Joint Beam Hopping and Precoding in HTS Systems

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Abstract. This paper presents a novel concept for offering payload resources flexibility in High Throughput Satellite (HTS) systems. The concepts makes joint use of two advanced techniques, namely beam hopping and precoding. The combination of these two techniques allows the system to really optimize the performance of beam hopping in terms of capability to follow the temporal and spatial variation of user traffic requests within the coverage. The performance of such an approach is demonstrated through computer simulations of an exemplary system. A similar approach can also be used by combing precoding with frequency flexible techniques. Additional combination of on-board power pooling techniques helps to further improve the system performance.

Keywords: HTS · Beam hopping · Precoding · Broadband · Payload flexibility

1 Introduction

The capability to flexibly allocate the satellite payload resources over the service coverage is becoming a must for next generation broadband satellites employing a number of spot beams. Indeed, past and current broadband systems have shown that large multi-beam High Throughput Satellites (HTS) are typically able to fill-up fairly quickly the capacity of some beams, while some others remain (almost) empty over a relatively long part of the satellite life time. The consequence is a loss of satellite operator's revenue due to the number of customers lost within the hot-spots (filled-up beams) and the waste of resources over the empty spots.

The primary goal of flexibility is to minimize the unused and unmet capacity. The introduction of flexibility helps a satellite operator to manage the risks accounted by the unpredicted changes, like regulatory context, competing context, socio-economic context.

Flexibility refers to the ability to change the configuration of the system during the operational life of the satellite.

In the following, we will focus on the flexibility in the forward link of HTS systems. The forward link consists of the uplink between the gateway ground station and the satellite and the downlink between the satellite and the user terminals. The forward (FW) link is anyway the most important in determining the revenues of the operator, as it is the main traffic direction in the network.

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1.1 Key Capacity Definitions

In order to correctly characterize the performance of a broadband HTS system the following definitions are in order:

- The capacity/throughput demand is the capacity that is requested by the users which is typically geographically non-uniform and time variant.
- The offered system capacity/throughput represents the maximum capacity of the system, while considering an infinite capacity demand per location.
- The usable system capacity/throughput is the capacity that is really sold taking into account the real capacity demand per location.
- The unused system capacity/throughput is the difference between the offered capacity and the usable system capacity.
- The unmet capacity/throughput demand is the difference between the capacity demand and the offered capacity.

1.2 Flexible Payload Techniques

A number of techniques are available to support flexibility. Ignoring for the moment the case of coverage flexibility, the following is a summary of such techniques:

Flexible power allocation

To better match the capacity demand in each beam, one approach is to distribute the total amount of payload power unevenly across the different beams. Lower power would be assigned to beams with lower capacity demand, while higher power would be given to hot spots. This technique is typically implemented by means of flexible Travelling Wave Tube Amplifier (FlexTWTA) technology [1, 2], where the saturated power of a TWTA is adjusted according to the capacity demand of beams served by the amplified carriers. In case of one High Power Amplifier (HPA) shared between two beams (which is a typical configuration), this technique works if the two beams have similar capacity demand. Alternatively, if the two beams have different capacity demand the power transfer from one beam to the other is done by suppressing part or all the carriers serving the beam of low demand.

An alternative approach for realizing flexible power allocation foresees the exploitation of Multi-Port Amplifiers (MPAs) [3] instead of FlexTWTA.

The drawbacks of flexible power allocation are that any power variation has intrinsically a limited impact to the offered beam capacity due to both the inherent diminishing return behavior of the Shannon function (spectral efficiency versus power), as well as the presence of residual intra-system co-channel interference. Other drawbacks concern the relatively high cost of the FlexTWTA and MPA components.

Flexible Bandwidth allocation

This technique consists in tuning the amount of band that is allocated to a given beam according to the relative capacity demand. Basically, part of the amount of bandwidth that is allocated to low demanding beams gets transferred to high demanding beams. This can be achieved, for example, by splitting unevenly the user bandwidth allocated to the two beams served by the same on-board HPA (which is a typical configuration for a four color scheme network) and flexibly routing the two portions of the bandwidths to different antenna feeds.

The drawback of such an approach is that in general additional intra-system co-channel interference will be generated due to the possible overlap of the bands assigned to two adjacent co-polar beams. Although some countermeasures can be conceived in order to partially limit the impact of the high co-channel interference in part of the user bandwidth (for example, by a cautious assignment of users to the highly interfered portion of the band), the result of this extra interference limits the efficiency of such technique particularly when considering certain traffic demand distributions.

Flexible time allocation, i.e. Beam Hopping (BH)

This technique [4] is exactly dual w.r.t the flexible bandwidth allocation technique, i.e. it can be explained by replacing time with frequency. Indeed, this solution can be implemented through the so-called BH scheme by which different co-channel beams served by the same HPA get allocated different time slots. By modulating the duration of the time-slots, different offered capacity values can be achieved in different beams. For an uneven capacity demand distribution, adjacent beams might end up being served by different HPAs with overlapping time slots thus generating excessive intra-system interference.

2 The Novel Flexible Payload Technique

Although the frequency flexible techniques can also be addressed, in the rest of the paper we will consider BH as the payload technique offering resource flexibility.

This paper proposes a solution which greatly improves the efficiency of BH by mitigating the co-channel interference that such techniques might end up generating for certain traffic demand distributions. This is graphically illustrated in the next figure where three hot-spot co-polar beams are located geographically close to each other. Due to their high composite user traffic requests, these beams are assigned by the network resource manager long time slots with large overlapping times where high co-channel interference is generated. This situation is typical of a cluster of hot spots within an HTS network.

If the extra generated interference could somehow be cancelled, BH would be able to more efficiently match any capacity demand distribution over the coverage, as the additional time allocation would basically be interference free and thus its benefit to the overall offered capacity would not be only higher but also much more predictable.

Precoding [5, 6] is ground-based technique that is used to pre-cancel co-channel intra-system interference by applying at the Gateway of the broadband network a linear combination of the transmitted signals over the different beams. In practice, the transmitted signals are weighted by complex coefficients from a so-called precoding matrix that performs a sort of inversion of the channel matrix. The coefficients of the linear combination are computed based on feedbacks provided by the user terminals (the channel estimates, including both the amplitude and phase).

According to the novel joint precoding and BH technique [7] proposed in this paper, following a re-configuration of time slots assignment to beams, the user terminals would perform a new channel estimation procedure (training phase). This is necessary as the precoding matrix is formed for each specific set of served user terminals. After a relatively short amount of time (typically much less than one second), the user terminals would be able to report the new estimates to the GW which in turn would apply precoding thus reducing the interference in situations like the one described in Fig. 1.

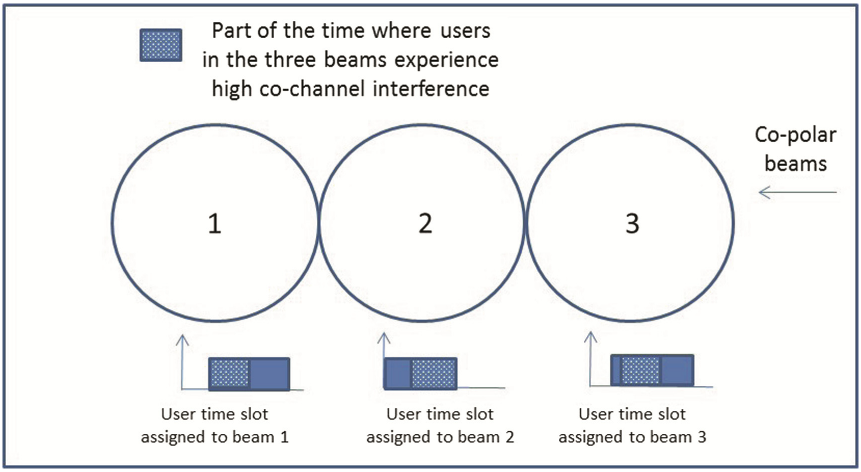

Fig. 1. The excessive co-channel interference issue in flexible payload beam hopping techniques

2.1 Basic Resource Allocation Algorithm

In order to take full advantage of the joint technique, a suitable payload resource allocation algorithm has to be devised.

The problem of resource allocation (RA) belongs to the more general framework of RA for MIMO systems [8]. Here a pragmatic approach for the derivation of the time illumination plan is used. Indeed, the RA algorithm (time illumination plan) is quite simple as the precoded system might be approximated as interference-free. Therefore, the number of illumination time slots to be assigned to each beam can be computed by dividing the traffic request in that beam by the spectral efficiency achievable in absence of interference. Finally, a normalization coefficient is applied to take into account the overall time resources offered by the HPA serving the beam under consideration. The relative equation reads as follows:

$$\tau_j = \frac{R_{req}(j) / \eta(j)}{\sum_{k=0}^{K_{HPA(i)}-1} \left(R_{req}(k) / \eta(k)\right)} W, j \in HPA_i,\ i = 0, 1, \ldots, K_{HPA} \tag{1}$$

where:

- τ_j represents the number of time slots allocated to beam j
- $R_{req}(j)$ represents the requested traffic throughput for beam j
- $\eta(j)$ represents the average spectral efficiency for beam j

- W represents the BH illumination period (total number of time slots)
- HPA_i is the set of indexes identifying the time slot for the i_{th} HPA
- K_{HPA} is the number of HPAs

When considering the scenario where the satellite network is served by a number of gateways (GWs), each GW typically addresses a cluster of 8–16 beams maximum. In this case, precoding can be easily applied as a 16 × 16 matrix across the full cluster but it cannot mitigate the co-channel interference between two beams belonging to two different clusters. This situation can be addressed and completely solved by using a centralized precoding approach whereby a central processor distributes the precoded signals to all GWs within the network. Alternatively, a mitigation of the issue can be achieved by modifying the resource allocation algorithm in order to make it "GW cluster aware" whereby the allocation of resources (time slots) is done in order to minimize the co-channel interference between adjacent beams belonging to adjacent GW clusters.

2.2 Adding Power Flexibility

An additional well known improvement in flexibility can be provided by flexibly allocating the power to the beams according to their capacity request. Differently to conventional (non-precoded) systems, when using precoding, any beam power unbalance results in direct throughput improvement due to the reduced intra-system interference.

Power flexibility can be achieved by replacing conventional tubes with either FlexTWTAs or MPAs (Multi-Port Amplifiers). An example of a payload architecture using power flexibility by means of MPAs and BH is shown in Fig. 2. MPAs are more suitable as they allow for a larger dynamic range, therefore providing a more flexible power partitioning among the beams. To be noticed that if the scheme with MPAs is used, one has to be careful in assigning beams to MPAs, as a good performance of these devices requires very low correlation among the carriers sharing the MPA. This means that carriers which are precoded together, in principle, should not be using the same

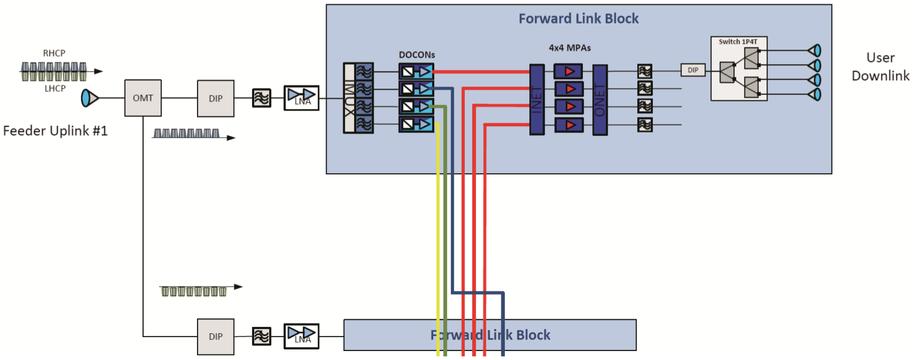

Fig. 2. Block diagram of a BH –based FW link payload with power pooling – only one feeder uplink shown for simplicity

MPA. This might imply that an MPA should be fed only by carriers belonging to distant beams as in this case precoding would only add a low correlation.

The precoding algorithm in the presence of non-uniform power unbalance has to be modified. If a linear precoding algorithm of the MMSE (minimum mean square error) variant is employed to calculate the precoding matrix **W** from the channel matrix **H** (both with complex elements), the calculation of the precoding matrix in the presence of non-uniform power is as follows:

$$\mathbf{W} = \left[\mathbf{H}^H \mathrm{diag}(\mathbf{P})\mathbf{H} + \mathbf{I}\right]^{-1} \mathbf{H}^H \mathrm{diag}(\mathbf{P}). \tag{2}$$

where $\mathbf{P} = \left[P_i\right]$ and P_i is the power emitted from feed i, $\mathbf{I}$ is the identity matrix and $\mathbf{H}^H$ is the Hermitian of matrix $\mathbf{H}$.

The power unbalance of the system is reflected by the vector **P** with one entry per transmit feed. If $\mathbf{W}_i$ is a row of the precoding matrix, to check if any of the rows of **W** violates the maximum power available from the totality of on board HPAs, the following norm must be calculated

$$n = \mathrm{norm}(\mathbf{W}_i)^2$$

Then, if $n > 1$, the following normalization is in order to ensure the total power is not exceeding the total available power on board $\mathbf{W}_i = \frac{1}{\sqrt{n}}\mathbf{W}_i$.

The optimization of the power allocation algorithm is in general a non-trivial task. Here we have followed a heuristic approach which, after some mathematical manipulations (not shown here for brevity), results in the following equation:

$$\Delta P_i = \frac{\left[2^{\left(\frac{R_{unmet,i}W}{\tau_i B}\right)}(SNR_i + 1)\right] - 1}{SNR_i} \tag{3}$$

Where:

$R_{unmet,i}$ is the unmet capacity of beam i;
B is the band served by each amplifier;
W is the number of time slots in the BH window;
SNR_i is the average SNR of beam i with uniform power.
The power transmitted per beam is then computed as:

$$P_i = P_{un} + \Delta P_i \tag{4}$$

where P_{un} is the power transmitted per beam in the uniform power case.

However, this computation does not yet ensure meeting any constraint concerning the total power. Indeed, we have to make sure that the total power at the level of a single

MPA is constrained. This is achieved by normalizing Eq. 4 w.r.t the total power of the MPA serving the considered beam.

3 System Simulation Results

In order to correctly characterize the benefits of joint BH and precoding for satellite broadband networks, a high number of simulations have been run against different system and traffic distribution assumptions. From an analysis of the results a first conclusion is that these are particularly sensitive to the type of geographical traffic distribution and the relative association of beams to on-board HPAs. In order to understand why, in the following the throughput results are shown for an exemplary broadband network which has been chosen with a relatively limited number of beams (64) in order to allow for an efficient representation of the results. Table 1 below outlines some key system parameters of the case study.

Table 1. Key system parameters of the simulated system

User frequency	Polarization	Number of HPAs	Number of beams	Number of carriers per HPA	On-board downlink EIRP	Air interface	User terminal antenna diameter
Ka-band 500 MHz	Only one used	16 (4 beams per HPA)	64	1	65 dBW	DVB-S2x (roll-off = 20%)	70 cm

The relative user link antenna pattern is shown in Fig. 3.

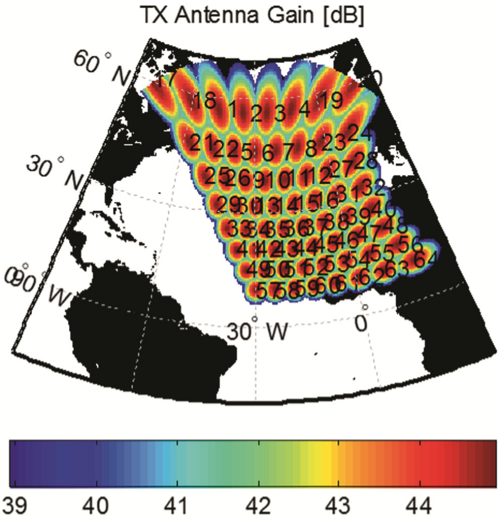

Fig. 3. Satellite gain antenna pattern in the forward user link of the system case study

The estimated flat FW link throughput of this system is around 15.5 Gbps (i.e. using BH with regular time slot allocation per beam).

We have then assumed to have a traffic distribution with a hot spot configuration whereby out of the 64 beams, 16 central beams are ‘hot’ beams each requesting 920 Mbps and the remaining 48 beams are ‘cold’ beams each requesting 10 times less traffic than the hot ones, i.e. 92 Mbps. For this traffic scenario, we assumed two different payload configurations. The first one, which will be dubbed FLEX OPT (as it represents the best configuration from the payload perspective), where each HPA is connected to 3 cold beams and 1 hot beam; the second configuration, which will be dubbed FLEX WRST (as instead represents the worst configuration from the payload perspective) where each HPA is either connected to 4 cold beams of 4 hot beams. It is clear why FLEX OPT is able to deliver the best performance in terms of usable capacity. Indeed, in this payload configuration each HPA resources can be really optimized for the hot spot by allocating the longest time slot to the hot beam and subtracting time resources to the other served low traffic beams. This cannot be done in FLEX WRST as all beams served by each HPA have similar traffic demand (Table 2).

Table 2. Simulation results in terms of offered and usable throughput for the system case study and the two payload configurations

	FLEX OPT offered throughput Gbps	FLEX OPT usable throughput Gbps	FLEX WRST offered throughput Gbps	FLEX WRST usable throughput Gbps
BH	12.5	11.8	9.4	8.8
BH + Precoding	16.9	16.8	9.6	9
BH + Flexible power				9.1
BH + Precoding + Flexible power				9.8

The results shows that joint BH and precoding allows to gain around 40% in usable throughput for FLEX OPT while the gain reduces to around 2% for FLEX WRST. The usage of flexible power has also been tested for FLEX WRST only. In this case, the gain of using precoding in addition to BH and flexible power is about 8%. The higher gain in this case is justified by the consideration that precoding, given the reduction of co-channel interference that it involves, it also allows to better exploit any power flexibility.

Simulation results using other systems showed that joint precoding and BH technique could deliver usable throughputs between 0 to 50% higher than BH alone, depending on the traffic geographical distribution and the relative allocation of HPAs to beams.

4 Conclusions

This paper has described a novel technique for allocating FW link throughput resources. It consists of a combination of well know techniques like Beam Hopping and Precoding. Additional power flexibility can also be added to further enhance the flexibility performance. The resource allocation algorithms are described in details and the overall system FW link usable throughput has been evaluated for an exemplary satellite broadband network. In general, the performance gains in terms of usable throughput w.r.t state of the art (i.e. BH only) vary quite significantly with the user traffic distribution within the network. A number of simulation results (not shown in the paper for reason of space limitation) show gains between 0 to 50%. This means that during the satellite life time, depending on how the traffic geographical distribution would change, the usable throughput might be boosted by the joint technique by up to 50%.

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