# Dynamic Bandwidth Allocation Criteria over Satellite Networks

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***Abstract*—The paper studies the performance of possible bandwidth allocation criteria over satellite network. The methods practically implemented in a simulation framework and evaluated are the "Value Function" (VALUE), the "Nash Bargaining Solution" (shortly NBS) and the "Utopia Minimum Distance" (UMD). All the methods, together with two simple approaches introduced for comparison (Fixed allocation (FIX) and a Heuristic method (HEU)), have been tested using TCP/IP traffic and the performance evaluation is carried out by varying the degradation level of the satellite channel in different satellite network conditions.**

***Keywords-Satellite Systems, Bandwidth Allocation, Performance Evaluation, Multi-Attribute Programming.***

## I. INTRODUCTION

In satellite environments one of the main cause of degradation is rain attenuation, which generates significant communication detriment, information loss and, consequently, QoS degradation. Allocating the bandwidth properly among the earth stations (which can be affected by different fading level) is topical to mitigate the problem and to increase the provided QoS. In this paper different allocation approaches, found in the literature, have been taken into account and implemented within a simulative framework based on the *ns2* simulator. In more detail, starting from the allocation criteria definitions, the contribution of the work concerns the practical implementation of them and the related comparison. As it will be clear in the following, the proposal presented is an introductive implementation approach useful to compare the considered allocation methods and, in particular, to open the door to the real employment of dynamic bandwidth allocation techniques in satellite systems.

The paper is structured as follows: Section II introduces the system scenario. The formalization of the bandwidth allocation methods are presented in Section III. The implementation of the allocation techniques and their performance evaluation have been introduced in Section IV. Section V lists the conclusions.

## II. SYSTEM SCENARIO

The network considered is composed of $Z$ earth stations connected through a Geostationary Satellite link. The control architecture is based on the presence of decision entities, also called Decision Makers (DMs), which may work in a centralized way, where an earth station (or the satellite itself, if switching on board is allowed) represents the master station that manages and provides the other stations with a portion of the overall bandwidth (e.g., TDMA slots) or in a distributed way, where each station can manage the bandwidth distribution independently of each others.

In the satellite network each user requests a TCP/IP service (e.g., Web page or a File transfer) by using the space channel itself (or also by other communication media). After receiving the request, ISPs send traffic through the earth stations and the satellite link. To carry out the process, each earth station conveys traffic from the directly connected ISPs and accesses the satellite channel in competition with the other earth stations. In this environment, one of the main causes of communications detriment is the fading. It may be modelled as bandwidth reduction. It means using a FEC code: each earth station may adaptively change it by applying a different amount of redundancy bits (e.g. the correction power of the code). The FEC applied depends on fading and it reduces the real bandwidth available for data.

## III. BANDWIDTH ALLOCATION CRITERIA

### A. General Problem Definition

Considering the above described satellite channel model from the mathematical viewpoint, it means that the bandwidth $C_z^{real}(t) \in \mathbb{R}$ available at time $t$ for the $z$-th station is composed of the nominal bandwidth $C_z(t) \in \mathbb{R}$ and of the factor $\beta_z(t) \in \mathbb{R}$, which is, in this paper, a variable parameter contained in the interval [0, 1].

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

A specific value $\beta_z(t)$, dependent on the FEC used, corresponds to a fixed attenuation level "seen" by the $z$-th station at time.

Each earth station has a single buffer gathering 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. It is worth noting that the channel state is variable over time and, as a consequence, the general bandwidth allocation problem, based on the MOP vector optimization formulated in the following, is valid from a fixed time instant to, theoretically, infinite (infinite-horizon optimization). Actually the bandwidth allocation will be provided periodically. In this way, the methodologies proposed can "follow" the channel state variability and allow providing satisfactory performance of the overall satellite network for each possible $\beta_z(t)$ value. In the following, for the sake of simplicity, the time variable $t$ will be omitted in the formulations proposed. Nevertheless, it should be clear that the bandwidth allocation problem and its possible resolution methods are valid in a fixed period where the $\beta_z(t)$ value is supposed to be constant.

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

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

where: $\mathbf{C}\in\mathbf{D}$, $\mathbf{C}=\left\{C_0,\dots,C_z,\dots,C_{Z-1}\right\}$ 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; $\mathbf{D}$ represents the domain of the vector of functions. The solution has to respect the constraint:

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

where $C_{tot}$ is the overall capacity, in [b/s], of the satellite channel. $\mathbf{F}(\mathbf{C})$, dependent on the vector $\mathbf{C}$, is the performance vector

$$\mathbf{F}(\mathbf{C})=\left\{f_0(C_0),\dots,f_z(C_z),\dots,f_{Z-1}(C_{Z-1})\right\};\tag{4}$$

The single $z$-th performance function $f_z(C_z)$ (or objective) is a component of the vector and is defined, in this work, as the TCP Packet Loss Probability (shortly PLP) $P_{loss}^z(\cdot)$ modelled as reported in [1]. It is supposed to be a decreasing function of the bandwidth ($C_z$). It is dependent on the number of active sources ($N_z$) and on the fading level $\beta_z$:

$$f_z(C_z)=P_{loss}^z(C_z,N_z,\beta_z)=P_{loss}^z\left(C_z^{real},N_z\right)\tag{5}$$

Each "performance function" $f_z(C_z)$ represents a single cost competing with the others to get bandwidth.

### B. *Allocation Criteria*

In this subsection possible solutions of the problem stated in (2) have been provided. In the following each criterion is synthetically described and the solution provided is formally reported.

The Utopia Minimum Distance (UMD) [2] – provides an allocation that approaches the ideal performance, which theoretically happens when each single station has the availability of all the channel bandwidth $C_{tot}$, by minimizing the Euclidean distance between the performance vector and the ideal solution of the problem. In practice, it can be solved by the following allocation under the constraint (3):

$$\mathbf{C}_{UMD}^{opt}=\arg\min_{\mathbf{C}}\left(\left\|\mathbf{F}(\mathbf{C})-\mathbf{F}^{id}\left(\mathbf{C}^{id}\right)\right\|_2\right)^2\tag{6}$$

where $\mathbf{C}^{id}=\left\{C_{tot},C_{tot},\dots,C_{tot}\right\}$ and $\|\cdot\|_2$ is the Euclidean norm.

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,

$$C_z=\frac{C_{tot}}{Z};\quad\forall z\in[0,Z-1],\quad Z\in\mathbb{N}\tag{7}$$

The constraint reported in equation (3) is obviously respected.

Heuristic Allocation (HEU) – being the traffic load offered to an earth station (expressed, in this paper, 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:

$$C_z=k_z\cdot C_{tot};\ \forall z\in[0,Z-1];\ k_z\in[0,1],\ k_z\in\mathbb{R}\tag{8}$$

where

$$k_z=\frac{N_z}{\beta_z}\cdot\left(\sum_{j=0}^{Z-1}\frac{N_j}{\beta_j}\right)^{-1}\ \text{with}\ \sum_{z=0}^{Z-1}k_z=1\tag{9}$$

Each HEU allocation can be obtained by a one-shot decision: it is sufficient to compute $k_z$.

The Value Function (VALUE) – it distributes the bandwidth by minimizing the sum of the single performance functions under the constraint (4):

$$\mathbf{C}_{VALUE}^{opt}=\arg\min_{\mathbf{C}}\sum_{z=0}^{Z-1}P_{loss}^z(C_z,N_z,\beta_z);\ \forall z\in[0,Z-1]\tag{10}$$

Nash Bargain Solution (NBS) – taking the problem definition directly from [3], it is necessary to define the utility functions: one for each earth station. In this paper the reciprocal value of the PLPs averaged over the fading levels (the performance functions) has been chosen and it can be easily shown that the allocation can be provided by:

$$\mathbf{C}_{NBS}^{opt}=\arg\min_{\mathbf{C}}\sum_{z=0}^{Z-1}\ln\left[P_{loss}^z(C_z,N_z,\beta_z)\right];\ \forall z\in[0,Z-1]\tag{11}$$

In practice, the NBS strategy distributes the bandwidth by minimizing the sum of the logarithms (base $e$) of each single performance function.


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## IV. Implementation Issues and Performance Study

The aim of the performance evaluation is to compare the different techniques proposed in terms of PLP. The action is fulfilled by using the *ns2* simulator, where the optimization procedures have been implemented. In the following tests, the comparison has got by varying the fading conditions. In practice, a given behaviour of the $\beta_z(t)$ parameter has been used in the simulations for each earth station considered.

### *A. Implementation of the Allocation Techniques*

In the simulated network considered, each station transmitting to the satellite receives a portion of the overall bandwidth $C_{tot}$ by implementing the allocation methodologies above introduced. The decision about the bandwidth distribution among stations is made by one decision maker for each earth station. It allocates the channel capacity by solving the problem defined in equation (2) with one of the possible approaches previously described.

The decision is based on an Information Vector $\mathbf{I}(t)$ representative of the "knowledge" about the Satellite channel state and the (TCP) traffic characteristics "seen" by each station in a specific time instant $t$. This "knowledge" is then employed, by using the traffic model applied, to compose the cost function of the optimization framework. From the mathematical viewpoint:

$$\mathbf{I}(t) = \left[\mathbf{I}_0(t) \,|\, ... \,|\, \mathbf{I}_z(t) \,|\, ... \,|\, \mathbf{I}_{Z-1}(t)\right] = \left[\boldsymbol{\beta}, \mathbf{N}, ...\right] \quad (12)$$

where each sub-vector $\mathbf{I}_z(t)$ is the Information Vector of the $z$-th earth station composed by the parameters used to define its PLP function such as $\beta_z$, $N_z$ ($\mathbf{I}_z(t) = (\beta_z, N_z, ...)$) and other necessary variables in dependence on the specific model used. Together, the sub-vectors compose the general Information Vector $\mathbf{I}(t)$, which is, as a consequence, defined by all the parameters needed to defined the overall cost functions such as $\boldsymbol{\beta} = (\beta_0, ..., \beta_z, ..., \beta_{Z-1})$ and $\mathbf{N} = (N_0, ..., N_z, ..., N_{Z-1})$. Actually, in the implementation evaluated in the following, the Information Vector is completed by $\mathbf{RTT} = (RTT_0, ..., RTT_z, ..., RTT_{Z-1})$ and $\mathbf{Q} = (Q_0, ..., Q_z, ..., Q_{Z-1})$, which are specific parameters of the packet loss probability model used as reference metric to be optimized [1].

In more practical words, $\mathbf{I}_z(t)$ is periodically sent, one transmission each allocation time $T_a$ (Fig. 1), from each $z$-th station to the DM over a *no interfering* channel supposed completely error free. As a consequence, all the parameters composing the sub-vector are supposed correctly received by the DM. In this way, a DM, which surely receives each $\mathbf{I}_z(t)$ being broadcast the downstream channel (from the satellite to the earth stations and other user terminals of the network), builds $\mathbf{I}(t)$, the related cost function, in dependence on the allocation criterion employed, and minimizes it. The solution vector $\mathbf{C}^{opt}$ is then assigned, component by component, as service capacity of earth stations. They use, in the specific case of the simulation framework considered, their capacities as separated and *no interfering* channels. At this stage, in practice, no specific implementation related to a real access system (for example based on a TDMA approach) have been taken into account but it is object of ongoing implementation and investigation.

The dynamic behaviour of the allocator system over the time is schematically reported in Fig. 1. Each $T_a$ the vector $\mathbf{I}(t)$ (where $t$ is multiple of $T_a$) is composed by the DM that collects each single $\mathbf{I}_z(t)$ $\forall z \in [0, Z-1]$, defines the cost and solves the problem (2), practically formulated in (13), in a negligible computational time $T_c$ ($T_c << T_a$). In more detail:

$$\begin{gathered}\mathbf{C}^{opt}(iT_a) = \underset{\mathbf{C}}{\arg\min}\left\{\mathbf{F}\left(\mathbf{C}, \mathbf{I}(iT_a)\right)\right\}; \\ \mathbf{F}\left(\mathbf{C}, \mathbf{I}(iT_a)\right) : \mathbf{D} \subset \mathbb{R}^Z \to \mathbb{R}^Z, \mathbf{C} \geq 0, \; i = 0,1,2,...\end{gathered} \quad (13)$$

where the index $i$ allows obtaining the periodic allocations aimed at following the system state (channel condition and offered traffic). The implementation here proposed uses one decision maker (DM) each earth station. The consequence of this approach, which is a distributed way to make the bandwidth allocation, is that each $z$-th earth station knows the global solution vector $\mathbf{C}^{opt}(iT_a)$ and, obviously, its specific component of the solution vector $C_z^{opt}(iT_a)$ representative of the bandwidth allocated to it. This approach avoids further transmissions of information over the satellite network surely necessary if the DM is centralized: in that case its decision, the allocation, must be communicated to the other stations. It is obvious that this approach may be affected by $\mathbf{I}_z(t)$ errors due to possible incorrect transmission, over the typically noisy satellite channel, and by synchronization problems that have been neglected in this work.

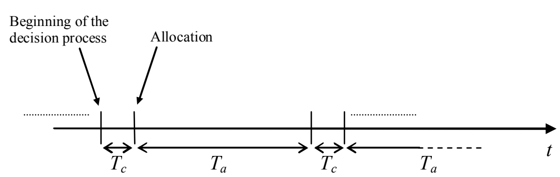


Fig. 1. Temporization of the Allocation Process.

### *B. Simulation Setup*

The network scenario considered is composed of 10 earth stations: Stations from 0 to 8 are always in clear sky condition, and Station 9, which varies its fading level, according to real fading levels taken from [4], over time as made explicit in the specific cases exploited in the following. Each station gathers traffic from TCP sources and transmits it to the terminal users through the Satellite system. The number of active TCP sources is set to $N_z = 10$, $\forall z \in [0, Z-1]$. The overall bandwidth available $C_{tot}$ is set to 10 [Mb/s] and the TCP buffer size is set to 10 packets (of 1500 bytes) for each earth station. The Round Trip Time value employed in the computation of the traffic model is supposed fixed and equal to 512 [ms] for all the stations. The allocation control, implemented by using all the techniques previously proposed, acts each $T_a = 30$ [s] and in all cases the simulated time is always fixed and equal to 3600 [s]. The TCP sources actives a FTP session at the beginning of the simulations. Each FTP transfer has been set as a persistent session for the overall duration of the simulations: in practice, sources have always packets to send. Each station is implemented as a Dumbell topology with a single common receiving node. The topology is composed of 10 source nodes that active 1 TCP connection and send its packets to an earth station by using a not congested and wideband link that does not represent a bottleneck during simulations. The earth station is, in practice, a single buffer where packets sent from TCP source are conveyed and forwarded if no congestion events are experienced. The service capacity, in [b/s], of the buffer representative of an earth station is the bandwidth allocated to it and the effect of the fading is considered by using the model proposed in equation (1): the fading is supposed completely compensated by using FEC schemes (no channel errors are considered in the simulations) and their impact is a mere bandwidth reduction represented by the $\beta_z$ parameter. The $\beta_z$ behaviour over time is established in dependence on the evaluated scenarios proposed in the following. As previously said, each portion of bandwidth allocated is supposed to be a *no interfering* channel with the other stations' communications.

### C. *Numerical Results*

In the first case analysed, only Station 9, out of the 10 earth stations, is supposed faded. In the first part of the simulation time ($0 < t \leq 2600$ [s]) the $\beta_9$ value varies between 1 and 0.8333 each 30 [s], then ($2600 < t \leq 3600$ [s]) between 0.3125 and 0.156. In Fig. 2 and Fig. 3, the measured PLP for a Clear Sky station (Station 0) and for the faded one (Station 9) are reported, respectively. The advantage of the dynamic allocation methodologies is clear: when the fading level significantly increases ($t \geq 2600$ [s]), the allocation strategies allow maintaining satisfactory level of measured PLP defined, in detail, as the ratio between the number of dropped packets and the overall number of sent packet from the TCP sources linked to a specific earth station during a $T_a$. More specifically, HEU, VALUE and UMD conserve constant the PLP for the faded station (Station 9) as reported in Fig. 3 and slightly penalize the clear sky stations when the fading level experienced is severe (it happens when $t \geq 2600$ [s]). This penalization does not imply a significant degradation of the performance and satisfactory levels of PLP are maintained. Among the mentioned techniques the UMD method is more conservative: the PLP behaviour is not particularly variable, it changes when the fading level significantly varies then it maintains constant its values. HEU has similar behaviour for the faded station case but its measured PLP varies when the clear sky stations are considered: it is higher than the other allocation approaches. Also VALUE technique has comparable performance with respect to HEU and UMD for both clear sky and faded cases but it is not conservative as UMD. FIX is not obviously efficient: it is the better technique for the clear sky station because does not penalize them in case of fading variation over other stations. Nevertheless, the PLP experienced by the faded station, if FIX is applied, is higher (around the double) than the clear sky cases, in particular when $\beta_9$ is very low. The NBS technique has a different behaviour: to maximize the overall revenue of the system (defined in [3]), it completely penalizes the faded station by excluding it from the bandwidth distribution (in practice, $C_9 = 0$). It is worth noting that the consequent advantage for the clear sky station is not however significant with respect to the other methods, which guarantee a good PLP performance (below the 10%) also for the faded station. The performance obtained by using the UMD is representative of the best compromise for the stations: it maintains constant the PLP in case of faded station and it does not heavily penalize the clear sky ones. It means that the optimization target represented by the utopia point (6) is the more preferable and fairer criterion among the presented methodologies.

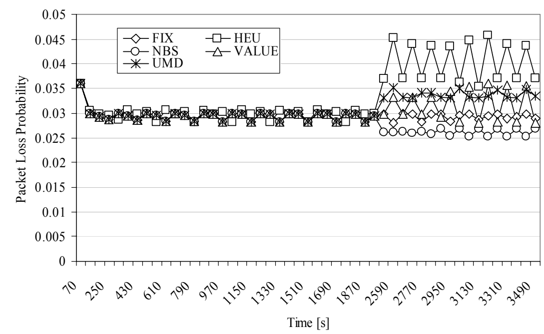


Fig. 2. Packet Loss Probability of a Clear Sky station in presence of variable fading over time.

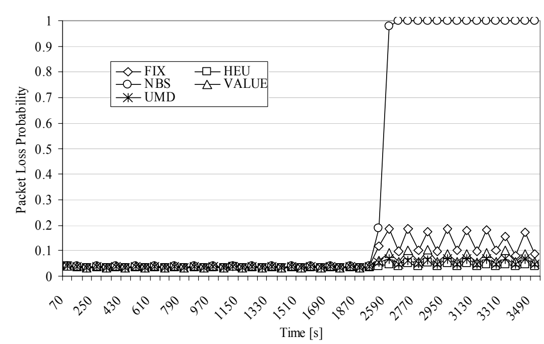


Fig. 3. Packet Loss Probability of the Faded station in presence of variable fading over time.

The second scenario considered concerns the case where the $\beta_9$ value deeply varies in a very fast way for the period $705 < t \leq 2615$ [s]: starting from 1 ($t = 705$ [s]) it becomes 0.156 and vice versa each 5 [s]. $T_a$ is now fixed equal to 5 [s]. Fig. 4 reports the PLP, averaged over the simulated time (3600 [s]) for all the techniques. The values shown concern the Station 9 (faded) and the Station 0 (clear sky). Also in this


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case, the controlled methods, excluded NBS, have better behaviours. In this specific case, UMD and HEU are the preferable ones. The former reaches lower values of averaged PLP in case of clear sky station but it is more penalizing if the Station 9 is considered. The latter maintains fixed the averaged PLP for both Stations 0 and 9 but the PLP for the clear sky station is higher than the PLP performed by the UMD. The performance is equivalent, but UMD suffers the fast variation of the fading. It is due to the necessity, for the UMD, of a minimization procedure, not needed in the HEU case that allocates with a one-shot decision (reported in equations (8) and (9)) when the $\mathbf{I}(t)$ vector is available. In practice, UMD decisions about allocation are provided slowly with respect to the fading variation considered in this scenario. It is worth noting that an investigation of the effect of delayed allocations with respect to fading variations will be proposed in the following. However, the shown problem of the UMD technique is a limitation of the method implementation but fast fading variation, from clear sky to a deep fading condition (only 5 [s]) are representative of a very challenging scenario actually not representative of real environments. Concerning the VALUE approach, similar considerations, with respect to the UMD, may be done. It particularly suffers the fast fading conditions for the same motivations. FIX and NBS do not provide satisfactory performance for the faded earth station. Their performance is comparable with the others for the clear sky ones.

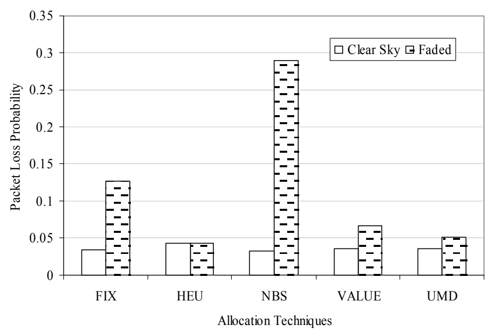


Fig. 4. Average Packet Loss Probability in presence of fast fading.

As previously introduced, the effect of delayed allocation with respect to fading variations has been evaluated. Fig. 5 shows the PLP obtained in presence of delayed decisions. In more detail, the fading, experienced by Station 9, during the simulation time, is equal to 1 for $0 < t \le 1200$ [s], 0.156 if $1200 < t \le 2400$ [s] and it commutes again to 1 if $t > 2400$ [s]. In the case evaluated, the allocation has been provided 1 [ms], 100 [ms] and 10 [s] after the fading variation instants (in this case $t = 1200$ and $t = 2400$). $T_a$ is again 30 [s]. Fig. 5 highlights the behaviour of the UMD method and shows that the allocator performance follows the fading dynamic and, in particular, that the unique case of significant performance detriment happens when the delayed decision is provided after 10 [s]. This result is similar also for the other techniques (not reported in Fig. 5 for the sake of clearness) but UMD has the lower level of PLP, when fading changes, with respect to VALUE and NBS. FIX obviously does not suffer any effect because there is not any decision procedure. HEU has actually a lower PLP peak when fading level commutes ($t = 1200$ [s]): it is due to its one-shot decision procedure, which is computationally lighter than the minimization approach implemented for the UMD. The effect above described (reported in Fig. 5) is also a more precise explanation of the results reported in Fig. 4: in case of very fast fading the decision could be provided in a delayed way with respect to the fading variation instant and, as a consequence, a decision could not be valid, when available, because the fading level is changed again. It is worth noting that the negative effect of the delayed decision impact only when fading change from good state (around the clear sky case) to deep fading situation and not vice versa (in the simulation shown, when $t = 2400$ [s]). Moreover, the problem due to delay decision is present only for very high decision delay value (10 [s]). From this result, it can be concluded that in real application the control methodologies proposed can be considered reliable also in presence of delayed decision because the time needed to compose $\mathbf{I}(t)$, the related cost and its minimization is reasonably lower than 10 [s].

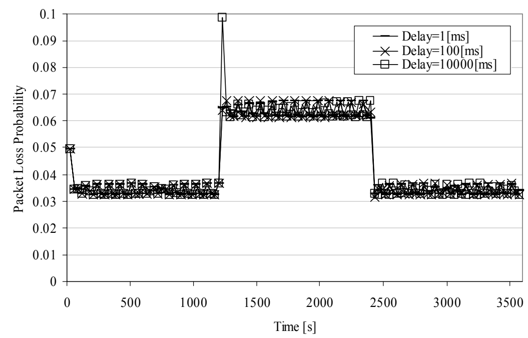


Fig. 5. Effect of the delayed allocation (Faded Station, with UMD method).

## V. CONCLUSIONS

The paper describes some bandwidth allocation schemes for Satellite TCP/IP networks and proposes also an introductive idea to implement them in real environment. The results, obtained by using the *ns2* simulator, have shown the performance of all the techniques in different scenarios of interest. From the results, UMD approach is representative of the better compromise, in terms of Packet Loss Probability performance, for all the stations involved in the satellite network.

## REFERENCES

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

[2] I. Bisio, M. Marchese, “Minimum Distance Bandwidth Allocation over Space Communications,” IEEE Communications Letters, vol. 11, no. 1, pp. 19-21, January 2007.

[3] H. Yaiche, R. Mazumdar, C. Rosenberg, “A Game-Theoretic Framework for Bandwidth Allocation and Pricing in Broadband Networks,” IEEE/ACM Transaction on Networking, vol. 8, no. 5, pp. 667-678, October 2000.

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


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