Design and Evaluation Guidelines for Bandwidth Allocation Solutions in Satellite Environments

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Abstract — **Next-generation Internet infrastructures have two specific macroscopic requirements: ubiquity and quality of service guarantee. Satellite and wireless systems can easily guarantee ubiquity but, due to noise and fading, they may fail matching quality of service requirements. Bandwidth Allocation algorithms are often used to smooth the problem but they must be properly designed, tuned and tested before their employment. It is important to fix guidelines to orienteer the design to have a correct evaluation of the results in line with the objectives. The basic idea is that bandwidth allocation should be fair and efficient, but what does it mean? What is the definition of fairness and efficiency? The answer of this article relies on Fairness and Bandwidth Utilization concepts, which are consolidated in the field, and on the idea of Performance Efficiency, proposed in this article. All of them may be translated in indexes that can be important to evaluate bandwidth allocation algorithms in satellite and wireless environments. This is exactly the aim of this article, which suggests some design and evaluation guidelines for bandwidth allocation schemes based on the mentioned concepts and considers some allocation methodologies proposed in the literature as a reference.**

Index Terms – **Satellite Networks, Bandwidth Allocation, Fairness, Bandwidth Utilization, Performance Efficiency.**

I. INTRODUCTION

RESOURCE allocation represents an important issue for next generation TCP/IP Quality of Service (QoS) - based satellite networks. Traditional Internet architectures were originally designed to get a robust and scalable infrastructure, able to support a huge number of applications. Users were supposed to stay at home, in their office, and to access the network by using wired channels. This structure is not particularly suited to address the needs of new users who want to access services regardless of their specific location under the paradigm "anytime and anywhere". Modern Internet network is widely heterogeneous. It is composed of cable, wireless, and satellite portions to match all remote access needs, from big cities to remote alpine valleys and hazardous areas, and uses many different protocols.

On the other hand, the development of new applications and the convergence of services transported through QoS-oriented dedicated infrastructures and protocols over TCP/IP-based networks impose a big technical challenge: QoS over Internet-based infrastructures. Best effort services, previously and still currently available over the Internet, are unacceptable for all the applications that require a specific level of assurance from the network such as safe database access to retrieve information, tele-medicine (transmission of clinical tests, x-rays, electrocardiograms, magnetic resonance), tele-control (remote control of robots in hazardous environments, remote sensors, systems for tele-manipulation), bank and financial operations, purchase and delivery, tele-learning, telephony, videoconferences, applications for emergencies and security.

In synthesis, the next-generation Internet infrastructure has two specific macroscopic requirements: Ubiquity and Quality of Service assurance.

Satellite links are not only a component of modern Internet but often represent the only remote access solution for areas where no cable and wireless connection is available. Using satellite communication systems simplifies the first requirement being satellites a broadcast technology. Nevertheless, a satellite based Internet access may fail matching the QoS requirement because satellite transmissions are often corrupted by noise and fading. Dynamic bandwidth allocation in satellite communication is not only a way to improve channel utilization but it is traditionally seen also as a noise and fading countermeasure giving more bandwidth to faded stations trying to compensate the penalization introduced by fading but, in the same time, taking bandwidth from the other stations. This concept is particularly applicable to satellite communications but it has also a broader focus.

All bandwidth allocation solutions in the literature tackle the problems of fairness and efficiency, generically intended as good channel utilization and not excessive unbalance either between the allocated bandwidth among different entities (e.g. satellite and wireless stations, routers,…) or, often, between the performance offered by the different entities. On the other hand fairness and efficiency are seldom formally defined. Many scientific articles claim their proposal is fair and efficient even if it is in strict contrast with other articles claiming exactly the same. Probably nobody lies and nobody is wrong. They likely use different definitions of fairness and efficiency.

This article examines some definitions of fairness, discusses the concept of bandwidth utilization, and suggests a definition of efficiency, with the aim of introducing guidelines for the design and performance evaluation of bandwidth allocation algorithms for satellite communication. The introduced concepts, even if focused on satellites in this article, may be applied also to other communication environments such as the wireless one.

The next Section introduces the generic concept of bandwidth allocation, tunes it to satellite communication, also reporting a simple model for satellite channels. Then the article revises possible definitions of fairness and introduces the related indexes, introduces the performance efficiency index, and summarizes the concept of bandwidth utilization. Successively the article reports some bandwidth allocation mechanisms which are compared in the performance evaluation Section by using fairness, bandwidth utilization and performance efficiency indexes introduced in this article.

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II. GENERALITIES OF BANDWIDTH ALLOCATIONS AND APPLICATIONS TO SATELLITE NETWORKS

A. *Bandwidth Allocation*

The basic concept of Bandwidth Allocation is very simple, independently of the target of the allocation. An overall amount of bandwidth must be shared among different Z entities. A control mechanism is devoted to this action. The overall bandwidth is C_{tot}. Each entity $z \in [0, Z-1]$ receives a portion C_z of C_{tot}. It is typically recommendable that $\sum_{z=1}^{Z-1} C_z = C_{tot}$. The allocation vector is defined as $\mathbf{C} = (C_0, ..., C_z, ..., C_{Z-1})$. The control architecture may be supposed either centralized, when one entity manages the resources and provides the other entities with a portion of the overall bandwidth or distributed, when each single entity decides its amount of bandwidth on the basis of remote information.

If this generic concept is applied to satellite (and wireless) communications, it takes a special interest because the bandwidth C_z given to entity z is not necessarily entirely used to send information, as should be clear in the following. As a consequence, the net bandwidth for information data is not C_z but less.

B. *Satellite Network Topology*

In detail, a generic satellite network is composed of a number (e.g. Z) of earth stations. They are connected through a satellite channel (Fig. 1). Each user may request service (e.g., Web page, data transfer, phone call, audio and video conferencing …) by using the satellite channel. To carry out the process, each earth station conveys traffic from the directly connected sources and accesses the channel in competition with the other earth stations. Channel bandwidth is shared and allocated among the earth stations. In this direction the earth stations are the entities indicated in the previous Section. Being the article focused on satellite networks, the two terms will be used equivalently, with the preference of "entity" when its use goes beyond the satellite framework and has a wider application.

Satellite links may be affected by fading and/or noise as shown for station $Z-1$ in Fig. 1. Earth stations are modelled as nodes gathering TCP/IP traffic from the sources in this article but, even if this has a great impact on the shown results, it may be considered an example and it does not affect the generality of the introduced concepts.

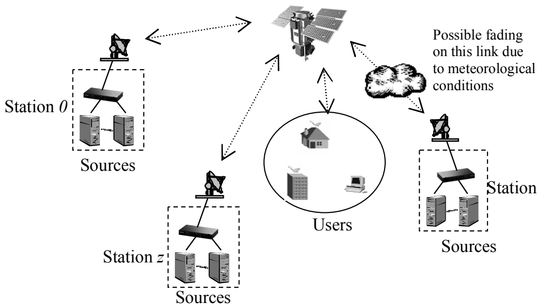

Fig. 1. The satellite network topology

C. *Simple Channel Model*

Mentioned noise and fading corruption typically due to rain is predominant at high frequencies especially above 10 GHz and must be compensated to assure efficient services. A widespread compensation solution applied at physical layer is the employment of Forward Error Correction (FEC) coding schemes, aimed at protecting the integrity of information under different noise and fading conditions by dedicating part of the bits to this aim. Enlarging the number of protection bits means extending the FEC code correction power but also reducing the information bit rate. Depending on the channel conditions, earth stations may provide either higher-rate services, when channel conditions are good, or lower-rate ones involving powerful FEC coding schemes, when noise and/or fading is severe. The consequence of the use of powerful coding scheme is bandwidth reduction, which may be applied, as in [1], through a proper factor. Numerically, it means that the real bandwidth C_z^{real} available for the z-th station is its nominal bandwidth C_z reduced of a factor β_z, which is, in general, a variable parameter contained in the real numbers interval [0,1]: $C_z^{real} = \beta_z \cdot C_z$. The corresponding vector that contains the bandwidth really used for data transmission is $\mathbf{C}^{real} = \left(C_0^{real}, ..., C_z^{real}, ..., C_{Z-1}^{real}\right)$.

III. DESIGN AND EVALUATION GUIDELINES FOR SATELLITE BANDWIDTH ALLOCATION ALGORITHMS

As said in the introduction, a bandwidth allocation algorithm should be both fair for the entities receiving bandwidth and efficient. Efficiency has two meanings: 1) The overall bandwidth must be completely used. This is the concept of Bandwidth Utilization. 2) Bandwidth use must be satisfactory from the user quality of service point of view. This is the Performance Efficiency. Fairness, Bandwidth Utilization and Performance Efficiency are discussed in the following.

A. *Fairness*

The concept of fairness is used in various frameworks such as economy, operating systems and telecommunication networks, when a limited amount of resources must be simultaneously allocated to different entities.

As said in [2], finding a common definition and a specific index to quantify and compare the degree of fairness of different resource allocation policies so to avoid ambiguous interpretations is highly desirable. That is particularly important in case of bandwidth allocation in satellite environments for the possible reduction of the assigned bandwidth due to fading.

Fairness might be considered the same as equality but this is not correct. Allocating the same amount of bandwidth to each entity may imply a strong performance unbalance among entities. An example concerning satellite networks may help understand: there are two earth stations and bandwidth is equally shared between them even if one of them is heavily affected by fading and uses a very small amount of bandwidth for information transport. Bandwidth distribution seems apparently fair but leads to a strong performance unbalance because the bandwidth actually used by the faded station to transmit information is only a portion of the allocated bandwidth. Is it really fair?

Fairness cannot be simply considered as equal resource distribution without taking into account system configuration and users' expectations (see [3] for example).

Avoiding these ambiguities imply a careful definition of fairness also considering that common notions taken from other application areas could be not enough accurate and not properly fit in the satellite networks field. Nevertheless, references [2] [4], and [5] even if apply the concept of fairness in traditional wired networks, introduce two interesting general purpose fairness indexes and one fairness concept: the Max-Min index [4], the Jain's index [2], and the Proportional Fairness concept [5]. They are summarized in the following. In all cases the real bandwidth ($\beta_z \cdot C_z$) used by a station z is applied to evaluate fairness so to consider the impact of satellite environment explicitly.

A1) Max-Min Fairness (MMF)

The concept of Max-Min Fairness was adopted by the ATM forum to specify fairness in wired data networks. The concept was proposed and formally defined in [4]. Max-Min Fairness (MMF) index I_{MMF}, adapted to the satellite environment discussed in Section II, is defined as:

$$I_{MMF} = \frac{\min\{\beta_0 \cdot C_0, ..., \beta_z \cdot C_z, ..., \beta_{Z-1} \cdot C_{Z-1}\}}{\max\{\beta_0 \cdot C_0, ..., \beta_z \cdot C_z, ..., \beta_{Z-1} \cdot C_{Z-1}\}} \qquad (1)$$

The denominator and nominator of equation (1) represent the maximum and minimum bandwidth provided to the earth stations composing the network, respectively. I_{MMF} ranges between 0 and 1. The latter is the ideal value because implies that all entities receive the same amount of bandwidth (the same $\beta_z \cdot C_z$, $\forall i \in [0, Z-1]$, in this article) and this is the real aim of Max-Min-based allocations. Actually Max-Min-based allocations look for the allocation that approaches to 1 the Max-Min Fairness index, so making close minimum and maximum allocations. Max-Min-based resource allocation in a network, due to the network constraints (the total amount of channel capacity), assigns the bandwidth so that each single allocation to an entity cannot be increased without decreasing at least one already smaller allocation. In other words, once Max-min assignation is completed, the allocation of more capacity to an earth station would imply the penalization of a station with lower capacity availability.

Intuitively any change of bandwidth allocation should imply a variation of the fairness index. This is a limitation of MMF index. Bandwidth changes not necessarily imply a variation of the MMF index. For example, if two totally different bandwidth allocations provide the same minimum and maximum capacity assignations the index is the same. In short, the variation of the I_{MMF} index is governed only by the ratio between minimum and maximum bandwidth allocations.

Even if Max-Min Fairness is a widely adopted fairness index in the analysis of wired network, as described in [3], it has clear drawbacks if applied in wireless and satellite networks. More specifically, the main point is that it neglects the distribution of the bandwidth among the stations and the use of this bandwidth. It does not consider any revenue of network operators, any channel status (except for the implicit effect of weight β_z), and any quality of service aspect.

A2) Jain Index

An alternative fairness definition comes from the Jain Fairness index [2] I_{JF}. Considering the bandwidth assigned to the entities the Jain index is defined as in (2).

$$I_{JF} = \left| \sum_{z=0}^{Z-1} \beta_z \cdot C_z \right|^2 \Big/ Z \cdot \sum_{z=0}^{Z-1} \left(\beta_z \cdot C_z\right)^2 \qquad (2)$$

where Z is the overall number of entities. It has the following properties [2]:

- *Population Size independence,* the index is applicable to any number of entities in the system, finite or infinite.
- *Scale and Metric independence*, it is independent of the scale and of the unit of measurement.
- *Boundedness*, the index is bounded between 0.5 and 1: in a completely fair system the fairness index is equal to 1, it is equal to 0.5 if the system is completely unfair.
- *Continuity*, when an allocation is changed also slightly the Jain fairness index varies.

Jain index measures the degree of distribution of the overall real bandwidth $\sum_{z=0}^{Z-1} \beta_z \cdot C_z$ among the different Z entities.

A3) Utility Based Fairness

A particular bandwidth allocation may be considered fair or unfair also dependently on the use of the bandwidth and of the possible user/network revenue. A proper index in this case is associated with the notion of Utility Based Fairness (UBF), which has been introduced in [5] and has its main strength in the flexibility of the concept that can be customized for a variety of different applications [5]. UBF can be defined by introducing a utility value for each considered entity as a function of the allocated bandwidth and of other parameters, and aimed at measuring the expectations of each entity in terms of revenue, quality and prize. Utility functions are supposed to be concave and typically denoted as $U_z(C_z, \beta_z, \cdot)$. Being Z the number of entities, a utility based fair allocation $\mathbf{C}^* = \left(C_0^*, ..., C_z^*, ..., C_{Z-1}^*\right)$ maximizes the sum of the utility functions over the overall number of entities $H(\mathbf{C}) = \sum_{z=0}^{Z-1} U_z(C_z, \beta_z, \cdot)$. Having an index that quantifies the "distance" of a given allocation with the utility based fair allocation may be useful. The aim is to measure how much the utility of the overall system is close to its maximum. Fixed $U_z(\cdot), \forall z$, the Utility Based Fairness (UBF) index I_{UBF}, originally introduced in this article, is defined as in (3). It may assume values in the interval $[0,1]$, where 1 corresponds to utility based fairness.

$$I_{UBF} = \frac{H(\mathbf{C})}{H(\mathbf{C}^{*})} = \frac{\sum_{z=0}^{Z-1} U_z(C_z,\beta_z,\cdot)}{\sum_{z=0}^{Z-1} U_z(C_z^{*},\beta_z,\cdot)} \qquad (3)$$

I_{UBF} represents a family of fairness indexes each of them defined by one specific utility function $U_z(\cdot)$.

A3.1) Proportional Fairness

An operative example of utility based fairness is the Proportional Fairness (PF), proposed also in [5], where the utility function is the logarithm of another function: $U_z(C_z,\beta_z,\cdot) = \ln(f_z(C_z,\beta_z,\cdot)), f_z(C_z,\beta_z,\cdot) > 0$. In this case the quantity to maximize to get a proportional fair allocation is the product $\prod_{z=0}^{Z-1} f_z(C_z,\beta_z,\cdot)$. The Proportional Fairness (PF) index I_{PF} may be defined as in (4), directly from I_{UBF}.

$$I_{PF} = \frac{H(\mathbf{C})}{H(\mathbf{C}^{*})} = \frac{\sum_{z=0}^{Z-1} \ln(f_z(C_z,\beta_z,\cdot))}{\sum_{z=0}^{Z-1} \ln(f_z(C_z^{*},\beta_z,\cdot))} = \frac{\prod_{z=0}^{Z-1} f_z(C_z,\beta_z,\cdot)}{\prod_{z=0}^{Z-1} f_z(C_z^{*},\beta_z,\cdot)} \qquad (4)$$

B. Performance Efficiency

Fairness does not consider the effective quality of service of connected users, even if the utility based fairness may be considered a first step in this direction. It is important to develop an efficiency index related to performance parameters such as throughput, delay, loss, and jitter. Quantity $Y_z(C_z,\beta_z,\cdot)$ is defined as the generic measured performance metric at entity z, $Y_z(C_z,\beta_z,\cdot)$ is assumed to be maximized.

For example, if the QoS metric is the packet loss probability $P_z^{loss}(C_z,\beta_z,\cdot)$ measured at station z, then $Y_z(C_z,\beta_z,\cdot) = 1 - P_z^{loss}(C_z,\beta_z,\cdot)$. The index introduced in this article to measure the Performance Efficiency is called η_{PEff} and is defined in (5). Index η_{PEff} ranges between the ideal value 0 and the value 1.

$$\eta_{PEff} = \frac{1}{Z} \cdot \sum_{z=0}^{Z-1} \frac{Y_z(C_z,\beta_z,\cdot)}{Y_z(C_{tot},\beta_z,\cdot)} \qquad (5)$$

C. Bandwidth Utilization

All described indexes do not give information about the full use of available bandwidth but, from the point of view of the allocation criterion design, this aspect seems important. It is referred as Bandwidth Utilization. Mathematically, referring to Section II.A, if the overall available bandwidth is C_{tot} and each entity-station $z \in [0, Z-1]$ receives a portion C_z of C_{tot}, full Bandwidth Utilization is represented by the constraint $\sum_{z=1}^{Z-1} C_z = C_{tot}$. A possible index μ_{PE}, introduced in this article, of the level of Bandwidth Utilization is in (6). It ranges between 0, which is the value that matches full bandwidth utilization, and 1, which indicates the maximum bandwidth waste.

$$\mu_{PE} = C_{tot} - \sum_{z=1}^{Z-1} C_z \Big/ C_{tot} \qquad (6)$$

It is important to remark that Bandwidth Utilization has nothing to do both with fairness, because a distribution that fully utilizes bandwidth may be highly unfair, and with performance efficiency, because being on the bandwidth constraint does not imply to have, for example, low loss and delay. An example in the considered satellite framework: overall bandwidth is divided into three equal portions and distributed to three uncorrupted earth stations. Jain index reaches his maximum when each earth station gets one-third of the total amount of bandwidth. It is also a solution that utilizes the overall bandwidth. An alternative option where two out of the three stations share the bandwidth and one gets no bandwidth at all is also utilizing all the bandwidth even if it is not fair by using Jain index. In both cases, nothing can be said about performance because no information is given on the number of traffic flows in each station and on performance parameters. For example, the case when one station does not receive any bandwidth, apparently so unfair, may be reasonable if no traffic is conveyed through that station.

On the other hand, a bandwidth distribution where each of the three stations gets only one-quarter of the overall capacity and the rest of the bandwidth is discarded is fair concerning Jain index but bandwidth is not fully utilized ($\mu_{PE} = 0.75$). This allocation probably leads to worst performance than a $\mu_{PE} = 1$ solution that includes it, as happens by giving one-third of the overall bandwidth to each station instead of one-fourth.

Full Bandwidth Utilization is a good starting point but, in general, it is recommendable to find, among the set points where $\mu_{PE} = 1$, the best points both concerning fairness and performance efficiency.

IV. BANDWIDTH ALLOCATION SOLUTION

A. Physical Constraint

The aim is to briefly summarize some bandwidth allocation solutions appearing in the literature so to allow a comparison among them by using the indexes defined above. The constraint $\sum_{z=0}^{Z-1} C_z = C_{tot}$ is imposed for all the methods so that full Bandwidth Utilization is matched. The quantity $Y_z(C_z,\beta_z,\cdot) = 1 - P_z^{TCP-loss}(C_z,\beta_z,\cdot)$ has been chosen for all cases as reference performance metric for station z. $P_z^{TCP-loss}(C_z,\beta_z,\cdot)$ is the loss probability of the TCP packets and its analytical expression is defined in [10]. Utility function $U_z(C_z,\beta_z,\cdot)$ in (3) is set to $\ln\left(\frac{1}{P_z^{TCP-loss}(C_z,\beta_z,\cdot)}\right)$, again for all the methods.

B. Fixed Allocation (FIX)

The bandwidth allocator assigns the same capacity to each station independently of noise, fading and traffic conditions: $C_z = \frac{C_{tot}}{Z}$.

C. Heuristic Allocation (HEU)

Assuming known the fading condition β_z and the traffic load expressed as number of active connections N_z offered at each earth station, the bandwidth provided to the z-th station is computed as a weighted portion of the overall available bandwidth $C_z = k_z \cdot C_{tot}$. The weight k_z is set to $N_z/\beta_z\left(\sum_{j=0}^{Z-1} N_j/\beta_j\right)^{-1}$. The bandwidth assigned to a station increases with the traffic offered to the station and decreases with the bandwidth reduction.

D. Value Function (VALUE)

The VALUE bandwidth allocation strategy [8] distributes the bandwidth by minimizing the sum of single functions $P_z^{TCP-loss}(C_z,\beta_z,\cdot)$. In short, the bandwidth is allocated by maximizing the function $\sum_{z=0}^{Z-1} Y_z(C_z,\beta_z,\cdot)$ where $Y_z(C_z,\beta_z,\cdot) = 1 - P_z^{TCP-loss}(C_z,\beta_z,\cdot)$.

E. Nash Bargain Solution (NBS)

The NBS approach, deeply investigated in [5], is based on the Nash bargaining problem, which originated from cooperative game theory [9]. It maximizes the "social benefit", which is the product of the utility functions. In short, the bandwidth is allocated by maximizing the function $\prod_{z=0}^{Z-1} \frac{1}{P_z^{TCP-loss}(C_z,\beta_z,\cdot)}$.

F. Utopia Minimum Distance Method (UMD) Algorithm

UMD has been though for a fully competitive environment and it is aimed at approaching the ideal performance, which theoretically happens when each single station has the full availability of all the channel bandwidth. UMD minimizes the square of the Euclidean distance between the performance vector $\left\{Y_0(C_0,\beta_0,\cdot),\ldots,Y_z(C_z,\beta_z,\cdot),\ldots,Y_{Z-1}(C_{Z-1},\beta_{Z-1},\cdot)\right\}$ and the ideal, not feasible, performance vector obtained by setting $C_z = C_{tot}$, $\forall z \in [0, Z-1]$. In short, the bandwidth is allocated by minimizing the function $\sum_{z=0}^{Z-1}\left(Y_z(C_z,\beta_z,\cdot) - Y_z(C_{tot},\beta_z,\cdot)\right)^2$, where, again, $Y_z(C_z,\beta_z,\cdot) = 1 - P_z^{TCP-loss}(C_z,\beta_z,\cdot)$.

V. COMPARISON AMONG THE ALLOCATION METHOD

A. Numerical Comparison

In this subsection, the bandwidth allocation methods previously described (FIX, HEU, VALUE, NBS and UMD) are compared in terms of fairness indexes and performance efficiency. The comparison is performed ex-post, i.e. fairness and performance evaluation indexes have not been used during the design of the methods and of the related cost functions, except for the case of NBS concerning proportional fairness, as evidenced in the comments of the results. The comparison allows both to check the effect of specific resource allocation criteria on fairness and performance and to better understand the meaning of the different indexes. Only TCP traffic is considered: assumptions reported in 4.1 are still true. The bandwidth reduction levels reported in [1] are used: $\beta \in \{0.15625,\ 0.3125,\ 0.625,\ 0.8333,\ 1\}$. The overall bandwidth available C_{tot} is set to 4 [Mbps] and the TCP buffer size to 10 packets of 1500 bytes for each earth station. TCP round trip time (RTT) is considered fixed and equal to 100 [ms] for all the stations. It can represent a MEO satellite but it is just an example: RTT numerical values have no impact on indexes behavioral trends. Two earth stations ($Z = 2$) have been taken into account (Station "0" and Station "1") and the number of active TCP sources is set to $N_z = 10$, $z = \{0,1\}$. Station 0 is supposed always in clear sky ($\beta_0 = 1$) while Station 1 varies its condition in the tests ($0 \le \beta_1 \le 1$).

B. Fairness

Figure 2 shows the values of Jain index over the fading level of station 1. Heuristic allocation method is the fairest. Its Jain index is almost constant independently of the bandwidth reduction level. All the other methods have an increasing behaviour with β_1. The UMD scheme results fairer than the others. NBS is less fair from Jain index viewpoint. Actually, even if neither VALUE nor UMD uses Jain index as guideline for the design, their cost functions automatically reach a sort of fading-level-weighted bandwidth distribution which increases Jain index. On the other hand NBS cost function has a totally different structure that, due to the utility function choice performed in this article, operatively is the same than maximizing the Proportional Fairness index. This is very clear in Fig. 3 where the Proportional Fairness index is shown versus the fading level of station 1. Max-min Fairness index is shown in Fig. 4. The same general comments reported for Fig. 2 are still valid.

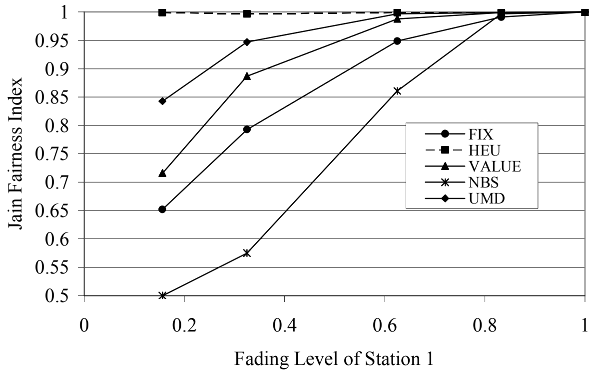

Fig. 2. Jain Fairness Index

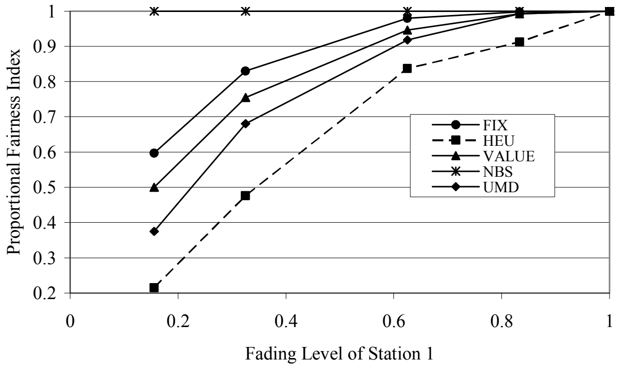

Fig. 3. Proportional Fairness Index

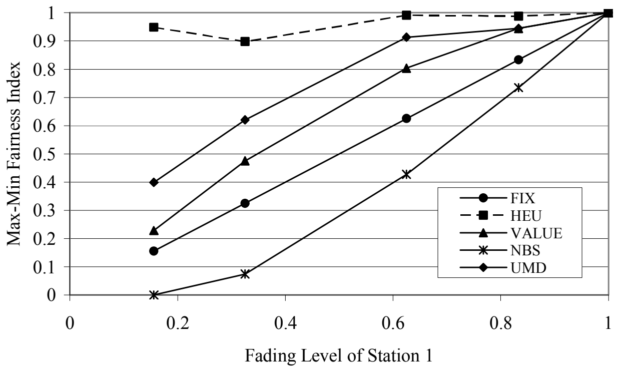

Fig. 4. Max-Min Fairness Index

C. *Performance Efficiency*

Performance Efficiency index μ_{PEff} is shown in Fig. 5. Also for this index no used cost function has been designed having μ_{PEff} in mind but it is true that VALUE and UMD functions are much more "similar" to the form of μ_{PEff} with respect to NBS cost function. That's the motivation of the behaviour in Fig. 5 for low fading level values. Approaching the clear sky condition, efficiency is comparable for all methods. It is worth saying that the high values of Jain and Max-min indexes for the heuristic method is paid in terms of efficiency. Actually it is true that the heuristic method has the only aim of getting β-weighted bandwidth distribution and ignores any performance aspect.

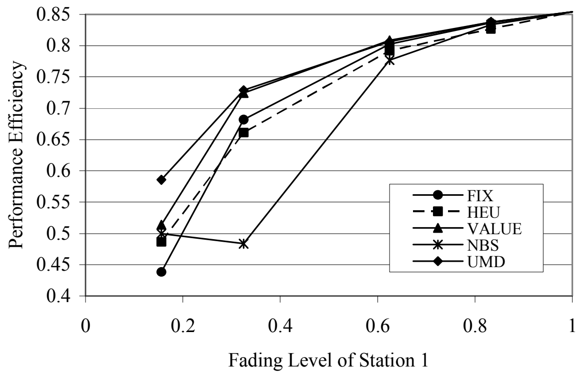

Fig. 5. Performance Efficiency

VI. CONCLUSIONS

Starting from the literature in the field, the article has discussed and formalized the concepts of Fairness, Performance Efficiency, and Bandwidth Utilization, and has introduced specific evaluation indexes. Fairness and performance efficiency indexes have been applied to several resource allocation methods for satellite communication taken in the literature. The evaluation has been performed ex-post with the aim of evaluating the level of fairness and efficiency of the chosen allocation methods, concerning the used indexes. Nevertheless, the basic idea of this article is that the mentioned concepts of fairness, efficiency, and bandwidth utilization may be used as guidelines for the design of bandwidth allocation strategies. In this direction the introduced indexes may be a valid operative help.

Finally yet importantly, this article has shown that the fairness concept has different meanings and that, consequently, may be measured through different indexes. Allocation algorithm may be fair concerning one index and unfair concerning another one (the case of NBS is evident from this viewpoint). This underlines the importance to have a precise definition of fairness (and efficiency) within a scientific work so to avoid ambiguities.

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