Resource Optimization for Cognitive Satellite Systems with Incumbent Terrestrial Receivers

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***Abstract*—We address the resource optimization issue for communications from terrestrial users to a multi-beam satellite when the bandwidth is shared with incumbent primary terrestrial systems. As a consequence, the satellite system is limited by interference temperature in order not to disturb the incumbent systems. Compared to the state of the art, we propose a relevant way to manage the interference constraints on the incumbent systems. Simulations exhibit a substantial gain in data rate when the number of incumbent systems grows.**

I. Introduction

Due to the huge increase of data traffic related to new applications, satellite communications are an alternative way to provide the users. As in terrestrial wireless systems, the bandwidth is a scarce resource. In order to satisfy the data rate requests, new bands are envisioned for satellite systems, typically, the Ka band around 28GHz for uplink. But these frequencies are already occupied by incumbent terrestrial systems, called *Fixed Service* (FS) [1]. Consequently, both types of systems have to share the same bandwidth. In uplink, the satellite systems interfere with the FS receivers and an interference management has to be carried out [2]. The cognitive radio paradigm is relevant since the FS corresponds to the primary system while the satellite based system is seen as the overlaying secondary system, as drawn in Fig. 1. In Fig. 1, the transmitter on the ground (called the cognitive terminal) sends data to the satellite which retransmits it to a terrestrial antenna (called server) via a wireless gateway. We assume that the gateway is perfect (no error and no data rate constraint). However a part of the transmit signal by the cognitive terminal is received by the incumbent terrestrial receivers of the FS system. This implies that the satellite based system is constrained by one interference temperature per FS beyond which it is forbidden to transmit.

In this paper, we propose new algorithms for maximizing the sum data rate by doing relevant resource allocations (related to subband assignment and power per subband) taken into account the interference temperature constraints in a more advanced way than the state-of-the-art associated with this satellite context [3], [4]. We show that the sum rate of the satellite-based system is significantly improved which makes the satellite system as a serious candidate for alleviating the future traffic bottleneck. The performance gap between our

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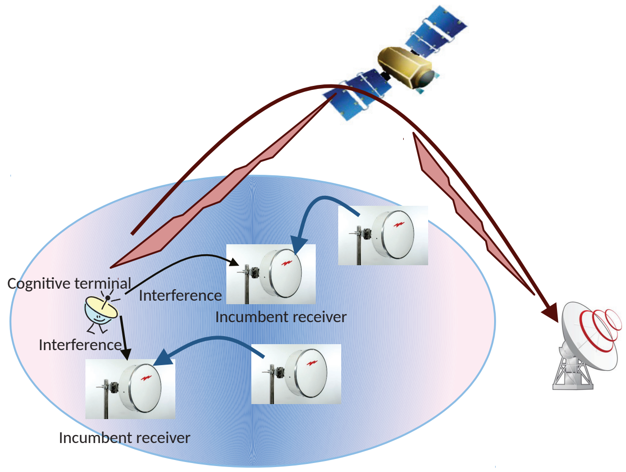

Fig. 1. FS based systems receiving interference from satellite systems.

propositions and the state-of-the-art increases when the number of FS receivers also increase which corresponds to a very likely setup in the future since FS may help 5G basestations to collaborate to each other. Moreover our propositions have been evaluated when the satellite is multi-beam with frequency reuse equal to 1 and equipped by two different types of decoders whose the first one (resp. the second one) views the inter-beam interference as a signal of interest (resp. as a noise).

In the context of cognitive satellite systems, solutions for sum data rate maximization have been proposed in [3], [4] mainly based on power optimization. In both papers, the authors propose to overcome the main technical difficulty which lies in the presence of multiple interference-temperature constraints by introducing two different heuristic approaches enabling to manage in a easier way these constraints. For instance, in [3], the interference-temperature constraints are translated beam per beam which enable the authors to decouple the optimization problem. This approach really makes sense when the number of FS receivers is small but is poor if the FS receivers becomes dense as expected in the future. In [4], the authors propose to optimize the power by managing the worst case, i.e., power of the most interfering user is adapted by assuming that the other users are full power, and so on. This conservative approach, once again, is reasonable with a few FS receivers but is not scalable. In our paper, we propose, on the one hand, to jointly optimize the subband assignment and the power allocation by keeping all the interference-temperature constraints as they stand, and on the other hand, we propose a novel heuristic approach for power optimization by handling in an other way the multiple interference-temperature constraints.

Actually, the allocation problem raised by the cognitive satellite systems (and explained in details in Section II) is close to allocation problems encountered in a multi-cell Orthogonal Frequency Division Multiple Access (OFDMA) system or in a Cloud Radio Access Network (CRAN) where a beam can be seen a cell and the beam antenna as a basestation. Nevertheless in most works, there is one system, and the multiple interference-temperature constraints vanish (see [5]–[7] and references therein). When interference-temperature constraints exist –typically in cognitive radio context or multi-tier system or energy-harvesting system [8]–[11]–, the optimization problem can not be solved in closed-form due to the multiple constraints. Indeed, in [8], [9], the optimization problem is written in the dual domain and the dual variables are optimized through gradient-ascent algorithm. For instance, in [10], [11], the proposed algorithm is iterative and requires a n-D search where n is the number of constraints. Unlike these papers, we propose, at least for the power allocation, a non-iterative simple algorithm.

II. System Model

We first describe the satellite system. We consider a satellite with B beams sharing the same band. This band is split into M subbands. In each beam, we assume a Frequency Division Multiple Access (FDMA) where the maximum number of users K is equal to the number of subband. So $K = M$. More precisely, in beam j, the set of active users is denoted by $\mathcal{K}_j$ with $|\mathcal{K}_j| = K$. We denote $\mathcal{K} = \cup_{j=1}^{B}\mathcal{K}_j$ the set of all users (so $|\mathcal{K}| = KB$). The matching between users and beams is pre-fixed based on the user location, and is not optimized in this paper.

The receive sample at the satellite on beam j and subband m is denoted by $z^{(j)}(m)$. The transmit symbol by the (active) user k on the subband m is denoted by $x_k(m)$ For any $m \in \{1, \dots, M\}$ and $j \in \{1, \dots, B\}$, we have

$$\begin{aligned} z^{(j)}(m) &= \sum_{k\in\mathcal{K}_j} H_k^{(j)}(m)a_k(m)\sqrt{P_k(m)}x_k(m) \\ &+ \sum_{\substack{i=1\\i\neq j}}^{B}\sum_{k\in\mathcal{K}_i} H_k^{(j)}(m)a_k(m)\sqrt{P_k(m)}x_k(m) \\ &+ w^{(j)}(m) \end{aligned}$$

with

- $H_k^{(j)}(m)$ the channel component on subband m from user k to beam j,
- $w^{(j)}(m)$ the white zero-mean unit-variance Gaussian noise.

Notice that inter-beam interference occurs since a certain subband is allocated to B users (one user per beam). However the users belonging to the same beam do not interfere to each other due to FDMA.

The purpose of this paper is to optimize the sum-rate of our system, under the following parameters:

- $\mathbf{a}(m) = [a_1(m), \cdots, a_{KB}(m)]$, which corresponds to subband assignment. If subband m is assigned to user k, then $a_k(m) = 1$, else 0.
- $\mathbf{p}(m) = [P_1(m), \cdots, P_{KB}(m)]$, where $P_k(m)$ corresponds to the transmission power of user k on subband m.

Problem objective function

The maximum sum-rate for the satellite system takes various closed-form expressions depending on the receiver we carry out, or equivalently, depending on the way the interference is treated.

Single Beam Decoder (SBD): If we consider a separate inter-beam decoder where each beam is decoded by having only its own observations and by assuming the inter-beam interference as a noise, we have a multi-user single-antenna channel model per beam. The interference received for user k on subband m in beam j is given by

$$J_k^{(j)}(m) = \sum_{\substack{i=1\\i\neq j}}^{B}\sum_{k\in\mathcal{K}_i} G_k^{(j)}(m)a_k(m)P_k(m).$$

As the interference is seen as a noise, the sum-rate is

$$R = \sum_{j=1}^{B}\sum_{k\in\mathcal{K}_j}\sum_{m=1}^{M} a_k(m)\log_2\left(1 + \frac{G_k^{(j)}(m)P_k(m)}{1 + J_k^{(j)}(m)}\right). \quad (1)$$

An optimization problem associated with this cost function is non-convex due to the interference term in the ratio. In order to overcome the problem, we advocate an other approach in this paper. When inter-beam interference are weak (which occurs if the users sharing the same subband are far away from each other or if the beams are well separate to each other), we may neglect the interferences to allocate the resources.

Multiple Beam Decoder (MBD): If we consider a joint inter-beam decoder at the satellite side, we have a multi-user multi-antenna channel model. By looking at only the sum rate, we have its maximum value given by

$$R = \sum_{m=1}^{M}\log_2\det\left(\mathbf{I}_B + \mathbf{H}(m)\mathbf{A}(m)\mathbf{P}(m)\mathbf{H}(m)^{\mathrm{H}}\right) \quad (2)$$

where

- ○ $\mathbf{H}(m) = (H_k^{(j)}(m))_{j=1,\cdots,B,k=1,\cdots,KB}$,
- ○ $\mathbf{A}(m) = \mathrm{diag}(\mathbf{a}(m))$,
- ○ $\mathbf{P}(m) = \mathrm{diag}(\mathbf{p}(m))$.

and the superscript $()^{\mathrm{H}}$ stands for the trans-conjugate.

Our proposed allocation algorithms assume the knowledge at the transmitter side of the channel gains, i.e., $G_k^{(j)}(m) = |H_k^{(j)}(m)|^2$. These gains can easily available since they depend on the user location which can be obtained through GPS. In contrast, the channel components, i.e., $H_k^{(j)}(m)$ (so including phase knowledge) are not available at the transmitter side since a periodic feedback mechanism between user and satellite is then required. Nevertheless these channel components are known at the receiver side (satellite) via a estimation step done with a training sequence.

Problem constraints

We now describe the interference-temperature constraints associated with the L primary FS receivers. As in [3], we assume that each primary receiver works on a set of band interval where each band interval corresponds to the set of S adjacent subbands of the satellite system. For a given FS band interval m', we denote the corresponding set of overlapping secondary user subbands $\mathcal{S}_{m'}$, with $|\mathcal{S}_{m'}| = S$. We put $T = M/S$, and for the sake of simplicity, we force T to be an integer. The Fig. 2 summarizes overlapping band between primary/secondary system and our notation.

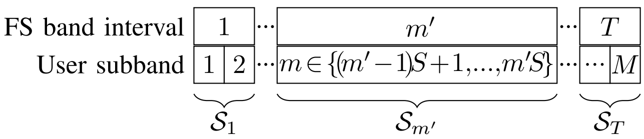

Fig. 2. FS band interval which includes many user subband.

On each band interval $m' \in \{1, \ldots, T\}$ for each FS receiver $\ell \in \{1, \ldots, L\}$, we have to satisfy the following interference-temperature constraints.

$$\sum_{k \in \mathcal{K}} \sum_{m \in \mathcal{S}_{m'}} F_k^{(\ell)}(m) a_k(m) P_k(m) \leq I_{th}^{(\ell)}(m') \tag{C1}$$

with

- $I_{th}^{(\ell)}(m')$ the interference-temperature at FS ℓ on band interval m' that to the satellite system has to satisfy.
- $F_k^{(\ell)}(m)$ the channel gain on subband m from user k to FS receiver ℓ.

We also add a peak power constraint on each subband:

$$0 \leq P_k(m) \leq P_{\max}, \forall k, m. \tag{C2}$$

Finally, allocating the sub-hand is an assignment problem where for each beam, each user has to be allocated to a single subband. Within a beam, as we assume that we have as many users as subbands, this means that the mapping user-subband is a permutation problem, i.e.,

$$\sum_{k \in \mathcal{K}_j} a_k(m) = 1, \forall j \in \{1, \ldots, B\}, m \in \{1, \ldots, M\} \tag{C3}$$

$$\sum_{m=1}^{M} a_k(m) = 1, \forall k \in \mathcal{K} \tag{C4}$$

$$a_k(m) \in \{0, 1\}, \forall k \in \mathcal{K}, m \in \{1, \ldots, M\} \tag{C5}$$

where constraint (C3) deals with FDMA per beam, constraint (C4) means that one user only belongs to one beam. This last constraint ensures that each user will be served and guarantees a certain level of fairness between users. The binary constraint (C5) is completely related to the assignment problem.

Problem statement

The allocation optimization when a MBD is carried out requires the knowledge of channel components at the transmitter side which is unrealistic as already explained above. Therefore in the following, except for comparison purpose, we advocate to optimize figures of merit requiring only the channel gains. So we focus on the SBD receiver and we consider the case of inter-beam interference free leading for an easier objective function, which can be transform into a convex optimization problem, as detailed in Section III.

The goal of this paper is to solve Problem 1 in order to obtain the allocation parameters $\mathbf{a} = [\mathbf{a}(1), \ldots, \mathbf{a}(M)]$ and $\mathbf{p} = [\mathbf{p}(1), \ldots, \mathbf{p}(M)]$.

Problem 1:

$$\max_{\mathbf{a},\mathbf{p}} \sum_{j=1}^{B} \sum_{k \in \mathcal{K}_j} \sum_{m=1}^{M} a_k(m) \log_2 \left(1 + G_k^{(j)}(m) P_k(m)\right) \tag{P1}$$

s.t. (C1), (C2), (C3), (C4), and (C5).

Notice that, in Section IV devoted to Numerical Results, the allocation parameters obtained by solving Problem 1 will be also apply to the figures of merit associated with the sum-rate presented in Eqs. (1)-(2) since only both figures are related to a practical decoder.

III. Proposed Algorithms

Problem 1 is not jointly convex in $\mathbf{a}$ and $\mathbf{p}$. Indeed, the non-convexity comes from the binary set and the product between $\mathbf{a}$ and $\mathbf{p}$. In this paper, we propose to apply both following approaches to deal with the non-convexity:

i) the first approach is inspired by [7], [12], where we start by relaxing the discrete constraint, following the well-known convex relaxation approach. Then, by a change of variables $(a_k(m), P_k(m)) \mapsto (a_k(m), Q_k(m))$ with $Q_k(m) = a_k(m)P_k(m)$, Problem 1 becomes convex with the following statement:

$$\max_{\mathbf{a},\mathbf{q}} \sum_{j=1}^{B} \sum_{k \in \mathcal{K}_j} \sum_{m=1}^{M} a_k(m) \log_2 \left(1 + G_k^{(j)}(m) Q_k(m)/a_k(m)\right)$$

s.t.(C3), (C4),

$$\sum_{k \in \mathcal{K}} \sum_{m \in \mathcal{S}_{m'}} F_k^{(\ell)}(m) Q_k(m) \leq I_{th}^{(\ell)}(m'), \forall \ell \in \{1, \ldots, L\},$$

$$0 \leq Q_k(m) \leq a_k(m) P_{\max},$$

$$a_k(m) \in [0, 1].$$

The solutions of this previous optimization problem are denoted by $\mathbf{a}^{\text{relax}}$ and $\mathbf{q}^{\text{relax}}$. Obviously $\mathbf{a}^{\text{relax}}$ is not binary vector, and we perform projection on the binary set to obtain $\mathbf{a}^\star$. Now we consider the optimization problem with fixed $\mathbf{a} = \mathbf{a}^\star$ and the obtained solution is denoted $\mathbf{q}^\star$. Yet, bounding the losses due to the convex relaxation for that problem is, to the best of our knowledge, an open problem, that we are currently investigating. We then have $\mathbf{p}^\star = \mathbf{a}^\star \odot \mathbf{q}^\star$ where $\odot$ stands for the Hadamard product.

ii) the second approach focuses only on power optimization by assuming a pre-defined subband assignment $\mathbf{a}$. The idea is to consider only one interference constraint i in the problem, and going through all interference constraints one by one. Indeed we can easily write the Karush-Kuhn-Tucker (KKT) conditions and find closed-form expression of the solution for one coupling constraint. The obtained transmit power will define the maximum power constraint of the next step $i+1$. By separating the problem for each FS band interval m', and then introducing the interference-temperature constraints one by one L-times, the final solution satisfies all interference constraints. So, considering the constraint $i \in \{1,\dots,L\}$, we wish to solve

$$\max_{\mathbf{p}} \sum_{j=1}^{B} \sum_{k\in\mathcal{K}_j} \sum_{m=1}^{M} a_k(m) \log_2\left(1 + G_k^{(j)}(m) P_k^{(i)}(m)\right)$$

s.t.

$$\sum_{k\in\mathcal{K}} \sum_{m\in\mathcal{S}_{m'}} F_k^{(i)}(m) a_k(m) P_k^{(i)}(m) \leq I_{th}^{(i)}(m'), \qquad \text{(C6)}$$

$$0 \leq P_k^{(i)}(m) \leq P_k^{(i-1)}(m), \forall m \in \mathcal{S}_{m'}.$$

In Fig. 3, the idea of our algorithm is shown. Obviously $P_k^{(0)}(m) = P_{\max}$. By writing the KKT conditions, we obtain the following closed-form expression

$$P_k^{(i)}(m) = \left[\frac{\mu}{F_k^{(i)}(m)} - \frac{1}{G_k^{(j)}(m)}\right]_0^{P_k^{(i-1)}(m)}$$

for (k,m) such that $a_k(m) = 1$ and j such that $k \in \mathcal{K}_j$. The waterlevel μ is chosen such that to satisfy the constraint (C6). Moreover $[x]_0^b = \min(b, \max(0,x))$. By default, $P_k(m) = 0$ for the other pairs (k,m).

Constraint i	1	2	3	4	···	L
Power $\mathbf{p}^{(i)}$	1	1	1	0.9		0.7
	1	0.7	0.6	0.5	···	0.3
	1	0.8	0.8	0.8		0.2
	1	1	0.9	0.9		0.7

Fig. 3. Step-by-step decreasing power, such that at the constraint i, all previous constraints are satisfied.

Power obtained by this second approach is clearly a sub-optimal solution and is denoted by $\mathbf{p}'$. Notice that the order in which the constraints are introduced plays a role in the final solution.

IV. Numerical Results

We consider a satellite system composed of $B = 2$ beams, where channel gains $\{G_k^{(j)}(m)\}_{k,j,m}$ and $\{F_k^{(\ell)}(m)\}_{k,\ell,m}$ are computed according to [3], [13], [14]. We consider $K = 6$ users per beam, $M = 6$ subbands, and $S = 2$. The maximum interference-temperature level is fixed to $I_{th}^{(\ell)}(m') = -90$dBm for any ℓ, m'. All numerical results have been averaged over 100 simulations.

For comparison, we implement two algorithms that already exist in the literature.

• In [3], this problem has been treated in a suboptimal manner as follows[1]: the interference-temperature constraint is decoupled beam by beam and subband by subband by replacing Eq. (C1) with, for any $j \in \{1,\dots,B\}$, $\ell \in \{1,\dots,L\}$ and $m' \in \{1,\dots,T\}$,

$$\sum_{k\in\mathcal{K}_j} F_k^{(\ell)}(m) a_k(m) P_k(m) \leq \frac{I_{th}^{(\ell)}(m')}{BS}. \qquad (3)$$

As FDMA is applied on each beam, only one term is active in Eq. (3). If user $k \in \mathcal{K}_j$ is active, then we have, for any $m \in \{1,\dots,M\}$ and $\ell \in \{1,\dots,L\}$,

$$P_k(m) = \min\left(P_{\max}, \frac{I_{th}^{(1)}(m')}{BS}, \dots, \frac{I_{th}^{(L)}(m')}{BS}\right), \qquad (4)$$

with the index $m' = \lceil m/s \rceil$. Once the power is obtained through Eq. (4), the subband assignment can be solved with the Hungarian method since the cost function (P1) is insensitive to inter-beam interference. We denote by $\mathbf{a}_{\text{hu}}$ and $\mathbf{p}_{\text{sota1}}$ the solutions of the previous algorithm. For sake of simplicity, we will hereafter assume $\mathbf{a}_{\text{hu}}$ as the pre-defined assignment policy.

• An other heuristic algorithm has been proposed in [4] to solve Problem 1 in the cognitive satellite context. The subband assignment is fixed, let us say, $\mathbf{a}_{\text{hu}}$. Then the authors proposed a conservative policy working band interval by band interval as follows: given m', they select the worst FS receiver in terms of constraint when all the users use the same power, i.e., $\ell_w = \arg\max_\ell \sum_{k\in\mathcal{K}} \sum_{m\in\mathcal{S}_{m'}} a_{\text{hu},k}(m) F_k^{(\ell)}(m) / I_{th}^{[\ell]}(m')$. Then they select the worst active user, i.e., $k_w = \arg\max_{k\in\mathcal{K}} \max_{m\in\mathcal{S}_{m'}} a_{\text{hu},k}(m) F_k^{(\ell_w)}(m)$. The power of this user is finally obtained by

$$P_{k_w} = I_{th}^{(\ell_w)}(m') / \sum_{k\in\mathcal{K}} \sum_{m\in\mathcal{S}_{m'}} a_{\text{hu},k}(m) F_k^{(\ell_w)}(m). \qquad (5)$$

This user is then removed from the interference-temperature constraint and the algorithm iterates until having managing all the users. We denote by $\mathbf{p}_{\text{sota2}}$ the obtained solution.

In Fig. 4, we plot the sum-rate for MBD receiver (Eq. (2)) and for SBD receiver in dotted line (Eq. (1)) versus L (when $P_{\max} = 47$dBm) for different resource allocations:

i) Subband assignment and power allocation are given by $\mathbf{a}^\star$ and $\mathbf{p}^\star$,

ii) Subband assignment is given by $\mathbf{a}_{\text{hu}}$, and power allocation is given by $\mathbf{p}^\star_{\text{cvx}}$ corresponding to the numerical solution of Problem 1 when $\mathbf{a} = \mathbf{a}_{\text{hu}}$,

iii) Subband assignment is given by $\mathbf{a}_{\text{hu}}$ and power allocation is given by $\mathbf{p}'$,

iv) Subband assignment is given by $\mathbf{a}_{\text{hu}}$ and power allocation is given by $\mathbf{p}^\star_{\text{mbd}}$ corresponding to the numerical solution of (2) subject to the constraints (C1) and (C2),

[1] Actually, in [3], the beams were assumed not to use the same band. But the main idea –dealing with a simpler way to manage the multiple interference-temperature constraints (C1)– can be straightforwardly extended to our case.

v) Subband assignment is performed by $\mathbf{a}_{\text{hu}}$ and power allocation is given by $\mathbf{p}_{\text{sota1}}$ corresponding to the state-of-the-art (4).

vi) Subband assignment is $\mathbf{a}_{\text{hu}}$ and power allocation is given by $\mathbf{p}_{\text{sota2}}$ corresponding to the state-of-the-art (5).

We show that our proposed allocation (from *i)* to *iv)*) offer better performance than the state-of-the-art, whatever the decoder, although the optimization has been done on the cost function related to Problem 1. Moreover, the proposed allocation with the simplest algorithm (i.e., *iii)*) performs well. More importantly, the gap between our allocations and the state-of-the-art grows when the number of FS receivers increases, which makes sense since better management of FS constraints is necessary and offers by our propositions.

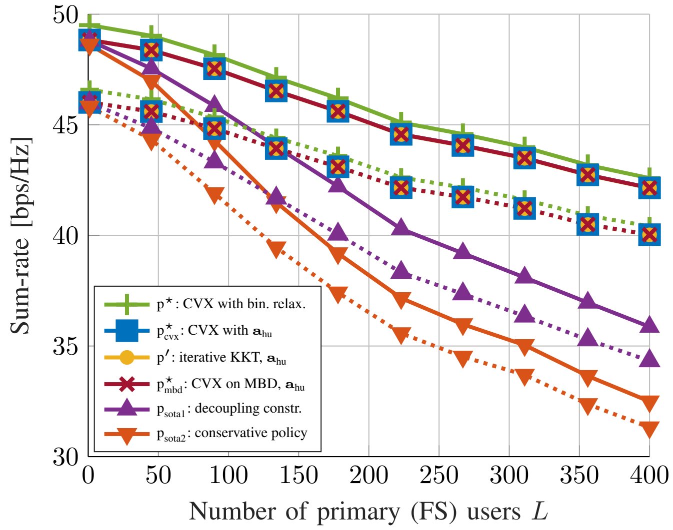

Fig. 4. Sum-rate vs. L for $P_{\text{max}} = 47$dBm.

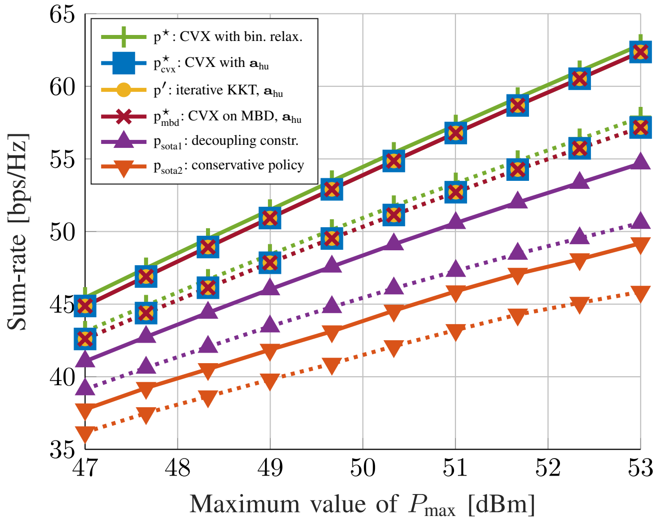

Fig. 5. Sum-rate vs. P_{max} for $L = 200$.

In Fig. 5, we plot the sum-rate for MBD receiver (Eq. (2)) and for SBD receiver in dotted line (Eq. (1)) versus P_{max} (when $L = 200$) for the six above-described allocations. We remark that the gap between our allocations and the state-of-the-art grows when P_{max} increases which makes sense since the interference constraints become a major issue and our propositions manage them more relevantly.

V. Conclusion

In the context of cognitive satellite communications, we have proposed an algorithm for joint optimization of power and subband assignment, and a sub-optimal algorithm for managing multiple interference-temperature constraints. For future works, we will study the case with several satellites belonging to different operators, leading for distributed processing.

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