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Performance assessment framework and concept of operations in live satellite communication systems

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Abstract

Accurate assessment of performance is a key and challenging topic in satellite communication (SatCom) systems. Key performance indicators (KPI) include latency, availability, capacity, and flexibility. KPI are important to assess and monitor at different steps of the design, implementation, and operation of a SatCom system. An efficient concept of operations, describing the capabilities of the system and how the system should be operated is also relevant and must rely on accurate performance assessment of selected KPI.

This paper proposes a common framework (MAPAN-Management and Performance of Access Networks) for performance assessment at the different phases of the system: planned performance based on theoretical assessment and expected configuration, actual or effective performance based on actual measurements, and predictive performance based on actual configuration and projection of expected or desired events.

A concept of operations of a live SatCom system based on the MAPAN framework is also proposed. It aims to optimize the efficiency of SatCom systems thanks to continuous adjustment of the contractible and allocable resources, based on actual and predicted system performances.

The paper introduces a reference terminal for planned performances, an algorithm for performance averaging throughout a beam and real-time link budget for performance prediction.

1. Introduction

It is a global trend to look for the improvement of satellite communications (SatCom) systems performances [1]. SatCom systems have a consequent chain of actors, which include satellite and ground system designers and manufacturers, satellite operators, and final satellite connectivity and service providers (C&SP). The system performances can then be computed based on different assumptions and different frameworks by this multitude of players. The C&SP is the closest actor in the chain to the end user and actual connectivity consumer. As represented in Figure 1, [2], the service provider usually buys resources, as raw data or bandwidth, from operators, sources and delivers end-user terminals or user equipment (UE), installs, manages and maintains the user ground segment required to deliver the

connectivity to end-users. The C&SP would also develop and sell value added services, provides an overview of

It is thus a key requirement for C&SP to have accurate performance assessment to optimize both purchases and sales. As the requirement might escalate, this is also applicable to satellite operator, especially with the new flexible satellite, in order to configure the satellite in line with the actual requirements and put the resources where they are needed. Finally, it is also applicable to the satellite manufacturer for the effective design of the spacecraft.

We claim in this article to provide a common framework for accurate performance assessments, from the live or operating SatCom system standpoint, driven by the C&SP.

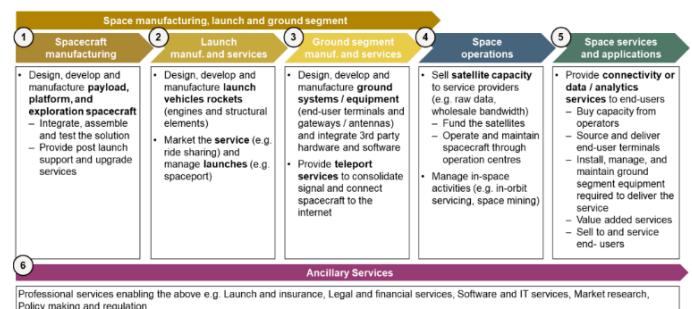


Figure 1: Space sector value chain from UK national strategy [2]

The framework is based on various known measured satellite performances and actual remotes with known equipment capabilities and locations.

2. Background

2.1. Overview of performance indicators in satellite communication systems

Despite the evolution of SatCom over the past decades, the main system performance indicators have not changed and remain the following: coverage, availability, latency, capacity, and flexibility.

Many of these parameters are defined at conception and once the satellite is operational in orbit, they are not modifiable or when they are, it is at a considerable cost. We refer to these parameters as static and semi-static parameters. For instance,

propagation latency is clearly associated with the altitude of the satellite, while coverage is associated with the shape of the antenna, especially with passive antennas. Recent software defined satellites claim to be able to modify the footprint quite fast thanks to active antennas and on-board processing.

Other parameters, which can be referred to as dynamic parameters, depend on the actual performances and constraints of the systems including propagation impairments, interferences, remotes distributions within the coverage, etc. The capacity of a satellite network (SatNet), in Mbit per second (Figure 3), is the main parameter of this category.

Accurate assessment of such static and dynamic parameters is thus important for several players in the satellite connectivity value chain to optimise the utilisation of the system. In this work, we focus on the estimation of the capacity at different moments in the system lifetime, from its design to its implementation and exploitation. We also propose a set of materials and algorithms for accurate capacity estimation, and we define a concept of operations (CONOPS) based on such an approach and related materials.

2.2. Capacity as the primary performance indicator

Capacity can be defined as the achievable throughput of the network [3]. It is one of the main performance indicators that is linked to several other parameters, and this can bias the estimation and expectations.

Note that in the literature, the term capacity may also refer to the achievable bandwidth (MHz), but this is not considered in this paper.

Initial capacity assessment is usually made based on link budgets, and a performance table which provides the expected spectral efficiency given the signal to noise ratio [4], [5]. It also depends on the distribution of the remotes in the coverage, the characteristics of these remotes, and the resource allocation to the remotes based on their service level agreement (SLA), actual traffic, etc [6].

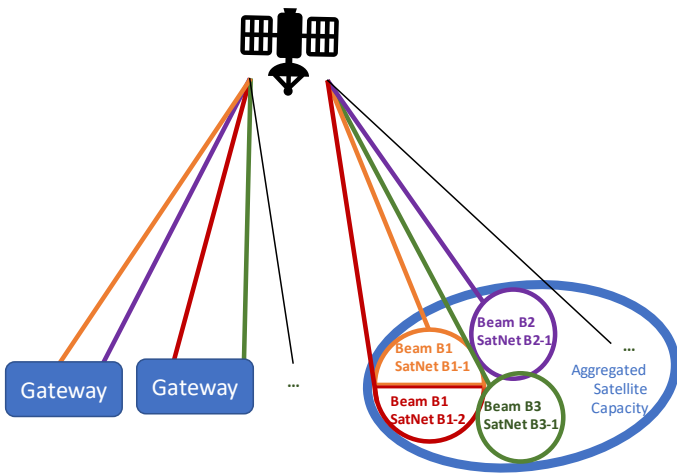


Figure 2: Capacity as different scales of a SatCom System

The equation (eq. 1) below provides the logic of this initial capacity assessment at SatNet level.

$$C_{SatNet} = BW * Eff \quad (eq. 1)$$

Where C_{SatNet} is the assessed capacity of a SatNet, BW the total bandwidth that can be allocated and Eff the spectral efficiency.

The Shannon law states that the maximum efficiency is provided by (eq. 2):

$$Eff = \log_2(1 + CINR_{SatNet}) \quad (eq. 2)$$

Where $CINR_{SatNet}$ is the average of carrier to interference plus noise ratio of the SatNet.

The estimated $CINR$ is based on well-known link budget models (combining carrier to noise ratio (CNR) and carrier to interference ratio (CIR)) [4]. It is an average of the computed $CINR$ for remotes in a representative set of location (latitude and longitude) of a beam.

The common link budget calculations are described by the equations (eq. 3), (eq. 4), and (eq. 5).

$$CINR_{(lat,lon)}^{-1} = CNR_{(lat,lon)}^{-1} + CIR_{(lat,lon)}^{-1} \quad (eq. 3)$$

$$CNR = EIRP + G/T - FSL - k - A_T - \log(BW_b) \quad (eq. 4)$$

$$CIR^{-1} = CCIR^{-1} + ACI^{-1} + IM^{-1} + ASI^{-1} \quad (eq. 5)$$

Where $EIRP$ is the effective isotropic radiated power of the transmitter, G/T is the figure of merit of the receiver, FSL is the Free Space Losses, k is the Boltzmann constant (-228.6 dBW/KHz), A_T the atmospheric attenuation, and BW_b the allocated bandwidth. CCI represents the co-channel interference and potentially includes cross-polar isolation, ACI is the adjacent channel interference, IM the intermodulation products, and ASI is the adjacent satellite interference.

Computed $CINR$ is then used to derive the energy per symbol to noise density ratio ($EsNo$) and to compared it to the threshold $EsNo$ of the considered waveform and modem, and considering the potential link margin (LM_{db}) to complete the assessment procedures [7].

We can conclude that it remains a complex, time and resources consuming process to provide a capacity assessment which is based on global assumptions, which can bias or limit the accuracy. We observed a deviation of ± 10 to $\pm 20\%$ between capacity assessed through this approach and the effective measured capacity.

Such capacity assessment needs to be accurate to master the service contracted by the end users and to adjust the resource allocation towards the remotes when necessary.

A common and more precise approach to assess system capacity is therefore necessary for several purposes, including the comparison between candidate systems, the mastery, and the adjustment of sold capacity to meet the connectivity SLA, and the planning of future system configuration to deliver expected new commitments. It would also be the basis for an adapted and efficient CONOPS.

3. System assumptions

The system considered for the application of the proposed performance assessment framework and the resulting CONOPS is a SatNet based on a geostationary (GEO) satellite, single beam, with single forward and return carriers as represented in Figure 2. We focus on the capacity as the main KPI, and the analysis is done at the SatNet level. It is assumed that Beam capacity and satellite capacity can both be easily derived from SatNet capacity (eq. 6), (eq. 7).

$$C_{beam} = \sum_i C_{SatNet \text{ in beam}} \quad (\text{eq. 6})$$

$$C_{satellite} = \sum_i C_{beam \text{ in satellite}} \quad (\text{eq. 7})$$

Figure 3 represents the capacity tree with the overall SatNet capacity, potential segmentation of such capacity per pre-defined groups or sets, and allocation to the remotes.

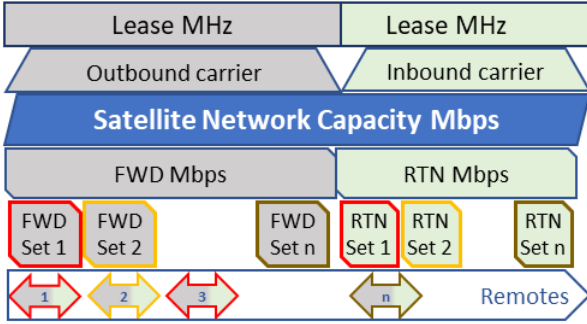


Figure 3: Distribution of assessed capacity to the remotes

The gateway (GW) can be based on initial specification of the teleport that will support the GW beam. It is not expected to change often.

4. Performance assessment framework

As part of the performance assessment of a SatCom system and for the motivation provided in section §1, we introduce the MAPAN (Management and Performance of Access Networks) framework for performance assessment throughout the lifetime of a SatCom system.

The framework is inspired by operational performance objectives and business performance measurement concepts as discussed in [8] and [9] and which introduce five main operational performance objectives: speed, quality, cost, flexibility, and dependability.

In the frame of the SatCom system, the performance assessment is basically required to size the connectivity system and the proposed framework aims to address the five main performance objectives [8] and [9].

Hence, the proposed MAPAN framework is based on three types of performances: planned performance, actual performance, and predicted performance as shown in Figure 4.

Further details are provided in this section. The MAPAN framework is also the basis for the proposed CONOPS, which is presented in section §6.

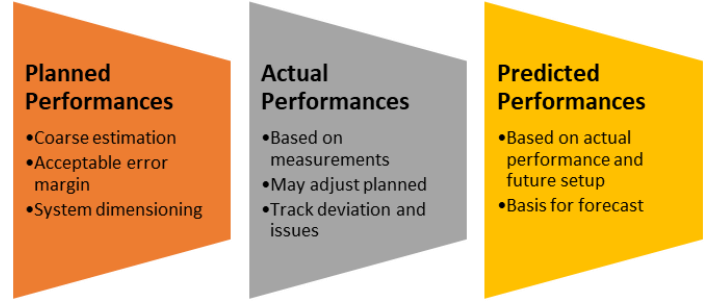


Figure 4: Concepts and purposes of the types of performances

4.1. Planned performance

Planned performance refers to the performance that can be expected from a SatNet based solely on initial raw parameters of the system. Planned performance is assessed based on initial configuration of the SatNet and includes physical beam characteristics such as allocated bandwidth, downlink EIRP, and distribution of the figure of merit over the coverage. It is also driven by the type of remotes and planned location set.

Planned performance is then necessary for the dimensioning of a SatNet prior to service commercialisation. It provides an overview of the performance that can be expected from a SatNet and can provide a good support for decision making and to evaluate the SatNet ability to address the expected demand.

4.2. Actual performance

Actual performance is the performance of the SatNet once remotes are in the network and generating traffic. Accurate estimation of actual performance is not obvious since it is not only the sum or average of measured performance of the remotes in the SatNet. Several other parameters need to be considered such as the fill rate of the network, the margin of the modulation and coding schemes on the user ground segment, and the priority associated with the SLA of the remotes or group of remotes.

Actual performance is necessary to monitor the deviation with planned performance and to ensure that the configuration of the SatNet is in line with the SLA of all the remotes in the network. It can also assist to identify potential issues or failures in the SatNet.

4.3. Predicted performance

Predicted performance is based on the actual configuration of the network (e.g., remote types and locations) and the projection of expected or desired events regarding the network or the remotes, on real-time basis and in the future. This can be technical changes (e.g., modification of a remote equipment, remotes entering or leaving the SatNet, etc.) or commercial changes (e.g., customer bandwidth upgrade, traffic prioritisation, etc.).

Predicted performance can then be used for service adjustment once the network is activated. It can also support feasibility analysis of connectivity requests on existing networks and support the identification of potential issues or failures.

5. Tools and algorithms for accurate assessment

For the assessment of the various types of performances, new tools and algorithms are introduced as part of the MAPAN framework. They are the basis for an integrated CONOPS of dynamic SatNet based on the proposed framework.

Those materials include the introduction of the reference terminal, the algorithm for averaging the capacity based on the performance variation within the coverage from beam peak (BP) to beam edge (BE), the introduction of the real-time link budget for capacity prediction based on remotes actual performances and locations.

5.1. Reference terminal for planned performance

Concept

The proposed approach to perform the planned performance assessment is to use a logic reference terminal.

The reference terminal is then a selected terminal with known characteristics, which is considered to be located at the beam peak of the coverage, both for forward and return directions. In reality, the remotes could actually be anywhere within the SatNet coverage.

As the purpose of the SatNet or of the user terminals can be very different, with different characteristics and performances, the characteristics of the reference terminal needs to be aligned with those of the future remotes in the SatNet.

Table 1: Reference terminal type per network type

Purpose of the SatNet	Selected Reference terminal
Premium Market	240 Cm Antenna, 100W BUC
Medium-High Market	150 Cm Antenna, 25W BUC
Common market	100 Cm Antenna, 8W BUC
Entry market	60 Cm Antenna, 8W BUC

The type of terminal and associated technical characteristics shall be in line with the purpose of the SatNet as shown in Table 1.

Process

A link budget is computed following the logic provided in (eq. 3) and considering the reference terminal characteristics and location.

For the forward link budget, it is considered that the entire bandwidth is allocated to the reference terminal.

For the return link budget, the theoretical power on the terminal should not be exceeded. However, it is considered that the terminal is not power limited when allocating the full return bandwidth.

The link budgets with the reference terminal will then provide the forward (FWD) and return (RTN) performance assessment.

In addition, in order to derive an effective capacity assessment of the SatNet based on the reference terminal, some link margins will be applied to the results based on the shape of the coverage and the delta between the beam peak (BP) EIRP (or G/T) and the beam edge (BE) EIRP (and G/T). Too optimistic assessment, based on rough link budget with the reference terminal at beam peak would then be avoided. Recommended FWD and RTN LM are provided by (eq. 8) and illustrated in Table 2 for the FWD link.

$$LM_{dir} = \begin{cases} 1, & \text{delta}_{dir} \leq 3dB \\ 2.5, & 3dB < \text{delta}_{dir} \leq 6dB \\ 3, & \text{delta}_{dir} > 6dB \end{cases} \quad (\text{eq. 8})$$

Where LM_{dir} is the link margin a given direction (FWD or RTN) in dB and delta_{dir} is :

- The difference between beam peak EIRP and beam edge EIRP for the FWD link; and beam peak G/T
- The difference between beam peak G/T and beam edge G/T for the RTN.

Table 2: Recommended reference terminal FWD link margin

LM FWD & RTN	Overview (FWD)
Delta BP vs BE delta ≤ 3 dB Recommended Margin LM = 1 dB	
Delta BP vs BE 3 < delta ≤ 6 dB Recommended Margin LM = 2.5 dB	
Delta BP vs BE delta > 6 dB Recommended Margin LM = 3 dB	

For instance, the planned capacity of a SatNet will be computed based on the reference terminal with proposed characteristics and assumptions, by selecting the achievable modcod given the computed EsNo (eq. 9), (eq. 10).

$$EsNo_{planned} = EsNo_{pb} - LM \quad (\text{eq. 9})$$

$$C_{planned} = BW_{SatNet} * \text{Max} \left(\begin{array}{c} \text{Eff} \\ EsNo_{planned} < EsNo \end{array} \right) \quad (\text{eq. 10})$$

Where $EsNo_{planned}$ is the resulting planned average EsNo of the SatNet, $EsNo_{bp}$ is EsNo at beam peak following the reference terminal specification, LM the applicable link margin given the shape of the coverage. $C_{planned}$ is the obtained planned capacity of the SatNet.

5.2. Actual performances measurements

The actual network performance is based on the measurement of the performance of the remotes with traffic in the network. While it might appear easy and obvious to make an average or sum of effective performances of the remotes in the network to derive the network performances, it actually depends considerably on the fill rate of the SatNet.

For a given period (e.g., 15 minutes):

- Let us consider a SatNet with a given number of remotes across the coverage.
- Let us consider the throughput per remote is measured and provided.
- Let us consider the modcod per remote is measured and provided.
- The allocated symbol rate (SR) per remote is either measured and provided or easily computed, based on the remote throughput and the spectral efficiency (Eff) of the remote modcod.
- Let us compute the fill rate $f = \frac{\sum SR_{remotes}}{SR_{SatNet}}$
- Let us compute the equivalent percentage of symbol rate allocation per remote $p_{remote} = \frac{SR_{remote}}{\sum SR_{remotes}}$
- Let us assume that SatNet unused symbol rate $SR_{SatNet} * (1 - f)$ is prorated to the remotes.
- Assuming the remotes use the same modcod, the symbol rate would be: $SR' = SR + p * (SR_{SatNet}) * (1 - f)$
- Finally, the actual capacity of the SatNet would be $C_{SatNet-Actual} = \sum_{remotes} SR_{remote} * eff_{remote}$

Figure 5: Capacity averaging process

Hence, a SatNet with a network fill rate close to 100% has quite small uncertainties on the remotes that will enter the network. It can then have a quite accurate performance

measurement based on average (e.g., for the EsNo) or sum (e.g., for the throughput or capacity) of the remote.

As the fill rate decreases (and the event uncertainty increases) the actual performance measurement of the SatNet remains an estimation.

Let us focus on the capacity as the performance to monitor. The approach provided in Figure 5 is a proposal for accurate actual capacity estimation.

Thus, when the fill rate is 100%, the capacity is actually the sum of the capacity of the remotes.

Note however that in the context of maritime network or any other types of SatNet with mobile user terminal, the future uncertainties remain considerable, even with high fill rate. This highlights the important of the period selected for the analysis, which needs to be in line with the dynamicity of the network.

5.3. Real time link budget for predicted performance

The idea of real time link budget for predicted performance is to perform a link budget based on the actual setup of the SatNet, including the distribution of the remotes, their types, and locations.

For instance, the model can include known upcoming plans in the network in order to access e.g., what would be the network redistributable capacity, or the updated fill rate.

The process to compute the predicted capacity is similar to the process provided in Figure 5 for the actual capacity computation. The only difference being that the modcod and the symbol rate will be provided by link budgets, and not remote measurements.

6. Concept of operations with the MAPAN framework and evaluation results

The CONOPS aims to describe how the SatNet will be operated to deliver the service to end users in line with their SLA while ensuring the required operation performance objectives (e.g., fill rate, load balancing) of the SatNet operator.

The proposed CONOPS in the MAPAN framework is based on the tree types of performance applied to the capacity, with the following logic:

- Setup the planned capacity as the expected capacity at the initiation of the SatNet.
- Establish and Maintain a MAPAN dashboard with the proposed three capacity definitions (planned, actual and predicted).
- Include the contractible capacity in the Dashboard as the capacity that can be contracted and expected by the customers (or the remotes).
- Use the MAPAN framework for troubleshooting by identifying capacity deviation and/or underperforming remotes, region, beams, or satellites.

The proposed MAPAN framework is considered with the capacity as the main KPI, given that is the most important performance indicator and the main parameter to optimise in the system configuration and thus CONOPS, at least for the initial version discussed in this paper.

In Figure 7, we performed a comparison of planned, actual, and predicted capacity at identical configuration.

The test are done with the same SatNet but considering different fill rates (100% and 50%).

The planned capacity is identical in both case as this performance indicator is not based on the fill rate.

We can observe that the deviation between planned capacity and actual capacity for all the cases is less than 10%.

But the delta between predicted capacity and actual capacity is most of the time negligible for the SatNet at 100% fill rate whereas it can be up to 20% for the SatNet at 50% fill rate.

An explanation of such delta is the fact that when the SatNet is not much loaded, the system tends to allocated larger symbol rates to the remotes while reducing the modcod in order to increase the robustness. Such behaviour shall be taken into account for the definition of the contractible capacity, which should be a wise balance between planned, predicted, and actual capacity.

The experimentation continued with the CONOPS, with the objectives to see how the MAPAN could contribute to the effective operation of a SatNet.

To complete such analysis, we included the remote booking which refers to the committed information rate (CIR) of the remotes. The maximum information rate (MIR) is set at 30% of the CIR.

We also tracked the contractible capacity, which is updated throughout the lifetime of the SatNet based on the performance assessment from the MAPAN framework and following the concept of operations provided in section §6 (detailed in Figure 6).

In Figure 8, we can observe the adjustment of the performance indicator following the voluntary triggered events (e.g., network upgrade / downgrade) and involuntary events (e.g., remote increase or decrease of traffic, failure).

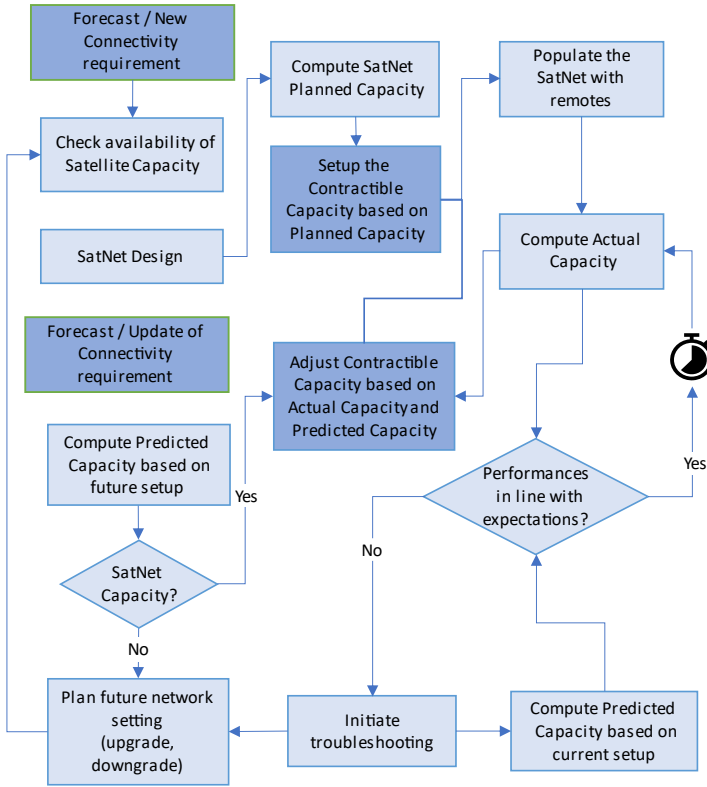


Figure 6: Flowchart of the capacity management with the MAPAN framework

The logic of the CONOPS based on the mentioned materials is provided as a flowchart in Figure 6.

7. Experimentation

We performed some tests of proposed MAPAN performance evaluation framework with the capacity as performance indicator in order to compare the accuracy of the proposed models for the assessment of the performances and the monitoring of the system.

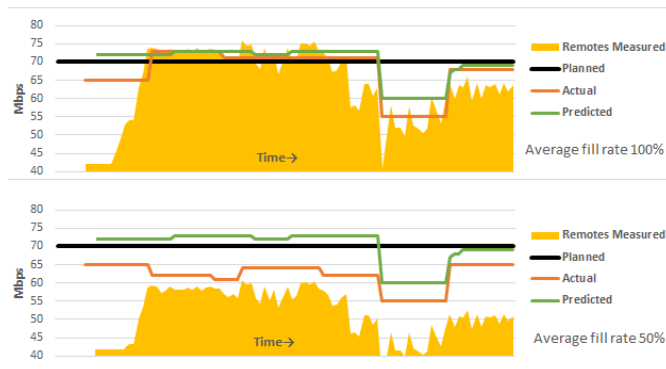


Figure 7: Planned vs Actual vs Predicted capacity

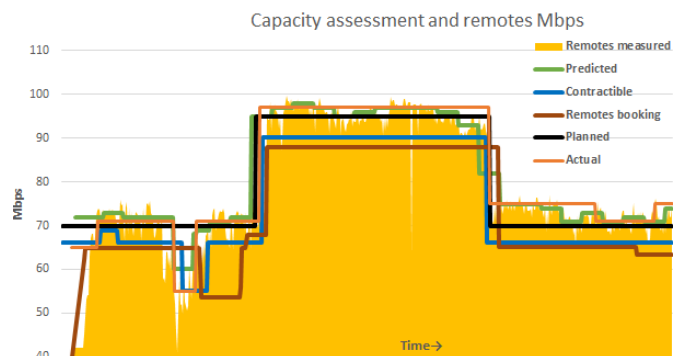


Figure 8: Capacity assessment with the MAPAN framework

8. Conclusion

We have introduced the challenge and the necessity to have an accurate performance estimation in live satellite systems. We proposed the MAPAN framework which introduces three types of performance and associated CONOPS which introduce another type of capacity:

- Planned capacity, based on a reference terminal, can be used for initial system comparison, configuration and for dimensioning of the connectivity offer.
- Actual Capacity, used to track deviations, guide load balancing, and eventually adjust contractible capacity.
- Predicted capacity, based on real-time link budgets, is used for theoretical benchmarking and forecasting.
- Contractible capacity, which is the capacity that can be sold, and which is continuously adjusted.

The proposed model allows to perform initial capacity assessment (planned capacity) with an acceptable error margin (less than 20%), and a reduced computation effort.

The proposed averaging algorithms combined with real time link budget were demonstrated to provide more accurate actual and predicted capacity assessment.

Future work may include the embracement of artificial intelligence for more accurate and responsive MAPAN framework and the extension of the concepts to non-GEO systems and flexible systems.

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