QOS-Constrained MOP-Based Bandwidth Allocation Over Space Networks

Igor Bisio, Mario Marchese

DIST - Department of Communication, Computer and System Science
University of Genoa, Via Opera Pia 13, 16145, Genoa, Italy
Phone: +39-010-3532806, Fax: +39-010-3532154,
e-mail: Igor.Bisio@unige.it, Mario.Marchese@unige.it

Abstract. The paper formalizes and analyzes the bandwidth allocation process over space communication systems modelled as a Multi – Objective Programming (MOP) in presence of Quality of Service (QoS) constraints. The reference allocation scheme considered is based on GOAL programming and is called "Minimum Distance" algorithm. The work proposes two different versions of the Minimum Distance scheme both aimed at assigning the bandwidth so to approach a non-competitive situation as close as possible and at guaranteeing a fixed performance for each traffic flow traversing the space network. The proposals have been tested over a faded channel by using TCP/IP traffic. The performance evaluation is carried out analytically by varying the degradation level of the channel.

1 Introduction

The advantage of using space communication systems (HAPs, GEO and LEO satellites, possibly integrated with terrestrial links) for TCP/IP applications is clear: to exchange ubiquitous information among geographically remote sites also in hazardous areas with large bandwidth availability. In such environments one of the main cause of degradation is rain attenuation, which generates significant communication detriment, information loss and, consequently, Quality of Service (QoS) degradation [1]. Quality of Service is the ability of a network element (e.g. an application, host or router or an earth station in satellite networks) to have some level of assurance that its traffic and service requirements can be satisfied. Each service has its own set of QoS parameters: *Delay*, which is the time for a packet to be transported from the sender to the receiver, *Jitter*, which is the variation in end-to-end transit delay, *Bandwidth*, that is the maximal data transfer rate that can be sustained between two end points, and *Packet loss*, which is defined as the ratio between the number of undelivered packets and the total number of sent packets.

It is worth noting that the channel capacity (bandwidth) is limited not only by the physical infrastructure of the traffic path within the transit networks, which provides an upper bound to available bandwidth, but is also limited by the number of other flows that share common components of the space network and by the channel error countermeasures typically used by the physical layer of space networks (e.g., Forward Error Correction Codes).

In this work, the proposed bandwidth allocation schemes, conscious of the aforementioned channel capacity limitations, are aimed at guaranteeing a fixed level of quality of service in terms of packet loss probability.

The rationale under this paper is considering bandwidth allocation as a competitive problem where each station is "represented" by a cost function that needs to be minimized at cost of the others. In practice, all the functions must be minimized simultaneously considering the QoS requirements. It is the definition of the Multi-Objective Programming (MOP) class of problems, which is the base of the methods introduced in the paper. The schemes are based on the "Minimum Distance" strategy, which is aimed at approaching the ideal performance obtained when each single station has the availability of all the channel bandwidth, by minimizing the Euclidean distance between the performance vector and the ideal solution of the problem.

The paper is structured as follows: section 2 introduces the network topology. The formalization of the bandwidth allocation is presented in section 3; the TCP packet loss probability model is contained in section 4. The Utopia Minimum Distance (UMD) algorithm, already presented by the authors [2], is revised in section 5. Two alternative mechanisms (CUMD and QDMD) aimed at guaranteeing a QoS requirement are described in section 6. Section 7 reports the performance evaluation and section 8 the conclusions.

2 Network Topology

The network considered (Fig. 1) is composed of Z earth stations connected through a space connection. The choice of the technology does not affect the general behaviour of the schemes and it has been left unspecified here for the sake of generality. It may be applied over GEO/LEO satellites and HAP platforms. The main difference

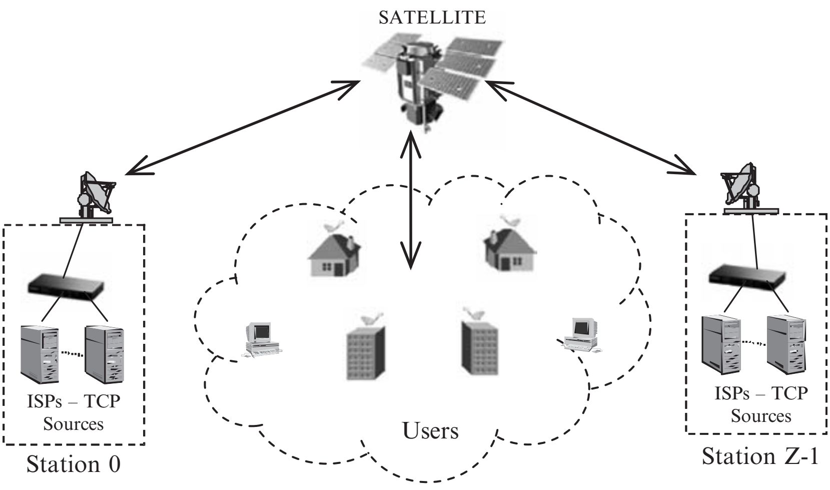

Fig. 1. Network topology.

stands in the round trip time (RTT). The results have been fulfilled by using RTT=520[ms] (GEO environment). The control architecture is centralized: an earth station (or the satellite itself, if switching on board is allowed) represents the master station, which manages the resources and provides the other stations with a portion of the overall bandwidth (e.g., TDMA slots); each station equally shares the assigned portion between its traffic flows (the fairness hypothesis is made).

Each user requests a TCP/IP service (e.g., Web page and File transfer) by using the space channel itself (or also other communication media). The request traffic is supposed negligible. After receiving the request ISPs send traffic through the earth stations and the space link. To carry out the process, each earth station conveys traffic from the directly connected ISPs and accesses the space channel in competition with the other earth stations.

Fading is modelled as bandwidth reduction. From the implementation viewpoint, it means using a FEC code where each earth station may adaptively change the amount of redundancy bits (e.g. the correction power of the code) in dependence on fading, so reducing the real bandwidth availability. Mathematically, it means that the bandwidth $C_z^{real} \in \mathbb{R}$, available for the z-th station, is composed of the nominal bandwidth $C_z \in \mathbb{R}$ and of the factor $\beta_z \in \mathbb{R}$, which is, in this paper, a variable parameter contained in the interval [0,1].

$$C_z^{real} = \beta_z \cdot C_z; \beta_z \in [0,1], \beta_z \in \mathbb{R} \tag{1}$$

A specific value β_z corresponds to a fixed attenuation level "seen" by the z-th station. An example of the mapping between Carrier Power to One-Side Noise Spectral Density Ratio (C/N_0) and β_z is contained in Table 1 (from [3]).

The values β_z shown in the table will be used in the performance evaluation section of this paper.

3 Bandwidth Allocation Problem Definition

Each earth station has a single buffer gathering TCP traffic from the sources (ISPs). The practical aim of the allocator is the provision of bandwidth to each buffer server by splitting the overall available capacity among the stations (the competitive entities of the problem). Analytically, the bandwidth allocation defined as a Multi – Objective Programming (MOP) problem may be formalized as:

$$\begin{aligned} \boldsymbol{C}^{opt} &= \left\{ C_0^{opt}, \ldots, C_z^{opt}, \ldots, C_{Z-1}^{opt} \right\} = \\ &\arg\min \left\{ \mathbf{F}(\mathbf{C}) \right\}; \mathbf{F}(\mathbf{C}) : \mathbf{D} \subset \mathbb{R}^Z \to \mathbb{R}^Z, \mathbf{C} \geq 0 \end{aligned} \tag{2}$$

where: $\mathbf{C} \in \mathbf{D}$, $\mathbf{C} = \{C_0, \ldots, C_z, \ldots, C_{Z-1}\}$ is the vector of the capacities that can be assigned to the earth stations; the element C_z, $\forall z \in [0, Z-1]$, $z \in \mathbb{N}$ is referred to the

Table 1. Signal to noise ratio and related β_z Level.

C/N_0 **[dB]**	66.6–69.6	69.6–72.6	72.6–74.6	74.6–77.1	>77.1
β_z	0.15625	0.3125	0.625	0.8333	1

z-th station; $\mathbf{C}^{opt} \in \mathbf{D}$, is the vector of optimal allocations; and $\mathbf{D} \subset \mathbb{R}^{z}$ represents the domain of the vector of functions. The solution has to respect the constraint:

$$\sum_{z=0}^{Z-1} C_z = C_{TOT} \tag{3}$$

where C_{tot} is the available overall capacity.

$\mathbf{F}(\mathbf{C})$, dependent on the vector $\mathbf{C}$, is the *performance vector*

$$\mathbf{F}(\mathbf{C}) = \left\{ f_0(C_0), \ldots, f_z(C_z), \ldots, f_{Z-1}(C_{Z-1}) \right\}, \forall z \in [0, Z-1], Z \in \mathbb{N} \tag{4}$$

The single z-th *performance function* is a component of the vector. Each *performance function* $f_z(C_z)$ (or *objective*) of the system is defined here as the average TCP packet loss probability. Actually any other convex and decreasing over bandwidth function may be used. The packet loss probability at TCP layer seems a reasonable choice but it may be regarded also as an operative example for the theory presented. The TCP packet loss probability $P_{loss}^{z}(\cdot)$ is a function of the bandwidth (C_z) as well as of the number of active sources (N_z) and of the fading level (β_z), for each station z. $P_{loss}^{z}(\cdot)$ is averaged on the fading level β_z, which is considered a discrete stochastic variable ranging among L possible values β_z^l happening with probability $p_{\beta_z^l}$.

$$\begin{aligned} f_z(C_z) &= \underset{\beta_z}{E}\left[P_{loss}^{z}(C_z, N_z, \beta_z) \right] \\ &= \sum_{l=0}^{L-1} \left[P_{loss}^{z}(\beta_z^l \cdot C_z, N_z) \right] \cdot p_{\beta_z^l}; \forall l \in [0, L-1], L \in \mathbb{N} \end{aligned} \tag{5}$$

In general, the problem defined above is a Multi – Object Programming problem where each considered function $f_z(C_z)$ represents a single competitive cost function. In other words, a single *performance function* competes with the others for bandwidth.

The optimal solution for MOP problems is called POP-Pareto Optimal Point [4], coherently with the classical MOP theory. It was adopted in economic environment and may be summarized as follows.

The bandwidth allocation $\mathbf{C}^{opt} \in \mathbf{D}$ is a POP if does not exist a generic allocation $\mathbf{C} \in \mathbf{D}$ so that:

$$\mathbf{F}(\mathbf{C}) \leq_P \mathbf{F}(\mathbf{C}^{opt}), \forall \mathbf{C} \neq \mathbf{C}^{opt} \tag{6}$$

Concerning the operator "$\leq_P$": given two generic performance vectors $\mathbf{F}^1, \mathbf{F}^2 \in \mathbb{R}^z$, $\mathbf{F}^1$ *dominates* $\mathbf{F}^2$ ($\mathbf{F}^1 \leq_p \mathbf{F}^2$) when:

$$\begin{aligned} &f_x^1 \leq f_x^2 \, \forall x \in \{0, 1, \ldots, Z-1\} \; \textit{and} \\ &f_y^1 < f_y^2 \text{ for at least one element } y \in \{0, 1, \ldots, Z-1\} \end{aligned} \tag{7}$$

Where f_x^1, f_y^1, f_x^2 and f_y^2 are the elements of the vector $\mathbf{F}^1$ and $\mathbf{F}^2$, respectively.

In practice, it means that once in a POP, a lower value of one function implies necessarily an increase of at least one of the other functions. In the allocation problem considered, the constraint in (3) defines the set of POP solutions, because, over that constraint, each variation of the allocation, aimed at enhancing the performance of a specific earth station, implies the performance deterioration of at least another station due to the decreasing nature of the considered performance function (as clarified in next section, in formula (8)).

It is worth noting that, in the proposed methodology, no on-line decision method is applied. The system evolution is ruled by stochastic variables. In practice, **F**(**C**) in the optimization problem (2) is considered to be the average value of the performance vector over all the possible realizations of the stochastic processes of the space network. The performance functions are representative of the steady-state behaviour of the system and the allocation is provided with a single infinite-horizon decision.

4 The TCP Packet Loss Probability Model

The TCP model considered is based on previous work of the authors [5]. Considering geostationary space systems, the round trip time *RTT* may be supposed fixed and equal for all the sources. This condition matches the hypothesis of fairness, which is an essential condition to get the used TCP packet loss probability model. Taking TCP Reno as reference and considering only the Congestion Avoidance phase of the TCP, the Packet Loss Probability (used in equation (5)) may be explicitly expressed as a function of the available bandwidth and of the number of TCP active sources as:

$$P_{loss}^{z} = 32N_z^2\left[3b\,(m+1)^2\left(\beta_z\tilde{C}_z\,RTT + \tilde{Q}_z\right)^2\right]^{-1} \tag{8}$$

where: N_z is the number of TCP active sources conveyed into the *z*-th earth station; *b* is the number of TCP packets covered by one acknowledgment; *m* is the reduction factor of the TCP transmission window during the Congestion Avoidance phase (typically $m = ½$); $\tilde{C}_z$ is the bandwidth "seen" by the TCP aggregate of the *z*-th earth station expressed in packets/s ($\tilde{C}_z = C_z/d$, where *d* is the TCP packet size); $\tilde{Q}_z$ is the buffer size, expressed in packets, of the *z*-th earth station. The model is valid at regime condition of the TCP senders, coherently with the infinite-horizon hypothesis reported in the previous section.

5 Minimum Distance Algorithm

The Minimum Distance method is a flexible methodology that allows the resolution of the allocation problem (2). It is part of the MOP resolution family called GOAL [4]. It bases its decision only on the ideal solution of the problem: the so called *utopia point*. In more detail, the *ideal performance vector* is:

$$\mathbf{F}^{id}(\mathbf{C}^{id}) = \left\{ f_0^{id}(C_0^{id}), \ldots,\ f_z^{id}(C_z^{id}), \ldots,\ f_Z^{id}(C_{Z-1}^{id}) \right\} \tag{9}$$

where

$$f_z^{id}(C_z^{id}) = \min_{C_z}\ \underset{\beta_z}{E}\left[P_{loss}^{z}(C_z, N_z, \beta_z)\right], C_z \in [0, C_{tot}] \tag{10}$$

From equation (10), called *single objective problem*, it is clear that the optimal solution is given by $C_z = C_{TOT}, \forall z \in [0, Z-1]$. *So*, $\mathbf{C}^{id} = \{C_{TOT}, C_{TOT}, \ldots, C_{TOT}\}$. In other words: the ideal situation would be when each station has the availability of

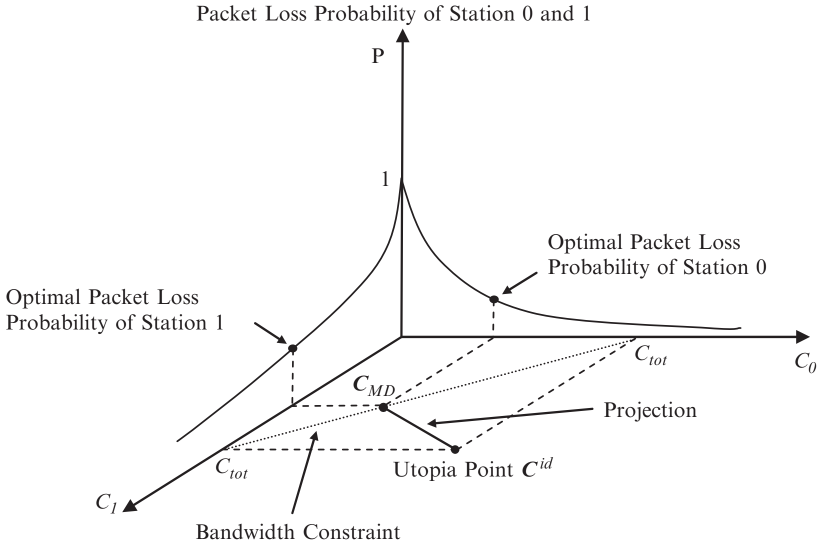

Fig. 2. UMD behaviour.

the overall channel bandwidth. Obviously it is a physically unfeasible condition that can be only approached due to constraint (3).

Starting from the definition of the *ideal performance vector*, the problem in equation (2) can be solved by the following allocation:

$$\mathbf{C}_{MD}^{opt} = \arg\min_{\mathbf{C}} \left(\left\| \mathbf{F}(\mathbf{C}) - \mathbf{F}^{id}(\mathbf{C}^{id}) \right\|_2 \right)^2 \tag{11}$$

where $\|\bullet\|_2$ is the Euclidean norm. The proposed technique allows minimizing the distance between the performance vector and the ideal solution of the problem. It is called Utopia Minimum Distance – UMD scheme, in the reminder of the paper. The Euclidean norm $\left(\| \mathbf{F}(\mathbf{C}) - \mathbf{F}^{id}(\mathbf{C}^{id}) \|_2 \right)^2$ is the decisional criterion of the UMD method. The minimization is carried out under the constraint (3).

Figure 2 describes the behaviour of the UMD strategy for 2 earth stations (Station 0 and Station 1) geometrically. On the basis of the fading conditions, UMD computes the projection of the *utopia point* that minimizes the packet loss probabilities of Stations 0 and 1 reported on the axis P simultaneously. C_0 and C_1 are the axes reporting the capacities allocated to Stations 0 and 1, respectively. Station 1 is supposed to be faded in Fig. 2 and its related packet loss probability (shown in the plane (C_1, P)) is higher than the packet loss of Station 0. In practice, the action of the proposed algorithm provides the bandwidth allocation as a solution of the problem (11), representative of the utopia point projection (which is not orthogonal in the capacity domain (C_0, C_1)) over the bandwidth constraint (3). Being a completely competitive environment where each station "makes its own interest", the solution tends to privilege the faded station.

6 QOS Constraints

Additional constraints may be added to match specific QoS performance requirements. The needed capacity may be provided by modifying the UMD method. In more detail, QoS constraints may be fixed for each earth station (i.e. for each *performance function*). Analytically it may be described as:

$$f_z(C_z) \le \gamma_z, \forall z \in [0, Z-1], Z \in \mathbb{N} \tag{12}$$

where $\gamma_z \in \mathbb{R}$ is the QoS requirement constraint for the z-th station. In terms of packet loss probability typical γ_z values may be set to 10^{-2}, for voice-streaming applications, to 10^{-3}, for more demanding applications. C_z^{thr} needs to be allocated to generic station z to satisfy constraint (12):

$$C_z^{thr} = \left\{ C_z : f_z(C_z) = \gamma_z, \forall z \in [0, Z-1], Z \in \mathbb{N} \right\} \tag{13}$$

The practical aim is to guarantee that the bandwidth allocated to z-th station is either larger or equal to, C_z^{thr}:

$$C_z \ge C_z^{thr}, \forall z \in [0, Z-1], Z \in \mathbb{N} \tag{14}$$

The main problem is to match the limitation of the overall available capacity (equation (3)). In facts: the sum of the required bandwidths C_z^{thr} may be larger than the overall capacity provided by the space channel. It implies two possible compromises: 1) bandwidth allocation penalizes some stations, whose traffic flows are considered pure best-effort, and guarantees the required bandwidth only for a subset of them, when possible. This approach is called Constrained Utopia Minimum Distance – CUMD; 2) the algorithm provides bandwidth so to approach the requested QoS as close as possible for all the stations. This approach is called QoS Point Minimum Distance - QPMD. This choice may imply that all the Z constraints are not satisfied, even if there is enough bandwidth to satisfy a portion of them.

6.1 Constrained Utopia Minimum Distance (CUMD).

The constraint set reduces the overall possible solutions defined in equation (11) by creating a subset of possible POPs. In more detail, the Euclidean norm $\left(\| \mathbf{F}(\mathbf{C}) - \mathbf{F}^{id}(\mathbf{C}^{id}) \|_2 \right)^2$ is the decisional criterion also of the CUMD method but the minimization is carried out both under the constraint (3) and under the set of Z constraints defined in (14).

There is no assurance that QoS requirements for each earth station are guaranteed, due to the limited amount of available capacity and to the fading conditions “seen” by the earth stations.

Considering only two earth stations for the sake of simplicity: given the plane (C_0, C_1) of Fig. 2, Figs. 3a and 3b try synthesizing what can happen.

Figure 3a contains the example when both requirements can be satisfied: constraint (14) defines a continuous set of points.

Figure 3b shows the situation when constraints (14) define a discontinuous set of points and cannot be satisfied in the same time.

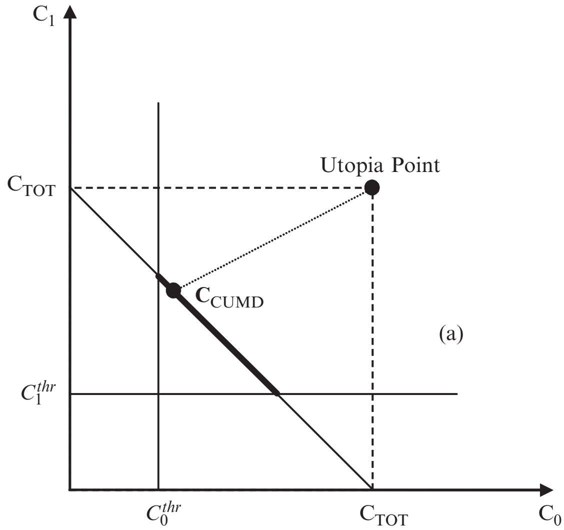

Fig. 3. (a) CUMD behavior – satisfied constraints.

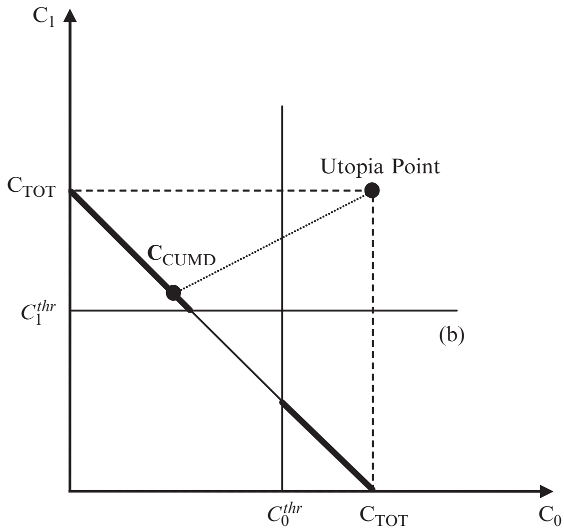

Fig. 3. (b) CUMD behavior – constraints not satisfied in the same time.

It means that just one station can reach its QoS level. The other station needs to provide a full best-effort service to its flows. The choice of the privileged station depends on the distance with the utopia point. The station assuring the minimum distance is chosen: Station 1 in the example. It holds true also for more than two stations. If two or more stations assure the minimum distance, the choice is random (it is true also for the situations described just below). Similar behavior is obtained if at least one of the requirements implies $C_z^{thr} \geq C_{TOT}$: the bandwidth is assigned to the station that requires feasible bandwidth ($C_z^{thr} < C_{TOT}$), so respecting the QoS constraint. The other station gets the residual channel capacity. If there is more than one station where $C_z^{thr} < C_{TOT}$, again the minimum distance choice is taken. The method allows guaranteeing at least one of the performance constraints if the bandwidth needed by one of the stations is lower that the overall capacity available. If $C_z^{thr} \geq C_{TOT}, \forall z$, then one of the station gets all the available channel capacity (through minimum distance choice) and the other(s) is(are) in complete outage condition.

6.2 QoS Point Minimum Distance (QPMD)

QPMD does not minimize the Euclidean distance from the *utopia point* (the situation with no competition) but the distance from the representative point of the desired QoS performance. In practice, it corresponds to use a new definition of the *ideal performance vector*. The new reference point (where QoS is guaranteed) is called *QoS Point* and the related vector is called *QoS performance vector*.

$$\mathbf{F}^{QoS}\left(\mathbf{C}^{QoS}\right)=\left\{f_0^{QoS}\left(C_0^{QoS}\right),\ldots,f_Z^{QoS}\left(C_{Z-1}^{QoS}\right)\right\} \tag{15}$$

where

$$f_z^{QoS}\left(C_z^{thr}\right)=\gamma_z, C_z^{thr} \in \mathbb{R} \tag{16}$$

which is directly derived from (13). From (15) and (16), obviously $\mathbf{C}^{QoS} = \left\{C_0^{thr}, C_1^{thr}, \ldots, C_z^{thr}\right\}$.

The problem in equation (2) can be now solved through:

$$\mathbf{C}_{QPMD}^{opt} = \arg\min_{\mathbf{C}}\left(\| \mathbf{F}(\mathbf{C}) - \mathbf{F}^{QoS}(\mathbf{C}^{QoS}) \|_2\right)^2 \tag{17}$$

The minimization is obviously carried out under the constraint (3).

Also in this case, the behaviour may be described by using the reference situation where two earth stations are considered. Two cases may happen:

1) the *QoS Point* satisfies the constraint (3) and it is within the set of feasible allocations (Fig. 4a); QoS requirements are matched and the overall performance is surely better than expected because more bandwidth than required is assigned to the stations.
2) the *QoS Point* is outside the feasible allocation region defined by the constraint (3). QPMD provides allocations through equation (17). QoS satisfaction can be only approached (Fig. 4b).

7 Performance Evaluation

The aim of this section is to compare the performance of the allocation techniques (UMD, CUMD and QPMD) in terms of allocated bandwidth and packet loss probability. The action is fulfilled analytically by varying the fading conditions of the earth stations. The considered network scenario is composed of 2 earth stations: Station 0, always in clear sky condition, and Station 1, which varies its fading level according with Table 1. Each station gathers traffic from TCP sources and transmits

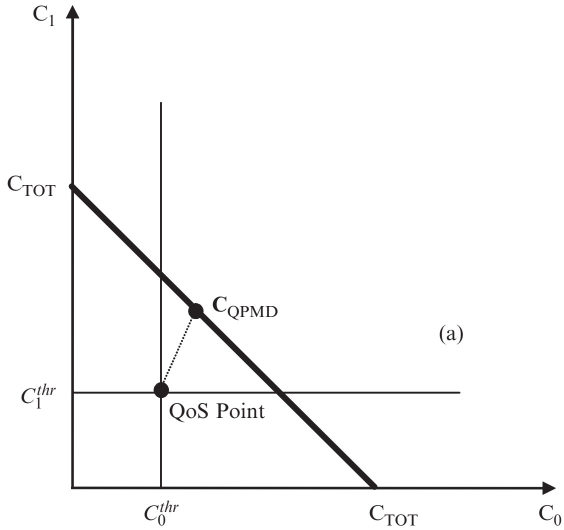

Fig. 4. (a) QPMD behaviour.

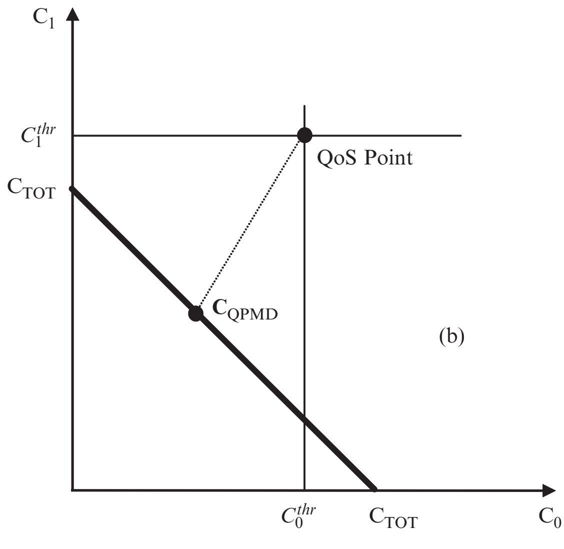

Fig. 4. (b) QPMD behaviour.

it to the terminal users through the space system (GEO satellite in this case). The number of active TCP sources is set to $N_z = 10$, $z = \{0, 1\}$. The fading level is a deterministic quantity ($L = 1$ and $p_{\beta_z^l} = 1$ $\forall z$, $\forall l$) in the tests. The overall bandwidth available C_{TOT} is set to 10.24 [Mbps] (10240 [Kbps]) and the TCP buffer size $\tilde{Q}_z$ is set to 10 packets (of 1500 bytes) for each earth station. The round trip time is supposed fixed and equal to 520 [ms] for all the stations, it is considered comprehensive

Table 2. Minimum bandwidth requirements to match $f_0\ (C_0) \le 0.01, f_1\ (C_1) \le 0.01$, stations 0 and 1.

β_1	C_0^{thr} [Kbps]	C_1^{thr} [Kbps]
0.156	2670	17116
0.312	2670	8558
0.625	2670	4272
0.833	2670	3205
1	2670	2670

of the propagation delay of the GEO channel and of the waiting time spent into the buffers of the earth stations. Bandwidth is considered a discrete quantity and the minimum amount of allocated capacity is set to 128 [kbps].

UMD represents a completely competitive problem with no constraint. Its aim is approaching the ideal point where each station (both, in this case) has the complete availability of C_{TOT} = 10.24 [Mbps]. CUMD solves the same problem but adds a set of constraints (in (12)) over each performance function so getting minimum bandwidth requirements (in (14)) for each station. Following the same philosophy QPMD tries respecting (or, if it is not possible, approaching) the constraint set (12) by originating a new ideal point represented by the bandwidth assignations that allow respecting constraints.

The performance analysis is carried out by setting two different sets of performance constraints (12) and showing bandwidth allocations and packet loss probabilities for the two involved stations.

In detail, the first set of tests is obtained by using: $f_0\ (C_0) \le 0.01, f_1\ (C_1) \le 0.01$. Table 2 contains the minimum capacity ($C_0^{thr}\ and C_1^{thr}$) requirements to match performance constraints for Stations 0 and 1. Figures 5 and 6 show the bandwidth assigned to Stations 0 and 1, respectively, versus the fading level of Station 1. Figures 7 and 8 contain the values of the packet loss probability for Stations 0 and 1, respectively, versus the fading level of Station 1.

The second set of tests is performed by setting: $f_0\ (C_0) \le 0.001, f_1\ (C_1) \le 0.001$. Table 3 shows the minimum capacity requirements to match performance constraints in this case. Figures 9 and 10 show the allocated bandwidth, similarly to Figs. 5 and 6, while Figs. 11 and 12 the values of packet loss probability, again for Stations 0 and 1, respectively, versus the fading level of Station 1.

Table 3. Minimum bandwidth requirements to match $f_0\ (C_0) \le 0.001, f_1\ (C_1) \le 0.001$, stations 0 and 1.

β_1	C_0^{thr} [Kb/s]	C_1^{thr} [Kb/s]
0.156	8942	57325
0.312	8942	28663
0.625	8942	14303
0.833	8942	10735
1	8942	8942

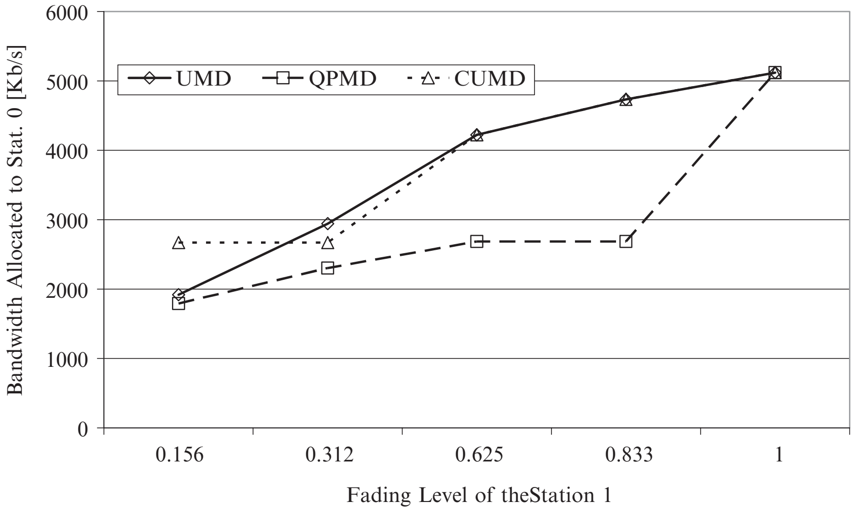

Fig. 5. Bandwidth allocated (Stat. 0, $\gamma_z = 0.01$).

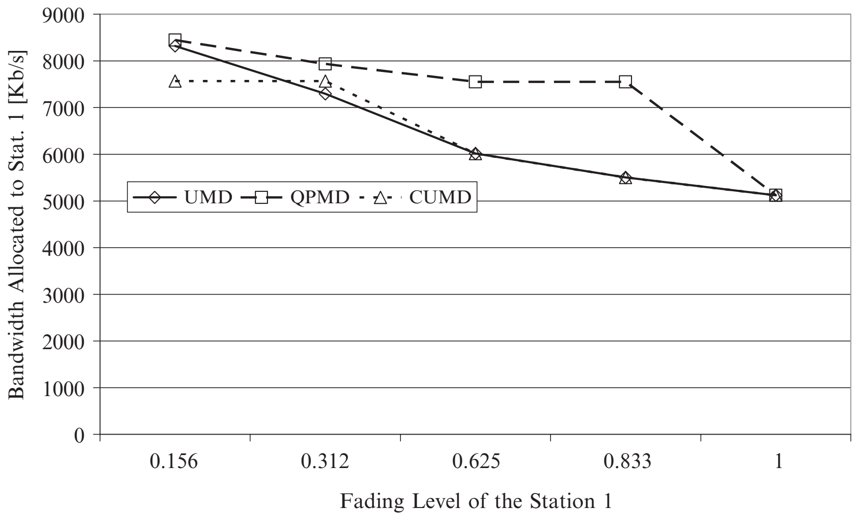

Fig. 6. Bandwidth allocated (Stat. 1, $\gamma_z = 0.01$).

Concerning the first group of tests and CUMD algorithm: values corresponding to $\beta_1 = 0.156$ are the most interesting to check the behaviour of the algorithms. It is the situation where constraints $f_0\,(C_0) \le 0.01, f_1\,(C_1) \le 0.01$ cannot be satisfied in the same time because the overall bandwidth is not sufficient ($C_1^{thr} \ge 10.24$ [Mbps], see the first row of Table 2). CUMD chooses to satisfy $f_0\,(C_0) \le 0.01$ because $C_0^{thr} = 2.67$ [Mbps] ≤ 10.24 [Mbps] and to consider traffic from Station 1 as best effort flows.

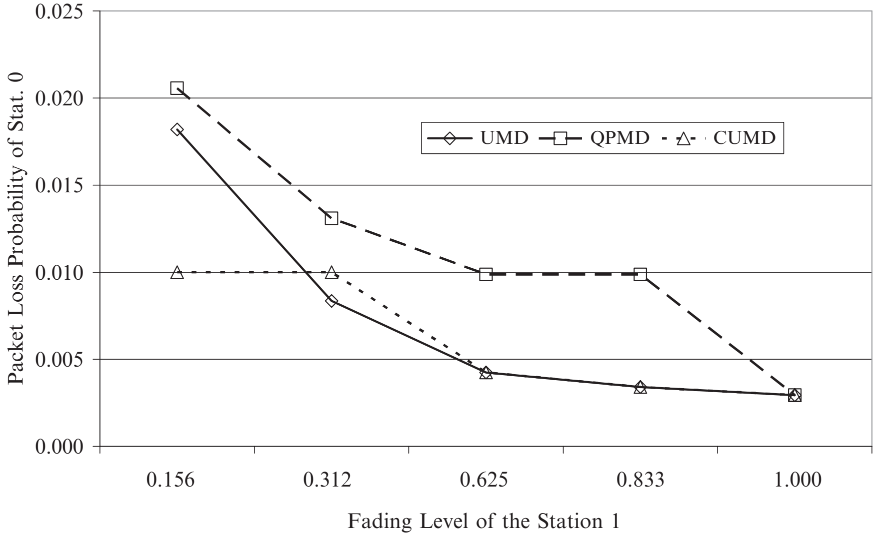

Fig. 7 Packet loss probability (Stat. 0, $\gamma_z = 0.01$).

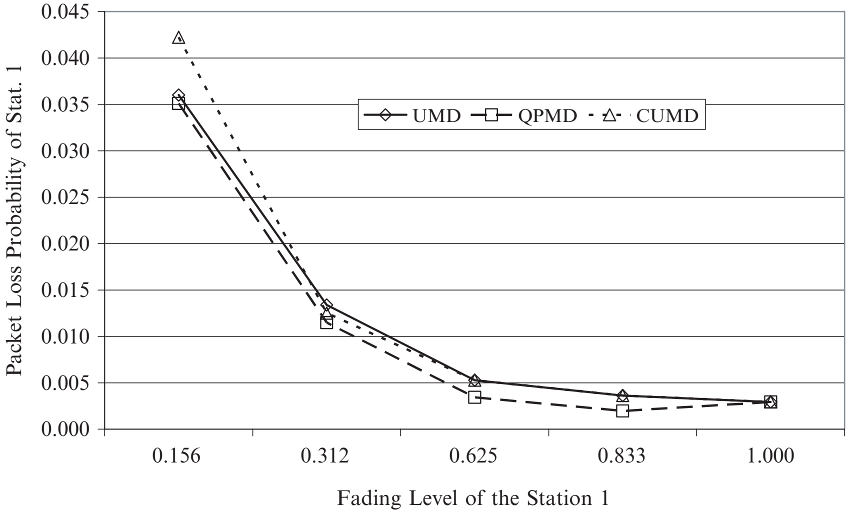

Fig. 8. Packet loss probability (Stat. 1, $\gamma_z = 0.01$).

The minimum bandwidth (2.67 [Mbps]), is assigned to Station 0 and Station 1 gets the residual capacity (7.57 [Mbps]), as clear in Figs. 5 and 6, respectively. The impact on the packet loss may be seen in Figs. 7 and 8. Station 0 value is below the threshold. Station 1 is obviously penalized: the packet loss probability value is far from the threshold. Also values corresponding to $\beta_1 = 0.312$ shows an interesting situation for CUMD because, again, constraints $f_0\ (C_0) \leq 0.01, f_1\ (C_1) \leq 0.01$ cannot

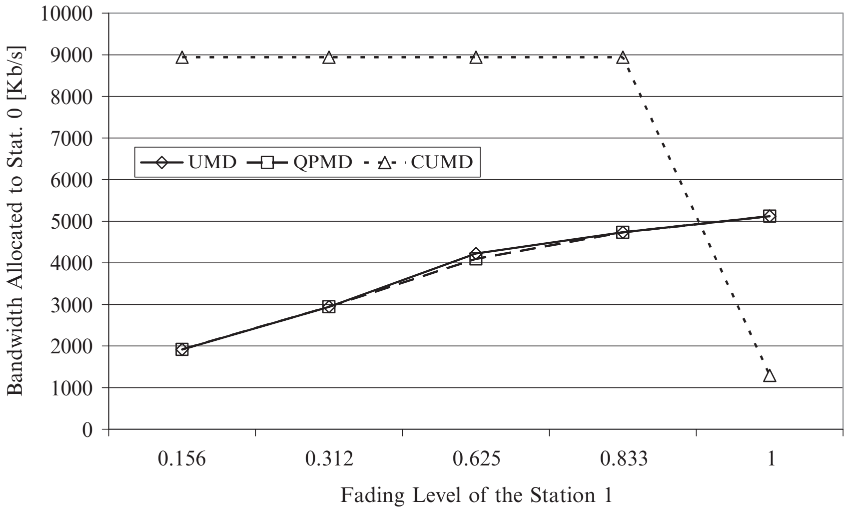

Fig. 9. Bandwidth allocated (Stat. 0, $\gamma_z = 0.001$).

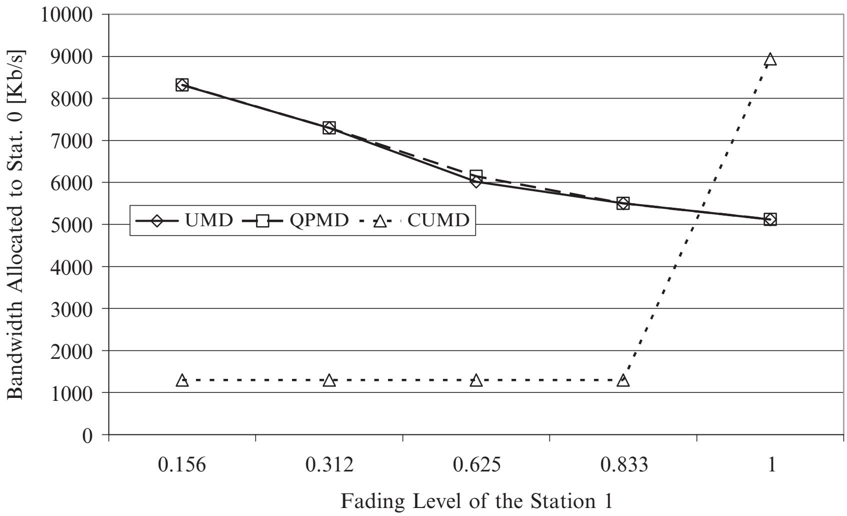

Fig. 10. Bandwidth allocated (Stat. 1, $\gamma_z = 0.001$).

be satisfied in the same time, but both could be satisfied separately. It is exactly the situation shown in Fig. 3.b. CUMD chooses to privilege Station 0 because the choice assures minimum distance with the utopia point. Bandwidth allocations are the same of the previous case (Figs. 5 and 6). The effect on the performance is reported in Figs. 7 and 8. Concerning the behavior of CUMD for $\beta_1 \geq 0.625$, being bandwidth requirements to get performance constraints within the set of feasible allocations, as reported in Table 2, it totally overlaps UMD. Actually, the two schemes have the allocation

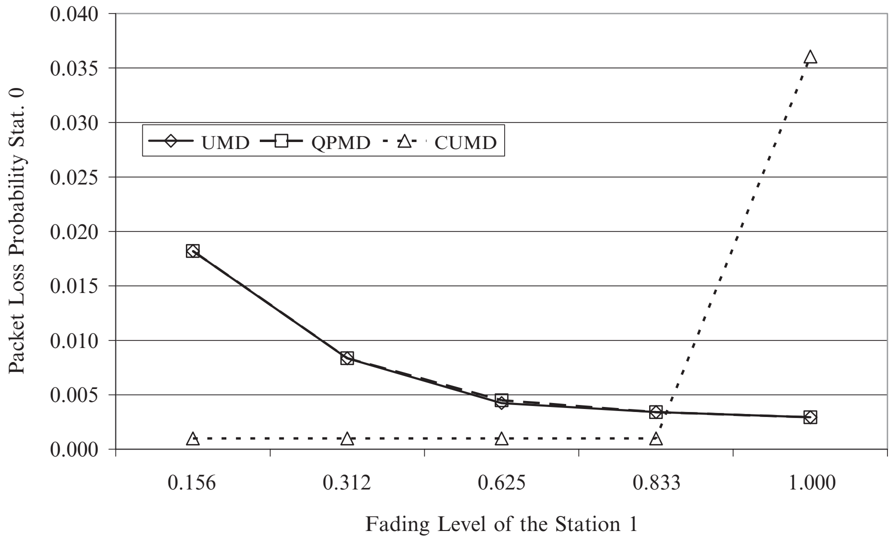

Fig. 11. Packet loss probability (Stat. 0, $\gamma_z = 0.001$).

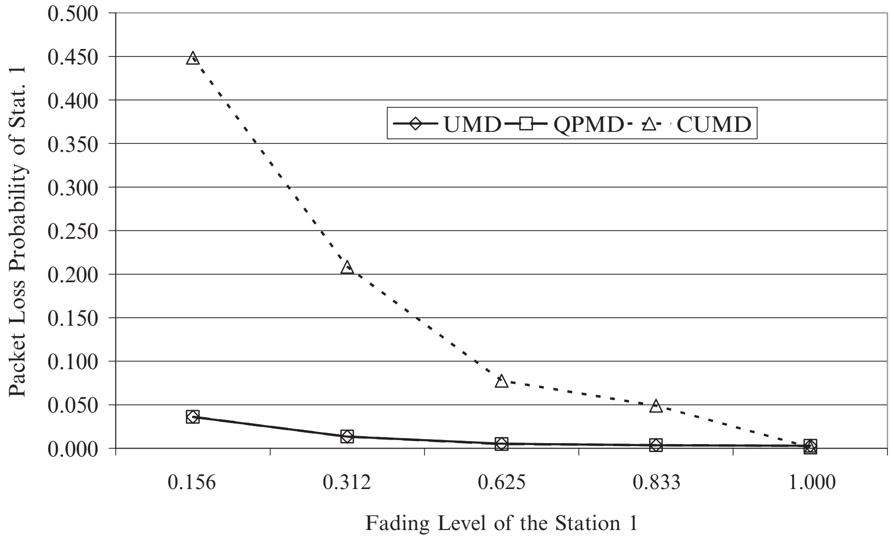

Fig. 12. Packet loss probability (Stat. 1, $\gamma_z = 0.001$).

mechanism based on the utopia point and, except for the constraint sets, which, even if acting, do not influence allocations if $\beta_1 \geq 0.625$, are the same algorithm.

UMD, being not constrained, has the only aim of minimizing the distance with the utopia point (i.e. to approach the behaviour where stations have the complete availability of channel bandwidth). It does not consider any global benefit for the network but acts in a completely competitive environment, where each station pursue its own benefit. Detailed comments about it have been reported in [2]: compared with methods where the overall benefit of the network is considered (e.g. minimizing the overall packet loss probability), faded stations are privileged, just because they are entities of the competitive problems exactly like the other stations.

QPMD changes the nature of allocation because it defines a new reference point (QoS Point), which, implicitly, contains the performance constraints. The QoS point values are the bandwidth allocations contained in Table 2. The shape of bandwidth allocations is similar to UMD but its aim is to keep minimum the quantity $\left(\|\mathbf{F}(\mathbf{C})-\mathbf{F}^{QoS}(\mathbf{C}^{QoS})\|_2\right)^2$. Being the performance requirements the same for both stations, QPMD privileges the faded station, compared to UMD. The behavior is clear in Fig. 5 and Fig. 6. The consequent packet loss probability values are shown in Figs. 7 and 8. As required by its aim, QPMD is the best scheme to have a common (among stations) way to approach performance constraints. The three approaches give the same allocations when they act in clear sky ($\beta_1 = 1$).

The commented behaviors for the three bandwidth allocation schemes hold true for the second set of tests. Performance requirements can never be matched together (Table 3). $C_1^{thr} \geq 10.24$ [Mbps], except for clear sky case. CUMD always chooses to match Station 0 requirements if $\beta_1 < 1$ because the available bandwidth allows it. Station 1 traffic is considered as a best-effort flow. The effect on the packet loss is evident in Fig. 11, where packet loss probability values of Station 0 are always below threshold, and in Fig. 12, where the values are well above the threshold. When $\beta_1 = 1$: the case is totally symmetric and both choices (either Station 0 or Station 1) guarantees minimum distance. As said in session 6.1, the choice is random (Station 1 is chosen, in this case). UMD and QMPD assigns bandwidth allocations to approach, respectively, the utopia point ($C_0 = 10.24$ [Mbps], $C_1 = 10.24$ [Mbps]) and the ideal QoS point got assigning the bandwidth values contained in Table 3 by varying β_1. QPMD behavior may be explained by observing Fig. 4.b, which reports exactly the situation in Table 3. If $\beta_1 < 1: C_1^{thr} \geq C_{TOT} = 10.24$ [Mbps] and $C_0^{thr} < C_{TOT}$. It means that the QoS Point is outside the feasible allocation region and C_1^{thr} is moving from 57.32 to 10.73 [kbps] when β_1 increases its value from 0.156 to 0.833. The projection of the QoS Point over the capacity equality constraint (14), called C_{QPMD}, in Fig. 4.b, corresponds to the projection of the utopia point in the UMD scheme (C_{MD}, in Fig. 2). That is the motivation because the same allocation is got for the two schemes. If $\beta_1 = 1$, $C_0^{thr} = C_1^{thr}$. The comments are similar to the previous case. Correspondence of UMD and QPMD is obvious in this case because the utopia point ($C_0 = 10.24$ [Mbps], $C_1 = 10.24$ [Mbps]) and the QoS point $C_0 = 8.94$ [Mbps], $C_1 = 8.94$ [Mbps] are located along the same straight line, which is orthogonal to the bandwidth constraint (14). Their projection (C_{QPMD} and C_{MD}) are obviously the same point.

8 Conclusions

The paper presents possible allocation schemes for satellite communications, aimed at guaranteeing specific Quality of Service requirements. Traffic is modelled as superposition of TCP sources. The considered framework is the Multi – Objective

Programming Optimization. In particular, the paper introduces two new techniques (CUMD and QPMD), based on the Minimum Distance mechanism, which exploit the features of MOP environment. The paper investigates the behaviour of the two schemes and compares the results with a reference MOP scheme, already published by the authors.

References

[1] S. Kota, K. Pahlavan, P. A. Leppänen, "Broadband Satellite Communications for Internet Access," Kluwer Accademic Publishers, Boston, 2004.

[2] I. Bisio, M. Marchese, "Bandwidth Allocation Strategies for TCP/IP Traffic over High Altitude Platform: a Multi-Objective Programming Approach," IEEE International Conference on Communications (ICC'06), Istanbul, Turkey, June 2006.

[3] N. Celandroni, F. Davoli, E. Ferro, "Static and Dynamic Resource Allocation in a Multiservice Satellite Network with Fading," International Journal of Satellite Communications, vol. 21, no. 4–5, pp. 469–488, July-October 2003.

[4] K. Miettinen, "Nonlinear Multi – Objective Optimization," Kluwer Accademic Publishers, Boston, 1999.

[5] I. Bisio, M. Marchese, "Analytical Expression and Performance Evaluation of TCP Packet Loss Probability over Geostationary Satellite," IEEE Communications Letters, vol. 8, no. 4, pp. 232–234, April 2004.