RESOURCE MANAGEMENT IN THE MULTIBEAM NOMA-BASED SATELLITE DOWNLINK

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ABSTRACT

A beam-free approach to channel allocation in a multi-beam four-color satellite coverage area is taken. Non-Orthogonal Multiple Access (NOMA) and Orthogonal Multiple Access (OMA) are compared as methods to serve users non-necessarily located on the reference beam. A proportional fairness policy is employed for the user scheduling. The naturally occurring SNR imbalances in the user terminal population are exploited in such a way that NOMA outperforms OMA, partly due to the blurring of the boundaries of the satellite beams, in such a way that a non-conventional approach to user pairing can reap more benefits from a system perspective.

***Index Terms*—** NOMA, Satellite, Beam, Scheduling.

1. INTRODUCTION

One of the challenges in satellite systems is the resource management due to different traffic needs across the coverage. Recent solutions have been proposed to improve the efficiency of satellite access to match the different traffic requirements thorough more flexible payloads [1, 2, 3]. However, the improvements are made at the cost of increasing the payload complexity. On the other side, if we want to keep a more traditional payload with less complexity, the flexibility when allocating resources in the satellite downlink can be achieved through resource pulling from neighbour beams [4]. Based on this, we propose a beam-free approach resource allocation in which the users are not necessarily served by their most dominant beam. Thus, this additional flexibility requires to re-evaluate more conventional resource allocation schemes.

Non-Orthogonal Multiple Access (NOMA) will be considered to serve more than one user a at a time with a given carrier; in particular, Power Domain NOMA (PD-NOMA) will be used with Successive Interference Cancellation (SIC) at the receivers. In order to keep the number of SIC stages at the receivers as low as possible, only two users will be simultaneously served. As benchmark, the same beam-free approach will be considered under a more conventional orthogonal multiple access (OMA).

The resource assignment problem for NOMA is well-known to be NP-hard [5, 6] and the optimal solution usually requires exhaustive search; this becomes more of an issue when users can be assigned to any beam carrier, not necessarily to their dominant beam. In the case under study, each satellite user terminal can be only tuned to one beam carrier at a time, so that the resource allocation problem with NOMA can be seen as a many-to-one matching problem, and practical sub-optimal solutions can be potentially used [7].

The rest of the paper is organized as follows. In Section II, the satellite system model is presented. Next, the resource optimization problem will be described in Section 3. After that, some numerical results are presented in Section 4 and, finally, some conclusions are given in Section 5.

2. SYSTEM DESCRIPTION

A multibeam satellite communication system with M beams and K users across the coverage is assumed, with $K > M$. To keep the payload complexity low, a four-colour frequency reuse scheme is considered, with W the available bandwidth per each of the four available channels (colors)[1], and a single feed per beam architecture with a power constraint per feed. Fixed duration V time transmission slots are considered, with a maximum of two users per slot and frequency channel to limit the complexity. In order to compute the achievable rates, the Signal-to-Noise Ratio (SNR) of the q-th user when served by the m-th beam is defined as SNR_k^m.

With OMA, if the k-th and p-th users are allocated to the

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[1] Each frequency band contains many carriers; for the sake of the presentation, we will work only with one carrier per frequency band, which would be the case if the whole channel (color) was allocated to a given user at at time.

m-th beam, the corresponding achievable rates are written as

$$r_k^m = W \cdot \alpha_{kp}^m \cdot \log_2(1 + \mathrm{SNR}_k^m) \tag{1}$$
$$r_p^m = W \cdot (1 - \alpha_{kp}^m) \cdot \log_2(1 + \mathrm{SNR}_p^m) \tag{2}$$

where α_{kp}^m and 1-α_{kp}^m denote the slot time fraction to serve the k-th user and the p-th users, respectively. With NOMA, if the k-th and p-th users are allocated to the m-th beam, with $\mathrm{SNR}_k^m > \mathrm{SNR}_p^m$, then the rates are given by

$$r_k^m = W \cdot \log_2(1 + \alpha_{kp}^m \, \mathrm{SNR}_k^m) \tag{3}$$
$$r_p^m = W \cdot \log_2 \left(\frac{1 + \mathrm{SNR}_p^m}{1 + \alpha_{kp}^m \, \mathrm{SNR}_p^m} \right) \tag{4}$$

where α_{kp}^m and $1 - \alpha_{kp}^m$ denote the power fraction allocated to the kth and pth users, respectively.

3. OPTIMIZATION PROBLEM

With a fair sharing of resources in mind, proportional fair scheduling (PFS) is used to choose the users to be served at each time slot, initially two per beam carrier. Note that PFS maximizes the geometric mean of the rates [8]. PFS keeps record of the long-term averaged rates, with evolve with time for the kth user, $k = 1, \ldots, K$, as

$$R_k(t+1) = \left(1 - \frac{1}{t_c}\right) R_k(t) + \frac{1}{t_c} r_k(t) \tag{5}$$

with $r_k(t)$ the instantaneous rate of the k-th user at time index t. If $u_k^m(t)$ denotes a binary scheduling variable that is equal to 1 when the m-th beam serves the k-th user at time index t, the instantaneous rate can be obtained as

$$r_k(t) = \sum_{m=1}^{M} u_k^m(t) r_k^m(t) \tag{6}$$

with $r_k^m(t)$ the achievable rate by user k at time index t when served by the mth beam. We will assume that a user, when served, is only attached to a beam at a time, so that $\sum_{m=1}^{M} u_k^m(t) = \{0, 1\}$ for all k, t. The PFS system metric to maximize at each time slot is given by

$$F(t) = \sum_{k=1}^{K} \frac{r_k(t)}{R_k(t)} \triangleq \sum_{k=1}^{K} w_k(t) r_k(t) \tag{7}$$

with $w_k(t)$ the weights of the weighted sum-rate (WSR) problem, inversely proportional to the long-term rates. To keep the notation simple, the time index is dropped in the remaining of the paper. For both OMA and NOMA cases, the optimization of the weighted sum rate can be posed as

$$\begin{aligned} \max_{u_{kp}^m, r_k^m, r_p^m} \; & \sum_{m=1}^{M} \sum_{k=1}^{K} \sum_{p=1}^{K} u_{kp}^m (w_k r_k^m + w_p r_p^m) \\ \text{s. to } & u_{kp}^m \in \{0, 1\} \; ; \forall \, k, p, m \\ & \mathrm{A1} : \sum_{k=1}^{K} \sum_{p=1}^{K} u_{kp}^m = 1 \, , \forall \, m \\ & \mathrm{A2} : \sum_{m=1}^{M} \sum_{k=1}^{K} u_{kp}^m \leq 1 \, , \forall \, p \\ & \mathrm{A3} : \sum_{m=1}^{M} \sum_{p=1}^{K} u_{kp}^m \leq 1 \, , \forall \, k \end{aligned} \tag{8}$$

where u_{kp}^m is a scheduling variable that is active when both k-th and p-th users are paired and assigned to the m-th beam. The constraints A1, A2 and A3 ensure that each beam carrier serves a maximum of two users at a time, and each satellite terminal gets assigned only one beam carrier when served. The use of WSR as resource allocation policy will determine the user scheduling through u_{kp}^m and the corresponding rates through r_k^m and r_p^m. In fact, the problem in (8) can be decoupled, since the power is managed at a beam level, in what is known as power per feed constraint, so that for a given pair of users served by the mth beam, we can maximize

$$\begin{aligned} \max_{\alpha_{kp}^m} f(\alpha_{kp}^m) = & w_k r_k^m + w_p r_p^m \\ & \text{s. to } 0 \leq \alpha_{kp}^m \leq 1 \, \forall k, p \in \{1, \cdots, K\}. \end{aligned} \tag{9}$$

The rates r_k^m and r_p^m are a function of the allocated fraction of resources α_{kp}^m, either time (OMA) or power (NOMA), although to keep the notation simple this dependency is not explicitely stated.

3.1. OMA

In the OMA case, it can be easily seen that $f(\alpha_{kp}^m)$ in (9) is a monotonic function of α_{kp}^m. Therefore, the whole slot would be only allocated to one of the users. With this, problem (8) boils down to a matching problem, which is expressed as

$$\begin{aligned} \max_{u_k} \; & \sum_{m=1}^{M} \sum_{k=1}^{K} u_k^m w_k r_k^m \\ \text{s. to } & u_k^m \in \{0, 1\} \; \forall \, k, m \\ & r_k^m = W \cdot \log_2(1 + \mathrm{SNR}_k^m) \\ & \mathrm{A1} : \sum_{k=1}^{K} u_k^m = 1 \, , \forall m; \;\; \mathrm{A2} : \sum_{m=1}^{M} u_k^m \leq 1 \, , \forall k. \end{aligned} \tag{10}$$

(A1) and (A2) are such that only one user is paired with one beam carrier beam at a time. The optimal matching can be obtained with the Hungarian algorithm [9].

3.2. NOMA

The optimization (9) for the NOMA case can be readily obtained and reads as follows:

1. $w_k \geq w_p$: $\alpha_{kp}^m = 1$.
2. $w_k < w_p$, $w_k\text{SNR}_k < w_p\text{SNR}_p$: $\alpha_{kp}^m = 0$.
3. $w_k < w_p$, $w_k\text{SNR}_k \geq w_p\text{SNR}_p$:

$$\alpha_{kp}^m = \min\left\{\frac{w_k\text{SNR}_k^m - w_p\text{SNR}_p^m}{\text{SNR}_k^m\text{SNR}_p^m(w_p - w_k)}, 1\right\}. \quad (11)$$

As to the user scheduling coming out of the maximization of the WSR (8), it is a similar problem to that found in PD-NOMA terrestrial cases [5, 6], which requires an exhaustive search or some sort of approximation. We will resort to exhaustive search to obtain the results in this paper, and leave out of the scope of this work an ad-hoc algorithm inspired on many-to-one matching theory [7], and which yields close results to optimal In short, this ad-hoc algorithm performs one-sided matching giving more priority to the maximization of the system WSR in (7) than to the individual rate of the users.

4. NUMERICAL RESULTS

The beam-free approach will be tested in a reduced multi-beam satellite scenario with $M = 4$ beams, so that the use of exhaustive search for optimization is affordable. Users will follow a uniform distribution on each beam nominal coverage area, with a potentially different user density across beams to illustrate non-uniform traffic demands which may occur in practical settings. Thus, there will be 20 users in the nominal coverage area of two beams, and a number L in the other two beams, so that if $L = 20$, we have a classical uniform user distribution, and as L changes, resource pulling of the resources is favored. To serve the different users across the beams, the number of time transmission slots V is set to 300, long enough to accommodate multiple transmissions for each user. 1200 Monte-Carlo simulations were run with the system parameters in Table 1. Both OMA and NOMA resource management techniques are compared in terms of geometric mean, minimum rate and sum-rate in Fig. 1, which displays the NOMA percentual improvement over OMA.

NOMA presents an improvement in fairness and sum-rate by raising the lower rates in the coverage with respect to the orthogonal case. For a better understanding of the results, the cumulative distribution of the average rates for L=10 is presented in Fig. 2. The average rate is computed as

$$\bar{r}_k = \sum_{t=1}^{V} r_k(t) \quad (12)$$

where $r_k(t)$ is the rate allocated to k-th user at the time index t. Both NOMA and OMA present similar higher rates distribution, although NOMA is able to raise the lower rates. The same conclusions can be taken for other cases with different L values.

Table 1. Satellite system parameters

Diagram pattern	Provided by ESA
EIRP [dBW]	63
Frequency band [GHz]	20
Beam Bandwidth [MHz]	250
Terminal G/T [dB/K]	17.68
SIC at user terminal	Perfect
Traffic distribution	Uniform

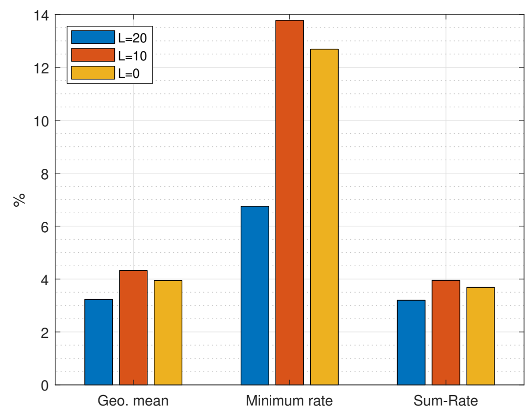

Fig. 1. Improvement of PD-NOMA over OMA for the beam-free approach.

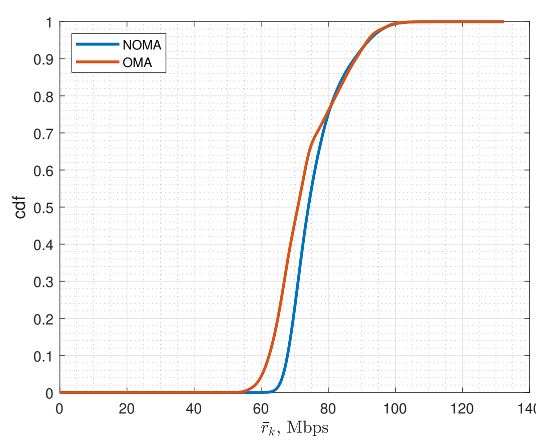

Fig. 2. Cumulative distribution of the average user rates for $L = 10$.

NOMA outperforms OMA as SNR asymmetries can be exploited; note that if the SNR values in a given pair are the same, all the power is assigned to the user with the highest weight, as easily concluded from (11). Fig. 3 illustrates the

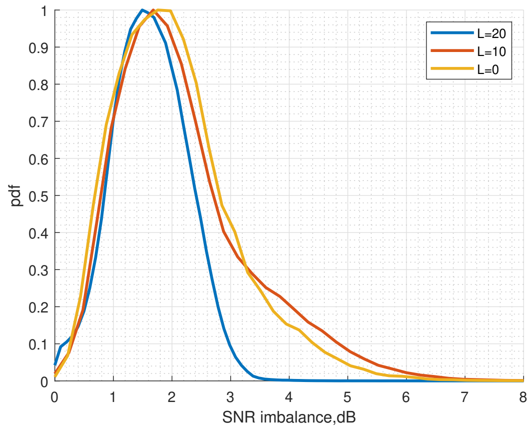

Fig. 3. Probability distribution of the SNR imbalance for the different cases.

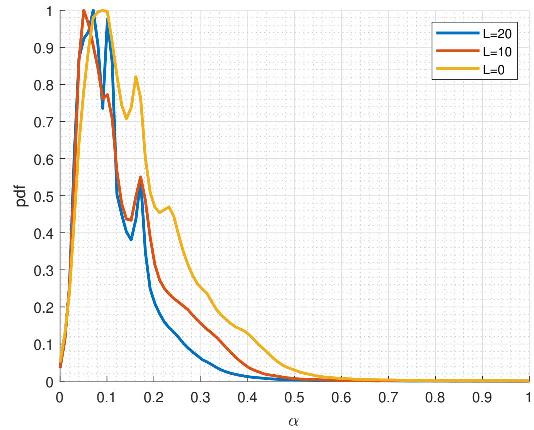

Fig. 4. Probability distribution of the power allocation in NOMA for different L values.

SNR imbalance in the NOMA pair assignments, for identical user terminals featured in Table 1, whereas Fig. 4 displays the distribution of the corresponding weight in (11). As the beams receive different traffic demands due to different numbers of users, then more asymmetric pairs are selected by the PFS-based algorithm, serving with the same carrier even users in different beams, in a form of resource pulling that is showcased in Fig. 5. In those cases, a user can be allocated to a neighbouring beam in an effort to improve the fairness of the rate allocation; on the contrary, OMA is not able to donate resources to neighbouring beams in such an efficient way. In the uniform case, with the same user density in all beams ($L = 20$), resource pulling will rarely occur, and the only SNR imbalance to exploit is caused by the tapering of the received power as users get closer to the boundary of their nominal beams. Thanks to the better PD-NOMA efficiency, users with lower SNR can benefit from a more frequent allocation of resources, especially when those near the beam boundaries can be served by neighbor donor beams.

As a final remark, higher NOMA gain with respect to OMA is expected if different user terminal classes with, for instance, different receive antenna gains, are to be served. This would occur, for example, if the same carrier is assigned to a large antenna fixed ground terminal and an aircraft with a smaller antenna.

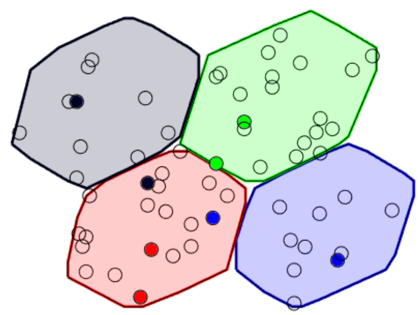

Fig. 5. Example of resource assignment with users represented as circles. Those users which are assigned to a given beam are filled with the respective beam color.

5. CONCLUSIONS

In this paper, a beam-free approach resource management is presented for both orthogonal and non-orthogonal access. The weighted sum-rate of the system is optimized, with the user weights set by the proportional fairness policy to maximize the geometric mean of the rates in the long term. Since the power limit applies per beam (carrier), the resource management problem can be split into rate optimization and resource assignment. Numerical results confirm how PD-NOMA outperforms OMA, substantially on the minimum rates, by exploiting the non-uniform SNR distribution inside each beam and also across beams. The latter is of particular relevance when the traffic needs vary across beams, so some beams can operate as donors to neighboring beams in order to reduce data rate differences among users. The way NOMA benefits from naturally occurring SNR differences across the coverage area of the satellite would lead to higher gains for populations of heterogeneous user terminals, for example when different antenna sizes coexist.

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6. REFERENCES

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