A QoS-aware Bandwidth on Demand Assignment Mechanism in a GEO Satellite System

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ABSTRACT

This paper deals with the problem of the design of a control-predictive based Demand-Assignment Mechanism for a satellite network guaranteeing a target Quality of Service (QoS) to Internet traffic, while efficiently exploiting the air interface. The proposed mechanism is in charge of dynamically partitioning the uplink capacity among the connections in progress in the considered spot-beam. Such a partitioning is performed aiming to match the QoS requirements of each connection and to maximize bandwidth exploitation. A Control Theory approach is adopted to address the problem of the delay between the bandwidth request and bandwidth assignment, and the signaling overhead caused by control messages.

I. INTRODUCTION

High-powered direct broadcast television satellites, using the European Digital Video Broadcast (DVB) standard, can be used to broadcast data directly to home terminals. Several technologies can be leveraged to design a terrestrial return channel for satellite services: PSTN, ISDN, xDSL, and GSM/GPRS are some example. However, there is a large world-wide interest for a DVB Return Channel via Satellite (DVB-RCS) [1], which could be suitable to support non real-time return connections, provided that an appropriate bandwidth management mechanism is designed.

In this paper we propose a dynamic bandwidth management mechanism, compliant with the DVB-RCS standard, for an efficient and flexible partitioning of the uplink capacity available in a given spot-beam among the in progress connections. In the considered scenario an on-board packet switch is in charge of addressing the IP packets towards a downlink carrier assigned to the destination spot-beam. However, the problems related to possible congestion of the downlink carriers, as well as the related Connection Admission Control (CAC) problems, are outside the scope of this paper. In this respect, uplink and downlink management procedures can be decoupled [2]. The considered scenario shows a 2-layer switch GEO Satellite system including a Hub Station (HS), many Satellite Terminals (STs), and a Network Control Center (NCC) in charge of performing traffic control tasks. In the return direction, each ST can manage one or more upstream(s) coming from the User Terminals (UTs). Each upstream is relevant to a different connection involving an UT and entails the transmission of packets from the considered UT, via the associated ST and the GEO satellite, to the HS and the backbone IP network. Each connection has its own specific requirements which are reflected in a QoS Contract established at connection set-up. In order to enhance the exploitation of the valuable satellite capacity, connections with not very stringent delay requirements are not fixedly assigned uplink bandwidth portions. For these connections, uplink bandwidth has to be managed according to demand-assignment mechanisms: STs periodically ask the NCC for the temporary assignment of a certain portion of bandwidth; the NCC, according to the received bandwidth requests, decides how the available uplink bandwidth should be optimally partitioned, and communicates the relevant decisions to the STs.

The proposed work has been partly developed in the framework of the SATIP6 project belonging to the IST programme of the European Union.

A key problem of this mechanism is that bandwidth assignments are received about half a second after bandwidth requests, because of the high propagation delays of satellite networks. In addition, in order to keep signaling overhead limited, a certain minimum time must elapse between two consecutive bandwidth requests from the same ST. These issues can cause further delays in data transfer, as well as ST buffer overflows. Over-assignment would solve this problem but this is not a practical solution since it would cause bandwidth waste and inefficiencies. This paper copes with the above-mentioned problem, by designing an original and innovative demand-assignment mechanism which has the twofold aim: i) avoid further delays in data transfer, and ii) guarantee an efficient exploitation of uplink satellite bandwidth. Up to authors' knowledge, a few papers have addressed the demand-assignment problem with QoS guarantees in systems subject to delays [3][4][5].

The paper is organized as follows. Section II introduces the basic concepts utilized in the paper, as well as the objectives of the designed procedures. Section III presents the Satellite Terminal (ST) architecture. Section IV describes the proposed demand-assignment procedure. Finally, Section VI concludes the paper.

II. BASIC DEFINITIONS AND QOS CONTRACT

In the following, by “uplink” we always mean the “return uplink”, i.e. the link from the ST to the satellite, whereas by “return” traffic we indicate the traffic originated by the UTs and directed to the HS via the STs and the satellite.

Let S denote the number of different STs that are in the considered spot-beam. Let $i \in [1, S]$ denote a generic ST with at least an in progress connection. Let $C(i)$ denote the number of different uplink connections simultaneously in progress involving the i^{th} ST. Let (i, j) denote a generic in progress uplink connection involving the i^{th} ST; so, j can range in the interval $[1, C(i)]$. Practically, the computations of the various variables will not be performed at any time t, but only at discrete time instants t_h periodically occurring with a proper period T_{short}, i.e. $t_{h+1} = t_h + T_{short}$. In the following, the discrete time instant t_h will be indicated as h. By h^{th} time interval, we will mean the time interval $[h, h+1]$. Let $R_{ij}^{in}(h)$ denote the bit rate of the return traffic relevant to the connection (i,j) which, at time h, is offered to the i^{th} ST. Such bit rate is computed during an appropriate monitoring period according to the following relationship:

$$R_{ij}^{in}(h) = \frac{\sum_{k=h-M}^{h} L_{ij}^{in}(k)}{M \cdot T_{short}} \tag{1}$$

where M is the duration of the monitoring period in discrete time instants and $L_{ij}^{in}(k)$ is the sum of the bit lengths of the return packets, relevant to the connection (i,j), which, during the k^{th} time interval, are incoming into the i^{th} ST.

Definition 1: Let D_{ij} denote the queuing delay which a packet experiences from the time it arrives at the ST (coming from an UT) to the time it may be forwarded towards the uplink air interface.

Definition 2: Let R_{ij}^{av} denote the average throughput of a connection (i,j), as the ratio between the number of bits transmitted during the connection lifetime and the connection duration.

The QoS guarantees which have to be granted to a connection are specified in a QoS Contract [6], established at connection set-up. The QoS Contract includes the following requirements:

1) The so-called *Static Bit Rate*, R_{ij}^{static}, which is the traffic to be anyhow granted to the connection (i,j). An appropriate Connection Admission Control (CAC) procedure assures that the *Static Bit Rates* of the in progress connections satisfy the following constraint:

$$\sum_{i=1}^{S} \sum_{j=1}^{C(i)} R_{ij}^{static} \leq R_{up}^{tot} \tag{2}$$

where R_{up}^{tot} is the overall uplink capacity available in the considered spot-beam.

2) If the connection (i,j) is a Real Time connection, a second fundamental QoS requirement (hereafter referred to as *Delay QoS Requirement*) concerns the maximum transfer delay, D_{ij}^{max}, which can be tolerated by the connection (i,j). This means that, in general, the queuing delay D_{ij} should not exceed D_{ij}^{max}. As a matter of fact, in case the queuing delay D_{ij} exceeds D_{ij}^{max} the packet is no more meaningful and it is discarded by the ST.

The algorithms proposed in this paper aim at the minimization of the Real Time traffic to be discarded because has waited more than the maximum tolerated delay, and at the maximization of the average throughput of the Non Real Time traffic. In this work we assume the traffic packet expiration due to the D_{ij}^{max} overcome as the only possible traffic loss, meaning that no queue overflows can occur (each queue is dimensioned in order to accept all possible coming packets).

The i^{th} ST avails of a semi-permanently assigned *Static Bit Rate* equal to the sum of the static bit rates R_{ij}^{static} relevant to the connections in progress at such ST. Moreover, it avails of a *Dynamic Bit Rate* which is temporarily granted by the NCC following the ST requests, according to an appropriate demand-assignment mechanism (detailed in Section IV). Let R_{up}^{dyn} denote the available dynamic uplink capacity defined as the uplink capacity relevant to the considered spot-beam which is not statically assigned, i.e. the capacity which can be dynamically assigned. Such a capacity can be easily computed according to the following equation:

$$R_{up}^{dyn} = R_{up}^{tot} - \sum_{i=1}^{S} \sum_{j=1}^{C(i)} R_{ij}^{static} \tag{3}$$

Let $R_{ij}^{dyn}[h_1; h_2]$ denote the *Dynamic Bit Rate* assigned to the connection (i,j) during the time interval $[h_1; h_2]$. Clearly, for any time interval $[h_1; h_2]$, the following uplink capacity constraint must be respected:

$$\sum_{i=1}^{S} \sum_{j=1}^{C(i)} R_{ij}^{dyn} \leq R_{up}^{dyn} \; \forall h \in [h_1; h_2] \tag{4}$$

III. Satellite Terminal (ST) System Architecture

The i^{th} ST is provided with a set of $C(i)$ FIFO Buffers: each of these buffers stores the packets of one of the uplink connections the ST in question is involved in. A Classifier, fed with the traffic coming from the UTs linked to the i^{th} ST, is in charge of sorting the packets towards the $C(i)$ FIFO Buffers. Let $q_{ij}(h)$ denote the number of bits stored in the queue (i,j) at time h. Let $\delta_{ij}^{ass}[h_1; h_2]$ denote the fraction of the available dynamic uplink capacity R_{up}^{dyn} granted by the NCC to the connection (i,j) for being used during the time interval $[h_1; h_2]$. In other words, $\delta_{ij}^{ass}(h) \cdot R_{up}^{dyn}$ represents the *Dynamic Bit Rate* at which, during the time interval $[h_1; h_2]$, the i^{th} ST is allowed to forward packets, relevant to the connection (i,j), towards the uplink air interface. Thus, the parameter $\delta_{ij}^{ass}[h_1; h_2]$ is always included in the range $[0, 1]$ and, for any time interval $[h_1; h_2]$, the following fundamental uplink capacity constraint (which is equivalent to eq. 4) must be respected:

$$\sum_{i=1}^{S} \sum_{j=1}^{C(i)} \delta_{ij}^{ass}(h) \leq 1 \; \forall h \in [h_1; h_2] \tag{5}$$

The packets stored in the queue (i,j) can be either forwarded over the uplink air interface or, if they are relevant to Real Time connections, discarded because they are expired, i.e. they have waited more than the maximum tolerated delay D_{ij}^{max}.

IV. Capacity Demand-Assignment Procedure

Let us introduce the following definitions (see Fig. 1):

- Let L denote the round-trip delay expressed in number of time intervals. Such a delay L is equal to $2 \cdot \lceil (D_{prop} + T_{comput})/T_{short} \rceil$, where D_{prop} is the maximum propagation delay from any ST to the NCC, and T_{comput} are the ST (or NCC) demand-assignment computing times.

- Let η denote the generic discrete time at which an ST performs a bandwidth demand. In this paper we assume that all STs synchronously carry out their bandwidth demands, and that bandwidth demands are periodically performed. Nevertheless, the concepts can be straightforwardly extended to the case in which the ST demands are asynchronous and the bandwidth demands are not periodic.
- Let T_{inf} denote the period occurring between two consecutive bandwidth requests, in number of time intervals.
- Let N denote the ratio between L and T_{inf}, (for instance, Fig. 1 is relevant to the case N=2). The choice of the parameter N has to be carried out by carefully trading-off the contrasting requirements, on the one hand, of frequently sending the bandwidth requests (thus allowing a tight tracking of the traffic arrived at the STs coming from the UTs) and, on the other hand, of limiting the signaling overhead caused by such bandwidth requests. Clearly, the former and the latter requirements drive towards high and low values for the parameter N, respectively.
- Let $R_{ij}^{in*}[\eta; h]$ denote the predictions, performed by the i^{th} ST at time η, of the average bit rate which will enter the queue (i, j) during the h^{th} time interval. In this paper a sliding moving window-based prediction model has been adopted.

In the proposed demand-assignment mechanism the STs do not directly calculate the bandwidth they require. Conversely, they just send to the NCC some key parameters which are used by the NCC itself to perform appropriate bandwidth assignments. So, whenever at a time η a bandwidth demand has to be performed, the i^{th} ST sends to the NCC the following information:

1) The $C(i)$ predictions of the lengths of the queues (i, j) at time $\eta + T_{inf}$; at time η, the i^{th} ST computes these predictions, indicated as $q_{ij}{}^*(\eta + T_{inf})$, according to the following equation:

$$q_{ij}{}^*(\eta{+}T_{inf}) = q_{ij}(\eta) + \sum_{k=\eta}^{\eta+T_{inf}-1} R_{ij}^{in*}[\eta; k] \cdot T_{short} + \\ -\delta_{ij}^{ass}[\eta; \eta + T_{inf}] \cdot R_{up}^{dyn} \cdot T_{inf} \qquad (6)$$

2) The $C(i)$ predictions of the average bit rates of the traffic which will enter the queue (i, j) during the time interval $[\eta + T_{inf}; \eta + T_{inf} + L]$; at time η, the i^{th} ST computes these predictions, indicated as $R_{ij}^{in*}[\eta + T_{inf}; \eta + T_{inf} + L]$, according to the following equation:

$$R_{ij}^{in*}[\eta{+}T_{inf}; \eta{+}T_{inf}{+}L] = \sum_{k=\eta+T_{inf}}^{\eta+T_{inf}+L-1} \frac{R_{ij}^{in*}[\eta; k]}{L} \qquad (7)$$

3) The $C(i)$ coefficients β_{ij} used to grant an higher weight to the queues (i, j) relevant to Real Time connections which are losing bits because of packet expirations. These coefficients are computed according to the following expression:

$$\beta_{ij} = 1 + K^{opt} \cdot \frac{B_{ij}^{loss}[\eta - T_{inf}; \eta]}{B_{ij}^{out}[\eta - T_{inf}; \eta]} \qquad (8)$$

where $B_{ij}^{loss}[\eta - T_{inf}; \eta]$ represents the amount of bits discarded from the queue (i, j) during the time interval $[\eta - T_{inf}; \eta]$ due to packet expirations; $B_{ij}^{out}[\eta - T_{inf}; \eta]$ represents the whole amount of bits that, during the same time interval, are either retrieved, or discarded from the queue (i, j). K^{opt} is an appropriate optimized feedback gain whose value determines the aggressiveness of the feedback control law (the optimal value K^{opt}=0.97 has been chosen in the simulation experiments reported in Section V).

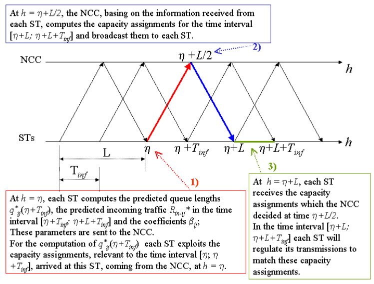


Fig. 1. Example of the proposed capacity assignment procedure (N = 2).

Basing on the information received from the STs, at time $\eta + L/2$, the NCC has to decide the capacity assignments $\delta_{ij}^{ass}[\eta + L; \eta + L + T_{inf}]$ for any (i, j) pair (see Fig. 1). Then, the proposed idea is to select these assignments aiming to empty the ST queues at time $\eta + L + T_{inf}$. The expected length of the queue can be computed according to the following equation:

$$q_{ij}^*(\eta + L + T_{inf}) = q_{ij}^*(\eta + T_{inf}) + \\ +R_{ij}^{in*}[\eta + T_{inf}; \eta + T_{inf} + L] \cdot L + \\ -\{\delta_{ij}^{ass}[\eta{+}T_{inf}; \eta{+}L] + \delta_{ij}^{ass}[\eta{+}L; \eta{+}L{+}T_{inf}]\} \cdot R_{up}^{dyn} \cdot L \qquad (9)$$

Note that the term $\delta_{ij}^{ass}[\eta + T_{inf}; \eta + L]$ is relevant to capacity assignments already performed by the NCC at the time(s) previous to $\eta{+}L/2$. Eq. 9 assumes $L > T_{inf}$ which is the most common case. Nevertheless, the extension to the opposite case is straightforward. Then, the *target capacity assignments*, indicated as $\delta_{ij}^{ass*}[\eta + L; \eta + L + T_{inf}]$, can be obtained by imposing that the right hand side of the previous equation is equal to zero. This yields:

$$\delta_{ij}^{ass*}[\eta + L; \eta + L + T_{inf}] = \frac{q_{ij}^*(\eta + T_{inf})}{R_{up}^{dyn} \cdot L} + \\ + \frac{R_{ij}^{in*}[\eta + T_{inf}; \eta + T_{inf} + L]}{R_{up}^{dyn}} + \\ -\delta_{ij}^{ass}[\eta + T_{inf}; \eta + L] \qquad (10)$$

However, the target capacity assignment can be actually granted only if the uplink capacity constraint, expressed in eq. 5, is satisfied. In order to force the respect of this constraint and to take into account the parameters β_{ij} in eq. 8, the actual capacity assignments $\delta_{ij}^{ass*}[\eta+L;\eta+L+T_{inf}]$ can be computed according to the following expression:

$$\delta_{ij}^{ass}[\eta+L;\eta+L+T_{inf}] = \\ = \frac{\beta_{ij}\cdot\delta_{ij}^{ass*}[\eta+L;\eta+L+T_{inf}]}{\sum_{i=1}^{S}\sum_{j=1}^{C(i)}\beta_{ij}\cdot\delta_{ij}^{ass*}[\eta+L;\eta+L+T_{inf}]} \quad (11)$$

In conclusion, the proposed demand-assignment procedure takes place according to the following steps (see also Fig. 1 which assumes $N=2$), hereafter described starting from the generic demand time η:

1) At time η the STs compute the forecast queue lengths $q_{ij}^{*}(\eta+T_{inf})$ according to eq. 6, the forecast bit rates $R_{ij}^{in*}[\eta+T_{inf};\eta+T_{inf}+L]$ according to eq. 7 and the coefficients β_{ij} according to eq. 8. All these parameters are sent to the NCC.
2) At time $\eta+L/2$, the NCC receives the information mentioned in the previous issue from the STs and computes, according to eqs. 10 and 11, the capacity assignments $\delta_{ij}^{ass}[\eta+L;\eta+L+T_{inf}]$ to be granted to the connections (i,j) during the time interval $[\eta+L;\eta+L+T_{inf}]$. Such assignments are broadcast to the STs.
3) At time $\eta+L$, the i^{th} ST receives the capacity assignments $\delta_{ij}^{ass}[\eta+L;\eta+L+T_{inf}]$ granted by the NCC. These assignments determine the amount of packets which the ST is authorized to forward from the queues (i,j) towards the uplink air interface during the time interval $[\eta+L;\eta+L+T_{inf}]$. Moreover, the ST utilizes these capacity assignments at next demand time(s) for the computation, according to eq. 6, of the forecast queue lengths.

As a final remark, note that the i^{th} ST can rearrange, among its connections (i,j), the capacity granted to it. In this rearrangement the i^{th} ST can take into account updated information concerning the present lengths of the queues (i,j) (this information was not available to the NCC when it computed the capacity assignments), according to appropriate criteria [7]. So, at time $\eta+L$, the i^{th} ST can compute the overall uplink capacity, indicated as $\alpha_i[\eta+L;\eta+L+T_{inf}]$, assigned to it during the time interval $[\eta+L;\eta+L+Tinf]$, according to the following equation:

$$\alpha_i[\eta+L;\eta+L+T_{inf}] = \sum_{j=1}^{C(i)}\delta_{ij}^{ass}[\eta+L;\eta+L+T_{inf}] \quad (12)$$

Therefore, the capacities actually granted to the connections during the time interval $[\eta+L;\eta+L+T_{inf}]$, $\delta_{ij}[\eta+L;\eta+L+T_{inf}]$, can differ from those granted by the NCC (i.e. $\delta_{ij}^{ass}[\eta+L;\eta+L+T_{inf}]$). Nevertheless, the following constraint must be respected:

$$\alpha_i[\eta+L;\eta+L+T_{inf}] \geq \sum_{j=1}^{C(i)}\delta_{ij}[\eta+L;\eta+L+T_{inf}] \quad (13)$$

TABLE I

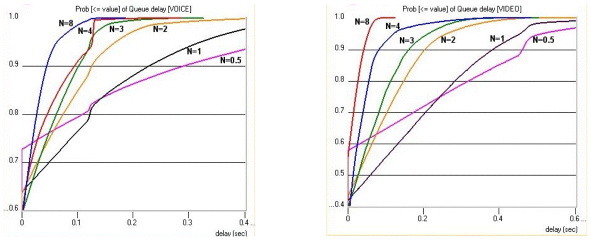
APPLICATION SOURCE PARAMETER DEFINITIONS

Source Parameter	**Distribution**
$Email\ inter.\ time\ [s]$	$exp\ (300)$
$Email\ size\ (KB)$	$unif\_int\ [1,99]$
$File\ transf.\ inter-req.time\ [s]$	$exp\ (180)$
$File\ transf.\ size\ (KB)$	$const\ (500)$
$WebPage\ inter.\ time\ [s]$	$exp\ (60)$
$Video\ frame\ frequency$	$15\ frame/s$
$Video\ frame\ size\ (KB)$	$unif\_int\ [2,3]$
$Voice\ Spurt\ Length\ [s]$	$exp\ (0.352)$
$Voice\ Silence\ Length\ [s]$	$exp\ (0.65)$
$Voice\ Encoder\ Scheme$	$G.711\ (Silence)$
$Voice\ Frames\ per\ Packet$	1

V. SIMULATION RESULTS

The SW tool OPNET Modeler has been adopted for testing the performance of the proposed algorithm. The statistical characteristics of the considered applications are reported in the Table I. We considered 2 Real Time applications, using UDP (Voice over IP and Video-conference), and 3 Non Real Time applications, using TCP (FTP, E-mail, and Web browsing). The simulated scenario includes a GEO satellite ($L \approx 500ms$). The considered spot-beam includes 3 STs. Each of these STs is connected with 5 User Terminals (UTs). Each of these UTs has 5 connections in progress relevant to the 5 applications listed in Table I, so that every UT is involved in 1 Voice over IP, 1 Video-conference, 1 FTP, 1 E-mail, and 1 Web-browsing connection ($S=3$ and $C(i)=5$ $(i=1,2,3)$). The parameters R_{ij}^{static} (see Section II) are all set to zero. For the Real Time traffic, following the QoS parameters proposed by the ETSI TIPHON project [8], we have considered the maximum queue delay $D_{ij}^{max}=50ms$ for both Voice over IP and Video-conference connections. The available uplink capacity in the considered spot-beam R_{up}^{tot} is equal to $10Mbit/s$.

Fig. 2 shows the cumulative distribution of the queuing delay D_{ij} experienced by the packets relevant to the Real Time applications, as the parameter N varies. Note that by increasing the value of N, the queuing delays decrease, but the signaling overhead increases. So, N must be selected by trading off these contrasting effects. Fig. 2 shows that $N=4$, adopted value for the remaining experiments, is the lowest value for N in order to respect the QoS Delay Requirement for the Real Time applications, with an acceptable probability. We also compared the performance achieved by using the proposed capacity assignment procedure (referred to as *all-dynamic*), based on a sliding window prediction algorithm tailored to the satellite IP traffic, with the one achieved by fixedly partitioning the available bandwidth among the three STs (referred to as *all-static*). Note that in the latter case each ST is fixedly assigned a third of the total available uplink capacity and no demand-assignment mechanism is required. The simulation parameters are the same previously described, but the available uplink capacity R_{up}^{tot}. We will consider the satellite system behavior when



(a) Voice CDF (b) Video CDF

Fig. 2. Queuing delay Cumulative Distribution Functions (CDFs)

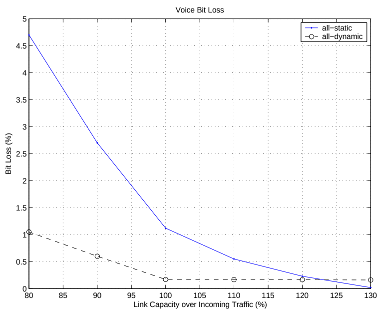


Fig. 3. Voice bit loss comparison for significant capacity values

R_{up}^{tot} is varied with respect to an *average offered uplink capacity* of $5.5Mbit/s$ defined as the ratio between the total traffic (expressed in bits) offered to the three STs by the UTs during the simulation, and the simulation time interval duration. We considered three cases in which the available uplink capacity is 80%, 100%, and 130% of the average offered uplink capacity, respectively. In these cases, the following key performance parameters are monitored:

- The *bit loss percentile* of the Real Time traffic, defined as the ratio between the bits discarded due to the exceed of the maximum delay, and the sum of the transmitted and discarded bits;
- The *average throughput* of the Non Real Time traffic.

Fig. 3 graphs the *bit loss percentile* for the Voice over IP application as a function of the above-mentioned capacity values. The dashed line refers to the *all-dynamic* case, while the solid line to the *all-static* one. The figure highlights that, if the satellite system is overloaded, the *all-dynamic* approach is remarkably more efficient than the *all-static* one, since the proposed demand-assignment procedure succeeds in exploiting the advantages of statistical multiplexing.

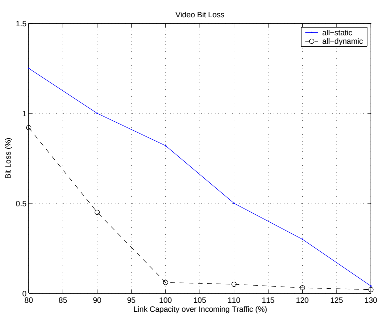


Fig. 4. Video bit loss comparison for significant capacity values

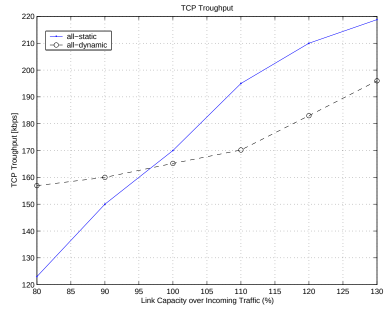


Fig. 5. TCP throughput comparison expressed for significant capacity values

Clearly, as the capacity availability grows, these advantages reduce and for a high capacity availability, the *all-static* has a slight advantage over the *all-dynamic* case, due to the fact that the former does not require the demand-assignment procedure (which entails delay and overhead savings). Fig. 4 is similar to Fig. 3, but refers to the video-conference application. The same considerations as in Fig. 3 apply. The lower bit loss percentile values obtained for video-conference depend on the higher maximum tolerated delay of this application with respect to the voice one. Finally, Fig. 5 graphs the average throughput for the Non Real Time applications where the same considerations hold.

VI. Conclusions

This work has proposed a novel approach to maximize the satellite uplink bandwidth exploitation, while guaranteeing Quality of Service requirements. The proposed algorithm dynamically partitions the uplink capacity among the in progress connections. It efficiently copes with both the satellite propagation delay and the delays inherent in the periodic nature of the bandwidth demand-assignment mechanism. The NCC, whenever performs a capacity assignment to the STs, predicts the length of the queues which will be experienced at the STs. This prediction is achieved through a sliding window based mechanism tailored to the IP satellite traffic. Simulation results demonstrated the effectiveness of the proposed solution.

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