48, 576, 1500, 0.559, 0.2)* distribution concerning their packet size variability. In order to verify the adaptability of the proposed control algorithm, an increase in the IP sources' aggregate bit rate is applied after 1.0 minute of simulation. The guaranteed IP PLP is fixed to $3\cdot10^{-2}$. We have obtained the equivalent bandwidth for the IP flow aggregate, visualized in Table 1, by simulation analysis. The width of the confidence interval over the following simulated loss performance is less then 1% for the 95% of the cases. Both the IP buffer and ATM buffer sizes were set to 150,000 bytes.

A sample path of the IP PLPs measured at the QoS-RN after the convergence of the proposed control algorithm is depicted for each side of the QoS-RN in Fig. 3. The optimisation algorithm (6) was applied by setting $\Delta T_{\theta^{ATM}}$ to 0.2 seconds and the gradient stepsize η_k to $1\cdot10^3, \forall k$. Fig. 4 shows the values of the ATM bandwidth allocations. The proposed control algorithm is able to equalize the IP PLPs of the two buffers of the QoS-RN after a transient period of about 10.0 seconds. Clearly, the ${}^{Opt}\theta^{ATM}$ is time dependent and reaches different steady states according to the time-varying IP sources' rate.

Time Interval (sec)	0.0-60.0	60.0-120.0
IP sources' bit rate (Mbps)	1.0	2.0
IP equivalent bandwidth for IP PLP $\le 3\cdot10^{-2}$ (Mbps)	9.55	19.0

Table. 1. IP sources' rate and IP equivalent bandwidth.

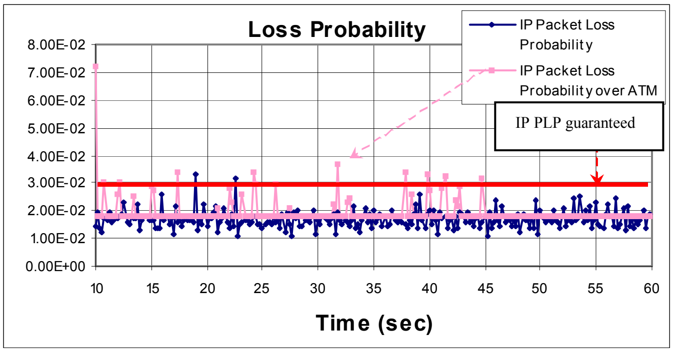

Fig. 3. IP PLP after ${}^{Opt}\theta^{ATM}$ has been reached.

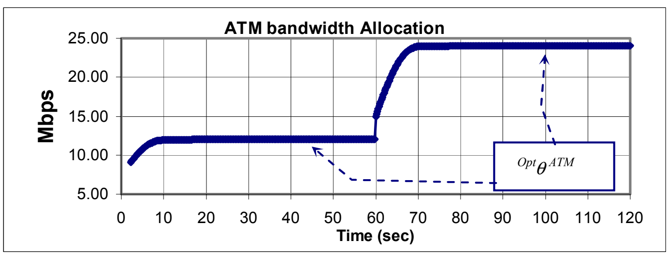

Fig. 4. Optimal ATM bandwidth allocation.

B. Equivalent bandwidth mapping at the QoS-Relay Node

We now compare the proposed control algorithm with a heuristic strategy that 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 for the ATM tunneling shown in Fig. 5 can be properly foreseen by means of the overhead effect of the AAL5 with LLC-SNAP encapsulation ([14, 18]), called *"Cell-Tax",* in the following. Since two octets have to be added to each IP packet at the AAL5 as LLC-SNAP overhead, the number of ATM cells for each IP packet is:

$$\#ATMCells = \left\lceil \frac{DimIPPacket + 16}{48} \right\rceil \tag{7}$$

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 foresee the overall overhead due to the encapsulation format on the ATM frame and then the percentile bandwidth increase on the ATM side of the network, denoted in the following by the instantaneous value $CellTax\%_{inst}$:

$$CellTax\%_{inst} = \frac{\#ATMCells \cdot 53 - DimIPPacket}{DimIPPacket} \cdot 100 \tag{8}$$

where 53 is the overall size (payload and overhead) of the ATM cell in bytes. If the IP source has its own packet's size distribution, the $CellTax\%_{inst}$ must consider the mean number of ATM cells in the ATM frame as

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

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, ($\sum_{i=1}^{n} p_i = 1$):

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

Supposing to introduce in the QoS-RN a homogeneous IP flow in which all the IP connections have the same packet's size distribution, a good forecast concerning the ATM bandwidth allocation would be:

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

We compare the performance of such a strategy, called in the following *"CellTaxAllocation"*, with the proposed control algorithm according to different traffic conditions. A *Pareto* distributed iterarrival time between the IP packets has been introduced in order to generate variable bit rate traffic flows with *self-similar* properties [19]. The mean interarrival times of IP packets used in the paper are 10 ms and 100 ms; the number of connections in the IP flow is set to 1, 20, 100. The packet's size distribution is *Trimodal(48, 576, 1500, 0.559, 0.2)*. The IP buffer size is set to 150 kbytes and the IP bandwidth allocation θ^{IP} guarantees an IP PLP $\leq 1 \cdot 10^{-2}$, which is also the IP PLP over the ATM subnetwork that the value ${}^{Opt}\theta^{ATM}$ will assure. A comparison between the *CellTaxAllocation* strategy and the proposed control scheme is shown in Tables 2 and 3. Table 2 reports the results obtained with an ATM buffer of 2830 cells (150 kbytes, as in IP); Table 3 of 200 cells (10600 bytes). From the left to the right: the mean interarrival times of the IP packets, the number of connection in the flow, the IP bandwidth allocation, the $CellTax\%$ and the ATM bandwidth allocation, both computed by the *CellTaxAllocation* strategy, the ${}^{Opt}\theta^{ATM}$ and the "real" $CellTax\%$ computed by the proposed control algorithm ($Simulated\ CellTax\% = \frac{{}^{Opt}\theta^{ATM} - \theta^{IP}}{\theta^{IP}} \cdot 100$) and the difference between the two computed $CellTax\%$ are visualized. As we have highlighted in the latter Section, the ${}^{Opt}\theta^{ATM}$ is the optimal value to dimension the bandwidth pipe assigned to the IP flow in the ATM subnetwork and it must be taken as the target value for the following comparison.

Arr-Time IP Packets	*#Conn*	θ*IP* **Mbps**	*CellTax%*	*CellTax*θ*ATM* **Mbps**	*Opt*θ*ATM* **Mbps**	*Simul. CellTax%*	*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	28.500	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 IP Packets	*#Conn*	θ*IP* **Mbps**	*CellTax%*	*CellTax*θ*ATM* **Mbps**	*Opt*θ*ATM* **Mbps**	*Simul. CellTax%*	*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	28.750	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.

Looking at the results shown in Tables 2 and 3, 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*% (shown in the 7th column of Tables 2 and 3), is below the 5% (see last column of Table 2). On the other hand, if the ATM buffer has only 200 cells (Table 3), such difference raises 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 motivation for such a behaviour comes from the fact that, increasing the mean interarrival time and with a small number of connections in the flow, the rate variability of the flow increases and it has strong impact on the error produced by the *CellTax*% computed by the *CellTaxAllocation* strategy.

V. CONCLUSIONS AND FUTURE WORK

A novel control algorithm has been proposed to manage the mapping of the QoS among heterogeneous networks. Showing a promising *"self-learning"* property, it is able to react to traffic changes, 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. The results shown in the paper concern the performance of IP over ATM, but the application scope is not limited to it. MPLS, for example, may be a good framework. The adoption of other performance metrics, such as delay and delay jitter, taking into account the proposed standards of [15-17] is under investigation. An acceleration of the control algorithm convergence, necessary for on-line management, is also a topic of ongoing research.

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