

# Study and Performance Evaluation of Bandwidth Controls over High Altitude Platforms

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**Abstract-**The demand of bandwidth for TCP/IP based services is growing significantly and the wireless networks are becoming a frequently employed solution to satisfy it. In the wireless scenario, High Altitude Platform (HAP) communications represent a reality, even if absorption and scattering of radio waves by atmospheric components may affect the performance of the communication system. In particular, rain causes severe attenuation so creating communications detriments. The dynamic bandwidth allocation among earth stations may be part of rain fading countermeasures aimed at improving the level of Quality of Service (QoS).

The paper formalizes the bandwidth allocation process as a Multi – Objective Programming (MOP) problem; describes four allocation schemes already in the literature by using the MOP framework and proposes one new algorithm that exploits MOP features: it is called Minimum Distance (MD) algorithm. The allocation strategies described are compared each other to highlight the peculiar characteristics for each of them and to show the performance of MD scheme. The reference metrics are the packet loss probability and the allocated bandwidth.

**Keywords-** HAP Communications, TCP, Dynamic Bandwidth Allocation, Multi-Objective Programming, Pareto Optimality, Performance Evaluation.

## I. INTRODUCTION

TCP-based services present new opportunities for medical assistance, education, business, content distribution, remote land monitoring and entertainment. In the same time, HAP systems may have an important role for the mentioned applications. The advantage of using HAP systems (possibly integrated with cable links) for the mentioned TCP/IP applications is clear: they can achieve ubiquitous information exchange among geographically remote sites with large bandwidth availability, so guaranteeing good perceived quality at affordable costs (without cabling). Also for HAP environments, as well as in traditional terrestrial networks, important issues to be addressed are: the Quality of Service guarantees and the methodologies the networks use to provide them. In HAP channels, one of the main causes of degradation is rain attenuation: rain fading often implies significant communication detriment, information loss and, consequently, QoS degradation.

Specific transmission/reception earth stations may be affected by different fading levels. Dynamic bandwidth allocation may

allocate more bandwidth to the faded stations. The additional bandwidth may be used to transmit more redundancy bits so increasing the protection. So, bandwidth control is topical to increase the overall QoS. Bandwidth allocation within the considered environment is intrinsically a MOP problem due to the presence of stations that compete with the others for the bandwidth resource. During the competition 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. It is exactly the MOP approach. The ideal hypothesis made in this paper is that there is no loss due to channel errors because the FEC code may be extended to a virtually infinite correction power. In practice, being the theoretical assumption unfeasible, the implementation carried out in the paper assumes that a Bit Error Ratio (BER) below  $10^{-7}$  may be obtained by increasing the correction bits. It implies that the bandwidth available for data is strongly reduced (down to about 15% of the overall bandwidth, as should be clear from the details reported in Section III), but makes the ideal hypothesis applicable, considering almost all the losses (actually all, as supposed in the paper) due to bandwidth bottleneck (to congestion) and not to channel errors. Supposing losses due to congestion allows using an analytical TCP traffic model and a related closed-form expression of the packet loss probability, which is the performance metric that rules the bandwidth allocation scheme proposed in this paper. The choice of the metric seems appropriate for TCP/IP based services over HAP environment because HAP channel features heavily affect the packet loss probability, which influences the throughput (in [b/s]), direct measure of the TCP end to end performance.

The paper formalizes the bandwidth allocation problem over TCP/IP HAP networks within MOP framework in presence of rain fading and proposes one scheme to allocate the bandwidth among earth stations accessing the HAP channel.

The paper is structured as follows: section II introduces the network topology. Section III contains the model of the HAP channel. The formalization of the bandwidth allocation is presented in section IV; the TCP packet loss probability is contained in section V; four allocation algorithms in the literature are described in section VI. The MD algorithm is introduced in section VII. Section VIII reports the performance evaluation and section IX the conclusions.

## II. NETWORK TOPOLOGY

The network considered (Fig. 1) is composed of  $Z$  earth stations connected through a HAP. Each station is considered

connected to Internet Service Providers (ISPs) and sends TCP/IP traffic flows to the terminal users. The control architecture is centralized: an earth station (or the HAP 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 (fairness hypothesis).

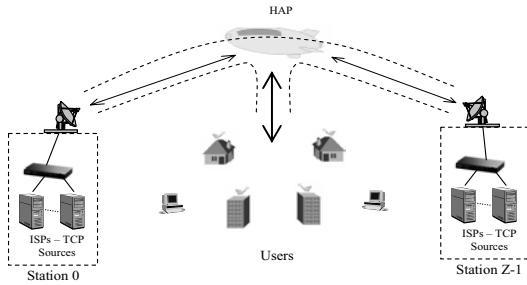


Fig. 1. Network Topology.

In this scenario, each user may request a TCP/IP service (e.g., Web page download or File transfer) by using the HAP channel itself (or also by other communication media). The request traffic is supposed negligible. After receiving the request, the ISPs send traffic through the earth stations and the HAP link. To carry out the process, each earth station conveys the traffic flows directly from the connected ISPs and accesses the HAP channel in competition with the other earth stations. The bandwidth allocation algorithms proposed in the following only concern this portion of the bandwidth. In practice, the reverse channel, transporting the acknowledgement, is considered constant and sufficient for the aim of the server. In theory, considering the acknowledgment channel totally separated by the data channel, the allocation problem solved for it may be applied again by considering each single user as an earth station. It is not done in this paper for the sake of simplicity.

### III. THE HAP CHANNEL MODEL

The HAP channels are typically corrupted by rain fading, which is predominant at higher frequencies (especially above 10 GHz). To compensate the corruption, a range of Forward Error Correction (FEC) coding schemes, often applied in HAP systems to provide efficient broadband services working under different attenuation conditions, may be used. The idea is that each earth station may adaptively increase and decrease the amount of redundancy bits (and the consequent correction power of the code) in strict dependence on the measured fading (or, alternatively, having statistical information about the probability of the fading event). As said in the Introduction, increasing the redundancy bits implies a reduction of the net bandwidth available for data, which can create possible network bottlenecks. It may affect the overall performance significantly. The bandwidth reduction mentioned is modelled here as a multiplicative factor of the bandwidth assigned to an earth station, coherently with reference [1]. Mathematically, it means that the real 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 a factor  $\beta_z \in \mathbb{R}$ , which is, in this paper, a variable parameter contained in the interval  $[0,1]$ .

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

A specific value  $\beta_z$  corresponds to a fixed attenuation level “seen” by the  $z$ -th station. An example of the mapping between the Carrier Power to One-Side Noise Spectral Density Ratio ( $C/N_0$ ) and the  $\beta_z$  parameter is contained in table 1 (from [1]). The shown  $\beta_z$  values are directly associated with the implementation of a specific FEC scheme (whose details are reported in [1]), which has the aim of keeping the bit error ratio (BER) below  $10^{-7}$ .

TABLE I.  
SIGNAL TO NOISE RATIO AND RELATED  $\beta_z$  LEVEL.

$C/N_0$ [dB]	$\beta_z$
> 77.13	1
74.63 – 77.13	0.8333
72.63 – 74.63	0.625
69.63 – 72.63	0.3125
66.63 – 69.63	0.15625
< 66.63	–

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

### IV. 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 capacity available among the stations, which are competitive entities of the problem.

Analytically, the bandwidth allocation defined as a Multi – Objective Programming (MOP) problem may be formalized as:

$$\begin{aligned} \mathbf{C}^{opt} &= \left\{ C_0^{opt}, \dots, C_z^{opt}, \dots, C_{Z-1}^{opt} \right\} = \\ &\arg \min_{\mathbf{C}} \{ \mathbf{F}(\mathbf{C}) \}; \quad \mathbf{F}(\mathbf{C}): \mathbf{D} \subset \mathbb{R}^Z \rightarrow \mathbb{R}^Z, \mathbf{C} \geq 0 \end{aligned} \quad (2)$$

where:  $\mathbf{C} \in \mathbf{D}$ ,  $\mathbf{C} = \{C_0, \dots, C_z, \dots, C_{Z-1}\}$  is the vector of the capacities assignable to the earth stations; the element  $C_z$ ,  $\forall z \in [0, Z-1], z \in \mathbb{N}$  is referred to the  $z$ -th station;  $\mathbf{C}^{opt} \in \mathbf{D}$ , is the vector of the optimal allocation; and  $\mathbf{D} \subset \mathbb{R}^Z$  represents the domain of the vector of functions. The solution has to respect the constraint:

$$\sum_{z=0}^{Z-1} C_z = C_{tot} \quad (3)$$

where  $C_{tot}$  is the available overall capacity.

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

$$\begin{aligned} \mathbf{F}(\mathbf{C}) &= \{f_0(C_0), \dots, f_z(C_z), \dots, f_{Z-1}(C_{Z-1})\}, \\ &\forall z \in [0, Z-1], Z \in \mathbb{N} \end{aligned} \quad (4)$$

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 as the average TCP packet loss probability. The choice is suited for HAP environment but does not limit the general applicability of the methodology. 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 attenuation level ( $\beta_z$ ), for each station  $z$ .  $P_{loss}^z(\cdot)$  is averaged on the attenuation level  $\beta_z$ , which is considered a discrete stochastic variable ranging among  $L$  possible values  $\beta_z^l$  happening with probability  $p_{\beta_z^l}$ .

$$f_z(C_z) = E_{\beta_z} \left[ P_{loss}^z(C_z, N_z, \beta_z) \right] = \sum_{l=0}^{L-1} \left[ P_{loss}^z(\beta_z^l \cdot C_z, N_z) \right] \cdot p_{\beta_z^l}; \forall l \in [0, L-1], L \in \mathbb{N} \quad (5)$$

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 other for bandwidth.

The optimal solution for MOP problems is called POP-Pareto Optimal Point [3], 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:

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

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:

$$\begin{aligned} f_x^1 &\leq f_x^2 \quad \forall x \in \{0, 1, \dots, Z-1\} \text{ and} \\ f_y^1 &< f_y^2 \quad \text{for at least one element } y \in \{0, 1, \dots, Z-1\} \end{aligned} \quad (7)$$

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 performance deterioration of at least another station due to the decreasing nature of the performance function considered (as clarified in next section (9)).

It is worth noting that, in the proposed methodology, no online decision method is applied. The system evolution is ruled by stochastic variables. In practice,  $\mathbf{F}(\mathbf{C})$  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 HAP 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.

## V. THE TCP PACKET LOSS PROBABILITY MODEL

The TCP model considered is based on a previous work of the authors [4]. Being the HAP quasi-geostationary, the round trip time  $RTT$  may be supposed fixed and equal for all the sources. This condition matches with the hypothesis of fairness, which is an essential condition for the analytical model proposed. Taking TCP Reno as reference and considering only the Congestion Avoidance phase of the TCP (supposed always active), the Packet Loss Probability may be analytically expressed as a function of the available bandwidth and of the number of active TCP sources as:

$$\begin{aligned} P_{loss}^z(C_z, N_z, \beta_z) &= \\ = 32 N_z^2 \cdot \left[ 3b(m+1)^2 (\beta_z \cdot \widetilde{C}_z \cdot RTT + \widetilde{Q}_z)^2 \right]^{-1} \end{aligned} \quad (8)$$

where:

- $N_z$  is the number of active TCP sources conveyed in 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  $m = \frac{1}{2}$ );
- $\widetilde{C}_z$  is the bandwidth “seen” by the TCP aggregate of the  $z$ -th earth station expressed in packets/s ( $\widetilde{C}_z = C_z/d$ , where  $d$  is the TCP packet size);
- $\widetilde{Q}_z$  is the buffer size, expressed in packets, of the  $z$ -th earth station.

The average packet loss probability, used within the allocation methods, is:

$$\begin{aligned} E_{\beta_z} \left[ P_{loss}^z(C_z, N_z, \beta_z) \right] = \\ = \frac{32}{3b(m+1)^2} \sum_{l=0}^{L-1} N_z^2 \cdot \left( \beta_z^l \cdot \frac{C_z}{d} \cdot RTT + \widetilde{Q}_z \right)^{-2} \cdot p_{\beta_z^l} \end{aligned} \quad (9)$$

$E_{\beta_z} \left[ P_{loss}^z(\cdot) \right]$  is a monotone (decreasing) function, convex  $\forall C_z \geq 0, \forall z \in [0, Z-1]$ .

The model is valid at regime condition of the TCP senders, coherently with the infinite-horizon hypothesis reported in the previous section.

## VI. BANDWIDTH ALLOCATION METHODOLOGIES

The solution of the allocation problem can be generated with different methodologies. The strategies reported in this paper provide just one solution of the problem (2), out of the overall set of solutions defined by the constraint (3).

Even if, from the point of view of the MOP problem, all the solutions defined by (3) are Pareto optimal, one of them may be preferred depending on a fixed criterion. For example, if the aim (the criterion) is to get the minimum average packet loss probability over all the earth stations, it is necessary to use a method to generate the solution that, within the space defined by the POP set, allows choosing the allocation that satisfy the criterion.

The solutions in the following have different decisional criteria. They are taken from the literature and framed within the MOP environment. It allows not only highlighting their characteristics but also to have an idea of the future possibility offered by the MOP framework.

The first two solutions are very simple and, even if within the POP set, are reported here only as a reference for comparison. The other two are:

- a proposal already published in [2] but presented in the new MOP context;
- a solution based on the bargaining theory [5].

#### A. Fixed Allocation (FIX)

The bandwidth allocator assigns the same quantity of capacity to each station independently of the meteorological and traffic conditions. Being  $Z$  the overall number of stations,

$$C_z = \frac{C_{tot}}{Z}; \quad \forall z \in [0, Z-1] \quad (10)$$

It is obvious to see that the constrain reported in equation (3) is respected and the solution is within the POP set.

#### B. Heuristic Allocation (HEU)

Being the TCP traffic load offered to an earth station (expressed in number of TCP active connections  $N_z$ ) and its fading condition (expressed in terms of  $\beta_z$ ) the crucial elements of the bandwidth allocation strategies proposed, a simple heuristic allocation scheme can be defined in terms of them. In more detail, concerning HEU, the bandwidth provided to a station is a weighted portion of the overall bandwidth available for TCP/IP communications.

From the analytical viewpoint, the capacity assigned to the  $z$ -th station is:

$$C_z = k_z \cdot C_{tot}; \quad \forall z \in [0, Z-1], \quad Z \in \mathbb{N}; \quad k_z \in [0, 1], \quad k_z \in \mathbb{R} \quad (11)$$

Where

$$k_z = \frac{N_z}{\beta_z} \cdot \left( \sum_{j=0}^{Z-1} \frac{N_j}{\beta_j} \right)^{-1} \quad \text{with} \quad \sum_{z=0}^{Z-1} k_z = 1 \quad (12)$$

The bandwidth assigned to a station increases coherently with the traffic offered to the station and with the rain attenuation level.

#### C. Average Bandwidth Allocation for Satellite Channels (ABASC)

The technique takes its origin from a bandwidth allocation scheme originally dedicated to geostationary satellite channels [2]. The cost function used there is the decisional criterion of this methodology in the MOP framework.

The ABASC method generates a solution compatible with the problem because it is a MOP method (it belongs to the

“preference function” methods family as defined in reference [3]). In particular:

$$J_{ABASC}(\mathbf{C}) = \sum_{z=0}^{Z-1} E_{\beta_z}^z \left[ P_{loss}^z(C_z, N_z, \beta_z) \right]; \quad \forall z \in [0, Z-1] \quad (13)$$

The ABASC strategy distributes the bandwidth by minimizing the sum of the single *performance functions*. The vector  $\mathbf{C}_{ABASC}^{opt}$  of the capacities assigned by ABASC is computed as:

$$\mathbf{C}_{ABASC}^{opt} = \arg \min_{\mathbf{C}} J_{ABASC}(\mathbf{C}) \quad (14)$$

under the constraint (3).

#### D. Nash Bargain Solution (NBS)

Taking the problem definition directly from [5], it is necessary to define the *utility functions*: one for each earth station. In this paper the reciprocal value of the TCP packet loss probabilities averaged over the attenuation levels (the *performance functions*) have been chosen.

$$U_z(C_z, N_z, \beta_z) = \frac{1}{E_{\beta_z}^z \left[ P_{loss}^z(C_z, N_z, \beta_z) \right]}; \quad \forall z \in [0, Z-1] \quad (15)$$

The utility of each station grows when the average packet loss probability decreases. In practice,  $U_z(\cdot)$  is an increasing function of the capacity assigned to the  $z$ -th earth station. It is also proportional to the average TCP throughput, which is the reciprocal value of the packet loss probability square-root multiplied for a constant [6]. In general, the bargaining problem deals with the maximization of each single utility function by finding a Pareto optimal allocation. The mentioned NBS solution may be found (as stated in [5]) defining:

$$J_{NBS}(\mathbf{C}) = \prod_{z=0}^{Z-1} U_z(C_z, N_z, \beta_z); \quad \forall z \in [0, Z-1] \quad (16)$$

and by solving:

$$\mathbf{C}_{NBS}^{opt} = \arg \max_{\mathbf{C}} J_{NBS}(\mathbf{C}) \quad (17)$$

Being each single *utility function* convex, the optimization problem defined in equation (17) may be equivalently expressed by using:

$$\hat{J}_{NBS}(\mathbf{C}) = \sum_{z=0}^{Z-1} \ln \left[ U_z(C_z, N_z, \beta_z) \right]; \quad \forall z \in [0, Z-1] \quad (18)$$

hence, the solution of the problem (17) may be also found by (19):

$$\mathbf{C}_{NBS}^{opt} = \arg \max_{\mathbf{C}} \hat{J}_{NBS}(\mathbf{C}) \quad (19)$$

In conformance to previously described methods, to have also for the NBS strategy, a minimization problem, it is necessary to change the  $\hat{J}_{NBS}(\mathbf{C})$  sign. Applying the logarithm properties:

$$\tilde{J}_{NBS}(\mathbf{C}) = -\hat{J}_{NBS}(\mathbf{C}) = \sum_{z=0}^{Z-1} \ln \left[ E_{\beta_z}^z \left[ P_{loss}^z(C_z, N_z, \beta_z) \right] \right]; \quad \forall z \in [0, Z-1] \quad (20)$$

In practice, the NBS strategy distributes the bandwidth by minimizing the sum of the logarithms of each single *performance function*. The vector  $\mathbf{C}_{NBS}^{opt}$  of the capacities assigned by the NBS method is computed as:

$$\mathbf{C}_{NBS}^{opt} = \arg \min_{\mathbf{C}} \tilde{J}_{NBS}(\mathbf{C}) \quad (21)$$

under the constraint (3).

## VII. MINIMUM DISTANCE METHOD (MD) ALGORITHM

The Minimum Distance method is a flexible methodology that allows the resolution of the allocation problem (2). It is a MOP resolution called GOAL approach [3]. It does not use “preference function” (e.g., the summation of the *performance functions*) but 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:

$$\mathbf{F}^{id}(\mathbf{C}^{id}) = \{f_0^{id}(C_0^{id}), \dots, f_z^{id}(C_z^{id}), \dots, f_Z^{id}(C_{Z-1}^{id})\} \quad (22)$$

where

$$f_z^{id}(C_z^{id}) = \min_{C_z} E \left[ P_{loss}^z(C_z, N_z, \beta_z) \right], \quad (23)$$

$$C_z \in [0, C_{tot}], \quad C_z \in \mathbb{R}$$

The method introduced represents the main contribution of this paper (together the overall formalization) and, at the best authors’ knowledge, no bandwidth allocation scheme based on the *utopia point* has been published.

From equation (23), called *single objective problem*, it is obvious that the optimal solution is given by  $C_z = C_{tot}, \forall z \in [0, Z-1]$ . So,  $\mathbf{C}^{id} = \{C_{tot}, C_{tot}, \dots, C_{tot}\}$ .

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

$$\mathbf{C}_{MD}^{opt} = \arg \min_{\mathbf{C}} \left( \|\mathbf{F}(\mathbf{C}) - \mathbf{F}^{id}(\mathbf{C}^{id})\|_2 \right)^2 \quad (24)$$

where  $\|\cdot\|_2$  is the Euclidean norm. The proposed technique allows minimizing the distance between the performance vector and the ideal solution of the problem (MD stands for Minimum Distance), where each single station “sees” the overall bandwidth. The Euclidean norm

$\left( \|\mathbf{F}(\mathbf{C}) - \mathbf{F}^{id}(\mathbf{C}^{id})\|_2 \right)^2$  is the decisional criterion of the MD method. The minimization is carried out under the constraint (3).

## VIII. PERFORMANCE EVALUATION

The aim is to compare the performance of the allocation techniques in terms of allocated bandwidth and packet loss probability. The action is fulfilled analytically by varying the fading conditions of the earth stations. The control strategies have been implemented in C++ language. The minimization algorithm is based on a dynamic programming procedure. The network scenario considered is composed of 2 earth stations: station 0, always in clear sky condition, and station 1, which varies  $\beta_z$  according with table 1. The network under

test is very simple to allow focusing on the features of the presented algorithms. Each station gathers traffic from TCP sources and transmits it to the terminal users through the HAP system. The number of active TCP sources is set to  $N_z = 10$ ,

$z = \{0, 1\}$ . The attenuation level is a deterministic quantity ( $L=1$  and  $p_{\beta_z^l} = 1 \forall z, \forall l$ ) for each single test. The overall bandwidth available  $C_{tot}$  is set to 4 [Mbps] and the TCP buffer size  $\widetilde{Q}_z$  is set to 10 packets (of 1500 bytes) for each earth station. The round trip time is supposed fixed and equal to 100 [ms] for all the stations, it is considered comprehensive of the propagation delay of the HAP channel and of the waiting time spent into the buffers of the earth stations. Figures 2 and 3 show the bandwidth allocated to stations 0 and 1 respectively versus the attenuation level ( $\beta_1$ ) of station 1. Data reported in Fig. 3 are the complement of those reported in Fig. 2. It is reported to simplify the comprehension. FIX method is completely inflexible: it distributes the bandwidth ignoring the fading of the HAP channel. HEU, ABASC and MD methods follow the behaviour of the channel: they provide more bandwidth to the faded station so penalizing the station in clear sky. In more detail, station 0 receives a low quantity of bandwidth if fading is particularly serious. On the other hand, the capacity allocated to the station 1 (Fig. 3) is higher when the HAP channel is much faded and decreases when the rain fading is less severe (i.e., the FEC used is less powerful). HEU penalizes station 0 severely when  $\beta_1$  is small. ABASC and MD distribute the bandwidth among the stations more fairly. NBS method has a different behavior: it provides a larger portion of capacity to the clear sky station in case of serious fading for station 1. The motivation of this behaviour is related to the nature of the utility function defined in equation (15): a maximization of the product of the utility function is obtained by assigning a larger quantity of bandwidth to the utility function that is not corrupted by fading because it gives a major contribution to the overall utility in (16). It means that the techniques ABASC and MD result preferable than the others (NBS, FIX and HEU) if the aim is to have a behaviour strictly dependent on channel fading and a fair distribution of the packet loss between the stations. Fig. 4 and Fig. 5 show the Packet Loss Probability versus the attenuation levels of station 1, for station 0 and 1, respectively. The values confirm the fairness of MD. FIX allows outstanding performance for station 0 but the results are very poor for the faded station. HEU is very “aggressive”: it allows very low packet loss probabilities for the faded station but it penalizes station 0 severely. NBS, coherently with previous observations, provides very good TCP packet loss probability values for the clear sky station but completely unacceptable performance for the faded station. ABASC and MD reach a compromise between the stations in terms of packet loss probability. MD trend is to privilege the faded station and assures results close to HEU for it. The performance for station 0 is slightly penalized with respect to ABASC. The “fairness” guaranteed by these techniques is not given to the research of a *Pareto Optimal Point* because all the solutions satisfying the

constraint (3) belong to the POP set. Actually the behaviour is due to the minimization criterion: ABASC and MD consider the competitive nature of the allocation problem differently from the simple FIX and HEU techniques. NBS method “knows” the competitive nature of the problem but the analytical properties of the utility functions imply a different behaviour. The results of Figs. 4 and 5 deserve an additional comment: the reported packet loss probabilities seem high for real applications. Actually they are, but showing results when the HAP channel is close to saturation is a choice of the authors. It allows stressing the behaviour of the allocation schemes when network resources are really limited, so evidencing advantages and drawbacks fairly.

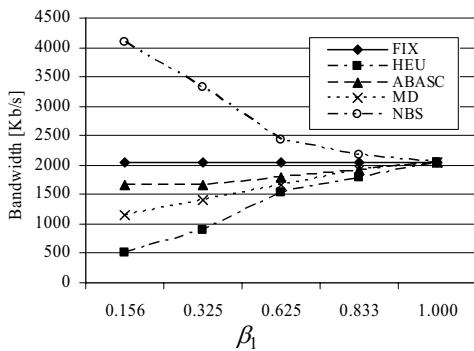


Fig. 2. Bandwidth allocated to Station 0 in presence of variable attenuation levels.

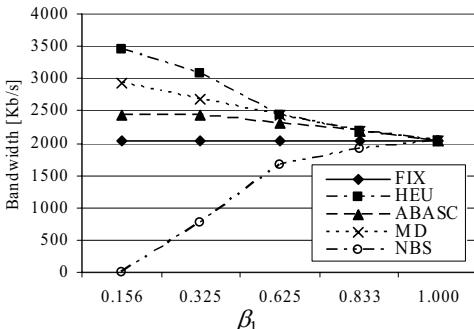


Fig. 3. Bandwidth allocated to Station 1 in presence of variable attenuation levels.

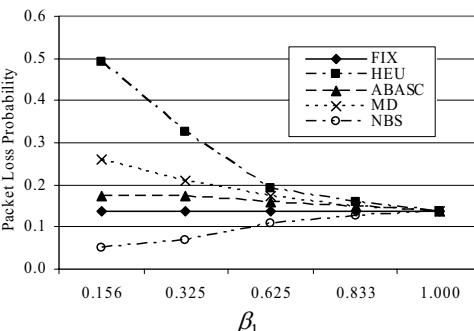


Fig. 4. Packet Loss Probability of Station 0 in presence of variable attenuation levels.

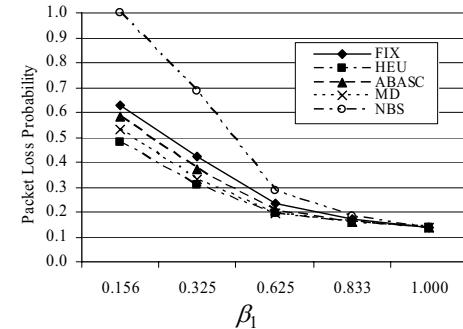


Fig. 5. Packet Loss Probability of Station 1 in presence of variable attenuation levels.

## IX. CONCLUSIONS

HAP systems represent an efficient solution for ubiquitous TCP/IP services. In real deployments, HAPs work at frequencies where fading due to atmospheric phenomena, in particular rain, has an important role. Bandwidth allocation may represent an efficient rain fading countermeasure. The paper presents possible allocation schemes by considering the presence of TCP/IP traffic modelled as a superposition of TCP sources, in the framework of Multi – Objective Programming Optimization. In particular, the paper introduces a new technique, called Minimum Distance (MD), which exploits the features of MOP environment, being fully conscious of the competitive nature of the bandwidth allocation problem. The results show that MD offer very good performance and, in view of future research, allows using heterogeneous performance metrics (i.e., packet delay and jitter together with packet loss), whose application is currently object of ongoing activity.

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