LEO CONSTELLATION FOR BROADBAND APPLICATIONS
SYSTEM DESIGN CONSIDERATIONS

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Abstract

The evolution of high throughput satellites (HTS), towards smaller beams (VHTS) sets a reference criterion in space segment cost per Mbps. New LEO constellations are being designed to address the delay associated with GEO satellite systems as well as reducing the cost per Mbps.

While a LEO satellites constellation has a much lower inherent delay, it requires the user terminals to track the satellites and be capable of handover between satellites without loss of data. These requirements impose a higher price tag on the user terminals (compared to fixed GEO user terminals) which must be compensated by a much lower space segment cost per Mbps.

In this paper, we will present the system design considerations of a LEO satellite constellation targeting broadband applications.

1. Introduction

Over the last decade, as broadband terrestrial and mobile networks services pricing have gone down considerably, the satellite industry had to adapt to be able to survive the new challenging market conditions. The evolution was achieved by decreasing the size of the user beams and introducing a 'cellular' like coverage on the ground. This approach increased the total capacity per Watt per beam, as the beam gain increases. In addition to the improvement in the link budget, the cellular coverage supports a significant increase in total capacity achieved by frequency reuse over the cluster of beams.

Traditional GEO satellite spot beams cover thousands of Kilometers on the ground with a beam width on the order of several degrees. The nature of this coverage has its roots in Broadcast Television service where all the users living in the same territory receive the same data. Broadband services are not shared, by nature, and the main criteria for a successful service is the price per Mbps.

The first HTS systems utilized beams size of ~0.8º. As pricing of competing broadband services continue to decline, the beams size continues to be reduced, going down to ~0.25º, as demonstrated in Figure 1. This trend represents an order of magnitude cost reduction per Mbps over a decade.

Figure 1- From spot to HTS (0.8º) to VHTS (0.25º)
Beam plots courtesy of Satellite Signals Ltd.,
ref: http://www.satsig.net/satellite/satellite-beam-design.htm

It is worth mentioning that since the cost per Mbps of HTS systems is much lower than traditional Broadcast-MHz cost, there is a need for much more bandwidth which drive the majority of the HTS satellites towards higher frequency bands. So, while the legacy DTH services operate at Ku band frequency, current HTS satellites typically operate at Ka band frequencies. The future evolution seems to be following the same trend and the new frequency bands candidates are Q and V which will probably be used initially by the feeder links.

2. GEO vs. LEO- System Design Guidelines

When we try to compare GEO HTS type of systems with LEO constellations, we should list the benefits and deficiencies of each system. A single GEO satellite covers 1/3 of the earth such that only 3 satellites are sufficient for global coverage (see Figure 2). Each satellite coverage can be tuned to meet the demand on the ground such that most of the space segment resources are utilized. The satellite location is fixed so all fixed terminals and gateways antennas are cost effective. Another benefit of a GEO network of satellites, is that a service could start with a single satellite and it is not a must to have global coverage from day one. The main disadvantages are the high delay associated with the geostationary orbit and the size (mass, power, volume) of each satellite.
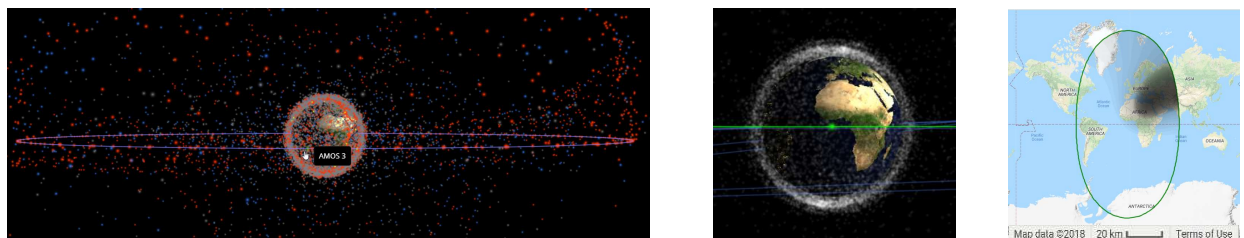

Figure 2- Geostationary satellite field of view [4], [5]

Theoretically, LEO constellations can achieve very high capacity quite cost-effectively, as was shown in [1]. A LEO constellation has the benefit of being much closer to the surface of the earth and hence the considerable smaller delay. Figure 3 shows examples of LEO constellations. The closer distance to the earth also enables a reduction in size of antennas and power amplifiers and has a potential to reduce cost per Mbps. However, these benefits come with a price: many satellites are required to be able to support any type of real time service. Another downside of LEO systems is that there is a large area that the satellites cover where the demand hardly exists. A LEO constellation requires tracking antennas on the ground capable of performing handover between satellites in real-time.
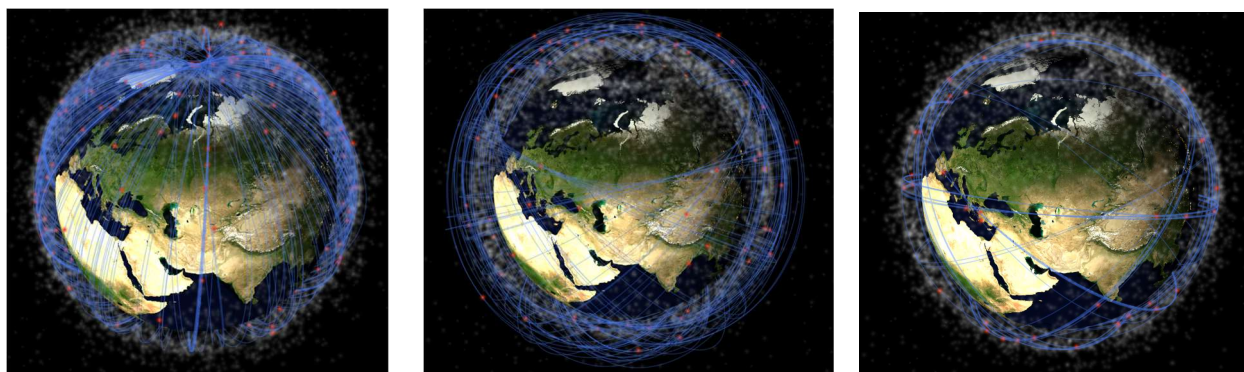

Figure 3- LEO constellations- Iridium (Left), Globalstar(Middle) and Orbcomm (Right) [4]
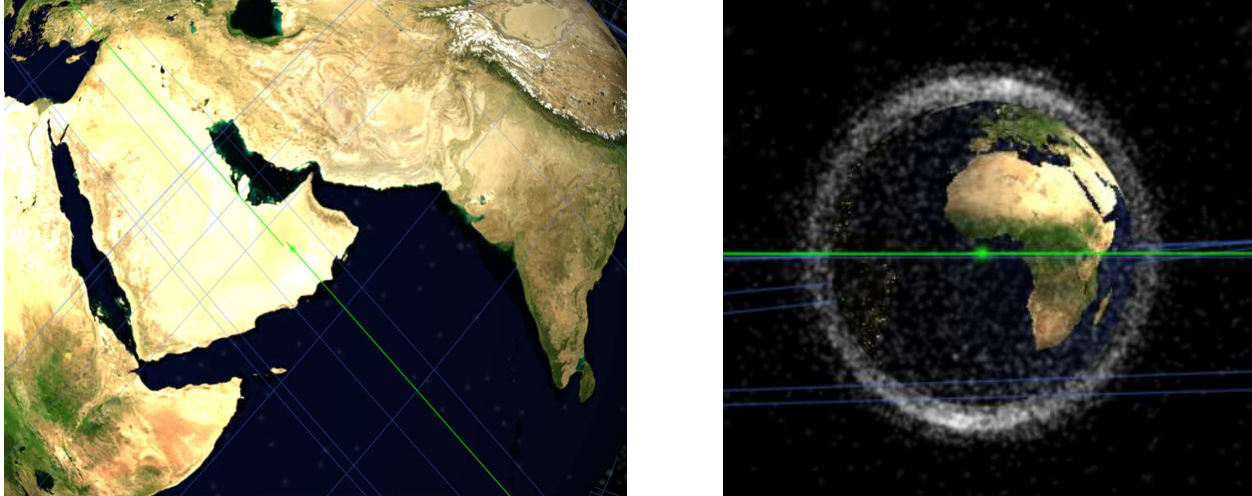
Figure 4- LEO FOV vs GEO FOV [4]

A typical commercial user terminal of a GEO HTS broadband service cost a few hundreds of dollars while an equivalent performance LEO user terminal will cost in the thousands. This fact implies that while GEOs will target more of the consumer type of customers, the LEOs will target the non-consumers that require higher quality of service in terms of delay, average and minimum committed data rates. The cost of these services over a LEO constellation must be considerably lower than the GEO alternative, to cover for the much higher CAPEX.

The most advanced HTS satellites as of today achieve a space segment cost of ~$1M/Gbps. This cost translates to a price per Mbps (w/o contention) for the end user well below $50 a month. Even if we assume that the LEO constellation will be able to support an order of magnitude more aggressive pricing for the capacity, it seems that to recover the CAPEX, the minimum data rate service will have to be on the order of 5-10Mbps uncontended.

3. Optimal Design for Initial LEO Constellation Deployment

To design a cost-effective LEO constellation, we should first define a set of requirements that will drive the design (different assumptions might lead to a different design). The initial design exercise will be based on polar orbits although it is probably wiser to use inclined orbits or a mixture of polar and inclined orbits to better fit the demand on the ground.

Requirements:

- Space segment cost per Mbps 10% of that of GEO HTS
- Minimum number of satellites.
- Minimum 30º elevation for a user terminal.
- Total capacity of ~3Tbps (equivalent to 3x GEO HTS)
- Orbital Altitude ~1000Km

The design exercise that will be presented in this paper will focus on optimizing the transmitted power efficiency in terms of Watts/Mbps. The power requirement of a spacecraft is a good metric associated with overall cost. The optimization process will be performed on the downlink user beam only as this is the most cost sensitive link.

It is known that power efficient modulations require low Es/No, however they are not bandwidth efficient.

The goal of the design exercise it to analyze whether a LEO constellation can be designed to meet the above requirements with as much as possible power efficient modulation schemes to support low cost service entry. These modulations correspond to Es/No values in the range of: -2.5:1.5dB. If DVB-S2/S2X waveforms [2] are used the spectral efficiencies are between 0.5-1.2bps/Hz.

To meet the minimum number of satellites and minimum elevation angles requirements, it can be shown that 11 planes of 18 satellites evenly spaced at 1000Km altitude achieve the requirements. The constellation Walker notation: ~90: 198/11/5.5 (198 satellites, 11 planes, relative spacing between satellites in adjacent planes 5.5x360/198=10 degrees). See Annex I.

For a GEO satellite with 5m antennas on board and 1000 beams, to achieve 1TBps of total capacity means ~1Gbps per beam. Assuming single carrier operation per PA and beams of 500MHz (~416Msps), the forward link budget should be designed for 2b/Hz of spectral efficiency. This spectral efficiency is achieved at 7-8dB of Es/No. If 1dB of margin is required and the average EIRP over the beam is 2dB lower than the peak, we require an Es/No at peak of ~10-11dB. This requires a radiating power per carrier (beam) of 2W. While TWTAs have an efficiency on the order of 50-60%, GaN SSPAs are probably closer to 25%. So, for 2W of SSPA power, we get ~8Wx1000x1.5≈12KW of payload power (the 1.5 factor is considering the additional power required for the return links). The link budget is summarized in Table 1.

Parameter	Value$_{for65cm}$
EIRPs[dBW]	61
[1]Output Back-off[dB]	0.5
Receive antenna G/T [dB/ºK]	17.5
Downlink path loss$_{@19.7GHz}$ [dB]	209.4
[2]Symbol rate [Mbps]	416.67
Es/No [dB]	11

Table 1- Geostationary satellite forward downlink budget (clear-sky @ beam peak)

(1) A GEO system can be designed to operate in a single carrier per PA with ~0.5 of output back-off. For LEO with multibeam-multicarrier, an output back-off of at least ~2.5dB must be maintained.
(2) The symbol rate considers 1.2 roll-off. The average bit rate is ~460Mbps.

This operating point corresponds to ~2.5b/Hz at beam peak and ~2b/Hz averaged over the beam.

It is important to note that this is not the most efficient power/bit operating point. Operating closer to 0dB Es/No would require ~40-50% of the power per bit, however the overall capacity would drop to ~40% of the one achieved at Es/No of ~10dB. So, instead of ~832Mbps per forward user beam at 12KW of payload power, we could get ~330Mbps and a payload power of ~2.0KW. So, while the high capacity design requires ~14mW/Mbps of forward traffic, the more power efficient design requires ~6mW/Mbps.

It seems that for a GEO satellite with 5m antennas, the size and mass are big enough such that the power savings are probably not worth it.

For a LEO constellation with altitude of 1000Km and minimum Elevation of 30º, the free space loss has a variation of 4.6dB from satellite rise to 90º elevation (average ~-1.4dB with respect to 90º elevation). In addition to the propagation loss variation, we should consider more than 10dB of fade margin required to keep the demodulator locked on the signal (~11dB for New York at 30º elevation, 19.70GHz availability of 99.5%), 2dB for user terminal G/T degradation at minimum elevation, 2dB for satellite scan loss and 1dB of margin.

Adding the figures, we would need ~20.6dB of dynamic range above the threshold of the minimum MODCOD. So, if we take the lowest VLSNR MODCOD threshold of -9.9dB, we get 10.7dB of Es/No for maximum elevation at clear-sky conditions and 2.1dB at minimum elevation at beam peak. Assuming 2dB of beam peak to average ratio, 1.4dB for average free space loss with respect to max elevation and 2dB for antennas scan loss, we get an average of 1.33bits/symbol for clear-sky capacity calculations.

A satellite EIRPs of ~36dBW is required to achieve Es/No of 10.7dB for 35cm user antenna at beam peak as shown in Table 2.

Parameter	Value$_{for35cm}$	Value$_{for60cm}$
EIRPs[dBW]	36	31.3
[1]Output Back-off[dB]	2.5	2.5
Receive antenna G/T [dB/ºK]	13.2	17.9
Downlink path loss$_{@19.7GHz}$ [dB]	178.33	178.33
[2]Symbol rate [Mbps]	416.67	416.67
Es/No [dB]	10.7	10.7

Table 2- LEO satellite forward downlink budget (clear-sky @ beam peak)

To compare GEO to LEO, we will assume a 60cm antenna for the user terminal and 500MHz carrier. The required EIRPs is 31.3dBW.
The antenna gain on the satellite must be 30dBi to achieve the same power efficiency (14mW/Mbps) as an SSPA based GEO system.

To achieve an order of magnitude improvement of payload power to bit efficiency the required antennas on the satellite would need to have a transmit gain of ~40dBi while the minimal EIRPs per active 500MHz should be ~31-36dBWi.
For Example: 3200 elements antenna with 0.42mW per element can support 10 simultaneous beams of 500MHz each. The total payload power associate with a single antenna would be ~3200x0.42mW/0.25x1.5=8.1W for a total bit rate of ~5.54Gbps (<1.5mW/Mbps).

Parameter	Base	Wideband	Multi Antenna
# of antennas on board	1	1	2
# of simultaneous beam per antenna	10	10	10
Bandwidth per beam [MHz]	500	1800	500
Payload transmit power [W]	8	29	16
Capacity per satellite [Gbps]	5.5	20	11
Constellation capacity [Tbps]	1.1	3.9	2.1

Table 3- Capacity & Power for different LEO Constellation Configurations

As can be seen in Table 3, a payload power of 30W per satellite is sufficient to achieve a total constellation capacity >3Tbps with a single antenna per satellite.
Further optimization can be achieved by assigning a combination of 500MHz, 1000MHz, 1800MHz channels dynamically, where the 500MHz channels should be allocated for the cells operating at lower elevations and the 1800MHz channel for the cells close to maximum elevation.

4. Simplified Comparison GEO-LEO

In the previous section, we tried to design the most power efficient LEO system under certain constraints and requirements. In this section a more simplified macro view will be used to demonstrate the main differences between LEO and GEO systems which will lead to some design guidelines for a LEO system.
While a GEO system under clear-sky conditions operates at a stable signal to noise ratio received by the terminal, a LEO system suffers from a variable reception level due to difference in distance to the satellite and the variation in the gain of the satellite and terminal antennas while scanning.
For a constellation with 1000Km altitude and minimum elevation of 30º, the clear-sky conditions reception level may vary ~10dB. This variation requires 10dB more margin than a GEO system and as a result, a LEO system cannot be designed to operate at low SNRs ~0dB but rather at ~10dB and above.

GEO systems could be designed to operate at SNRs close to 0dB, however it seems that due to the size and mass of such a platform it would be wiser to increase the power and operate at SNRs of ~10dB and above.

So, if both systems are designed to support the same SNR under clear-sky conditions, the only factor that would impact the power efficiency would be the size of the transmitting user beam as being received on the ground. The near future of GEO satellites will achieve a beam width of ~0.25º with beam size as narrow as 160Km (over the subsatellite point).

For a LEO constellation of 1000Km altitude and minimum elevation of 30º, the maximum path length is ~1700Km and the ratio between GEO to LEO path lengths is ~21-36. So, a 5m GEO antenna will have the same performance as of a 14-24cm LEO antenna. For a LEO system to gain 10dB of power efficiency over such a GEO system, the antenna gain will have to be at least 10dB higher which results in a minimum antenna gain of 40dBi (~3200 elements).

Smaller antennas are at risk of not being capable to compete with advanced VHTS GEO systems.

5. Future Expansion and Evolution

Previous sections analyzed and compared the power efficiency of LEO and GEO systems and set a guideline for LEO systems antenna size. In this section we will try to propose means of ramping up such a system efficiently. Due to the facts that LEO satellites have shorter life span than GEO and that it would probably take a few years to launch the entire constellation, it seems reasonable to keep improving the technology over time to support higher capacities.

Following this approach, it would probably be wise to design the first satellites with maximum size antenna that the industry can support today (limited by 40dBi transmit gain) at a reasonable cost/gain. In addition, the number of beams can be limited as well as the overall bandwidth per beam.

For example, 1 antenna supporting 4 simultaneous 500MHz beams, generating a total bit rate of ~2.2Gbps per satellite (equals ~440Gbps for the constellation).

As the demand ramps up, the new satellites should support bigger antennas, more beams and wider bandwidth per beam.

6. Constellations Parameters Tradeoffs

As presented above, a LEO constellation with altitude of 1000Km and minimum elevation of 30º, requires antennas of 40dBi gain, both on board the satellite as well as on the user terminal side. Both antennas should be capable of scanning a wide view angle range (±50º for the satellite and ±60º for the user terminal). These requirements are challenging, and it would be useful to compare other type of constellations that will have less strict requirements from the antennas.

Parameter	Base	Reduced Scanning Angle	Lower Altitude
Altitude [Km]	1000	1000	500
Minimum elevation [º]	30	70	30
Satellite antenna gain$_{@19.7GHz}$[dBi]	40 (3200 elements)	45 (10,000 elements)	34 (800 elements)
Terminal antenna gain$_{@19.7GHz}$[dBi]	40	35	35
Number of satellites	200 (10x20)	3256 (44x74)	589 (19X31)
Scanning angle- satellite [±º]	48.5	17.2	53.4
Scanning angle- terminal [±º]	60	20	60
# of beams per satellite	10	10	4
Payload transmit power per satellite [W]	8 for 5.5Gbps	8 for 5.5Gbps	13.2 for 2.2Gbps
Power Efficiency Factor over GEO	~10	~10	~2.35

Table 4- Comparison of LEO Constellations

In Table 4, a comparison is shown between several constellations. The left column corresponds to the design exercise presented in the previous sections of this paper. The second column represents a scenario

where the scanning angle was reduced considerably. The scanning angle reduction, simplifies the design as several elements can be combined to a single virtual element, however the number of satellites is increased by an order of magnitude. A third tradeoff is presented in the third column, where the altitude was reduced to 500Km. This lower altitude improves the budget by 6dB which can reduce the antenna on one of the sides of the link. Decreasing the antenna size on both sides degrades the power efficiency to 2.35 times that of GEO which is probably not sufficient.

Another constellation worth mentioning is a MEO constellation. An example of a MEO system that has the potential to achieve competitive pricing is presented in Table 5.

Parameter	Small Terminal~35cm	60cm Terminal
Altitude [Km]	7000	7000
[1]Minimum elevation [º]	66º (±24º scan)	66º (±24º scan)
PAFR reflector size [m]	5	3
Terminal antenna gain@19.7GHz[dBi]	35	40
Number of satellites	160 (10x16)	160 (10x16)
Scanning angle- satellite [±º]	11.15	11.15
# of beams per satellite	~6800	~2500
# of active beams per satellite	100	100
Payload transmit power [W]	60	60
Total constellation capacity [Tbps]	~9	~9
Power efficiency factor over GEO	>10	>10

Table 5- MEO Constellation

(1) Lower scanning angle will probably allow for Hybrid BFN on the ground terminal (4 elements combined).

7. Power Consumption- Realistic Model

The optimization process, that was used in previous sections, was naive in the sense that it assumed that most of the payload power is associated with the power amplifier. While this assumption is true for relatively high-power amplifiers (GEO), it is definitely not the case when the amplifier power required from link budget considerations, is low (<<100mW per element).
To optimize a LEO constellation design, we should consider the power consumption of the entire Tx/Rx chains (RF front end and digital beam forming) and not just the power amplifier.
The optimization exercise assumes the following simplified power consumption model:

$$P_{Payload} = N \times (1.6 \times P_{Sat} + 50mW + 3mW \times M)$$

Where

$P_{Payload}$ is the payload power associated with the Forward Link
N is the number of antenna elements
M is the number of beams created by the BFN
P_{Sat} is the saturation power of the amplifier (we assume 4dB of output back off and 25% efficiency)
50mW of power is considered for the RF front end
and 3mW of power for the digital beam former per a 500MHz beam

As the number of antenna elements increases, the required power from the amplifier decreases $(P_{Sat} \propto 1/N^2)$, however, below a certain power level, the fixed power starts to dominate and the overall power per Mbps starts to go up.
An optimization process for the best power efficiency (minimum payload power per Mbps) was performed for the following system parameters:

- Altitude 1000Km- polar orbit constellation
- Frequency 19.7GHz
- Carrier BW of 500MHz
- User terminal G/T of 13.2dB/K
- P_{sat} values range: 20, 100, 200, 400mW
- Number of simultaneous active beams range: 1, 2, 4, 8, 16, 32, 64, 128

The best power efficiency was achieved for the following configurations shown in Table 6:

N	P_{PA} [mW]	Power Efficiency [mW/Mbps]	Number of beams	Satellite Forward Capacity [Gbps]
1024 (32x32)	100	11.9	32	26
1024 (32x32)	200	10.9	64	53
1024 (32x32)	400	10.4	128	105
2304 (48x48)	100	11.4	128	120
2304 (48x48)	200	10.8	128	160

Table 6- Optimal Antenna/ PA sizing for 35cm User Terminal

Table 7 shows the results for a 60cm user terminal with G/T of 17.9dB/K:

N	P_{PA} [mW]	Power Efficiency [mW/Mbps]	Number of beams	Satellite Forward Capacity [Gbps]
576 (24x24)	100	5.7	32	26
576 (24x24)	200	5.2	64	52
576 (24x24))	400	4.9	128	104
1024 (32x32)	100	4.2	128	74
1024 (32x32)	200	4.7	128	122

Table 7- Optimal Antenna/ PA sizing for 60cm User Terminal

8. Summary

A comparison between future Geostationary high throughput satellites to next generation LEO constellations was presented. It was shown that for a LEO constellation to compete with GEO systems, the beam size on the ground (cell) must be reduced considerably compared to GEO.
It seems that a 1024 elements antenna on board the satellite is a reasonable compromise (for now) between complexity, efficiency and overall capacity for the constellation described in this paper.
It was shown that for 35cm user terminals, LEO achieves a slightly better efficiency than GEO. For 60cm user terminals, the efficiency is about 3 times better than GEO. It is obvious that with the evolution of technology, the power associated with beam forming networks and the non-radiated RF front end will

continue to be reduced enabling bigger antennas on board which will improve the power efficiency of the satellites and as a result the pricing per Mbps.

While this paper focused on the constellation design optimization from cost per Mbps perspective (i.e., power efficiency), it is worth to mention that a LEO constellation has an inherent advantage, compared to a single GEO satellite, capable to aggregate high capacities to hot-spots by serving the same cell from multiple satellites.

It is obvious that a LEO constellation must use all the latest advanced technologies to reduce the cost and risk as much as possible. Some of these technologies could be applied for GEO satellites as well, however they are a necessity for a LEO constellation aiming towards broadband type of services.

The following list describes these technologies:

- Beam Hopping- Due to the nature of the dynamics of a LEO constellation and the narrow cells on the ground, both satellite and user terminal should support beam hopping for dynamic allocation of resources as well as handover between satellites and gateways.
- Digital Multi-Beam Forming- It is obvious the tens of beams must be supported by each user antenna on the satellite. It would also be beneficial if a user terminal could support multi-beam operation for a 'make before break' handover.
- Half-Duplex user terminals- LEO user terminal antenna must track the satellite constantly. A terminal based on an electronically steered multi-beam array antenna has great value since it has no moving parts. A dramatic cost reduction of the user terminal antenna can be achieved if the system will be designed to support both half-duplex and full-duplex terminals. This can be achieved with a negligible effect on system capacity but with a huge impact on terminals cost.
- On Board Processing- Regeneration on board the satellite maximizes the performance per each link and as a result optimizes the overall capacity of the system. Regeneration also reduces cost on the gateways' infrastructure by a factor of 2.5-3 applying higher order modulations for the feeder links which cannot be done on a legacy bent-pipe satellite architecture.

References

[1]   D. Rainish, Bounds on satellite system capacity and inter-constellation interference, *23rd Ka and Broadband Communications Conference,* (Ka-2017), Triest, Italy, Oct. 2017

[2]   ETSI EN 302 307: Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications; Part 1 and Part 2 (2014-11)

[3]   J. G. Walker, Satellite constellations, Journal of the British Interplanetary Society, vol. 37, pp. 559-571, 1984

[4]   http://stuffin.space/
[5]   https://www.satellite-calculations.com/Satellite/footprintplotter.php

Annex I- Polar Orbit Constellation

This section will describe how to calculate the number of satellites per plane and the number of planes required for a given altitude and minimum user terminal elevation.
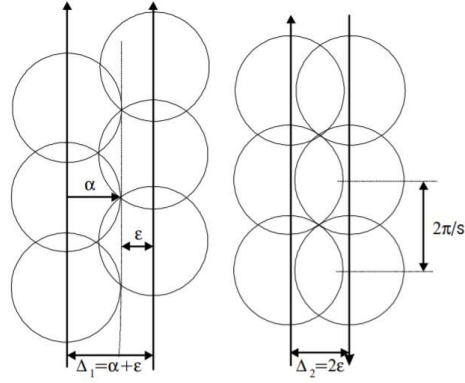

Figure 5- Polar Orbits Co-Rotating Interface (Left) and Counter-Rotating (Right)
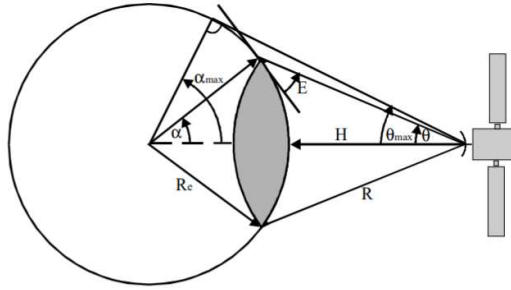

Figure 6- Satellite-Terminal-Earth Geometry

It can be shown that:

$$\Delta_1 = \varepsilon + \alpha$$

and

$$\Delta_2 = 2\varepsilon$$

where

$$\varepsilon = cos^{-1}\left(\frac{cos(\alpha)}{cos\left(\frac{\pi}{s}\right)}\right)$$

and α

$$\alpha = cos^{-1}\left[\frac{R_e}{(R_e + H)}cos(E)\right] - E$$

where E is the minimum elevation angle from the terminal to the satellite, s represents the number of satellites in each orbital plane and H is the altitude of the satellites over the earth surface.

For p planes, the following constraint applies:

$$(p-1)\Delta_1 + \Delta_2 = \pi$$

and we get:

$$(p+1)cos^{-1}\left(\frac{cos(\alpha)}{cos\left(\frac{\pi}{s}\right)}\right) + (p-1)\alpha = \pi$$

For our case, where:

H=1000Km

E=$30^0 = {}^{\pi}/_6\,Rad$

we get:

$$\alpha = 11.54°$$

and the most efficient allocation for planes and number of satellites per plane is: 11 planes and 18 satellites per plane.