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Two-Color Scheme For A Multi-Beam Satellite Return Link: Impact Of Interference Coordination

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***Abstract*—The return link of broadband satellite systems has recently received more attention due to the spread of multi-beam antennas which enable spatial frequency reuse, and thus increase drastically the number of users that can potentially be served by one satellite. While interference isolation has so far been the way to go, with regular four-color frequency reuse scheme, there is a growing interest in densifying the frequency usage as is being done in cellular networks.**

In this paper we address the return link radio resource allocation challenges, from spectral resource allocation to user scheduling including modulation and coding scheme (MODCOD) selection. Our contributions highlight the potential gains of a two-color scheme and shed light on several levers to reap its benefits through interference management.

We first consider the possibility to use a two-color scheme, while keeping the MODCOD selection and the scheduling local to each beam and we show that even though it yields a potential performance gain (+16%) with respect to the state-of-the art (SoA) (based on four colors), it is not viable due to a very high block loss rate.

Therefore, we propose a simple -yet fast and efficient- coordinated MODCOD selection process that alleviates the need of estimating interference and reduces drastically decoding failures. This coordination step offers significant gains (+58%) over the SoA, while leaving the per beam scheduler unchanged.

Finally, we formulate a joint user scheduling and MODCOD selection problem across all beams and propose an offline heuristic to solve it efficiently. We obtain a 83% gain wrt the SoA, but with higher computational complexity. Still, it confirms the great potential of coordinated scheduling.

I. INTRODUCTION

Recent advances in satellite technologies, such as multi-beam antennas [1], have made satellite networks serious contenders to offer high speed Internet access across the world. Multi-beam antennas enable channel re-utilization (i.e., coloring) and hence, increase massively the total throughput that a satellite can offer. However, channel re-utilization implies a large increase in the interference and this increase has to be properly managed.

Most of the work on multi-beam satellites has logically focused on the forward link (FL), which carries the most traffic. Yet, as in cellular networks, the traffic on the return link (RL) is also increasing and radio resource management (RRM) on the RL is not a straightforward extension from the RRM on the FL mostly due to the different sources of interference (other co-located satellite antennas on the FL and other devices on the RL), and the framed structure of MF-TDMA, used for the RL of DVB-RCS2 [2].

Critical to RRM on both the FL and the RL is the notion of interference. Considering the RL and a transmitter in a certain beam using a certain channel, the most important component of the interference at the beam receiver (on the satellite) is from other transmitters in other beams using the same channel (i.e., same polarization and carrier) at the same time. This is called co-channel interference (CCI).

There are three different system characteristics that affect the CCI: the beam layout, the coloring scheme, and scheduling. The first one describes how the different beams are placed with respect to each other to cover the required area, it is given by the multi-beam antenna design and generally cannot be changed. However, it is important to consider interference during the antenna design, as it has an important impact on the mean CCI experienced by each beam. Traditional regular beam layouts such as the hexagonal grid inherited from cellular networks are quickly being replaced by more efficient ones. In a dual polarization scenario, it has been shown that a beam layout taking advantage of this parity, for example a square grid such as introduced by Thales Alenia Space in [3], increases the distances between same polarization beam centers, reducing CCI substantially.

The second and more widely studied approach is coloring, i.e. carrier re-utilization. We call a *color* a subset of channels using the same polarization (we only consider orthogonal polarizations, e.g. right or left hand circular polarization (RHCP or LHCP)). Each coloring scheme defines a base coloring pattern by assigning each beam to a color. It is characterized by its frequency reuse factor (FRF), the proportion of beams where the color is used. A 4-color scheme can mean 4 sub-bands and one polarization or 2 sub-bands and 2 polarizations, as shown on Figure 1. The latter is very popular in dual-polarization satellite systems, as there are convenient beam layouts for the embedded antennas [1]. This coloring scheme has excellent interference isolation properties, i.e., the CCI is very low, but is inherently limited in per-beam bandwidth (FRF = 1/4) and hence in performance. Therefore, using more aggressive coloring schemes such as a 2-color scheme, e.g., 1 sub-band (the whole band) per polarization (FRF = 1/2) is essential to increase the system capacity, providing twice as much bandwidth to each beam. An example of a 2-color scheme is given on Figure 2, in a dual-polarization system.

Using more aggressive coloring schemes (i.e., with less colors) provides more bandwidth, but it also implies that the interference isolation is weaker. Moreover, increasing the total bandwidth available to each beam has a cost on the

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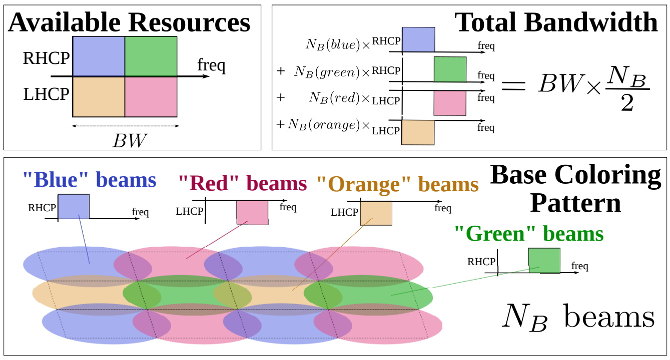

Figure 1. A 4-color coloring scheme on an example square grid layout and 2 polarizations.

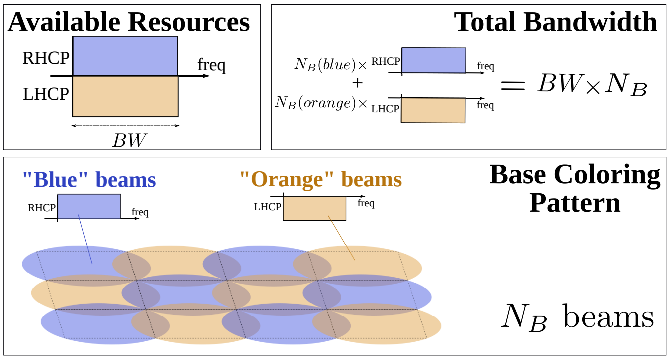

Figure 2. A 2-color coloring scheme on the same example. The total required bandwidth is doubled, as the total available bandwidth per beam.

payload and satellite-gateway links (feeder links). Therefore it is critical to consider the actual achievable capacity increase relative to the bandwidth increase (i.e. bandwidth efficiency), to ensure that a coloring scheme will be profitable to the satellite system.

The third aspect is scheduling performed every frame. Its objective is to be efficient and fair. Typically, proportional fairness is considered [4]. The scheduler allocates on the RL at most one resource block per time-slot to a terminal and then selects the proper Modulation and Coding Scheme (MODCOD) for each resource block based on a more or less precise estimate of the Signal to Interference plus Noise Ratio (SINR). If the MODCOD is selected correctly then the receiver will be able to decode the resource block, otherwise if the SINR is under-estimated, the receiver might not be able to decode, yielding a block loss (and the need for retransmission).

The scheduling and MODCOD selection are typically performed by the beam's gateway (a typical satellite system has many gateways, each of them responsible for a certain number of (not necessarily adjacent) beams) with only local (to the beam) information and in that case, the processes for all beams under the control of a gateway can be parallelized within the gateway. In that case the interference produced by the other beams is unknown and needs to be estimated. The trend is to centralize the control of the gateways via a SatCloudRAN (a satellite cloud radio access network) [5] and in that case, the processes for all beams can be performed in a *coordinated* fashion to better control the interference. This coordination can be more or less fine grained as will be discussed in the paper. Understanding the level of coordination that is necessary to strike a good trade-off between performance and complexity is one of the objectives of this paper.

The performance of a RRM suite comprising the paving scheme, the coloring scheme, the scheduling and the selection of the MODCOD is measured in terms of **goodput** (effective throughput) to take losses due to bad interference estimation into account [6]. This is critical as the block loss rate is one of the most important performance key indicators for satellite networks.

The state-of-the-art (SoA) RRM suite we consider is the combination of a 4-color scheme on a square grid[1] and a randomized round robin (RRR) per beam scheduler which is *locally* proportional fair [7] (i.e. fair between users in each beam).

The purposes of this study are i) to show how the 2-color scheme can provide much better performance than the SoA if the RRM suite is well-designed and ii) to understand the trade-offs between the level of coordination, the performance and the complexity of the RRM processes.

The contributions of the paper are the following:

1) We show that if we use the scheduler and MODCOD selection process of the SoA on a 2-color scheme, i.e., without any coordination, the best achievable goodput (i.e. without the losses) is on average 16% better than the SoA. Yet, the high loss rate (23%) is prohibitive, especially in a satellite context where the cost of re-transmission is high due to the important transmission delay.
2) We propose a simple coordinated MODCOD selection process to perform after scheduling the resource blocks to the terminals, on a per-beam basis (as in the SoA). It alleviates the need for estimating the interference and we show that when used with a RRR scheduler and a 2-color scheme, it produces a significant 58% gain in goodput wrt the SoA. When used with a 4-color scheme, the gain is only 1.1%, which confirms the interference isolation provided by 4-color scheme. Since we compute the MODCOD in a coordinated fashion after scheduling, interference can be precisely known and then errors are minimal. Having a low complexity, high performances and high flexibility (very low impact on the scheduling process), this RRM suite is very appealing and could be considered for implementation.
3) We formulate a joint scheduling and MODCOD selection problem across all beams using the same polarization and propose a heuristic to solve this problem efficiently. This heuristic yields a 83% gain in goodput wrt the SoA (86% in capacity) however it is too complex to be solved online. It yields a bandwidth efficiency very close (93%) to that of the SoA (on a 4-color scheme), demonstrating that highly profitable gains can be achieved through coordinated scheduling.
4) All solutions are validated via extensive simulations that take errors due to bad interference estimation into account for all schemes relying on it (e.g. the SoA and the first proposed scheme).

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[1] The analysis presented in this paper uses a square grid, but it holds for an hexagonal grid, though with lower performances, and could be extended to other paving patterns.

The paper is organized as follows: in Section II we survey the main work on the topic, before presenting our model in Section III. Then, in Sections IV, V and VI we successively present our three RRM suites, and compare their respective performances in Section VII. Finally, we conclude in Section VIII.

II. RELATED WORK

Static Interference Management: Several alternative static interference management schemes have been proposed in the literature, both for cellular and satellite networks. They generally focus on defining a coloring scheme, coupled with power pre-allocation or time restriction depending on the position of users. Then, user scheduling and MODCOD selection is left to implementation. For example, the Fractional Frequency Reuse scheme splits a beam into two areas (beam center and beam edge) and uses three sub-bands: one for the beam center area, reused in each beam and the two others for the beam edge areas, alternating between the two sub-bands. However, this puts high operational constraints on a beam spectral resources, and thus reduces the system flexibility and adaptability to non-uniform demand distribution. They are well surveyed in [8] and [9]. These approaches may increase the amount of bandwidth available in each beam, but they are limited by their capacity to isolate interference properly. Therefore, this type of approaches should be combined with other interference coordination techniques (e.g., such as presented in this paper) to reach higher performance.

Channel State Adaptation: Adaptive Coding and Modulation (ACM) [10] is a decentralized and measure-based mechanism designed to adapt to continuous and slow changes in the channel state. The mechanism is based on periodical measures of the channel state (direct measures in the return link, and reports in the forward link), which are used by a channel-state estimator and then fed to the MODCOD selector. While it has initially been designed to cope with channel variations due to meteorological events, it may also help adapt to interferences as long as their behavior is similar to an additive noise, and not too variable in time. This is not the case for a 2-color scheme in the return link, where interferences depend on which users are scheduled together, and thus may vary from very low to very high from one time-slot to the next.

Dynamic Interference Management: Even though the topic is quite recent, and thus the literature around it scarce, there are several articles worth mentioning. In the FL, several articles consider non regular frequency reuse patterns, based on a full frequency reuse (i.e. a 1-color scheme) [11], [12], and propose different algorithms to dynamically assign carriers (and power) to beams, according to the beam demands and considering co-channel interference, assuming a flexible satellite payload. In [13], the authors benefit from a highly flexible satellite payload with beam-hopping to perform user scheduling, avoiding transmission in a beam if it would interfere too much with a user in a neighboring beam. In the RL, [9] implements a *max-min* greedy heuristic to re-organize the frame assuming that the number of slot per user is known, in a fractional frequency reuse scenario. In [14] and [13] multi-partite graph matching is used to jointly schedule users in a 7-beam-clustered Multi-user MIMO scenario, benefiting from successive interference cancellation techniques at the gateway. In [15], the authors compare different interference-aware genetic algorithm-based schedulers, in a full frequency reuse scenario. Finally, in our previous paper [16], we studied a system using an hexagonal grid layout. We presented and detailed a model aiming to maximize a time-slot sum-rate capacity (over all beams), without taking fairness into consideration, nor offering practical solutions. The present work has much wider ambitions, studying a range of RRM suites, from the most standard to more sophisticated solutions, and together with a global proportional fairness objective.

Proportional Fair Scheduling: The Proportional Fair Sharing scheduling policy [17], or its adaptations to the LTE SC-FDMA uplink [18] or WLAN downlink [19] cannot be straightforwardly applied in the satellite fixed access case with DVB-RCS2, since there are some specific and very limiting constraints inherited from the MF-TDMA frame structure and the highly variable interference environment. To the authors knowledge, there is no work to date tackling the problem of interference-aware proportional-fair scheduling for the uplink, and especially in the return link of multi-beam satellites.

III. SYSTEM MODEL

In this section, we will present our general framework. The notations are summarized in Table I. We consider the return link of a system composed of a gateway, a transparent multi-beam satellite operating in the Ku/Ka band and several RCS2 Terminals (RCST) (see Figure 3). The satellite has N_B directive antenna feeds, defining N_B beams. The beams are organized in a square grid and split over the two polarizations, like a chessboard, as shown on Figure 3 and presented in [3]. To simplify the notations, we will limit our study to one of the polarizations. Each beam k has a set of fixed RCSTs[2] $\mathcal{U}_k$ indexed by i, able to transmit using a set of MODCODs, indexed by m. We assume that the system is controlled by a satellite cloud radio access network (SatCloudRAN) [5], that can coordinate the beam schedulers as long as the coordination is not too time-consuming since scheduling has to be computed often and very quickly.

Notation	Description
k, i, t, c, m	Beam/user/time-slot/channel/MODCOD
$\mathcal{U}, \mathcal{U}_k$	Set of all users/users in beam k
$N_U, N_U(k)$	Number of users/users in beam k
N_B	Number of beams (1 polarization)
N_{tti}, N_C	Number of time-slots/channel
$x_{i,m}^{t,c}(k)$	Decision variables
Γ_m, r_m	SINR threshold/Rate of MODCOD m
I_{est}^k	Per carrier estimated interference at beam k
$R_i(I_{est}^k)$	Throughput of user i given I_{est}^k
μ	Noise power per carrier
$G_k(i)$	Channel gain from user i to sat. antenna k
P_i	Transmit power of user i

Table I
NOTATIONS

We consider a DVB-RCS2 [2] Demand Assign Multiple Access (DAMA) scheme where resource requests are sent by terminals to the gateway periodically. We consider a given DVB-RCS2 MF-TDMA frame, composed of N_{tti} time-slots and N_C equal bandwidth, identical carriers. We call

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[2] In the following we use the terms RCST, user terminal or user interchangeably.

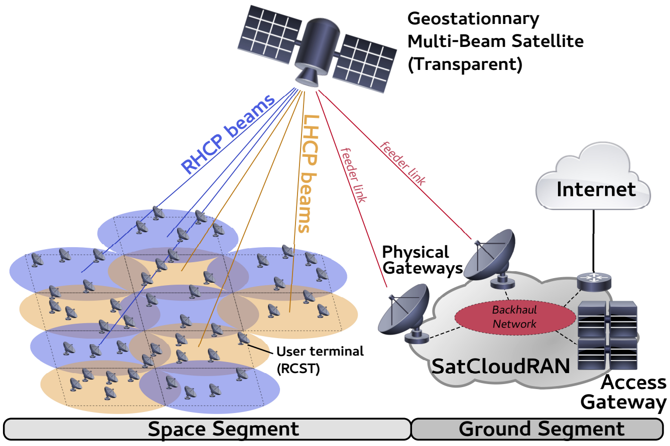

Figure 3. System Architecture

Bandwidth Time Unit (BTU), or resource block, a (time-slot, carrier) pair. A user may only transmit on a single carrier at a time, since MF-TDMA does not allow the transmission of two bursts on different carriers simultaneously on a single transmission chain. Therefore the DAMA scheduler allocates at most one BTU per time slot to a terminal and assigns the MODCOD to use. Once assigned, the resources allocation table (one per beam) is broadcast to the users. In this paper we will treat adjacent channel interference (ACI) and cross-polarization interference (CPI) as constant noises.

A. Interference Model and MODCOD Selection Process

Let the binary variable $x_{i,m}^{t,c}(k)$ indicates whether RCST $i \in \mathcal{U}_k$ is allocated BTU (t,c) to transmit with MODCOD m or not in the current frame ($x_{i,m}^{t,c}(k) = 0$ if $i \notin \mathcal{U}_k$). Then, for each RCST $i \in \mathcal{U}_k$ the real SINR on a BTU (t,c) is:

$$SINR_i^k(t,c) = \frac{P_i G_k(i)}{\mu + \sum\limits_{\substack{k'\neq k\\ j\in\mathcal{U}_{k'},m'}} x_{j,m'}^{t,c}(k') P_j G_k(j)} = \frac{P_i G_k(i)}{\mu + I^k(t,c)} \qquad (1)$$

where P_i is the transmission power for user i, $G_k(i)$ is the reception gain of beam k for user i, μ incorporates the thermal noise, the ACI and CPI noises, and finally $I^k(t,c)$ is the interference power at beam k on the BTU (t,c). $G_k(i)$ is assumed flat across all channels and constant within a frame. $G_k(i)$ takes into account the antenna gain, its directivity but also every other signal attenuation phenomenon like antenna pointing error, atmospheric losses, path loss, etc.

To compute $SINR_i^k(t,c)$, we need to know $G_k(i), \forall i \in \mathcal{U}_k$ and either all the $(G_k(j))$'s or an estimate of $I^k(t,c)$. Therefore, we assume in the following that the scheduler responsible for beam k has a perfect knowledge of $G_k(i)$ for all $i \in \mathcal{U}_k$.

Remark 1: *Power Control.* It is possible to use power control on the RL, forcing user terminals to reduce or increase their transmission power. However, the power control implemented in DVB-RCS2 is not fine-grained (once every couple of seconds) and thus can certainly not be used to adjust the interference at the BTU level. Therefore, in this paper we do not consider user power as variable but rather as a parameter of the system. We assume that all users transmit at their maximum power, considered equal among all users.

Remark 2: *Difference with the Forward Link.* Note that contrarily to the FL, where the interference from the other beams is independent of who are scheduled in other beams (as long as the power is the same on all BTUs), the interference $I^k(t,c)$ on the return link of beam k in BTU (t,c) is dependent on the users scheduled in each beam $k' \neq k$ and cannot be known precisely without knowing who have been scheduled to transmit in the other beams on the same BTU. Hence, if there is no coordination between the beams, $I^k(t,c)$ would have to be estimated.

Once $SINR_i^k(t,c)$ is computed, the best MODCOD $m^*(i)$ is selected using:

$$m^*(i) = \arg\max_m \left\{ r_m \mid \Gamma_m \leq SINR_i^k(t,c) \right\} \qquad (2)$$

where Γ_m is the minimum required SINR for MODCOD m, i.e., to decode the BTU.

Of course, if the interference is not estimated correctly, the SINR might be incorrect too. We consider that a transmission using MODCOD m is lost if and only if $SINR_i^k(t,c)$ is strictly lower than Γ_m[3]). While this is not theoretically exact, since to an SINR and a MODCOD corresponds a block loss rate (BLR), in practice the behavior is very close to this binary decision, the BLR slope is very steep as for example illustrated in [20, Table 10.6].

B. Performance Metric

One of the objectives of this paper is to study the impact of using a more aggressive coloring scheme in term of satellite capacity increase. However, maximizing the sum of the throughput over all users is unfair when there is not enough resources for all users, as some users may never receive a single allocation. We use a form of fairness which yields a good compromise between throughput and fairness: proportional fairness, as introduced by Kelly in [4]. This fairness is provided on a per frame basis. In that case, to measure performance and fairness we can use a single metric [6]: the geometrical mean (GM) of the throughput over all beams defined as:

$$\mathbb{G}_{GM} = \Big(\prod_{\substack{k\\ i\in\mathcal{U}_k}} \lambda_i\Big)^{1/N_U} \qquad (3)$$

where λ_i is the throughput of user i. In the rest of the paper, every RRM suite performance is thus measured by this metric.

C. RRM Suite Notation

In the following we are going to study and compare several RRM suites with the same paving. We will use the following nomenclature for representing an RRM suite: [{2, 4}C, User Scheduler (US), MODCOD selection (MS)]. The benchmark described in Section IV-A is SoA = [4C, $\texttt{RRR}_L$, $\texttt{MS}_L$], the one in Section IV-C is [2C, $\texttt{RRR}_L$, $\texttt{MS}_L$], the one in Section V is [2C, $\texttt{RRR}_L$, $\texttt{MS}_C$] and the one in Section VI is [2C, `Joint-US&MS`]. The $_L$ stands for local, and the $_C$ for coordinated.

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[3] In this study we considered the SINR thresholds Γ_m corresponding to a Block Loss Rate of 10^{-5} for that MODCOD.

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IV. The Benchmark

A. The Benchmark: [4C, $\texttt{RRR}_L$, $\texttt{MS}_L$]

In this section, we will present and justify our benchmark, i.e., the SoA based on proportional fairness.

1) Coloring scheme: 4C: The reference coloring scheme is the 4-color scheme (called 4C in the following), which is still very popular in the literature [21], [22] corresponding to 2 subbands and two polarizations.

2) Interference Estimation and Local MODCOD Selection: $\texttt{MS}_L$*:* Even though a 4C scheme isolates interference efficiently, it remains possible that a combination of users may generate too much interference, increasing the BLR. To cope with this imperfect interference isolation, we will compute the SINR of user i in beam k on any BTU (t, c) as:

$$SINR_i^k(t, c, I_{est}^k) = \frac{P_i G_k(i)}{\mu + I_{est}^k} \tag{4}$$

where I_{est}^k is an estimate of the CCI generated by other beams' users and is selected to be the same on any BTU (t, c) of the frame. Note that in that case, under our assumptions, user i $SINR_i^k(t, c, I_{est}^k)$ is the same for all BTUs and hence can be written as $SINR_i^k(I_{est}^k)$. Note that if we under-estimate the interference, we might not be able to decode the block at the receiver (and this would cause the loss of the block), while if we over-estimate the interference, we will lose in performance.

In the following, we will show the performance in terms of goodput as a function of I_{est}^k and in particular, we will evaluate the performance of a very simple estimation based on the average of the reception gain over all beam users where:

$$I_{est}^k = \eta \cdot \frac{1}{N_U(k)} \sum_{\substack{k' \in \mathcal{B}(k) \\ k' \neq k}} \sum_{j \in \mathcal{U}_{k'}} G_k(j) P_j = \eta \bar{I}_k \tag{5}$$

η is a tunable parameter used to adjust the estimation and $\mathcal{B}(k)$ is the set of beams using the same color as beam k. $\bar{I}_k$ is thus a parameter that is specific to a beam (it characterizes its neighborhood). Given a system and its set of fixed terminals, we can compute the $(\bar{I}_k)$'s ahead of time.

3) Local Proportional Fair Scheduling given I_{est}^k*:* $\texttt{RRR}_L$*:* Recall that the SoA schedules each beam independently and locally. Hence, we focus on the scheduling on beam k and we design it to be proportional fair. It is equivalent to maximize the geometrical mean of the user throughputs [7] or equivalently the sum of the logarithms of the throughputs.

As the interference estimate I_{est}^k is given, the SINRs $SINR_i^k(I_{est}^k)$ for all $i \in \mathcal{U}_k$ can be computed ahead of time and hence the per BTU rate $R_i(I_{est}^k)$ for user i is known using the MODCOD selection rule in eq. (2). When the MODCOD is performed based on a local estimation of the interference, we call it $\texttt{MS}_L$.

We note that, under our assumptions (flat channels and non time dependant at the scale of the frame), all BTUs in a frame are identical, the scheduling problem is equivalent to allocate a certain number α_i of BTUs to terminal i. Hence, the scheduling problem in beam k can be written as the following integer non-linear program, which aims at finding the PF-optimal BTU count allocation, given the $(R_i(I_{est}^k))$'s.

$$\max_{\vec{\alpha}} \quad \sum_{i \in \mathcal{U}_k} \log\left(\alpha_i R_i(I_{est}^k)\right) \tag{6a}$$

$$\textbf{s.t.} \quad \sum_{i \in \mathcal{U}_k} \alpha_i \leq N_C N_{tti} \tag{6b}$$

$$\alpha_i \in [\![1, N_{tti}]\!] \ \forall i \in \mathcal{U}_k \tag{6c}$$

Note that with this formulation we lose the BTU individuality, and hence we will have to ensure that our solutions are feasible, i.e., that we find a BTU allocation that assigns no more than one BTU per time-slot to a terminal.

The $(R_i(I_{est}^k))$'s being fixed for a give I_{est}^k, they can be taken out of the objective, and the objective is then to maximize $\sum_i \log(\alpha_i)$. Therefore, the solution to the integer relaxation of this problem is that every user gets the same amount of BTUs. To actually assign BTUs to users, we can use a Round Robin (RR) scheduler. However in the case where $N_C > N_U(k)$, we have to leave $N_C - N_U(k)$ resource blocks empty for each time-slot. In practice it is better to add some randomness in the round robin scheduling, to ensure that the same users are not always scheduled together. This way, we avoid systematic degradation of a user's throughtput, which is more fair. In the following, we will use a randomized RR (RRR) scheduler for the benchmark, and we call this scheduler $\texttt{RRR}_L$.

B. Calibration of the Interference Estimation

Recall that the interference estimate I_{est}^k (see eq. (5)) is a function of the tunable parameter η (the larger (resp. lower) η, the more (resp. less) conservative the estimate). To evaluate the impact of the interference estimate on the goodput, we generated 1000 random realizations[4] for a system characterized by the parameters in Table IV. For each realization, we can compute the $(\bar{I}_k)$'s and for different values of η (the same η for all beams), we can then compute the estimated throughput for terminal i, $\lambda_i(\eta) = \alpha_i R_i(I_{est}^k)$, using problem (6) and via simulation, we can measure the corresponding goodput $G_i(\eta)$, as well as the block loss rate $BLR(\eta)$.

Figure 4 shows $\mathbb{T}_{\mathbb{GM}}(\eta)$ (resp. $\mathbb{G}_{\mathbb{GM}}(\eta)$), the arithmetic mean over the 1000 realizations of the geometric means (over all beams) of the estimated throughputs (resp. the goodputs), as a function of η. The green area in these figures represents the block loss rate due to decoding failures (averaged over the 1000 realizations).

The figure exhibits interesting properties. For example, let η_{4C}^* be the value of η corresponding to the maximum goodput. We can see that as long as η is chosen greater than a certain value, e.g., $1.1 \times \eta_{4C}^*$, the estimated throughput and the goodput are almost equal (i.e., the losses are negligible) and their decrease is slow when η increases. Hence it is possible to customize the value of η for an arbitrarily small $BLR(\eta)$ value, without impacting too much the system goodput GM.

C. Changing to a 2C Scheme

The same user scheduling and MODCOD selection process can be applied to a system using a 2-color scheme.

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[4] A realization is defined by the channel gains $(G_k(i))_{k,i \in \mathcal{U}}$ and a cell selection policy that maps each user to a beam.

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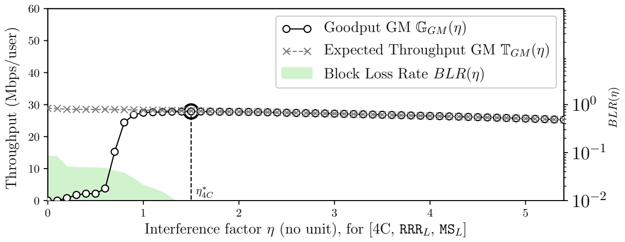


Figure 4. The benchmark (4C case): expected throughput/goodput comparison as a function of η

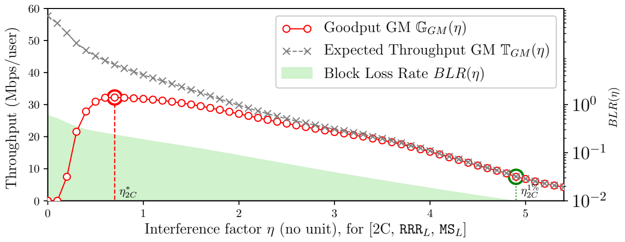


Figure 5. The benchmark (2C case): expected throughput/goodput comparison as a function of η

The whole reasoning is the same, but the expected behavior should be different since more interference will be generated in the 2-color scheme.

The results for the 2-color scheme (or 2C) are shown on Figure 5. Clearly using the SoA with a 2-color scheme yields a slightly higher maximum goodput (a gain of 16%). However, this increase in goodput comes with very significant losses which makes selecting $\eta = \eta^*_{2C}$ (the red circle) not practical. If, for example, we want the losses to be on average less than 1%, then we need to choose $\eta \geq \eta^{1\%}_{2C}$ (the green circle) and in that case the goodput is much lower than the goodput offered by the 4C scheme. This can be explained by the fact that a beam-wide interference estimation is too coarse-grained, resulting in either an over-estimation of the interference (and hence a sub-optimal MODCOD selection) or an under-estimation (causing the loss of the BTU). Losses being very costly in the high delay context of satellite, the benchmark RRM suite is not viable with a 2C scheme and we need to design a more individualized interference management scheme to reap the benefits of the 2C scheme.

Next, we propose a simple addition to the benchmark to take advantage of the C-RAN without making the RRM process much more complex.

V. COORDINATION OF MODCOD SELECTIONS ACROSS BEAMS: $\mathtt{MS}_C$

The latter approach (i.e., the benchmark) is completely uncoordinated, i.e., the scheduling and MODCOD selection are performed by the SatCloudRAN (or by each beam's gateway) on a per beam basis with only local information, i.e., without any coordination across beams. In that case, RRR is performed first and a MODCOD is selected for each BTU based on the estimate of the SINR which depends on terminal it was allocated to, the interference estimate and the channel gain. The fact that there is an interference estimate decouples the beams and allows the selection of the MODCOD to be local.

In this section we present a simple modification to this process performed by the SatCloudRAN, where the scheduling remains unchanged but the MODCOD selection is performed in a coordinated way across all beams.

The first step is therefore to schedule users locally, using the same Randomized Round Robin (RRR) than in the benchmark. Then, when the beam schedulers have filled all the allocation tables (one per beam), the SatCloudRAN starts the coordinated process of allocating MODCOD to each BTU. Indeed, the SatCloudRAN now has the knowledge of all scheduled users $\vec{u}(t,c) = (u_k(t,c))_{1 \leq k \leq N_B}$ on each BTU (t,c) (where $u_k(t,c) = i$ iff $\sum_m x^{t,c}_{i,m}(k) = 1$). It can then precisely compute the interference for each BTU, compute the SINR according to Eq. (1) and select the appropriate MODCOD for each BTU individually. The interference experienced by the scheduled user in beam k, for BTU (t,c) is:

$$I^k(t,c) = \sum_{k' \neq k} P_{u_{k'}(t,c)} G_k(u_{k'}(t,c)) \tag{7}$$

With this process, a user may have different MODCOD from one slot to the other, according to the interference, as enabled by the TBTP2 [2].

Remark 3: *On the scheduling process*. Note that in this RRM suite, the scheduling is performed *locally*, without any knowledge of other beam's interference. The interference estimation and adaptation is delayed and left to the coordinated MODCOD selection process.

Remark 4: *On the additional complexity*. Even though computing the SINR in a coordinated fashion has a cost ($O({N_B}^2 N_C N_{tti})$ operations), this cost is polynomial and does not depend on the number of users N_U.

The RRM suite [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_C$] presented in this section, offers very significant gains (+58% wrt [4C, $\mathtt{RRR}_L$, $\mathtt{MS}_L$]) in terms of goodput GM as shown in Table II where the results are given for the value of η that yields the largest goodput. It also solves the problem of losses due to bad interference estimation. The reason this suite performs so much better than the two previous suites is that by selecting precisely and individually the MODCOD we can avoid losses and under-utilization.

The performance of the RRM suite [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_C$] is already very convincing, yet there is still an unexploited degree of freedom (coordinated scheduling) in our RRM suite and one question remains unanswered: how far are we from an RRM suite where the scheduling and the selection are done jointly across all beams?

RRM suite	$\mathbb{T}_{GM}$†	*BLR*	$\mathbb{G}_{GM}$†	$\mathbb{G}_{GM}$ Gain
[4C, $\mathtt{RRR}_L$, $\mathtt{MS}_L$]	28.0	6×10^{-2}	27.9	0.0%
[2C, $\mathtt{RRR}_L$, $\mathtt{MS}_L$]	42.5	2.34×10^{-1}	32.2	+15.7%
[2C, $\mathtt{RRR}_L$, $\mathtt{MS}_C$]	44.1	$\leq 10^{-5}$	44.1	+58.2%

† Throughputs are expressed in Mbps

Table II
AVERAGE RESULTS FOR [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_C$], FOR 100 RANDOM REALIZATIONS, WITH TABLE IV SYSTEM PARAMETERS.

VI. TOWARDS COORDINATED SCHEDULING: JOINT-US&MS

A. Problem Formulation

In [16], we formulated a generic joint scheduling and MODCOD selection problem across all beams, aiming at maximizing any utility function F of the individual throughputs. It takes the form of the following integer program:

$$\begin{array}{lll}
\underset{\vec{x},\vec{\lambda}}{\textbf{Maximize}} & F(\vec{\lambda}) & \text{(8a)}\\
\forall k,t,c & \sum\limits_{i\in\mathcal{U}_k,m} x_{i,m}^{t,c}(k) \le 1 & \text{(8b)}\\
\begin{array}{c}\forall k,t,\\ i\in\mathcal{U}_k\end{array} & \sum\limits_{c,m} x_{i,m}^{t,c}(k) \le 1 & \text{(8c)}\\
\begin{array}{c}\forall k,t,c,\\ i\in\mathcal{U}_k,m\end{array} & \begin{array}{l} x_{i,m}^{t,c}(k)\frac{P_i G_k(i)}{\Gamma_m} \ge (x_{i,m}^{t,c}(k)-1)\mathbf{B}+\mu\\ \quad + \sum\limits_{\substack{k'\neq k\\ j\in\mathcal{U}_{k'},m'}} x_{j,m'}^{t,c}(k')P_j G_k(j)\end{array} & \text{(8d)}\\
\forall k, i\in\mathcal{U}_k & \lambda_i = \sum\limits_{t,c,m} x_{i,m}^{t,c}(k) r_m & \text{(8e)}\\
\begin{array}{c}\forall k,t,cn\\ i\in\mathcal{U}\end{array} & \left\{\begin{array}{l} x_{i,m}^{t,c}(k)\in\{0,1\} \text{ if } i\in\mathcal{U}_k\\ x_{i,m}^{t,c}(k)=0 \text{ if } i\notin\mathcal{U}_k\end{array}\right. & \text{(8f)}
\end{array}$$

where $\vec{x}$ (resp. $\vec{\lambda}$) is the vector of all $x_{i,m}^{t,c}(k)$ (resp. of all λ_i). The first constraint (8b) expresses that only one user per beam can transmit on a BTU. Constraint (8c) comes from MF-TDMA, which limits a user to a single carrier assignment per time-slot. Constraint (8d) is the SINR constraint, ensuring that if a user is assigned a BTU, its SINR will be greater than the SINR threshold (Γ_m) of the chosen MODCOD. Note that the $(x_{i,m}^{t,c}(k)-1)\mathbf{B}$ term is here to ensure the validity of this constraint even when $x_{i,m}^{t,c}(k)=0$, where $\mathbf{B}$ is a large enough real for this purpose. For more details, refer to [16].

Remark 5: *On the information needed to solve this problem.* This type of coordinated problem requires much more information than the previous RRM suites. Indeed, now all the gains $G_k(j)$'s for all k and k' and all $j\in\mathcal{U}_{k'}$ are necessary.

To this formulation we add the global proportional fairness objective:

$$F(\vec{\lambda}) = \sum_k \sum_{i\in\mathcal{U}_k} \log(\lambda_i) \qquad (9)$$

With this objective, the problem previously defined becomes an Integer Non-Linear Program (INLP), which we will call Proportional Fair Global Optimization: **PF-GO**.

This INLP problem is very hard to solve efficiently for systems of medium to large size in a reasonable time, hence, in the following we will present a heuristic scheduler to provide approximate feasible solutions to this problem. This heuristic scheduler might not be fast enough for large scale networks, but it gives an idea about what coordinated joint US and MS could yield in performance gain.

The main size issue in problem **PF-GO**, is the large number of time-slots, which introduces an exponential number of equivalent solutions: under our assumptions, from the PF metric standpoint, it does not matter on which BTU a user is scheduled, as long as the user is scheduled. On the other hand, we cannot simply find the optimal number of slots assigned to a user, as we would not be able to know which users are interfering with each other, which is at the heart of the problem.

The problem is not rigorously separable into N_{tti} time-slot sub-problems, because the objective function is not linear. Hence, we propose an approximate formulation, inspired by the work of Kushner [17]. This work derived mathematically the online proportional fair sharing (PFS) scheduling policy in a single channel case. It consists of selecting at each time-slot the user with the maximum instant rate over mean rate ratio. The PFS scheduling policy maximizes the first derivative of the PF objective function, and as it is concave, it tends to maximize the long term geometric mean, like in a *steepest-ascent* algorithm. Note that PFS is not trying to offer per-frame fairness which departs from what **PF-GO** is trying to achieve.

Additionally, in [16] we studied the impact of solving sequentially the problem on each carrier instead of solving it jointly for all carriers and we showed that the optimality degradation was very low (≤ 4%) as long as there are more users than carriers, which is the case we consider here. However, the problem solved in [16] was maximizing the capacity, and not the proportional fairness, so it will be necessary to check experimentally that the optimality loss is low here as well. Using this approximation reduces considerably the time necessary to solve the problem, as its complexity becomes linear in the number of carrier.

B. Heuristic

The idea here is to generalize the PFS scheduling policy to our (multi-carrier multi-beam system), and to solve it sequentially for each time-slot. We can do this if we keep track of what has been given to each user in the past. We consider time-slot t and let the goodput (in bit/s) that has been offered so far[5] to user i to be $\bar{\delta}_i(t)$. Then the goodput after time t would be $\bar{\delta}_i(t+1) = (T\bar{\delta}_i(t)+\lambda_i(t))/(T+1)$ where $T = t - t_0$ is the time since begining of observation and $\lambda_i(t)$ is the rate received by user i in time-slot t. The objective function at time t becomes:

$$\textbf{Max} \sum_k \sum_{i\in\mathcal{U}_k} \log\left(\frac{T\bar{\delta}_i(t)+\lambda_i(t)}{T+1}\right) \qquad (10)$$

$$\text{Or equivalently: } \textbf{Max} \sum_k \sum_{i\in\mathcal{U}_k} \log\left(1+\frac{\lambda_i(t)}{T\bar{\delta}_i(t)}\right) \qquad (11)$$

$$\approx \textbf{Max} \sum_k \sum_{i\in\mathcal{U}_k} \frac{\lambda_i(t)}{T\bar{\delta}_i(t)} \qquad (12)$$

since $\log(1+x)\approx x$ for x small.
Then the problem at time t becomes, given $(\bar{\delta}_i(t))$'s:

$$\begin{array}{lll}
\underset{\mathbf{x}}{\textbf{Maximize}} & \sum\limits_k \sum\limits_{i\in\mathcal{U}_k} \frac{\lambda_i(t)}{T\bar{\delta}_i(t)} & \text{(13a)}\\
\forall k,c & \sum\limits_{i\in\mathcal{U}_k,m} x_{i,m}^{t,c}(k) \le 1 & \text{(13b)}\\
\forall k, i\in\mathcal{U}_k & \sum\limits_{c,m} x_{i,m}^{t,c}(k) \le 1 & \text{(13c)}\\
\begin{array}{c}\forall k,c,m\\ i\in\mathcal{U}_k\end{array} & \begin{array}{l} x_{i,m}^{t,c}(k)\frac{P_i G_k(i)}{\Gamma_m} \ge (x_{i,m}^{t,c}(k)-1)\mathbf{B}+\mu\\ \quad + \sum\limits_{\substack{k'\neq k\\ j\in\mathcal{U}_{k'},m'}} x_{j,m'}^{t,c}(k')P_j G_k(j)\end{array} & \text{(13d)}\\
\forall k, i\in\mathcal{U}_k & \lambda_i = \sum\limits_{c,m} x_{i,m}^{t,c}(k) r_m & \text{(13e)}\\
\begin{array}{c}\forall k,c,m,\\ i\in\mathcal{U}\end{array} & \left\{\begin{array}{l} x_{i,m}^{t,c}(k)\in\{0,1\} \text{ if } i\in\mathcal{U}_k\\ x_{i,m}^{t,c}(k)=0 \text{ if } i\notin\mathcal{U}_k\end{array}\right. & \text{(13f)}
\end{array}$$

After solving this problem, the $(\bar{\delta}_i(t+1))$'s need to be computed for the next step. This problem is an ILP over all carriers and beams at time t and hence is still large.

---

[5] We could consider a window of fixed duration to account only for the recent past.

To simplify it further, we solve one carrier at a time. Hence, for a given time-slot, we will start with carrier 1, allocate in each beam one user to that BTU, then update the goodput offered so far to these terminals, remove them from the list of potential candidates for this time-slot and move to carrier 2. Once all the carriers have been allocated, we start a new time-slot of the frame after resetting the set of poential candidates in beam k (for all k) to be $\mathcal{U}_k$. The per time-slot and per carrier heuristic is given below: given t, c, $(\bar{\delta}_i(t))$'s and the sets $(\mathcal{U}_k^c)$'s of terminals that are potential candidates to be allocated BTU (t, c):

$$\underset{\mathbf{x}}{\textbf{Maximize}} \quad \sum_k \sum_{i\in\mathcal{U}_k^c} \frac{\lambda_i(t)}{T\bar{\delta}_i(t)} \tag{14a}$$

$$\forall k \quad \sum_{i\in\mathcal{U}_k^c, m} x_{i,m}^{t,c}(k) \le 1 \tag{14b}$$

$$\begin{aligned} \forall k, m, \quad & x_{i,m}^{t,c}(k)\frac{P_i G_k(i)}{\Gamma_m} \ge (x_{i,m}^{t,c}(k)-1)\mathbf{B} + \mu \\ i \in \mathcal{U}_k^c \quad & \quad + \sum_{\substack{k'\neq k \\ j\in\mathcal{U}_{k'}^c, m'}} x_{j,m'}^{t,c}(k') P_j G_k(j) \end{aligned} \tag{14c}$$

$$\forall k, i \in \mathcal{U}_k^c \quad \lambda_i = \sum_m x_{i,m}^{t,c}(k) r_m \tag{14d}$$

$$\begin{aligned} \forall k, m, \\ i \in \mathcal{U} \end{aligned} \quad \begin{cases} x_{i,m}^{t,c}(k) \in \{0,1\} \text{ if } i \in \mathcal{U}_k^c \\ x_{i,m}^{t,c}(k) = 0 \text{ if } i \notin \mathcal{U}_k^c \end{cases} \tag{14e}$$

Then $\forall k$, if $\sum_m x_{i,m}^{t,c}(k) = 1$ then $\mathcal{U}_k^{c+1} = \mathcal{U}_k^c \setminus \{i\}$.

This formulation is very practical because it is a simple weighted sum-rate maximization, over a limited number of variables $(N_U(k) \times N_B \times N_M)$, meaning it can be solved in reasonable time by commercial solvers like Gurobi [23].

Clearly as seen next, Problem (14) yields much better results than [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_C$] with an increase in complexity which is reasonable.

VII. RESULTS AND DISCUSSION

In the previous sections, we have presented four RRM suites:

1) [4C, $\mathtt{RRR}_L$, $\mathtt{MS}_L$], which is the SoA, with local scheduling and MODCOD selection, on a 4C coloring scheme.
2) [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_L$], which kept the SoA scheduling and MODCOD selection, but on a 2C coloring scheme.
3) [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_C$] was introduced to cope with the high *BLR* of [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_L$], it also implements a local scheduling but uses a coordinated MODCOD selection.
4) Finally, [2C, `Joint-US&MS`] uses a more sophisticated heuristic to jointly schedule user and select MODCOD across all beams, in a coordinated fashion.

In this section we compare their performances in terms of goodput GM and discuss their complexity.

A. Results

In Figure 6 we show results in terms of GM goodput, arithemtic mean goodput (i.e., the capacity), the execution time per time slot and the bandwidth efficiency ($BW_{eff} = Capa_{tot}/BW_{tot}$) for a small system comprising 18 beams, 20 terminals per beam and 12 carriers per polarization. As seen before, the RRM suite [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_L$] is able to increase the mean goodput wrt to the SoA at the expense of a increase in the *BLR*, which is not acceptable for satellite systems. [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_C$] offers very substantial gains, with more than 58% mean goodput gain wrt SoA, and considerably lower computational times than [2C, `Joint-US&MS`]. This RRM suite yields a good compromise between performance and computational times. The suite [2C, `Joint-US&MS`] based on our heuristic aims at increasing the performance and yields 83% goodput GM gain over the benchmark RRM suite.

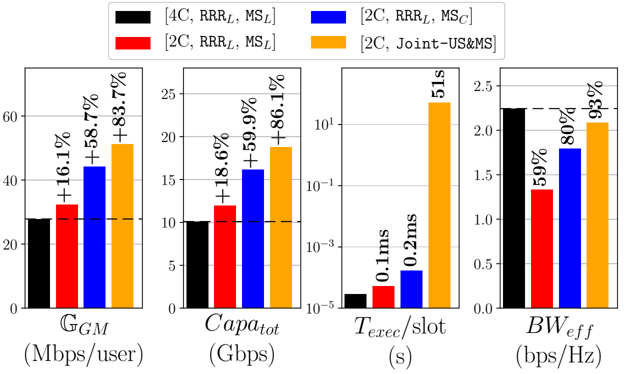


Figure 6. Results for 40 small size system realizations. $N_B = 18$, $N_U(k) = 20$, $N_C = 12$. A 2-color scheme bandwidth efficiency is always less than that of 4-color, then the closer to 100% relative bandwidth efficiency, the better.

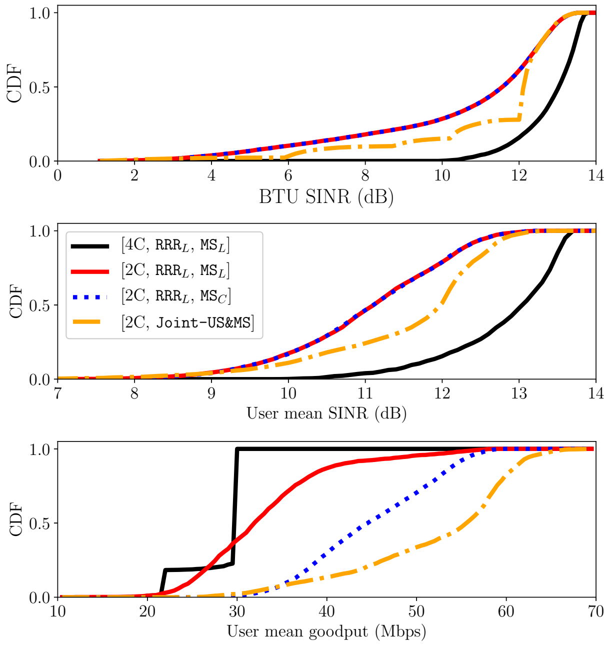


Figure 7. CDF of the individual BTU SINRs, per user mean SINR and per user mean throughput. The shape of user mean throughputs for the [4C, $\mathtt{RRR}_L$, $\mathtt{MS}_L$] is due to the good interference isolation and fixed MODCOD per user, given the estimated interference.

On Figure 7, the Cumulative Distribution Functions (CDF) are shown for the individual per-BTU SINR, the per-user mean SINR and the per-user mean goodput. These figures highlight the gains brought by the late MODCOD coordination mechanism: [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_C$] and [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_L$] have the exact same SINR distribution, but [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_C$] resulting goodput distribution is by far superior, for every user. Finally, the per-user goodput CDF shows that [2C, $\mathtt{RRR}_L$, $\mathtt{MS}_C$] and [2C, `Joint-US&MS`], despite increasing the interference experienced, increase the mean goodput of every user, including those in high interference conditions (≈ 30 Mbps for both RRM suites, where [4C, $\mathtt{RRR}_L$, $\mathtt{MS}_L$] offers ≈ 20 Mbps).

MODCOD (id in [2])	QPSK-1/3 (13)	QPSK-5/6 (17)	8PSK-3/4 (19)	8PSK-5/6 (20)	16QAM-5/6 (22)
Γ_m (dB) @ PER = 10^{-5}	-0.51	5.94	8.77	10.23	12.04
Burst payload (bits/BTU)	984	2664	3200	3552	4792

Table III

AWGN PERFORMANCES FOR THE DIFFERENT MODCODS

Parameter	**Value**	**Parameter**	**Value**
Grid type	Square	MODCOD ids	cf. Table III
N_B	18 over 1 polar.	N_C	12
N_U	360	$\forall k,\ N_U(k)$	20
N_{tti}	300	Burst size	1616
Total bw.	500 MHz	$\forall i,\ \delta_i$	10^{-5}
B	50	Opt. Tolerance	0.05

Table IV

SYSTEM PARAMETERS

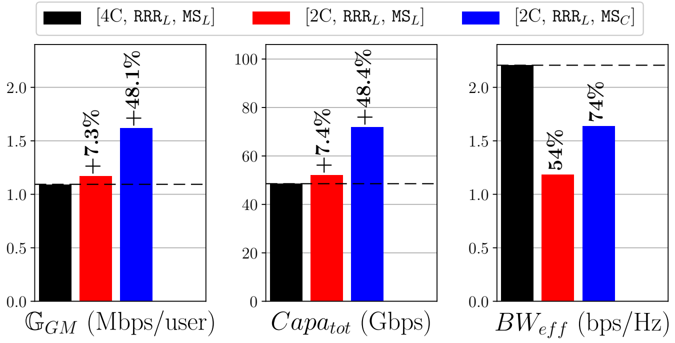


Figure 8. Results for 100 larger system realizations. $N_B = 88$, $N_U(k) = 500$, $N_C = 300$

Other metrics, such as the system total capacity or the bandwidth efficiency are of particular interest to satellite operators. [2C, `Joint-US&MS`] carries some promising results, with a 86% theoretical capacity increase, or in other words, a bandwidth efficiency close to the 4-color case. [2C, $\texttt{RRR}_L$, $\texttt{MS}_C$] bandwidth efficiency is lower, but is still extremely good. A satellite operator willing to use this RRM suite can use the gain in performance in two ways:

1) One satellite may cover up to 60% more users (or alternatively provide 60% increased data rates) for the same coverage, with the same licensed uplink bandwidth.
2) One satellite may cover the same demand with up to 38% less licensed uplink bandwidth.

Remark 6: *Joint carrier problem.* Note also that instances of the problem (13) were also solved and the loss in GM goodput of problem (14) wrt problem (13) is very low ($\leq$ 1%) whereas the time needed to solve problem (13) increases exponentially with the problem size.

To confirm our results on larger systems we generated one hundred random realizations, with 88 beams per polar and 500 active users per beam for 300 carriers. The results of these simulations are shown on Figure 8. For these realizations, we were not able to obtain results for `Joint-US&MS`, as computational times are too high. The system capacity ($Capa_{tot}$) gain is still important for [2C, $\texttt{RRR}_L$, $\texttt{MS}_C$] (+48%) wrt to the SoA even if it is not as large as for small systems, due to the additional cumulated interference.

VIII. CONCLUSION

In this paper, we address the challenges of designing RRM suites for the return link of a satellite system. We present the different levers that can be pulled to increase the bandwidth density of a satellite system: paving, coloring, scheduling, and MODCOD selection. We then extensively studied the possibility to use a 2-color scheme, with 3 specific RRM suites. Our results show that using a 2 color scheme with the same RRM suite as the SoA, i.e., a per beam scheduler RRR_L based on local information and a simple interference estimation-based MODCOD selection is only possible at the expense of a high block loss rate, which is not convenient for high delay satellite transmissions. Therefore, it is necessary to use a more individualized interference management, or in other words, interference coordination.

Then we presented a simple MODCOD coordination-based RRM that takes advantage of a SatCloudRAN architecture. Along with RRR_L it offers important gains wrt the SoA (+58%). Finally, to know if a more sophisticated coordination could reach even higher gains, we formulated a coordinated joint user scheduling and MODCOD selection problem. We solved it with an heuristic inspired by the proportional fair sharing algorithm, which yields a +83% goodput increase wrt the SoA, at the expense of longer computational times.

REFERENCES

[1] M. Schneider, C. Hartwanger, and H. Wolf, "Antennas for multiple spot beam satellites", *CEAS Space Journal*, vol. 2, no. 1, pp. 59–66, 2011.

[2] ETSI, "EN301 545-2 v1.2.1: Second Generation DVB Interactive Satellite System (DVB-RCS2)", in, 2012.

[3] A. Hirsch, P. Bosshard, D. Le Boulc'h, and J. Pressense, "Broadband multibeam satellite radio communication system with improved reuse of frequencies on the forward channel, and associated method for reuse", pat. EP3082275B1, 2016.

[4] F. Kelly, "Charging and rate control for elastic traffic", *European Transactions on Telecommunications*, vol. 8, no. 1, pp. 33–37, 1997.

[5] T. Ahmed, E. Dubois, J.-B. Dupé, R. Ferrús, P. Gélard, and N. Kuhn, "Software-defined satellite cloud ran", *International Journal of Satellite Communications and Networking*, 2017, sat.1206.

[6] Y. Özcan and C. Rosenberg, "Efficient loss-aware uplink scheduling", in *IEEE GLOBECOM*, submitted for publication.

[7] D. Fooladivanda and C. Rosenberg, "Joint resource allocation and user association for heterogeneous wireless cellular networks", *IEEE Transactions on Wireless Communications*, vol. 12, no. 1, pp. 248–257, 2013.

[8] R. Kwan and C. Leung, "A survey of scheduling and interference mitigation in lte", *JECE*, vol. 2010, 1:1–1:10, 2010. [Online]. Available: http://dx.doi.org/10.1155/2010/273486.

[9] U. Y. Ng, A. Kyrgiazos, and B. Evans, "Interference coordination for the return link of a multibeam satellite system", in *Advanced Satellite Multimedia Systems Conference and the 13th Signal Processing for Space*

Communications Workshop (ASMS/SPSC), 2014 7th, IEEE, 2014, pp. 366–373.

[10] S. Cioni, R. D. Gaudenzi, and R. Rinaldo, "Adaptive coding and modulation for the forward link of broadband satellite networks", in *IEEE GLOBECOM*, vol. 6, 2003, 3311–3315 vol.6.

[11] J. Lei and M. A. Vazquez-Castro, "Joint power and carrier allocation for the multibeam satellite downlink with individual sinr constraints", in *IEEE ICC*, 2010, pp. 1–5.

[12] G. Cocco, T. D. Cola, M. Angelone, and Z. Katona, "Radio resource management strategies for dvb-s2 systems operated with flexible satellite payloads", in *2016 8th Advanced Satellite Multimedia Systems Conference and the 14th Signal Processing for Space Communications Workshop (ASMS/SPSC)*, 2016, pp. 1–8.

[13] S. Dimitrov, S. Erl, B. Barth, S. Jaeckel, A. Kyrgiazos, and B. G. Evans, "Radio resource management techniques for high throughput satellite communication systems", in *2015 European Conference on Networks and Communications (EuCNC)*, 2015, pp. 175–179.

[14] V. Boussemart, M. Berioli, and F. Rossetto, "User scheduling for large multi-beam satellite mimo systems", in *2011 Conference Record of the Forty Fifth Asilomar Conference on Signals, Systems and Computers (ASILOMAR)*, 2011, pp. 1800–1804.

[15] B. Makki, T. Svensson, G. Cocco, T. de Cola, and S. Erl, "On the throughput of the return-link multi-beam satellite systems using genetic algorithm-based schedulers", pp. 838–843, 2015.

[16] Y. Couble, E. Chaput, T. Deleu, C. Baudoin, J.-B. Dupé, C. Bes, and A.-L. Beylot, "Interference-aware frame optimization for the return link of a multi-beam satellite (regular paper)", in *IEEE International Conference on Communications (IEEE ICC)*, IEEE, 2017.

[17] H. J. Kushner and P. A. Whiting, "Convergence of proportional-fair sharing algorithms under general conditions", *IEEE Transactions on Wireless Communications*, vol. 3, no. 4, pp. 1250–1259, 2004.

[18] S. Lee, I. Pefkianakis, A. Meyerson, S. Xu, and S. Lu, "Proportional fair frequency-domain packet scheduling for 3gpp LTE uplink", in *INFOCOM 2009. 28th IEEE International Conference on Computer Communications, Joint Conference of the IEEE Computer and Communications Societies, 19-25 April 2009, Rio de Janeiro, Brazil*, 2009, pp. 2611–2615.

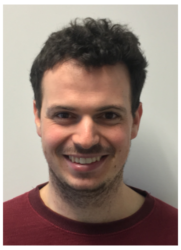
[19] D. M. Blough, G. Resta, and P. Santi, "Interference-aware proportional fairness for multi-rate wireless networks", *IEEE INFOCOM*, pp. 2733–2741, 2014.

[20] ETSI, "TR101 545-4 v1.1.1: Second Generation DVB Interactive Satellite System (DVB-RCS2); part 4 Guidelines for Implementation and Use of EN301 545-2", in, 2014.

[21] "BATS project - D4.5.1 - Overall Strategy and Algorithms for Interference Management", 2015.

[22] J. Pérez-Trufero, B. Evans, A. Kyrgiazos, M. Dervin, B. Garnier, and C. Baudoin, "High throughput satellite system with q/v-band gateways and its integration with terrestrial boradband communication networks", in *32nd AIAA Int. Communications Satellite Systems Conf.*, 2014, pp. 255–264.

[23] I. Gurobi Optimization, *Gurobi optimizer reference manual*, 2016. [Online]. Available: http://www.gurobi.com.



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