# Minimum Distance Bandwidth Allocation over Space Communications

Igor Bisio, *Student Member, IEEE,* and Mario Marchese, *Senior Member, IEEE*

***Abstract*— The letter formalizes the bandwidth allocation process over space communication systems as a Multi-Objective Programming (MOP) problem and proposes an allocation called "Minimum Distance" algorithm. The algorithm assigns the bandwidth so to approach the ideal situation where each station has the overall channel bandwidth available, as close as possible. The performance evaluation is carried out analytically by varying the fading level of the space channel.**

***Index Terms*— Space communications, bandwidth allocation, multi-objective programming, performance evaluation.**

## I. Introduction

ALLOCATING bandwidth properly among satellite earth stations is topical to mitigate the problem of space link degradation due to rain fading. Earth stations compete for bandwidth: the rationale under this paper is considering bandwidth allocation as a competitive problem where stations are "represented" by cost functions that need to be minimized simultaneously. It is the definition of the Multi-Objective Programming (MOP) class of problems, which is the base of the algorithm presented in this letter.

## II. Network Topology and Channel Model

$Z$ earth stations are connected through a space connection. The choice of the technology (GEO, LEO, HAP) affects only the round trip time ($RTT$, intended here as the TCP round trip time). The control architecture is centralized. Each station equally shares the assigned portion between its traffic flows (the fairness hypothesis is made). Each station conveys traffic and accesses the space channel in competition with the other earth stations. Fading is modeled as bandwidth reduction [1]. Mathematically, it means that the bandwidth $C_z^{real} \in \mathbb{R}$ available for $z$-th station traffic is composed of the bandwidth $C_z \in \mathbb{R}$, assigned to $z$-th station, and of the factor $\beta_z \in \mathbb{R}$, which is, in this letter, a variable parameter contained in the interval [0,1]. A specific value $\beta_z$ corresponds to a fixed fading level "seen" by the $z$-th station.

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

## III. Bandwidth Allocation Problem Definition

### A. Problem Formalization

Each earth station has a single buffer gathering TCP traffic. The practical aim of the allocator is the provision of bandwidth to each buffer by splitting the overall capacity available among the stations.

Analytically, the bandwidth allocation defined as a MOP problem may be formalized as:

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

where: $\mathbf{C} \in \mathbf{D}$, $\mathbf{C} = \{C_0, ..., C_z, ..., C_{Z-1}\}$ is the vector of the capacities assignable to the earth stations; the element $C_z$, $z \in \{0, 1, ..., Z-1\}$, is referred to the $z$-th station; $\mathbf{C}^{opt} \in \mathbf{D}$, is the vector of the optimal allocation; $\mathbf{D}$ represents the domain of the vector of functions. The solution has to respect the constraint (3), where $C_{tot}$ is the overall capacity available:

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

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

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

Each "*performance function*" $f_z(C_z)$ (or *objective*) is a component of the vector and represents a single station competing with the others to get bandwidth. The proposed allocation methodology requires only that each $f_z(C_z)$ is convex and decreasing. The specific choice performed in this paper, which affects the numerical results reported in the performance evaluation, is specified in sub-section III.C. The optimal solution is called POP-Pareto Optimal Point [2]. In the considered problem, a POP is a bandwidth allocation where any change to get a lower value of one of the performance functions implies the increment of at least one of the other functions. 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 objective functions. The rationale of the proposal contained in this letter is that all the $Z$ performance functions need to be minimized simultaneously (MOP problem). If there were no conflicts (non-competitive case) among performance functions, a trivial solution would be obtained by solving $Z$ optimization problems separately (one for each station-performance function), so getting the ideal performance vector (in (5)), as a solution. Actually, in this ideal solution, all the earth stations would obtain all the bandwidth available in the same time (*utopia point*). Unfortunately the allocation problem treated in this paper is not the trivial non-competitive case. Each station is in contrast with the others to get bandwidth. The *utopia point* does not

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The authors are with the Department of Communications, Computer and Systems Science, University of Genoa, Italy (e-mail: {igor.bisio, mario.marchese}@unige.it).
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belong to the admissible domain because, obviously, not all the stations may receive $C_{tot}$ in the same time.

### *B. Minimum Distance Bandwidth Allocation (MD)*

The problem is to choose a single configuration to allow bandwidth allocation, among the Pareto optimal solutions defined by (3). For this choice, in MOP problems, it is possible to have a "decision maker", which may help select one solution among the POP set. The literature classifies the solutions into categories. One of them is identified as *no preferences family*, where the decision maker has no role. The most popular method belonging to it is called GOAL [2], which is used in this letter as bandwidth allocation. It looks for the solution by minimizing the euclidean distance with a generic reference point.

A possible choice is to select the *utopia point* (supposed known) as reference. It is just the choice followed by the algorithm (called *MD*) proposed in this paper.
In more technical words:

$$\mathbf{F}^{id}(\mathbf{C}^{id}) = \left\{f_0^{id}(C_0^{id}), ..., f_z^{id}(C_z^{id}), ..., f_{Z-1}^{id}(C_{Z-1}^{id})\right\} \quad (5)$$

where

$$f_z^{id}(C_z^{id}) = \min_{C_z} E_{\beta_z}[P_{loss}^z(C_z, \beta_z)], \; C_z \in [0, C_{tot}] \quad (6)$$

From equation (6), 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, $\mathbf{C}^{id} = \{C_{tot}, C_{tot}, ..., C_{tot}\}$.
Starting from the definition of the *ideal performance vector*, the problem stated in equation (2) can be solved by the following allocation under the constraint (3):

$$\mathbf{C}_{MD}^{opt} = \arg\min_{\mathbf{C}} \left(\left\|\mathbf{F}(\mathbf{C}) - \mathbf{F}^{id}(\mathbf{C}^{id})\right\|\right) \quad (7)$$

where $\|\cdot\|_2$ is the Euclidean norm.

Additionally: 1) *MD* does not use any decision maker. It means that no overall system interest is considered; the problem is totally competitive and each station tries to get its best. No station is damaged because all of them compete. 2) Approaching the *utopia point* (where all the stations have the full bandwidth availability) seems reasonable and desirable, not only because it is the GOAL solution, but also because to have the complete bandwidth availability is really an ideal situation for a station and, intuitively, approaching this situation seems the best a station can obtain. On the other hand, not considering explicitly the benefit of the overall network is the point of view of the users, who wish to maximize the benefit of the station where they have access. The effect of it, as should be clear from the results, is a reduced penalization of the faded stations and a consequent performance improvement of the users attached to them.

### *C. Definition of the Performance Function*

Each "*performance function*" $f_z(C_z)$ is defined in this paper as the average of the TCP packet loss probability $P_{loss}^z(\cdot)$ over the fading level $\beta_z$, considered a discrete stochastic variable ranging among $L$ possible values $\beta_z^l$ happening with probability $p_{\beta_z^l}$ (where $l = 0, 1, ..., L-1$):

$$f_z(C_z) = E_{\beta_z}[P_{loss}^z(\beta_z, C_z)] = \sum_{l=0}^{L-1}[P_{loss}^z(\beta_z^l C_z)]p_{\beta_z^l}. \quad (8)$$

Operatively, from reference [3]:

$$P_{loss}^z(\beta_z^l C_z) = \frac{32(N_z)^2}{3b_n^z(m_z+1)^2(\beta_z^l C_z RTT + Q_z)^2} \quad (9)$$

where: index $z$-th identifies the earth station, $N_z$ is the number of TCP sources; $b_n^z$ is the number of TCP packets (one, in this paper) covered by one acknowledgment; $m_z$ is the multiplicative decrease parameter ($m_z = 1/2$, in this paper); $\beta_z C_z$ is the available bandwidth for the $z$-th station as specified in Section II; $Q_z$ is the TCP/IP traffic buffer size. Channel errors are corrected by FEC codes (considered through $\beta_z$) so getting negligible Bit Error Ratio (BER) values. It implies that the bandwidth available for data is strongly reduced (down to about 15.6% of $C_z$, as in Figs. from 1 to 3), but makes feasible considering almost all the losses (actually all, as assumed in [3]) due to a bandwidth bottleneck (to congestion) and not to channel errors.

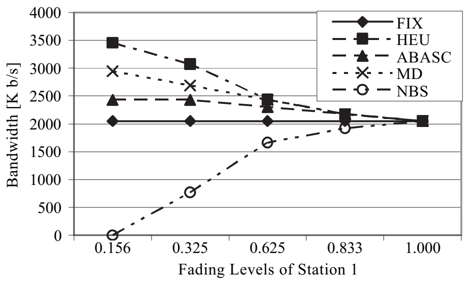


Fig. 1. Bandwidth allocated to Station 1 in presence of variable fading.

## IV. Performance Evaluation

*MD* is compared with the following schemes in terms of allocated bandwidth and packet loss probability: FIX, where the allocator assigns the same capacity to each station independently of the meteorological and traffic conditions. HEU, where the bandwidth allocation is directly proportional to the traffic offered ($N_z$) and inversely proportional to the fading level ($\beta_z$). ABASC [1], where the cost minimized is the sum of the packet loss averaged over the fading level. NBS [4], where the cost is the sum of the logarithms base $e$ of the packet loss of each station averaged over the fading levels. The last two methods imply the explicit intervention of a decision maker that minimizes a cost function synthesizing the supposed benefit of the overall network.

The first part of the results considers 2 stations: "0", always in clear sky, and "1", which varies its fading level $\beta_1$ according to real measures also used in [1]. 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 4 [Mbps] and the TCP buffer size is 10 packets of 1500 bytes for each earth station. TCP round trip time is considered fixed and equal to 100 [ms] for all the stations. This value is computed by

TABLE I
EUCLIDEAN DISTANCE FROM THE *Utopia Point*

| $\beta_1$ | FIX | HEU | ABASC | MD | NBS |
|---|---|---|---|---|---|
| 0.156 | 0.58209 | 0.61451 | 0.54506 | 0.51488 | 0.9480 |
| 0.325 | 0.38234 | 0.37571 | 0.33444 | 0.32374 | 0.6332 |
| 0.625 | 0.20045 | 0.19941 | 0.18810 | 0.18786 | 0.2408 |
| 0.833 | 0.14484 | 0.15133 | 0.14234 | 0.14234 | 0.1504 |
| 1 | 0.1187 | 0.1187 | 0.1187 | 0.1187 | 0.1187 |

TABLE II
PACKET LOSS PROBABILITIES VS NUMBER OF STATIONS

| $Z$ | MD-F | MD-C | ABASC-F | ABASC-C | NBS-F | NBS-C |
|---|---|---|---|---|---|---|
| $N_z = 5$; $\beta_1 = 0.156$ | | | | | | |
| 2 | 0.130 | 0.065 | 0.144 | 0.043 | 1 | 0.012 |
| 4 | 0.178 | 0.081 | 0.210 | 0.065 | 1 | 0.052 |
| 6 | 0.200 | 0.106 | 1 | 0.087 | 1 | 0.081 |
| 8 | 0.234 | 0.114 | 1 | 0.114 | 1 | 0.114 |
| $N_z = 5$; $\beta_1 = 0.156$ | | | | | | |
| 2 | 0.523 | 0.260 | 0.583 | 0.175 | 1 | 0.051 |
| 4 | 0.714 | 0.327 | 0.852 | 0.260 | 1 | 0.218 |
| 6 | 0.802 | 0.425 | 1 | 0.350 | 1 | 0.350 |
| 8 | 0.936 | 0.470 | 1 | 0.460 | 1 | 0.470 |

supposing a buffer occupancy of 8 packets and an allocated rate of about 2 [Mbps]. Anyway $RTT$ values do not affect the qualitative behavior of the schemes, even if, obviously, the specific values change.

Table I shows the Euclidean distance from the *utopia point* for all the considered schemes by varying the fading level. *MD* minimizes it and, in a totally competitive environment, where all the stations aim at getting as much bandwidth as possible without any agreed cooperation with the other entities, it provides the optimal allocation. The difference with the other schemes is more evident for serious fading conditions ($\beta_1 \leq 0.625$, in Table I) because, approaching a clear sky condition, all the performance functions (the components of the vector (4)) tend to have the same value.

Fig. 1 shows the bandwidth allocated to station 1 versus the fading levels. The allocations to station 0 may be simply computed by subtracting the bandwidth allocated to station 1 from $C_{tot} = 4$ [Mbps]. FIX method ignores channel fading. HEU, ABASC and *MD* follow the behavior of the channel and provide more bandwidth to the faded station. *MD*, due to the motivations reported in Section III, does not penalize the faded station too much. No substantial difference in the computational load has been measured for the schemes under test. The effect on the Packet Loss Probability versus the fading levels is reported in Figs. 2 and 3, for stations 0 and 1, respectively. The quantity is shown also for the ideal condition where each station uses all the channel bandwidth. The help for the faded station is clear for *MD* with respect to the other algorithms.

The second part of the results varies the number of stations $Z = \{2, ..., 8\}$ and the number of TCP sources $N_z = \{5, 10\}$. One station out of $Z$ is seriously faded ($\beta_1 = 0.156$). All the others operate in clear sky. Table II contains the packet

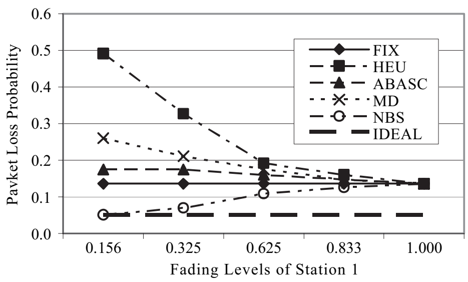


Fig. 2. Packet Loss Probability of Station 0 in presence of variable fading.

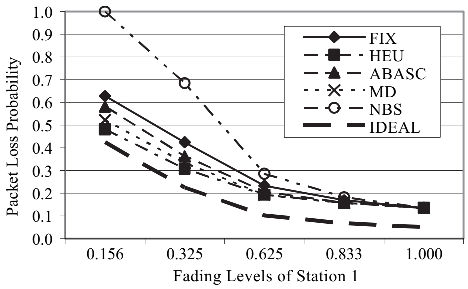


Fig. 3. Packet Loss Probability of Station 1 in presence of variable fading.

loss probability for the faded station (suffix “-F”) and for the other stations (suffix “-C”). In this last case, the single values are averaged over the number of stations in clear sky. *MD*, ABASC, and NBS are considered. The advantage of *MD* is very clear: it does not punish the faded station and allows, for $N_z = 5$, to get packet loss values feasible with most current services (e.g., voice and video streaming) for users connected both through the faded station and through the other stations, so allowing, if necessary, interaction among them. This is not reachable with ABASC and NBS. The trend is the same for $N_z = 10$ but the overload does not allow getting practical loss values in any case.

## V. CONCLUSIONS

The letter has proposed a new allocation scheme over space links, called *MD* and based on a Multi-Objective Optimization technique. The results have shown an optimal performance within a fully competitive view of the nature of the bandwidth allocation problem.

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