INTERNATIONAL JOURNAL OF SATELLITE COMMUNICATIONS AND NETWORKING
Int. J. Satell. Commun. Network. 2013; **31**:123–139
Published online 7 March 2013 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/sat.1024

Dynamic uplink frame optimization with adaptive coding and modulation in DVB-RCS2 satellite networks

Antonio Pietrabissa*,† and Andrea Fiaschetti

Dept. of Computer, Control, and Management Engineering 'Antonio Ruberti', University of Rome 'Sapienza', via Ariosto 25, 00185 Rome, Italy

SUMMARY

In the current generation of satellite networks, modulation and coding schemes can be dynamically changed in real-time to face different link conditions. Therefore, the link budget is not anymore required to be computed under the worst case, with relevant advantages in terms of efficiency. The new digital video broadcasting-return channel via satellite 2 standard extends the dynamic modulation and coding to the return link: by using different modulation and coding schemes within the uplink frame, the terminals experiencing good link conditions transmit at very high bitrates, whereas the terminals experiencing fade events transmit at lower bitrates. This paper addresses the problem of optimizing the uplink frame modulation and coding schemes based on the current link conditions experienced by the terminals and on their transmission capacity requirements. The problem is formulated as an Integer Program and an efficient Linear Program approximation is proposed. Simulation results validate the proposed approach. Copyright © 2013 John Wiley & Sons, Ltd.

Received 18 June 2012; Revised 19 November 2012; Accepted 10 January 2013

KEY WORDS: DVB-RCS2; ACM; frame optimization; integer programming; linear programming

LIST OF ACRONYMS

ACM	Adaptive coding and modulation
CRA	Constant rate assignment
DRA	Dynamic rate adaptation
DAMA	Demand assignment multiple access
DVB-S	Digital video broadcasting-satellite
DVB-RCS	Digital video broadcasting-return channel via satellite
FMT	Fade mitigation techniques
IP	Integer programming
LP	Linear programming
MONET	Mechanisms for optimization of hybrid *ad hoc* networks and satellite NETworks
NCC	Network control center
NLIP	Nonlinear integer programming
SATSIX	Satellite-based communications systems within IPv6 networks
SNR	Signal-to-noise ratio
ST	Satellite terminal

*Correspondence to: Antonio Pietrabissa, Dept. of Computer, Control, and Management Engineering 'Antonio Ruberti' University of Rome 'Sapienza', via Ariosto 25, 00185 Rome, Italy.
†E-mail: pietrabissa@dis.uniroma1.it

TAP	Time slot assignment problem
TBTP	Terminal burst time plan
VBDC	Volume-based dynamic capacity

1. INTRODUCTION

Multimedia satellite systems operating at high frequency bands (Ka-band and above) are subject to attenuations caused by rain, tropospheric scintillations, and Gaussian noise (introduced by thermal and system internal interferences), which limit the satellite communication link availability and therefore, the overall system performances.

To avoid fixed margin based on the poorest channel quality (worst case of the coverage), new communication systems, with high attenuation levels, adapt the system transmission parameters to the signal fading. This allows the channel to be used more efficiently, because the power and the rate can be allocated to take advantage of favorable conditions. Those methods that counteract the atmospheric propagation losses and permit link adaptation are referred to as fade mitigation techniques (FMT) ([1]). The basic idea behind adaptive transmission is to maintain the bit error rate under a given threshold and therefore to regulate the quality of service, during a fade event by adapting the transmission parameters to the propagation conditions; parameters that can be adapted are either the transmitted power, the transmission symbol rate, the constellation size, the coding rate/scheme, the space diversity, or any combination of them.

Thus, while maintaining the bit error rate below the required value, these schemes provide a high average spectral efficiency by transmitting at high rates under favorable channels conditions (clear sky) and then reducing the throughput as the channel degrades (rain conditions). Beside the higher efficiency in link utilization, the exploitation of FMT is also significant because it is capable of keeping the link availability to critical terminals (such as terminals involved in disaster relief or emergency scenarios) even in degraded channel conditions.

Hereafter, the case of a DVB-S2 satellite network is considered ([2]), because it represents an example of a satellite network capable of performing FMT and adaptive coding and modulation (ACM). In particular, the focus is on the return channel, where the impact of ACM on resource management is more relevant. In fact, to exploit ACM techniques, the frame structure must be dynamically adapted to the current link conditions and satellite terminals (STs) traffic.

The framing problem was dealt with by the satellite-based communications systems within IPv6 networks (SATSIX) project ([3]), where it was solved by a heuristic algorithm ([4]). Besides SATSIX, in the literature, ACM impact on uplink framing has been analyzed in [5] and in [6]. However, in those papers, the objective was to optimize the time slot assignment over an already determined frame structure, whereas the objective of this paper is to optimize the (physical) frame structure itself. In [7], the radio resource allocation problem in presence of heterogeneous resources and heterogeneous subscribers for digital video broadcast-return channel via satellite (DVB-RCS) systems has been studied as a time slot assignment problem and formulated, as a consequence, as a nonlinear integer programming problem, where the integer variables are decision variables indicating the time slot assignment to given service classes. The problem of bandwidth efficiency has been discussed also in [8], where the efficiency of different scheduling policies is investigated and the optimization of bandwidth segmentation is solved by formulating and solving a Knapsack problem, which is an integer programming (IP) problem. In this formulation, the integer variables indicate the number of carriers of a specific type that are needed to guarantee that the linear constraint on the bandwidth is satisfied and the weight function is maximized.

On the basis of the state-of-the-art review, up to the authors' knowledge, the proposed algorithm (preliminary presented in [9], with a simpler problem formulation where no traffic differentiation was considered) represents the first attempt to optimize the uplink frame structure availing of ACM techniques; furthermore, as analyzed in the following Sections, the proposed procedure is compliant with the new DVB-RCS2 standard ([10]).

The paper is organized as follows. Section 2 positions the problem with respect to the resource management procedures and to the DVB-RCS2 standard. In Section 3, the optimization problem is defined. Section 4 presents the simulation results. And finally, in Section 5, the conclusions are drawn.

DOI: 10.1002/sat

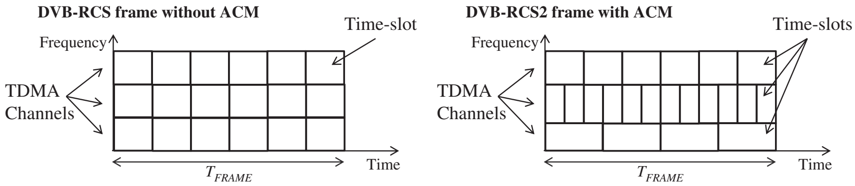


Figure 1. Frame composition without (left) and with (right) ACM.

Standard notation is used, with vectors denoted with lower case bold characters, matrixes denoted with upper case bold characters, $\mathbb{N}_+$ and $\mathbb{R}$ denoting the integer non-negative numbers set and the real numbers set, respectively, and $\lfloor \cdot \rfloor$ and $\lfloor \cdot \rfloor$ denoting the lower and upper integer operators, respectively.

2. DYNAMIC FRAME COMPOSITION IN MF-TDMA UPLINKS

In this Section, the dynamic rate adaptation (DRA) procedures are described with reference to an MF-TDMA uplink (Section 2.1) and to the whole resource management problem (Section 2.2). Hereafter, the DVB-RCS2 case study will be considered; nonetheless, the algorithm developed in Section 3 may be adapted to any satellite network standard based on MF-TDMA (Multi-Frequency, Time Division Multiple Access) uplink frames and supporting ACM.

2.1. Dynamic rate adaptation in digital video broadcasting-return channel via satellite 2 networks

In the DVB-S2 standard ([2]), DRA is defined as the mechanism that maintains the return link of each ST; by switching the type of carrier, it is allowed to use according to the variable return link conditions experienced by the ST itself. The advantage of DRA is to use the variation of spectral efficiency and symbol rate to cope with system power variation instead of requiring a large power dynamic range. It thus helps in reducing ST cost, because the ST includes a less powerful amplifier ([4]). A type of carrier is defined by a triplet of symbol, modulation, and coding rates. In the SATSIX project ([3]), a finite set of triplets was selected, which allows sufficient flexibility in the choice of carrier type. Hereafter, each triplet defining a carrier type will be referred to as 'DRA scheme', whereas the set of feasible carrier types will be referred to as 'DRA pool'.

In the DVB-RCS2 uplink, packet transmission is organized in frames, whose length is denoted with T_{FRAME}; each frame is composed by a given number of carriers; each carrier transports one physical TDMA channel and is associated to a DRA scheme. Each DRA scheme has a different spectral efficiency; this fact means that by associating different DRA schemes to the frame carriers, the carriers themselves will be characterized by different bandwidth and different number of time slots.[†] Figure 1 shows a simple example of frame composition with and without ACM. Table 1 summarizes the characteristics in terms of bandwidth and time slot per frame of the DRA pool identified in SATSIX ([3]) for DVB-RCS uplink; the DRA schemes are numbered from 1 to 9, where DRA scheme 1 is the one with the lowest spectral efficiency, and the DRA scheme 9 is the one with the highest spectral efficiency.

Two options are possible to handle the radio resource management with ACM: static and dynamic framings.

The former solution relies on a logical separation of the resources on the uplink frame: each DRA scheme is statically assigned to a given number of uplink frame carriers. In this case, the frame composition is performed once, on the basis of the average conditions of the link over the spot beam. Clearly, this kind of approach leads to a non-optimal resource management, with a statically configured set of fragmented resources that cannot adapt to user needs and link conditions.

On the other hand, with the dynamic frame composition strategy, the carriers are periodically associated to the DRA schemes, based on current uplink conditions as measured by the STs of the spot

[†]In the satellite uplink, MAC frames (MPEG-2 or ATM) are transmitted over fixed-size packets; each uplink time slot may be used to transport one MAC layer frame.

DOI: 10.1002/sat

Table I. DVB-RCS uplink DRA pool.

DRA scheme number *d*	Bandwidth (Hz)	Time slots per frame
1	0.096	2
2	0.096	3
3	0.096	6
4	0.192	12
5	0.192	17
6	0.384	34
7	0.384	42
8	0.768	84
9	0.768	105

DRA, dynamic rate adaptation pool.

beam. The algorithm proposed in the following Section is aimed at providing an optimal solution to the dynamic framing problem.

The framing algorithm is particularly relevant in DVB-RCS2 ([10]), in which the modulation and coding schemes of the uplink frame carrier are communicated along the time slots allocations to the terminals, by means of the so-called Terminal Burst Time Plan (TBTP2 in DVB-RCS2) table, an improved version of the DVB-RCS TBTP table. The TBTP2 is focused on the concept of 'transmission modes', which are the DRA schemes on which the specific terminal can operate. Also, given the fact that the new standard was released as draft only in 2011, this paper constitutes the first example of intensive use of ACM potentiality for the next generation of satellite interactive networks; in particular, the algorithm proposed in the following Section is aimed at providing an optimal solution to the dynamic framing problem.

2.2. Frame composition and resource management

The framing algorithm is strictly interconnected to the resource management algorithms. In this Section, a schematic description of the modules, which manage the uplink resources of a satellite network is given. With reference, a single uplink spot beam, two kinds of entities are involved in the uplink resource management (see Figure 2): the STs in the spot beam, which receive the traffic and have the task of sending it over the satellite network and the Network Control Center (NCC), which manage the uplink resources. The traffic can be classified in two types (see [11] for more details).

- High-priority traffic, whose calls need statically allocated capacity for their whole duration: the STs send call requests to the NCC, which has to decide upon their admission by means of the call admission control module (CAC) and in case of acceptance has to reserve the needed time slots on the uplink frame.
- Low-priority traffic, for which the uplink capacity is on-demand: on the ST side, the demand assignment multiple access (DAMA) agent module computes the time slots requests based on the received traffic; on the NCC side, the DAMA controller module collects all the time slots

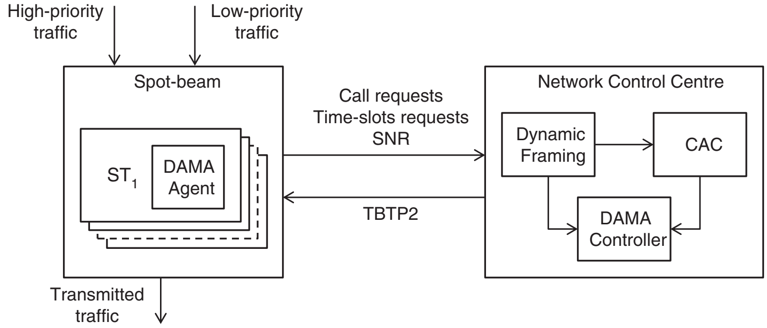


Figure 2. Resource management with adaptive coding and modulation.

requests and allocates the frame time slots, according to a given fairness criterion and considering the time slots already reserved by the CAC module.

Since in the ACM case, the frame carriers have different coding and modulation schemes, each ST also regularly communicates to the NCC the signal-to-noise ratio (SNR) of its channel. The SNR measures are used by the NCC modules to check which carriers are not suitable for the call and capacity requests of each ST, that is, which carriers are associated to the DRA schemes which require a higher SNR. Because of this additional constraint, the CAC and the DAMA controller algorithms are more complex with respect to the ones developed for satellite networks without ACM. Note also that it may happen that the SNR of a given ST decreases, and that the ST cannot transmit the packets of a high-priority call on the reserved time slots, because they are on a carrier associated to a DRA scheme, which requires a higher SNR. In this case, the CAC module has the additional task of checking whether enough time slots are available on the suitable frame carriers; if there are not enough resources, the CAC has to terminate the call (forced *call dropping*).

Dynamic framing impacts on these mechanisms because it dynamically changes the frame composition. Therefore, as illustrated in Figure 2, each time the frame composition is changed, it is communicated by the dynamic framing module to both the CAC and the DAMA controller modules. The proposed algorithm should not be misunderstood with these mechanisms, because they address different phases of the allocation process: in fact, the framing algorithm produces as output the physical composition of the frame; then, the CAC and DAMA modules allocates time slots to the STs based on the frame whose composition is given as input. If the optimization if well performed, the subsequent scheduling process should cope with a more efficient physical resource.

As mentioned in the previous Section, in DVB-S2, both the current frame composition and the high-priority and low-priority time slots allocations are communicated by the NCC to the STs via the TBTP2.

3. FRAME OPTIMIZATION ALGORITHM

This paragraph describes the optimization problem formulation. For the sake of simplicity, the traffic is classified in low-priority and high-priority traffics: the former traffic includes the traffic served on-demand (typically, best-effort or delay-tolerant calls), whereas the latter includes the traffic that needs bandwidth reservation (typically, real-time or critical calls). Finer grain classification within the considered traffic kinds can be straightforwardly achieved by defining proper weights in the scheduling procedures of the DAMA controller.

Preliminarily, in Section 3.1, the problem is defined considering only low-priority, best-effort type of traffic; the problem is then extended in Section 3.2, which considers also the presence of high-priority, guaranteed type traffic. Finally, in Section 3.3, implementation issues are dealt with by defining an approximated algorithm.

The problem being faced is to assign DRA schemes to the uplink frame carriers in such a way that the traffic carried by the STs is served in an efficient and fair way, based on the estimated capacity requests and on the link SNR measures of the STs. The capacity requests and the SNR measures are the main drivers of the algorithm because they provide a quantitative, measurable picture of the overall uplink resource needs: SNR measures indicate which DRA scheme can be used by each ST; then, the aggregate of the capacity requests of the STs associated to a given DRA scheme represents the amount of traffic that has to be served on carriers with that DRA scheme.

The frame optimization is performed dynamically every T_{FRAMER} seconds. In general, T_{FRAMER} is larger than the superframe duration, and it is the parameter which leads the trade-off between fast adaptation to changes in link conditions and control traffic overhead (in fact, every time the frame composition is changed, it has to be communicated to the STs of the spot beam). The task is to decide the frame structure for the following T_{FRAMER} period based on the current information. It turns out that any optimization algorithm would find the optimal frame structure for the following T_{FRAMER} period only in case the actual requests and the link conditions in the following T_{FRAMER} period were exactly equal to the estimated ones. Thus, generally, the optimal solutions of the optimization problems of

DOI: 10.1002/sat

Sections 3.1 and 3.2 and are just sub-optimal solutions for the actual frame structure optimization problem, and the approximated approach of Section 3.3 is justified.

3.1. Basic carrier to dynamic rate adaptation association problem

The uplink frame is characterized by its total available bandwidth BW_{TOT}. The DRA pool is defined by D possible DRA schemes; each DRA scheme $d, d = 1, \ldots, dD$, in turn is defined by the bandwidth requirement $BW_{CARRIER}(d)$ and by the number of time slots per frame $TS_{CARRIER}(d)$ (see, for example, the DRA schemes defined in Table 1 of Section 2). The maximum integer number of carriers, which can be associated to the DRA scheme d within the frame bandwidth is the $N_{CARRIER}^{MAX}(d) = \frac{BW_{TOT}}{BW_{CARRIER}(d)}, d = 1, 2, \ldots, D$. Let also d^{MAX} denote the most efficient DRA scheme, that is, $d^{MAX} = \arg\max_{d=1,\ldots,D} TS_{CARRIER}(d)$. Finally, the maximum number of time slots per frame (i.e., the number of time slots in a frame where all the carriers are associated to the most efficient DRA scheme) is $TS_{FRAME}^{MAX} = TS_{CARRIER}(d^{MAX})N_{CARRIER}(d^{MAX})$

Every superframe, the NCC receives the bandwidth requests and the SNR measures from the STs. On the basis of the SNR, the NCC associates each ST with the suitable DRA scheme. Then, on the basis of the time slot requests, the framer algorithm computes the total number of time slots requested by STs with DRA $d, d = 1, \ldots, D$. Note that the inputs of the framer algorithm are in practice estimates of the ST needs and of the uplink conditions in the next control period T_{FRAMER}. More precisely, the requests received in the last control periods are considered as indicators of the ST needs in the next T_{FRAMER} period; similarly, the uplink conditions in the next control period are inferred from the uplink conditions experienced in the last control period. Let $REQ_{ST}(d)$ be the estimated cumulative time slot requests of the STs associated to the DRA scheme $d, d = 1, \ldots, D$. From the previous discussion, it turns out that the framer algorithm which has to compute the frame for the ith control period would find the optimal frame structure only in case the actual ST requests per DRA scheme during the $(i+1)$th control period were exactly equal to the estimated ones.

It is important underlining that the requests of the STs with a given DRA scheme d can be fulfilled by carriers with DRA scheme $d' \leq d$ In fact, if the SNR of an ST is such that the ST can use the DRA scheme d, it can use also less efficient schemes. Moreover, a single ST is assumed to be capable of using different carriers in the same frame (*frequency hopping*), that is, a single ST can transmit over two (non-simultaneous) time slots of different carriers. Finally, let $TS_{ST}^{MAX}(d), d = 1, \ldots, D$ be the maximum number of time slots that can be used by the STs with DRA d (this limit derives from the fact that an ST cannot simultaneously transmit on more than one carrier: for example, with reference to Table 1, assuming that two STs are associated with the DRA scheme 4, the maximum number of time slots that the ST can use is $12 \times 2 = 24$). The algorithm inputs are collected in Table 2.

The objective of the framer algorithm is to define the frame structure that guarantees the best s-atisfaction of the ST requests. Thus, the optimal frame structure is the one obtained by optimizing the time slot allocations (i.e., the assignment of the frame time slots to the STs) mapped on the frame itself. Note that the framer algorithm is not responsible of performing the actual time slot allocation procedure: in fact, this latter task is performed every superframe, whereas, generally, the former is performed less frequently. For this reason, in the optimization problem defined hereafter, some constraints of the actual time slot allocation procedure are neglected, and the cumulative requests

Table II. Framing algorithm inputs.

Parameter	Meaning
BW_{TOT}	Total frame bandwidth
$TS_{CARRIER}(d), d = 1, \ldots, D$	Number of time slots per carrier associated to DRA scheme *d*.
$BW_{CARRIER}(d), d = 1, \ldots, D$	Bandwidth per carrier associated to DRA scheme *d*.
$N_{CARRIER}^{MAX}(d), d = 1, \ldots, D$	Maximum number of carriers associated to the DRA scheme *d*.
$REQ_{ST}(d), d = 1, \ldots, D$	Number of time slots requested by the STs with DRA *d*.
$TS_{ST}^{MAX}(d), d = 1, \ldots, D$	Maximum number of time slots that can be used by the STs with DRA *d*.

DRA, dynamic rate adaptation; ST, satellite terminal.

(aggregated per DRA scheme) are considered. Therefore, there will be differences between the allocations foreseen by the optimization algorithm and the actual time slot allocation performed by the NCC.

The problem variables are defined as follows.

- The first set of D variables, collected in the vector $z_{CARRIER}$, which is the main algorithm outcome, indicates how many carriers are associated to each DRA scheme

$$z(d) \in \left\{1, 2, \ldots, N_{CARRIER}^{MAX}(d)\right\}, d = 1, \ldots, D. \tag{1}$$

- The second set of D variables, collected in the vector z_{ST}, indicates how many time slots are assigned to the STs associated to a given DRA scheme

$$z_{ST}(d) \in \left\{1, 2, \ldots, \min\left(REQ_{ST}(d), TS_{ST}^{MAX}(d)\right)\right\}, d = 1, \ldots, D \tag{2}$$

(note that these variables are bounded because it would be useless to assign to the STs associated to a DRA scheme more time slots than the ones they can actually use).

- Finally, the third set of variables is collected in the vector z_{DRA}, whose generic element $z_{DRA}(d_C,d_{ST})$ indicates how many time slots are assigned to the STs associated to a given DRA scheme d_{ST} on carriers associated to a given DRA scheme d_C

$$z_{DRA}(d_C, d_{ST}) \in \left\{0, 1, \ldots, TS_{CARRIER}^{MAX}(d_C)\right\}, d_{ST} = 1, 2 \ldots, D, d_C = 1, 2, \ldots, d_{ST} \tag{3}$$

In Equation (3), the carrier DRA index d_C is limited by ST DRA scheme index d_{ST} because the ST cannot transmit on more efficient schemes. The number of elements of z_{DRA} is $D(D+1)/2$.

The variables are collected in the variables vector $(z_{CARRIER}, , z_{ST}, , z_{DRA}) \in \mathcal{Z}_1 \subset \mathbb{N}_+^{\left(D^2+5D\right)/2}$.

The following constraints must be enforced.

- First of all, the total available bandwidth cannot be exceeded.

$$\sum\nolimits_{d=1,\ldots,D} BW_{CARRIER}(d) z_{CARRIER}(d) \leq BW_{TOT} \tag{4}$$

- Secondly, it is required to check that the total amount of time slots on the carriers associated to a given DRA assigned to the STs do not exceed the available ones, considering that it is possible that time slots are assigned to STs with lower DRAs

$$\sum\nolimits_{d_{ST}=1,\ldots,d_C} z_{DRA}(d_C, d_{ST}) \leq TS_{CARRIER}(d_C) z_{CARRIER}(d_C), d_C = 1, 2, \ldots, D \tag{5}$$

- Finally, consistency between carrier and overall allocations must be guaranteed

$$z_{ST}(d_{ST}) = \sum\nolimits_{d_C=1,2\ldots,d} z_{DRA}(d_C, d_{ST}), d_{ST} = 1, 2, \ldots, D \tag{6}$$

Concerning the objective function, it must pursue a twofold objective: on the one hand, it should try to optimize the resource utilization by maximizing the overall throughput, that is, the sum of the time slot allocation; on the other hand, it should try to perform fair resource allocation among the STs with different DRA schemes.[‡] The two objectives are expressed by the first and second terms, respectively, of the following objective function (to be maximized)

[‡]Note that the framing algorithm takes into account fairness among aggregate STs, grouped on the basis of the DRA scheme, whereas the DAMA controller, which performs the actual time slots allocations, is in charge of guaranteeing fairness among the STs. In practice, the real aim of the fairness term in Equation (7) is to avoid that the framer algorithm excessively favor higher DRA schemes, which offer higher efficiency transmission.

DOI: 10.1002/sat

$$J(z) = w_{THR} \sum\nolimits_{d=1,\ldots,D} z_{ST}(d) + w_{FAIR} \min\nolimits_{d=1,\ldots,D} \left(\frac{1}{REQ_{ST}(d)} z_{ST}(d) \right) \tag{7}$$

where w_{THR} and w_{THR} express the relative importance of the overall throughput and of the achieved fairness, respectively. Note that the second term of the objective function (7) aims at allocating the capacity proportionally with respect to the time slot requests (different fairness criteria may be followed by weighting in a different way the variables $z_{ST}(d), d = 1, \ldots, D$ in the second term of equation (7)).

The optimization problem is then to maximize the objective function (7) subject to constraints (4), (5), and (6).

The problem is a nonlinear, integer programming problem. However, it is possible to render the objective function (7) linear (i) by introducing another integer variable in the variable vector z

$$z_{FAIR} \in \left\{0, 1, \ldots, TS_{FRAME}^{MAX}\right\} \tag{8}$$

(ii) by modifying the objective function (7) as follows

$$J(z) = w_{THR} \sum\nolimits_{d=1,\ldots,D} z_{ST}(d) + w_{FAIR} z_{FAIR} \tag{9}$$

and (iii) by adding D constraints

$$z_{FAIR} \leq \frac{1}{REQ_{ST}(d)} z_{ST}(d) \tag{10}$$

In fact, by maximizing the second term of the objective function (9), the constraint (10) set the variable z_{FAIR} to the minimum value among the normalized integer allocations $\frac{z_{ST}(d)}{REQ_{ST}(d)}, d = 1, 2, \ldots, D$.

The (linear) IP problem is then to maximize is the objective function (9), subject to the equality constraint (6), and to the inequality constraints (4), (5), and (10). By adding z_{FAIR}, the total number of variables becomes $(3D + 1)/2 + 1$, and the variable vector of this IP problem becomes $\mathbf{z} = (\mathbf{z}_{CARRIER}, \mathbf{z}_{ST}, \mathbf{z}_{DRA}, z_{FAIR}) \in \mathcal{Z}_2 \subset \mathbb{N}_+^{\left(D^2+5D+2\right)/2}$.

3.2. Algorithm extension to deal with different types of traffic

The extension to the generic case, where both high-priority and low-priority traffics are present, is straightforwardly dealt with based on the problem formulated in the former Section.

First of all, for the group of STs with DRA $d, d = 1, \ldots, D$, two kinds of time slot requests are considered: the average number of time slots requested on-demand by low-priority calls, denoted with $REQ_{ST}^{LOW}(d)$ and the average number of time slots required by high-priority calls, denoted with $REQ_{ST}^{HIGH}(d)$.

The optimization objective is then a threefold.

(1) The first aim is to compose the frame to maximize the high priority assignments; up to $REQ_{ST}^{HIGH}(d)$ time slots should be assigned to the STs with DRA $d, d = 1, \ldots, D$;
(2) The second aim is to maximize the low priority assignments; up to $REQ_{ST}^{HIGH}(d)$ time slots should be assigned to the STs with DRA $d, d = 1, \ldots, D$;
(3) Finally, to allow unrequested capacity to be used in case of need, the framer should compose the frame in order to maximize the time slots assigned to the STs as 'free' capacity allocations.

The three aforementioned sub-objectives are strictly prioritized: low priority assignments must be considered only after that the high-priority assignments are maximized, and free capacity assignments must be considered only after that also the low-priority assignments are maximized.

To cope with the different types of assignments, we substitute the set of variables $z_{ST}(d), d = 1, \ldots, D$ with three sets of variables

DOI: 10.1002/sat

$$z_{ST}^{HIGH}(d) \in \{0, 1, \ldots, \min\left(REQ_{ST}^{HIGH}(d), TS_{ST}^{MAX}(d)\right)\} \tag{11}$$

representing the allocations to the high-priority calls,

$$z_{ST}^{LOW}(d) \in \{0, 1, \ldots, \min\left(REQ_{ST}^{LOW}(d), TS_{ST}^{MAX}(d)\right)\} \tag{12}$$

representing the allocations to low-priority calls,

$$z_{ST}^{FREE}(d) \in \{0, 1, \ldots, TS_{ST}^{MAX}(d)\} \tag{13}$$

and representing the free time slot allocations.

Correspondingly, the fairness variable z_{FAIR}^{FREE} is substituted by three variables z_{FAIR}^{HIGH}, z_{FAIR}^{LOW}, and z_{FAIR}^{FREE}.

The total number of variables is then $D+3D+D(D+1)/2+3=(D^2+9D+6)/2$, and the variable vector is $\mathbf{z} = \left(\mathbf{z}_{CARRIER}, \mathbf{z}_{ST}^{HIGH}, \mathbf{z}_{ST}^{LOW}, \mathbf{z}_{ST}^{FREE}, , \mathbf{z}_{DRA}, z_{FAIR}^{HIGH}, z_{FAIR}^{LOW}, z_{FAIR}^{FREE}\right) \in \mathcal{Z}_3 \subset \mathbb{N}_+^{\left(D^2+9D+6\right)/2}$.

The objective function and the constraints are straightforwardly modified accordingly.

The objective function (9) becomes

$$\begin{aligned} J(z) = w^{HIGH}&\left(w_{THR}^{HIGH}\sum\nolimits_{d=1,\ldots,D} z_{ST}^{HIGH}(d) + w_{FAIR}^{HIGH} z_{FAIR}^{HIGH}\right) + \\ w^{LOW}&\left(w_{THR}^{LOW}\sum\nolimits_{d=1,\ldots,D} z_{ST}^{LOW}(d) + w_{FAIR}^{LOW} z_{FAIR}^{LOW}\right) + \\ w^{FREE}&\left(w_{THR}^{FREE}\sum\nolimits_{d=1,\ldots,D} z_{ST}^{FREE}(d) + w_{FAIR}^{FREE} z_{FAIR}^{FREE}\right) \end{aligned}, \tag{14}$$

where w^{HIGH}, w^{LOW}, and w^{FREE} are weights that express the prioritization among the three types of allocations, and recalling the problem defined in Section 3.1, the threshold and fairness weights have a straightforward interpretation. Clearly, given that high-priority traffic has bandwidth guarantees and that free capacity assignments should be considered only after that the low-priority requests are fulfilled, it is advisable to select $w^{HIGH} \gg w^{LOW} \gg w^{FREE}$.

Constraints (4) and (5) still holds, whereas constraint (6) becomes

$$z_{ST}^{HIGH}(d) + z_{ST}^{LOW}(d) + z_{ST}^{FREE}(d) = \sum\nolimits_{d_c=1,\ldots,d} z_{TS}(d_C, d), d = 1, \ldots, D, \tag{15}$$

Constraint (10) becomes

$$z_{FAIR}^{HIGH} \leq \frac{1}{REQ_{ST}^{HIGH}(d)} z_{ST}^{HIGH}(d), d = 1, \ldots, D, \tag{16}$$

$$z_{FAIR}^{LOW} \leq \frac{1}{REQ_{ST}^{LOW}(d)} z_{ST}^{LOW}(d), d = 1, \ldots, D, \tag{17}$$

$$z_{FAIR}^{FREE} \leq \frac{1}{REQ_{ST}^{HIGH}(d) + REQ_{ST}^{LOW}(d)} z_{ST}^{FREE}(d), d = 1, \ldots, D. \tag{18}$$

Furthermore, the following constraints have to be added to avoid that the STs associated to a DRA scheme are assigned more time slots than the ones they can actually use

$$z_{ST}^{HIGH}(d) + z_{ST}^{LOW}(d) + z_{ST}^{FREE}(d) \leq TS_{ST}^{MAX}(d), d = 1, \ldots, D. \tag{19}$$

Note that, by enforcing constraint (18), the aim of the problem is to allocate free capacity proportionally with respect to the total requests, that is, for each DRA scheme d, $REQ_{ST}^{HIGH}(d) + REQ_{ST}^{LOW}(d)$; different free capacity assignment policies may be enforced by changing the weights of the variables $z_{ST}^{FREE}(d)$ in Equation (7)).

DOI: 10.1002/sat

The overall IP problem is then the following

$$
\begin{array}{l}
\text{maximize}_z\, J(\mathbf{z}) \\
s.t. \\
A\mathbf{z} = 0 \\
A^{dis}\mathbf{z} = \boldsymbol{b}^{dis} \\
\mathbf{z} \in \mathcal{Z}_3 \subset \mathbb{N}^{(9D+7)/2}
\end{array}
\tag{20}
$$

where $J(\mathbf{z})$ is the objective function (14), the matrix $\boldsymbol{A}$ expresses the equality constraint (15), and the matrix $\boldsymbol{A}^{dis}$ and the vector $\boldsymbol{b}^{dis}$ express the inequality constraints (4), (15), (16), (19), (5), (16), (17), and (18).Hereafter, this problem will be referred to as problem **IP1**.

Unfortunately, even if the defined problem is linear, it is an IP one: therefore, the solution algorithms are NP hard and cannot be efficiently executed in real-time. The following Section deals with this problem by defining a problem relaxation to fast find an approximated solution.

Remark: note that past call and capacity request are used by the algorithm to estimate the per DRA scheme load, whereas the actual time slot allocations are decided by the DAMA controller. A future integrated algorithm performing both the dynamic framing and the DAMA controller tasks may increase the overall efficiency.

3.3. Implementation considerations and approximated algorithm

In this Section, the implementation issues are discussed and an approximated procedure is developed. As mentioned in the beginning of Section 3, the IP problem of Section 3.2 would find the optimal frame structure for the following T_{FRAMER} period only in case the actual ST requests and DRA schemes were exactly equal to the estimated ones, and, thus, the optimal solution of the integer programming problem **IP1** of Section 3.2 is indeed a sub-optimal solution for the actual ST traffic and DRA schemes. It is then conceivable to consider a linear programming (LP) relaxation and successively to implement an approximation procedure to obtain integer carrier allocations from the optimal fractional solution of the linear problem.

To obtain an LP relaxation of the IP (20), it is sufficient to define continuous variables instead of the integer variables defined in the former Section

$$x_{CARRIER}(d) \in \left[0, N_{CARRIER}^{MAX}(d)\right], d = 1, \ldots, D, \tag{21}$$

$$x_{ST}^{HIGH}(d) \in \left[0, TS_{ST}^{MAX}(d)\right], d = 1, \ldots, D, \tag{22}$$

$$x_{ST}^{LOW}(d) \in \left[0, TS_{ST}^{MAX}(d)\right], d = 1, \ldots, D, \tag{23}$$

$$x_{ST}^{FREE}(d) \in \left[0, TS_{ST}^{MAX}(d)\right], d = 1, \ldots, D \tag{24}$$

$$x_{DRA}(d_C, d_{ST}) \in \left[0, TS_{FRAME}^{MAX}\right], d_{ST} = 1, \ldots, D, d_C = 1, \ldots, d_{ST}, \tag{25}$$

$$x_{FAIR}^{HIGH} \in \left[0, TS_{FRAME}^{MAX}\right] \tag{26}$$

$$x_{FAIR}^{LOW} \in \left[0, TS_{FRAME}^{MAX}\right] \tag{27}$$

$$x_{FAIR}^{FREE} \in \left[0, TS_{FRAME}^{MAX}\right] \tag{28}$$

The variable vector is then $\boldsymbol{x} = \left(\boldsymbol{x}_{CARRIER}, \boldsymbol{x}_{ST}^{HIGH}, \boldsymbol{x}_{ST}^{LOW}, \boldsymbol{x}_{ST}^{FREE}, \boldsymbol{x}_{DRA}, x_{FAIR}^{HIGH}, x_{FAIR}^{LOW}, x_{FAIR}^{FREE}\right) \in \mathcal{Q} \subset \mathbb{R}^{\left(D^2+9D+6\right)/2}$.

By considering these continuous variables, the NP-hard IP problem **IP1** is then relaxed into the following LP problem **LP1** (where the same notation of problem (20) is used)

DOI: 10.1002/sat

$$\begin{aligned}&\text{maximize}_x\, J(\boldsymbol{x})\\&s.t.\\&\boldsymbol{Ax}=\boldsymbol{0}\\&\boldsymbol{A}^{dis}\boldsymbol{x}=\boldsymbol{b}^{dis}\\&x\in\mathcal{Q}\subset\mathbb{R}^{\left(D^2+9D+6\right)/2}\end{aligned}\tag{29}$$

that is, maximize Equation (14) subject to constraints (4), (15), (16), (19), (5), (15), (16), (17), and (18). Given the small number of variables (which linearly grows with D, which, by itself, is a small number, as will be said in Section 4), the problem **LP1** is efficiently solvable by standard algorithms (e.g., simplex or internal point methods).

By solving the problem **LP1**, a fractional solution is obtained. The corresponding value of the objective function represents an upper-bound on the value of any feasible solution of the original problem **IP1**. The fractional solution must be converted into an integer solution, that is, to a feasible solution of the original problem **IP1**. This procedure is called *rounding* the fractional solution and is evaluated by gap analysis, that is, by comparing the value of the obtained integer solution to the value of the fractional solution.

A simple rounding algorithm is proposed in the following. More advanced techniques are available in the literature, such as, for example, randomized rounding approaches (e.g., [12]). However, as already mentioned, the optimization is performed over estimated data. Therefore, in comparison with the solution obtained with simpler techniques, the application of such advanced techniques guarantees that the found solution is better only if the real data are exactly the same as the estimated data but may be equal to or even worse in the other cases. Therefore, the advantages of applying such techniques appear not compensating their greater implementation complexity.

The key of the simplicity of the proposed rounding algorithm is that it is aimed at rounding only the (few) variables $x_{CARRIER}$ associated to the number of carriers. In fact, it would not make sense to provide also a feasible time slot allocation on the frame, because the actual allocations will be performed by the resource management algorithms of the NCC based on the actual requests and coping with further constraints not considered in the framer optimization.

The proposed approximation algorithm is performed in two steps.

(1) It simply performs a preliminary upper rounding of the variables $x_{CARRIER}(d), d=1,\ldots,D$ of the fractional solution;
(2) On the basis of the *credit* of the DRA schemes (i.e., on the basis of the differences between the fractional numbers of carriers and the integer numbers of carriers computed in step 1), it heuristically 'adjusts' the obtained integer solution in such a way that

  a. The total frame bandwidth constraint is met; and
  b. The residual bandwidth is less than the minimum bandwidth required by the DRA schemes.

The algorithm pseudo-code is shown in Table 3 and returns a set of integer values $n_{CARRIER}(d)$, representing the number of carriers associated to each DRA scheme $d, d=1,\ldots,D$.

As already mentioned, the gap analysis evaluation is usually performed by computing the ratio between the reward of the integer solution and the reward of the fractional solution. However, the implemented rounding procedure furnishes only integer values for the number of carriers associated to the DRA schemes. Then, the following evaluation method is followed.

(i) The optimization problem **LP1** is solved; let the optimal fractional solution be $\bar{\boldsymbol{x}}=\left(\bar{\boldsymbol{x}}_{CARRIER},\bar{\boldsymbol{x}}_{ST}^{HIGH},\bar{\boldsymbol{x}}_{ST}^{LOW},\bar{\boldsymbol{x}}_{ST}^{FREE},\bar{\boldsymbol{x}}_{DRA},\bar{x}_{FAIR}^{HIGH},\bar{x}_{FAIR}^{LOW},\bar{x}_{FAIR}^{FREE}\right)$;
(ii) The integer numbers of carrier $n_{CARRIER}(d), d=1,\ldots,D$ are obtained by the rounding procedure described in Table 3;
(iii) The LP problem **LP2** is defined by fixing the number of carriers by adding the D constraints $x_{CARRIER}(d)=n_{CARRIER}(d), d=1,\ldots,D$ to the problem **LP1**;
(iv) **LP2** is solved; let the optimal solution of this modified problem be $\tilde{\boldsymbol{x}}=\left(n_{CARRIER},\tilde{\boldsymbol{x}}_{ST}^{HIGH},\tilde{\boldsymbol{x}}_{ST}^{LOW},\tilde{\boldsymbol{x}}_{ST}^{FREE},,\tilde{\boldsymbol{x}}_{DRA},\tilde{\boldsymbol{x}}_{FAIR}^{HIGH},\tilde{\boldsymbol{x}}_{FAIR}^{LOW},\tilde{\boldsymbol{x}}_{FAIR}^{FREE}\right)$;
(v) The gap between the two solutions is computed as follows

DOI: 10.1002/sat

Table III. Rounding algorithm.

Step 1.	Compute, for $d = 1, \ldots, D$
	$n_{CARRIER}(d) = \lceil x_{CARRIER}(d) \rceil$
	$credit(d) = n_{CARRIER}(d) - x_{CARRIER}(d)$
Step 2.	If $BW_{TOT} - \min_{d=1,\ldots,D}(BW(d)) < \sum_{d=1,\ldots,D} n_{CARRIER}(d) BW(d) < BW_{TOT}$
	(i.e., if the bandwidth constraint is met and no more carriers can be added)
	End of algorithm
	Else
	Rank d with respect to $credit(d)$
	If $\sum_{d=1,\ldots,D} n_{CARRIER}(d) BW(d) > BW_{TOT}$ (i.e., if the bandwidth constraint is not met)
	Select d' as the DRA scheme with the largest credit
	Update $n_{CARRIER}(d') \leftarrow n_{CARRIER}(d') - 1$, and $credit(d') \leftarrow credit(d') - 1$
	Else (i.e., if the bandwidth constraint is met but more carriers can be added)
	Select d' as the DRA scheme with the smallest credit such that
	$\sum_{d=1,\ldots,D} n_{CARRIER}(d) BW(d) + BW(d') \leq BW_{TOT}$ (i.e., the DRA scheme with the smallest credit which fits the frame bandwidth)
	Update $n_{CARRIER}(d') \leftarrow n_{CARRIER}(d') + 1$, and $credit(d') \leftarrow credit(d') + 1$
	Repeat Step 2.

$$gap = \frac{J(\bar{x}) - J(\tilde{x})}{J(\bar{x})} \tag{30}$$

4. SIMULATION RESULTS

To test the proposed dynamic framing, a realistic scenario was set up on the basis of the models of spot beam and rain event attenuations developed within the SATSIX project ([3]).

In particular, a spot beam with a 250 km radius and with a 10 Mbps capacity was considered, with n_{ST} STs, randomly placed within the spot beam. The maximum DRA scheme, which a given ST can use in clear sky conditions depend on the position of the ST within the spot beam according to Table 4.

As ST is experiencing a rain event, its antenna experiences an attenuation, which forces the ST to lower its DRA scheme. Rain events were generated by the model described in the succeeding text, which is a simplified version of the one in [3] (where a more realistic model was needed because the research was focused on the physical layer FMT). In the beginning of the simulation, n_{CLOUD} rainy clouds are randomly placed over the spot beam. Each cloud is circular, with random radius between 1 and 5 km and causes a lowering between 1 (very light rain even) and 5 (very strong rain event) DRA schemes. The clouds are subject to a random wind field, with random initial speed from 5 to 50 km/h, random initial direction, and random variation both in speed and directions. As two or more rainy clouds collide, it is assumed that the combined DRA lowering effect is the sum of the effects of the single clouds.

Table IV. Maximum DRA pool scheme in the spot beam areas.

Distance from the spot beam center [km]	0–210	210–230	230–240	240–245	245–250
Maximum DRA	9	8	7	6	5

DRA, dynamic rate adaptation.

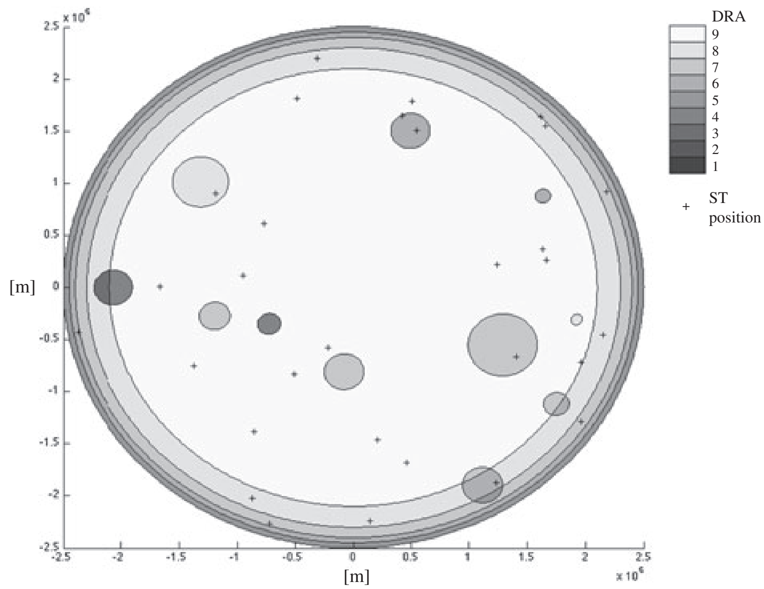


Figure 3. Example scenario, with $n_{\mathrm{ST}} = 30$ and $n_{CLOUD} = 11$.

Figure 3 shows an example of a scenario; the grey scale indicates the different DRA scheme available to the STs depending on their position in the spot beam and on the rain events.

The simulation, which was implemented in MATLAB (The MathWorks Inc., MA, USA) and availed of the GLPK solver (GNU Linear Programming Kit, http://www.gnu.org/software/glpk/) to solve the **LP1** and **LP2** problems, is a discrete-time one, with the step equal to the superframe period $T_{SUPERFRAME}$. Simulation length T_{SIM} was equal to 30 h. Basic CAC and DAMA controller algorithms were implemented (more advanced and effective resource management algorithms are available in the literature, both for the admission control problem, e.g., [13], and for the dynamic bandwidth assignment problem, e.g., [11]). However, they may need to be modified to cope with the ACM framework due to the time-varying frame composition.

At every step, the position of the rainy clouds is updated, and the DRA scheme of the STs is updated accordingly.

At every step, each ST also generates requests for admission of high-priority calls. Calls are generated according to an exponentially distributed inter-arrival time, with mean λ^{HIGH}. The transmission rate in clear sky conditions, expressed in packet per frame, is β^{HIGH}. The cumulative requests, grouped by the DRA scheme of the STs, constitute the framer input $REQ_{ST}^{HIGH}(d)$. A simple CAC algorithm is implemented, which admits the new call only if there are enough free time slots on the carriers available to the ST. In case of acceptance, the required number of time slots is reserved on the carriers whose DRA scheme is suitable for the ST, starting from the next TBTP and until the call termination (constant rate assignment). As a call terminates, the time slots in use are available again from the next TBTP. The call duration is exponentially distributed with mean $\frac{1}{\mu^{HIGH}}$; furthermore, also, forced call dropping is considered, which may occur because of variations of the DRA schemes of the STs caused by the cloud movements.[§]

At every step, each ST also receives low-priority packets, with rate generated according to a Poisson distribution with mean β_{LOW}, and stores them in a buffer. The STs request a capacity for the low-priority packets according to a simple volume-based dynamic capacity (VBDC) strategy: each ST requests the number of packets currently stored in its buffer. The aggregate VBDC requests represent the framer input $REQ_{ST}^{LOW}(d)$. The TBTP is then computed by a simple DAMA controller implementing to a round-robin algorithm that allocates the leftover time slots (i.e., the time slots which are not reserved to high-priority calls) to each ST according to their DRA scheme, until either there is

[§]A more advanced call dropping control algorithm is proposed in [14], which computes both the optimal call admission and dropping strategies.

DOI: 10.1002/sat

Table V. Simulation parameters.

Parameter	Symbol	Value
Spot beam uplink bandwidth	BW_{TOT}	10 MHz
Spot beam radius	R_{SB}	250 km
Simulation length	T_{SIM}	6 h
Superframe length	$T_{SUPERFRAME}$	1 s
Framer control time	T_{FRAMER}	300 s
Number of DRA schemes (see the DRA pool of Table 1)	D	9
ST number	n_{ST}	30
Cloud number	n_{CLOUD}	$20 \div 60$

DRA, dynamic rate adaptation pool; ST, satellite terminal.

Table VI. Objective function weights.

Parameter	w^{HIGH}	w^{LOW}	w^{FREE}	w^{HIGH}_{THR}	w^{HIGH}_{FAIR}	w^{LOW}_{THR}	w^{LOW}_{FAIR}	w^{FREE}_{THR}	w^{FREE}_{FAIR}
Value	1	0.1	0.01	0.1	1	0.1	1	1	0.1

no available time slot on the TBTP or the VBDC request is fulfilled. Finally, the transmission rates of the calls feeding the STs are lowered to match the current DRA schemes of the STs**: the effective transmission rates are computed as $\beta_{HIGH} \frac{TS_{DRA}(d)}{TS_{DRA}(d^{MAX})}$ and $\beta_{LOW} \frac{TS_{DRA}(d)}{TS_{DRA}(d^{MAX})}$ for the high-priority and low-priority traffics feeding an ST with DRA scheme d, respectively.

In the simulations, two approaches are compared: the dynamic framing and the static framing approaches.

For each simulation, firstly, the dynamic framing approach is simulated, in which every T_{FRAMER}, the proposed framing algorithm is executed on the basis of the average per DRA scheme capacity requests of the STs in the last T_{FRAMER} period. The computed frame configuration is then used in the following T_{FRAMER} control period.

Subsequently, the static framing approach is simulated. This simulation is characterized by the same traffic and cloud dynamics of the first simulation, but the frame composition is fixed and computed *a posteriori* based on the traffic per DRA scheme that was received during the first simulation, averaged over the whole simulation. The same optimization algorithm used for the dynamic framing approach is used to compute this static frame configuration.

Simulation and algorithm parameters are detailed in Tables 5 and 6, respectively, whereas traffic and cloud parameters were set as in Table 7. Note that $D = 9$ and therefore, the number of variables is $(D^2 + 9D + 6)/2 = 84$, which is a really small number for LP solvers, which can efficiently solve problems with thousands of variables. To evaluate the procedures under different traffic conditions, as shown in the table, 11 simulations were executed, in which the amount of packets received by the STs was varied by a parameter ρ, hereafter referred to as traffic ratio.

Figure 4 shows the output of the simulations. The figure shows the ratio between the number of packets arrived in the ST buffers during the simulation runs and the number of time slots, which were actually allocated onto the uplink frame, for the high-priority and low-priority traffics (upper and middle plots) and for the total traffic (lower plot). The figure shows the results for both the dynamic and static framings. In the first two simulations, with traffic ratio $\rho = 0.75$ and $\rho = 0.825$, both strategies manage to allocate all the requested traffic. With $\rho = 1$, the static algorithm cannot allocate all the requested traffic, and consequently, the low-priority traffic allocation ratio noticeably decreases. As the traffic ratio grows, with the static algorithm, also, the high-priority traffic allocation ratio starts decreasing ($\rho = 1.125$) and for $\rho = 1.5$, no low-priority traffic is served to favor the high-priority one. The same behavior is experienced with the dynamic approach but for higher values of traffic ratio. The advantage is about 25% (e.g., the high-priority traffic is totally allocated until $\rho = 1$ and $\rho = 1.25$

**This behavior is introduced to mimic higher layer control mechanisms, which adapt the transmission rate to the available capacity, such as the TCP congestion control at the transport layer ([15]) or the multilayer coding at the application layer ([16]).

DOI: 10.1002/sat

Table VII. Traffic parameters for each satellite terminal and cloud parameters.

Parameter (symbol)	Value
Birth rate of high-priority traffic calls (λ_{HIGH})	Exponentially distributed with mean 1/180 [s^{-1}]
Termination rate of high-priority traffic calls (μ_{HIGH})	Exponentially distributed with mean 1/120 [s^{-1}]
Transmission rate of high-priority traffic calls (β_{HIGH})	$52.5\cdot\rho$ [packets/frame]
Transmission rate of low-priority traffic (β_{LOW})	$26.25\cdot\rho$ [packets/frame]
ρ	{0.75,0.875,1,1.125, 1.25,1.375,1.5,1.625,1.75,1.875,2}
Cloud radius	Random between 5 and 25 [km]
Cloud attenuation	Random between −1 and −4 DRA schemes
Initial speed of the windfield	Random between 10 and 20 [m/s]
Initial angle of the windfield	Random between 0° and 360°
Speed variation of the windfield	Random between $-0.5\ 10^{-5}$ and $0.5\ 10^{-5}$ [(m/s)/ $T_{SUPERFRAME}$]
Angle variation of the windfield	Random between $-0.5\ 10^{-5}$ and $0.5\ 10^{-5}$ [degrees/ $T_{SUPERFRAME}$]

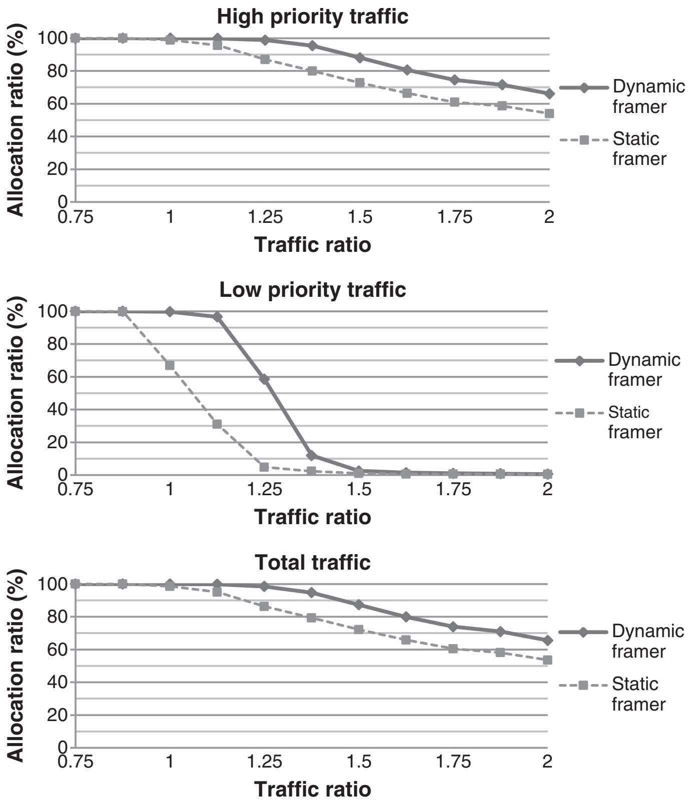


Figure 4. Algorithm performance versus traffic ratio.

for the static and dynamic approaches, respectively). At high traffic ratios, the advantage in total allocation ratio is about $12 \div 18\%$.

Figure 5 shows an example of simulation results, with $\rho = 1.125$. The figure shows the per-DRA scheme allocation ratios (i.e., the sum of the time slot allocated the STs with DRA scheme d is divided by the sum of their time slots requests, for $d = 1, \ldots, 9$) for the high-priority and low-priority traffics. The results show that (i) the high-priority traffic requests are fully satisfied by the dynamic framer (98.87%) and not by the static framer (87.00%); (ii) the low-priority traffic is better served by the dynamic framer (58.53% vs. 4.83%); and (iii) allocation ratios are fairly balanced among the DRAs (fairness).

The simulation runs allowed also the evaluation of the approximation procedure used to round the fractional solution. The average value of the gap (Equation (30)) was about 8%.

DOI: 10.1002/sat

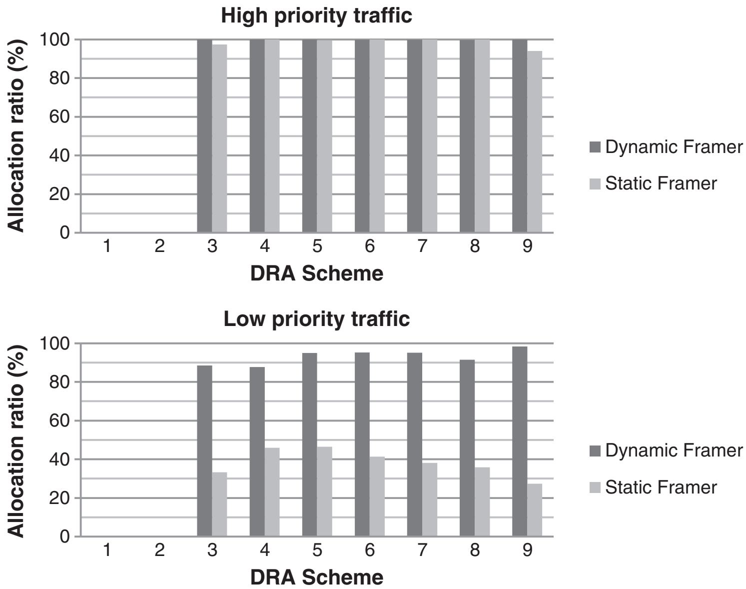


Figure 5. Algorithm performance in an example of simulation run.

5. CONCLUSIONS

This paper proposes the first (up to the authors' knowledge) optimization algorithm for satellite networks with aCM, which dynamically adapts the frame structure of satellite uplinks to the time-varying ST link and traffic conditions: the carrier of uplink frame is dynamically associated to the modulation and coding schemes that maximize the overall link throughput while guaranteeing a grade of fairness among the STs. The optimization problem is formalized as an IP problem; because the algorithms that solve IP problems are NP hard, for the sake of the actual implementation of the algorithm, also, a linear relaxation of the IP problem and a heuristic approximation procedure are proposed. Simulation results confirm the effectiveness of the proposed algorithm with respect to a static frame solution.

The paper shows that the achievable impact of ACM on the satellite systems is high (provided that the resource management algorithms are capable of making use of it): on the one hand, it greatly increases the link capacity in clear sky conditions; on the other hand, it also increases the link availability. In fact, even under severe attenuation, thanks to the possibility of optimizing the frame structure on a short-time horizon, a given terminal is involved in crucial activities (e.g., the ones described in the MONET project ([17]), where disaster recovery scenarios are considered) can be given the possibility to transmit by utilizing robust coding and modulation schemes.

ACKNOWLEDGEMENTS

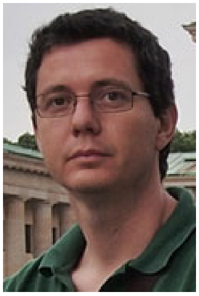
This work was supported in part by the MONET project, funded under the European Commission (seventh FP) ([17]).

REFERENCES

1. Castanet L, Deloues T, Lemorton J. Channel modelling based on N-state Markov chains for satcom systems simulation. In: Twelfth International Conference on Antennas and Propagation (ICAP 2003), 2003, **1**:119–122.
2. ETSI TR 102 376 V1.1.1 (2005-02), Digital video broadcasting (DVB): user guidelines for the second generation system for broadcasting, interactive services, news gathering and other broadband satellite applications (DVB-S2), February 2005.
3. SATSIX - Satellite-based communications systems within IPv6 networks project (2006), contract IST-2006-26950: http://www.ist-satsix.org/
4. Pietrabissa A, Baudin C. Radio resource management for next generation DVB-RCS systems, presented at International Workshop on IP Networking over Next-generation Satellite Systems (INNSS'07). 2007
5. Morell A, Seco-Granados G, Vazquez-Castro MA. 2006. Joint time slot optimization and fair bandwidth. In Proc. of IEEE Globecom 2006.
6. Morell A, Seco-Granados G, Vazquez-Castro MA. Cross-layer design of dynamic bandwidth allocation in DVB-RCS. *IEEE Systems Journal*, 2008, **2**, 1, 62–73

7. Lee KD, Chang KN. A real-time algorithm for timeslot assignment in multirate return channels of interactive satellite multimedia networks. *IEEE Journal On Selected Areas In Communications*, 2004, **22**, 3, 518–528. DOI: 10.1109/JSAC.2004.823433.
8. Castro MAV, Ronga LS, Werner M. Dynamic rate adaptation (DRA) and adaptive coding and modulation (ACM) efficiency comparison for a DVB-RCS system. 2nd International Symposium on Wireless Communication Systems, 2005, 822–826, DOI: 10.1109/ISWCS.2005.1547824.
9. Pietrabissa A, Fiaschetti A. Dynamic uplink frame optimization with ACM in DVB-RCS2 satellite networks, in Proc. of the 1st IEEE AESS European Conference on Satellite Telecommunications (ESTEL 2012), Rome (IT), 2-5 October.
10. ETSI EN 301 545-2 (2012-01), Digital video broadcasting (DVB); second generation DVB interactive satellite system; Part 2: Lower Layers for Satellite standard v1.1.1, January 2012.
11. Pietrabissa A. A multi-model reference control approach for bandwidth-on-demand protocols in satellite networks. *Control Engineering Practice*. 2008, **16**(7), 847–860, DOI: 10.1016/j.conengprac.2007.10.001.
12. Raghavan P, Clark D, Tompson CD. Randomized rounding: a technique for provably good algorithms and algorithmic proofs. *Combinatorica*. 1987, **7**(4), 365–374, DOI: 10.1007/BF02579324.
13. Pietrabissa A. An alternative LP formulation of the admission control problem in multiclass networks. *IEEE Transactions on Automatic Control*, 2008, **53**(3), 839–845, DOI: 10.1109/TAC.2008.919516.
14. Pietrabissa A. Optimal call admission and call dropping control in links with variable capacity. *European Journal of Control*. 2009, **15**(1), 56–67, DOI: 10.3166/ejc.15.56-67.
15. Secchi R, Sathiaseelan A, Potortì F, Gotta A, Fairhurst G. Using quick-start to enhance TCP-friendly rate control performance in bidirectional satellite networks. *International Journal of Satellite Communications and Networking*. 2009 **27**(3), 141–161, DOI: 10.1002/sat.929.
16. Schwarz H, Marpe D, Wiegand T. Overview of the scalable video coding extension of the H.264/AVC standard circuits and systems for video technology, *IEEE Transactions on Circuits and Systems for Video Technology*. 2007 **17**(9), 1103–1120.
17. MONET (Mechanisms for optimization of hybrid *ad-hoc* networks and satellite NETworks) EU Project , contract no. 247176, 2010-2012, www.ict-monet.eu

AUTHOR’S BIOGRAPHIES



Dr. Antonio Pietrabissa graduated in Electronic Engineering from the University of Rome “La Sapienza”, in 2000, where he received the Ph.D. in System Engineering in 2004. Since 2010, he is Assistant Professor with the Department of Computer, System and Management Engineering of the University of Rome “La Sapienza”. He is member of the Technical Committe of the Consortium for the Research in Automation and Telecommunication (CRAT). Since 2000, he has been participating in 9 European Union projects, 2 ESA projects and 2 National projects on telecommunications. His research focus is the application of system and control theory methodologies to communication networks, with specific interest to the design of resource management protocols (e.g., connection admission control, congestion control, routing, medium access control) for multimedia broadband satellite systems, wireless networks and next-generation heterogeneous networks. He is author of about 60 papers on these topics.

Mr. Andrea Fiaschetti obtained his Bs.C. degree in Automation and Control Systems Engineering in 2005 and his Ms.C. degree in Systems Engineering in 2009 at the University of Rome “La Sapienza”, where he is currently pursuing his Ph.D. in System Engineering. Since 2008, he serves as a Researcher for CRAT (Consortium for Research in Automation and Telecommunications) founded by ElsagDatamat, Qualcomm and Thales Alenia Space. His studies focus on the design of innovative algorithms for network control and resource management, with particular attention to Security and Broadband Satellite Communications. He exploited the results of his research in 4 European Union projects and in one National project. He is author of several papers on these topics.