Transmission Rate Allocation over Satellite Networks with Quality of Experience - Based Performance Metrics

Igor Bisio, Stefano Delucchi, Fabio Lavagetto and Mario Marchese

***Abstract*—Assuring a satisfactory level of Quality of Experience (QoE) to users is nowadays an important challenge for network service providers. At the same time, power consumption minimization is another important issue for network management. Consequently, the ideal goal is to maximize the QoE and, meanwhile, to minimize the power transmitted by network nodes. In telecommunications networks QoE is often linked to the transmission rate assured to a given application. Actually higher guaranteed transmission rate, lower packet loss, delay and jitter, which have a direct impact on QoE. In this view the requirement of maximizing QoE and minimizing power consumption conflict with each other because higher is the transmit rate better the QoE but higher required transmitted power.**

By taking the session time of a web navigation as a reference metric, in this paper, the authors propose a transmission rate allocation algorithm for satellite networks aimed at finding a satisfactory compromise between QoE and Transmitted Power (TP). Earth stations communicate with a satellite by using a common channel with an overall available transmission rate of R_{TOT}. The allocation algorithm is formulated starting from the Multi Objective Programming theory and the L_p-problem and it is called L_p-problem based Rate Allocation (L_pRA). Numerical results show that L_pRA assures satisfying operative compromise between QoE improvement and power saving.

***Index Terms*—Quality of Experience, Power Management, Resource Allocation, MOP theory, Satellite Network**

I. Introduction

Satellite networks provide worldwide communication coverage and can provide network facilities to areas without adequate infrastructures such as islands, rural and mountain zones. Enhancing satellite networks performance, in terms of Quality of Service (QoS) as well as optimizing resource management represent key research issues [1]. Coherently with the state of the art in the field (see [2], [3] and [4] among many others), the network scenario considered in this paper and shown in Figure 1 is composed of Z earth stations that receive different traffic flows and forward them through a common satellite channel.

Nowadays Quality of Experience (QoE) is an hot topic in the definition of new network control algorithms. As a matter of fact the trend is to move from the consolidate network centric approach to a user centric approach, moving from the QoS to the explicit consideration of QoE. The user is the client that decides if he will continue to pay for the service he obtains or not; consequently his judgement is becoming a fundamental issue in network performance evaluations. So classical QoS metrics such as packet loss, packet delay and packet jitter, are being replaced by the direct use of the Mean Opinion Score (MOS), which is a measure of the human perception. MOS is obtained through the judgement of the users that evaluate a service (e.g., web browsing, file download, VoIp and video streaming) and assign a score according to the following values: *i)* 5 - Excellent, *ii)* 4 - Good, *iii)* 3 - Fair, *iv)* 2 - Poor, *v)* 1 - Bad.

Even if objective QoS metrics have a clear impact on user perception, a precise relation can be hardly established. As a matter of fact a meaningful QoS variation may not correspond to a QoE variation of the same significance. This happens because a variation in the QoS may not be perceived by the user. The relationship between QoS and QoE is investigated in [5]. MOS measure requires a large amount of data and the involvement of many users. Consequently several efforts (e.g., [6], [5], [7], [8] and [9] among the others) are done to develop analytical models that, starting from QoS metrics, which are easier to obtain, predict the MOS values for different network services and applications.

The goal of this paper is to present a rate allocation algorithm aimed at maximizing QoE and, at the same time, limiting the transmitted power. We use a MOS model in the literature and a transmitted power model, already proposed by the same authors ([10] and [11]). The adopted mathematical framework is represented by the Multi-Objective Programming (MOP) theory. It defines a family of problems whose goal is to optimize simultaneously the value of two or more objective functions, frequently in contrast each other. The solution of this type of problem is not represented by a unique point but by a set of points called Pareto Optimal Points (POPs) set. To define a single solution within this set (i.e. one transmission rate allocation) we apply the L_p-problem [12], which selects a single point by minimizing the distance with a reference goal point. The algorithm is called L_p-problem based Rate Allocation (L_pRA).

The rest of the paper is organized as follows: Section II presents the proposed allocation algorithm, Section III describes the adopted objective functions and Section IV reports the performance analysis. Conclusions are drawn in Section V.

II. QoE Based Transmission Rate Allocation Algorithm

The rate allocation model proposed in this paper is based on MOP theory. As firstly defined in [13], the reference scenario, shown in (2), is composed as follows:

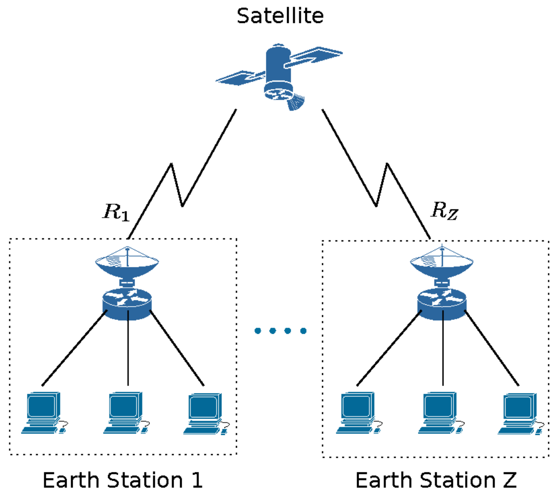

Fig. 1. The Reference Scenario.

- Z physical entities, each of them modelling a earth station.
- Y_z virtual entities for the $z-th$ physical entity, modelling each couple buffer-server inside the earth station identified by $y_z \in [1, Y_z]$.
- M_{y_z} objective functions which represent the performance metric values adopted to evaluate the y_z a couple buffer-server. The index $m \in [1, M_{y_z}]$ identifies each objective function of the considered queue.

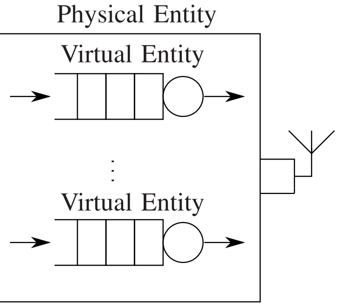

Fig. 2. The Proposed Model for a Physical Entity.

The value assumed by each objective function of each virtual entity is function of the transmission rate allocated to the virtual entity. The transmission rate allocation algorithm developed in this paper is aimed at allocating a portion of the overall available transmission rate, R_{TOT}, to each virtual entity of each physical entity so that the values of each objective function is optimized. Globally, the rate assigned to an earth station is equal to the sum of the rate allocated to each its virtual entity. Practically, the rate allocated to the physical entity z is $R_z = \sum_{y=1}^{Y_z} R_{y_z}$

A. MOP based rate allocation problem

Two vectors are adopted in this work to formulate the rate allocation algorithm: (1) and (2) are, respectively, the vectors containing the rate allocated to each virtual entity and the objective function vector.

$$\mathbf{R} = (R_{1_1}, R_{2_1}, \cdots, R_{Y_1}, \cdots, R_{1_Z}, R_{2_Z}, \cdots, R_{Y_Z}) \quad (1)$$

$$\begin{aligned}\mathbf{F}(\mathbf{R}) = (&F_{1,1_1}(\mathbf{R}), \cdots \\ &F_{M_{1_1},1_1}(\mathbf{R}), \cdots, F_{1,Y_Z}(\mathbf{R}), \cdots, F_{M_{Y_Z},Y_Z}(\mathbf{R}))\end{aligned} \quad (2)$$

where $F_{m,y_z}(\mathbf{R})$ is the $m-th$ objective function of the $y-th$ virtual entity of the $z-th$ physical entity. Formally, MOP transmission rate allocation is defined in (3) and it has to be solved under the constraint (4) that defines the feasibility region.

$$\begin{aligned}\mathbf{R}_{opt} = \Big(&R_{1_1,opt}, R_{2_1,opt}, \cdots, R_{Y_1,opt}, \cdots, \\ &R_{1_Z,opt}, R_{2_Z,opt}, \cdots, R_{Y_Z,opt}\Big) = \arg\min_{\mathbf{R}} \mathbf{F}(\mathbf{R}); \\ &R_{y_z} \geq 0, \forall y_z \in [1, Y_z].\forall z \in [1, Z]\end{aligned} \quad (3)$$

$$\sum_{z=1}^{Z} \sum_{y=1}^{Y_z} R_{y_z} \leq R_{TOT} \quad (4)$$

The problem defined in (3) and (4) determines a solution composed of a set of points called POP set. The structure of the POP set strongly depends on the proprieties of the objective functions: *i)* the POP set is located on the boundary of the feasibility region if all objective functions are strongly decreasing [12], i.e. decreasing for all its variables and strictly decreasing for at least one function and one variable; *ii)* on contrary all the points inside the feasibility region and on its boundary may represent a POP if at least one function is strongly increasing, i.e. increasing for all its variables and strictly increasing for at least one variable. It is worth noticing that the hypothesis of strongly decreasing objective-functions expressed in the first case (i.e considering, for example, Packet Loss Probability, Packet Delay and Packet Jitter which decrease if the allocated rate increases) implies that the overall available rate (R_{TOT}) is shared among all the considered entities. This is not true considering also other metrics such as the transmitted power which increases if the rate increases; in this case the POP solution may correspond to not allocate the overall available rate (R_{TOT}).

B. L_p-problem based Rate Allocation (L_pRA)

Solving an allocation problem corresponds to find out a single solution that identifies the amount of transmission rate that has to be allocated to each entity. Consequently, it is necessary to determine a single point inside the POP set, obtained by solving (3) under constraint (4). The idea is to select a transmission rate which belongs to the POP set and which minimizes the distance with the points where each objective function attains its ideal value. Two further vectors are defined to find the aforementioned single solution: *i)* the ideal decision variable vector, that contains the points where each objective function attains its optimum value (5) and *ii)* the vector which contains the optimum values of each objective function (6).

$$\begin{aligned}\mathbf{R}_{id}^{F_{k,y_z}} = &\Big(R_{1_1,id}^{F_{k,y_z}}, R_{2_1,id}^{F_{k,y_z}}, \cdots, R_{Y_1,id}^{F_{k,y_z}}, \cdots,\\ &R_{1_Z,id}^{F_{k,y_z}}, R_{2_Z,id}^{F_{k,y_z}}, \cdots, R_{Y_Z,id}^{F_{k,y_z}}\Big)\\ &\forall k \in [1, M_{y_z}], \forall y_z \in [1, Y_z], \forall z \in [1, Z]\end{aligned} \tag{5}$$

$$\begin{aligned}\mathbf{F}_{id} = \Bigg(&F_{1,1_1,id}\Big(\mathbf{R}_{id}^{F_{1,1_1}}\Big), .., F_{k,y_z,id}\Big(\mathbf{R}_{id}^{F_{k,y_z}}\Big), \cdots,\\ &F_{M_{Y_Z},Y_Z,id}\Big(\mathbf{R}_{id}^{F_{M_{Y_Z},Y_Z}}\Big)\Bigg)\end{aligned} \tag{6}$$

This point is called utopian or ideal because it may not belong to the feasibility region: each component of the vector in (5) can assume a value between 0 and R_{TOT}, independently of the values of its other components.

The optimal transmission rates allocated on the basis of the proposed algorithm are reported in (7).

$$\begin{aligned}&\mathbf{R}_{all} = (R_{1_1,all}, R_{2_1,all}, \cdots, R_{Y_1,all}, \cdots, R_{1_Z,all}, R_{2_Z,all}, \cdots,\\ &R_{Y_Z,all}) = \arg\min_{\mathbf{R}\subset\mathbf{R}_{opt}} \left(\sum_{z=1}^{Z}\sum_{y=1}^{Y_z}\sum_{k=1}^{M_{y_z}} w_{k,y_z}\cdot\right.\\ &\left.\cdot\left|F_{k,y_z}(\mathbf{R}^{F_{k,y_z}}) - F_{k,y_z,id}\Big(\mathbf{R}_{id}^{F_{k,y_z}}\Big)\right|^p\right)^{1/p}\end{aligned} \tag{7}$$

III. The Adopted Objective Functions

According to [5] a Mean Opinion Score (MOS) model for web navigation depending on the session time is expressed by the logarithmic law reported in (8).

$$MOS_z = 4.379 - 1.299 \cdot log\big(ST_z\big) \tag{8}$$

ST_z is the Session Time (ST) for the $z-th$ earth station. Obviously lower ST, higher MOS value. This metric represents the web browsing service and not the file transmission. Nevertheless, it is possible to use it also in this case because these two services have similarities. The used MOS evaluation for web browsing is a function of the session time, which could be considered as the time necessary to transmit the file that represents the web page and to show it.

Obviously, different services require different MOS models. For a detail overview of them see [6] among the others. It is worth noticing that our proposed algorithm is applicable also for different services, using the appropriate MOS models.

ST is modelled as $ST_z(R_z) = \dfrac{f_z}{R_z}$, where f_z is the size of the file transmitted by the $z-th$ earth station and R_z is the transmission rate allocated to it. Considering the proposed ST formulation, the MOS model can be re-written as an increasing function of the allocated transmission rate:

$$MOS_z\big(R_z\big) = 4.379 - 1.299 \cdot log\Big(\frac{f_z}{R_z}\Big) \tag{9}$$

The Transmitted Power (TP) of the $z-th$ earth station is modelled as in (10):

$$TP_z(h_z, R_z) = (2^{\frac{R_z}{W_z}} - 1) \cdot \frac{1}{h_z} \tag{10}$$

TP is a function of the bandwidth assigned to the $z-th$ earth station, W_z. R_z is the allocated transmission rate. The constant $h_z > 0$, defined in (11), is referred to the satellite link budget. The $z-th$ station transmission antenna gain is G_{T_z}; the satellite receiver antenna gain is G_R (common for each station) both assumed equal to 10^4 in this paper. Boltzman constant is $k = 1.38 \cdot 10^{-23} J \cdot K^{-1}$; the noise temperature T is set to 290 [K] (considering additive white Gaussian noise); the channel bandwidth is $W_z = 1[MHz] \quad \forall z$; and the Free Space Loss (*FSL*) is set to 10^{19}, as defined in [14].

$$\frac{1}{h_z} = \frac{k \cdot T \cdot W_z \cdot FSL}{G_{T_z} \cdot G_R} \tag{11}$$

The Transmitted Power function (10) is obtained by inverting the Hartley-Shannon law $R_z = W_z \cdot log_2\Big(1 + \Big(\frac{C}{N}\Big)_z^{FSL}\Big)$, where $\Big(\frac{C}{N}\Big)_z^{FSL} = \frac{G_{T_z} \cdot G_R \cdot TP_z}{k \cdot T \cdot W_z \cdot FSL}$ is the carrier to noise ratio [14], due to FSL component.

IV. Numerical Results

A. Algorithm Formulations

In this work we set the ideal value, for the first objective function (i.e., the MOS) to a value R^* in which the MOS attains its maximum, equal to 5 (i.e. $MOS(R^*) = MOS^{id} = 5$). The ideal value of the second objective function is set in $R = 0$, where TP attains its minimum, being an increasing function with R. Consequently, the optimal transmission rates, defined in (7), is reported below:

$$\begin{aligned}&\mathbf{R}_{all} = (R_{1_1,all}, R_{2_1,all}, \cdots, R_{Y_1,all}, \cdots,\\ &R_{1_Z,all}, R_{2_Z,all}, \cdots, R_{Y_Z,all}) =\\ &= \arg\min_{\mathbf{R}\subset\mathbf{R}_{opt}} \sum_{z=1}^{Z} w_{1,z} \cdot |MOS_z(R_z) - MOS^{id}|^p\\ &+ w_{2,z} \cdot TP(R_z)^p\end{aligned} \tag{12}$$

Three different weights configurations ($w_{1,z} = 0.25, w_{2,z} = 0.75$, $w_{1,z} = w_{2,z} = 0.5$ and $w_{1,z} = 0.75, w_{2,z} = 0.25$) are applied to differentiate the importance of the objective functions in each earth station. A further allocation criterion is used: it allocates all the available R_{TOT} among the earth stations. This algorithm is aimed at maximising the QoS (in this case minimizing the session time) without considering the transmitted power. This criterion is called Reference Allocation (Ref.) and it is implemented as a comparison with L_pRA. Each file transmitted by the $z-th$ station has a dimension f_z in the set [1.0, 1.5, 2.0, 2.5, 3.0] Mbps. We apply the norm 2 (i.e. $p = 2$) and we consider two earth stations $Z = 2$, transmitting the same set of 60 files, in a random order. For each file the amount of transmission rate R_z to be allocated to each station is computed and consequently the obtained values

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of TP, ST and MOS as proposed in Section III.

The transmission rate globally allocated at the two considered

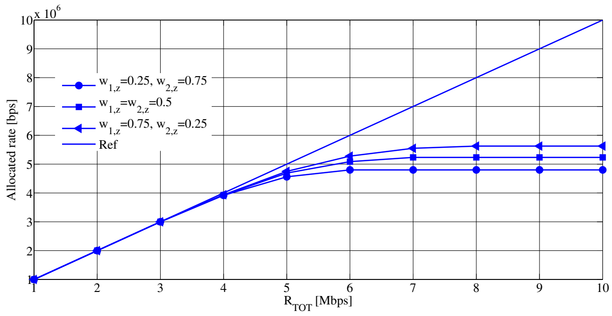

Fig. 3. Transmission rate allocated for different R_{TOT} values.

earth stations is plotted in Figure 3. It is possible to observe that for $R_{TOT} \leq 4$ Mbps the L_pRA algorithm and the reference algorithm converge on the same allocation represented by the overall available rate (R_{TOT}). In practice the optimal solution stays on the constraint of the feasibility region. If $R_{TOT} \geq 5$ [Mbps] the allocated rate obtained with the L_pRA algorithm does not stay on the constraint and not all the available rate is shared among the earth stations, as instead happens for the reference allocation. Moreover it is possible to see that the L_pRA solution converges to a constant value, called rate bound, when $R_{TOT} \geq 7$ [Mbps]. The rate bound values are between 4.5 and 5.5 [Mbps] according to the value of the weights used by the L_pRA algorithm. It is possible to see that a great amount of transmission rate can be saved using the proposed L_pRA method.

An important consequence of the rate allocation obtained

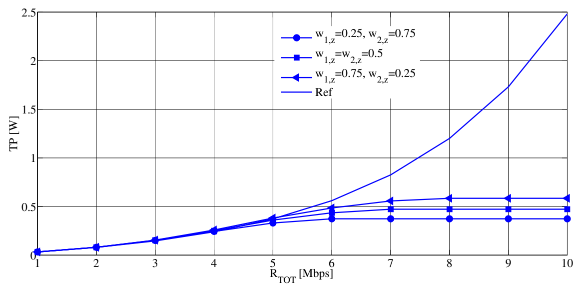

Fig. 4. Transmitted Power (TP) obtained for different R_{TOT} values.

using L_pRA, is the TP necessary for the two stations to transmit data at the allocated data rate. Observing TP values plotted in Figure 4 some considerations can be done: *i)* TP increases exponentially with R_{TOT} in the reference method because it allocates all the available rate; *ii)* the same trend characterizes the TP of the L_pRA algorithm when the rate allocation approaches to R_{TOT}, like the reference allocation; this happens when $R_{TOT} \leq 4$ [Mbps]; *iii)* when the L_pRA allocations converge to the rate bound (i.e., for $R_{TOT} \geq 7$) TP is constant. Observing Figure 4 TP reduction obtained by applying L_pRA is evident with respect to the allocation of the overall available rate R_{TOT}.

Session Time (ST), computed as the file size divided for the

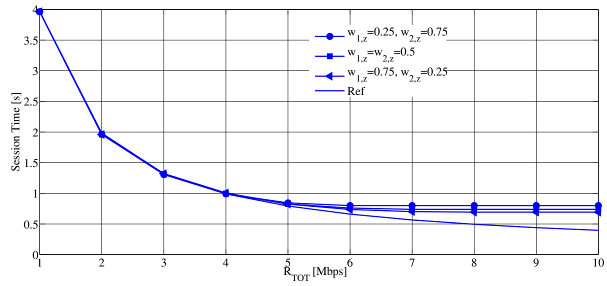

Fig. 5. Session Time (ST) obtained for different R_{TOT} values.

allocated rate, is plotted in Figure 5. It is possible to see that if R_{TOT} increases, ST decreases, according to the rate allocation plotted in Figure 3. Also in this case ST converges to a constant value, when the rate allocated by the L_pRA algorithm converges to the rate bound. Instead the ST obtained with the reference allocation decreases if R_{TOT} increases, because all the available rate is always used by this method. Nevertheless, ST differences between reference and L_pRA allocations are quite small, always under 0.5 [s], for all considered weights values.

Figure 6 shows the MOS values calculated through (8),

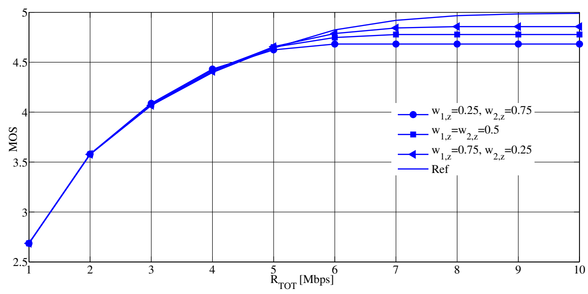

Fig. 6. Mean Opinion Score (MOS) obtained for different R_{TOT} values.

given the ST values in Figure 5. MOS values are the same if $R_{TOT} \leq 5$ [Mbps]. After this value the MOS remains quite similar. This happens for two reasons: *i)* when $R_{TOT} \leq 4$ [Mbps] the two algorithms converge on same solutions; *ii)* when $R_{TOT} \geq 5$ [Mbps] the rate allocations are different but the obtained ST values are quite similar for both algorithms (Figure 5) and consequently the MOS values are similar.

Considering the results shown in this section, L_pRA algorithm assures significant TP reduction and, at the same time, assures no relevant MOS degradation. In other words the rate bound, where the rate allocation of the proposed algorithm converges, is a sort of threshold: allocating a transmission rate higher then the rate bound produces useless TP increase and does not assure any QoE improvement (i.e. the MOS remains almost constant).

V. Conclusions

In this paper the authors present a transmission rate allocation algorithm called L_pRA aimed at maximizing the Quality

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of Experience (QoE) of the users, and at the same time, of minimizing the Transmitted Power (TP). The reference scenario is composed of a satellite network in which Z earth stations communicate with a satellite by using a common channel, and competing each other to obtain part of the overall available transmission rate, equal to R_{TOT}.

The mathematical framework adopted is the Multi Objective Programming (MOP). The problem is formulated as the optimization of two objective functions modelling QoE and TP. The L_p-problem is used to determine the solution (i.e the rate allocation of all stations). The numerical results show that L_pRA assures great benefit with respect to the typical approaches which allocate all the available transmission rate, trying to maximize the QoE without taking into consideration the TP. In particular two key points can be highlighted: *i)* L_pRA algorithm allocates globally less transmission rate, converging on a solution called rate bound. Consequently less TP is required; *ii)* QoE obtained, measured through the Mean Opinion Score (MOS), is similar in both cases, because the allocated rate reduction of the L_pRA algorithm is not perceived by the users.

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