Beam Hopping in Multi-Beam Broadband Satellite Systems: System Performance and Payload Architecture Analysis

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Abstract

When considering the inherent uncertainty of the broadband communication market evolution as well as the spatial non-uniform distribution of capacity requests through the satellite coverage, flexibility to adapt to different traffic configurations is a key requirement for future satellite systems to maintain their competitiveness. Beam hopping solutions appear as good candidates to match system offered capacity with traffic demand. Although the introduction of flexible bandwidth and power allocation to beams brings some benefits in terms of demand satisfaction for hot spots with respect to traditional systems with regular frequency reuse and equal power to beam allocation, utilization of beam hopping techniques offers an additional mean to cope with irregular and time variant traffic distributions.

In this paper the forward link of a multibeam transparent satellite system for providing broadband Internet access to users sparse over the coverage area is analyzed. The utilization of Adaptive Coding and Modulation (ACM) techniques is considered, according to the recently approved DVB-S2 standard. The advantage in terms of system performance brought by the utilization of beam hopping techniques is assessed. In this type of system, only a few beams of the overall coverage are selected at each time-slot for transmission. This set of illuminated beams changes on a slot-by-slot basis over the duration of a repetition window. This creates a time and spatial transmission plan that repeats periodically with a given duty cycle.

In the present contribution the problem of optimizing the beam hopping transmission plan in order to best match the traffic demand is tackled. Genetic algorithms appear as the most suited optimization tool because of their global optimization nature, their capability of working with a large number of optimization parameters and their suitability to accept a discontinuous figure of merit function. Extensive simulations have been carried out to adapt genetic algorithms functions and parameters to the problem under investigation. The target has been optimizing the beam allocation in the transmission plan to maximize system capacity. System performance is assessed considering the traffic demand distribution over Europe foreseen for broadband satellite services in 2015, as derived by recent market analysis studies. A throughput increase of about 30% compared to a system with regular power and bandwidth allocation capabilities is achieved.

The impact of a beam hopping type of system at payload level is then investigated. In particular, efficient ways to implement beam hopping combining payload flexibility with affordable complexity are investigated. Both Direct Radiating Array (DRA) and Array Fed Reflector (AFR) solutions are considered.

I. Introduction

Because of relatively long satellite life period and high market unpredictability, flexibility in adapting to different traffic request is a crucial asset for future broadband satellite systems. The challenge is to maximize revenues through provision of high capacity in those areas of the coverage region with a high demand, while minimizing the amount of resources dedicated to low loaded regions. As well known, bandwidth and time are alternative ways to segment resources in a communication system. Following this principle, one may follow two different approaches for enhancing system flexibility. The first one consists in segmenting the total available bandwidth in a number of channels, which can be flexibly allocated to the satellite user beams. Unlike current systems, where a regular frequency reuse pattern is normally assumed, the proposed approach allows for an irregular reuse of the bandwidth channels. The novel reuse pattern shall be optimized to best match capacity request. This approach is discussed in [3]. However, payload complexity poses constraints on the minimum carrier granularity allowed in the system, thus constraining flexibility in resource allocation to beams. A different approach is to segment the time axis. This is

actually what is done in beam hopping systems. Technological limitations in the beam switching time are certainly less important than the limitation mentioned on the carrier granularity; Spaceway, for instance, has a beam hopping time slot duration of 23 μsec. Following this approach the time line is organized in windows, which are segmented in a number of time slots. A certain (optionally variable) number of beams is illuminated in a given time slot. The pattern is repeated with a period which is the product of the window length and the time slot duration. The larger the window length, the higher the degree of flexibility the system can provide. Therefore, selection of the window length shall be done taking into account system performance. As the worst case delay equals the beam hopping plan repetition period, possible jitter requirements of real time packets should also be considered.

The problem of beam allocation in the beam hopping plan is a resource optimization problem, which shall be aimed at capacity maximization in a certain traffic scenario. In presence of a traffic demand mutation, the beam hopping plan can be easily modified following a novel optimization. A combined approach where both time and bandwidth resource are segmented in order to provide the required flexibility is also an option. In this case, each beam in the beam hopping plan is illuminated with a fraction of the total available bandwidth.

Optimization of the beam hopping plan is a particularly heavy task, as it involves a large number of parameters and non-linear functions. While in [4] the problem was addressed with a heuristic ad hoc algorithm, in the present contribution global optimization techniques like genetic algorithms have been applied to the problem under investigation. Results are certainly dependent on the specific scenario considered. Particularly difficult is indeed to accommodate scenarios where traffic demand is concentrated in clusters of hot spots. In this case, some regions are heavily interference limited and high loaded beams cannot take advantage of an optimized resource distribution between hot and cold spots. In some specific cases, a uniform time/bandwidth allocation within the hot spot cluster offers the best performance.

The present paper is organized as follows: in Sect. II adoption of beam hopping techniques is analyzed from a system perspective and the capacity function is derived. In Sect. III some considerations related to possible payload architectures for implementing beam hopping are carried out. Sect. IV presents the optimization algorithm, which has been implemented. In Sect. V the reference system study cases is illustrated, and the obtained results are discussed. Finally, in Sect. VI conclusions are drawn.

II. System Assumptions

We focus here on the forward link of a multibeam satellite access system, which is aimed at providing connection to the Internet and, in general, broadband interactive applications to users sparse over the coverage region. We assume that users are connected transparently through the satellite to N_{GW}, which are linked to the terrestrial network. However, the focus will be in the following on the satellite-to-user link (downlink), where the beam hopping concept is applied.

As reported in [3], the traffic demand is normally very unbalanced over the coverage region. Figure 1shows the traffic request distribution over the extended European region foreseen for year 2015, as obtained through a recent market analysis study. This distribution has been assumed as study case for the following analysis. Apparently, high demanding beams (hot spots) are concentrated in clusters, which makes the system easily interference limited.

Following nomenclature defined in [3], we indicate with $\hat{R}_b^i$ the traffic demand in beam *i,* while $\overline{R}_b^i$ is the capacity the system can offer in the same beam. The average system throughput is then provided by:

$$T = \sum_{i=1}^{N_b} \min(\hat{R}_b^i, \overline{R}_b^i) \tag{1}$$

where N_b is the number of beams in the satellite coverage.

Let now assume that the beams are illuminated following a beam hopping plan BH(i,n), where i is the beam index and n is the time slot index. The maximum number of simultaneously illuminated beams per time slot is indicated with N_{MAX}, which shall be dimensioned following payload and system constraints. Assuming each time slot of duration T_S, the total beam hopping plan period is $T_F=T_S*W$, where W is the window length and defines the time granularity for the resource allocation problem.

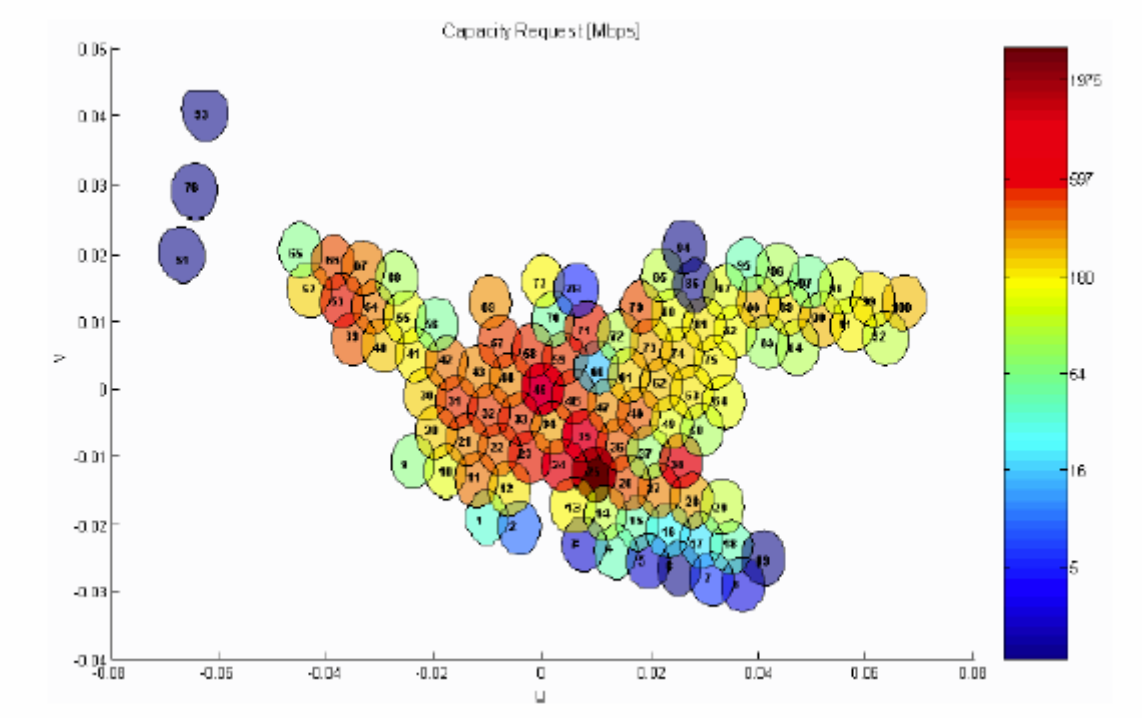


Figure 1: Traffic demand over the EU25 region

Let indicate with B the total available downlink bandwidth. When Ka-band is considered, B=500 MHz is available in each polarizations. Like the recently launched Anik-F2 and IPstar multibeam satellites, we consider here Ka-band utilization because it provides the largest available bandwidth, while allowing for link budget closure for consumer satellite terminals. For simplicity, we focus in the following on a single polarization.

The total available bandwidth can in general be split in N_f channels of bandwidth B_j. Each channel can multiplex N_C carriers of bandwidth $B_C = B_j/(N_C * C_S)$, where C_S is the carrier spacing. Although one may think of aggregating adjacent and simultaneously illuminated carriers in a single TDM multiplex, in the following of the paper we assume for simplicity a single carrier bandwidth B_C. The carrier baud rate will then be $R_S=B_C/(1+\alpha)$, where α is the roll-off factor. Given the limited front-end capabilities of current demodulators for consumer applications, a carrier bandwidth larger than 62.5 MHz would not be recommended. In order to reduce terminal complexity it is then advisable to split the total available B=500 MHz bandwidth into multiple carriers. While carrier bandwidth is limited by terminal front end cost, bandwidth granularity is a system parameter, which shall be selected depending on system performance. In general, a bandwidth granularity $B_C<B_j<B$ shall be considered. We indicate with f_j the center frequency of the j-th frequency slot within B. We consider that each bandwidth segment B_j has the same bandwidth occupation and fills the frequency slot of center frequency f_j.

The beam hopping plan can then be described by the matrix BH(i,n,j), where BH(i,n,j)=1 if the bandwidth channel in the j-th slot of the i-th beam in slot n is active. Otherwise, BH(i,n,j)=0. It holds: $1 \le i \le N_{MAX}$, $1 \le n \le W$, $1 \le j \le N_f = B_C/B_j$.

In order to simplify payload architecture, we consider a uniform power allocation among carriers. If we indicate with $F^i_j(n)$ the set of beams, which are interfering with the i-th beam in the j-th frequency slot and in the n-th time slot, the C/I figure in each location (x,y) of the coverage belonging to the i-th beam can be written as:

$$\frac{C}{I}(x, y, F_j^i(n)) = \frac{G^i(x, y)}{\sum_{m \in F_j^i(n)} G^m(x, y)} \tag{2}$$

where $G^i(x,y)$ is the i-th beam gain towards location (x,y). The interference level experienced in each grid point is therefore heavily dependent on the beam hopping plan, in addition to the satellite antenna pattern. In particular, both beam selection and carrier frequency allocation concur in a similar way to the definition of the interference scenario.

The available beam capacity in the n-th slot and in the j-th frequency slot $[\hat{R}_b]_j^i(n)$ can then be derived following the approach described in [5] and [4], as an average over the beam region and over of the channel time-variant conditions of the punctual link efficiency. The total average available capacity in the i-th beam, $\overline{R}_b^i$,is then obtained through:

$$\overline{R}_b^i = \frac{1}{W}\sum_{n=1}^{W}\sum_{i=1}^{N_{MAX}}\sum_{j=1}^{N_f}[\overline{R}_b]_j^i(n)BH(i,n,j) \tag{3}$$

III. Payload Architectures

The use of a steerable spot beam which can be rapidly scanned across the entire service region was initially introduced by Reudnik et alii in the paper [1]. The paper visionary foresaw the implementation of the fast beam steering via a phased array antenna. The main reason driving the selection was the possibility of implementing phase steering prior to the high RF power section thus achieving potential high steering rates without incurring in high power switch problems.

It is noteworthy that first practical beam-hopping system was implemented with the NASA Advanced Communications Technology Satellite (ACTS) with an architecture at the opposite antenna extreme. Indeed the ACTS beam-hopping antenna was producing a single step-steerable beam employing a single TWT. Beam-hopping was performed by the high-power BFN illuminating a cluster of radiating elements with the position of the cluster steerable by setting a series of switch position of the output section.

These two opposite pioneering works still constitute today the extremes of possible beam-hopping payload/antenna configurations.

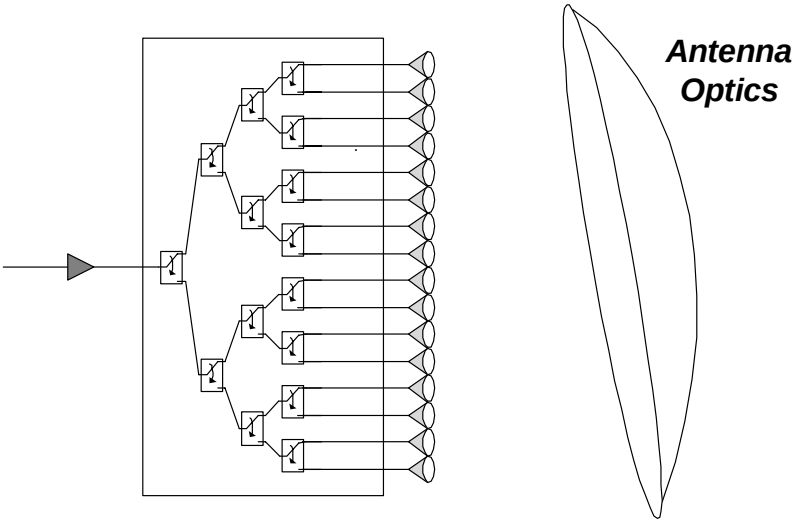


Figure 2: Single-Beam High-Power Beam-Hopping Network

High power beam-hopping networks are constituted of a set RF switches that route the beam signal to the right beam port (e.g. a feed input in a single feed-per-beam antenna configuration). A single-beam example is shown in **Error! Reference source not found.**. The configuration offers evident advantages if the power amplifiers can be operated in single carrier (highest DC-to-RF efficiency). A high hopping rate can only be achieved with ferrite switches.

The network complexity increases when more than one beam is contemporarily hopping. To achieve a full interconnectivity without experiencing any blocking conditions a full cross-bar network would be needed. Unfortunately the complexity of a cross-bar increases with the product of the number of input ports (active beams)

times the number of output ports (possible beam positions). Accordingly with the complexity increases also the number of consecutive switches that are encountered by the beam amplified signal and in turn the experienced losses. To avoid these drawbacks coverage repartitioning has been proposed in the past (e.g. by mean of reduced interconnectivity networks, multiple partially overlapping single beam-hopping antennas, etc) but unfortunately these systems show a reduced efficiency in using the RF power efficiently because of the nonuniform traffic demands not always matching the imposed architectural constraints.

The beauty of Phased Array solutions (either Direct Radiating or magnified by other optical systems as lenses or reflectors) stands in their power pooling capability. All the amplifiers are contemporarily working on all the beam signals (refer to Figure 3) giving an intrinsic flexibility in spatially moving the power within a wide coverage area. The distributed amplification provides on one side a certain degree of robustness to individual failures and forces, on the other, to an increase of the amplifiers back-off to limit non-linearity impairments.

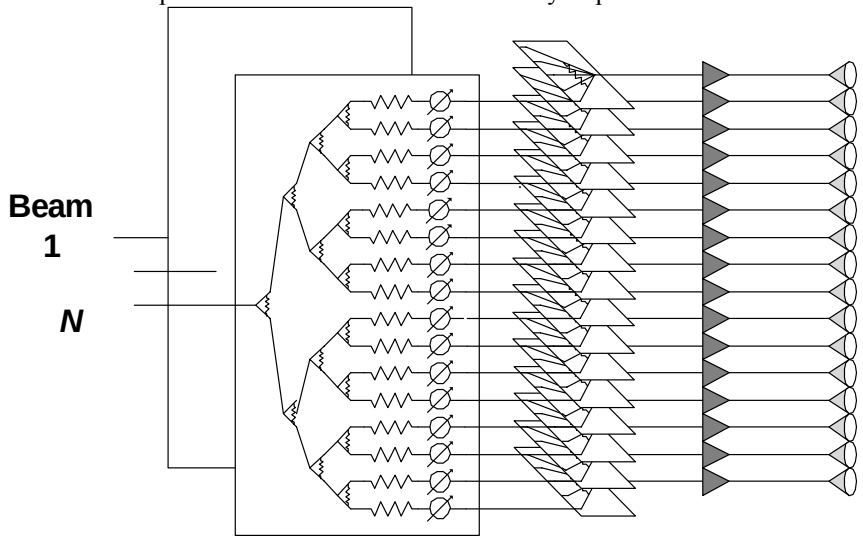


Figure 3: Direct Radiating Array Block Diagram

IV. Optimization algorithm

The optimization problem consists in determining the beam hopping time plan in order to best match the traffic demand over the coverage region and satisfy possible power/mass constraints induced by the selected platform. In [4] a heuristic approach was followed to optimize the beam allocation in the beam hopping plan. According to this approach, the beams are allocated to the time plan following a priority, which is dependent on the beam requested traffic. The beam allocation algorithm forces adjacent beams not to be illuminated within the same time slot, thus eliminating co-channel interference from adjacent spot beams. At each iteration, the window length W is increased of one unit and beams are assigned to the new slots of the beam hopping plan through the above procedure. The key limitation of the considered heuristic approach is that the beam allocation is achieved through a feed-forward process, where beam hopping plan assignments are not revised as a function of the obtained system capacity.
In the present work, a global optimization approach has been pursued. Main motivations have been the global nature of the problem and the lack of simple rules for beam allocation, which interrelate capacity gain with resource assignment. This is mainly due to the several non-linear functions involved in the optimization: capacity as a function of interference level, interference as a function of beam allocation, throughput as a function of available capacity (due to the traffic request variability over the coverage).
Given a window length W and a maximum number of bandwidth channels N_f, the space of possible beam hopping plans has the dimension given by the expression $[2^{Nb}]^{(W*N_f)-1}$. This includes the possibility of illuminating a variable number of beams per slot in the beam hopping plan, as well as a variable number of beams can be assigned to the same bandwidth channel. However, the expression does not include any possible payload constraint, which limits the number of simultaneously illuminated beams. It is clear from the above expression how bandwidth

segmentation and time segmentation can offer equivalent solutions to the resource allocation problem. Given the large number of independent parameters to be optimized and the large dimension of the possible solution space, together with the highly non linear behavior of the capacity function, genetic algorithms (GAs) have been selected.
As it is well known from literature, GAs are based on the creation of an environment where a population of possible solutions competes and evolves until the fittest individual survives. In the following optimizations, the fitness function has been assumed equal to the total system throughput T. Some fairness criteria could in general be introduced to shape the resulting available capacity profile: as an example, one may think of guaranteeing the provision of a certain ratio of the traffic demand per beam $\hat{R}_b^i$, or of a certain minimum constant throughput per beam. However, in the following, the simple capacity maximization has been assumed. Introduction of RF/DC power constraints can be achieved through a multi-objective fitness function F, which can be expressed as:

$$F(BH(i,n,j)) = xT(BH(i,n,j)) + y / P(BH(i,n,j)) \tag{4}$$

where P can be the RF or DC power, depending if payload architecture and amplification efficiency are considered in the computation. x and y are weighting factors for the total system capacity T and the consumed power, which shall be set depending on system/payload design criteria. (Note that the fitness function introduced above is only valid when using a maximizing GA).

The fitness function introduced above will be used to evaluate every one of the individuals (i.e. possible solutions to the problem) composing the successive generations of population existing in the artificial environment created within the optimizer. According to previous assumptions, the structure of every individual, indicated as chromosome in the following, contains two matrixes (beam plan and frequency plan) of dimensions $W*N_{MAX}$ and $W*N_{MAX}*Nf$ (Figure 4)

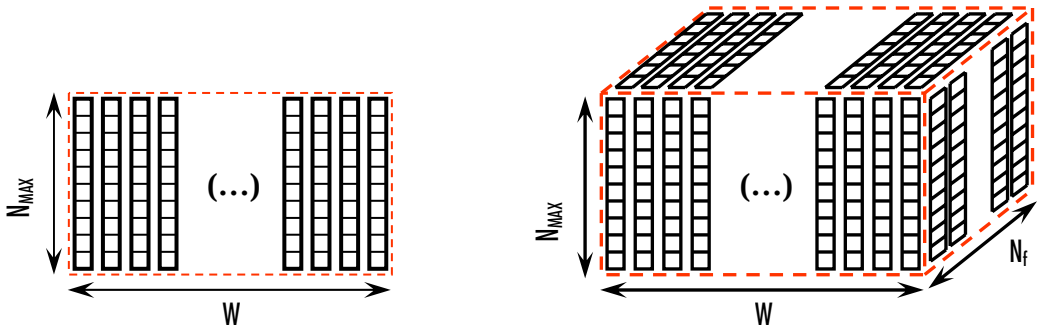


Figure 4: GA individual representation

As a well known fact, the size of the population is, with the crossover and mutation rate, one of the most important parameters that can guarantee the success of the algorithm or ensure its failure. The available literature provides only lower bounds and reference values, valid only under certain assumptions on the particular statistic of the reference problem. Hence, given that the problem under study is too complex to be formally analyzed, the determination of the population size, for instance, is the result of a heuristic process consisting of many runs of the GA. In the following, the size of 10 has been considered, providing an acceptable trade off between accuracy and computational speed.

Several initial populations can be considered as a starting point for the optimization. A random beam and carrier allocation could be utilized. However, in the following, we have considered as one of the individuals of the initial population a beam hopping plan, where beams have been allocated following a regular pattern. Within a given time slot, the set of beams simultaneously illuminated are the ones, which would utilize the same frequency band in a traditional non beam-hopping type of systems, where a regular 1:3 or 1:4 frequency reuse pattern is assumed.

Given the enormous size of the search space (containing all possible instances of chromosomes), two mechanisms are included in the original flowchart of the GA to explore the space and determine the global optimal solution. In

first place, the crossover operator provides an efficient mean to explore different regions of the search space, preventing the algorithm from getting blocked in a local optimum value. In a second place, the mutation mechanism generates small leaps over the space to exploit any particular area, which is not reached through crossover.

Crossover operator. Many options are available to configure this operator on the beam hopping plan but the most effective method (due to the inherent structure of the chromosome) consist on recombining the selected parents at slot level, i.e. every couple generate two children, resulting from the uniform random combination of the genitors' slots. On the frequency plan's side, two mechanisms are considered. When crossing two slots, those beams appearing in both of them combine uniformly its carriers. Otherwise, the carrier distribution is substituted by another randomly generated.

Mutation mechanism. In a similar way, the mutation operator must be considered from both the beam hopping plan and the frequency plan point of view. On the Beam Plan, a mutation consists on the introduction of either a new and non-repeated beam in a time slot, or the disconnection of one of the beams already illuminated. On the Frequency Plan side, the mutation provides a change in only one of the carriers in one of the illuminated beams of the Beam Plan.

V. Simulation results

In order to assess possible benefits of beam hopping techniques, a system study case representative of a typical broadband access system has been assumed. N_b=100 beams provide service over the EU25 geographical region. Although beam hopping offers the flexibility of adapting to different traffic demand configurations, the specific distribution of Figure 1 is considered here in order to test beam hopping gain. However, it shall be noted that capacity gain is in general heavily dependent on the traffic request; the configuration assumed here is particularly difficult to match, because of the hot spot concentration and of the average high demand.
The system parameters considered for the beam hopping system are included in the following table:

Parameter	Value
Carrier frequency	20.0 GHz
Total bandwidth B	500 MHz
Satellite antenna beams N_b	100
Antenna peak gain	52.3 dB
Antenna EOC gain	48.27 dB
Antenna losses	1 dB
Output Losses	1.8 dB
Receiver antenna diameter	0.75 m
Receiver antenna efficiency	60%
Pointing losses	0.5 dB
Feed Losses	0.3 dB
ST Clear sky G/T	17.2 dB
Other System interference C/I	18.73 dB
Feeder link C/(N+I)	17.8 dB
Channel bandwidth B_j	250 MHz
Carrier bandwidth B_C	62.5 MHz
Power density	60W/ 250 MHz
Roll off α	0.25
Carrier spacing C_S	1.11
Maximum number of simultaneously illuminated	35

beam N_{MAX}	
Window length W	12

Table 1: System parameters

A Direct Radiating Array configuration is considered. A constant power per carrier is assumed to simplify payload architecture. The DVB-S2 standard including the utilization of Adaptive Coding and Modulation is assumed as air interface for the satellite to terminal link. The large number of possible modulation formats (from QPSK to 32 APSK) and coding rates (1/4 to 9/10) allowed by the standard allows for adapting to a wide range of SNIR conditions. In [4] it has been shown how the DVB-S2 standard can be utilized in beam hopping systems, despite the time-variant frame format.
For derivation of link efficiency, results of extensive end-to-end physical layer simulations have been utilized [6]. Losses due to physical layer adaptation, synchronization and implementation have been taken into account. In the following table the OBO and total degradations, which have been obtained for N_C=2 and N_C=5 carriers per TWTA, are shown. It shall be noticed that, in case a larger number of carriers is considered, no significant additional degradation with respect to the N_C=5 case is experienced.

	OBO(N_C=2)	OBO (N_C =5)	D(N_C =2)	D(N_C =5)
QPSK	1 dB	1.17 dB	0.37 dB	0.85 dB
8PSK	1.05 dB	1.7 dB	0.7 dB	1.4 dB
16 APSK	1.6 dB	2.8 dB	1.5 dB	1.6 dB

Table 2: DVB-S2 physical layer performance

As a reference for the capacity gain assessment, a conventional state-of-the-art system utilizing a regular frequency reuse 1:4 is assumed. The same system parameters shown in Table 1 are utilized. In this case, N_C =2 carriers per beam are considered with a carrier bandwidth B_C=62.5 Mz. No optimization of power allocation is done and the power per beam is assumed constant. Physical layer degradations as from Table 2 for the N_C =2 case have been taken into account. Figure 5 reports the system capacity as a function of the RF transmitted power per beam, when the traffic distribution of Figure 1 is considered.

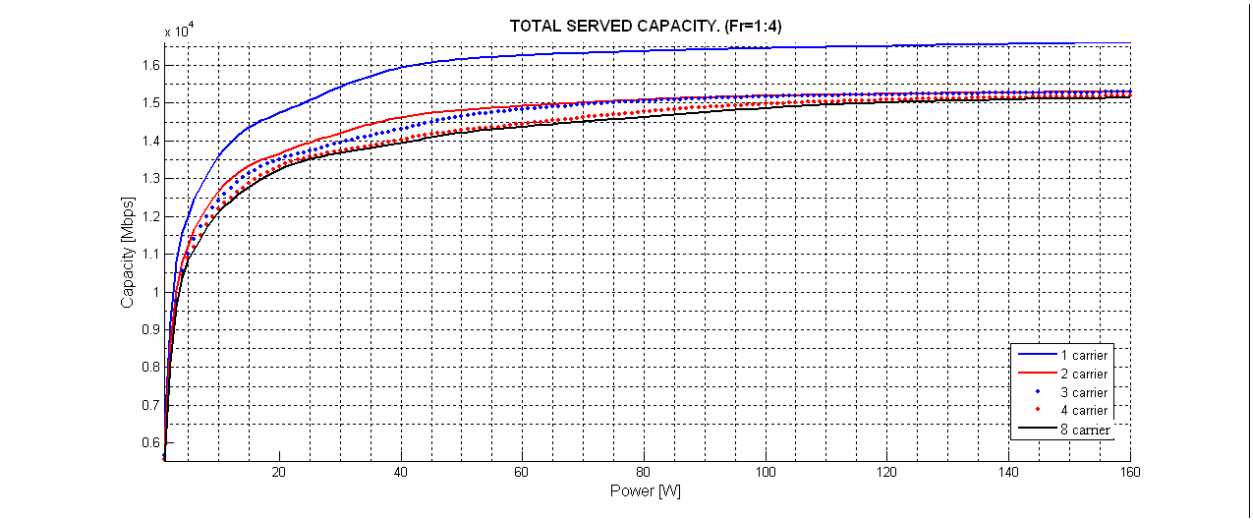


Figure 5: Conventional system capacity

The beam hopping system has been analysed assuming the optimization approach outlined in Sect. IV. The figure of merit of eq. 4 has been utilized, with x=1 and y=0. The following Figure 6 shows the obtained results in terms of capacity per beam. In each beam, the "available" capacity, which is the throughput $\overline{R}_b^i$ the system can provide, is

compared with the requested capacity $\hat{R}_b^i$. The black line represents the available throughput the conventional system with no beam hopping capabilities and regular frequency reuse can provide for the same total RF transmitted power of 3.3 kW. It should be noted how this system, which assumes a single feed per beam architecture and N_C =2 carriers per beam, benefits from a milder degradation at physical layer (see Table 2) with respect to the beam hopping system, where a DRA architecture with a more pushed multicarrier operation is assumed. As it can be seen, the beam hopping system outperforms in most of the cases the conventional one. In particular, the best results are achieved in isolated hot spots, where the traffic demand can be achieved by the optimized beam hopping system. In the cold spots, the low traffic demand is met thanks to assignment of a reduced number of time slots. In the hot spot clusters, a capacity larger than the uniform case cannot be easily provided without penalizing adjacent spots.

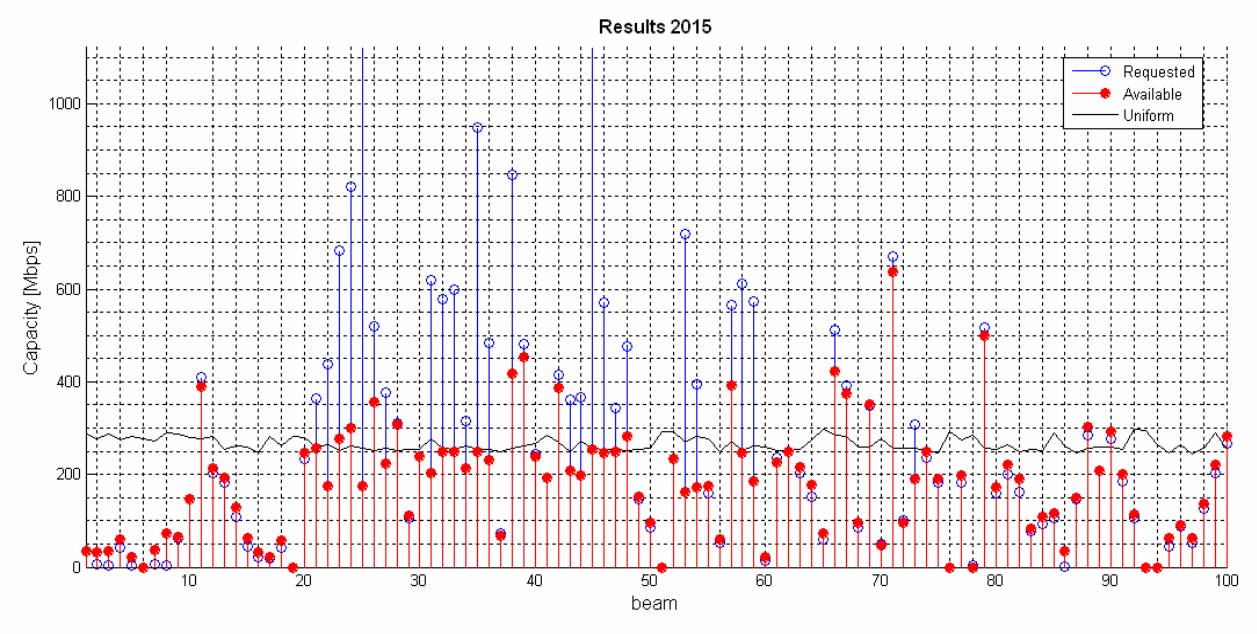


Figure 6: Beam hopping system capacity

As an example, in the following Figure 7 the beams illuminated in time slots 5 and 10 are shown. The beams, which are illuminated with both bandwidth channels, are coloured in red. The ones illuminated with only one channel are coloured in green and blue, depending on the high/low centre frequency of the channel within the total bandwidth B. It can be noticed that in the hot spot central cluster, as identified by Figure 1, the beam illumination pattern is rather regular. On the contrary, in isolated hot spots or at the cluster boarders, simultaneous illumination of adjacent beams is adopted, in order to increase the available capacity. This is what happens, for instance, for beams 28-38, 44-57 and 39-54. In certain cases, complementary bandwidth channel are utilized in order to minimize co-channel interference, as in beams 66-67, 70-71-72. It can be seen that, if the traffic demand is relatively sparse over the coverage region, the beam hopping system can provide up to a factor 3 gain in capacity with respect to the conventional system, as in the present study case in isolated hot spots like beam 71, where 650 Mbit/sec can be provided versus 220 Mbit/sec of the conventional system. The total obtained system capacity is 17.4 Gbit/sec, versus 13.3 Gbit/sec achieved by the conventional non beam-hopping system, with a 30% capacity gain.

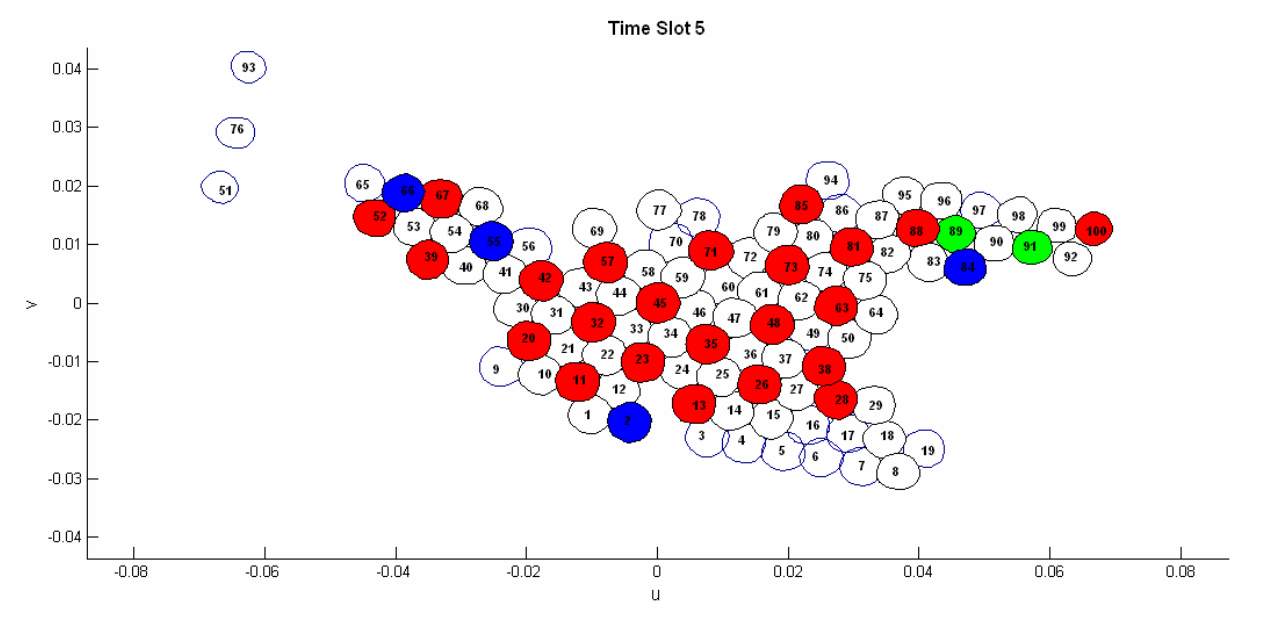


Figure 7: Beam illumination in time slots 5 and 10

VI. Conclusions

The present contribution aimed at assessing the advantage brought by the utilization of beam hopping techniques in the forward link of a multibeam broadband satellite system. The inherent flexibility of beam hopping system allows optimizing resource allocation as a function of the time-variant traffic request distribution over the satellite coverage region. Different options at payload/antenna level for implementing beam hopping have been outlined. Genetic algorithms have been utilized for optimizing the beam hopping time plan in a realistic system study case. Results have shown that a capacity gain of 30% can be achieved with respect to a conventional system, despite the unfavorable considered traffic configuration, where the traffic demand is concentrated in hot spot clusters. Further work should be performed in order to analyze the sensitivity of beam hopping systems to parameters like the window length, the channel bandwidth granularity and the maximum number of simultaneously illuminated slots. Further, constraints at system level derived by the assumed payload architecture shall be considered. Finally, system performances should be traded-off versus consumed DC power.

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