# Beam Hopping in Multi-Beam Broadband Satellite Systems:

## System Simulation and Performance Comparison with Non-Hopped Systems

J. Anzalchi, A. Couchman
EADS Astrium Ltd
Gunnels Wood Road, Stevenage, Herts, United Kingdom

P. Gabellini, G. Gallinaro, L. D'Agristina
Space Engineering SpA
Via Dei Berio, 91-00155, Rome, Italy

N. Alagha, P. Angeletti
European Space Agency - ESTEC
Keplerlaan 1, 2200 AG Noordwijk, The Netherland

***Abstract*—A key requirement for the future multi-beam broadband satellite design is the provision of flexibility to adapt to different traffic demands by re-assigning capacity to beams in accordance with changing traffic distributions. Such flexibility would enable the best match to be maintained between the system resources and traffic demands over the satellite lifetime, thereby greatly enhancing the system utilisation and competitiveness. The current paper examines the use of beam hopping to provide such flexibility. It investigates the advantages of beam hopping and compares the performance and capacity capabilities of a beam hopped with that of equivalent non-hopped systems also designed to provide flexibility.**

***Keywords-Satellite; Beam Hopping; Multi-beam; Broadband;***

## I. INTRODUCTION

A particular concern with multi-beam broadband satellite design is the inclusion of flexibility to enable the system to adapt to changing traffic demands. Such flexibility would enable the best match to be maintained between system resources (capacity) and traffic demands over the satellite lifetime, thereby greatly enhancing the system utility and competitiveness. Succinct

Various methods have been considered and applied to multi-beam systems to achieve capacity re-allocation. These include the use of flexible TWTs and multiport amplifiers to provide variable power per beam, and analogue or digital processors to assign bandwidth per beam on demand [1]. Another method, which can have distinct advantages, is the use of beam hopping techniques in which only a subset of beams is illuminated at a given time. This results in a time and spatial transmission plan with a pre-defined repetition rate or "window" length [2].

Within a time slot, a selected beam can have full access to the available spectrum or a fraction of that spectrum depending on the traffic demands of that beam. Moreover, for some types of payload architecture the TWTs can be operated at saturation, ie at maximum efficiency and switched between beams in accordance with the time slot plan such that each accessed beam is supported with maximum power at optimum efficiency. Such a feature leads to an efficient overall payload design with high EIRP, which is essential for operation with small consumer terminals.

This paper summarises the results of a joint ESA/Astrium/Space Engineering study into the performance, design and optimization of multi-beam hopped systems operating at Ka-band [3].

In order to demonstrate advantages of beam hopping, a comparison is made with equivalent non-beam-hopped systems operating within the same system scenario and conditions. Detailed comparisons were then made of the respective performances of these systems in terms of degree of satisfaction of traffic demand. The non-hopped equivalents include non-flexible single feed per beam (SFPB) systems representative of current Ka-band architectures, and flexible SFPB systems using flexible TWTAs or multiport amplifiers.

The study focused on the Gateway to User (forward) link with the assumption of the DVB-S2 air interface. In the case of beam hopped systems this interface was modified to operate within the beam hopped format. A pan-European coverage operating with typical User terminals adapted for beam hopping was assumed. A traffic distribution with large and shifting demand patterns for the time period 2010 – 2025, was generated in order to assess the adaptability of the various systems to changing capacity requirements over a typical satellite lifetime.

A key part of the study is the development and use of software simulation tools to optimize not only the performance of the beam hopped systems, but also the non-hopped systems which are used for the comparison purposes. Some details of the optimisation methods are provided in the paper.

## II. System Assumptions

The system used as the basis for the comparative assessment of beam hopped with non-beam hopped schemes provides broadband coverage in Ka-band of the major part of the European continent plus Turkey. The system is assumed to have the following key features:

- Coverage of Europe plus Turkey from 33°E with 70 x 0.5° spot beams in Ka-band (30/20GHz) as shown in Fig. 1 [4]. A dual polarization is assumed at system level, which is managed at beam level as single polarization for non-hopped schemes and dual polarization for hopped schemes over the full coverage area.
- Provision of broadband services from a set of Gateways to Users within the coverage region. The Gateways are linked to the 70 User downlink beams in

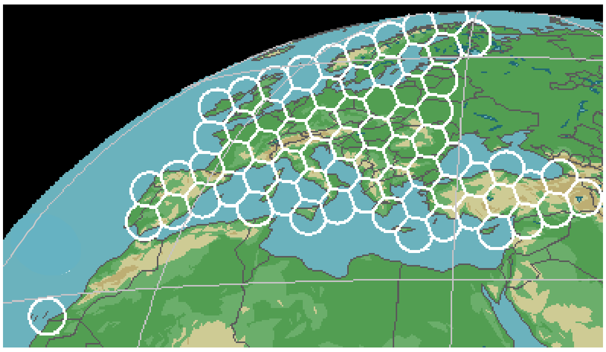

Fig. 1. Coverage Area and Beam Layout from 33°E

  a multi-star configuration with each Gateway accessing a fixed set of beams. The specific bands used by the Gateways and User are shown in Fig. 2.
- In the case of the non-beam hopping system, the assumption is made of the use of the DVB-S2 air interface standard for the Forward links with the DVB-

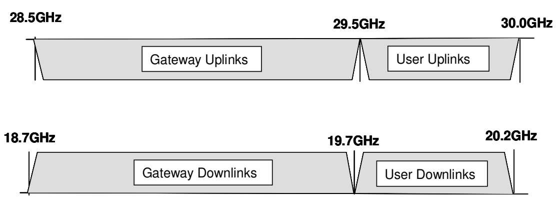


**Fig. 2. Basic System Frequency Plan**

  RCS standard for the Return links. The DVB-S2 downlink transmission rate is variable in steps of 45MSymbol/sec (an occupied bandwidth of 62.5MHz, assuming a roll-off factor of 25%, and filtering shape factor of 1.111). Up to 8 maximum symbol rate (45MSymbol/sec) transmissions may be accommodated in the 500MHz downlink band.
- In the case of the beam-hopped system, either a single high symbol rate transmission of 360MSymbol/sec or 8 symbol rate transmissions of 45MSymbol/sec are assumed to occupy the whole of the 500MHz downlink band, again assuming a 1.25 roll-off factor with a filtering shape factor of 1.111. A signal with Adoptive Coding and Modulation (ACM) is assumed, with characteristics similar to that of DVB-S2 but with a signal format compatible with the operation of the beam hopped system – namely with the discontinuous nature of the downlinks.
- It is assumed that the User terminals are designed for residential use – 0.75m antenna with 1W SSPA HPA and a receiver with a typical noise temperature of 207K. It is assumed that these terminals can operate with a maximum symbol rate of 45MSymbol/sec in the case of the non-hopped DVB-S2 transmissions, and either 360 or 45 MSymbol/sec in the case of the beam hopped system. Symbol rates as high as 400MSymbol/sec have already been proposed for beam hopping systems by the Hughes Electronics Corporation (now Boeing) [5], which is indicative of future trends in data transmission by satellite.
- An end-to-end link availability for both the Forward and Return paths of 99.7% is assumed for Quasi-error free transmission.

In order to assess the relative capabilities of the hopped and non-hopped systems a model of the traffic demand distribution across the coverage area was used. The model, corresponding to predicted demands for 2010 was taken directly from the original ESA DDSO (Digital Divide Satellite Offer) study [6] is shown in Fig. 3. It shows the predicted capacity per beam in Mbits/sec for the coverage presented in Fig. 1.

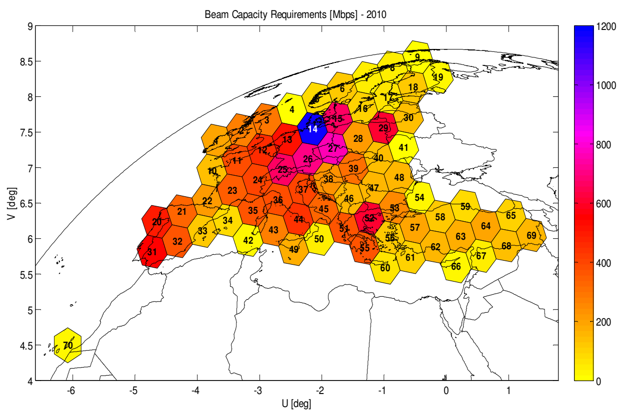


**Fig. 3. Assumed Traffic Distribution 2010**

## III. PAYLOAD ARCHITECTURES

The payload architectures for both the non-hopped and hopped system are in many respects the same – whereas the non-hopped payload provides continuous but variable bandwidth transmissions to the Users depending on traffic demand, the hopped design provides discontinuous (hopped) transmissions of wide, fixed bandwidth with an aggregate dwell time dependent on demand.

Since both architectures share many common features, they provide a good basis for the direct comparison of the performances of both types of system.

The essential configurations of the two architectures are represented in Fig. 4.

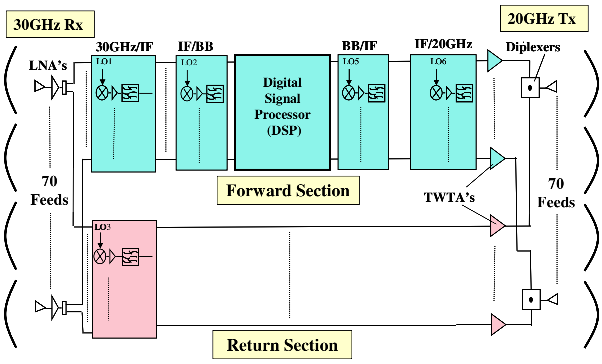


Fig. 4. Basic Payload Architecture for Both Hopped and Non-hopped System

The key features and functionalities of the architectures are as follows:

- The payloads are of the Single Feed per Beam (SFPB) design which is based on the use of spot beam reflector antennas operating with feed arrays. Within these arrays each spot beam is provided with a corresponding feed in both Rx & Tx
- Reception and transmission is by a set of 4 such spot beam antennas, which between them provide a set of 70 interleaved, contiguous beams over the defined coverage. The Tx and Rx antennas are shown as separate in Fig. 4. In reality these may be combined.
- The payload comprises a Forward Section for reception of Gateway uplinks and downlink transmission to the User beams, and a Return Section for reception and onward transmission of the User uplinks to the Gateways.
- Reception of the Gateway and User uplinks is via a set of low noise amplifiers (LNAs) located immediately after the Rx feed arrays. The outputs of the LNAs are split into two paths – one which goes to the Forward Section, and the other to the Return Section.
- In the case of the Forward Section the Gateway uplinks are downconverted from 30GHz to baseband via a suitable IF and anti-aliasing filter to baseband for presentation to the inputs of a Digital Signal Processor (DSP).
- The operation of this DSP depends on whether the system is the non-hopped or hopped scheme.

  In the case of the non-hopped system, the DSP carries out high speed analogue to digital conversion of the Gateway signals (with currently available commercial technology sampling rates of up to 1.25Gsamples/sec corresponding to a bandwidth of 500MHz may be assumed for each DSP input), demultiplexes the digitised signals into bandwidth segments of 62.5MHz in correspondence with the system symbol rate of 45MSymbol/sec and then assigns to each beam the required destination transmissions and a bandwidth or number of 62.5MHz segments in accordance with the traffic demand of that beam. This allocation is defined by a previously uploaded set of commands which configures the DSP bandwidth allocations per beam in accordance with the traffic demand distribution. The bandwidth allocation can vary from that of minimum bandwidth segment of 62.5MHz up to the full 500MHz (ie 8 x 62.5MHz).

  After the bandwidth allocation the digitised signals are converted to analogue form and then up-converted from baseband to 20GHz for downlink transmission into the required destination beams.

  In the case of the hopped system, instead of assigning a bandwidth to each beam, the DSP assigns a time slots to each beam in accordance with the system illumination plan. During a time slot duration the full 500MHz downlink bandwidth is allocated to the relevant beam.
- In each case, non-hopped or hopped downlink transmission is assumed to use different amplification strategies in order to assess the most advantageous one(s) among Single-Port (SPA) and Multi-Port Amplifiers (MPA) based on a set of either fixed or flexible TWTs. The latter are flexible in the sense that the saturation power level can be varied without greatly affecting the HPA efficiency. This enables the power level into each beam to be changed, for example to compensate for rain fades or changes in capacity demand without placing overly high demands on the spacecraft power supply. The typical consumption characteristics of the flexible TWT assumed for the current study is presented in Fig. 5, where the branch with power setting equal to 0 dB also represents the consumption of the equivalent fixed TWT.
- With regard to the Return Section a simple, single conversion bent pipe architecture is assumed with no DSP included. It is proposed that since the return link capacity requirement is likely to be a fraction of that of the Forward links, then no flexible allocation of capacity is required either through flexible bandwidth allocation or beam hopping. A fixed bandwidth

capable of coping with any likely return demand is therefore assumed.

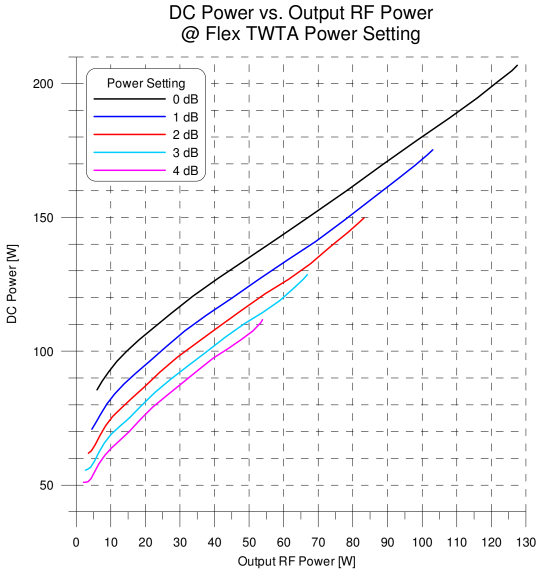


Fig. 5. Typical Flexible TWT Characteristics

- Concerning the non-hopped architecture it is assumed to feed 2 beams with each amplifier output port by sharing the amplifier bandwidth via post-amplification filtering. Therefore the total number of needed TWTAs is 35 in case of SPA schemes while in case of MPA schemes it depends on the selected order of MPA. Assuming an order equal to 8 and terminating one output port per MPA, the total number of active output ports is 35 while the number of TWTAs is 40.
- Concerning the beam hopping architecture it is assumed to feed 4 beams with each amplifier output port by means of a post-amplification switching strategy where only 1 of the 4 beams is connected to the output port at each time slot. Since each dual polarization is assumed for all the beams, the total number of required amplifier output ports is 35, which again corresponds to 35 and 40 TWTAs respectively for SPA and MPA schemes.

## IV. OPTIMISATION ALGORITHM

The general optimization strategy proposed for the design of both Non-Beam-Hopped (NBH) and Beam-Hopped (BH) Systems is schematically shown in Fig. 6 and consists of a System Optimization Loop (SOL) aimed at identifying the best System configuration based on the assigned Capacity Requirements, the selected Antenna configuration, the selected Merit Function and Bandwidth/Power Constraints.

The optimum System configuration, focusing on user segment of forward link, in turn consists of:

1. **Illumination Plan** (if applicable, i.e. in case of Beam-Hopping only);
2. **Power Plan**;
3. **Frequency Plan** (if applicable, i.e. only in case of bandwidth segmentation for both Non-Beam-Hopped and Beam-Hopped systems);

Two main modules can be identified in the optimization tool overall architecture of Fig. 6, namely:

1. **The System Optimization Loop** (SOL) module;
2. The **SOL Merit Figure Generator** module.

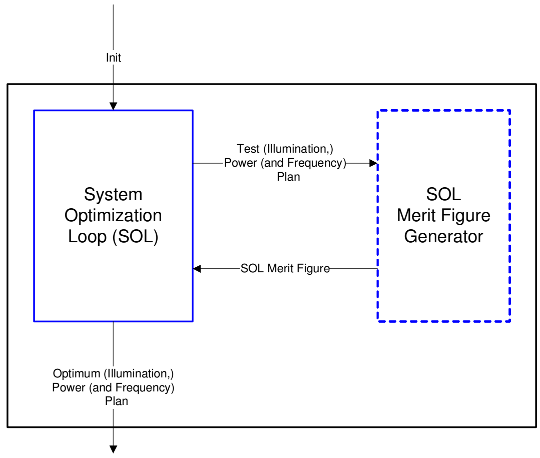


Fig. 6. Optimization Tool Overall Architecture

Due to intrinsic combinatorial nature of the SOL goal, i.e. identifying the best (Illumination,) Power (and Frequency) Plan, the proposed architecture for the SOL module is composed of a sequence of optimization modules suitable for such task, as shown in Fig. 7:

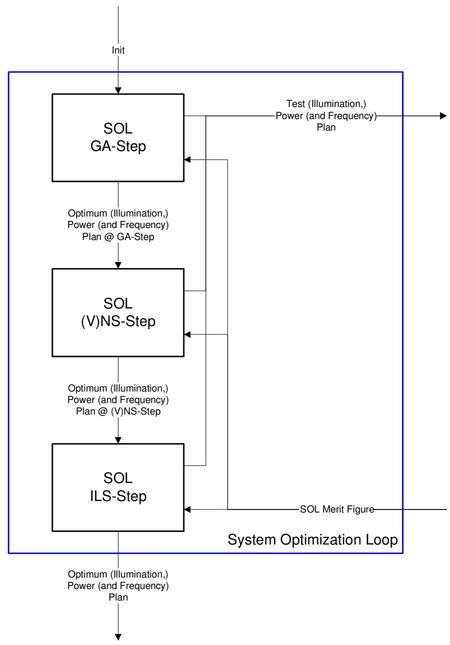


Fig. 7. System Optimization Loop Architecture

1. The **SOL GA-Step** is a module in charge for carrying out an initial screening of the space of solutions, whose envisaged strategy consists of a Genetic Algorithms (GA) approach possibly targeting parallel implementation to limit computation time.
2. The **SOL (V)NS-Step** is a module in charge for a further single step of optimization intensification starting from the solution supplied by the previous SOL GA-Step. The envisaged strategy consists of a (Variable) Neighbourhood Search approach.
3. The **SOL ILS-Step** is a module in charge for a further multiple step of refinement of system optimization starting from the solution supplied by the previous SOL (V)NS-Step. The envisaged strategy consists of an Iterated Local Search approach with number of steps selected by the user in order to allow trade-off between computation time and quality of optimum.

The proposed architecture for the SOL Merit Figure Generator module is shown in Fig. 8, where 3 main modules can be identified, namely:

1. The **Link Budget Analysis** is a module in charge of the evaluation of the Offered Beam Capacities related to the current (Illumination,) Power (and Frequency) Plan tested by the System Optimization Loop. Such an evaluation is carried out by means of a multidimensional link budget based on the use of the ACM strategy.
2. The **SOL Merit Figure Generation** is a module in charge of the evaluation of the assumed system optimization merit figure, e.g. Unmet System Capacity or Differential System Capacity [7], on the basis of the Required and Offered Beam Capacities.

The definition of the Unmet System Capacity (USC) is assumed to be as follows:

$$USC = \Sigma_i \max [C_{rqs}(i) - C_{off}(i), 0],\ i = 1 \div N_b$$

Where $C_{rqs}(i)$ and $C_{off}(i)$ respectively are the Required and Offered Capacity (i.e. the Bit Rate in Mbps) for the beam **i** and the sum spans the set of beams. According to such definition, offered beam capacities exceeding the requirement do not contribute to the Merit Figure and then do not impact the optimization process.

On the other hand the definition of the Differential System Capacity (DSC) is assumed to be as follows:

$$DSC = \Sigma_i \text{abs} [C_{rqs}(i) - C_{off}(i)],\ i = 1 \div N_b$$

Differently from USC, in DSC the offered beam capacities exceeding the requirement contribute to the Merit Figure and then drive the optimization to allocate the minimum overall power budget to meet at best the requirements.

The **SOL Merit Figure Penalization** is a module in charge of penalizing the Merit Figure according to the level of violation of the assumed system and payload constraints supplied in input by the user. The final SOL Merit Figure is then returned to the System Optimization Loop. The constraints to be checked are:

- Maximum Number of Illuminated Beams per Time Slot
- Upper Bound at Total Processed Bandwidth
- Lower Bound at Beam Capacity
- Lower Bound at Availability
- Upper Bound at HPAs' Output RF-Power
- Upper Bound at Total DC-Power Budget for HPAs

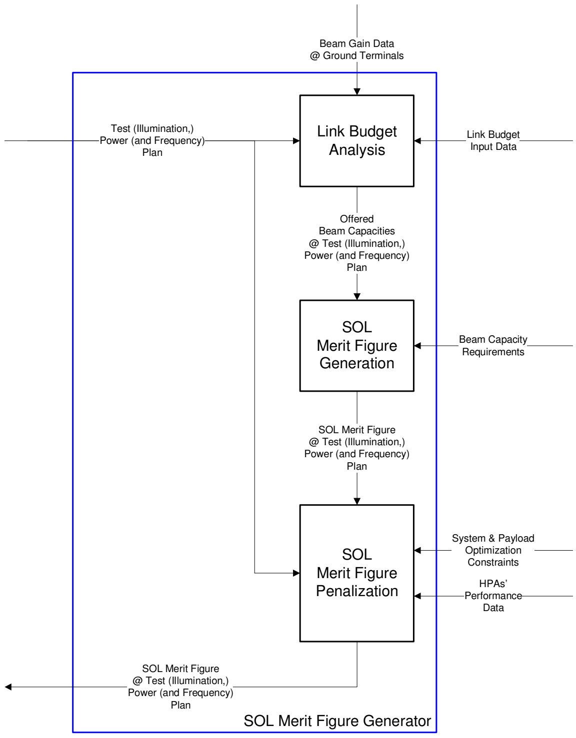


Fig. 8. SOL Merit Figure Generator Architecture

## V. SIMULATION MODEL

According to the optimization methodology described in the previous section, the computation of the Merit Figure to be used in the optimization requires the computation of the Offered Capacity at the ground terminals, which is in turn derived by means of a Link Budget Analysis based on the use of the Adaptive Coding Modulation (ACM) scheme. The Offered Capacity is then defined as:

$$C_{off}(x,y) = R_b(x,y) = R_s \bullet SE_{ACM} [SNIR(x,y)]$$

Where $\mathbf{R_b(x,y)}$ is the Bit Rate, i.e. the Offered Capacity, at earth pixel (x,y), $\mathbf{R_s}$ is the Symbol Rate, $\mathbf{SE_{ACM}}$ is the ACM Spectral Efficiency function, **SNIR(x,y)** is the Signal to Noise plus Interference Ratio at earth pixel (x,y) given by:

$$SNIR(x,y) = S(x,y) / [N_o(x,y)\ R_s + I(x,y)]$$

Where **S(x,y)** is the Nominal Carrier Power, **$N_o$(x,y)** is the Noise Power Density at receiver and **I(x,y)** is the aggregate Interfering Power, being the latter in turn given by the sum of Co-Channel, Adjacent-Channel and Inter-Modulation Interference. The assumed model of C/I due to inter-modulation is derived by the simulation data presented in [8] as function of IBO/OBO, number of carriers and modulation.

Once the Offered Capacity is computed, the optimization Merit Figure is derived according to the selected definition, i.e. USC or DSC, on the basis of the assumed Beam Capacity Requirements. The selected capacity requirement profile is a prediction of the traffic demand on year 2010 carried out within the ESA study [6] and as already presented in Fig. 3.

The assumed system and payload environment for the optimizations is:

- Link Type: User segment of Forward-Link
- Frequency Band: 19.7-20.2 GHz (Ka-Band)
- Total User Bandwidth per Beam: 500 MHz
- Capacity Requirements: DDSO 2010
- Total Capacity Request: 17629.6 Mbps
- Number of Beams: 70
- Feeding Scheme: Single Feed per Beam
- Polarization Scheme at System Level: Dual
- HPA Type: 128÷150 W Fixed/Flexible TWTs
- Maximum DC Power Budget: 7 KW
- Minimum System Availability: 99.7 %.

Three types of system arrangements have been optimized in the frame of such environment in order to compare their performance, i.e.:

- Conventional System with Uniform Allocation of Power and Bandwidth to Beams
- Non-Beam-Hopped System with Flexible Allocation of Power and Bandwidth to Beams
- Beam-Hopped System.

As far as the Conventional and the Non-Hopped Flexible System are concerned the following parameters have been assumed for the bandwidth management which target state-of-the-art commercial modem technology:

- Polarization Scheme at Beam Level: Single
- Number of Beams per Amplifier O/P: 2
- HPAs Utilisation Mode: Multi-Carrier
- Bandwidth Granularity: 62.5 MHz (8 Carrier Slots)
- Symbol Rate: 45 MSymbol/sec

On the other hand, bandwidth segmentation has not been at the moment considered for the Beam-Hopped System, leading to the following bandwidth management parameters which target custom modem technology:

- Polarization Scheme at Beam Level: Dual
- Number of Beams per Amplifier O/P: 4 (switched)
- HPAs Utilisation Mode: Single/Multi-Carrier
- Bandwidth Granularity: 500/62.5 MHz (1/8 Carrier Slot)
- Symbol Rate: 360/45 MSymbol/sec
- Beam Hopping Window Length: 4, 12

## VI. SIMULATION RESULTS

Preliminary optimizations aimed at identifying optimum resources allocation for both the system arrangements described in the previous section, i.e.:

- Frequency and Power Plan in the Non-Beam-Hopped Flexible System
- Beam Illumination, Frequency and Power Plan in the Beam-Hopped System for different values of Window Length have been carried out targeting the minimization of the DSC Merit Figure specified in section 4.

The resulting performance in terms of USC Figure (see section 4) and DC Power consumption of Beam-Hopped System is summarized in TABLE 1 as compared to the Non-Hopped Systems for fixed (TWTA) and flexible (FTWTA) single-port amplifiers along with multi-port amplifiers with fixed (MPA) and flexible (FMPA) tubes.

TABLE 1. Hopped vs. Non-Hopped System Performance

| Payload Architec. Type | Window Length | Bandwidth per Beam [MHz] | HPA Type | USC [Mbps] | DC Power [W] |
|---|---|---|---|---|---|
| Convent. | N/A | 250 | TWTA | 1141.47 | 6932.09 |
| Non-Hopped | N/A | 250 Flex | TWTA | 375.83 | 4277.31 |
| | | | FTWTA | 712.37 | 3085.72 |
| | | | MPA | 374.41 | 6710.56 |
| | | | FMPA | 548.79 | 4004.75 |
| Beam-Hopped | 12 | 500 | TWTA | 134.01 | 3308.73 |
| | | | FTWTA | 567.10 | 2616.80 |
| | | | MPA | 364.24 | 5438.62 |
| | | | FMPA | 1106.14 | 4166.55 |
| | 4 | 500 Flex | TWTA | 312.10 | 4784.00 |
| | | | FTWTA | 1113.29 | 3688.03 |
| | | | MPA | 173.09 | 5760.93 |
| | | | FMPA | 1243.13 | 4774.17 |

The general comment deriving from the comparative evaluation of the reported figures is that the beam-hopping technique allows an improved capacity performance w.r.t. an equivalent conventional system with a simultaneous reduction of likely up to 50% of DC consumption. Moreover, the beam-hopped system performance can be also better than an equivalent non-hopped flexible system especially when the former is operated in single carrier, with reduced impact of inter-modulation w.r.t. multi-carrier operation.

The beam capacity distribution of the system architectures listed in TABLE 1 is shown in Fig. 9 for the conventional system and in Fig. 10 and Fig. 11 respectively for SPA and MPA-based Non-Hopped Flexible systems.

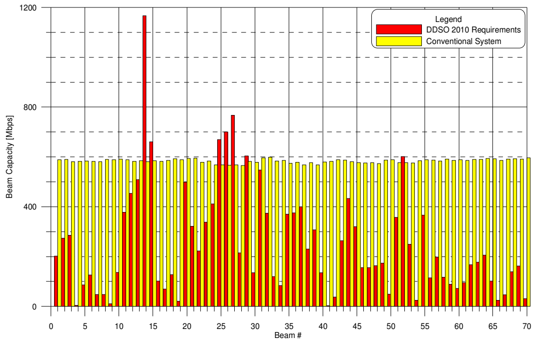


**Fig. 9 Conventional System Capacities**

The beam capacities performance offered by the beam-hopping systems as compared to the requirements are shown in Fig. 12 to Fig. 15 respectively for SPA and MPA-based Single and Multi-Carrier operation Beam Hopping Window Length equal to 4, 8, 12 and 16.

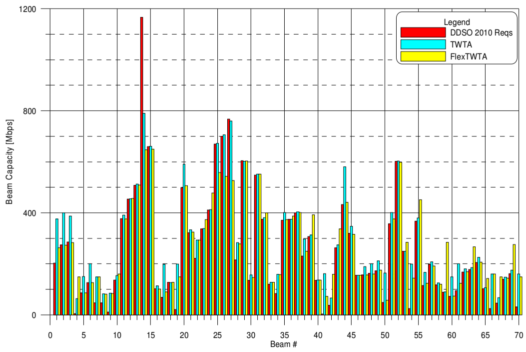


**Fig. 10 Non-Hopped Flex-System Capacities @ SPAs**

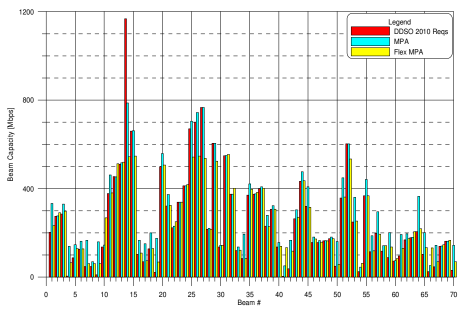


**Fig. 11 Non-Hopped Flex-System Capacities @ MPAs**

The beam capacities performance offered by the beam-hopping systems as compared to the requirements are shown in Fig. 12 to Fig. 15 respectively for SPA and MPA-based Single and Multi-Carrier operation Beam Hopping Window Length equal to 4, 8, 12 and 16.

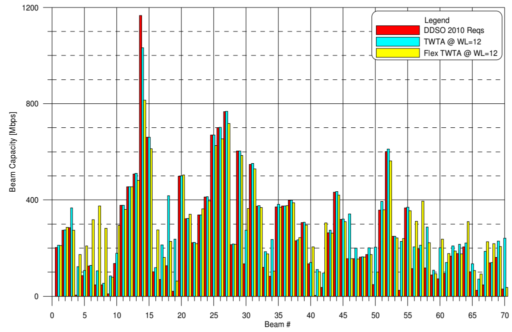


**Fig. 12 Beam-Hopped Single-Carrier Capacities @ SPAs**

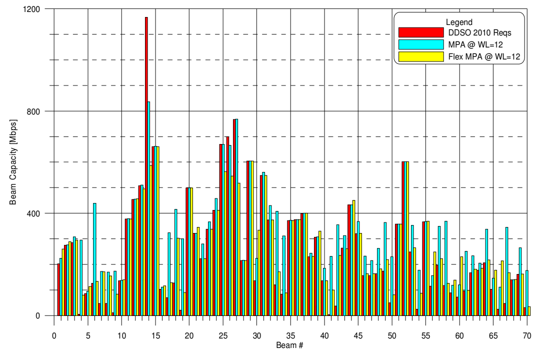


**Fig. 13 Beam-Hopped Single-Carrier Capacities @ MPAs**

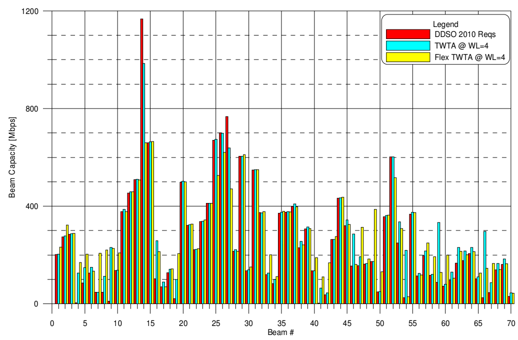


**Fig. 14 Beam-Hopped Multi-Carrier Capacities @ SPAs**

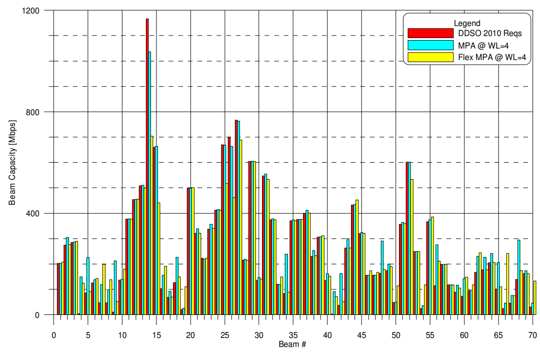


**Fig. 15 Beam-Hopped Multi-Carrier Capacities @ MPAs**

## VII. CONCLUSIONS

This paper has illustrated the merits of Beam Hopping Techniques and the advantage in a high degree of flexibility offered in the forward link of a multibeam broadband satellite system by optimizing the allocation of system resources.

The technique operates on the basis of illuminating a subset of beams at a given time, enabling time and spatial transmission plan with a pre-defined repetition rate or "window" length.

In order to assess the relative capabilities of the hopped and non-hopped systems a model of the traffic demand distribution across the coverage area was used. The model, corresponding to predicted demands for 2010 was taken directly from the DDSO (Digital Divide Satellite Offer) study.

The general optimization strategy for the design of both Non-Hopped and Beam-Hopped Systems consisting of a system optimisation loop aimed at identifying the best System configuration based on the assigned Capacity Requirements, the selected Antenna configuration, the selected Merit Function and Bandwidth/Power Constraints was presented.

A Simulation model according to the proposed optimization methodology and the computation of the Merit Figure based on the use of the Adaptive Coding Modulation (ACM) scheme was described.


## ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of ESA under the ARTES program.


## REFERENCES


[1] R. Rinaldo, X. Maufroid and R. Casaliez Garcia, "Non-Uniform Bandwidth and Power Allocation in Multi-Beam Broadband Satellite Systems", Proceedings of the AIAA, Rome, 2005.

[2] P. Angeletti, D. Fernandez Prim and R Rinaldo, "Beam Hopping in Multi-Beam Broadband Satellite Systems: System Performance and Payload Architecture Analysis", Proceedings of the AIAA, San Diego, 2006.

[3] J. Anzalchi, A. Couchman, C. Topping, P. Gabellini, G. Gallinaro, L. D'Agristina, P. Angeletti, N. Alagha and A. Vernucci, "Beam Hopping in Multi-Beam Broadband Satellite Systems", Proceedings of the AIAA, Edinburgh, 2009.

[4] L. Thomasson, M. Vaissière, F. Joly, MP. Kluth, S. Taylor, C Elia and R de Gaudenzi "DDSO: the satellite contribution to European government actions for the e-Inclusion of citizens and regions.", Proceedings of the AIAA International Space Communication Systems Conferences, Rome, September 2005. The original system had 72 beams. The current scheme has removed the two beams over the Azores resulting in 70 beams in total.

[5] R. J. Heath, Hughes Electronics Corporation, "System for Providing Satellite Bandwidth on Demand employing uplink frame formatting for smoothing and mitigating jitter and dynamically changing numbers of contention and data channels", US Patent 6,842,437 B1, March 2000.

[6] F. Joly, MP Kluth "Target 2 System Architectural and Design Trade-offs", DDS.DDD.00002.T.ASTR, ESA DDSO Study, Contract No. ESTEC 18194/04/NL/US, February 2005.

[7] P. Gabellini, N. Gatti, G. Gallinaro, G. Vecchi, F. Della Croce, R. Rinaldo and P. Angeletti, "Proposed Architecture of a System and Payload/Antenna Co-Design Tool for Multi-Beam Broadband Satellite Systems", *Proc. ESA Workshop on Advanced Flexible Telecom Payloads*, Noordwijk (The Netherlands), November 2008.

[8] M. Aloisio, P. Angeletti, E. Casini, E. Colzi, S. D'Addio and R. Oliva-Balague, "Accurate Characterization of TWTA Distortion in Multicarrier Operation by means of a Correlation-Based Method", IEEE Trans. on Electron Devices, Vol. 56, No. 5, May 2009, pp. 951÷958.