Bandwidth Allocation Strategies for TCP/IP Traffic over High Altitude Platform: a Multi-Objective Programming Approach

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Abstract—**The paper formalizes the bandwidth allocation process as a Multi – Objective Programming (MOP) problem, revises an algorithm already in the literature (identified as ABASC) in the framework of the MOP and proposes a novel scheme (called Minimum Distance – MD method), which fully uses the MOP features. All the schemes are suited to be used in the High Amplitude Platforms (HAPs) environments and are aimed at improving the level of Quality of Service (QoS) of the communications system. The rain attenuation effect, typical of the HAP channels, is considered and modelled as a reduction of the available bandwidth. Only TCP/IP traffic is considered. The two strategies investigated are compared each other and with a fixed and a heuristic allocation. The performance evaluation is carried out analytically by varying the degradation level of the HAP channel and the traffic load offered to the earth stations.**

Keywords-HAP, TCP, Dynamic Bandwidth Allocation, Multi-Objective Programming, 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 High Altitude Platforms (HAPs) may have an important role for the mentioned applications. HAPs are air vehicles in quasi-stationary position used as a fixed station in the stratosphere to support wireless services [1]. Differently from a satellite system, they provide line-of-sight links with low loss and propagation delay. The advantage of using HAP systems (possibly integrated with cable terrestrial links) for the mentioned TCP/IP applications is clear: it can make possible to achieve ubiquitous information exchange among geographically remote sites with large bandwidth availability and limited delay, so guaranteeing good perceived quality and affordable costs (without cabling). Also for HAPs environments, as well as for traditional satellite and terrestrial networks, the major issues to be addressed are the Quality of Service guarantees and the methodologies the networks use to provide them. In HAP channels, the main cause of degradation is rain attenuation: rain fading causes significant communication detriment, information loss and, consequently, QoS degradation. In such environment, allocating bandwidth properly among the earth station (which can be affected by different fading level) so minimizing the packet loss probability is topical to increase the provided QoS. In this paper, coherently with the state of the art, the performance decrease due to meteorological precipitations is supposed mitigated by Forward Error Correction (FEC) codes. Actually the ideal hypothesis for this paper would be that there is no loss due to channel errors because the FEC code may be extended to a virtually infinite correction power by increasing the correction bits and reducing bandwidth for data. In practice, being the theoretical assumption unfeasible, the implementation carried out in the paper assumes a Bit Error Ratio (BER) below 10^{-7} by increasing the correcting bits. It implies that the bandwidth available for data is strongly reduced (down to about the 15% of the overall bandwidth, as should be clear from the details reported in Section III), but makes feasible considering almost all the losses (actually all, as supposed in the paper) due to a 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 schemes proposed in this paper.

In more details: the paper formalizes the bandwidth allocation problem over HAP networks used for TCP/IP services in presence of rain fading; proposes a new algorithm (called Minimum Distance – MD method) to allocate the bandwidth among earth stations accessing the HAP channel; and revises an alternative already in the literature (called ABASC) relying on the Multi-Objective Programming (MOP) criterion. Actually, Bandwidth allocation within the satellite environment is intrinsically a MOP problem: the stations compete each other for the bandwidth resource, and 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 paper is structured as follows: Section II introduces the reference HAP network; Section III describes the channel model considered. Section IV defines the allocation problem. The used average packet loss probability model is summarized in Section V. The allocation methods along with the alternatives for comparison are contained in Section VI. Section VII shows the performance evaluation and Section VIII lists the conclusions.

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II. NETWORK TOPOLOGY

The considered network (Fig. 1) is composed of Z earth stations connected through a High Amplitude Platform (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 (the fairness hypothesis is made).

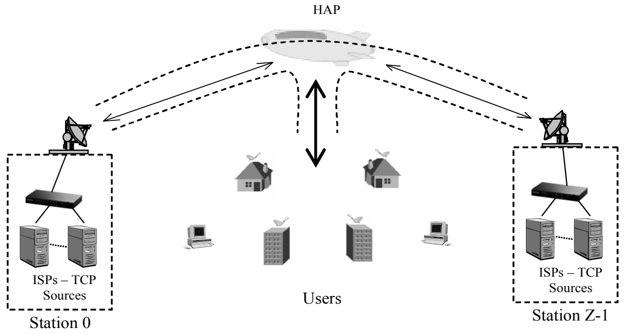

Fig. 1. Network Topology.

In this scenario, each user may request a TCP/IP service (e.g., Web page or a File transfer) by using the HAP channel itself (or also by other communication media). The request traffic is supposed negligible. After receiving the request, ISPs send traffic through the earth stations that access the HAP channel in competition each others.

III. RAIN FADING AND FORWARD ERROR CORRECTION SCHEMES: 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 HAPs to provides efficient broadband services working under different attenuation conditions [2], 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) [1]. As said in the Introduction, increasing the redundancy bits implies a reduction of the net bandwidth available for data.

The mentioned bandwidth reduction is modelled here as a multiplicative factor of the bandwidth assigned to an earth station, coherently with reference [3]. 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].

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

A specific value β_z corresponds to a fixed attenuation level "seen" by the z-th station. An example of the mapping between the Carrier Power to One-Side Noise Spectral Density Ratio (C/N_0) and the β_z parameter is contained in table 1 (from [3, 4]). The shown β_z values are directly connected with the implementation of a specific FEC scheme (whose details are reported in [3]), which has the aim of keeping the bit error ratio (BER) below 10^{-7}.

TABLE I.
SIGNAL TO NOISE RATIO AND RELATED β_z LEVEL.

***C/N₀* [dB]**	β_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 β_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:

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

where: $\mathbf{C} \in \mathbf{D}$, $\mathbf{C} = \left\{C_0, \ldots, C_z, \ldots, C_{Z-1}\right\}$ 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 have to respect the constraint:

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

where C_{tot} is the overall capacity available.

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

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

The single z-th *performance function* is a component of the vector. Each *performance function* $f_z\left(C_z\right)$ (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. Fixed the β_z value, the TCP packet loss probability is a function of the bandwidth (C_z), of the number of active sources (N_z) and of the fading level β_z, for each station z. $P_{loss}^z\left(\cdot\right)$ 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 $p_{\beta_z^l}$.

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

In general, the problem defined above, is a Multi – Object Programming problem where each considered function $f_z\left(C_z\right)$ represents a single competitive cost function that competes for bandwidth.

The optimal solution for MOP problem (called POP-Pareto Optimal Point [6]), coherently with the classical MOP theory, 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:

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

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

$$\begin{aligned}&f_x^1\le f_x^2\ \ \forall x\in\left\{0,1,...,Z-1\right\}\text{ and}\\&f_y^1<f_y^2\ \text{ for at least an element } y\in\left\{0,1,...,Z-1\right\}\end{aligned} \tag{7}$$

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 an increase of at least one of the other functions. In the 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 one, due to the decrescent nature of the performance function considered (as clarified in section V).

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 previous work of the authors [7]. Being the HAP quasi-stationary, 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, 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:

$$P_{loss}^z\left(C_z,N_z,\beta_z\right)= \\ =32{N_z}^2\cdot\left[3b\left(m+1\right)^2\left(\beta_z\cdot\widetilde{C_z}\cdot RTT+\widetilde{Q_z}\right)^2\right]^{-1} \tag{8}$$

where: N_z is the number of TCP active 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 $m=1/2$); $\widetilde{C_z}$ 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.

VI. BANDWIDTH ALLOCATION METHODOLOGIES

The solutions of the allocation problem can be generated with different methodologies. The strategies investigated 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 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 reported in the following have different decisional criteria. 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 as a reference for comparison. The other two (derived from MOP theory) are:

- a proposal already published in [4] but presented in the new MOP context;
- a novel method based on the GOAL programming [6].

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,

$$C_z = \frac{C_{tot}}{Z}; \quad \forall z \in [0, Z-1], \quad Z \in \mathbb{N} \tag{9}$$

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 β_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:

$$C_z = k_z \cdot C_{tot}; \forall z \in [0, Z-1], \; Z \in \mathbb{N}; \; k_z \in [0,1], \; k_z \in \mathbb{R} \tag{10}$$

Where

$$k_z = \frac{N_z}{\beta_z} \cdot \left(\sum_{j=0}^{Z-1} \frac{N_j}{\beta_j} \right)^{-1} \quad \text{with} \quad \sum_{z=0}^{Z-1} k_z = 1 \tag{11}$$

The bandwidth assigned to a station increases coherently with the traffic offered to the station and with the severity of the rain fading that corrupts the HAP channel.

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

The technique takes its origin from a bandwidth allocation scheme originally dedicated to geostationary satellite channels [4]. The cost function used there is the decisional criterion of this methodology. The ABASC method generates a solution compatible with the problem because it is a MOP method belonging to the "*preference function*" methods family, as defined in reference [6]. In particular:

$$\begin{gathered} J_{ABASC}(\mathbf{C}) = \sum_{z=0}^{Z-1} \underset{\beta_z}{E}\left[P_{loss}^{z}(C_z, N_z, \beta_z) \right]; \\ \forall z \in [0, Z-1], \; Z \in \mathbb{N} \end{gathered} \tag{12}$$

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

$$\mathbf{C}_{ABASC}^{opt} = \arg\min_{\mathbf{C}} J_{ABASC}(\mathbf{C}) \tag{13}$$

under the constraint (3).

D. *Minimum Distance Method (MD)*

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 [6]. 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:

$$\mathbf{F}^{id}\left(\mathbf{C}^{id}\right) = \left\{ f_0^{id}\left(C_0^{id}\right), \ldots, f_z^{id}\left(C_z^{id}\right), \ldots, f_Z^{id}\left(C_{Z-1}^{id}\right) \right\} \tag{14}$$

where

$$\begin{gathered} f_z^{id}\left(C_z^{id}\right) = \min_{C_z} \underset{\beta_z}{E}\left[P_{loss}^{z}(C_z, N_z, \beta_z) \right], \\ C_z \in [0, C_{tot}], \; C_z \in \mathbb{R} \end{gathered} \tag{15}$$

From equation (15), 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, $\mathbf{C}^{id} = \{C_{tot}, C_{tot}, \ldots, C_{tot}\}$.

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

$$\mathbf{C}_{MD}^{opt} = \arg\min_{\mathbf{C}} \left(\left\| \mathbf{F}(\mathbf{C}) - \mathbf{F}^{id}\left(\mathbf{C}^{id}\right) \right\|_2 \right)^2 \tag{16}$$

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

VII. PERFORMANCE EVALUATION

The aim is to evaluate the performance of the allocation techniques studied in terms of bandwidth allocated and packet loss probability. The performance evaluation is carried out analytically by varying the fading conditions and the number of TCP active sources.

A. *Variable Fading Level*

The first set of tests is aimed at evaluating the performance by varying the fading level "seen" by a station without traffic variations. The network scenario considered is composed of 2 earth stations: the station 0, always in clear sky condition, and the station 1, which varies its fading level according with table 1. Each station gathers traffic from TCP sources and transmits it to the terminal users through the HAP. 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 performed. 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 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 the station 0 and station 1, respectively. The FIX method is an inflexible approach, which distributes the bandwidth ignoring the fading status of the HAP channel seen by the station 1. 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, the station 0 receives a low quantity of bandwidth if the faded station is particularly corrupted. The assigned bandwidth grows when the β_z parameter of the station 1 (i.e., β_1) increases. 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).

The HEU method penalizes severely the station 0 when the fading level is low. ABASC and MD distribute the bandwidth among the stations more fairly. They result preferable than the others (FIX and HEU) if the aim is to have a fair distribution of the packet loss between the stations. Fig. 4 and Fig. 5 show the Packet Loss Probability for the station 0 and 1, respectively: FIX method allows outstanding performance for station 0 but the results are very poor for the faded station. HEU scheme is very "aggressive": it allows very low packet loss probabilities for the faded station 1 but it penalizes the station 0 severely. ABASC and MD reach a compromise between the stations in terms of packet loss probability. 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. In particular, MD assumes a completely competitive environment and approach the behaviour of an ideal environment where each station has the full availability of the channel bandwidth.

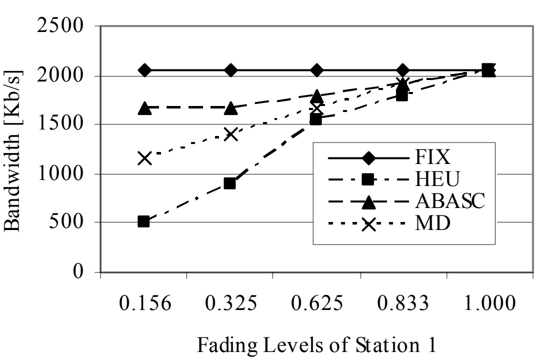

Fig. 2. Bandwidth allocated to Station 0 in presence of variable fading level.

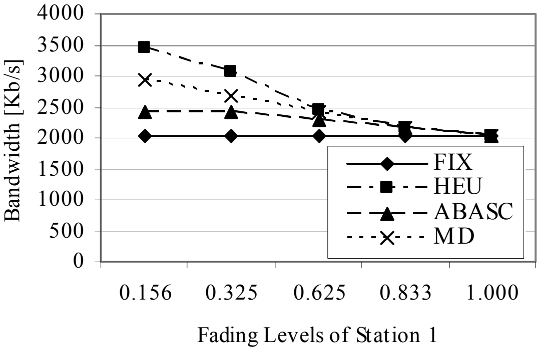

Fig. 3. Bandwidth allocated to Station 1 in presence of variable fading level.

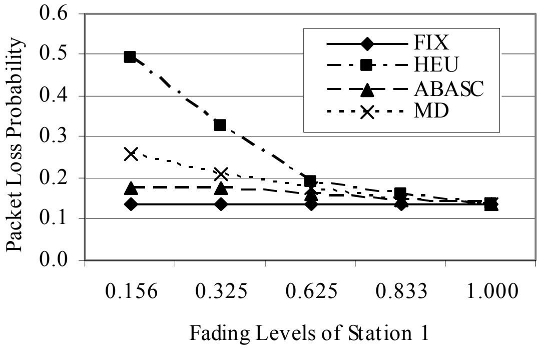

Fig. 4. Packet Loss Probability of Station 0 in presence of variable fading level.

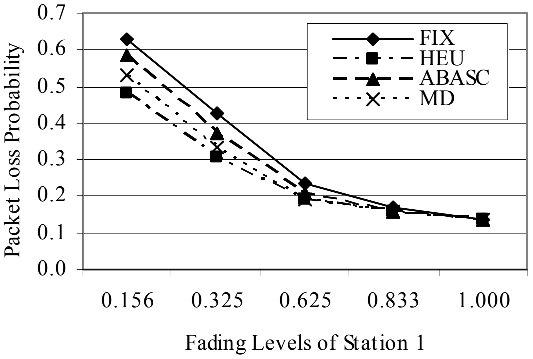

Fig. 5. Packet Loss Probability of Station 1in presence of variable fading level.

B. Variable Number of TCP Sources

The second set of tests is aimed at evaluating the performance by varying the number of active TCP sources gathered in the stations. The network scenario is the same considered in sub-section A but, in this case, both stations are in clear sky conditions. The difference is only the number of activated TCP sources. In detail, $N_0 = 10$ is fixed in all tests, while N_1 varies as reported in the x-axis of the figures from 6 to 9. Again the FIX method does not provide any flexibility in terms of bandwidth allocated (Figs. 6 and 7). Concerning the packet loss probability, it gives satisfying results only for station 0 (Fig. 8), which is not overloaded, but completely unacceptable for station 1 (Fig. 9). HEU scheme, ignoring the competition gives some bandwidth to both stations, even if, when the station 1 is overloaded ($N_1 = 40$), it does not take any benefit concerning the packet loss probability. On the other hand, ABASC and MD, which, in this tests, provide approximately the same results, do not give any bandwidth to station 1, when overloaded, and reserve the bandwidth to the other station, obviously improving its performance.

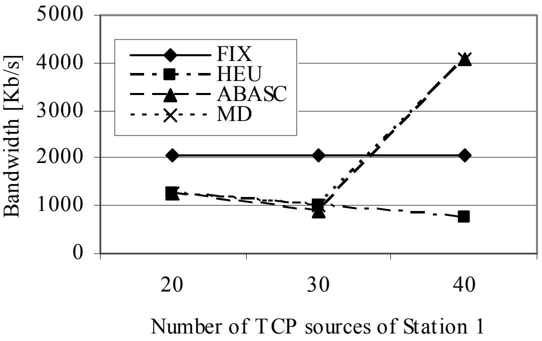

Fig. 6. Bandwidth allocated to Station 0 in presence of variable number of TCP sources.

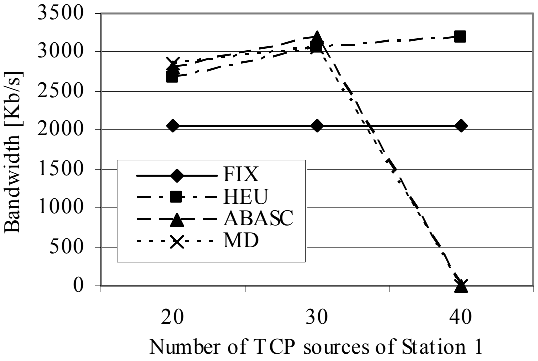

Fig. 7. Bandwidth allocated to Station 1 in presence of variable number of TCP sources.

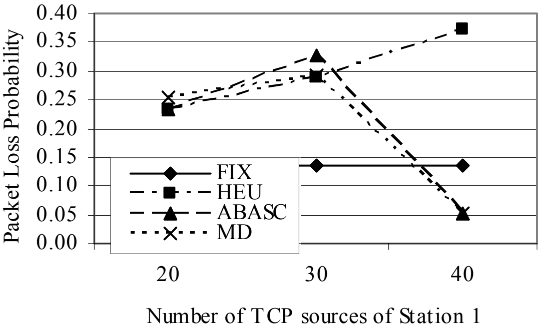

Fig. 8. Packet Loss Probability of Station 0 in presence of variable number of TCP sources.

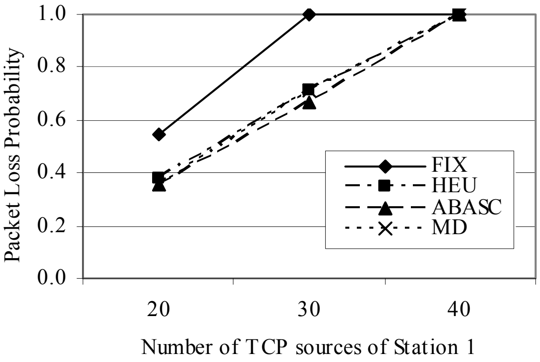

Fig. 9. Packet Loss Probability of Station 1 in presence of variable number of TCP sources.

VIII. CONCLUSIONS

HAPs represent a low-cost efficient solution for ubiquitous TCP/IP services. In real deployments, HAP systems work at frequencies where the fading due to atmospheric phenomena, in particular rain, has an important role. The bandwidth allocation may represent an efficient rain fading countermeasure. The paper revises an existing approach (ABASC) in the framework of MOP problems and presents a new algorithm (MD) that considers bandwidth allocation as a fully competitive problem and tries approaching an ideal behaviour where each station has the full availability of bandwidth. The results show that both ABASC and MD offer very good performance.

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