Power Saving Bandwidth Allocation over GEO Satellite Networks

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***Abstract*—The problem of bandwidth allocation may be simply stated, independently of the target of the allocation: an amount of bandwidth must be shared among different entities. Each entity receives a portion of the overall bandwidth. Bandwidth allocation may be formalized as a Multi-Objective Programming (MOP) problem where the constraint is the maximum available bandwidth. The objectives of the allocation such as loss and power may be modelled through a group of objective functions possibly contrasting with each other. It is quite intuitive that using more bandwidth will reduce losses, but also that transmitted power will increase with the bandwidth. Which is the balance among these needs? This letter proposes an extended model for bandwidth allocation and uses a modified version of a MOP-based bandwidth allocation [1] to provide a possible solution to the mentioned balancing problems.**

***Index Terms*—Bandwidth allocation, multi-objective programming, power and bandwidth saving, satellite communications.**

I. Introduction

THIS letter defines bandwidth allocation as a competitive problem where each entity accessing the shared available bandwidth is "represented" by a group of cost functions that need to be minimized at cost of the others. Cost functions model physical quantities such as data loss and transmitted power, possibly in contrast with each other, versus bandwidth. If this happens, the allocated bandwidth must necessarily be a compromise. Modeling bandwidth allocation as described allows using Multi-Objective Programming (MOP) theory, which defines the multi-objective optimization problem and the set of Pareto Optimal Points (POPs). Each POP is often referred to a vector analogue for optimal solutions because the optimal solution for MOP is not defined. Optimal bandwidth allocations are chosen among POPs. Even if each POP is optimal from Pareto viewpoint, we must allocate a precise amount of bandwidth to each entity, to retain one single point as a solution. This is often recommendable, mandatory in bandwidth allocation. The action of selecting one solution among the POP set is called "decision making" and is performed by a "decision maker" which can express preferences among alternatives. A possibility, used in this letter, is minimizing the square value of the Euclidean distance with a reference goal point. The solution is called Utopia Minimum Distance (UMD) allocation [1]. The letter formalizes an extended model for bandwidth allocation, and introduces a modified version of the UMD allocation called W-UMD (Weighted-UMD). W-UMD provides a flexible compromise to find a balance between different performance metrics, such as loss and power, and to differentiate the importance of the single metrics in dependence of provided service and providers' / users' needs. Other schemes in the literature are not directly comparable with our proposal; they do not assign bandwidth trying to keep low packet loss and power within the MOP framework; they allocate bandwidth by minimizing power with minimum bandwidth constraints to assure performance requirements [2], or they allocate constrained power and bandwidth [3], [4]. It does not mean that a comparison cannot be done, but that the comparison should concern the overall communication-control system. This issue is left to further research. The rest of the letter is structured as follows. The next section presents the extended model for bandwidth allocation as a MOP problem. Section III shows that the use of the overall bandwidth or not depends on the form of the objective functions. This concept was not focused before in the literature to the best of our knowledge. Section IV presents the W-UMD approach. Section V describes the models for loss and transmitted power used in this letter and presents the performance of W-UMD through simulation results. Section VI contains the conclusions.

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II. Bandwidth Allocation Model

A. Introduction

The model proposed in this letter is an extension of the model proposed in [1] and in [5] and is based on three main components: physical entities, virtual entities, and objective functions. [1] introduces the bandwidth allocation based on physical entities and objective functions; [5] opens the door to the concept of virtual entity by using more than one buffer for physical entity even if the term virtual entity is never mentioned. The main differences introduced by this letter concerning the model are the full formalisation of virtual entities and the introduction of a variable number of objective functions for each virtual entity. A physical entity is a device such as a satellite earth station. A virtual entity is a component within a physical device such as a single buffer-server. Each virtual entity is represented by a group of objective functions that model performance parameters such as, for instance, loss and power consumption. Bandwidth allocations are performed by a centralized entity: an overall bandwidth C_{TOT}, shared by all physical entities, is partitioned and assigned to virtual entities in dependence on the objective functions value. An example may be a satellite station composed of two buffers where each buffer receives a specific bandwidth allocation. The two buffers are two virtual entities.

B. Definitions

Z is the total number of physical entities; each physical entity is identified by $z \in [1, Z]$. Y_z is the number of virtual entities of the $z-th$ 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 is identified by the index $m_{y_z} \in [1, M_{y_z}]$. C_{y_z} is the bandwidth allocated to the virtual entity y of the physical entity z.

$$C = (C_{1_1}, C_{2_1}, C_{3_1}, ..., C_{Y_1}, ..., C_{1_Z}, C_{1_Z}, C_{1_Z}, ..., C_{Y_Z}) \quad (1)$$

is the vector that contains the bandwidth allocated to each virtual entity. It is the decision variable vector. $C_z = \sum_{y=1}^{Y_z} C_{y_z}$ is the bandwidth allocated to physical entity z. $F_{m,y_z}(C)$ is the $m-th$ objective function of the $y-th$ virtual entity of the $z-th$ physical entity. The full set of objective functions is contained in the vector

$$F(C) = \Big(F_{1,1_1}(C), ..., F_{M_{1_1},1_1}(C), ..., F_{1,Y_z}(C), ..., F_{M_{Y_Z},Y_Z}(C)\Big) \quad (2)$$

C. Formalization of bandwidth allocation problem

Given the definitions above and given C_{TOT} the available physical bandwidth, shared by all Z entities, the following constraint must hold:

$$\sum_{z=1}^{Z} \sum_{y=1}^{Y_z} C_{y_z} \leq C_{TOT} \quad (3)$$

The equality in (3) means that the available bandwidth is fully used. Bandwidth allocation is defined as a MOP problem through (4), which must be solved under the constraint (3).

$$\begin{aligned} C_{opt} = (&C_{1_1,opt}, C_{2_1,opt}, .., C_{Y_1,opt}, .., \\ &C_{1_Z,opt}, C_{2_Z,opt}, .., C_{Y_Z,opt}) = \arg\min_{C} F(C); \\ &C_{y_z} \geq 0, \forall y_z \in [1, Y_z]. \forall z \in [1, Z] \end{aligned} \quad (4)$$

III. About the Structure of the Objective Functions

The set of solutions deriving from (4) is called POP set. In general, getting the overall POP set is not simple but the structure of the objective functions helps take decision in some cases. For example, it is simple to prove that given the problem (4), subject to the constraint (3), if all objective functions are strongly decreasing [6], i.e. decreasing for all its variables and strictly decreasing for at least one function and one variable, then a solution C is a POP if and only if the solution is on the constraint boundary $\sum_{z=1}^{Z} \sum_{y=1}^{Y_z} C_{y_z} = C_{TOT}$. This is the case we have considered in [1], [5]. It is also true that, given inequality constraint (3), 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 and also points for which $\sum_{z=1}^{Z} \sum_{y=1}^{Y_z} C_{y_z} < C_{TOT}$ 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 packet loss, packet delay and packet jitter rates are quantities that decrease their values when the allocated bandwidth value increases. This is not true if also other important metrics are used: power, but also processing and computation effort. It is simple to prove that, given problem (4) and constraint (3), if at least one function is strongly increasing, i.e. increasing for all its variables and strictly increasing for at least one variable, then a solution C on the constraint ($\sum_{z=1}^{Z} \sum_{y=1}^{Y_z} C_{y_z} = C_{TOT}$) may be not a POP. From the communication system viewpoint this is an important result because it means that the optimal POP bandwidth allocation may not use all available bandwidth. On the other hand, only the strongly decreasing hypothesis allows defining the overall POP set. So, to make a decision about the bandwidth allocation when there are also strongly increasing objective functions we need to find at least one solution of problem (4) constrained by (3).

IV. W-UMD Bandwidth Allocation

In this letter we minimize the square value of the Euclidean distance with a generic reference goal point, which gives origin to a POP solution [6]. The idea is to allocate bandwidth so that the value of each objective function is as close as possible to its ideal value. The set of ideal capacities, i.e. the ideal vector (5) composed of the ideal decision variable vector elements $C_{y_z,id}^{F_{k,y_z}}$ for which F_{k,y_z} attains the minimum value, may be known having information about the features of the objective functions, as explained in the following. This definition of the ideal capacities set is not the only choice, e.g., if hard constraints on metrics were given, the ideal vector may contain the minimum bandwidth allocations so to assure these constraints.

$$\begin{aligned} C_{id}^{F_{k,y_z}} = &\Big(C_{1_1,id}^{F_{k,y_z}}, C_{2_1,id}^{F_{k,y_z}}, ..., C_{Y_1,id}^{F_{k,y_z}}, ..., \\ &C_{1_Z,id}^{F_{k,y_z}}, C_{2_Z,id}^{F_{k,y_z}}, ..., C_{Y_Z,id}^{F_{k,y_z}}\Big) \\ &\forall k \in [1, M_m], \forall y_z \in [1, Y_z], \forall z \in [1, Z] \end{aligned} \quad (5)$$

Each element $C_{y_z,id}^{F_{k,y_z}}$ can assume a value between 0 and C_{TOT}, independently of any physical constraint and of the values of the other components of vector (5). It is called ideal (utopian) for this. For example, if a generic objective function is decreasing versus bandwidth, it is obvious that it is ideal allocating all the possible bandwidth C_{TOT}, while if it is increasing versus bandwidth, it is ideal allocating no bandwidth at all. The values of vector (5) are considered known in the remainder of the paper. Vector in (6) contains each objective function attaining its ideal value.

$$F_{id} = \left(F_{1,1_1,id}\left(C_{id}^{F_{1,1_1}}\right), ..., F_{k,y_z,id}\left(C_{id}^{F_{k,y_z}}\right), ..., F_{M_{Y_Z},Y_Z,id}\left(C_{id}^{F_{M_{Y_Z},Y_Z}}\right)\right) \quad (6)$$

The allocated optimal bandwidth based on the minimum distance with the ideal vector (6) is called Weighted - Utopia

Minimum Distance (W-UMD) and is reported in (7).

$$C_{all} = (C_{1,all}, C_{2_1,all}, ..., C_{Y_1,all}, ..., C_{1_Z,all}, C_{2_Z,all}, ..., C_{Y_Z,all}) = \arg\min_{C \subset C_{opt}} \left(\sqrt{\sum_{z=1}^{Z} \sum_{y=1}^{Y_z} \sum_{k=0}^{M_{y_z}} \alpha_{k,y_z} \left(F_{k,y_z}(C) - F_{k,y_z,id}\left(C_{id}^{F_{k,y_z}}\right)\right)^2} \right)^2 \quad (7)$$

where $\sum_{k=0}^{M_{y_z}} \alpha_{k,y_z} = 1$ and $\alpha_{k,y_z} \geq 0, \forall k \in [1, M_y]$, $\forall y_z \in [1, Y_z], \forall z \in [1, Z]$ so to assure the Pareto optimality of the solution as indicated in reference [6, p. 98]. L_2 norm seems to represent a good compromise between performance and computational complexity; it has been preferred to L_1 because it allows saving more bandwidth without penalizing one of the used performance metric (packet loss) too much and to L_p, $p > 2$, because assures better performance metric and lighter computational load. The use of weights α_{k,y_z} allows allocating bandwidth to virtual entities by differentiating the importance of the performance metrics for different virtual entities up to neglecting one or more metrics, if necessary. This may be important to give more elasticity to bandwidth allocation also in dependence on the provided service (e.g., telephony, video-conferencing, audio/video streaming, web transactions) and on the provider and user requirements (e.g., bandwidth and energy costs, objective performance metrics versus P-QoS), user will to pay on different P-QoS, user reaction to P-QoS changes.

V. Objective Functions and Results

The *ns2* simulator is used for W-UMD performance evaluation. A satellite network composed of 2 earth stations (Station 1 and 2) modeled as single buffers (as a consequence, physical and virtual entities are not differentiated) is simulated. C_{TOT} is 12582912 [bit/s]. For each entity two objective functions are defined to model the physical quantities: *i)* packet loss probability due to congestion ($F_{1,1_z}$) and *ii)* transmitted power ($F_{2,1_z}$). The former is modeled through $F_{1,1_z} = k_z \cdot N_z^2 \cdot (R_z C_z rtt_z/l + Q_z)^{-2}$, a decreasing function versus allocated bandwidth taken from [7], which employs only TCP traffic generated by persistent FTP acting at application layer. For each entity the number of active TCP connections N_z is 10, the buffer size Q_z is 10 packets of $l = 1500$ Byte and the Round Trip Time rtt_z is 512 [ms]. k_z, set to $128/81$ in this paper, is a constant depending on TCP parameters. Concerning the transmitted power, the inverse of the *Carrier-to-Noise ratio* $(Carrier/Noise)_z = [(P_t \eta_t A_t \eta_r A_r)/(k T_n W_z)](f_c/(c \cdot h))^2$, from [8], applied to the satellite up-link, is used. Chosen the modulation and its spectral efficiency, the transmitted power $P_t = F_{2,1_z}$ can be written in terms of bit rate, here supposed equal to the bandwidth allocated to the entity. The transmitted power is an increasing function versus allocated bandwidth. Link budget parameters, equal for each station, are: satellite altitude $h = 36,000$ [Km], carrier frequency $f_c = 25$ [GHz], terrestrial antennas area $A_t = 3.5[m^2]$, satellite antenna area $A_r = 0.5[m^2]$, antennas efficiencies $\eta_t = \eta_r = 0.7$. Noise is supposed AWGN. Noise temperature T_n is 500K. c is the light speed and k is the Boltzmann constant. BPSK modulation is applied and, considering the whole transmission system ideal, its spectral efficiency is 1 [b/s/Hz]. As a consequence W_z, expressed in [Hz], is equal to C_z, expressed in [b/s]. Channel conditions vary over the time and, in this letter, the experienced *Carrier/Noise* for each station represents the satellite channel status. Each satellite station is supposed to apply different code rates dynamically depending on the channel status. Code rates are assigned as in Table I.

TABLE I
Applied Code Rates

$Carrier/Noise$ $[dB]$	4.25-4.75	4.75-5.25	5.25-5.75	5.75-6.25	6.25-6.75
Code Rate R_z	1/2	2/3	3/4	5/6	7/8

TABLE II
Allocated Bandwidth [bit/s]

Simulation phase in $[s]$	Station 1 Loss Only	Station 1 Loss and Power	Station 2 Loss Only	Station 2 Loss and Power
$0 \leq t \leq 150$	6291456	2621440	6291456	2621440
$150 < t \leq 300$	5242880	2621440	7340032	3538944

Performed tests simulate 300 [s] of network behavior. The following *Carrier/Noise* ratios are experienced for the two stations: for Station 1, 6 [dB], constant during all tests; for Station 2, 6 [dB], in the first 150 [s] and 4.5 [dB] in the second part of the test. *Carrier/Noise* value is considered known when the allocation algorithm acts (each 5 [s]). If low code rates are applied, a significant portion of capacity is dedicated to redundancy and, as a consequence, to maintain good levels of packet loss probability, more bandwidth is needed. On the other hand, transmitting with higher bit rates implies greater power consumptions. Two cases are considered in the tests: “Loss only”, where the power is not explicitly considered as an objective function (i.e., its weight is 0); “Loss and Power” , where packet loss probability and transmitted power are simultaneously considered and the weights of each objective function are equal to 1/2. Evaluated metrics are: *i)* Transmitted Power [W] (TP) computed through the objective function itself; *ii)* Packet Loss Rate (PLR) measured at each allocation period as the number of lost packets over the number of sent packets; *iii)* Allocated Bandwidth (AB) in [bit/s]. Table II shows the allocated bandwidth for $0 \leq t \leq 150$ and $150 < t \leq 300$ [s]. When power is not considered and the aim is minimizing losses, the amount of allocated bandwidth is much larger. Considering power has the obvious effect of saving bandwidth. The transmitted power, which is proportional to the allocated bandwidth for the model used, is shown in Fig. 1. Clearly, the amount of transmitted power is much lower when the power is part of the allocation objectives. The information contained in Fig. 1 is more interesting if analyzed with Fig. 2, which contains the packet loss rate in the same situation. The loss performance of the two stations is practically the same. It is interesting to note that, even if higher than the “Loss only” case, the packet loss rate in the “Loss and Power” test is very satisfying. After few initial seconds, it is

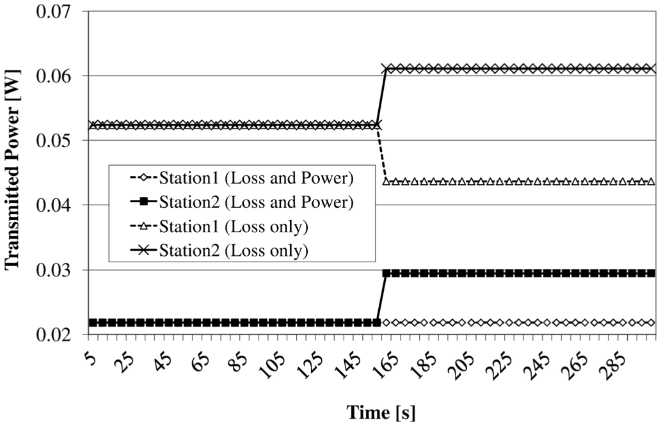

Fig. 1. Transmitted power over time.

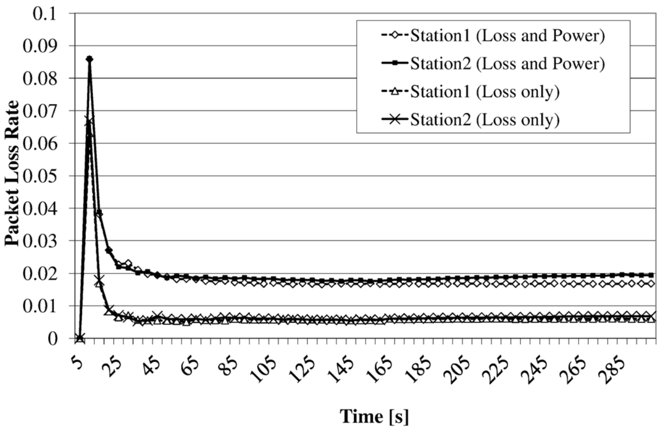

Fig. 2. Packet loss rate over time.

constantly below 2% and this assures full operative conditions for many practical applications even if may not be sufficient for specific cases. Combined with the low transmitted power shown in Fig. 1, this result makes the allocation, which is a compromise between loss and power needs, provided by W-UMD really satisfying from a practical viewpoint.

It is worth noticing from Table II that W-UMD does not employ the overall available capacity in the "Loss and Power" case. When the loss is the only aim, channel capacity is fully employed but, when power is also part of the objectives, only 41.67% of the overall bandwidth is used by the two stations when time is below 150 [s] and only 48.96% after channel status change when time is above 150 [s]. Saved resources could be exploited by other stations, if present. Allocation is much more flexible when weights are used. Table III shows Allocated Bandwidth (AB), Packet Loss Rate (PLR), and Transmitted Power (TP), averaged over the entire simulation duration described above, for station 1 (Stat1) and station 2 (Stat2) by varying the loss probability function weight, kept the same for both stations $\alpha_{1,1_1} = \alpha_{1,1_2}$. Obviously, $\alpha_{2,1_1} = 1 - \alpha_{1,1_1}$ and $\alpha_{2,1_1} = \alpha_{2,1_2}$. A minimum bandwidth allocation of 1024 [bit/s] is always guaranteed. It is interesting to see the variation of power and loss values when the relative importance of the two metrics is changed through the weights. Anyway, not considering the extreme cases of ignoring one of the metrics by setting the relative weight to 0, in all cases power and capacity savings are not severely paid in terms of PLR, which is always below 2.5%. In numerical

TABLE III
AVERAGE PERFORMANCE WITH VARIABLE WEIGHTS

$\alpha_{1,1_1} = \alpha_{1,1_2}$	0	0.25	0.5	0.75	1
AB Stat1	1024	2097152	2621440	3145728	5784644
AB Stat2	1024	2477260	3064900	3652539	6798267
PLR Stat1	1	0.0249	0.0187	0.0148	0.0069
PLR Stat2	1	0.0259	0.0200	0.0161	0.0073
TP Stat1	8.524E-06	0.0174	0.0218	0.0261	0.0481
TP Stat2	8.524E-06	0.0206	0.0255	0.0304	0.0565

terms, it is possible saving from 40% ($\alpha_{1,1_1} = 0.75$) to 60% ($\alpha_{1,1_1} = 0.25$) of transmitted power and about the same percentage of capacity with respect to the "Loss only" case, also keeping the packet loss on values acceptable for many (even if not all) applications.

VI. CONCLUSION

This letter proposes a bandwidth allocation called W-UMD, which allows optimizing different objective functions representative of virtual entities related to physical entities and allows differentiating them through weights. The paper key points highlighted in the performance evaluation are: W-UMD provides a very good compromise between loss and power needs; W-UMD is made flexible by the presence of weights.

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