BEAM HOPPING SYSTEM DESIGN CONSIDERATIONS

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Abstract

The introduction of high throughput satellites (HTS), with multi-spot beams, as well as the emergence of LEO and MEO constellations, provide a significant increase in available satellite communication throughput but brings about new challenges in optimally utilizing the satellite bandwidth, beam and power resources in cases of varying demand between beams, non-uniform traffic patterns during the day (peak hours) and the effect of multiple time zones in traffic load distribution. Current and future satellites introduce flexible techniques, such as flexible power allocation, flexible bandwidth allocation and beam-hopping to cope with those challenges.

Of all those techniques, beam-hopping was shown to provide a level of flexibility that makes it possible to increase served traffic, reduce areas of unmet demand while enabling the reduction of power consumption on-board.

In [17] various issues regarding beam-hopping, from the terminal, payload and eco-system point of view, were addressed. In the paper, we discuss and analyze the system considerations for implementation of beam-hopping in a multi-beam environment and the trade-offs required for different applications. These include the effects of beam switching time, synchronization accuracy, revisit-time constraints, waveform constraints, receiver and payload synchronization.

1. Introduction

The introduction of high throughput satellites (HTS), with multi-spot beams, provides a significant increase in available satellite throughput but brings about new challenges in optimally utilizing the satellite bandwidth, beam and power resources in cases of varying demand between beams, non-uniform traffic patterns during the day (peak hours) and the effect of multiple time zones in traffic load distribution. Current and future satellites introduce flexible techniques, such as flexible power allocation, flexible bandwidth allocation and beam hopping to cope with those challenges.

Together with the HTS, new low earth orbit (LEO) and medium earth orbit (MEO) constellations are being discussed and introduced in the satellite market. For those types of satellites as well, flexibility could be a key feature to enable cost-effective provision of services to areas with variable demand.

In this paper, we concentrate on Beam Hopping (BH). BH as one of the most flexible techniques, is a technique in which the satellite resource- the transmission beam is shared in time among the users. Unlike conventional TDM, transmission takes place within a directional beam pointing at the destination, either as switching the transmission to a given beam within a bank of fixed multi-spot beams, or by means of a fast-steerable antenna. Obviously, several such transmitters can be installed in the satellite.

Beam Hopping was part of early experimental systems, such as the Advanced Technology Communication Satellite (ACTS) program [1]. In [2] and [3], a beam-hopping architecture in the context of the Teledesic Network is presented. The importance of beam hopping is emphasized in this article, saying “In general, the spot beam downlink architecture makes efficient use of the RF spectrum and satellite resources. First, it permits an increase in system capacity by allowing for frequency reuse through spatial isolation between beams. Second, it makes efficient use of satellite power by focusing the radiated RF power only where it is needed. Finally, the use of a number of beams operating over the entire allocated frequency band, which can hop from one cell to another on a per-packet basis, allows for statistical multiplexing of traffic destined to various destinations in the satellite footprint."

[4] Describes architectures for beam hopping payload antenna and analyzes the problem of the beam hopping time planning. Results have shown that a capacity gain of 30% can be achieved with respect to a conventional system. An important conclusion from that article is: "… 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".

[6]-[10] are a some of the publications resulted from a comprehensive study made under the support of the European Space Agency ([11],[12]). [6] compares beam hopping to other flexible payload techniques, such as flexible frequency allocation with and without Multi Port Amplifier (MPA) and flexible TWTA's. Comparison was made in terms of capacity (reduction of unmet capacity and exceeding capacity and increase the usable capacity) and in terms of DC payload power consumption. The analyses and simulations performed were made against varying demand scenarios over Europe in the years 2010-2020. In all scenarios tested, pure beam -hopping showed advantage over conventional and other flexible payload methods. [7] and [8] refer to the same scenarios, albeit with a different algorithm for resource allocation. Those papers conclude that frequency domain and time domain flexibilities are equivalent in terms of performance, and claim that there is a duality both types of flexibilities, and actual implementation depends on cost and complexity.
[9] and [10] are more introductory showing the results of the study stating: "In general, the beam-hopped payload offers more throughput than the other two (Dynamic Bandwidth Allocation and Flexible Power Allocation) and better meets the traffic demand. The flexibility is limited to the maximum capacity a beam can offer. A beam-hopped payload has intrinsically more potential due to the fact that a beam can access the entire bandwidth in both polarizations."

The problem of optimal allocation of resources in a beam-hopping system, including power, bandwidth, allocation time as well as gateway resource is also considered in [18], by decomposing the joint bandwidth and power allocation problem into two independent sub-problems.

In order to get some practical, order-of-magnitude number, [13] can be referred to. [13] is the guideline for implementation of the DVB-S2X standard, including the use of superframes for beam-hopping. The document summarizes the advantage of beam hopping, stating:

- Lower DC power consumption (<50%)
- Capacity increase by +15%
- Reduction of the unmet and excess capacity by 20%
- Better flexibility in allocating capacity to the beams with high traffic demand

Combined with antenna design, [15] shows that using beam hopping an advantage can be achieved by designing narrower spot beams, thus increasing gain and reducing interference between beams.

An interesting use of the flexibility beam-hopping provides is described in [16], where a secondary satellite, cognitive of a primary beam-hopping transmission plan, provides significant additional capacity to a served area with minor deterioration of the primary service.

In addition to those advantages, a beam hopping system presents some technical challenges:

- The terminals are required to receive burst transmissions in the forward link, whereas the current terminals for GEO and LEO satellites are mostly designed for continuous reception (always-on Forward Link)
- The beam hopping introduces additional delay, and in some instances, delay jitter.
- The payload should be capable to switch transmissions to the right beam, and, depending on the payload architecture, be synchronized to the gateways
- The beam-hopping time plan, or, more generally, the resource allocation per beam in terms of time, bandwidth, and power, should be correctly planned as to optimize the utilization of those resources and to provide for the required demand effectively.

Despite those challenges, there is a growing number of BH capable satellites designed to be launched in the near future. [17] looks at beam hopping from the point of view of the whole eco-system. It addresses the technical as well as the non-technical issues that may hinder its adoption in the market, including availability of ground segment equipment, confidence from operators and required standardization to enable a multivendor open market for highly flexible systems.

Beam Hopping is a technique that may apply to a variety of implementations and applications. This paper surveys a number of use cases and presents some design considerations as well as performance that can be expected in those cases.

2. Beam Hopping Systems – Scope of Use Cases

Beam hopping may be applied to a variety of platforms, system architectures, applications, and user types. There are distinctions between:

- Broadcast vs. multi-cast applications
- Continuous vs, packetized data streams
- Fixed vs. mobile users
- High data rate vs. low data rate applications
- Delay tolerant vs. delay sensitive applications

And, regarding the implementation:

- GSO platform vs. LEO/MEO
- Transparent payload ("bent-pipe") vs. regenerative payload
- Multi-beam switching vs. steerable antennas
- Predefined vs. data-driven illumination

Over a GEO satellite, being a large platform with large coverage area, a variety of applications might be carried, typically by different network operators sharing the bandwidth. The large footprint of a beam, would cover many users, which would mean a high degree of multiplexing, both in the frequency and time domain during the dwell time. The relatively long lifetime of a GEO satellite would typically lead to a design based on a transparent payload, to enable independence on future communication standards.
A smaller LEO/MEO satellite with a smaller footprint would typically be operated by a single operator, and provide a low number of beams. The smaller beam area entails a small number of terminals to be served, hence a low degree of multiplexing. Regenerative payload will be typically preferred as the shorter life time of operation allows the use of state-of the art payload, efficient use of uplink and downlink with smaller risk of being prematurely obsolete.

3. Beam Hopping Basic System Considerations and illumination strategies

In this paper, the following terminology is used:

- *Beam*: the directional radio signal transmitted from a satellite
- *Cell*: an area on the ground illuminated by a beam
- *Transmission channel or just Transmitter*: The power amplifier and additional components handling the transmission, and shared among beams
- *Cluster*: A set of beams served by one transmitter
- *Dwell time*: the time duration in which a given transmission channel is allocated to a given beam.
- *Off time*: the time duration in which a given cell is not illuminated
- *Transmission Packet*: The transmission that occurs during the dwell time
- *Beam Hopping Transmission plan*: the absolute transmission times and dwell times allocated for each beam
- *Revisit time*: The maximal time -period in which a terminal is revisited
- *Cycle*: The period of time during which a transmitter covers all the beams within its allocated cluster.

Those terms refer, for the sake of simplicity, to the downlink direction, namely transmissions from the satellite to the Earth stations. In the uplink direction, a similar can be applied, with interchanging the transmitters to receivers.

As beam-hopping is a time domain technique, the timing diagrams can best describe its operation. Figure 1 shows a timing diagram for a transparent payload case. The diagram shows the timing of transmissions from two gateways, each feeding four beams for two cycles. The different colors and patterns indicate to which beam the payload is destined.

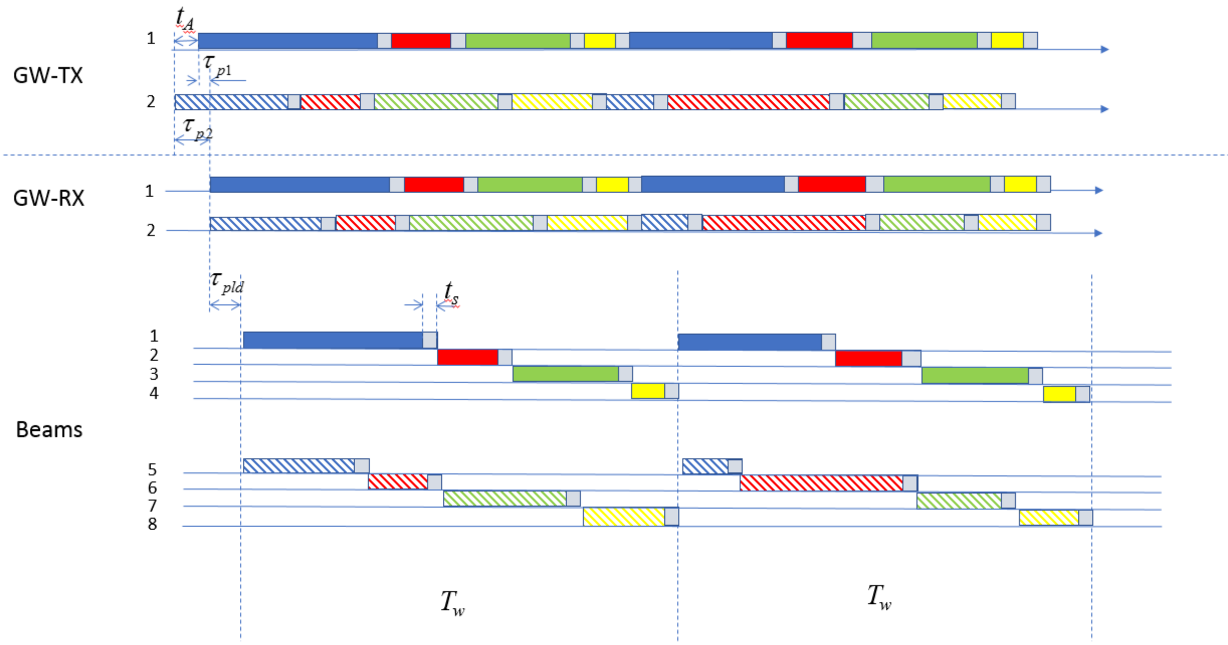


Figure 1: Timing Diagram- Transparent Payload

Gateways transmissions (GW-TX) are to be timed such that they arrive at a known time instant at the payload, taking into account the propagation delay each goes through (τ_{p1}, τ_{p2} in the diagram, drawn extremely out of scale). For that purpose, gateways may be required to apply a time advance (t_A). The payload distributes the transmissions to the different beams, after some inherent delay τ_{pld}. Time should be allocated in the payload for the switching of the transmitters to the beams, or for the antennas to settle in the relevant direction. This time, denoted t_s in Fig.1 is to be allocated at every beam hop. t_s also includes the uncertainly in synchronization between the gateways and payload, measured at the payload.

The switching time is one of the more important parameters in determining the system efficiency and it directly affects the mode of operation. The penalty in system efficiency due to beam-hopping can be expressed as a factor (<1) by which the system effective data rate should be multiplied by. If we further denote by $\bar{t}_{dw}$ the average dwell time, the efficiency factor of a beam- hopping system can be expressed as:

$$\eta_{BH} = 1 - \frac{t_s}{\bar{t}_{dw}} \quad (1)$$

Another important parameter is the time it takes a transmitter to illuminate all the beams allocated to it. This time, denoted T_w in the figure, is the beam-hopping cycle, and it is the upper bound for the revisit time- the maximal time duration for a terminal in any beam to be revisited. This time is a result of various constraints in the system including:

- Terminal stability and ability for re-acquisition after a period of no- reception.
- Worst case latency allowed for a message to arrive to destination.

Each transmitter performs a cycle of transmissions to the beams it covers per each T_w cycle, where the illumination time per beam is determined by the known statistics of the demand in each.
In this case, in which the illumination is periodic, $\bar{t}_{dw} = N_{cl} t_s / T_W$, N_{cl} is the number of cells in a cluster.

In addition, one may also observe that the upper bound, η_{BH}^{UP} , and the lower bound, η_{BH}^{LB} , on the efficiency would be:

$$\eta_{BH}^{UB} = 1 - \frac{t_s}{T_W},\ \eta_{BH}^{LB} = 1 - \frac{t_s}{T_{\min}} \quad (2)$$

where $T_{\min}$ is the minimal dwell time.

Another source of inefficiency might be the case where the instantaneous traffic is not enough to fill up the transmission packet for the entire dwell time. As incoming traffic is statistical in nature, margins must be taken to reduce overflows (which may cause extended latencies) so statistically empty room is unavoidable. Exact analysis of this case highly depends on the application and traffic model.

In addition to system efficiency, another important parameter to be considered is the overall latency, a data packet undergoes to. Obviously, in any data communications network, packets incur delays resulting from propagation delays, queuing and buffering, and a satellite beam-hopping communication system is no exception. However, the beam-hopping technique gives rise to further delays.

The total latency budget of a packet arriving at a gateway is expressed in

$$\tau_{delay} = \tau_{Bg} + \tau_{wg} + \tau_{pgs} + \tau_{pld} + \tau_{Ag} + \tau_{Bs} + \tau_{pst} \quad (3)$$

- τ_{delay} is the total delay
- τ_{Bg} is the buffering delay in the gateway needed to accumulate the data to fill out the transmission packet.
- τ_{wg} is the waiting time from the point the transmission packet is ready till transmission. In a worst-case scenario, this value may reach the cycle time (or even beyond that, in case of traffic surges)
- τ_{pgs} is the propagation delay between the gateway and the satellite
- τ_{pld} is the inherent delay in the payload, mentioned above.
- τ_{Ag} is the time needed to align the downlink transmissions to transmissions from other gateways. (typically compensated for by advancing the gateway transmission time)
- τ_{Bs} is further buffering that might be needed aboard the satellite, might be relevant for regenerative payloads.
- τ_{pst} is the propagation delay between the satellite and the terminal.

The scheme presented in Fig. 1 is basically pre-defined according to prior information on the expected load. It is not necessarily the only possible strategy in the design of the beam-hopping illumination plan. Other strategies determine the hopping plan according to the data arrival time, thus avoiding mismatch between the actual demand distribution and the BHTP. The most extreme example would be a “point-and-shoot” approach where each packet is routed directly to its destination cell on a first comes - first served basis., thus avoiding buffering delays. On the other hand, each transmission would be tolled by an additional switching time and if data packets are small, it might substantially reduce the total efficiency.

Figure 2 shows an example for the timing diagram of an illumination strategy, based on fixed transmission time intervals. In this strategy the packets for each cell are queued. At constant instants, beams are transmitted to the cells with the longest queues, or, to cells for which the revisit time constraint has expired. Figure 2 shows an example for one beam serving 4 cells, arranged per their load.

Another possible strategy would call for a constant transmission packet size (in bits, or in symbols). As above, packets for each cell are queued and once the set transmission packet size is met, the packet is routed for transmission, again with re-visit time constraints. Variants of this scheme might be to set different transmission packet size for each beam, according to the demand in that beam. In this case, the dwell time matches the demand data rate, similarly to the periodic predefined structure described in Fig. 1.

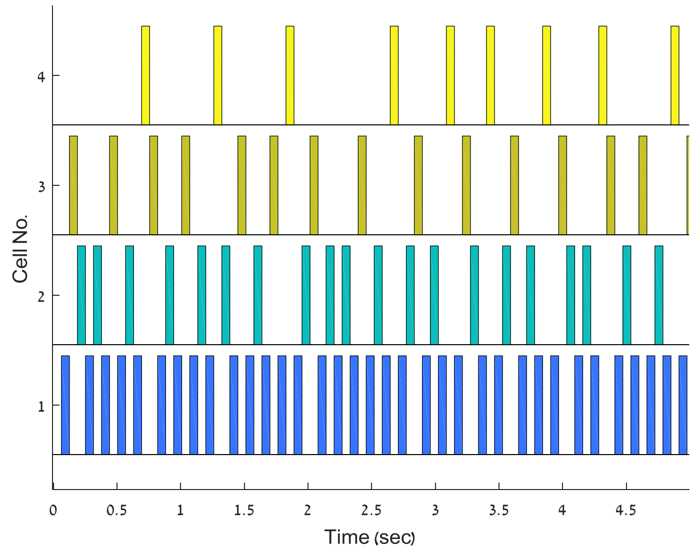


Figure 2: Beam Illumination Timing Diagram- Point and Shoot

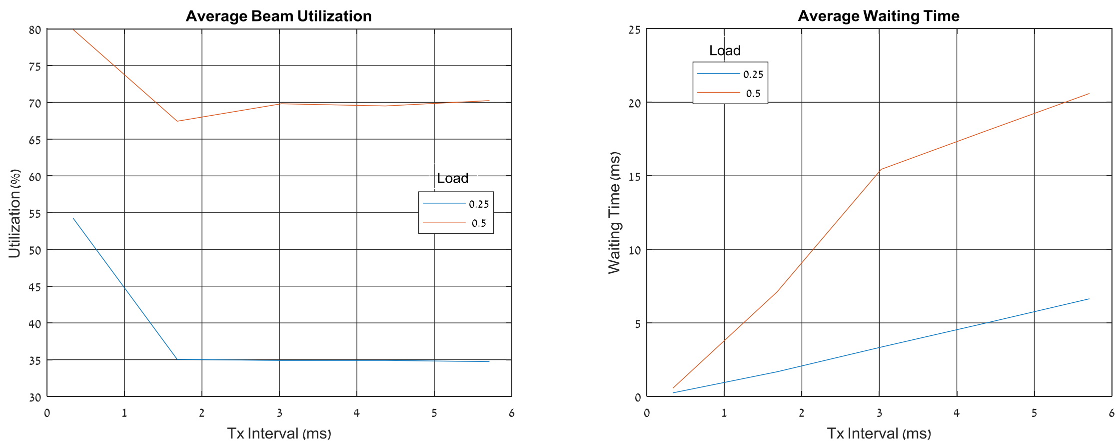
If the cycle and dwell times are selected optimally, the performance, in terms of efficiency and latency, of both method would be similar. However, they differ from implementation point of view. While in the first scheme transmissions are made according to a predefined scheme, in the second case transmissions depend on the arriving traffic. The periodic scheme would be preferable for the case of a transparent payload. In this case the gateways and payload should maintain an acceptable level of synchronization, and exchange beam-hopping timing plan information when necessary. In the data driven approaches are to be implemented over a transparent payload, each transmission should be tagged with the routing information, to be decoded at the payload, for the relevant beam. The periodic scheme has an advantage from the point of view of the terminal, which can be switched off at predictable times. The data driven strategy would be more adequate for a regenerative payload, where the routing decision is made on-board, thus saving on buffering time.

3.1 Fixed Transmission Time Strategy- Latency and Beam Utilization

To learn the effect of transmission interval size as a function of data rate on the resulting latency and beam utilization a simulation was performed with the following parameters:

- 10 cells, 4 Beams, 100 users
- Users are distributed exponentially among cells
- BW= 100 MHz
- SNR per user (in dB) is randomly selected from a Gaussian distribution $\sim N(10,3)$ dB
- Spectral efficiency per user- as per Shannon's formula (with 2dB penalty)
- Load: 0.25 and 0.5 of Total Capacity
- Demand data rate per user, randomly selected from a truncated Gaussian distribution, with average bit rate commensurate with the mean SNR. Simulations were run with data rate equal to 0.25 and to 0.5 of the SNR
- Packet arrival rate: randomly selected from a Gaussian distribution $\sim N(20,10)$ packets/sec, correlated with the data rate per use (with correlation factor of 0.8). The arrival process per user is Poisson, with the random arrival rate.
- Revisit time: 30 msec

The resulting beam utilization and average waiting time for each data rate case, as a function of the transmission interval size are given in Figure 3 (a) and (b) respectively:



(a) Beam Utilization (b) Average Waiting Time

Figure 3: Constant Transmission Interval- Performance

Clearly, the lower the transmission interval, the better is the beam utilization and the lower is the waiting time. However, the result does not reflect switching time effect, which causes a reduction of efficiency as the interval gets lower. Notably, beam utilization gets flat above approximately 2msec, which is the point where most of the arrival data packets are smaller than transmission packet interval. The waiting time grows linearly with the interval time for low load scenario. When the load is higher the slope of the decrease is higher.

4. Beam Hopping Adaptation to Demand

One of the key advantages of beam-hopping is its ability to adapt the resource allocation to the demand. To evaluate the advantages of BH in varying demand conditions and scenarios.

4.1 Broadband Service, Continental Coverage

In this case we refer to [6], which presents the results of analysis of a HTS Beam-Hopping system, performed over several demand distributions over Europe, and compare the results to other distributions and scenarios.

The demand density can be presented by the demand within each cell, where the cells partition the coverage area. Examples for such distributions are given in Fig.4, which shows the total distribution of capacity in each cell, as taken from [6] (expected demand at 2020), and, in addition, an artificial distribution, using similar parameters, but distributed according to the US population distribution, taken from open sources. The cells are sorted according to the demand. For the artificial US distribution, we used the same cell size and capacity as the one used in the study, and extended the number of cells.

The horizontal line in Figure 4 describes the case of a conventional system offering the same level of service, in terms of offered capacity to every cell. Four regions can be distinguished in this graph:

- The “Usable” region, describing the actual traffic served
- The “Exceeding” region, where the offered traffic is above the demand
- The “Unmet” region where the demand exceeds the offered traffic.

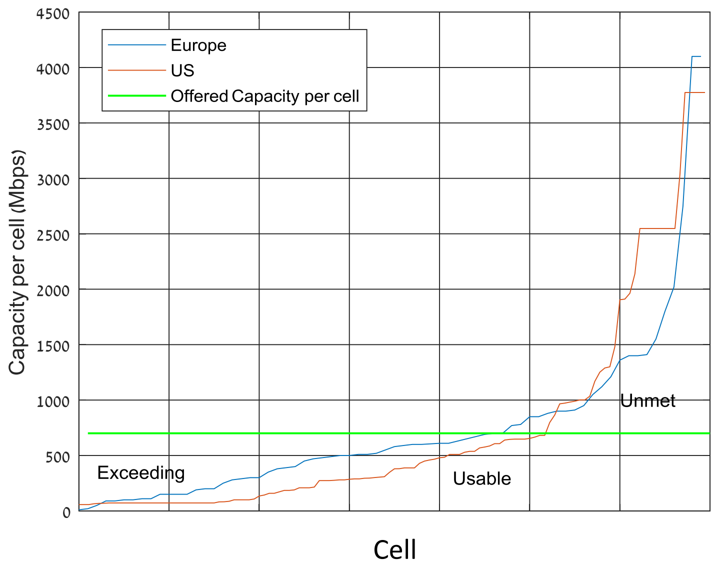


Figure 4: Demand Distribution

We can also define the “Offered Traffic” as the total area under the horizontal line. A flexible system would be able to shift the allocated resources from the “Exceeding” region, into the “Unmet” region. The quality of the system depends on the maximal offered traffic available to a cell, and the granularity in the demand allocation it has.

To see the capability of a system based on frequency domain sharing, consider a multi-beam satellite, where the available spectrum, W, is shared among a cluster of N_{cl} cells, and assume that the minimal bandwidth that can be allocated to a beam is W_{min}. Thus, assuming that all cells in a cluster are to be illuminated, the maximal bandwidth that can be allocated to a cell is:

$$W_{\max} = W - \left(N_{cl} - 1\right) W_{\min} \tag{4}$$

In this paper, we will not elaborate on the actual implementation issues of sharing in the frequency domain, however it should be noted that implementation limits the achievable ratio between the minimal and maximal bandwidth. So, the adaptation is limited. Another aspect of frequency domain sharing is the frequency planning aspect, in systems where the total number of beams is larger than the cluster size- a typical case for HTS and VHTS satellites. In this case the designer is faced with a frequency planning problem, with non-uniform frequency allocation.

Similarly, for a periodic beam-hopping system, using a cycle time of T_W a minimal dwell time per cell of $T_{\min}$ and a cluster of N_{cl} cells, the maximal dwell time that can be allocated to a beam would be:

$$T_{\max} = T_w - \left(N_{cl} - 1\right) T_{\min} \tag{5}$$

Figure 5 below shows the capacity per cell, against the demand per cell for the demand distributions shown above in Fig. 4 (albeit with the number of cells extended to 120 in the US case), and two types of flexible systems- bandwidth flexibility and beam- hopping.

For the bandwidth flexible system, the following parameters (taken essentially from [6]) were used:

- 2 channel of bandwidth 250MHz (a reuse factor of 4 color scheme, 2 frequency channels, 2 polarizations)
- Minimal Bandwidth – 62.5 MHz
- Cluster size= 4
- Average offered capacity per cell: 585 Mbps

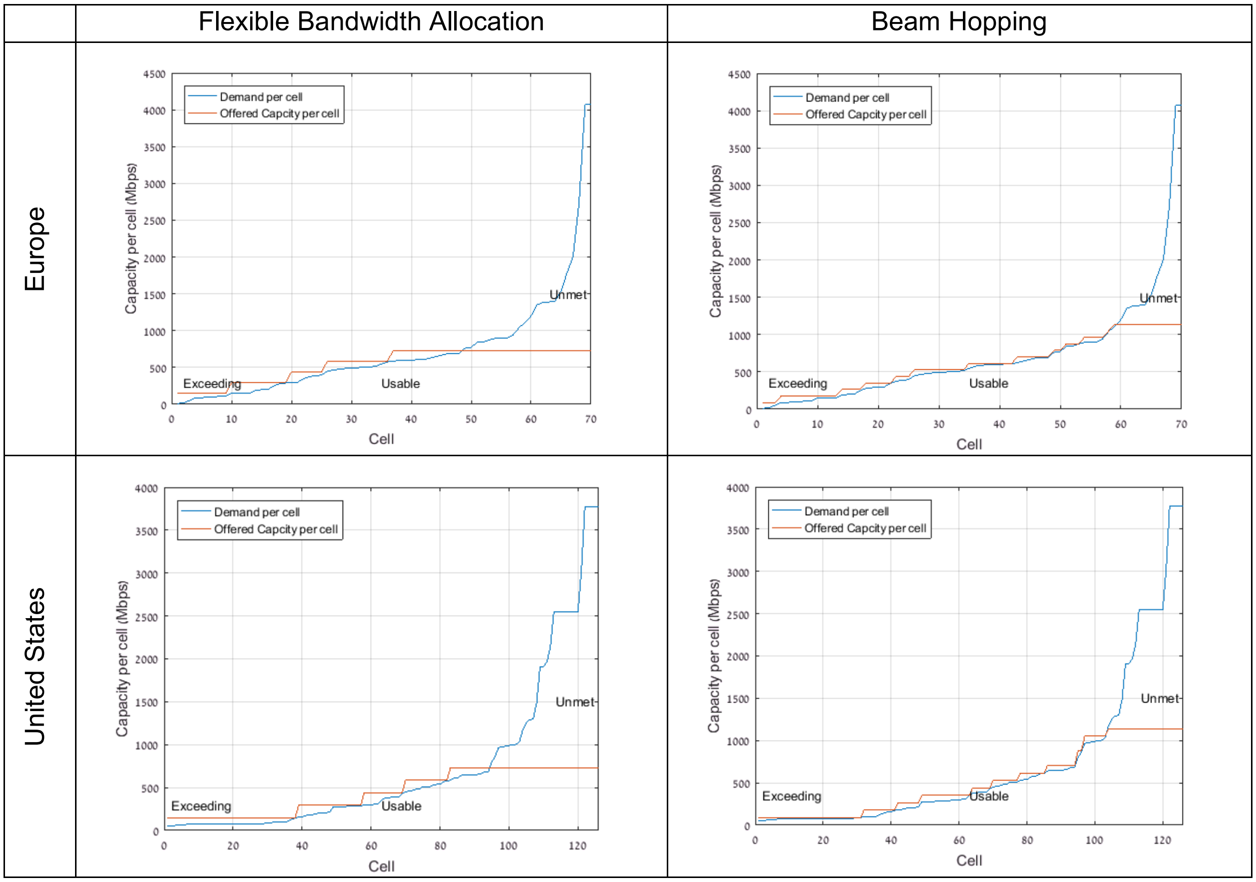


Figure 5: Demand distribution vs. Offered Capacity in Flexible Systems

For the beam-hopping system we used:

- A single channel of 500MHz bandwidth
- Cluster size = 4
- A ratio of $T_w/T_{\min} = 16$

Using a single channel in the BH system, a lower Back-off can be taken for the power amplifier. Additionally, the beam hopping operation allows for lower interference and thanks to wider channel statistical multiplexing can be readily used. As a result, 20% increase in available capacity per cell can be safely assumed.

Table 1 below shows the total offered capacity, usable capacity, unmet capacity and exceeding capacity for the two methods and two distribution scenarios. Aside of the calculated values in Gbps, the percentage difference, relative to a conventional system is presented. The advantage of flexibility is very significant, and that of beam-hopping is even more so.

The two distributions shown are similar but there are some differences that merit noting:

1. The population distribution in the US is characterized by several large metropolitan centers with very high capacity demand, many medium sized cities, which still pose a large demand. Together, these facts result in a “fat” high demand region within the distribution, compared to the case in Europe.
2. The “tail” of the distribution, with low traffic demand, in the case of the US, falls more rapidly that of Europe, indicating large sparsely populated areas.

Table 1: Comparison of Flexible Systems

		Offered		Usable		Unmet		Exceeding	
Distribution	**Method**	Gbps	%	Gbps	%	Gbps	%	Gbps	%
Europe	Conventional	40.9	0	30.1	0	20.6	0	10.7	0
	Freq. Flex	38.1	-6.8	33.9	12.6	16.8	-18.5	4.1	-61.3
	BH	42.7	4.6	39.3	33.7	11.4	-49.4	3.5	-77.3
US	Conventional	73.5	0	43.9	0	47.3	0	29.6	0
	Freq. Flex	56.0	-23.8	49.3	12.2	42.0	-11.4	6.7	-77.2
	BH	64.9	-11.8	60.7	38.3	30.5	-35.5	4.1	-86.0

As a result, the improvement achieved by BH in the US, compared to the conventional system and the flexible system, is more impressive in reducing the “Exceeding” capacity relative to the improvement observed for the Europe distribution. On the other hand, the reduction of the “Unmet Capacity” is lower. However, it should be noted that the large and medium metropolitan areas are most likely to be served by terrestrial communication systems, thus the available market in those area for satellite communication is much lower.

4.2 Aeronautical Service- In Flight Communication

In Flight Communication (IFC) service, providing internet access to airliners via satellite is one of the main services that can benefit from beam hopping. Using a flight tracking application, a snap shot of airliners traffic over the north Atlantic corridor between the UK and Maine/ Quebec, is given in Fig. 6, together with a layout of 24 cells of a satellite system covering the area. This snap shot, together with snapshots taken at other time instants show a large variability in the number of planes in each beam as a function of time of day and beam location. Figure 7 shows a bar diagram of the number of planes per beam in the northern beams (numbered west to east from 1 to 12) and southern beams (numbered 13 to 24, west to east), in AM times and PM times taken at 7 time instants- 0:00, 01:00, 02:00, 03:00, 12:00, 14:00 and 15:00 UTC.

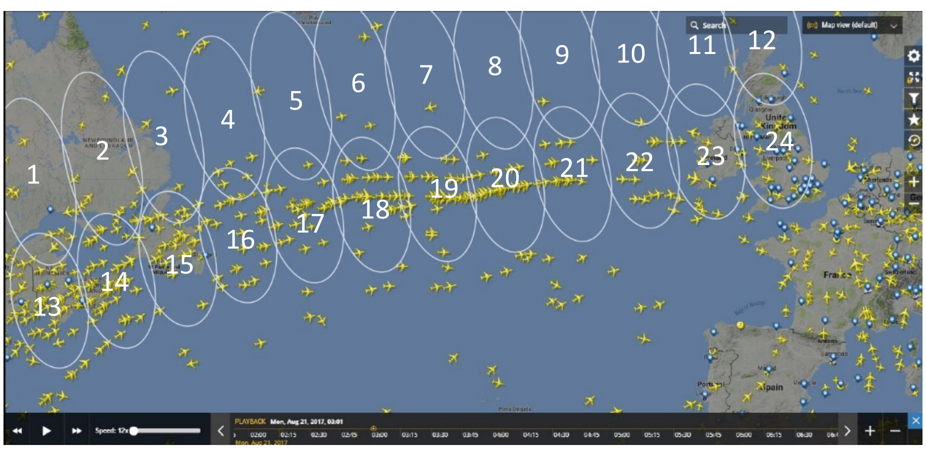


Figure 6: Snap shot- Airliners Traffic Over the Atlantic

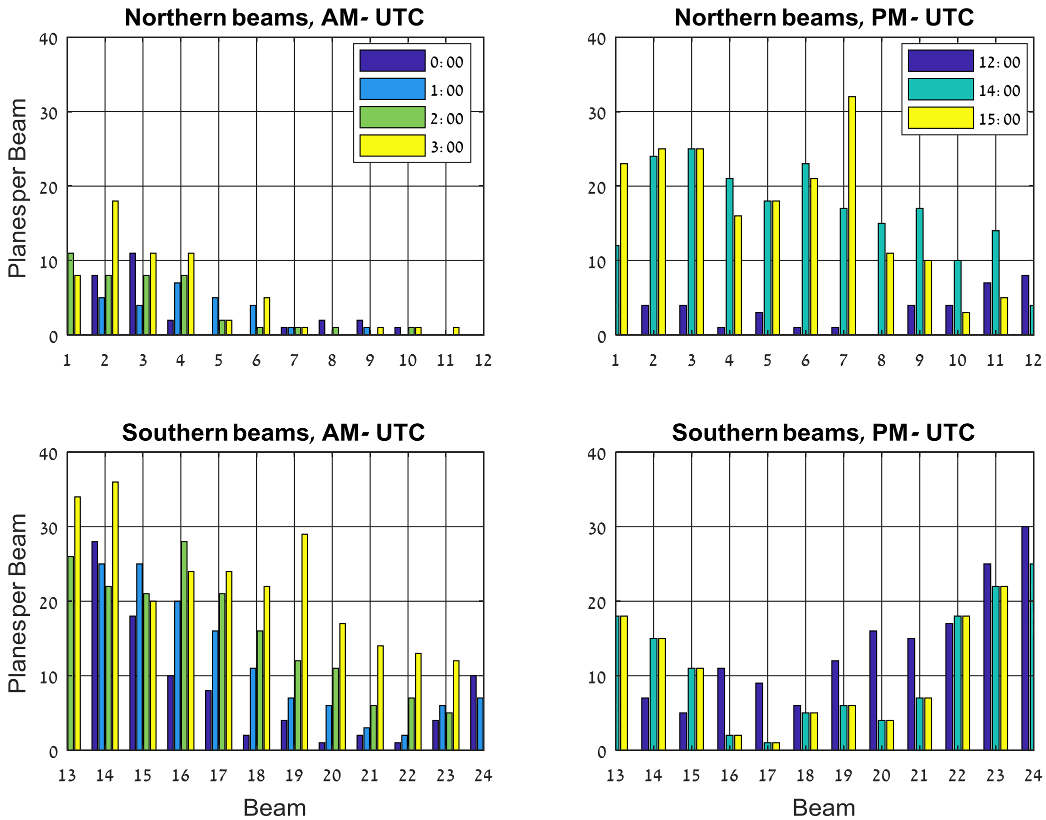


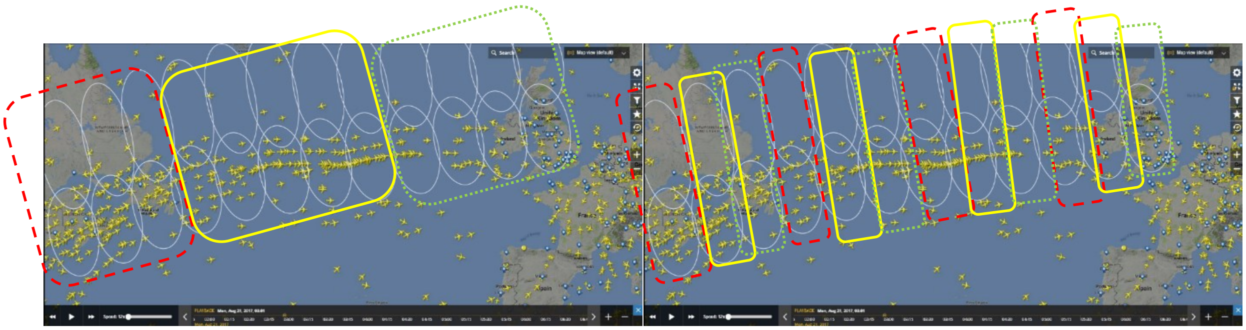
Figure 7: Number of Airplanes in Beams. 7 Time instants

If we take those examples as representative of the load and distribution in this route, we can learn about the advantages of beam-hopping. Assuming full coverage, a conventional system would be designed to cover the maximal number of planes per each beam over the entire day, in this case 535 planes, while a BH system would need to cover the maximal number of planes simultaneously in the air at each instant. In this case this number amounts to 334. Thus, in terms of offered capacity, a beam hopping system would be designed for 38% less capacity than a conventional system. A beam-hopping system can also adapt itself very well to the varying scenario, enjoying the predictability of flight patterns. As an airplane crosses a beam in about 30 minutes, the beam hopping time plan can be updated every 15 minutes, in order to optimally adapt it to the instantaneous traffic pattern frequently enough.

Let us study a practical scenario to assess the limitations. Assume the following:

- Required capacity per airplane: 25Mbps
- Number of airplanes served: a quarter of overall airplane traffic
- Available bandwidth: 500MHz, 2 Polarizations.
- Spectral efficiency per beam: 2bps/Hz.
- Revisit time constraint: 30msec

In this case the required capacity to be offered by the system would be 25 Mbps * 334/4= 2.1 Gbps. Since each channel provides 500 MHz * 2 bps/MHz = 1Gbps, we need at least 3 transmission channels to provide full coverage.



(a) (b)

Figure 8: Beam to Cluster Allocation methods (a) adjacent allocation, (b) non-adjacent

In order to avoid interference, a good practice would be to allocate a cluster of beams covered by each transmitter to adjacent cells, while adjacent clusters would use orthogonal polarization. From the point of view of load, it is better to allocate distant cells to a cluster as it is expected that this would balance the traffic. Figure 8 depicts two example allocations where cells of the same cluster are surrounded by an ellipsoid of the same color and pattern. Fig. 8(a) shows adjacent cells allocation, while Fig. 8(b) shows non-adjacent allocation. Note that in the allocation in Fig. 8(a) the number of cells served by each transmitter is different, to balance the load.

In both cases, assuming adjacent clusters use orthogonal polarizations, the adjacent cell interference is limited, so independent hopping plans can be used for each cluster.

The beam hopping time plan would vary in time and among transmitters. Using the allocation of Figure 8 (a), one can summarize the different plan parameters for each transmitter, in each of the time instants as in Table 2:

Table 2: Cluster Size and Load Ratios at different time Instants

	ToD:	0:00	1:00	2:00	3:00	12:00	14:00	15:00
Tx 1	N_{cl}	6	6	6	6	6	6	6
	Ratio	9:1	6:1	7:2	9:2	2:1	6:3	6:3
	Load (Gbps)	0.675	0.575	0.625	0.825	0.175	0.675	0.75
Tx 2	N_{cl}	6	8	7	8	6	9	9
	Ratio	3:1	5:1	7:1	7:1	4:1	6:1	8:1
	Load (Gbps)	0.225	0.5	0.625	0.85	0.375	0.725	0.75
Tx 3	N_{cl}	4	4	4	5	8	8	8
	Ratio	3:1	2:1	2:1	4:1	8:1	6:1	6:1
	Load (Gbps)	0.15	0.15	0.15	0.35	0.70	0.775	0.625

The table helps us determine the trade-off between the cycle time, T_w, and the minimal dwell time, T_{min}. Figure 9 below depicts the beam hopping time plan for each of the three transmitters, at 3 of the time instants indicated above. The plan was made for a DVB-S2X waveform using the superframe structure, with roll-off of 20%, yielding a superframe time of 1.53ms. As none of the beams carry a load higher than 1Gbps, which can be provided by each transmitter, it is not necessary to fill up the entire cycle time, which was set here to be equal to the revisit time. The spare time can be traded off by, for example, a lower cycle time to reduce latencies, lower transmission power for non-active beams, just turn off the transmitter, or a combination of those measures.

It should be noted, however, that if a revisit time of 20msec would have been required, it would not be possible to use the granularity of 1.53ms imposed by the superframe waveform, and keep the revisit time window without trading off some capacity.

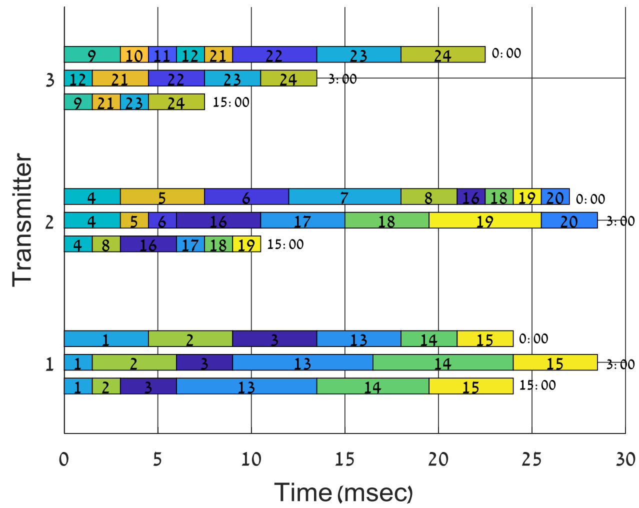


Figure 9: Beam Hopping Time Plans for 3 transmitters at 3 points in time.

Summary and Conclusion

Beam Hopping is a technique which was considered for multi-beam satellite systems, such as HTS GEO Satellites, as well as for LEO and MEO constellations, for quite a long time, and is considered for implementation in many satellites in the very near future. The advantages of this technique in the flexibility it provides, which makes it possible to optimally balance the load at the satellite and enable cost-effective payload design, thus reducing the total life-cycle cost of the system as well as the cost of usage.

There is a large variety of types and flavors for beam-hopping systems, depending on the platform, payload types and application. In this paper, we introduced the principles of beam-hopping, in terms of the basic timing, efficiency and latency constraints and presented two quite different approaches periodic time plane and "point-and-shoot" strategies, which can achieve, in average, similar performance in terms of efficiency and latency, but are quite different in terms of implementation.

We also looked at some deployment scenario and the effects that varying demand distributions might have over the effectiveness of operation of beam-hopping in comparison to conventional and adaptable bandwidth systems. For the continental coverage case, following [6], we showed the difference in terms of capacity (useful, exceeding and unmet) the advantage of beam hopping over a frequency flexible system, in different demand distributions. We also introduce a test case for IFC deployment showing different beam allocation strategies and an example for beam hopping time plan design. The flexibility given by beam-hopping in this scenario cannot be matched by any other technique.

Beam-hopping is very advantageous for the new age of satellite communications, however, in order to achieve the advantages, a total eco-system supporting it should be in place, including ground equipment and standardization.

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