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A gateway architecture for IP satellite networks with dynamic resource management and DiffServ QoS provision

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SUMMARY

IP satellite networks are gaining a considerable interest mainly due to their ability to deliver high bandwidth services to nation-wide areas. However some difficulties still exist to implement IP-based transport mechanisms on geostationary satellite networks (i.e. TCP-based protocols are affected by the large delay-bandwidth product). The satellite network architecture presented in this paper is designed to provide a complete QoS support for IP traffic based on the DS paradigm, while minimizing the waste of the valuable satellite resource. The proposed technique operates on two time scales: a short-term reaction compensates fast traffic variations by an appropriate scheduling while a medium term resource allocation mechanism reduces the wasted bandwidth. Copyright © 2003 John Wiley & Sons, Ltd.

1. INTRODUCTION

IP satellite networks are gaining a considerable interest and this is mainly due to their ability to deliver high bandwidth services to nation-wide areas. The market is rapidly moving to a great variety of services and the number of users served by Internet is increasing exponentially. Internet2, the global Internet upgrade, will probably be able to satisfy the requirements but its deployment will probably occur gradually. Satellites are the perfect candidates to provide high-quality IP services in the development phase of fast terrestrial networks. It is also well known that satellites also prove to be cost-effective when the coverage area is large or the population is sparse.

Some difficulties exist, however, to implement IP-based transport mechanisms on geostationary satellite networks. TCP-based protocols are affected by the large delay-bandwidth product, a typical scenario for GEO satellites delivering large bandwidth services [1]. Also the coexistence of UDP and TCP traffic causes performance degradation; the dependence of TCP performance from UDP makes it very difficult to provide a suitable pricing policy for both.

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One solution is to design the communication system overestimating the requested capacity, but unfortunately the satellite bandwidth is extremely limited and the deployment costs of a satellite system do not allow waste of resources.

For this reason an efficient resource management technique has to be integrated with the QoS support to obtain the two main goals of spectrum efficiency and user quality of service [2, 3].

Several papers in the literature report analysis and implementations of DiffServ and resource management techniques separately; only a few present a combined approach to the QoS and resource allocation problem. Gallardo [4] presented a resource management scheme in the presence of different real time services for terrestrial border gateways. Katz [5] addressed the various problems in the delivery of TCP services over GEO satellite links. A DiffServ implementation for a satellite gateway was proposed by Kota [6] for both TCP and UDP traffic.

Starting from the last contribution we developed an experimental real-time IP satellite gateway and completed it with a resource management mechanism. The scenario considered in the paper is characterized by a number of earth stations connected to a fully-meshed satellite system, as shown in Figure 1. The gateway provides connectivity to local clouds of users so that the traffic flowing through it can be considered a medium sized (10–100) aggregation of traffic sources. An example may be the Internet connection for a large cruises, long haul flights, isolated communities, worldwide distributed companies, oceanic platform and many others. To be more specific in the definition of the target satellite system, the user considered in the paper is allowed a maximum outbound bandwidth of 2 Mbps. Under this classification can be found several recently deployed satellite systems from such as Alenia's SkyplexNet [7] SES-ASTRA Two-Way satellite system and others.

The satellite architecture presented in this paper is designed to provide a complete QoS support for IP traffic based on the DS paradigm, along with a resource management scheme based on a dynamic bandwidth allocation method. The gateway is constituted by the following functional blocks also represented in Figure 2:

- *Traffic marking* (*classifier*) the incoming traffic is classified and marked in the TOS field in order to provide the desired quality of service to the different traffic classes (Real-Time, First-class TCP, Economy TCP, First-class UDP, Economy UDP, Generic Best Effort).
- *Priority management* (*scheduler*) with a combination of RED, GRED (the Linux RED variant), FIFO policies in order to fulfill the short-time target performance on the PHB (per-hop-behaviour) quality requirements.
- *Dynamic resource management* (*bandwidth manager*) performing the long-time‡ bandwidth reservation to follow the variation of the incoming traffic.

The paper is organized as follows. Section 2 describes the model of the generic satellite system considered in the design of the gateway. Section 3 explains the joint scheduling/resource management technique used in the gateway. In Sections 4 and 5 are presented the emulated behaviour of the satellite gateway. We selected two different conditions for the evaluation of the proposed architecture in order to better isolate the contribution of each functional block to the overall performance. The first one, described in Section 4, aims at evaluating the impact of the selected resource management scheme in the presence of time-varying delay sensitive IP traffic. The second operating point of the system, described in Section 5, reports the behaviour of the

‡ Long-time because the resource request is handled by a long round-trip time reservation process due to the unavoidable propagation delay.

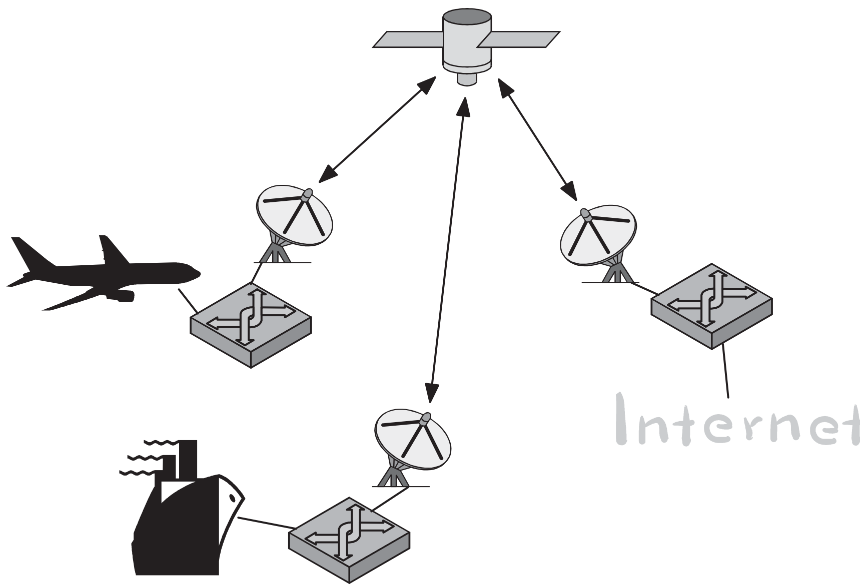

Figure 1. Fully meshed satellite environment.

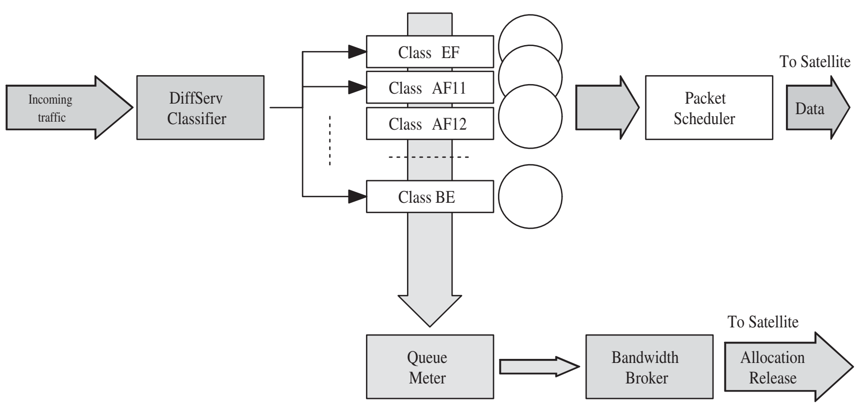

Figure 2. Earth gateway architecture.

gateway with a fixed bandwidth allocation and mixed UDP and TCP traffic. Section 6 contains some concluding remarks.

2. THE SATELLITE SYSTEM MODEL

The satellite environment we consider is a fully-meshed bidirectional MF-TDMA satellite system based on a single geostationary satellite. The satellite is transparent (with the capacity management and conditional access on earth).

Each earth station represents a relatively small aggregate of IP traffic of various type (say 10–100 mixed terminals). We consider the presence of time-sensitive real-time flows, quality-marked TCP connections, quality-marked UDP flows and TCP/UDP best-effort filling traffic.

Every earth station competes with any other for the satellite capacity. Depending on the amount of active transmitting stations and the bandwidth allocated, new capacity increases may be denied by the system.

The system presents a distributed allocation mechanism, where each earth terminal performs the following main tasks:

1. classify the traffic coming from the land-side to be transmitted on the space segment,
2. operate the scheduling of the packets to be transmitted to the satellite, following the QoS strategy implemented locally to maintain the short-term QoS performance with a constant satellite link bandwidth,
3. measure the total amount of bandwidth needed to remain within the target QoS performances,
4. request medium-term bandwidth variation to accommodate new traffic states.

3. A JOINT RESOURCE MANAGEMENT AND DIFFSERV MARKING APPROACH

The two competing issues in a satellite system are bandwidth efficiency and Quality of Service provision for incoming traffic. The proposal described in this paper is a combination of Resource Management and QoS provision mechanism employing the DiffServ approach.

The gateway architecture is represented in Figure 2. The traffic incoming from the earth side of the network is classified based on the DiffServ rules. The classifier directs the packets to the appropriate queue, where they will wait to be served by the scheduler.

A measuring thread continuously computes the relevant statistics of the various queues, passing them to the *Bandwidth Broker* block. This process is responsible for the decisions related to the bandwidth needs which are forwarded to the satellite control channel.

Each traffic class is assigned a different queue in the earth gateway. The proposed method continuously monitorates all the queues and takes the decisions about the foreseen bandwidth needs. The bandwidth is requested or released depending on the following rules:

- when the queue length of a certain class exceeds a threshold with a given increase rate a bandwidth request is issued
- when a queue remains empty for a given time, a bandwidth release is performed
- each class of traffic has its own set of decision parameters

The system is designed to perform quickly the increases of bandwidth assigned to EF traffic, a bit more slowly requests for AF traffic and slowly the BE class requests. The reaction time is reversed for bandwidth releases. The resulting effect is a preference in the allocation of resources for EF class that deserves greater attention due to the time-sensitive nature of its content (mainly real-time media).

The proposed allocation procedure is summarized in the flowchart of Figure 3 (Figure 4). The main control loop in the *NORMAL* state encounters the bandwidth allocation procedure. If a bandwidth modification is needed, the request is passed to the signaling process that forwards it

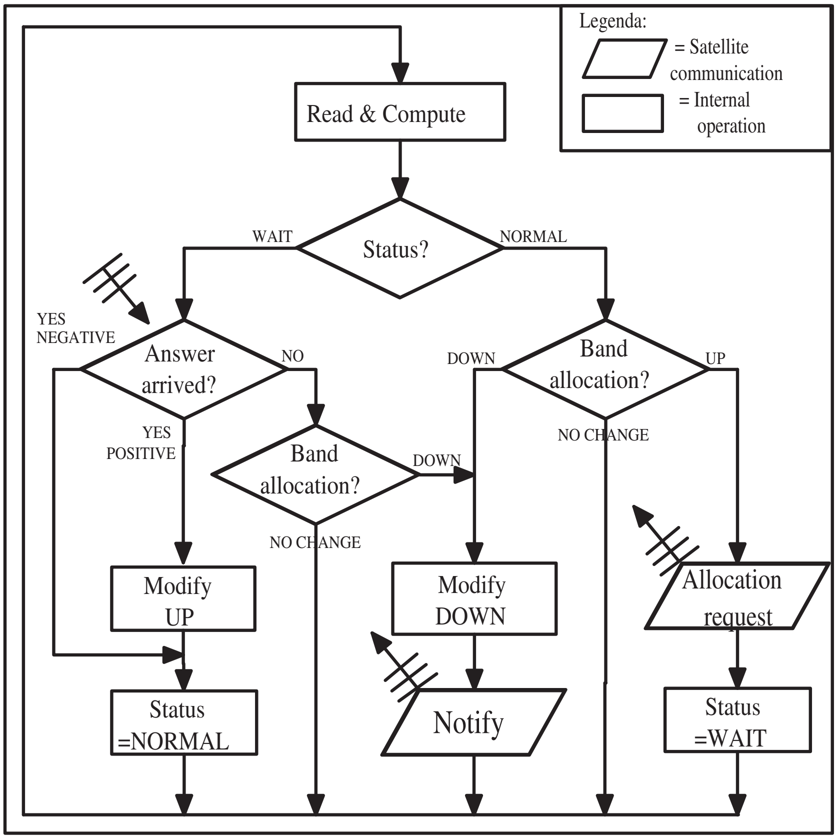

Figure 3. Local resource allocation procedure.

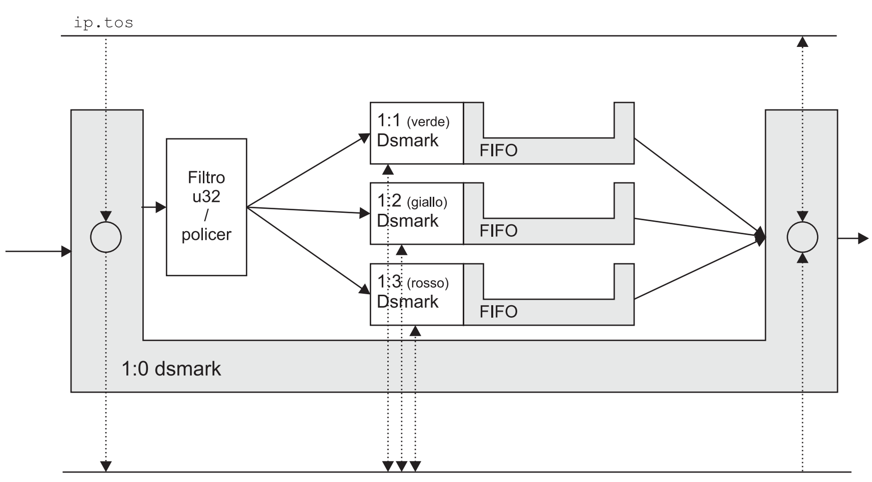

Figure 4. DS marker implementation.

to the Master satellite station. The gateway enters the soft *WAIT* state preventing any other bandwidth increase request until a reply arrives.

The algorithm uses two different approaches to decide if new bandwidth is needed (thus starting a request), or if the current bandwidth can be released.

In order to estimate the future incoming traffic, the algorithm continuously inspects the lengths of the DiffServ queues and predicts the needed bandwidth as

$$R_{\text{new}} = R + \sum_i K_i Q_i \tag{1}$$

where R is the current bitrate, R_{new} the estimated future bitrate and Q_i is the ith DiffServ queue length, smoothed with an exponential average function (EWMA), as usual for Linux kernel measures. K_i are constant parameters which influence the speed of reaction to a bitrate variation in the given DiffServ class.

Moreover the used (output) bandwidth is monitored and smoothed with an exponential average function to evaluate the opportunity to release bandwidth

$$\tilde{R} = (1 - w)\tilde{R}_{\text{old}} + wR, \quad w \in (0, 1] \tag{2}$$

where $\tilde{R}$ is the smoothed used bandwidth and R is the measured output rate. Both the Q_i computation and the output rate measurement in (2) employ the same EWMA smoothing function. The former is implemented in the Linux kernel while the latter has been introduced by us in oder to compensate instantaneous variations in the R measure.

A bandwidth release is performed whenever the occupied bandwidth falls below a threshold and all the buffers are empty. The threshold is dynamically computed based on the actual bandwidth share ratio given to each DiffServ class.

When the reply comes from the Master, the gateway enters again the *NORMAL* state, allowing further increases of bandwidth.

Capacity releases are supposed to be always accepted so a notification only is sent to the Master station.

The RM in the satellite network described above is useful to manage long-term bandwidth management due to long round-trip delay of the bandwidth request. In order to meet QoS requirements without waste of bandwidth, however, it is necessary to react quickly to rate variation of EF traffic, while it is possible to use a relaxed rule for BE class flows. AF class traffic, to which we associate TCP connections, has to be protected against congestion in the satellite link, while maintaining possibly low delays.

In the literature several methods have been proposed to provide quality of service control on IP networks [8]. The most scalable approach is the Differentiated Services (DS) [9]. With the DS mechanism, the IP packet is classified at the boundary of the network and an appropriate mark, the codepoint, is inserted in the header. In the core network, the codepoint is used to determine the so called Per-Hop-Behaviour (PHB) that maps a global delivering requirement to a local link transmission treatment.

The DS approach is considered for use on this satellite scenario for three main reasons:

- The local clouds of users may be large enough to meet the well known scalability limit of the competing Integrated Services approach.
- The satellite network can be easily integrated with core networks, where a DS approach is usually adopted.

Table I. AF PHB classes.

	Class 1	Class 2	Class 3	Class 4
Low discard prob.	AF_{11}	AF_{21}	AF_{31}	AF_{41}
Mid discard prob.	AF_{12}	AF_{22}	AF_{32}	AF_{42}
High discard prob.	AF_{13}	AF_{23}	AF_{33}	AF_{43}

- With DS approach users in the hosting local cloud receive QoS provision without the need of explicit application level signaling.

The DiffServ approach maps different traffic types into a set of classes characterized by different Per Hop Behaviours (PHBs), which define the way the gateway handles the packets of a given class. In the present proposal the DiffServ classification has a direct impact on the bandwidth allocation decisions.

The PHB-EF [10] is mainly adopted for tightly time constrained traffic, like real-time media streams. BE is the PHB used for unclassified traffic, as in the current (best effort) Internet.

The PHB-AF, defined in Reference [11], is the policy suggested for non real-time QoS enabled traffic. It is divided into four independent forwarding sub-classes. In each class, the packets can receive four different discarding probabilities. Table I shows the recommended AF code-points and their discarding probabilities. In the table a packed belonging to class i with discarding priority j is classified with the DiffServ code-point (DSCP) $AF_{i,j}$.

We adopt colours to represent the different discarding probabilities in the proposed gateway; the packets with low discard probability will be called 'green' packets, those with medium discard probabilities 'yellow' ones and those with high discard probability 'red'.

All the packets in the AF top level class receive a DS classification based on the following ruleset:

1. Each aggregate is assigned a 'green' rate, i.e. the minimum assured rate that will correspond to the minimum amount of guaranteed bandwidth. A Token Bucket [9] mechanism is employed to determine if a packet belongs to the 'green' rate of its aggregate and, in this case, its DSCP is marked with the 'AF_{11}' label (Green).
2. Excess traffic is first classified with its transport protocol (TCP or UDP). UDP excess traffic is assigned a high discard priority with the DSCP set to 'AF_{13}', the 'red' one. Excess TCP traffic whose rate is greater than the 'green' rate but less than the 'yellow' plus the 'green' rate, is marked as 'yellow' (AF_{12}). All the remaining TCP traffic is colored as 'red' (AF_{13}).

4. EMULATION RESULTS—RESOURCE MANAGEMENT

We developed a real-time testbed for the performance evaluation of the proposed architecture. The satellite gateway has been implemented in a Linux PC. Another Linux PC emulates the satellite in terms of propagation delay and capacity constraint. The gateway emulator has been connected to a LAN representing the remote user aggregation of traffic.

In this section we evaluate the capability of the proposed resource management mechanism to limit the waste of bandwidth preserving the QoS level for the IP flows coming from the terrestrial side of the network.

To analyse the behaviour of the RM scheme we focus on two representative cases:

- *Max Speed Link*, the link capacity allowed to the gateway corresponds to the peak of the traffic generated by the sources, i.e. 2 Mbps;
- *Half Speed Link*, where the gateway has a 1 Mbps link, corresponding to the long-term mean value of the source traffic.

To test the system, we consider the case of overlapping flows, where a flow of a given type (EF, AF or BE) start transmitting while another flow type is already up. Each flow is characterized by a piece-wise linear traffic shape over time. To analyse both the transient and the steady state behaviour of the RM technique, each flow traffic is kept constant for at least 20 s. This option has been chosen to better evaluate the response speed of the system when there is an instantaneous variation in the input rate, as in the case of the start of a fresh real-time service.

The dynamic resource management scheme has been evaluated in terms of amount of wasted bandwidth and QoS offered to EF flow. In order to evaluate the EF flow QoS, we consider the jitter parameter; since EF class is expected to carry mainly real-time traffic, a large jitter is the main QoS impairment. The same performance indexes are reported for the constant bandwidth link cases cited before.

Figures 5–7 show the chronological behaviour of the incoming traffic along with the instant allocated capacity of the satellite link. We can observe that in the *Max Speed Link* case most of the time there is a large bandwidth waste.

In the *Half-Speed Link* the waste of bandwidth is reduced at the expense of a dramatic limitation on the throughput for the BE and AF classes. The EF class is better served, but when the total bandwidth request reach the link capacity (between 80 and 100 s in Figure 6), it suffers from the bandwidth sharing with the other classes.

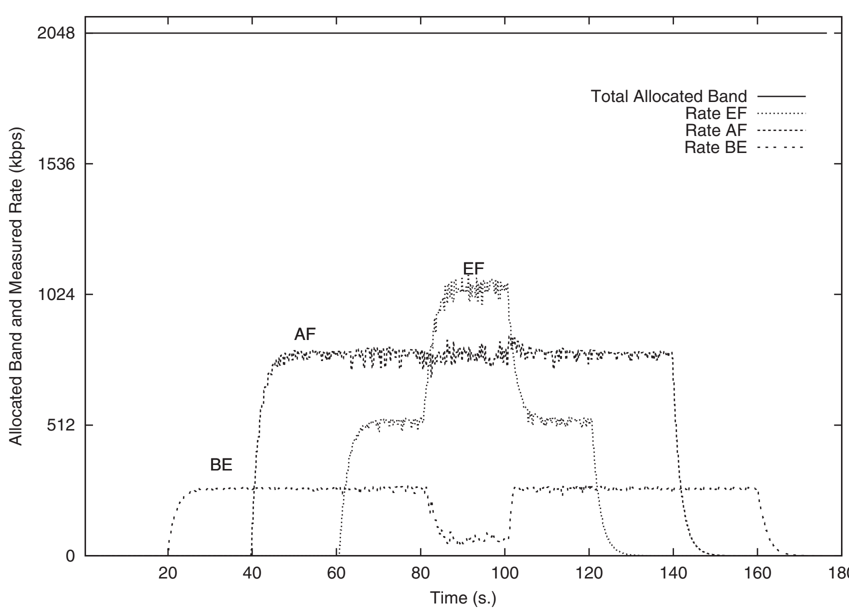

Figure 5. High speed link—allocated bandwidth and throughput for EF, AF and BE traffic.

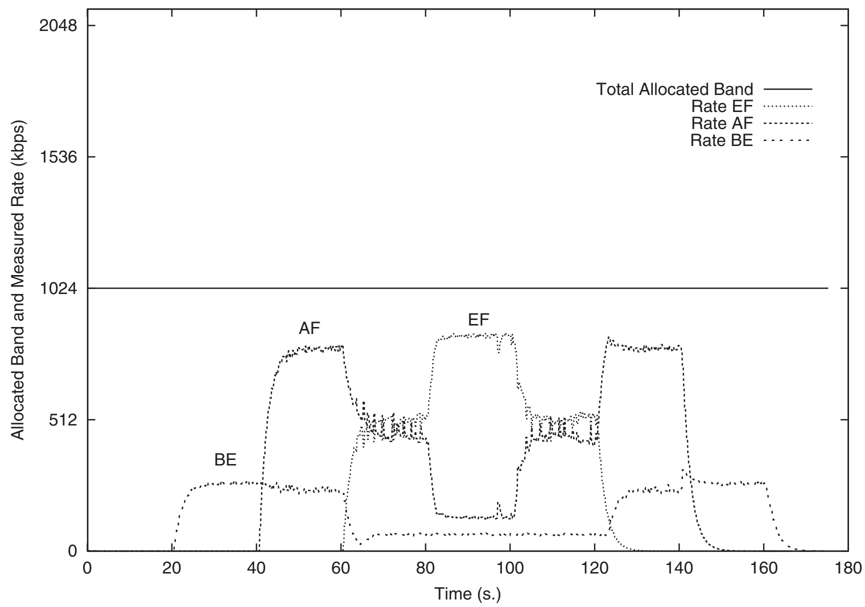

Figure 6. Half-speed link—allocated bandwidth and throughput for EF, AF and BE traffic.

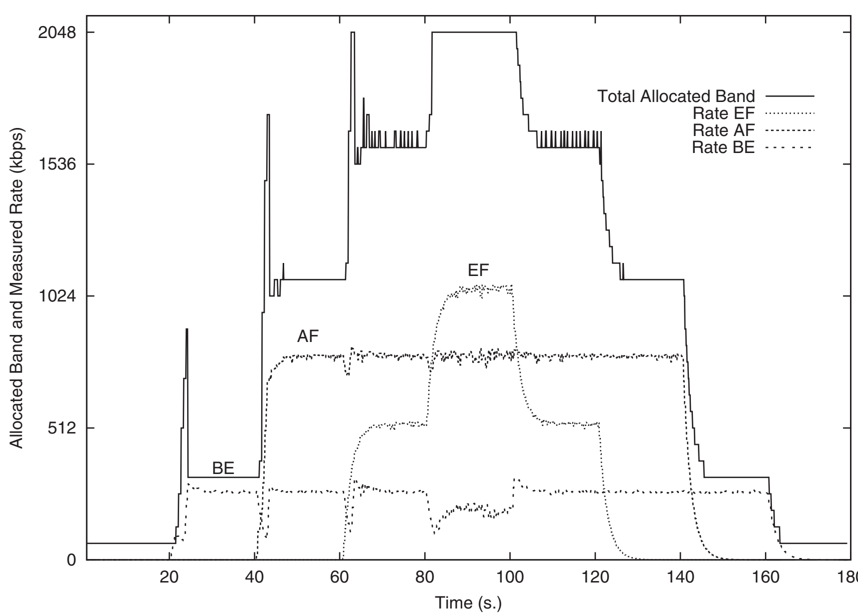

Figure 7. Dynamic link—allocated bandwidth and throughput for EF, AF and BE traffic.

Finally the proposed scheme behaviour is depicted in Figure 7. The instant allocated capacity closely follows the incoming traffic variations allowing a contained bandwidth waste and a throughput profile of all classes similar to the *Max Speed Link* case.

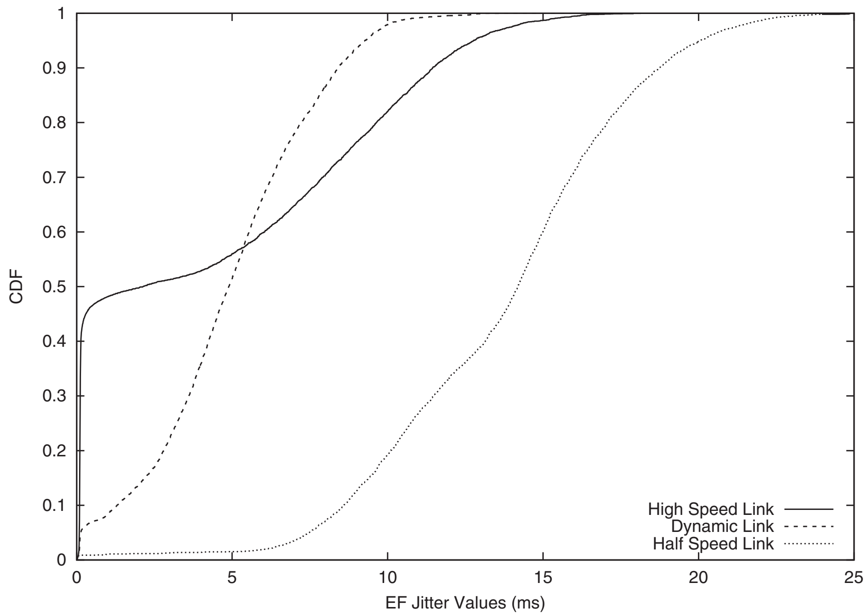

Figure 8. Jitter CDF for the EF class.

Figure 8 shows the jitter CDF for the EF class, for all the emulated cases. It is worth noting from the figure that the proposed dynamic allocation method presents a lower jitter value with respect to the fixed allocation cases.

5. EMULATION RESULTS—TRAFFIC CONDITIONING

In this section we evaluate the ability of the proposed scheduling mechanism to protect TCP flows against the unruled UDP traffic on the same class type (AF).

We consider a static bandwidth situation where a common pipe of 1.5 Mbps is shared among a small set of TCP connections and UDP flows.

The considered scenario is composed by

- 10 real TCP (New-RENO) and UDP sources: 9 TCP aggregates (each characterized by 5 single TCP flows) plus a single UDP source which represents the aggregate of several UDP flows. The UDP source produces a constant traffic of 1.28 Mbps.
- Two earth gateways interconnected through a satellite.
- A satellite link with a total bandwidth of 1.5 Mbps, characterized by an error-free channel and a propagation delay of 250 ms.

The system parameters are summarized in the following list:

- *green rate*, this is the average granted bandwidth for each specific aggregate subject to QoS.

- *yellow rate* (for TCP flows only), when the rate of a flow is between 'green rate' and 'green + yellow rate' the packets of that flow are marked as 'yellow'. If the yellow rate is '0' the TCP and UDP traffic are not distinguished by the QoS mechanism.
- *buffer sizes for the green and yellow token bucket*, which have influence on the reactivity of the QoS mechanism. The larger is the buffer, the slower is the response to fast changes in traffic rates.
- max_p min_{th} and max_{th}, for each of the three RED discarding classes. These are the main parameters that controls the discard process. The discard probability for each traffic colour is defined by a piecewise linear function like the one represented in Figure 9.

For each traffic aggregate a throughput measurement has been taken at the end of the transmission chain. The throughput is the total traffic at destination for UDP flows and the acknowledged traffic for TCP. The measure is split into 'green' and 'out-of-green' (i.e. 'yellow and red') throughput. As an additional index of performance we consider also the Fairness Index (see [6]), defined by

$$\text{Fairness Index} = \frac{(\sum_{i=1}^{10} x_i)^2}{10 \sum_{i=1}^{10} (x_i^2)} \qquad (3)$$

where x_i is the 'out-of-green' rate for the ith aggregate. The Fairness Index is a measure of how even is the distribution of excess traffic among competing traffic flows. Ideally it becomes '1' when all the aggregates receive the same amount of excess traffic.

The first chart in Figure 10 shows the effect of the sharing of a limited bandwidth between UDP and TCP aggregates without QoS support. The UDP throughput dominates the link as expected.

When the QoS support is enabled as described in the previous sections, the throughput of the aggregates are reported in Figures 11a and 11b for 'green rates' of 1.6 and 12.8 kbps, respectively. The other system parameters are shown in Table II.

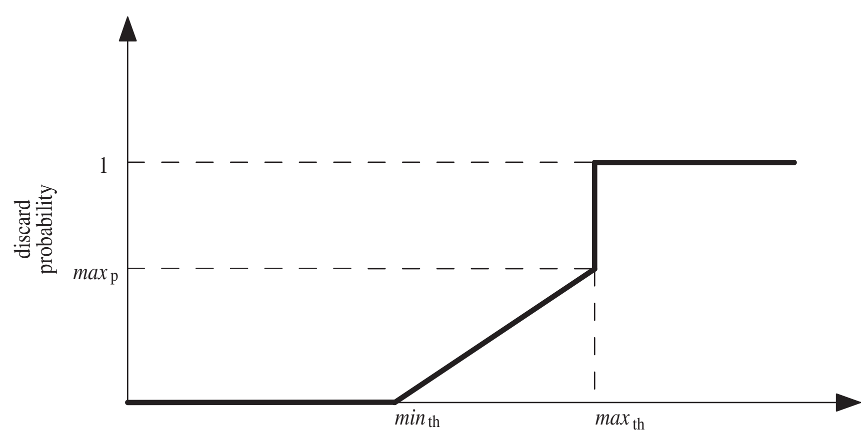

Figure 9. Discard probability law.

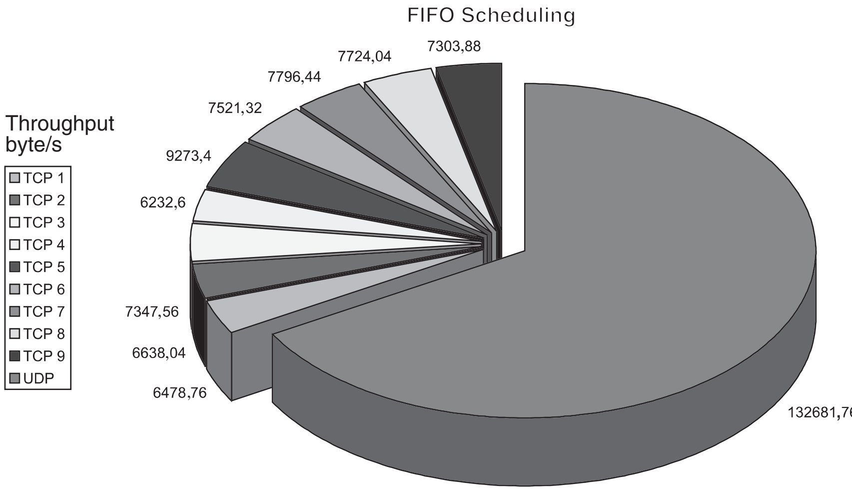

Figure 10. Performance of a FIFO IP satellite gateway.

In both the operating conditions is shown a good balance between TCP and UDP traffic. The *fairness index*, however, is smaller in the case of a larger *green rate*. This is confirmed by the 'out-of-green' throughput analysis reported in the Figures 12a and 12b for 'green rates' of 1.6 and 12.8 kbps, respectively.

Here the total 'green' throughput is shown aside, while the excess throughput for each aggregate is detailed. In the case of a small *green rate* (1.6 kbps), also the excess traffic is equally distributed among the sources. When the green rate represents a considerable fraction of the overall available bandwidth, the proposed balancing mechanism is less effective. We consider, however, that when the excess traffic is small compared to the total available bandwidth, the need for a balancing method is less important since the 'green rate' already provides a good way to distribute the resource and to protect TCP flows.

6. CONCLUSIONS

In this paper a combined resource allocation and DS scheduling technique has been proposed for a fully meshed, geostationary, satellite system. The main objective has been the efficient use of the satellite capacity along with provision of QoS for TCP/IP traffic generated by small size aggregates of users (i.e. Internet access for small communities, international flights, trans-oceanic cruises). The proposed technique operates on two time scales: a short-term reaction compensates fast traffic variations by an appropriate scheduling, succeeding in maintaining a good level of QoS for the protected UDP and TCP services. For long-term traffic fluctuactions (i.e. longer than the GEO RRT), a resource allocation mechanism reduces the waste of bandwidth maintaining an high QoS level. The proposed technique is evaluated with a real-time emulation of the satellite environment and it is compared to reference cases, i.e. fixed allocation technique and a simple FIFO scheduling. The performance has been evaluated in terms of

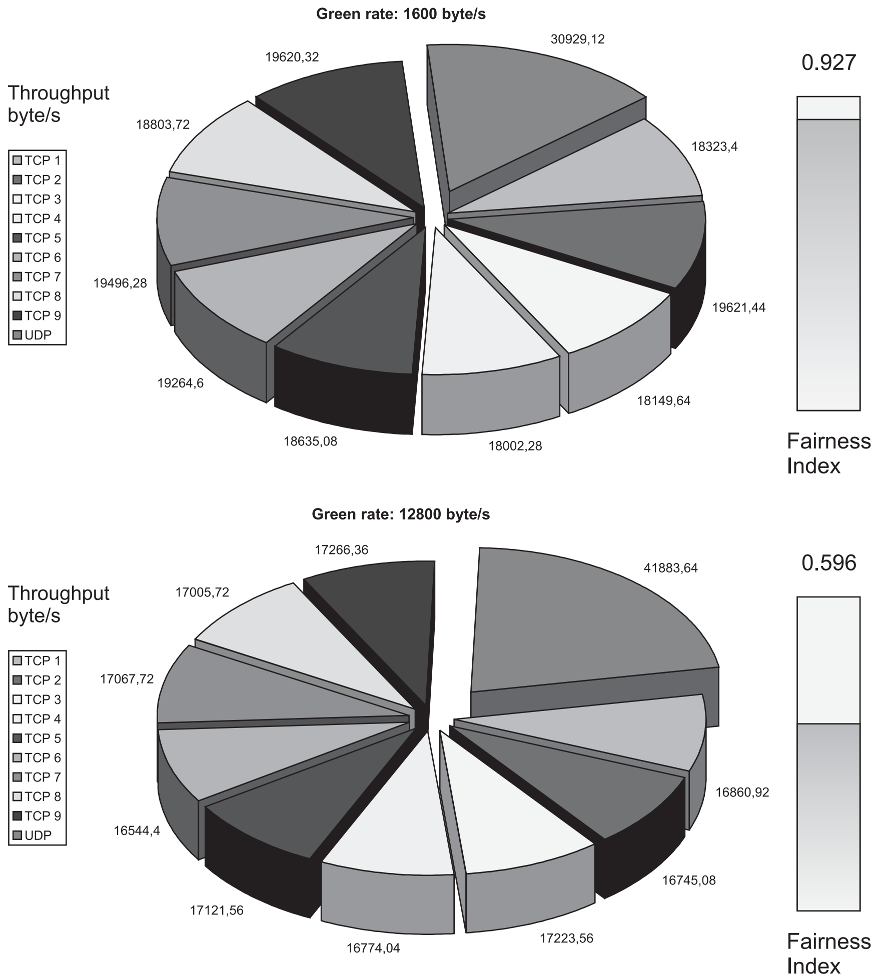

Figure 11. Throughput distribution of AF classified TCP and UDP traffic (minimum guaranteed bandwidth: 1.6 kbps(a) and 12.8 kbps(b)).

Table II. AFxx scheduling—constant bandwidth.

Green Rate (bps)	1600	12 800
Green Bucket (bytes)	4672	4672
Yellow Rate (bps)	19 056	6611
Yellow Rate (bytes)	18 688	18 688
Green min_{th}	23 040	23 040
Green max_{th}	34 560	34 560
Green max_p	0.5	0.5
Yellow min_{th}	11 520	11 520
Yellow max_{th}	23 040	23 040
Yellow max_p	0.5	0.5
Red min_{th}	1024	1024
Red max_{th}	2880	2880
Red max_p	1.0	1.0

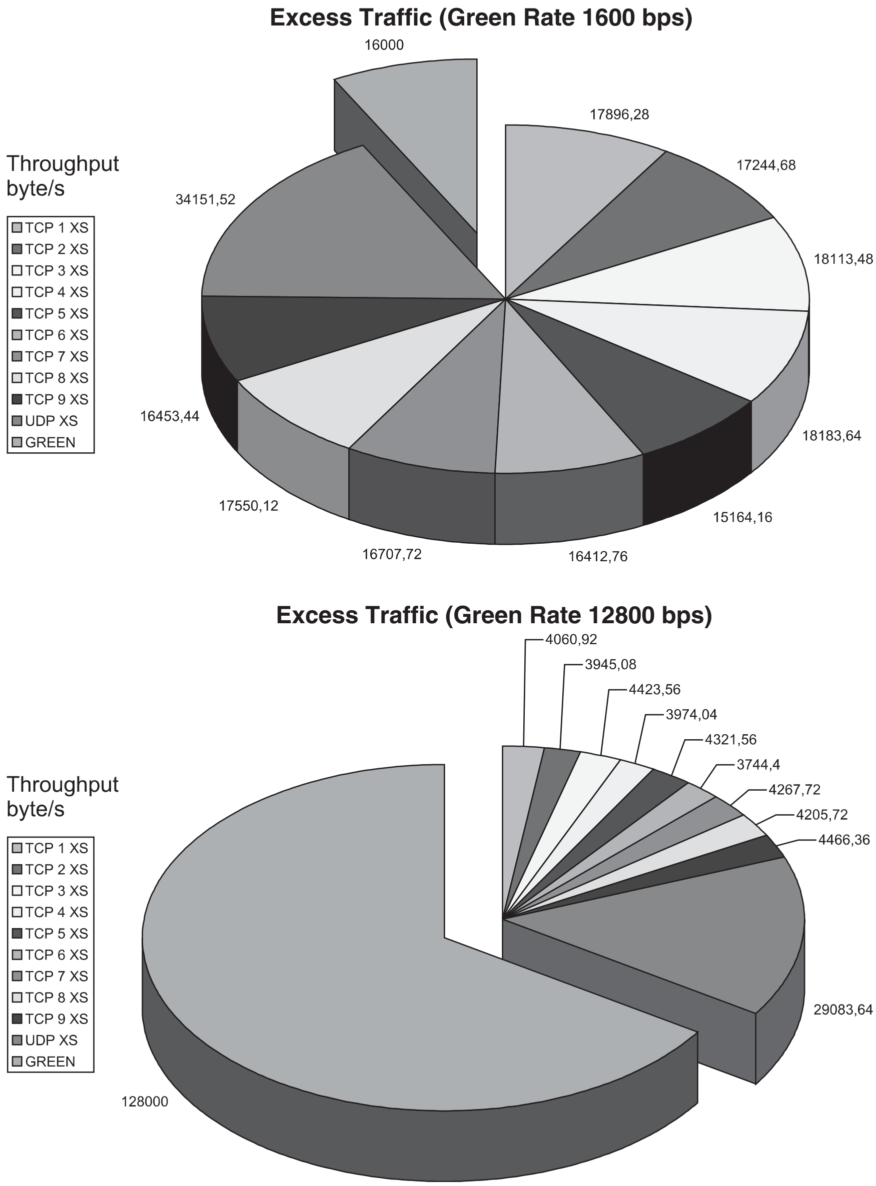

Figure 12. Excess throughput distribution of AF classified TCP and UDP traffic (minimum guaranteed bandwidth: 1.6 kbps(a) and 12.8 kbps(b).

throughput, packet jitter, TCP protection against UDP flooding and wasted bandwidth on the satellite link. The technique results in a simple and efficient solution to QoS provision on long round-trip delay satellite systems, with a very limited bandwidth waste.

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