High Throughput Satellites:
Issues in Comparing Capacities

Alban Duverdier
CNES,
Paris, France
alban.duverdier@recherche.gouv.fr

Michel Bousquet
MIDIVAL,
Toulouse, France
prof.michel.bousquet@gmail.com

***Abstract* - Since the early 2000s, satellite telecommunications have evolved significantly with the deployment of high throughput satellite systems offering Terabps capacity. Most often, operators and analysts evaluate this system capacity adding the forward and return data rates, obtained by multiplying the number of satellites by the available bandwidth, the frequency reuse factor and a typical spectral efficiency for each link. After presenting this first level solution, the paper proposes a methodology to evaluate HTS system capacity in three steps: IP throughput from link budget analysis, capacity obtained at the satellite level, influence of system configurations (users, gateways, services).**

Keywords—HTS, system architecture, satellite payload, air interface, link budget, propagation, mobility

I. INTRODUCTION

Since the early 2000s, satellite telecommunications have evolved significantly with the deployment of high throughput satellites (HTS) in geostationary orbit (GEO) offering single satellite capacity increase by an ever-growing factor, initially equal to 10 and now close to 1000. With global HTS systems introduced in the following decade and the deployment of constellations in medium Earth orbit (MEO) and low Earth orbit (LEO), the capacity of a single satellite becomes less significant and it has to be computed for the global system.

Operators and analysts evaluate typically a satellite system capacity adding the forward and return data rates, obtained by multiplying the number of satellites by the available bandwidth, the frequency reuse factor and a typical spectral efficiency (useful bit rate over symbol rate) for each link. Even if this first level solution allows a quick system comparison, it is not well adapted to compare systems so different in terms of orbits, architectures, payloads and user requirements.

Even if [1] proposed to establish a list of the different parameters playing role in capacity, most of the technical comparisons propose an analysis based on link budgets [2] [3]. In the paper, the authors review and compare the main characteristics of the existing and future HTS systems. After the link budget calculation for different types of HTS systems, they propose a methodology to estimate more accurately the capacity of different HTS system.

II. MAIN CHARACTERISTICS OF THE EXISTING AND FUTURE HTS SYSTEMS

The fundamental change introduced by HTS systems is the focus on unicast services while previous systems where optimized for broadcasting. This has led to specify, rather than wide beams, multiple spot beams covering the desired service area and offering higher receive and transmit satellite antenna gains, as the antenna gain is inversely proportional to its beamwidth. Then multiple beam footprints can be arranged such that several beams reuse the same frequency and polarization. A final consequence is to see HTS services as a part of a global telecommunication service, as proposed in the 5G standards with non-terrestrial networks (NTN) integrated to terrestrial networks for mobile broadband scenarios.

A. System architecture

The legacy network architecture of HTS systems, depicted in Fig.1, is a star configuration where a GEO satellite provides connectivity between a large number of user terminals or satellite access points, and a few gateways interconnected by a terrestrial optical backbone.

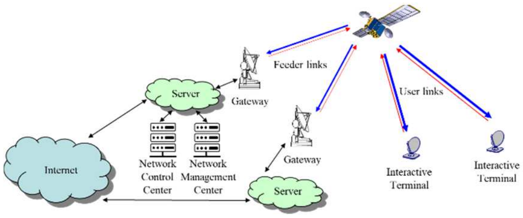

Fig. 1. Typical HTS system

Two types of radiofrequency links are involved, the feeder links (between gateway and satellite) and the user links (between user terminals and satellite). Even if splitting the available bandwidth allows the use of the same frequency band for both links in Ka-band (or even in Ku-band), many systems propose a hybrid configuration to maximize the radio resource for the user links by moving the feeder links to higher bands. Typically, feeder links are in Ka-band with user links in Ku-band or, with new systems, feeder up-link is in Q-band and feeder downlink is in V-band while user links are in Ka-band. The use of optical feeder links is also considered.

On the gateway side, each dedicated feeder beam can reuse the full frequency band assuming sufficient spatial separation between beams. This allows minimizing the number of gateways subject to they can handle the total amount of traffic.

On the user side, a large number of narrow beams (up to several hundreds) provides service across the targeted satellite coverage. Narrowing the width of the beams results in a two-fold advantage, higher receive and transmit satellite antenna gains and a larger reuse factor considering a given service coverage. As beams are contiguous, frequency reuse introduces interference. Interference is controlled using a pattern of beams with different frequencies and polarizations, also called colors, say 3, 4 or 7 colors. A typical 4 color-pattern is obtained by splitting the user allocated bandwidth in two and using both polarizations.

Even if a star configuration is the baseline, an increasing number of applications request direct user-to-user connectivity to optimize data exchanges. This is possible with a double hop through gateways or with the help of on-board switching provided by the payload. Some systems propose on-board routing and a mesh configuration, but it requests a much more complex regenerative payload.

B. Antenna and payload

A traditional communication satellite payload is organized as a generic chain of receive antenna, low-noise amplifier (LNA), down-converter, channel input filters (IMUX), channel high power amplifiers (HPA), output channel filters (OMUX) and transmit antenna.

The key parameter of the HPA is the RF power it delivers. Another parameter is the RF to DC power efficiency that conditions the amount of consumed DC power. It is common practice to measure the maximum RF power in a single carrier drive mode that generally corresponds to the maximum power efficiency of the amplifier. As the HPAs are non-linear at highest power, for multicarrier operation, they are operated with output back-off (OBO) reducing the delivered RF power. This typically reduces the RF to DC efficiency. For travelling wave tube amplifier (TWTA), the highest power, called saturation point, corresponds to an efficiency about 50 to 60%. For solid-state power amplifier (SSPA), maximum power is defined at the 1dB compression point and the efficiency is around 35%. As DC power used by the HPAs is about 80% of the available payload power, the latter bounds the total RF power delivered by the HPAs.

Even if an HTS keeps the general structure of a traditional telecommunication satellite, it has to handle differently forward and return links. Forward links between a gateway up-beam and a set of user down-beams make use of wideband carriers, each carrying a time-multiplex of data packets bound for a given user beam. The HPA typically handles one or a few carriers, therefore operated with limited OBO. Return links between a user up-beam and a given gateway down-beam are many narrowband carriers with different and variable power levels. Multi-carrier operation of the on-board HPA requires the use of large OBO to maintain intermodulation to an acceptable level.

For most of the first generation HTS, the multiple beam coverage is obtained by a multifeed reflector antenna in a single feed per beam configuration (SFPB). If we position feeds side by side with the relevant diameter to get a good antenna efficiency, i.e. a taper about 12dB, the gain difference between center and crossover of the beams would be higher than 10dB. To maintain a difference of about 3dB, the solution is then to distribute the colors of the selected pattern among three or four reflectors with stringent pointing requirements that poses accommodation constraints and mass increase.

Another solution is to consider a multiple feed per beam configuration (MFPB), where each beam results of the combined radiation of a cluster of feed fed by the relevant amplitude and phase distribution obtained by a beam-forming network (BFN). Antennas with the MFPB configuration generate the multibeam coverage by using clusters of feeds where most of the feeds are used for contiguous set of beams. This allows providing the whole coverage area with a single reflector, reducing accommodation issues, even if HTS usually separate the uplink or downlink functions, requiring two antenna systems.

The most flexible solution is phase array antenna, which allows creating a large number of beams with fully controllable frequency and power distribution, each beam resulting of the combined radiation of a group of the feeds of a large feed array. The phase array can radiate on its own, being then a direct radiating antenna (DRA), or combined with reflectors, e.g. phase-array feed reflector (PAFR).

The phase array antenna concept combines nicely with that of active antenna where each feed integrates a microwave power module associating an HPA on transmit side and an LNA on receive side. With an active antenna, the BFN can be analog, digital or combine both techniques, the last option offering appropriate flexibility for a medium hardware complexity. Digital implementation can be part of the functionalities of an on-board processor (OBP) providing direct connections between user beams without double hop through gateways. Its common implementation today is the digital transparent processor (DTP) doing on-board dynamic time-slot switching without demodulation and decoding.

If instead of sampling and digitizing the carriers, they are on board demodulated and decoded, the information data packets are now available on-board and the switch acts as a router able to manage traffic priorities before coding and modulation for downlink retransmission. The OBP is then a regenerative processor implying a much more complex hardware implementation.

Finally, the wish for the coming HTS generation is to maximize the frequency reuse, by reusing the full satellite allocated bandwidth for each beam. Even if literature proposes solutions based on precoding, a short-term solution is beam-hopping. The OBP distributes the forward links on a subset of transmit beams active only for some portion of time. The subset, based on a time-space transmission pattern, changes in each time-slot, but repeats periodically. This removes the limitation in the available bandwidth per beam that the conventional space domain frequency re-use beam coloring system implies. Furthermore, beam-hopping allows the capacity allocated to each beam to be flexibly adjusted in time as a function of the requested resources. Overall, the beam-hopping patterns optimize the C/I on the forward link.

C. From regional to global services

Even if first HTS have proposed regional services, as Viasat and Echostar over the US coverage, the combination of GEO satellites have offered global services especially to mobile users, as Inmarsat/GlobalXpress or Intelsat/EPIC.

The next step was to rediscover constellations, already proposed in the 1990's, as they easily offer a global coverage and propose in addition much shorter latencies of interest for real-time telecommunication services. At first, O3b introduced a MEO constellation minimizing the number of satellites while increasing the global capacity. Then, Oneweb and SpaceX/Starlink started the deployment of LEO constellations, followed by announcements of a few others.

There is today no doubt that these constellations will take a share of the satellite telecommunication market. Their main drawbacks compared with GEO HTS systems are still the higher capital expenses (CAPEX) required for their deployment, the higher operational expenses (OPEX) needed to manage the data on the ground and a more complex and costly terminal that shall regularly manage handover procedures between satellites without losing the connection.

The last generation of constellations proposed to use inter-satellite links. It requires on-board switching or routing between ground and other satellites. Moreover, the system can implement packet routing by selecting optimal satellite routes for the traffic. Such a solution offers in particular much shorter transmission latencies than terrestrial fibers for long-distance communications.

III. CAPACITY OF AN HTS SYSTEM

Once designed the architecture of an HTS system for a given type of services, the next step is to optimize its business plan. Firstly, the frequency resource deserves the most efficient air interfaces for forward and return links and protocols have to be compatible with those used in terrestrial networks. Secondly, relevant choice of technology and software allows maximizing the data capacity per satellite given by link budgets in typical conditions. Eventually, it is possible to combine these results to obtain an upper bound of the system capacity, used to establish the business plan.

A. Air interfaces and high layers

It is well-known that the minimum bandwidth necessary for a given symbol rate is given by Nyquist rules and that, with a transmission using Nyquist filters, the carrier-to-noise ratio (C/N), calculated in the Nyquist bandwidth, is equal to the energy per symbol to noise density (Es/N0). Therefore, the objective of the new air interfaces developed in the 2000's was to offer solutions maximizing the spectral efficiency for a given Es/N0, as near as possible from the bound established by Shannon.

Among them, the DVB-S2 [4] and its update, the DVB-S2X [5], are the most implemented solution on the forward link. They propose high data rate carriers conveying a time division multiplex of the traffic to all terminals in a given beam. Thanks to on-the fly adaptive coding and modulation (ACM), the transmission is adapted to the specific link performance of each terminal of the multiplex varying the modulation and coding (MODCOD) and required Es/N0.

On the return link, even if transmissions based on continuous single carriers built as forward link are possible, most of the applications only request discontinuous transmissions of short packets. It allows implementing multiple access solutions that optimize the bandwidth use, but is less efficient by 1-2 dB in Es/N0 compared to forward link.

Both links constitute the first layer of an interactive network interfaced to internet by means of a medium access control (MAC) and a link layer control (LLC), as standardized by the DVB-RCS2. The network control center (NCC) controls the network in real-time, while the management control center (NMC) manages fault, configuration, accounting, performance, and security (FCAPS). A terrestrial optical backbone connects the gateways together and to Internet, middleboxes interfacing with the internet protocol (IP) and the transport control protocol (TCP),

Link budgets compute Es/N0 that gives the link spectral efficiency as shown in Fig. 2 comparing DVB-S2 and DVB-S2X to Shannon bound. The DVB-S2X NL data correspond to results with a real satellite payload optimizing HPA OBO and non-linear distortions. ITU-R S2131-1 [6] proposes an empirical formula to match these measures. It allows obtaining the useful bit rates from the link budget, multiplying the spectral efficiency by the Nyquist bandwidth. The satellite IP throughput, measured with real terminals, is lower than the useful bit rate to take into account the overhead due to the MAC layer.

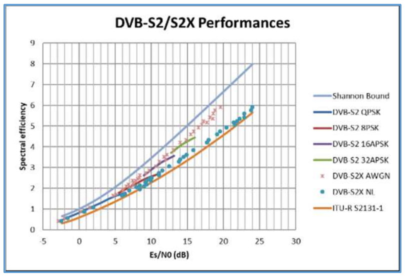

Fig. 2. Typical performances on the forward link

B. Link performance

The classical formula of a link budget [7] defines the uplink or downlink C/N such that:

$$\left(C/N\right)_{dB} = EIRP_{Tx} - L + \left(G/T\right)_{Rx} + 228.6 - B \quad (1)$$

The effective isotropic radiated power (EIRP) defines the transmit end performance, while the figure-of-merit (G/T) defines the receive end performance. The path loss (L) includes the free space loss, function of the range, atmospheric loss, and mobile channel fading loss in case of mobile user. The C/N appeals to the Nyquist bandwidth (B), smaller than the real carrier bandwidth depending on roll-off and guard bands.

The typical link budget analysis for an HTS considers clear sky situation, as significant rain attenuation occurs only for limited percentage of time, and fixed terminals. Atmospheric loss, due to gases, amounts then to a few tens of dB. The free space loss takes into account a minimum elevation value for GEO HTS, considering high performance terminals at the coverage edge. It takes into account a nominal minimum elevation for LEO HTS, corresponding to the system minimum elevation angle for a terminal with a fully deployed constellation.

In complement to thermal noise evaluated in C/N on up and down links, there is inter-system and intra-system interference coted as a carrier to interference ratio (C/I). While ITU-R declarations limit inter-system interference, an HTS can suffer from adjacent channel interference (ACI) originating from neighboring carriers at different frequencies and co-channel interference (CCI) created by frequency reuse, either by quasi-orthogonal polarization or between beams of the same color. In practice, with appropriate design of bandpass filters and choice of roll-off, the ACI is small with respect to CCI.

For both forward and return links, the overall link performance results from the combination of up-link C/N downlink C/N and interference C/I. The overall available C/(N+I), to be compared to the required Es/N0, expresses in linear such that:

$$\left(C/\left(N+I\right)\right)_T = \left(\left(C/N\right)_{\uparrow}^{-1} + \left(C/I\right)_{\uparrow}^{-1} + \left(C/N\right)_{\downarrow}^{-1} + \left(C/I\right)_{\downarrow}^{-1}\right)^{-1} \quad (2)$$

Thanks to the much larger EIRP and G/T of the gateway compared to that of the user terminal, the feeder up and down C/N are significantly larger than the user down and up C/N. The user link drives then the overall link performance, while considering that feeder link introduces a limited degradation, such as 0.6 dB or 1 dB if the difference in C/N remains higher than 10 dB or 5 dB.

On the forward link, the satellite EIRP is the most sensitive parameter as it integrates the on-board multibeam antenna gain and HPA RF power including back-off. For the terminal G/T, parameters are available from commercial equipment. On the return link, the terminal EIRP differs depending on the allocated bandwidth B, while the satellite G/T depends on the gain of the on-board multibeam antenna as a function of the position of the terminal in the beam coverage.

Uplink and downlink C/I are negligible for the feeder links as the beams focus on largely separated gateway positions. Instead, uplink and downlink C/I are significant for user links depending on the performance of the satellite multibeam antenna, the color pattern, the number of beams, and the position of the terminal within the beam and the beam position within the service coverage. The user downlink C/I is almost constant for a fixed terminal, and becomes negligible if case of beam-hopping. In contrast, the user uplink C/I varies in time depending on how many terminals in neighboring beams are transmitting in the same time slot and frequency. Difference in rain attenuation and mitigation techniques is adding another source of variability.

C. Link budget and capacity computation

We propose to apply the elements presented in the previous sections to compute the IP throughput on the forward link (FL) and the return link (RL) for five HTS systems. We select a LEO HTS at 550km transmitting to a low-cost terminal in Ku-band, a LEO HTS at 1200km transmitting to a professional terminal in Ku-band, a LEO HTS at 600km transmitting to an experimental terminal in Ka-band, a GEO HTS in Ku-band for mobile terminals, and a GEO HTS in Ka-band for fixed terminals. These examples make use of available data for Starlink, Oneweb, Kuiper, Epic, Viasat-2, but do not expect to present the actual performance of these systems, as only partial information is available.

To harmonize the comparison, the link budgets in Fig 2 and 3 use the same parameters for elevation (25°), carrier bandwidth (250MHz in FL, 10MHz in RL), air interface efficiency (DVB-S2X LN in FL, 1.5dB less in RL), C/I (18 dB in FL, 13 dB in RL) and MAC overhead (20% in FL, 30% in RL). They also suppose almost clear sky conditions (1dB for atmospheric losses), even if this does not correspond to the same availability in Ku- and Ka-bands. With these assumptions, the link budgets allow to compare in broad terms the offered system IP throughputs.

Forward Link Budget : Satellite to Terminal						
Satellite altitude	km	550	1200	600	36000	36000
Elevation	°	25,0	25,0	25,0	25,0	25,0
Transmission bandwidth	MHz	250,0	250,0	250,0	250,0	250,0
Nyquist bandwidth	MHz	227,3	227,3	227,3	227,3	227,3
Communication Link						
Downlink frequency	GHz	12,0	12,0	20,0	12,0	20,0
Availability	%	99,0	99,0	90,0	99,0	90,0
Maximum EIRP density	dBW/4kHz	-15,0	-13,4	-7,9	12,4	20,1
Satellite EIRP per carrier	dBW	32,5	34,1	39,6	59,9	67,6
Free space loss	dB	175,0	180,9	180,1	205,9	210,3
Atmospheric loss	dB	1,0	1,0	1,0	1,0	1,0
Terminal G/T	dB/K	8,4	12,2	11,5	11,5	18,5
Downlink C/N0	dBHz	93,5	93,1	98,6	93,1	103,4
Downlink C/N	dB	9,9	9,5	15,0	9,6	19,8
Total C/N	dB	8,9	8,5	14,0	8,6	18,8
Total C/I	dB	18,0	18,0	18,0	18,0	18,0
Total C/(N+I)	dB	8,4	8,0	12,6	8,1	15,4
Total Es/N0 with implementation loss	dB	7,4	7,0	11,6	7,1	14,4
Spectral efficiency (ITU-R S2131-1)		1,8	1,7	2,6	1,7	3,2
Data rate	Mbps	407,1	390,1	590,8	393,2	729,8
MAC overhead	%	20,0	20,0	20,0	20,0	20,0
IP throughput	Mbps	325,6	312,1	472,6	314,6	583,8
Example of similar system		*Starlink*	*Oneweb*	*Kuiper*	*Epic*	*Viasat-2*

Fig. 3. Simplified forward link budgets for five HTS systems

Return Link Budget : Terminal to Satellite						
Satellite altitude	km	550	1200	600	36000	36000
Elevation	°	25,0	25,0	25,0	25,0	25,0
Transmission bandwidth	MHz	10,0	10,0	10,0	10,0	10,0
Nyquist bandwidth	MHz	6,7	6,7	6,7	6,7	6,7
Communication Link						
Uplink frequency	GHz	14,0	14,0	30,0	14,0	30,0
Availability	%	99,0	99,0	90,0	99,0	90,0
Terminal EIRP per carrier	dBW	26,1	30,6	34,7	46,5	48,4
Free space loss	dB	176,4	182,2	183,7	207,2	213,9
Atmospheric loss	dB	1,0	1,0	1,0	1,0	1,0
Satellite G/T	dB/K	4,9	-4	7,4	10,4	18,5
Uplink C/N0	dBHz	82,2	72,0	86,1	77,3	80,6
Uplink C/N	dB	14,0	3,7	17,8	9,0	12,4
Total C/N	dB	13,4	3,1	17,2	8,4	11,8
Total C/I	dB	13,0	13,0	13,0	13,0	13,0
Total C/(N+I)	dB	10,2	2,7	11,6	7,1	9,3
Total Es/N0 with implementation loss	dB	9,2	1,7	10,6	6,1	8,3
Spectral efficiency on return link		1,8	0,6	2,1	1,3	1,7
Data rate	Mb/s	12,2	4,1	14,0	8,7	11,2
MAC overhead	%	30,0	30,0	30,0	30,0	30,0
IP throughput	Mb/s	8,6	2,9	9,8	6,1	7,9
Example of similar system		*Starlink*	*Oneweb*	*Kuiper*	*Epic*	*Viasat-2*

Fig. 4. Simplied return link budgets for five HTS systems

Fig. 3 shows that forward links in clear sky on 250 MHz can offer 300 Mbps to 600 Mbps depending on the system. Fig. 4 presents return links in clear sky on 10 MHz offering 3 Mbps to 10 Mbps. These results are consistent with published measures done on terminals. However, much lower IP throughputs may appear on commercial offers, as service providers share the link data rate between users.

It is worth noting that there is a bias in the comparison, because the selected type of terminals corresponds to the main service of each system (e.g. customer, professional, mobile user…). The IP throughput obtained with a low-cost terminal would be much higher with a more complex and then expensive terminal, but this may not correspond to the targeted customers of the service provider.

The IP throughput per satellite can be prorate from the link budget bandwidth considering the overall bandwidth taking into account the reuse of frequency at satellite level. The next step is to infer the global IP throughput at system level. The simplest way is to multiply each IP throughput per satellite by the number of satellites in the system. However, this gives an overestimated upper bound of the global IP throughput, as the latter is constrained by the global coverage inhomogeneity, the available gateways, and the user irregular distribution.

IV. OTHER ISSUES WHEN COMPARING HTS SYSTEMS

The estimation of the IP throughput discussed above is done in three steps: link budget for a carrier, pro rata for a satellite, combination of the satellites for the system. For the link budget, the estimation has to consider the specificities of the payload and channel. The throughput per satellite is constrained by the orbit that affects coverage and latency and platform that limits payload mass and DC power. Finally, the system capacity should take into account system configurations, especially in case of mobility.

A. Comparison at the link level

A single link budget cannot represent a good overview of the capacity observed with different scenarios: EIRP for a considered carrier depends on the possible multi-carrier operation and the associated back-off, satellite EIRP and G/T depend on the terminal position, terminal G/T depends on the atmospheric attenuation for a given elevation.

Regarding channel impairments, ITU-R propagation models [8] show that high rain attenuations occur on limited percentages of time and mobile channel models [9] introduce shadowing loss and add constraints on minimum elevation angle because of the terminal antenna physical mounting (e.g. on aircraft or ship). However, fade mitigation techniques (FMT) and protocols allow keeping the service availability by adapting the transmission parameters thanks to the knowledge - or at least an estimation - of the current and future state of the channel, in near real time to ensure the service continuity.

Considering the different terms of equation (1), only limited options exist to mitigate an increase in transmission losses. In addition to ACM that adapts the required C/N and modifies the spectral efficiency:

- Up-link power control (UPC) increases the EIRP of fixed terminals to compensate attenuation on the uplink, provided the ground amplifier operates with back-off in clear sky;
- Site diversity (SD) proposes to use a redundant antenna site that is not impaired by attenuation;
- Dynamic rate assignment (DRA) reduces the data rate to reduce the bandwidth of the carrier impacted by attenuation.

Even if all these techniques can be combined, their use is different for gateways and terminals, such as for forward and return links. Moreover, it is important to note that the NCC takes all the decisions even when the gateways and terminals realize the measurements at a distance, yielding to some delays and the need for signalling.

Estimation of rain attenuation on the feeder link is obtained in general by ground monitoring of a satellite on-board beacon and using a frequency-scaling model to infer the attenuation at feeder frequency most often different from that of the beacon. To estimate attenuation on the user link with possibly mobile terminal, it is only possible to measure the overall C/(N+I). It yields a widely imprecise estimation of the attenuation as user uplink interference can vary more rapidly and significantly than the channel, (e.g. when new users connect or disconnect).

In case of FMT implementation, the loss in capacity is then due to not only attenuation, but also a margin taking into account the control loop delay, hysteresis, and the imprecise estimation of the rain attenuation. All translates in a systematic reduction in the capacity during rain events.

Today, new HTS systems consider higher frequency bands (Q/V-band or even W-band) to increase further the capacity taking advantage of larger bandwidths. The adoption of higher frequencies also allows the generation of high gain beams in a multibeam coverage, using relatively small satellite antenna sizes. This increase in frequency comes up against a greater vulnerability of the propagation channel to atmospheric conditions and more users in a same beam under rain at the same time, as the beams are becoming ever narrower. Moreover, 3GPP Release 17 introduced 5G NR [10] support for satellite communications with one project focusing on satellite backhaul communications for customer premises equipment using HTS systems and direct low data rate services for handhelds.

It is then necessary to realize link budget analysis in different channel conditions to evaluate accurately the spectral efficiency (η) of the link for the required availability (p_{max}):

$$\eta = \sum_{i>0} (p_i - p_{i-1})\eta_i \Big/ p_{\max} \text{ with } p_0 = 0 \quad (3)$$

with a spectral efficiency η_i computed for a given availability p_i such that the C/(N+I) varies by regular steps (say 0.5dB) when i increases.

B. Comparison at the satellite level

GEO HTS systems are ideally suited for providing regional coverage of regions with small to mid-latitudes. As over 75% of the globally addressable population for broadband services resides within 35 degrees of latitude north and south of the Equator, the service economics of GEO HTS systems are quite appealing considering their limited CAPEX and OPEX. Moreover, they can steer spot-beam capacity towards hot spot areas and they request terminals with fixed pointing antennas that are thus low-cost.

The limitations of GEO HTS arise to serve locations of high latitude as the elevation angle reduces with latitude, in particular with mobile terminals that can lose visibility of the satellite in rugged terrain and cities or due to their physical mounting on aircraft or ship. Another main drawback is the latency as the earth-satellite-earth trip takes around 250 ms or 500 ms for the round trip time (RTT) required by some protocols.

With LEO HTS systems, as low altitude limits satellite visibility of the Earth's surface, it is difficult to focus the deployed capacity globally to the limited areas with the largest target population. The lower the altitude, the smaller is the satellite field of view, considering that a minimum elevation angle for the terminal to see the satellite is selected, limiting further opportunities for capacity steering. Indeed, an angle too small creates masking issues by the terminal environment and interruption of the service.

With hundreds if not thousands of satellites, recent constellations aims at having always a satellite above the user with a large elevation angle and a minimum range that minimizes free space and atmospheric losses. If there is always a satellite at zenith of the terminal, this simplifies also the tracking function of the terminal and then help to reduce the cost of a terminal for LEO HTS systems, even it still stays higher compared to those for GEO HTS systems. This also offers a definite advantage for mobile terminals in rugged terrain and cities, on aircrafts or on ships.

Another interest of LEO HTS systems compared to GEO HTS systems is that the potential for reusing the allocated frequency band is function of the number of satellites chosen by system. Moreover, LEO HTS systems offer reduced latency, thus helping to optimize the IP throughput.

In addition to orbit characteristics, the satellite platform mass and power can introduce capacity limitations. With a GEO satellite, capacity is bounded by the available DC power (around 12-15 kW) and payload mass (around 1500-1200 kg), considering a launch mass of 6-7 tons using upper range launch vehicles and legacy chemical propulsion for moving the satellite from geostationary transfer orbit (GTO) to GEO. With the use of electric propulsion for orbit raising since the years 2010, the comparison with previous generations requests to consider the bias due to the fuel reduction by more than 95%. Then, the launch mass can be just above half of the launch mass with chemical propulsion or, for a given launch mass, it is possible to increase the DC power (up to above 20 kW) and the payload mass (up to a few tons). However, the maximum DC power still limits the number of beams and then the IP throughput at satellite level.

The situation is even more complicated to compare mass and DC power of LEO and GEO satellites. Indeed individual LEO satellite mass is depending on the target altitude (lower bound about 550 km or upper bound about 1800 km), resulting in a mass range between 150 to 750 kg, much less than GEO satellites. Nevertheless, the large number of satellites and in the end the total system mass is much larger (hundreds tons!) than that of a few GEO satellites if global coverage is to be provided. Finally, the mass comparison depends on the launch cost, which decreases for lower altitude transfer orbit and a large number of satellites launched together.

Regarding DC power, in spite of the limited mass of the spacecraft, a LEO satellite can accommodate solar panels of significant size, 10s of m^2 being affordable and offering an available DC power of a few kW. With the goal of a minimum elevation angle above a given value (several 10s degrees), each satellite operates only a few 10s of beams, and then a significant amount of RF power is available per beam in the accordance with the regulatory limitation on the power flux density. It even leaves a lot of room to power inter-satellite links and on-board processing.

For a given payload mass and power, its architecture plays also a role in the satellite capacity [11]. Indeed, most of the payload DC power is consumed by the HPAs, with some kW reserved for the DTP if embarked. TWTA is the most current technology with high RF power, high efficiency, high operating frequency and wide operating bandwidth, but its mass requests that it serves two or more beams, implying the use of an output multiplexer with some loss, a limited flexibility in beam bandwidth adjustability and an OBO for multicarrier operation. SSPA on the contrary offers only limited RF power in particular when frequency increases and suffers from low efficiency, but the small mass and reduced volume facilitates the one HPA per beam implementation. The possibility to place the SSPA near to the antenna feed without loss make the use of SSPA more and more proposed today in particular with active phase array antenna.

All these elements have to be considered to bound the computation of the IP throughput per satellite.

C. Comparison at the system level

From the given amount of payload mass, power and hardware bounded by the limits discussed in the previous section, a limited number of beams could be served by the satellite whatever it is a GEO HTS or a LEO HTS. The user distribution between beams being uneven implies likely that a few beams are saturated and many other are underutilized even if some flexibility is introduced in the allocation of power and bandwidth between beams. The gateway characteristics, especially their number, can also be a bottleneck on the capacity delivered by the satellite. The achieved capacity per satellite is then lower that the nominal one it can provide. For mobile users, it depends also on the target of service operators. As example, in-flight entertainment and connectivity depends on a few major airline routes.

In addition, in case of global coverage, as oceans cover more than 70% of the Earth surface and population density in rural area can vary between 5 and 300 inhabitants per square kilometer [12], the achievable capacity for a given satellite will depend significantly on its position above Earth surface. Therefore, the global capacity at system level cannot be the product of each nominal capacity per satellite by the number of satellites in the system. In Fig. 5, we present a methodology and the elements needed to estimate more accurately the system capacity.

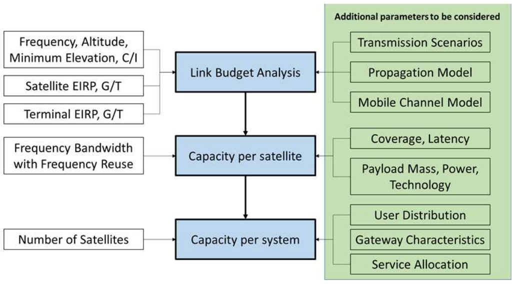

Fig. 5. Methodology to estimate capacity

V. CONCLUSION

Many system choices affect the capacity estimation, especially for HTS payloads offering regular beams in size, bandwidth and power and for LEO HTS because of limited visibility of the Earth's surface, as even flexible beams can only cover areas in this visible surface. After computing examples of link budgets, the paper proposes a methodology to estimate HTS system capacity in three steps. For the link budget analysis, different transmission scenarios and channel conditions should be used for a more accurate evaluation of the spectral efficiency. Then, the satellite orbit and the payload mass and power need to be considered to bound the result at the satellite level. Finally, the system configurations (users, gateways, services), combined with the previous results, play a role to establish the system capacity. Further work is to focus on a detailed analysis and evaluation of the parameters to be used in the three steps of the capacity estimation.

REFERENCES

[1] M. Bjorkman, C. Voboril, A Proposed Framework for High-Throughput Satellite Capacity Calculations Standardization, Ka and Broadband Communications Conference, October 2018

[2] I. Del Portillo, B. Cameron, E. Crawley, A technical comparison of three low earth orbit satellite constellation systems to provide global broadband, Acta Astronautica, June 2019

[3] D. Gazelle, LEO Constellation for Broadband Applications, System Design Considerations, Ka and Broadband Communications Conference, October 2018

[4] ETSI EN 302 307-1 V1.4.1, 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: DVB-S2

[5] EN 302 307-2 V1.3.1, 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 2: DVB-S2X

[6] ITU-R S.2131-1 (01/2022), Method for the determination of performance objectives for satellite hypothetical reference digital paths using adaptive coding and modulation

[7] G. Maral, M. Bousquet, Z. Sun, Satellite Communications Systems: Systems, Techniques and Technology, 6th Edition, April 2020

[8] HU H., Future HTS Satellite Output Section Design, AsiaSat White Paper, September 2017

[9] ITU-R P.618-13, Propagation data and prediction methods required for the design of Earth-space telecommunication systems, 12/2017

[10] Y. Lee and J. P. Choi, Performance Evaluation of High-Frequency Mobile Satellite Communications, IEEE Access vol. 7, 2019

[11] X. Lin, S. Rommer, S. Euler, E. A. Yavuz and R. S. Karlsson, 5G from Space: An Overview of 3GPP Non-Terrestrial Networks, IEEE Communications Standards Magazine, December 2021

[12] NSR Team, Capabilities and Limitations of Non-GEO Constellations, NSR White Paper, January 2022