L_p-Problem-Based Transmission Rate Allocation With Packet Loss and Power Metrics Over Satellite Networks

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***Abstract*—This paper tackles the classical problem of transmission rate allocation in satellite networks where fading may negatively impact communications. Within the framework of multiobjective programming (MOP), this paper introduces a transmission rate allocation criterion among Earth stations (ESs) called L_p-problem-based rate allocation (L_pRA). The allocations provided by L_pRA are representative of a compromise among the need of different performance metrics such as packet loss and transmission power (TP). This paper determines the condition for the existence and the value of a L_pRA transmission rate allocation bound R^{bound}, to which the transmission rate globally allocated by L_pRA converges when the overall available transmission rate R_{TOT} tends to infinity. The performance analysis, which is carried out through simulations under different satellite channel conditions, is aimed at investigating L_pRA features, at showing the existence of the rate bound and the advantages concerning the rate allocation given by using L_pRA, and at comparing L_pRA with two other schemes in the literature concerning allocated rate, packet loss rate, transmit power, and execution time.**

***Index Terms*—L_p-problem-based transmission rate allocation, multiobjective programming (MOP), performance analysis, satellite communications.**

I. Introduction

An emergency network is designed to provide reliable communications during emergency situations and when disasters suddenly strike a certain area. A challenge that arises with disasters is that the telecommunication services both provided by cellular networks (e.g., third-generation and Long-Term Evolution) and Internet infrastructures are usually interrupted. In order to deal with this challenge, designing an efficient disaster resilient network has recently gained a significant interest. Satellite communication networks have been considered a leading technology in this domain. Satellites assure the continuous availability of wireless communication channels and can be exploited for the fast deployment of urgently required communication supports. Coherently with the state of the art in the field (see [1]–[5] among many others), we consider a practical disaster network scenario, which is shown in Fig. 1, composed of a number of mobile nodes (MNs) transmitting traffic flows through access nodes, which are called mobile satellite gateways (MSGs). MSGs forward traffic to a shared satellite channel. A group of MNs and a single MSG define a single Earth station (ES). ESs are deployed in different zones of the disaster area. Z is the overall number of ESs.

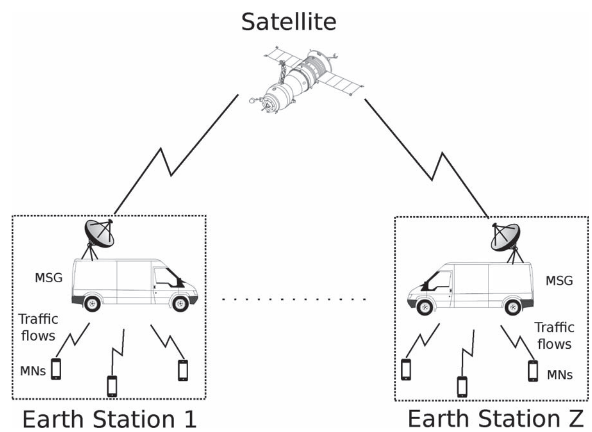

Fig. 1. Reference network.

Traffic flow management and variable satellite channel quality due to several impairments, such as rain fading, limited energy, and bandwidth constraints are topical problems in this field and have a great impact on performance. Optimizing resource management represents a key research issue in such environment [6]. In this framework, this paper proposes an algorithm to allocate transmission rate to ESs. The algorithm is identified as L_p-problem-based transmission rate allocation (L_pRA) and addresses two aims: maximizing communication performance by limiting the packet losses and, simultaneously, minimizing the energy consumption by limiting the transmission power (TP).

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The choice of the specific satellite environment does not affect the general behavior of the allocation scheme proposed in the paper, and as a consequence, it has been left unspecified for the sake of generality. Possible application environments are: geostationary Earth orbit (GEO), medium Earth orbit, and low Earth orbit satellites, and high-altitude platforms (HAPs). The main difference among them stands in the propagation delay and consequent round trip time (RTT). This paper compares L_pRA with alternative resource allocation methods through simulations. In summary, this paper contains the following contributions:

- a survey of the state of the art about resource allocation in satellite and wireless communications, in Section II;
- the presentation of the L_pRA, which is the extension of the MOP-based method introduced in [5];
- the definition of the existence conditions of a rate bound R^{bound}, which arisen from L_pRA, to which the overall L_pRA allocation converges when the system transmission rate availability tends to infinity, in Section IV;
- the analytical formulations employed to model the used performance metrics: packet loss probability (PLP) and TP, in Section V;
- the verification of the Transmission Rate Bound existence conditions presented in Section IV for L_pRA, in Section VI;
- a simulative performance evaluation of L_pRA and a comparison with other approaches available in the literature, in Section VII.

The conclusions are reported in Section VIII.

II. State of the Art

Resource allocation over satellite and wireless channels is a well-investigated topic. The most considered "resource" by allocation algorithms is either the transmission rate, which is expressed in bits per second, available for traffic flows, or the transmission bandwidth, which is expressed in hertz, often simply referred to as "bandwidth."

Due to the multiple use of the terms transmission rate and bandwidth, whose meaning in the literature is also a consequence of the different reference scientific community (e.g., communications, computing, networking, etc.), to avoid misunderstanding, we prefer specifying the definition of bandwidth that we use in this paper and the mathematical relation between bandwidth and transmission rate. The transmission bandwidth is the measure in hertz of the width of the range of frequency where a given zth ES with $z \in [1, Z]$ or the overall system composed of Z ES operates. Let W_z be the bandwidth of the zth station, the transmission rate R_z available for the zth station is given (as done in [2], [7]–[9]) by the Hartley–Shannon law for a white Gaussian channel as follows:

$$R_z = W_z \cdot \log(1 + h_z \cdot \text{TP}_z) \qquad \forall\, z \in [1, Z] \tag{1}$$

where TP_z is the TP in watts, and h_z is the channel gain of the zth station. h_z is defined in (27) of this paper, which is shown below.

In the past, the aim of allocation algorithms was the maximization of the transmission rate, which is employed by a single entity, to improve the quality of communications [1], [7], [8]. The action was carried out without considering power, or energy, consumption. More recently, algorithms are for joint transmission rate and power allocation, e.g., in [2], [3], and [9]–[15]. L_pRA may be included in this category. Most joint transmission rate and power allocation schemes in the state of the art may be classified in one of the following formulations.

A. Sum Capacity Maximization With Constrained Power

The total amount of power is not part of the cost function, but it is constrained under a given threshold. This approach maximizes the weighted sum of the transmission rates $\mathbf{R} = (R_1, \ldots, R_z, \ldots, R_Z)$ assigned to each entity through two sets of variables: bandwidth $\mathbf{W} = (W_1, \ldots, W_z, \ldots, W_Z)$ and power $\mathbf{P} = (P_1, \ldots, P_z, \ldots, P_Z)$, The problem is formalized in the following:

$$\begin{cases} \max\limits_{\mathbf{W},\mathbf{P}} \sum\limits_{z=1}^{Z} \alpha_z R_z(\mathbf{W}, \mathbf{P}) \\ \sum\limits_{z=1}^{Z} W_z \le W_{\text{TOT}}; \quad \sum\limits_{z=1}^{Z} P_z \le P_{\text{TOT}} \end{cases} \tag{2}$$

$\boldsymbol{\alpha} = (\alpha_1, \ldots, \alpha_z, \ldots, \alpha_Z)$ is a vector of weights.

Formulation in (2) represents a generalized version of a group of methods applied in different scenarios and reported in the following. In more detail, the algorithm proposed in [2] is aimed at maximizing the weighted sum of downlink transmission rates by allocating downlink bandwidth and power to a given number of users in a wireless packet data system. In [9], an allocation problem was formulated to maximize the information rate in a multihop network based on an orthogonal frequency-division multiplexing (OFDM) technique with power and subcarrier constraints. In [10], an adaptive radio resource allocation algorithm for different traffic flows was described. Considered resources are power and bandwidth and are assigned first to real-time users to guarantee their requirements. Remaining resources are allocated to non-real-time users. The aim of the algorithm is to maximize the weighted sum of non-real-time user throughput. In [11], the goal is to maximize a quantity defined as *average energy efficiency* $\overline{EE}$. In [11], the packet loss effect in wireless transmissions is taken into account, particularly the ratio between successfully delivered bits and total consumed power. The sum of allocated transmission rates is not explicitly taken into account; nevertheless, the mentioned *average energy efficiency* is a function of the bandwidth allocated to each entity.

B. Power Minimization With Constrained Capacity

A second set of algorithms, such as in [3] and [12]–[14], which are grouped here as power minimization (PM), is aimed at minimizing the TP by the variable bandwidths $\mathbf{W} = (W_1, \ldots, W_z, \ldots, W_Z)$, i.e.,

$$\begin{cases} \min\limits_{\mathbf{W}} \sum\limits_{z=1}^{Z} \beta_z P_z(\mathbf{W}, \mathbf{R}) \\ \sum\limits_{z=1}^{Z} W_z \le W_{\text{TOT}}; \quad R_z \ge R_{\text{th}} \quad \forall\, z \in [1, Z] \end{cases} \tag{3}$$

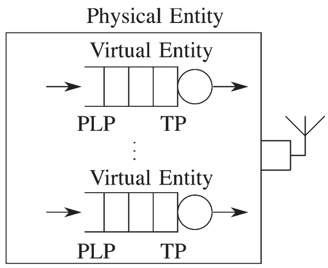

Fig. 2. Proposed model for a physical entity.

$\boldsymbol{\beta} = (\beta_1, \ldots, \beta_z, \ldots, \beta_Z)$ is a vector of weights. The transmission rate employed by each entity must be greater or equal to R_{th} to assure a certain level of quality for the communication.

III. L_p-Problem-Based Allocation

A. Model of the ES

The model proposed in this paper cannot be included in the two groups presented in Section II; it uses MOP theory, which is detailed in Section III-D, and is based on three main components: physical entities, virtual entities, and objective functions. A physical entity is a system such as a satellite ES. A virtual entity is a component within a physical system such as a single-pair buffer–server. Each virtual entity is "represented" by a group of objective functions that model performance parameters such as, in this paper, PLP and TP. Fig. 2 schematically represents the proposed model for a single physical entity.

B. Aim and General Structure of the Proposed Allocation Algorithm

Assuming overall transmission rate R_{TOT} and bandwidth W_{TOT}, L_pRA distributes R_{TOT} among the Z stations (obviously, it is true that $\sum_{z=1}^{Z} R_z \leq R_{\text{TOT}}$ and $\sum_{z=1}^{Z} W_z \leq W_{\text{TOT}}$).

The transmission rate allocation is carried out by a centralized decision maker, which splits R_{TOT} among all virtual entities. The rate allocated to each physical entity is the sum of the rates allocated to each related virtual entities. The centralized decision-maker is localized within an ES (or in the satellite/HAP itself, if switching on board is allowed) that represents the master station (MS). Each satellite channel can be corrupted by path loss, noise, and fading. We suppose that each ES applies a forward-error-correcting code as a countermeasure and may adaptively change the amount of redundancy bits (e.g., the correction power of the code) depending on the channel status. It implies, in practice, a reduction of the rate to transmit the information. Consequently, not only a change of the offered load but also different channel conditions imply a modification of the transmission rate that needs to keep a given level of quality of service for the communication. Different from other approaches in the literature, which focus on the optimization through a single metric and satisfy the other metrics by using constraints, this paper considers all the metrics at the same time through a multiobjective optimization and finds a compromise solution among the needs of the different metrics.

As proposed in previous works of the same authors (see Section II), this paper also considers the transmission rate, which is expressed in bits per second, as the shared resource and the allocation process as a competitive problem where each entity (i.e., ES) accessing the shared available transmission rate is "represented" by a group of functions that need to be optimized. These functions model the used metrics (PLP and TP) used, in this paper, as a function of the transmission rate allocated to the entity, because the metrics are possibly in contrast with each other, the allocation must necessarily represent a compromise. Multiobjective programming (MOP) theory defines the multiobjective optimization problem and represents the theoretical reference of the proposed allocation algorithm.

C. Previous Scientific Work of the Same Authors

This paper originated with [4], where MOP was used to allocate resources over satellite communications by the authors for the first time. In [4], only packet loss is used as a performance metric. It is extended in [16] by also including packet delay. The first time that an MOP-based transmission rate allocation was presented to minimize, jointly, packet loss and power, was in [5], which also contained the original idea, the formulation, and the preliminary results. The existence of a transmission rate bound was observed through simulation results in [17], whereas the consequent possible bandwidth saving was experimentally shown in [18]. This paper starts from the original idea in [5], presents the overall transmission rate allocation scheme, formally checks the existence of the rate bound, and presents a deep performance evaluation, which is aimed at showing the practical impact of the presented algorithm.

D. Multiobjective Programming Theoretical Framework

As in [19], a MOP problem is defined as

$$\begin{cases} \min \{f_1(\mathbf{x}), \ldots, f_i(\mathbf{x}), \ldots, f_k(\mathbf{x})\} \\ \text{subject to } \mathbf{x} \in S \\ S = \{\mathbf{x} \in \mathbb{R}^n | g(\mathbf{x}) = (g_1(\mathbf{x}), g_2(\mathbf{x}), \ldots, g_m(\mathbf{x}))\}, \ k \geq 2 \end{cases} \tag{4}$$

where f_i: $\mathbb{R}^n \rightarrow \mathbb{R}$ $\forall i \in [1, k]$ are the objective functions that compose the objective function vector $\boldsymbol{f}(\mathbf{x}) = \{f_1(\mathbf{x}), f_2(\mathbf{x}), \ldots, f_k(\mathbf{x})\}$. $\mathbf{x}$ is the decision vector that belongs to a feasible region S, which is a subset of the space $\mathbb{R}^n$. In this paper, the objective functions represent performance metrics (i.e., packet loss and RP) that need to be optimized. The feasible region is the set of all available resources (i.e., the overall available transmission rate R_{TOT}) shared among the virtual entities. The set of solutions of the problem described in (4) is called the Pareto optimal point (POP) set, which contains all the acceptable solutions of the MOP problem. According to [19], a formal definition of Pareto optimality is the following: A decision vector $\mathbf{x}^* \in S$ is *Pareto Optimal* if another decision vector $\mathbf{x} \in S$ does not exist such that $f_i(\mathbf{x}) \leq f_i(\mathbf{x}^*)$ for all $i = 1, \ldots, k$, and if $f_j(\mathbf{x}) < f_j(\mathbf{x}^*)$ for at least one index j. The definition practically means that any other decision vector that improves the value of an object function without worsening, at least, another one does not exist.

E. Transmission Rate Allocation Model

As said earlier, the transmission rate allocation problem is modeled as a MOP problem in this paper. The system is composed of Z physical entities; each physical entity is identified by the index $z \in [1, Z]$. Y_z is the number of virtual entities of the zth physical entity. Each virtual entity is identified by $y_z \in [1, Y_z]$. M_{y_z} is the number of objective functions for each virtual entity y_z. Each objective function, of a given y_zth virtual entity, is identified by the index $m \in [1, M_{y_z}]$. R_{y_z} is the rate allocated to the virtual entity y of the physical entity z, i.e.,

$$\mathbf{R} = (R_{1_1}, R_{2_1}, R_{3_1}, \dots, R_{Y_1}, \dots, R_{1_Z}, R_{2_Z}, R_{3_Z}, \dots, R_{Y_Z}) \tag{5}$$

is the vector that contains the rate allocated to each virtual entity, and

$$R_z = \sum_{y=1}^{Y_z} R_{y_z} \tag{6}$$

is the rate allocated to the physical entity z. $F_{m,y_z}(\mathbf{R})$ is the mth objective function, which is analytically defined in Section V, of the yth virtual entity of the zth physical entity. The full set of objective functions is contained in the vector

$$\mathbf{F}(\mathbf{R}) = \Big(F_{1,1_1}(\mathbf{R}), \dots, F_{M_{1_1},1_1}(\mathbf{R}), \dots \\ F_{1,Y_Z}(\mathbf{R}), \dots, F_{M_{Y_Z},Y_Z}(\mathbf{R})\Big). \tag{7}$$

Given the definitions above and being R_{TOT} the overall available transmission rate, i.e., shared by all Z entities, the following constraint must hold:

$$\sum_{z=1}^{Z}\sum_{y=1}^{Y_z} R_{y_z} \le R_{\text{TOT}}. \tag{8}$$

Transmission rate allocation is defined as an MOP problem through the following, which must be solved under constraint (8) that defines the feasibility region:

$$\mathbf{R}_{\text{opt}} = (R_{1_1,\text{opt}}, R_{2_1,\text{opt}}, \dots, R_{Y_1,\text{opt}}, \dots \\ R_{1_Z,\text{opt}}, R_{2_Z,\text{opt}}, \dots, R_{Y_Z,\text{opt}}) = \arg\min_{\mathbf{R}} \mathbf{F}(\mathbf{R}) \\ R_{y_z} \ge 0 \quad \forall\, y_z \in [1, Y_z]\, \forall\, z \in [1, Z]. \tag{9}$$

The set of solutions derived from (9) is called the POP set. In general, getting the overall POP set is not simple, but the structure of the objective functions helps take the decision in some cases. For example, it is simple to prove that given problem (9), subject to the constraint (8), if all objective functions are strongly decreasing [19], i.e., decreasing for all its variables and strictly decreasing for at least one function and one variable, then a solution $\mathbf{R}$ is a POP if and only if the solution is on the constraint boundary, i.e.,

$$\sum_{z=1}^{Z}\sum_{y=1}^{Y_z} R_{y_z} = R_{\text{TOT}}. \tag{10}$$

This is the case we have considered in [4] and [16]. It is also true that, given the inequality constraint (8), if all objective functions are decreasing, all the points on the constraint boundary are POP solutions, but not all POP solutions necessarily belong to the constraint, as well as points for which

$$\sum_{z=1}^{Z}\sum_{y=1}^{Y_z} R_{y_z} < R_{\text{TOT}} \tag{11}$$

can be POP solutions. The strongly decreasing assumption concerning the objective-function vector is quite typical because common performance functions applied in telecommunication networks such as PLP, packet delay, and packet jitter are quantities that decrease their values when the allocated capacity value increases. This is not true if other important metrics are also used: power and processing and computation effort. It is simple to prove that, given problem (9) and constraint (8), if at least one function is strongly increasing, i.e., increasing for all its variables and strictly increasing for at least one variable, all the points inside the feasibility region and on the constraint boundary may be POPs.

F. L_p-Problem-Based Capacity Allocation Criterion

Optimal allocations are chosen among POPs, and each POP is optimal from the Pareto viewpoint. Nevertheless, for operative reasons, it is necessary to choose one solution (i.e., one transmission rate allocation). A possibility, used also in this paper, is selecting a single POP minimizing the distance, in the sense of L_p-problem [19], with a reference goal point. The idea is to allocate transmission rate, within the POP set (9), so that the value of each objective function is as close as possible to its ideal value. The set of ideal rates [i.e., the ideal vector (12)] is defined as composed of the ideal decision variable vector elements $R_{y_z,\text{id}}^{F_{k,y_z}}$ for which F_{k,y_z} attains the optimum value and may be known having information about the features of the objective functions, as discussed in Section III-E and as explained in the following. This definition of the ideal transmission-rate set is not the only possible choice, e.g., if hard constraints on metrics were given, the ideal vector may contain the minimum rate allocations to assure these constraints, i.e.,

$$\mathbf{R}_{\text{id}}^{F_{k,y_z}} = \Big(R_{1_1,\text{id}}^{F_{k,y_z}}, R_{2_1,\text{id}}^{F_{k,y_z}}, \dots, R_{Y_1,\text{id}}^{F_{k,y_z}}, \dots \\ R_{1_Z,\text{id}}^{F_{k,y_z}}, R_{2_Z,\text{id}}^{F_{k,y_z}}, \dots, R_{Y_Z,\text{id}}^{F_{k,y_z}}\Big) \\ \forall\, k \in [1, M_{y_z}]\ \forall\, y_z \in [1, Y_z]\, \forall\, z \in [1, Z]. \tag{12}$$

Each element $R_{y_z,\text{id}}^{F_{k,y_z}}$ can assume a value between 0 and R_{TOT}, independently of any physical constraint and of the values of the other components of vector (7). It is called ideal (utopian) for this. For example, if a generic objective function is decreasing versus transmission rate, it is obvious that it is ideal allocating all the possible rate R_{TOT}, whereas if it is increasing versus rate, it is ideal to allocate no rate at all. The values of vector (12) are considered known in the remainder of this paper. The vector in the following contains each objective function attaining its ideal value:

$$\mathbf{F}_{\text{id}} = \left(F_{1,1_1,\text{id}}\left(\mathbf{R}_{\text{id}}^{F_{1,1_1}}\right), \ldots, F_{k,y_z,\text{id}}\left(\mathbf{R}_{\text{id}}^{F_{k,y_z}}\right), \ldots \right.$$
$$\left. F_{M_{Y_Z},Y_Z,\text{id}}\left(\mathbf{R}_{\text{id}}^{F_{M_{Y_Z},Y_Z}}\right)\right). \quad (13)$$

The optimal transmission rates allocated based on the proposed L_pRA criterion are reported in

$$\begin{aligned}\mathbf{R}_{\text{all}} &= (R_{1_1,\text{all}}, R_{2_1,\text{all}}, \ldots, R_{Y_1,\text{all}}, \ldots, R_{1_Z,\text{all}}, \ldots \\ &\quad R_{2_Z,\text{all}}, \ldots, R_{Y_Z,\text{all}}) \\ &= \arg\min_{\mathbf{R}\subset\mathbf{R}_{\text{opt}}} \hat{J}_p(\mathbf{R})\end{aligned} \quad (14)$$

where

$$\hat{J}_p(\mathbf{R}) = \left(\sum_{z=1}^{Z}\sum_{y=1}^{Y_z}\sum_{k=1}^{M_{y_z}} w_{k,y_z} \left| F_{k,y_z}(\mathbf{R}^{F_{k,y_z}}) - \right.\right.$$
$$\left.\left. + \; F_{k,y_z,\text{id}}\left(\mathbf{R}_{\text{id}}^{F_{k,y_z}}\right)\right|^p\right)^{\frac{1}{p}} \quad (15)$$

subject to the constraint reported in (8) and where

$$\sum_{k=1}^{M_{y_z}} w_{k,y_z} = 1, w_{k,y_z} > 0 \quad \forall k \in [1, M_{y_z}]$$
$$\forall y_z \in [1, Y_z] \, \forall z \in [1, Z] \quad (16)$$

so to assure that the solution is chosen in the POP set defined by (9), i.e., to guarantee the Pareto optimality of the solution, as proven in the Appendix. In practice, we select the point inside the POP set that minimizes the p-norm (i.e., the "distance") with respect to the utopia point. The use of weights w_{k,y_z} and of different norms allows allocating transmission rate to virtual entities by differentiating the importance of the performance metrics for different virtual entities up to neglecting one or more metrics if necessary. Section VII contains a comparative performance analysis, which is carried out by varying weight combination.

From the operative viewpoint, (15) can be simplified because the exponent $(1/p)$ can be dropped without affecting the L_p-problem solution. L_p-problems with or without the mentioned exponent are equivalent for $1 \leq p \leq \infty$ [19, pp. 68]. As a consequence L_pRA is written and solved by using the following:

$$\begin{aligned}\mathbf{R}_{\text{all}} &= (R_{1_1,\text{all}}, R_{2_1,\text{all}}, \ldots, R_{Y_1,\text{all}}, \ldots \\ &\quad R_{1_Z,\text{all}}, R_{2_Z,\text{all}}, \ldots, R_{Y_Z,\text{all}}) \\ &= \arg\min_{\mathbf{R}\subset\mathbf{R}_{\text{opt}}} J_p(\mathbf{R})\end{aligned} \quad (17)$$

$$J_p(\mathbf{R}) = \left(\sum_{z=1}^{Z}\sum_{y=1}^{Y_z}\sum_{k=1}^{M_{y_z}} w_{k,y_z} \left| F_{k,y_z}(\mathbf{R}^{F_{k,y_z}}) - \right.\right.$$
$$\left.\left. + \; F_{k,y_z,\text{id}}\left(\mathbf{R}_{\text{id}}^{F_{k,y_z}}\right)\right|^p\right). \quad (18)$$

From the implementation viewpoint, the proposed method can be applied to traditional dynamic time-division multiple-access (TDMA) method usually applied to satellite systems [20]. Indeed, TDMA is a method used to enable multiple ESs to transmit intermittently on the same frequency, but with the timing of their transmissions so arranged that the bursts do not overlay when they arrive at the satellite but arrive in sequence and thus are all successfully received by the receivers. The operation of TDMA requires an outlink control to all the ESs that contains some control information. This outlink carrier also had a frame structure that provides accurate timing information for all the ESs: the burst time plan (BTP). This approach include an MS, which is often called network control center, that tells each ES what particular time slot to use in the TDMA frame, and this time plan information is broadcast to all ESs periodically. In general, the BTP may be fixed, to allocate each ES a particular proportion of the total TDMA frame time, or may be dynamic, whereby the time slot allocated is adjusted in response to the rate needs of each ES. The latter approach is compatible with the allocation method proposed in this paper: Each ES communicates its traffic parameters' values (i.e., the parameters needed to define the objective functions), and through the same outlink control channel, the TDMA BTP is broadcast to inform all ESs with the timing plan obtained by running the proposed allocation approach. This BTP might be applied unchanged if the allocation does not require different rate distribution, or it might be changed every few seconds according to the allocation result.

This means that the proposed L_pRA criterion does not need particular implementation solution and can be easily applied to the widely employed TDMA-based satellite networks.

IV. Transmission Rate Bound

A. *Condition for the Existence of the Transmission Rate Bound*

L_pRA expressed in (17) and (18) is a function of the rate vector $\mathbf{R}$. Nevertheless, if the performance metrics are decreasing functions of the transmission rate (such as packet loss, as in this paper, and delay), the related component of the ideal vector (12) is the overall available transmission rate R_{TOT}. As a consequence, R_{TOT} is a parameter of the cost (18) that may be written as $J_p(\mathbf{R}, R_{\text{TOT}})$. It is important to remark that R_{TOT} is not a variable of the minimization process in (18), but it is a parameter influencing the value (18), as should be clearer from Section V-C, where the form of (18) will be specified. This section determines the conditions for the existence of a finite bound, R^{bound}, independent of R_{TOT}, where the sum of the transmission rates allocated by L_pRA converges when R_{TOT} tends to ∞.

The conditions for the existence of a unique solution $\mathbf{R}_{\text{all}}$ that minimizes $J_p(\mathbf{R}, R_{\text{TOT}})$ are the following.

Condition 1: The solution must represent a coordinate of an equilibrium point, i.e., $\exists$ at least a vector $\mathbf{R}_{\text{all}}$ so that

$$\frac{\partial J_p\left(R_{1_1}, R_{2_1}, \ldots, R_{Y_1}, \ldots, R_{1_Z}, R_{2_Z}, \ldots, R_{Y_Z}, R_{\text{TOT}}\right)}{\partial R_{y_z}}$$
$$= \frac{\partial J_p(\mathbf{R}, R_{\text{TOT}})}{\partial R_{y_z}} = 0 \quad \forall y_z \in [1, Y_z] \, \forall z \in [1, Z]. \quad (19)$$

Condition 2: The Hessian matrix of problem (17) only with respect to the vector $\mathbf{R}_{\text{all}}$, $\mathbf{H}(\mathbf{R}_{\text{all}})$ must be positive semidefinite in the same point in which Condition 1 is verified, i.e.,

$$\det\left[\mathbf{H}(\mathbf{R}_{\text{all}})\right] \geq 0 \quad \forall R_{y_z} \in [0, R_{\text{TOT}}). \tag{20}$$

Moreover, if $\mathbf{R}_{\text{all}} = (R_{1_1,\text{all}}, R_{2_1,\text{all}}, \ldots, R_{Y_1,\text{all}}, \ldots, R_{1_Z,\text{all}}, R_{2_Z,\text{all}}, \ldots, R_{Y_Z,\text{all}})$ must be independent of R_{TOT} when $R_{\text{TOT}} \to \infty$, the following condition must hold.

Condition 3:

$$\lim_{R_{\text{TOT}}\to\infty} R_{y_z,\text{all}}(R_{\text{TOT}}) = R_{y_z}^{\text{bound}} \quad \forall y_z \in [1, Y_z]\, \forall z \in [1, Z]. \tag{21}$$

Due to Condition 1, it is clear that Condition 3 is equivalent to

$$\lim_{R_{\text{TOT}}\to\infty} \frac{\partial J_p(\mathbf{R}, R_{\text{TOT}})}{\partial R_{y_z}} = J_{p,y_z}(\mathbf{R}) < \infty \qquad \forall y_z \in [1, Y_z]\, \forall z \in [1, Z]. \tag{22}$$

In practice, the limits of the partial derivatives of function $J_p(\mathbf{R}, R_{\text{TOT}})$ as R_{TOT} approaches to infinity must exist, must be finite, and must be function only of the rate vector $\mathbf{R}$.

If $R_{y_z}^{\text{bound}}$ exists $\forall y_z \in [1, Y_z]\, \forall z \in [1, Z]$, the value R^{bound} is defined as

$$R^{\text{bound}} = \sum_{z=1}^{Z} \sum_{y=1}^{Y_z} R_{y_z}^{\text{bound}}, R^{\text{bound}} < R_{\text{TOT}}. \tag{23}$$

1) Impact of the Transmission Rate Bound on the Allocation Scheme: If $R_{\text{TOT}} < R_{\text{bound}}$, the global transmission rate allocated by L_pRA is R_{TOT} (in practice, all the available transmission rate is used). If $R_{\text{TOT}} \geq R_{\text{bound}}$, L_pRA globally allocates a global transmission rate below R_{bound} but infinitesimally close to it. If $R_{\text{TOT}} = R_{\text{bound}} - \epsilon$, where ϵ is an arbitrarily small positive number, L_pRA allocates a global transmission rate of R_{TOT}, whereas if $R_{\text{TOT}} = R_{\text{bound}}$, L_pRA allocates globally a transmission rate R_{all}: $R_{\text{bound}} - \epsilon < R_{\text{all}} < R_{\text{bound}}$. Practically, if $R_{\text{TOT}} \geq R^{\text{bound}}$, the L_p-problem provides approximately the same solution (i.e., the capacity allocation among entities does not change meaningfully by increasing R_{TOT}), which means that, when $R_{\text{TOT}} \geq R^{\text{bound}}$, the system performance does not practically change even if the overall available transmission rate indefinitely grows. In practice, given a certain R_{TOT} if the value of R^{bound} is lower or equal to R_{TOT}, it is possible to avoid allocating the amount of transmission rate $[R_{\text{TOT}} - R^{\text{bound}}]$, without performance detriment.

V. Objective Functions and Cost Functions

In the remainder of this paper, each physical entity represents one ES that transmits through a satellite channel and is provided with a single buffer (i.e., one virtual entity each) that receives a specific transmission rate allocation. As a consequence, physical and virtual entities are not differentiated ($y_z \equiv z$). Each considered entity is represented by two objective functions: PLP, i.e., $F_{1,1_z} = P_{\text{loss}_z}(R_z)$ and TP, i.e., $F_{2,1_z} = W_{\text{tx}_z}(R_z)$. The constraint is defined by the overall amount R_{TOT} of available transmission rate in (8).

A. Packet Loss Probability Function

The PLP model used in this paper considers a transmission control protocol (TCP)-based traffic. It has been defined, including all parameters' value, in [21], and it is reported in

$$P_{\text{loss}_z}(R_z) = \frac{k_z \cdot N_z^2}{\left(\frac{\text{CR}_z \cdot R_z \cdot \text{RTT}_z}{l} + Q_z\right)^2} \tag{24}$$

k_z is a constant depending on TCP parameters, and N_z is the number of active MNs. Each MN of station z generates a single TCP connection for the zth station. In practice, there are N_z TCP connections for each zth station. Q_z is the buffer size for the MSG of the zth station. RTT_z is the RTT, and l is the TCP packet size expressed in bytes. The parameters' values used in the performance evaluation are specified in Section VII. CR_z and R_z are the code and transmission rate allocated to the zth station, respectively. Channel conditions vary over time, and in this paper, the experienced carrier-to-noise ratio $(C/N)_z$ for each station represents the satellite channel status. $(C/N)_z$ includes both a free-space loss (FSL) component, also used in Section V-B to model TP, and a rain attenuation component, which is ignored concerning the TP. Each ES z supports different code rates CR_z depending on the channel status. Code rates are assigned in this paper to allow considering feasible the assumption that packet losses are only due to congestion because channel errors may be considered negligible due to the application of suitable code rates. This assumption allows considering PLP and TP independent of each other. In the following, we rewrite (24), and it will be useful in Section VI to simplify mathematical tractability:

$$P_{\text{loss}_z}(R_z) = \frac{A_z}{(D_z \cdot R_z + Q_z)^2} \tag{25}$$

where $A_z(N_z) = k_z \cdot N_z^2$, and $D_z(\text{CR}_z) = (\text{CR}_z \cdot \text{RTT})/l$ are positive constants.

B. Transmission Power Function

By assigning a bandwidth W_z, the model of the TP TP_z of the zth station is reported in

$$\text{TP}_z(h_z, R_z) = \left(2^{\frac{R_z}{W_z}} - 1\right) \cdot \frac{1}{h_z}. \tag{26}$$

The constant $h_z > 0$, which is defined the following, takes into account the parameters whose numerical values for performance evaluation are contained in Section VII related to the link budget, i.e., zth station transmission antenna gain G_{T_z}, satellite receiver antenna gain G_R (common for each station), Boltzmann's constant k, and noise temperature T (considering additive white Gaussian noise), channel bandwidth $W_z = W_{\text{TOT}}\ \forall z$, and FSL):

$$\frac{1}{h_z} = \frac{k \cdot T \cdot W_z \cdot \text{FSL}}{G_{T_z} \cdot G_R}. \tag{27}$$

The TP function (26) is obtained by inverting the Hartley–Shannon law as follows:

$$R_z = W_z \cdot \log_2\left(1 + \left(\frac{C}{N}\right)_z^{\mathrm{FSL}}\right) \tag{28}$$

where

$$\left(\frac{C}{N}\right)_z^{\mathrm{FSL}} = \frac{G_{T_z}\cdot G_R \cdot \mathrm{TP}_z}{k\cdot T\cdot W_z \cdot \mathrm{FSL}} = \frac{\mathrm{TP}_z}{h_z} \tag{29}$$

is the carrier-to-noise ratio [22], due to FSL component.

C. *Analytical Definition of the Objective Function Vector* $\mathbf{F}(\mathbf{R})$ *and of the Cost* $J_p()$

Both objective functions (24) and (26) are continuous and differentiable in $\mathbb{R}$ so assuring the existence of a solution of the L_p problem. The analytical definition of the objective function vector $\mathbf{F}(\mathbf{R})$, which is introduced in (7), is reported in the following, with $y_z \equiv z$, $R_{1_1} = R_1$, $R_{1_2} = R_2$, and $R_{1_z} = R_z$

$$\mathbf{F}(\mathbf{R}) = \left(\frac{A_1}{D_1R_1+Q_1}, \left(2^{\frac{R_1}{B}}-1\right)\frac{1}{h_1}, \ldots \frac{A_Z}{(D_ZR_Z+Q_Z)^2}, \left(2^{\frac{R_Z}{B}}-1\right)\frac{1}{h_z}\right). \tag{30}$$

According to (13), the utopia values for the employed objective functions are $F_{1,1_z,\mathrm{id}} = A_z/(D_zR_{\mathrm{TOT}}+Q_z)^2$ and $F_{2,1_z,\mathrm{id}} = 0$. Consequently, as assumed at the beginning of Section IV, $J_p(\cdot)$ in (18) is a function of the vector $\mathbf{R}$ and has the overall available transmission rate R_{TOT} as a parameter. $J_p(\mathbf{R}, R_{\mathrm{TOT}})$ is explicitly indicated in

$$J_p(\mathbf{R}, R_{\mathrm{TOT}}) = \sum_{z=1}^{Z} w_{1,1_z}\left(\frac{A_z}{(D_zR_z+Q_z)^2} - + \frac{A_z}{(D_zR_{\mathrm{TOT}}+Q_z)^2}\right)^p + w_{2,1_z}\left(\left(2^{\frac{R_z}{B}}-1\right)\frac{1}{h_z}\right)^p. \tag{31}$$

VI. Verification of the Transmission-Rate-Bound Existence Conditions

Here, our aim is to check the transmission-rate-bound existence conditions presented in Section IV for the formulation of $J_p(\mathbf{R}, R_{\mathrm{TOT}})$ expressed in (31).

A. *Condition 1*

Concerning *Condition 1*, we show that the derivative $\partial J_p(\mathbf{R}, R_{\mathrm{TOT}})/\partial R_{y_z}$ assumes here a value equal to zero at least in one point ($\mathbf{R}_{\mathrm{all}}$) by applying the Bolzano Theorem.

Being $(\partial J_p(R_z, R_{\mathrm{TOT}})/\partial R_z)\ \forall z$ continuous, because it is a derivative of R^2 functions, defined for $R_z \in [0, R_{\mathrm{TOT}}] \to \mathbb{R}$ and

$$\frac{\partial J_p(\mathbf{R}, R_{\mathrm{TOT}})}{\partial R_z} = p\left(w_{1,1_z}\left(\frac{A_z}{(D_zR_z+Q_z)^2} - \frac{A_z}{(D_zR_{\mathrm{TOT}}+Q_z)^2}\right)^{p-1} \cdot \frac{-2A_zD_z}{(D_zR_z+Q_z)^3} + w_{2,1_z}\left(2^{\frac{R_z}{B}}-1\right)^{p-1}\cdot\frac{2^{\frac{R_z}{B}}\ln(2)\frac{1}{h_z^p}}{B}\right) \tag{32}$$

where

$$\frac{\partial J_p(0, R_{\mathrm{TOT}})}{\partial R_z} = p\cdot w_{1,1_z}\left(\frac{A_z}{Q_z^2} - + \frac{A_z}{(D_zR_{\mathrm{TOT}}+Q_z)^2}\right)^{p-1} \cdot \frac{-2A_zD_z}{Q_z^3} < 0 \tag{33}$$

$$\frac{\partial J_p(R_{\mathrm{TOT}}, R_{\mathrm{TOT}})}{\partial R_z} = p\cdot w_{2,1_z}\left(2^{\frac{R_{\mathrm{TOT}}}{B}}-1\right)^{p-1} \cdot \frac{2^{\frac{R_{\mathrm{TOT}}}{B}}\ln(2)\frac{1}{h_z^p}}{B} > 0. \tag{34}$$

Equation (19) has, at least, one solution, and *Condition 1* is satisfied.

B. *Condition 2*

$$\frac{\partial^2 J_p(R_z, R_{\mathrm{TOT}})}{\partial R_z^2} = p\cdot w_{1,1_z}\Bigg((p-1)\left(\frac{A_z}{(D_zR_z+Q_z)^2} + - \frac{A_z}{(D_zR_{\mathrm{TOT}}+Q_z)^2}\right)^{p-2}\left(\frac{-2A_zD_z}{(D_zR_z+Q_z)^3}\right)^2 + \left(\frac{A_z}{(D_zR_z+Q_z)^2} - \frac{A_z}{(D_zR_{\mathrm{TOT}}+Q_z)^2}\right)^{p-1} \times\left(\frac{6A_zD_z^2}{(D_zR_z+Q_z)^4}\right)\Bigg) + p\cdot w_{2,1_z} \times\left((p-1)\left(2^{\frac{R_z}{B}}-1\right)^{p-2}\cdot\left(\frac{2^{\frac{R_z}{B}}\ln(2)\frac{1}{h_z^p}}{B}\right)^2 + \left(2^{\frac{R_z}{B}}-1\right)^{p-1}\cdot\left(\frac{2^{\frac{R_z}{B}}(\ln(2))^2\frac{1}{h_z^p}}{B^2}\right)\right). \tag{35}$$

Equation (35) depends only on R_z. As a consequence, the Hessian is a diagonal matrix, as shown in (36) and (37) at the bottom of the next page. Equation (37) is a product of only positive quantities $\forall\mathbf{R}$. Matrix (36) is positive semi-definite $\forall\mathbf{R}$. This implies that Condition 2 is satisfied.

TABLE I
OBJECTIVE FUNCTION PARAMETERS' VALUES

PLP	TP
$k_z = \frac{128}{81}$	$k = 1.38 \cdot 10^{-23}$ $[J \cdot K^{-1}]$
$N_z = 10$	$T = 290$ [K]
$Q_z = 10$ [Packets]	$W_{TOT} = 1$ [MHz]
$rtt_z = 512$ [ms]	$FSL = 10^{19}$
$l = 1500$ [byte]	$G_{T_z} = G_R = 10^4$

C. Condition 3

From (22), we have

$$\lim_{R_{\mathrm{TOT}}\to\infty} \frac{\partial J_p(R_z, R_{\mathrm{TOT}})}{\partial R_z} = p\left(w_{1,1_z}\left(\frac{A_z}{(D_zR_z+Q_z)^2}\right)^{p-1} \cdot \frac{-2A_zD_z}{(D_zR_z+Q_z)^3} + w_{2,1_z}\left(2^{\frac{R_z}{B}}-1\right)^{p-1} \cdot \frac{2^{\frac{R_z}{B}}\ln(2)\frac{1}{h_z^p}}{B}\right) < \infty. \quad (38)$$

The limits of the partial derivatives in (38) exist, are finite, and do not depend on R_{TOT}. Condition 3 is satisfied.

VII. PERFORMANCE ANALYSIS

The scenario considered in this performance evaluation has been implemented through the ns-2 simulator. It is composed of Z ESs, including MNs that transmit TCP traffic over a common GEO satellite channel through the MSG. TCP traffic features are specified at the beginning of Section V-A. The overall duration of the simulation is 300 s. The transmission rate allocation is performed each 5 s (the allocation period). Used values for objective functions parameters (see Sections V-A and B) are specified in Table I $\forall z$. The channel status $(C/N)_z$, which assumes the values, kept constant in each allocation period, as reported in Table II together with the code rates CR_z.

Function (31) has been used with $p = 2$, and the employed procedure to find the minimum is based on a classical dynamic programming algorithm [23]. To practically implement the allocation procedure, the transmission rate to be allocated is discrete, i.e., divided in units called minimum allocation units (MAUs) set to 128 kb/s for the results reported in the following. It means that the performed allocations are not the exact solutions of the minimization problem but a very good approximation. A consequence of using MAUs is that, when the existence of the transmission rate bound has been checked through simulations in Section VII-B, the allocated transmission rate behavior versus R_{TOT} is not asymptotic. The sum of the allocations of the Z stations coincides with R^{bound}. The employment of very small MAUs, which is not shown in this paper for the sake of brevity, highlights the asymptotic behavior.

Due to the need to fully understand L_pRA behavior, performance analysis from Section VII-A to D) is performed by using $Z = 2$ ES. The number of stations is varied in Section VII-E).

TABLE II
APPLIED CODE RATES

$\left(\frac{C}{N}\right)_z [dB]$	0.0 - 1.0	1.0 - 2.0	2.0 - 3.0	3.0 - 4.0	4.0 - 5.0
CR_z	1/2	2/3	3/4	5/6	7/8

A. L_pRA Reaction to Channel Status Changes

Here, the aim is to check the reactive behavior of L_{pRA} for different weight configurations in the case of channel status variations. The performed tests consider the two ESs with the following carrier-to-noise ratio: Station 1 ($S1$) has 5 dB for the overall duration of the simulation (300 s), and Station 2 ($S2$) has 5 dB in the first 150 s and 0 dB for the rest of the simulation. Related code rates CR_z are consequently chosen according to Table II. The channel status is considered known when the allocation algorithm acts. The overall available transmission rate R_{TOT} is set equal to 4 Mb/s.

TP, in watts, is computed through (26). The packet loss referenced as packet loss rate (PLR) has been computed at each allocation period as the ratio between the number of lost and sent packets. Three weights configurations are applied to both stations ($z = 1$ and $z = 2$) to differentiate the importance of the objective functions: $w_{1,1_z} = 0.1$ and $w_{2,1_z} = 0.9$; $w_{1,1_z} = 0.5$ and $w_{2,1_z} = 0.5$; and $w_{1,1_z} = 0.9$ and $w_{2,1_z} = 0.1$. Two additional weight configurations have been implemented but will be used in Section VII-B.

$$H\left(J_p(\mathbf{R}, R_{\mathrm{TOT}})\right) = \begin{pmatrix} \frac{\partial^2 J_p(R_1,R_{\mathrm{TOT}})}{\partial R_1^2} & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \ddots & \frac{\partial^2 J_p(R_z,R_{\mathrm{TOT}})}{\partial R_z^2} & \ddots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & \frac{\partial^2 J_Z(R_Z,R_{\mathrm{TOT}})}{\partial R_Z^2} \end{pmatrix} \quad (36)$$

$$\det\left(H\left(J_p(\mathbf{R}, R_{\mathrm{TOT}})\right)\right) = \prod_{z=1}^{Z} \frac{\partial^2 J_p(R_z, R_{\mathrm{TOT}})}{\partial R_z^2} > 0. \quad (37)$$

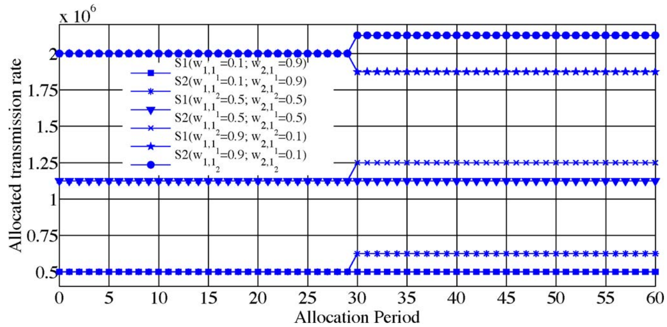

Fig. 3. Allocated transmission rate to stations $S1$ and $S2$ for different weights; $S2$ channel status changes at $t = 150$ s (30th allocation period).

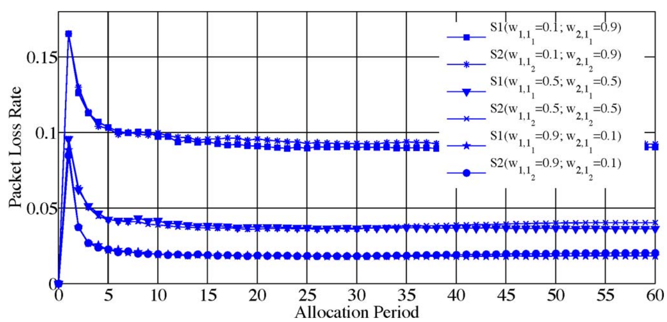

Fig. 4. PLR of stations $S1$ and $S2$ for different weights by using the allocated transmission rates in Fig. 3.

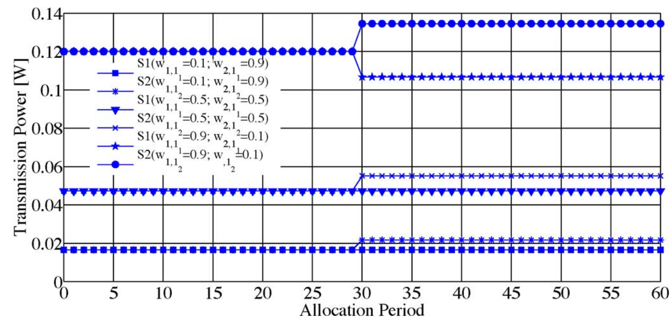

Fig. 5. TP by $S1$ and $S2$ for different weights and by using the allocated transmission rates in Fig. 3.

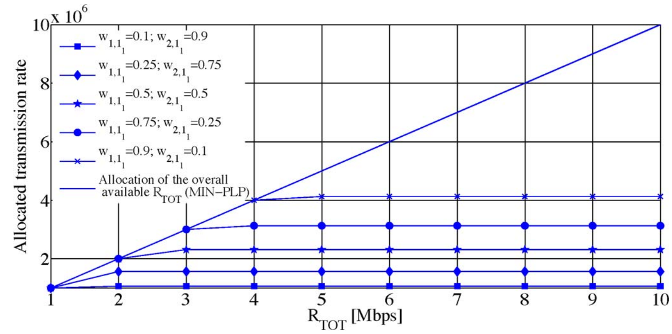

Fig. 6. Overall transmission rate allocated to $S1$ and $S2$ versus R_{TOT} for different weights configurations.

Fig. 3 reports L_pRA transmission rate allocations over time, for the two stations $S1$ and $S2$. If $t < 150$ s, both stations receive the same amount of transmission rate that depends on the applied weight configuration: When $w_{1,1_z}$ increases and stresses the packet loss importance, each station receives a larger amount of transmission rate; when $w_{2,1_z}$ makes the TP more rewarded, less of a rate is allocated to each station, thus saving power.

This general comment is still true for $t \geq 150$, but in this case, the rate allocated to $S2$ grows to compensate the penalizing channel status and the related employment of a specific code rate. $S1$ receives the same amount of rate of the $t \geq 150$ case, except for $w_{2,1_z} = 0.1$, where the rate allocated to $S1$ must decrease because the overall allocated rate is equal to R_{TOT} and increasing R_{1_2} implies, obviously, decreasing R_{1_1}.

Fig. 4 shows the PLR of both stations obtained by allocating the transmission rates in Fig. 3. PLR is approximately the same for both stations because the rate allocated to $S2$, penalized by the channel status, is larger than the rate assigned to $S1$ to compensate the reduction of the rate employed for information bits due to the use of a more protective code rate. Fig. 4 allows checking the effect of the weight configurations on the PLR. Similar comments may be reported for Fig. 5, which shows the TP of the two stations by using again the transmission rate allocations in Fig. 3. In practical use, it is hard to strike a balance between these two metrics. The use of different weights assures more flexibility in the allocation problem, to meet the preference of the service provider concerning performance metrics. For example, by observing Figs. 3–5, setting $w_{1,1_1} = 0.1$ allows allocating rates to get relevant power saving but a PLR close to 0.1, which is too high for most applications. On the other hand, setting $w_{1,1_1} = 0.09$ assures PLR of about 0.02 but larger TP. Tuning weights allows driving L_pRA allocations suitably.

B. Transmission Rate Bound and L_pRA Comparison With a Method Aimed Only at PLP Minimization

A key concept of this paper is the transmission rate bound R^{bound} to which the overall allocated transmission rate (the sum of the allocated transmission rates) converges if $R_{\mathrm{TOT}} \to \infty$.

All the tests in Figs. 6–8 assume a random channel status uniformly distributed among all possible levels in Table II. Again, the channel status is considered known when L_pRA acts. Each value in Figs. 6–8 represents the average of the values obtained by a number of simulation runs sufficient to guarantee a confidence interval of 10% with a confidence level of 95%.

Fig. 6 shows the overall transmission rate allocated to the two stations versus R_{TOT} whose value varies in the interval [1–10] Mb/s. Different weight configurations are considered. The allocation of the overall available transmission rate R_{TOT} has been reported as a reference to allow an immediate comparison with the allocation method that, keeping the same structure of the L_pRA, minimizes only PLP in (24) and ignores TP in (26). Let this allocation method be referenced as MIN-PLP in the remainder of this paper. As expected, the allocated rate stays on the constraint R_{TOT} if $R_{\mathrm{TOT}} \leq R^{\mathrm{bound}}$ and converges to R^{bound} when $R_{\mathrm{TOT}} \to \infty$ if $R_{\mathrm{TOT}} > R^{\mathrm{bound}}$. In Fig. 6, the allocated capacity if $R_{\mathrm{TOT}} > R^{\mathrm{bound}}$ is exactly R^{bound}.

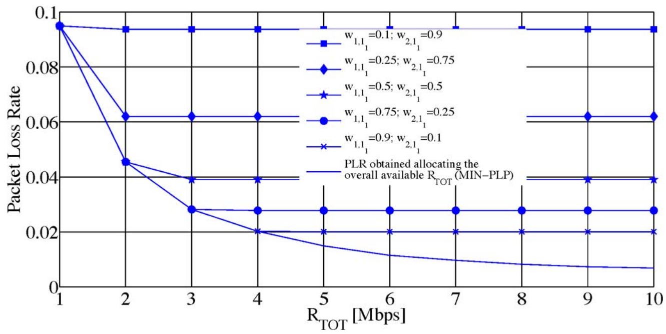

Fig. 7. PLR versus $R_{\rm TOT}$ variation by using the allocated transmission rates in Fig. 6.

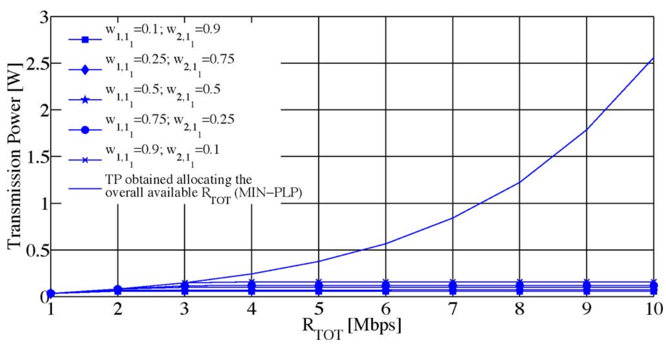

Fig. 8. TP versus $R_{\rm TOT}$ variation by using the allocated transmission rates in Fig. 6.

This is due to the used MAU value, as previously discussed. If $R_{\rm TOT} > R^{\rm bound}$, increasing $R_{\rm TOT}$ does not modify the $L_{\rm pRA}$ solution. Fig. 6 allows checking numerically the effect of the weight configurations on the transmission rate allocation and on the value of $R^{\rm bound}$, which ranges from 4.1 Mb/s, for $w_{1,1_1} = 0.1$, to 1 Mb/s, when $w_{1,1_1} = 0.9$.

Fig. 7 shows the average PLR of the overall system composed of two stations versus $R_{\rm TOT}$ by using the allocated transmission rates reported in Fig. 6. It is clear that, if $R_{\rm TOT} > R^{\rm bound}$, the PLR does not change when $R_{\rm TOT}$ increases. A similar comment may be reported for Fig. 8, which shows the TP used by the overall system versus $R_{\rm TOT}$: If $R_{\rm TOT} > R^{\rm bound}$, the TP does not change if $R_{\rm TOT}$ increases. As commented for Figs. 4 and 5, a proper tuning of weights can adapt L_pRA allocations to match application requirements.

The TP is constantly lower than 0.1 W when $R^{\rm bound} < R_{\rm TOT}$, and the overall allocated capacity is $R^{\rm bound}$. If the allocations should follow $R_{\rm TOT}$ availability, the TP would grow exponentially.

Another important observation, which is valid also if concerning the Section VII-A, is that privileging packet loss with respect to TP through suitable weight configurations does not imply a huge increase of the TP. Figs. 7 and 8 allow a comparison between $L_{\rm pRA}$ and MIN-PLP that optimizes PLR ignoring TP and obviously uses all available transmission rate $R_{\rm TOT}$. As evident in Fig. 7, and as expected, PLR obtained through MIN-PLP decreases when $R_{\rm TOT}$ increases, and its values, assumed by a full use of the available transmission rate, are lower than the PLR values guaranteed by L_pRA. On the other hand, the TP (see Fig. 8) required by MIN-PLP is higher than the one required by $L_{\rm pRA}$. This is quite obvious, but the real challenge comes from the numerical values. Is the gain concerning PLR (paid by a relevant power increase) assured by using full available rate really perceived by users? For example, looking at Figs. 7 and 8, when $R_{\rm TOT} = 7$ Mb/s, L_pRA $[w_{1,1_z} = 0.9, w_{2,1_z} = 0.1]$ guarantees PLR $= 0.02$ and TP $=$ 0.16 W; full $R_{\rm TOT}$ use assures a minimum PLR $= 0.01$ but implies using TP $= 0.86$ W. Is this relevant additional power applied at benefit of the users or is it only a waste? The answer is obviously in service level specifications, where performance requirements agreed upon between user and service provider are stated, as well as in the power availability of the provider and in its cost.

C. Performance Enhancement Analysis

Let the quantity $R_z^{\rm ref}$ be the transmission rate allocated to the zth station by the MIN-PLP method. Obviously, $\sum_{z=1}^{Z} R_z^{\rm ref} = R_{\rm TOT}$. Let the quantities $\text{PLR}_z(R_z^{\rm ref})$ and $\text{TP}_z(R_z^{\rm ref})$ be, respectively, the PLR and the TP of the zth station obtained by allocating $R_z^{\rm ref}$.

With the transmission rate allocated by $L_{\rm pRA}$ being $R_{\rm all}$ in (17) because physical and virtual entities are undifferentiated ($y_z = z$), as said at the beginning of Section V, we can write $R_{\rm all} = (R_{1,\rm all}, \ldots, R_{z,\rm all}, \ldots, R_{Z,\rm all})$, where $R_{z,\rm all}$ is the transmission rate allocated by L_pRA to the zth ES.

It is true that

$$\sum_{z=1}^{Z} R_{z,\rm all} \leq R^{\rm bound} \tag{39}$$

but if $R_{\rm TOT} \geq R_{\rm bound}$

$$\sum_{z=1}^{Z} R_{z,\rm all} \approx R^{\rm bound}. \tag{40}$$

In the presented results, we have equality for the explained reasons linked to MAUs. We define the quantity transmission rate gain (TRG) (41) as the percentage of saved transmission rate obtained by using L_pRA with respect to MIN-PLP, i.e.,

$$\text{TRG} = \frac{\left| R_{\rm TOT} - \sum\limits_{z=1}^{Z} R_{z,\rm all} \right| \cdot 100}{R_{\rm TOT}}. \tag{41}$$

A practical consequence of the TRG obtained through L_pRA is the possibility to serve additional stations over the same channel, without increasing $R_{\rm TOT}$ and without a degradation (or with a forecast and expected degradation) of the performance perceived by the users. Even if the real number depends on the channel conditions, an estimation of the average number of additional stations allowed by L_pRA is contained in the following:

$$N\Big(R_{\rm TOT}, \sum R_{z,\rm all}, Z\Big) = \left\lfloor \left(R_{\rm TOT} - \sum_{z=1}^{Z} R_{z,\rm all}\right) \cdot \frac{Z}{\sum_{z=1}^{Z} R_{z,\rm all}} \right\rfloor \tag{42}$$

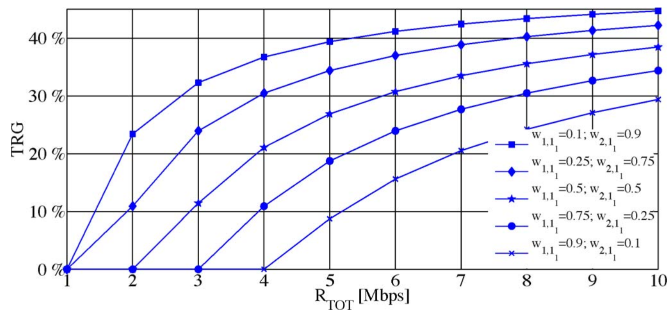

Fig. 9. TRG in (41).

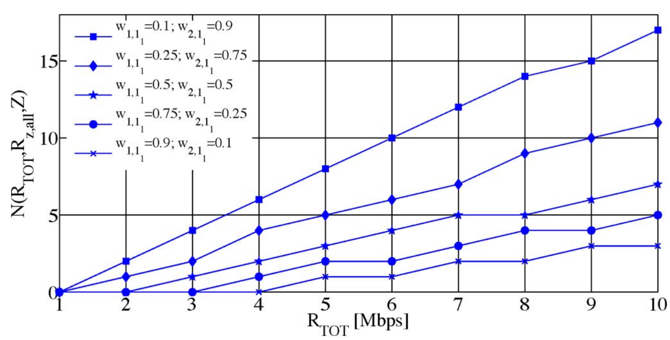

Fig. 10. Average number of possible additional ESs in (42) by using the allocated transmission rates in Fig. 6.

where Z is the overall number of ESs. Fig. 9 shows TRG versus R_{TOT} for different weights by using the transmission rates in Fig. 6.

Fig. 10 shows the average number of possible additional ESs in (42) versus R_{TOT}, again for different weights and by using the allocated transmission rates in Fig. 6.

D. Comparison With Other Approaches

We report a performance comparison among sum capacity maximization (SCM) in (2), PM in (3), and L_pRA. R_{TOT}, which does not influence SCM and PM methods because they use bandwidth and power, has been set to $R_{\mathrm{TOT}} = 3$ Mb/s.

Moreover, in this case, the performed tests consider two ESs characterized by random fading levels uniformly distributed among all possible levels shown in Table II. The code rate is chosen consequently. Again, the fading level is considered known when the allocation is performed. The obtained values are the average of the values obtained by a number of simulations that guarantee a confidence interval of 10% with a confidence level of 95%. Weights α in (2), β in (3), and w in (31) are fixed to 0.5 for each station (i.e., $\alpha_1 = \alpha_2 = \beta_1 = \beta_2 = w_{1,1_1} = w_{2,1_1} = 0.5$). The total amount of bandwidth W_{TOT} employed by SCM and PM is kept constant and equal to 1 MHz. Two values of power availability P_{TOT} (1 and 2 W) have been considered as SCM constraint. In the PM case, we employed two possible transmission rate thresholds R_{th}: 1 and 1.5 Mb/s.

Table III reports the globally allocated transmission rate, the metrics PLR and TP (in watts), both referred to the overall system of two stations, as well as the execution time (in seconds), for L_pRA, SCM, and PM.

The minimum PLR, which is approximately 0.03, is obtained by PM (with $R_{\mathrm{th}} = 1.5$ Mb/s). L_pRA allows a satisfying PLR $= 0.039$. On the contrary, SCM, concerning PLR, provides incompatible results with many applications. In practice, SCM gives the overall bandwidth W_{TOT} to the less faded station, and as a consequence, the other station experiences relevant losses.

Concerning TP, the minimum value is obtained by L_pRA. SCM uses all available power (i.e., TP is equal to the power constraint). PM, in the case of $R_{\mathrm{th}} = 1.5$ Mb/s, uses much more capacity and obviously more power, whereas in the case of $R_{\mathrm{th}} = 1$ Mb/s, it uses less transmission rate, thus requiring less power. This last case is interesting because, although it keeps power at 0.08 W, it assures a PLR $= 4\%$. Considering these metrics, it is possible to conclude that L_pRA, which guarantees PLR $= 3.9\%$ and TP $= 0.1$ W, and PM $R_{\mathrm{th}} = 1$ Mb/s provide a good performance compromise. In summary, referring to the metrics PLR and TP, SCM seems not suitable for the operative environment of this paper; maximizing the weighted sum of downlink transmission rates implies getting allocations that privilege less faded stations and that lead to huge PLR values. Working on weights may mitigate this drawback. PM can be very efficient in this environment. The constraint R_{th} allows controlling the PLR. Minimizing the power is the aim of the allocation scheme. The drawback is that R_{th} update and related PLR control are not automatically performed within PM. R_{th} is a parameter that PM uses as a threshold. Its computation may be either heuristic or analytical, but it is not part of PM allocation. In L_pRA, even if it cannot assure to give a threshold on PLR and/or on TP because it does not use fixed constraints (obviously except for the maximum available transmission rate), minimizing, jointly, PLR and TP, allows getting allocations (tunable through weights) that are a satisfactory performance compromise. Another key point to be considered for comparison is represented by the computational complexity. The last row of Table III reports the time spent during the overall simulation time (of 300 s) for the considered resource allocations. With the allocation period being 5 s, each reported value represents the time needed to execute 60 allocations. Shown values consider also specific operations of the simulator (e.g., READ/WRITE log files) not included in real systems, but this is true for all considered resource allocation approaches. PM assures the best performance: 0.07/0.08 s. L_pRA requires a slightly higher execution time, i.e., 0.2 s. In SCM, the execution time is larger because, with this algorithm, both power and bandwidth are allocated, and there are two control variables involved in the optimization problem.

E. L_pRA Performance Analysis by Using Multiple Stations

L_pRA performance is analyzed by using more than two ESs. The tests are performed as done in Section VII-B assuming a random channel status, uniformly distributed among all levels shown in Table II, and assigning a consequent code rate for all involved stations whose number varies in the range $Z = [2, 4, 6, 8, 10]$. Values for $Z = 2$, which have already been shown in

TABLE III
COMPARISON AMONG RESOURCE ALLOCATION APPROACHES

Metrics	L_pRA	SCM ($P_{TOT} = 1$ [W])	SCM ($P_{TOT} = 2$ [W])	PM ($R_{th} = 1$ [Mbps])	PM ($R_{th} = 1.5$ [Mbps])
Allocated Transmission Rate [Mbps]	2.2	3.7	4.7	2	3
Packet Loss Rate	0.039	0.15	0.12	0.04	0.03
Transmission Power [W]	0.1	1	2	0.08	0.14
Execution Time [s]	0.2	3.5	12	0.07	0.08

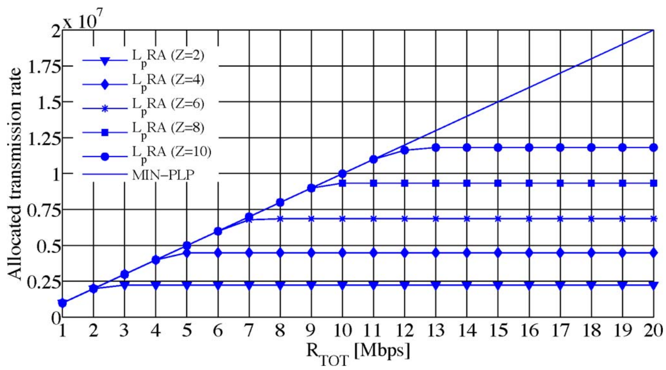

Fig. 11. Overall transmission rate allocated to different number of stations versus R_{TOT}, using L_pRA with $w_{1,1_1} = w_{2,1_1} = 0.5$ and MIN-PLP.

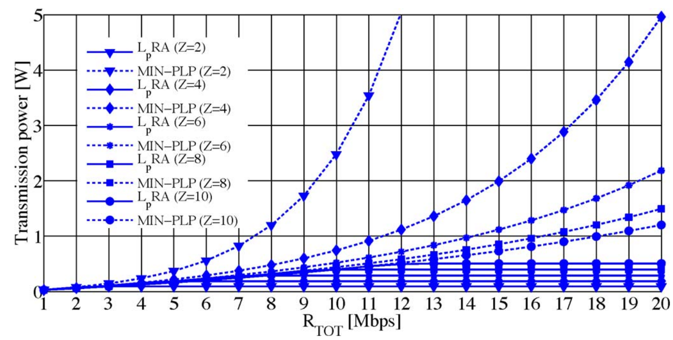

Fig. 13. TP versus R_{TOT} variation by using the allocated transmission rates in Fig. 11.

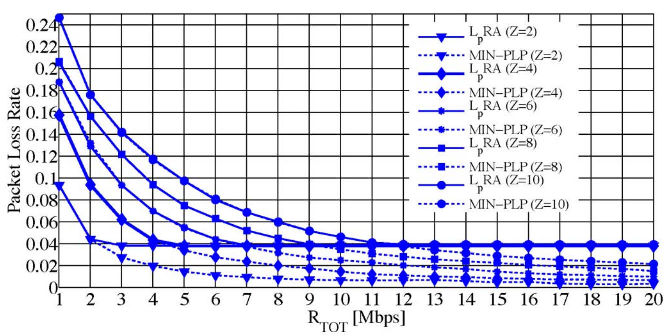

Fig. 12. PLR versus R_{TOT} variation by using the allocated transmission rates in Fig. 11.

Section VII-B, are reported again for the sake of comparison. L_pRA weights are set as follows: $w_{1,1_z} = w_{1,1_z} = 0.5 \, \forall \, z$.

Fig. 11 shows the overall transmission rate allocated to the Z stations for L_pRA and MIN-PLP. The trend is exactly the same for each Z value, and the comments reported for Fig. 6 are still valid. Additionally, we can say that, given that MIN-PLP globally allocates R_{TOT} independently of the number of stations, each station receives less transmission rate when Z increases. The effect on the performance metrics is clear in Figs. 12 and 13, which show, respectively, PLP and TP values referred to the overall system composed of Z stations and corresponding to the allocations in Fig. 11: PLP increases, and TP decreases with the number of stations. L_pRA behavior is the same if $R_{\mathrm{TOT}} < R_{\mathrm{bound}}$, but when $R_{\mathrm{TOT}} \geq R_{\mathrm{bound}}$, L_pRA allocations converge to R_{bound}, whose value, as obvious from (23), increases with Z, the number of stations. Consequently, L_pRA PLP (Fig. 12), when $R_{\mathrm{TOT}} \geq R_{\mathrm{bound}}$, is also independent of the number Z of stations. L_pRA TP values are shown in Fig. 13 for different Z values.

VIII. CONCLUSION

This paper has introduced the L_pRA, which is aimed at allocating transmission rates among the ESs of a satellite network suited to be employed in emergency situations. The network is composed of different MNs accessing the satellite channel through an MSG. The obtained allocation is representative of a compromise between packet loss and TP, which are simultaneously considered as performance metrics. This paper has highlighted the existence of a rate bound independent of the overall available rate R_{TOT}, to which the L_pRA allocations converge when $R_{\mathrm{TOT}} \to \infty$. The proposed performance analysis is obtained through simulations for scenarios composed of ESs characterized by different fading conditions. It analyses the L_pRA reaction to changes in the channel status, compares L_pRA with a method aimed only at PLP minimization, evaluates the practical effect of the rate bound on the performance metrics, compares L_pRA with two allocation schemes in the literature, and shows L_pRA behavior in the case of multiple ESs.

The obtained results allow the conclusion that L_pRA provides satisfactory performance both in terms of computational complexity and of PLP and TP. The obtained values are compatible with the requirements of most practical applications.

APPENDIX

For the sake of completeness, the proof of the Pareto optimality of the L_p problem solution, if $\sum_{k=1}^{M_{y_z}} w_{k,y_z} = 1$, $w_{k,y_z} > 0 \, \forall \, k \in [1, M_{y_z}]$, $\forall \, y_z \in [1, Y_z]$, $\forall \, z \in [1, Z]$, is now reported. It is worth noticing that the proposed proof is well known [19]. It has been formulated here by using the model proposed in Section III-D. The solution of the weighted L_p-problem (when $1 < p < \infty$) is Pareto optimal if either the solution is unique or all the weight coefficients are positive. We start from the second condition and remember that the L_pRA problem, which is defined in (15), can be written as follows:

$$\arg\min \left(\sum_{z=1}^{Z} \sum_{y=1}^{Y_z} \sum_{k=1}^{M_{y_z}} w_{k,y_z} \left| F_{k,y_z}(\mathbf{R}^{F_{k,y_z}}) - \right.\right.$$
$$\left.\left. + F_{k,y_z,\mathrm{id}}\left(\mathbf{R}_{\mathrm{id}}^{F_{k,y_z}}\right) \right|^p \right)^{\frac{1}{p}}$$
$$\text{subject to } \sum_{z=1}^{Z} \sum_{y=1}^{Y_z} \sum_{k=1}^{M_{y_z}} \mathbf{R}^{F_{k,y_z}} \leq R_{\mathrm{TOT}}. \tag{43}$$

Let $\mathbf{R}_{\mathrm{opt}}^{F_{k,y_z}}$ be a solution of the problem proposed in (43), with $w_{k,y_z} > 0\, \forall\, k \in [1,\ldots,M_{y_z}]\, \forall\, y \in [1,\ldots,Y_z]$ and $\forall\, z \in [1,\ldots,Z]$.

Supposing that $\mathbf{R}_{\mathrm{opt}}^{F_{k,y_z}}$ is not a POP, $\mathbf{R}^{F_{k,y_z}}$ should exist such that

$$\begin{aligned} &\left| F_{k,y_z}(\mathbf{R}^{F_{k,y_z}}) - F_{k,y_z,\mathrm{id}}\left(\mathbf{R}_{\mathrm{id}}^{F_{k,y_z}}\right) \right|^p \\ &\quad \leq \left| F_{k,y_z}\left(\mathbf{R}_{\mathrm{opt}}^{F_{k,y_z}}\right) - F_{k,y_z,\mathrm{id}}\left(\mathbf{R}_{\mathrm{id}}^{F_{k,y_z}}\right) \right|^p \\ &\quad \forall\, k \in [1,\ldots M_{y_z}],\ \forall\, y \in [1,\ldots Y_z]\ \forall\, z \in [1,\ldots Z] \end{aligned} \tag{44}$$

$$\begin{aligned} &\left| F_{k,y_z}(\mathbf{R}^{F_{k,y_z}}) - F_{k,y_z,\mathrm{id}}\left(\mathbf{R}_{\mathrm{id}}^{F_{k,y_z}}\right) \right|^p \\ &\quad < \left| F_{k,y_z}\left(\mathbf{R}_{\mathrm{opt}}^{F_{k,y_z}}\right) - F_{k,y_z,\mathrm{id}}\left(\mathbf{R}_{\mathrm{id}}^{F_{k,y_z}}\right) \right|^p \\ &\quad \text{for at least one } k\ \in [1,\ldots,M_{y_z}], y \in [1,\ldots Y_z] \\ &\quad z \in [1,\ldots,Z]. \end{aligned} \tag{45}$$

Since $w_{k,y_z} > 0,\ \forall\, k \in [1,\ldots,M_{y_z}]\ \forall\, y \in [1,\ldots,Y_z]\ \forall\, z \in [1,\ldots,Z]$, we have

$$\begin{aligned} &\sum_{z=1}^{Z} \sum_{y=1}^{Y_z} \sum_{k=1}^{M_{y_z}} w_{k,y_z} \left| F_{k,y_z}(\mathbf{R}^{F_{k,y_z}}) - F_{k,y_z,\mathrm{id}}\left(\mathbf{R}_{\mathrm{id}}^{F_{k,y_z}}\right) \right|^p \\ &\quad < \sum_{z=1}^{Z} \sum_{y=1}^{Y_z} \sum_{k=1}^{M_{y_z}} w_{k,y_z} \left| F_{k,y_z}\left(\mathbf{R}_{\mathrm{opt}}^{F_{k,y_z}}\right) - F_{k,y_z,\mathrm{id}}\left(\mathbf{R}_{\mathrm{id}}^{F_{k,y_z}}\right) \right|^p. \end{aligned} \tag{46}$$

This contradicts the assumption that $\mathbf{R}_{\mathrm{opt}}^{F_{k,y_z}}$ is a solution of the weighted problem; thus, $\mathbf{R}_{\mathrm{opt}}^{F_{k,y_z}}$ must be Pareto optimal. (q.e.d.)

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