Ka-band High Throughput Satellites for 5G Based Applications: The Athena-Fidus Case Study

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Abstract. The 5G standardization activities are going to be finalized. The full set of specifications for the next generation telecommunication systems, which will be based on flexible network management and new services definition, is expected for mid 2018 (release 15) and for mid 2019 (release 16). At the same time, High Throughput Satellite (HTS) platforms faced a wide adoption for the provision of Internet access and are recently gaining a significant interest as complementary connectivity able to support 5G architectures, leading to significant investments for the development and deployment of future platforms. In the view of a synergy between terrestrial and satellite networks to provide 5G services, the satellite access can play a meaningful role to support/complement terrestrial networks for its peculiar characteristics of coverage, broadcasting/multicasting, synchronization, etc. To this aim, the system availability and bandwidths available must be carefully assessed when the hybrid network is tailored to specific 5G services. The Athena Fidus system has been realized to support civil and governmental services and is today operational. In this paper, the characteristics of Athena Fidus DVB-S2/DVB-RCS links are considered to identify the set of services that will be possible to offer, focusing on nominal IP-based bandwidth and availability. The objective is to draw the operational context to be considered for the potential utilization of Athena Fidus in the next communication systems.

Keywords: 5G · Athena Fidus · Link budget · Ka-band

1 Introduction

The forthcoming fifth generation of telecommunication networks is deemed to provide relevant advances and revolutions both for end-users and carriers. From the user point of view, the dramatic improvements on bandwidth and latency, together with the possibility of tailoring the network configuration and deploying

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application components at the network edge (mobile edge computing), pave the way to novel communication services including enhancing massive mobile broadband (eMBB), Ultra-Reliable and Low Latency Communications (URLLC) and mMTC (massive Machine Type Communications), with possible use cases ranging from 4K video, to Autonomous Driving to IoT/smart city related applications. From the operator point of view the introduced innovations are even more disruptive. The network functions will be softwarized and virtualised giving the capability to provide the "Network as a Service". The possibility to create slices leveraging network segments and function of different owners will open new business opportunities based on new business models. In other words, the envisioned 5G network aims at seamlessly supporting the widest range of services and applications ever witnessed in past wireless mobile networks. To realize such a vertical integrated vision of multiple end-to-end services deployed on the same mobile infrastructure, future 5G networks will embrace the vision of "customer-facing on-demand network slicing". As described in the 5GPP architecture white paper [1] a network slice is exactly "a composition of adequately configured network functions, network applications, and the underlying cloud infrastructure (physical, virtual or even emulated resources, RAN resources etc.), that are bundled together to meet the requirements of a specific use case, e.g., bandwidth, latency, processing, and resiliency, coupled with a business purpose".

High Throughput Satellites (HTS) platforms allow to achieve high-rate (today up to 20 Mbit/s per user, with the goal of offering more than 100 Mbit/s in the next years) bi-directional links, through Very Small Aperture antenna satellite Terminals (VSATs) at the users premises. Such platforms are already available worldwide and represents currently an effective access link to the Internet. HTS typically use Ka-band, in a multi-spot beam configuration, and make use of geostationary satellites (such as Ka-Sat by Eutelsat). In addition, ongoing initiatives are designed to use LEO constellations, so that the experienced latency is greatly reduced, with the deployment of hundreds or thousand of satellites and the capability to offer very large data rate making this platforms suitable to 5G communications.

As introduced in [2], the feasibility of using HTS platforms to implement broadband service is already investigated, looking at well known problems in terms of propagation in Ka-band, opening the way to further 5G oriented integrations. In particular, the consensus and wider agreement on what satellite brings to achieving the 5G goals are:

Ubiquity. Satellite provides high speed capacity across the globe using the following enablers: capacity in-fill inside geographic gaps, overspill to satellite when terrestrial links are over capacity, general global wide coverage, backup/resilience for network fall-back and especially communication during emergency.

Mobility. Satellite is the only readily available technology capable of providing connectivity anywhere on the ground, sea or air for moving platforms, such as airplanes, ships and trains.

Broadcast (Simultaneity). Satellite can efficiently deliver rich multimedia and other content across multiple sites simultaneously using broadcast and multicast streams with information centric networking and content caching for local distribution.

All the three above features are due to satellite's ability to serve coverage areas much wider than those of other wireless communications technologies. Moreover, they can provide cost-effective coverage to many areas of the globe, which can go underserved by terrestrial infrastructures. In summary, satellite can offer complementary connectivity options, seamless user experience, and provide important benefits.

In this regard, over the last few years satellite networks have been envisioned as an important missing piece of 5G networks and several scenarios that could benefit from a mature satellite/terrestrial network integration have been identified [3]. Indeed, satellites are the only means to provide truly ubiquitous geographic coverage and mobility. This feature is important to the successful deployment and operation of 5G use cases, such as:

- Complementing connectivity to mobile nodes (aerial, maritime, vehicles and trains);
- Guarantee 5G connectivity in the areas not covered by terrestrial infrastructures;
- Ensuring 5G for rural connectivity (in both developed and underdeveloped countries);
- Providing emergency response/disaster relief recovery communications.
- Providing backhauling services to fixed and mobile stations
- Efficient content distribution to feed CDNs
- Remote automation and sensing
- Highly geographically distributed networks.

In this new very challenging scenario, the satellite can be fruitfully included in hybrid communication architectures, to contribute to ensure the full respect of all the requirements and capabilities associated to the 5G deployment, as preliminarily discussed in [4,5].

This paper investigates the potentiality of using IP-based bearer services offered by Athena Fidus, which is an operational HTS platform covering the Italian territory. The authors will describe in details its characteristics, configuration and, by means of simulations, link budget margins and achievable bitrates, suitable to support 5G applications, with a determined quality of service and availability.

The rest of the paper is organized as follows: Sect. 2 includes the description of the Athena Fidus platform; Sect. 3 describes the detailed radio-frequency channels specification in relation with system availability; in Sect. 4 a detailed analysis of Ka-band link attenuations is presented; in Sect. 5 simulation results including link-budgets and relative resulting bearer channel are shown. In Sect. 6 conclusions are drawn and possible future works are described.

2 Athena Fidus Characteristics and Architecture

The Athena Fidus (Access on THeaters for European allied forces Nations-French Italian Dual Use Satellite) system [6,7] is the result of a space program developed jointly by ASI (the Italian Space Agency) and CNES (Centre National d'Etudes Spatiales). The Athena Fidus satellite hosts Italian and a French payloads (which are completely independent in characteristics, operations and coverages), either for civil or military use; therefore, four separated and independent payloads are operative at the same time in a geostationary orbit, at a position of 37.8°E. Athena-Fidus has 14 antennas, 7 of which are steerable for dynamic spot-coverage (with a spot diameter of 1750 Km) to serve areas on demand at high bitrates; France owns 5 beams and Italy 2.

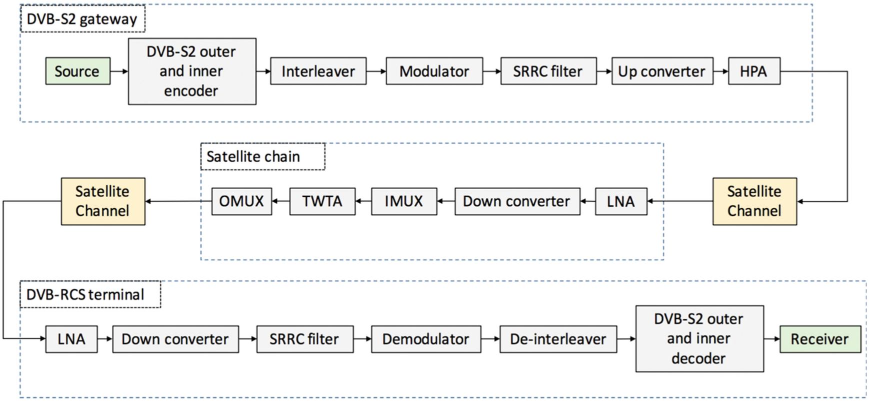

Fig. 1. Communication model for the forward link, [10].

The Athena Fidus goal is to support a telecommunication infrastructure able to replace or complement terrestrial networks for a large set of civil and governmental applications, both broadband and narrowband beams using different bands, namely Ka-band and EHF. While EHF is adopted for military operations, which are undocumented and outside the scope of this work, the civil allotment will be considered in the rest of the paper. More specifically, Italy is the geographical reference area considered, where a single beam in Ka-band is available, for broadband national services: the overall expected data rate is over 1 Gbit/s. In its current setup, Athena-Fidus ground segment makes us of DVB-RCS [8] for return link communications on a shared channel, and point to point links (for mesh communications) or DVB-S2 [9] broadcasting for forward links, to offer state of the art transmission efficiency and service availability.

Athena Fidus Italian civil payload can possibly enable new IP-based and 5G services in remote and underserved areas, or where the terrestrial infrastructure

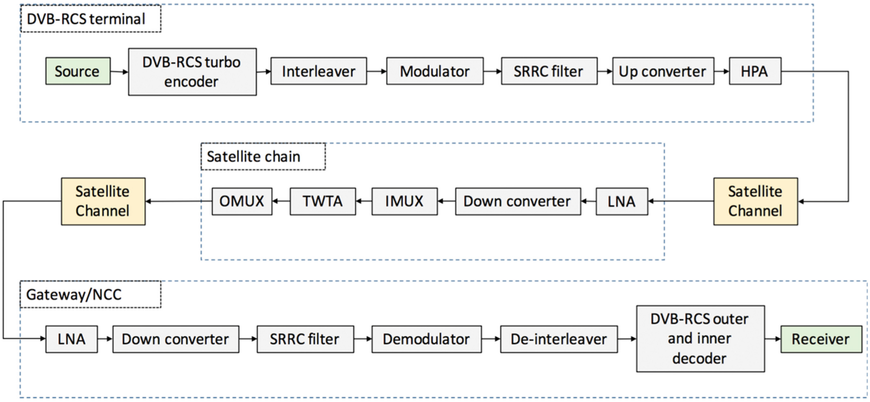

Fig. 2. Communication model for the return link, [10].

is missing or damaged due to emergency situations. In fact, Athena Fidus offers the following key features:

- a single high efficiency beam coverage, specifically tailored on the Italian national territory by the use of a pre-formed antenna: this aspect allows to offer the same services irrespectively on the user location;
- uses standards suitable to transport IP packets, using proper encapsulation methods (such as Generic Stream Encapsulation, GSE), enabling interactive return channel via satellite for full-IP services;
- requires a a small antenna (i.e., typically 85 cm), and a simple installation and deployment in lack of any other telecommunication infrastructure.

Nonetheless, the available capacity to the 5G/IP based service depends on the physical characteristics of the satellite channels which are defined to respect the transmission standards. In particular, the overall bandwidth allotment must be divided into sub-carriers with different layouts according to the type of service and the transmission direction. Furthermore, it is necessary to consider carefully other system parameters such as EIRP (Equivalent Isotropic Radiated Power) at transmission, G/T (Antenna gain-to-noise-temperature, the specific figure of merit of the antenna in use = G_R/T in reception) and other losses (due to distortion, interferences, etc.).

To conclude the overview on Athena Fidus, a block diagram of the transmission and reception chain considered is provided for both DVB-S2 (used in forward link) and DVB-RCS links in [8] and [9] (used in return link) and shown in Figs. 1 and 2 respectively. All the functional blocks impact the overall performance and contribute to the determination of the Signal to Noise Ratio (SNR) thresholds for the link budget, and have been considered as well in the following analysis and simulations.

3 Service Overview and Channel Design

Link availability represents the percentage of time in which the link is suitable for transmission or, in other words, shows enough signal to noise margin to support the identified transmission mechanism. This value is calculated as a % over the year, and it is usually fixed to a target value agreed with users in the Service Level Agreement (SLA). While this value can be exactly calculated a-posteriori by continuous monitoring of the link status (i.e., to verify if the SLA was respected by the Satellite Operator), what is of interest is to consider this value as a statistical target and perform dimensioning and tuning of the system on that.

Therefore, the dimensioning of the system envisages first the determination of a reference link availability % and then the tuning of the best combination of other parameters (such as transmitter power, antenna gain, etc.), in accordance to statistical propagation models which take into account variable aspects such as rain attenuations, fading, etc. Once this activity, called link budget, is concluded, it is then finally possible to determining the modulation and coding to use and consequently the available bitrate at IP level.

Satellite commercial systems typically provide connectivity based services with 99.7% of availability. Of course, most critical services belonging to 5G specifications could require higher values so, in the analysis presented hereinafter, also values higher than 99.7% will be considered.

In order to perform an exhaustive analysis and determine the other system parameters, in this paper we considered a distribution of 2166 terminals across the Italian territory with the aim to cover different specific location characteristic (e.g., distance to the sea, altitude, rainy areas, etc.). The distribution of terminals adopted for the following simulations is represented in Fig. 3. The typical values for the current commercial Ka-band terminals which are used for the evaluation of link budget, which are: $G_R = 42$ dB and EIRP = 48 dBW [11].

Well assessed rain models are then applied using parameters which depend on the geographical location of the terminal. Each terminal location, expressed in terms of longitude, latitude and real altitude above sea level, will be used in all the calculations and simulations for the service evaluation.

On the basis of these simulations, and for each specific target Link availability (%), the nominal IP bandwidth that can be exploited by a Ka-band terminal by these characteristics can be evaluated taking into account the Carrier Symbol Rate (kbit/s) and the Modulation and Coding scheme (MODCOD) which can be used.

Table 1 summarizes the channel breakdown (bandwidth allotment) on the Athena Fidus transponder, as extracted from technical specifications available and considering the transmission and reception standards, equipment, antenna types and maximum amplifier power. For each channel the main parameters impacting the link budget computation are reported. In the present study, the star-based network architecture is considered as a baseline, where Athena Fidus makes use of a common broadband forward link, whereas a shared return link is used by many remote peers along the territory in time division.

Fig. 3. Identified terminal locations; Gateway is located at Fucino plateau.

Table 1. Athena Fidus channel repartition, [10].

Channel #	Connectivity	F_{UP} (MHz)	F_{DOWN} (MHz)	Carrier
15 + 17(1)	Star return (DVB-RCS)	29600	19520	10
15 + 17(2)	Star return (DVB-RCS)	29600	19520	144
15 + 17(3)	Star return (DVB-RCS)	29600	19520	116
16	Star forward (DVB-S2)	29427.5	19887.5	1
18	Star forward (DVB-S2)	29302.5	19762.5	1

The broadcast forward channels are number 16 and 18, with 75 and 125 MHz bandwidths respectively, making use of DVB-S2 standard. Then, Athena Fidus offers many carriers to be used in time division multiple access (TDMA defined in DVB-RCS standard) or as exclusive access. Such carriers are defined within the combination of channel 15 and 17, defining three different classes with different bandwidths (identified as (1), (2) and (3) leveraging the combined 15 + 17 channel). For each channel class, a different number of carriers is defined (last column) and, as reported in Table 2, a different respective bandwidth in MHz. Depending on the supported symbol rate/bandwidth per channel, this allows to create different narrowband links, with an overall bandwidth of about 200 MHz.

Table 2. Athena Fidus channel characteristics, [10].

Channel #	Symbol rate (MSym/s)	Roll-off	BW per carrier (MHz)	EIRP density (dBW/MHz)	G/T (dB/K)
15 + 17(1)	1.9	0.35	2.565	28	9
15 + 17(2)	0.64	0.35	0.864	28	9
15 + 17(3)	0.32	0.35	0.432	28	9
16	60	0.25	75	32.5	10
18	100	0.25	125	32.5	10

Definitively, the Athena Fidus terminals will be associated to only one of such carrier for the return link, and each single carrier can be associated to multiple terminals competing for the carrier bandwidth as defined by multiple access techniques required by DVB-RCS standard. Multiple access (TDMA) is normally enforced on channel 15 + 17(1), while the other 2 classes can be used also without contention (one carrier per terminal). On the other hand, for the forward link, all terminals will make use of the shared broadcast link (either channel 16 or 18).

4 Evaluation of Ka-band Attenuations

Once the channels are defined, the Ka-band propagation models [12–16] are applied to assess the attenuation margin as a function of the terminal coordinates/altitude above the sea level and of the target availability. This dynamic parameter, combined with the other system parameters discussed before, allows to evaluate accurate per-terminal link budgets. Taking as a reference the Athena Fidus coverage, the two frequencies $f_1 = 19.8$ GHz and $f_2 = 29.4$ GHz are considered as reference for downlink and uplinks, respectively, to show the attenuation margins. The other frequencies involved are considered in the correspondent simulations (e.g., 29.6 GHz for the return link uplink, and 19.52 MHz for the return link downlink), but attenuation results are not presented (presenting marginal differences with regard to the case discussed below).

Figure 4 shows the attenuation distribution due to propagation effects in the downlink (at $f_1 = 19.8$). It is obtained as a normalized histogram (so that the sum of all bins value equals to 1) of the values obtained from terminals, then representing an approximation of the Probability Density Function (PDF). This view allows to spot easily the attenuation trend, for different availability values of 99.9%, 99.5% and 99%, and the correspondent mean value. If the considered target application, which will make use of this kind of satellite segment, has an availability requirement of 99.9%, it can be satisfied designing the system to counteract an attenuation varying in the range 6–9.5 dB. The simulation results show that the higher attenuation values are encountered for sites located in North-East of Italy. With a lower availability requirement (i.e. 99.5%), the attenuation value to consider drops below 5 dB.

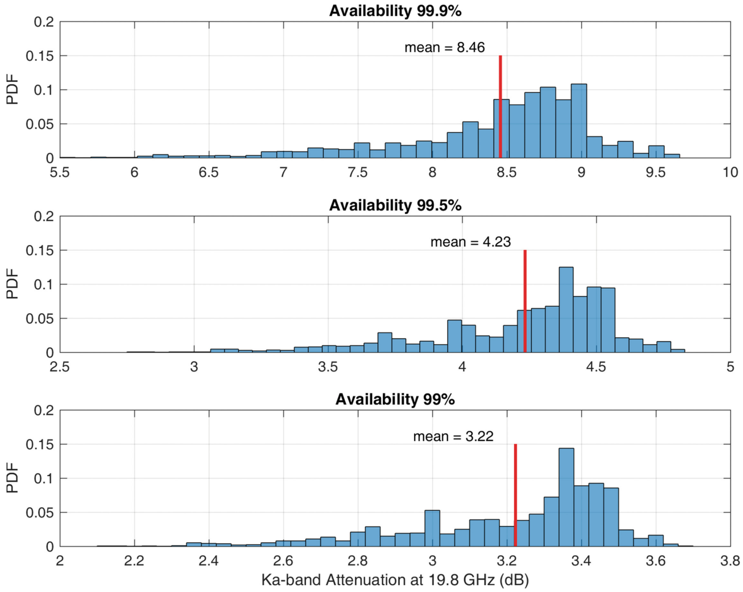

Fig. 4. Ka-band attenuation for $f_1 = 19.8$ GHz.

The same simulation output is reported for $f_2 = 29.4$ (related to the uplink) in Fig. 5. In comparison with the downlink, for an availability of 99.9%, the attenuation varies in the range 11–18 dB. This is due to the greater dependence on rain fading within this frequency range. It is clear that, for the overall link budget evaluation for a transparent HTS platform, such as the one considered in this paper, the uplink represents the most critical link with regard to the attenuation.

The same data have been post processed to provide another representation, where on the y-axis there is the attenuation value in ascending order and the x-axis represents the percentage of terminals considered in the simulation (from 0 to 100), positioned over the Italian territory as shown in Fig. 3. In this way, it is possible to assess the percentage of terminals of a given population which can be considered with attenuation below a target reference value. The results are shown in Fig. 6 for $f_1 = 19.8$ GHz, and in Fig. 7 for the uplink at $f_2 = 29.4$ GHz. This representation allows to focus on a specific percentage of terminals which will statistically suffer of that attenuation, allowing to support with more details the link budget evaluation for the system dimensioning, in case the position of the terminals to consider is not known in advance. It is possible for instance to identify the margin for the system dimensioning, only based on a subset of terminals. If considering 50% of terminals, it is possible to obtain the median of all attenuation values. For $f_1 = 19.8$ GHz and a required availability of 99.5% the median is 4.3 dB, while for $f_2 = 29.4$ GHz is 8 dB (so slightly different from the mean value showed before). As additional example, and reported with the

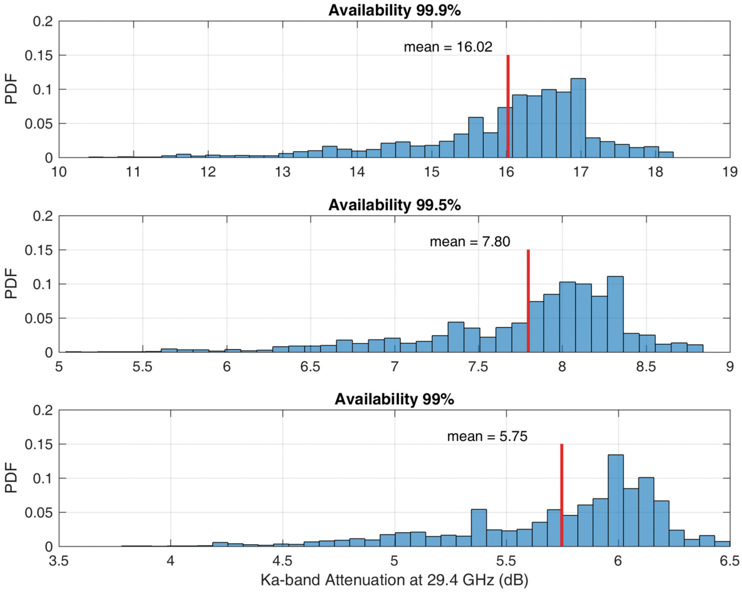

Fig. 5. Ka-band attenuation for $f_2 = 29.4$ GHz.

dotted lines in the plot, for an availability of 99.9% and considering the margin which allows to take into account 20% of terminals, the attenuation to consider is 8 dB for $f_1 = 19.8$ GHz and 14.7 for $f_2 = 29.4$ GHz, lower than both mean and median values. The presented results are referred to a distribution of terminals over the entire national territory but of course it would be possible to perform more limited analysis at regional level.

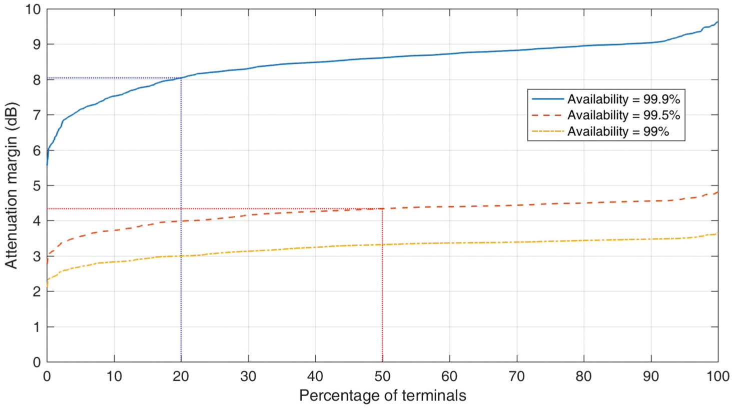

Fig. 6. Ka-band attenuation for $f_1 = 19.8$ GHz.

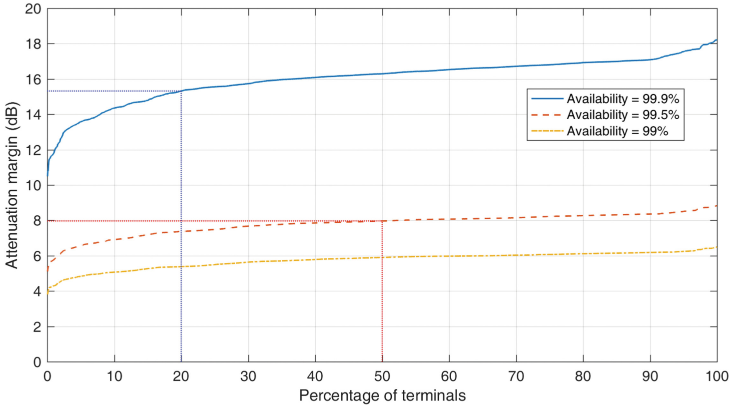

Fig. 7. Ka-band attenuation for $f_2 = 29.4$ GHz.

To conclude, a detailed analysis of "non-linear losses" in Athena Fidus is provided in [6]. The main loss contributions are due to High Power Amplifiers (HPA) distortions, up-conversion and down-conversion, Input-Multiplexed (IMUX) and Output-Multiplexer (OMUX) filters. An example of the main degradation contributions are summarized in Table 3, for some of the channels available and depending on the target modulation and coding scheme to use. For the simulations, they are combined as average in root sum square in order to consider adequately the overall attenuation value due to non-linear effects.

Table 3. Summary of Athena Fidus non-linear degradations.

			Average value of degradations (dB)			
Channel	ModCod	Carrier BW (MHz)	AM/AM AM/PM	Phase noise	Group delay variation	Amplitude variation
Fwd link Ka-band	QPSK 1/2	75	0.3	0.01	0.34	0.1
	8PSK 3/4		0.49	0.05	0.93	0.34
	16APSK 2/3		0.56	0.06	1.16	0.39
Ret link Ka-band	QPSK 1/2	5.4	0.3	0.01	0.2	0.1

5 Link Budget Results

All the parameters discussed in Sect. 3, supported by the propagation models described in Sect. 4, have been modeled and integrated in a MATLAB simulator aimed to compute link budget for both return and forward link of the target system, at all possible satellite links configurations. Relevant propagation models and ITU standards have been considered, specifically considering the attenuation margins achieved by previous simulations. The goal of the proposed analysis is to determine, given a certain degree of availability associated to a specific service, the useful channel capacity (in terms of available bit/s for TCP/IP traffic), which is indicated as C_{IP}.

Before computing link budget, the target signal-to-noise ratio (ideal SNR_0), to be used as lower-bound threshold for the link budget, were determined as a function of the eligible coding and modulation schemes and real channel choices. This in turns allows to determine the associated value of raw capacity available (C) in baseband, and consequently the capacity available at the IP level (C_{IP}) to support 5G services. In particular, the link budget requirements for a specific carrier are described in the next sections by means of:

- Mode – MODCOD reference for possible choice of "*Modulation scheme*" and "*coding rate*";
- Target (ideal) E_b/N_0 – as obtained from standards and test results found in literature, i.e. [17];
- Spectral Efficiency (η) – transmitted bits per Hz, computed as ratio between radiofrequency bandwidth (IF) and channel bandwidth $C = SR{\cdot}R_c{\cdot}log_2(M)$, where SR = Symbol Rate, R_c = overall coding rate, M = number of modulation symbols);
- Target (ideal) SNR_0 – signal to noise ratio computed as $E_b/N_0 + \eta[dB] + SR[dB]$;

The simulations will allow to identify the MODCOD to use according to the required availability, for each of the channel identified, and then derive the associated baseband capacity C, using the spectral efficiency values reported in the tables. From this C value, it is then possible to derive C_{IP} (Mbit/s), which is the capacity effectively available at the IP layer using the relations, discussed in [18] for average sized IP packets, of $C_{IP} = C \cdot 0.95$ for the forward link and $C_{IP} = C \cdot 0.86$ for the return link. The required SNR_0 for decoding and attenuation are evaluated for each of the 2166 terminals for all possible channel configurations.

5.1 Return Link

The summary of the link budget requirements and MODCOD selection presented hereafter, are based on [19], where the values for E_b/N_0 are referred to the useful bit-rate, so taking into account the factor 10 $log_{10}188/204$ (≈0,36 dB) due to the Reed-Solomon outer code) and include the modem implementation margins.

Link Budget Requirements and Calculation of the Nominal Capacity. Considering the channel configuration characterized by a symbol rate of 320 kSym/s (carrier $15 + 17(3)$), the maximum throughput allowed at the IP level is below 400 kbit/s, as summarized in Table 4. This rate is sufficient to set up low

Table 4. DVB-RCS link budget requirements for 320 ksym/s channels, [10].

Mode	Ideal E_b/N_0 [dB]	Spectral efficiency (η)	Ideal SNR_0 [dB]	C_{IP} (kbit/s)
QPSK 1/2	4.5	0.57	**57.14**	**213**
QPSK 2/3	5	0.76	**58.89**	**284**
QPSK 3/4	5.5	0.86	**59.9**	**320**
QPSK 5/6	6	0.95	**60.86**	**356**
QPSK 7/8	6.4	1.0	**61.47**	**373**

data rate services such as messaging, Voice over IP (VoIP), small file transfer, small data M2M and sensor networks data exchange.

Table 5 summarizes requirements and associated maximum capacity available at the IP layer over channels with symbol rate equal to 640 ksym/s $(15 + 17(2))$. The allowed IP capacity ranges from 427 to 747 kbit/s depending on the selected MODCOD. Such values are compliant with application requirements of medium data rate such as real time video streaming, file transfer, web browsing, distributed monitoring [20]. In fact, the obtained data rates are comparable with the ones experienced in the common ADSL return link, allowing satellite either to offload traffic coming from congested terrestrial networks or to backup terrestrial links during failures or outages.

Table 5. DVB-RCS link budget requirements for 640 kSym/s channels, [10].

Mode	Ideal E_b/N_0 [dB]	Spectral efficiency (η)	Ideal SNR_0 [dB]	C_{IP} (kbit/s)
QPSK 1/2	4.5	0.57	**60.1**	**427**
QPSK 2/3	5	0.76	**61.9**	**569**
QPSK 3/4	5.5	0.86	**62.9**	**641**
QPSK 5/6	6	0.95	**63.8**	**712**
QPSK 7/8	6.4	1.0	**64.4**	**747**

Finally, Table 6 concerns requirements for connectivity over 1.9 MSym/s channels (15-17(1)). Of course, requirements in terms of C/N_0 are more severe, while the allowed IP capacity is much higher: from 1.2 Mbit/s up to more than 2 Mbit/s. With data rates in this range even wideband services such as HD TV can be provided. Also this configuration is considered for link budgets.

Link Budget Analysis. Figures 8, 9 and 10 show results of link budget calculations for the whole set of terminals in terms of SNR_0, obtained by setting the transmitting antenna gain at 42 dB. Note that the results for different gain

Table 6. DVB-RCS link budget requirements for 1.9 MSym/s Channels, [10].

Mode	Ideal E_b/N_0 [dB]	Spectral efficiency (η)	Ideal SNR_0 [dB]	C_{IP} (kbit/s)
QPSK 1/2	4.5	0.57	**64.87**	**1268**
QPSK 2/3	5	0.76	**66.62**	**1691**
QPSK 3/4	5.5	0.86	**67.63**	**1903**
QPSK 5/6	6	0.95	**68.59**	**2114**
QPSK 7/8	6.4	1.0	**69.2**	**2220**

values of the antenna (in dB) can be immediately obtained by linearly up or down shifting the curves. The link budget margin (SNR_0) is reported on the abscissa, sorted in ascending order, for different availability targets. On x-axis it is reported the % of terminals considered for the analysis, similarly to the previous figures related to the attenuation study. On each plot, the reference thresholds for the selection of a specific MODCOD are indicated, by means of dashed lines.

For the $15+17(3)$ channel, availability curves are shown in Fig. 8, ranging from 99.9% to 99.5%. In this configuration, about the 10% of the the terminals is able to exceed the QPSK 1/2 threshold for an availability of 99.9%. If considering a slightly lower availability target, all the terminals are able to

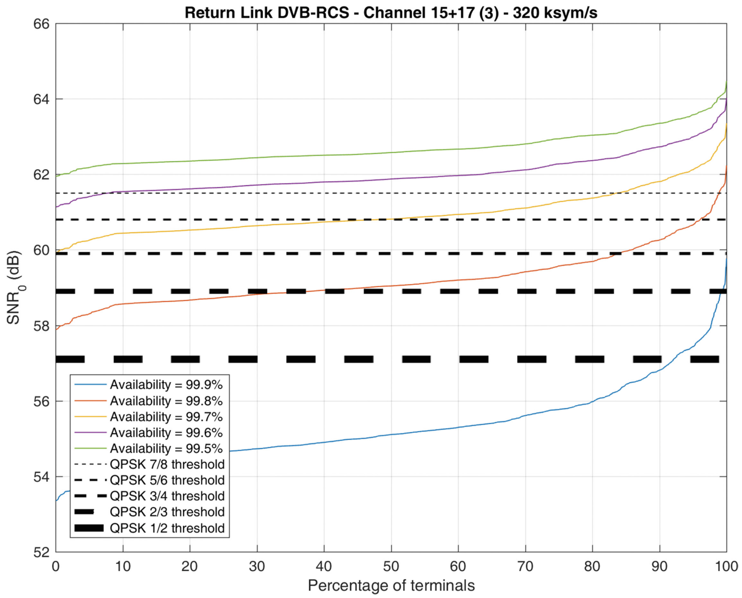

Fig. 8. Link budgets for 320 kSym/s carriers.

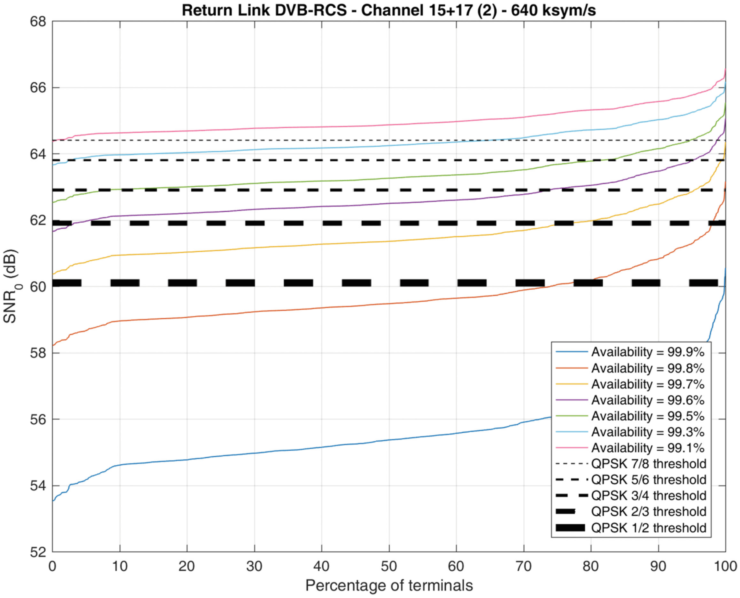

Fig. 9. Link budgets for 640 kSym/s carriers. (Color figure online)

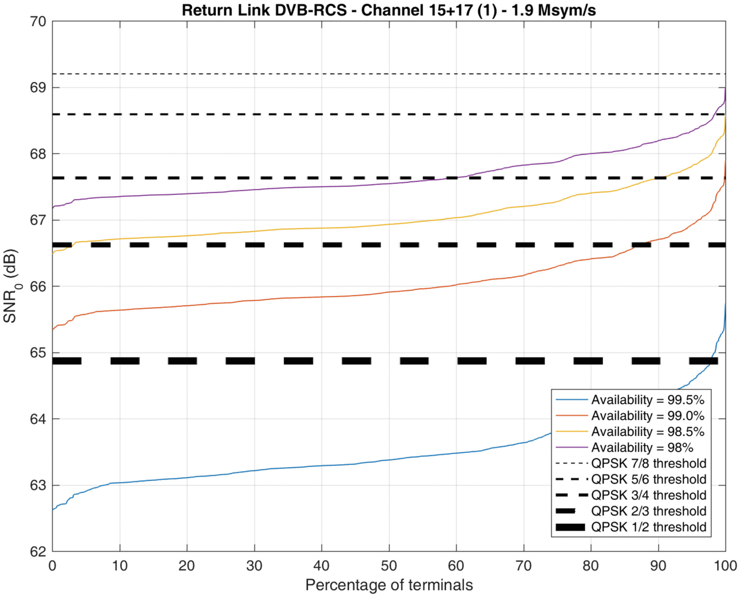

Fig. 10. Link budgets for 1.9 MSym/s carriers.

use the QPSK 1/2 and, in many cases, lower MODCODs. This type of channel, rather than offering multimedia and wide band communication, can become very important for narrow band ultra reliable services, part of the 5G applications portfolio. It is important to note that, narrow band channels can be achieved also if adopting bandwidth on demand (BoD) techniques, as described in DVB-RCS standard, or random access techniques [21], leveraging the broader channels (such as, $15 + 17(1)$). Nonetheless, this may require an higher SNR_0 as it will be shown in the following, although the channel can be shared among several terminals more efficiently rather than assigning a carrier in a dedicated way.

Figure 9 shows results for the $15 + 17(2)$ channel, offering a 640 ksym/s carrier, with the colored curves associated with different values of link availability selected for the link budget spanning from 99.1% (pink uppermost curve) up to 99.9% (blue curve). With an availability of 99.9% (blue curve), almost all the terminals are not able to comply with the link budget. A similar situation occurs with 99.8%, where only about 20% of terminals are above the QPSK 1/2 threshold. Setting availability to 99.7% (typical value exhibited for commercial services), all the terminals satisfy link budget requirements. About 20% of the terminals can even use more efficient MODCODs, thus working at rates up to 747 kbit/s. Finally, results improve even more when decreasing availability requirements. For instance, with 99.3% all terminals can work at a maximum rate higher than 700 kbit/s.

Figure 10 shows results when considering the highest capacity channels of 1.9 MSym/s. In order to guarantee that all the terminals satisfy link budget requirement, the target availability must go down to 99%. For higher values (i.e. 99.5%) only a small subset of terminals complies. On the other hand, while link budget respects the requirements, the amount of capacity available at the IP layer is much higher than the one allowed with the 640 ksym/s channel (in any configuration). In fact, with availability of 99% all the terminals can transmit at a maximum rate of at least 1.26 Mbit/s, while about 10% of the terminals can achieve up to 1.69 Mbit/s. As a general conclusion, these broad channels can be used for broadband applications that do not require commercial-like availability.

5.2 Forward Link

Communication on the forward link over channel #16, and Channel #18, characterized by parameters resumed in Tables 1 and 2, is specifically addressed. DVB-S2 standard is adopted, enabling a large number of combinations among modulation and coding schemes, as presented in [19]. For the evaluation of target E_b/N_0, and related ideal (nominal) SNR_0, Quasi Error Free conditions ($PER = 10^{-7}$) and white noise Gaussian channel are considered, with FEC Frame length set as normal (64800 bits). If considering short FEC Frame (16200 bits), an additional degradation of 0.2 dB to 0.3 dB has to be taken into account. Please note that the η efficiency parameter is the $(bit/s)/Hz$ ratio (considering the available baseband bitrate, or C), and not $(bit/s)/Sym$ as otherwise used.

Table 7. DVB-S2 link budget requirements for Channel #16, considering useful MODCODs.

Mode	Ideal E_b/N_0 [dB]	Spectral efficiency (η)	Ideal SNR_0 [dB]	C_{IP} (Mbit/s)
QPSK 1/4	−2.35	0.4	**75.43**	**28.53**
QPSK 1/3	−1.24	0.53	**76.54**	**38.04**
QPSK 2/5	−0.3	0.64	**77.48**	**45.64**
QPSK 1/2	1	0.8	**78.78**	**57.06**
QPSK 3/5	2.23	0.96	**80.01**	**68.47**
QPSK 2/3	3.1	1.06	**80.88**	**76.08**
QPSK 3/4	4.03	1.2	**81.81**	**85.59**
QPSK 4/5	4.68	1.28	**82.46**	**91.29**
8PSK 3/5	5.5	1.44	**83.28**	**102.7**
8PSK 2/3	6.62	1.6	**84.4**	**114.12**
8PSK 3/4	7.91	1.8	**85.69**	**128.38**
16APSK 2/3	8.97	2.13	**86.75**	**152.16**
16APSK 3/4	10.21	2.4	**87.99**	**171.18**
16APSK 4/5	11.03	2.56	**88.81**	**182.59**
16APSK 5/6	11.61	2.66	**89.39**	**190.2**
32APSK 3/4	12.73	3	**90.51**	**213.97**
32APSK 4/5	13.64	3.2	**91.42**	**228.24**
32APSK 5/6	14.28	3.33	**92.06**	**237.75**
32APSK 8/9	15.69	3.55	**93.47**	**253.6**
32APSK 9/10	16.05	3.6	**93.83**	**256.77**

Link Budget Requirements and Calculation of the Nominal Capacity. Some of several Modulation and Coding (MODCOD) configurations in the DVB-S2 forward link transmission are not of practical interest. Figure 11 shows the ideal SNR_0 as function of possible MODCODs for both Channel #16 and Channel #18, as inferred by the work by same authors in [10]. Some combinations of MODCODs at the same nominal SNR_0 offer a lower C_{IP} and can be discarded. For instance, if considering Channel #18 (100 MSym/s), and assuming a received SNR_0 in the range of 90–91 dB, either 8PSK 5/6, 8PSK 8/9, 8PSK 9/10 or 16APSK 3/4 offer a lower throughout at IP level compared to 16 APSK 3/4. Therefore, the possible channel configurations of interest for the forward link are presented for Channel #16 and Channel #18 respectively in Tables 7 and 8, where in particular η represents the spectral efficiency in terms of radio frequency bandwidth (MHz) and available bitrate (Mbit/s).

Link Budget Analysis. Target SNR_0 values are taken as thresholds to be compared to values achieved through link budget simulations related to all the

Table 8. DVB-S2 link budget requirements for Channel #18, considering useful MODCODs.

Mode	Ideal E_b/N_0 [dB]	Spectral efficiency (η)	Ideal SNR_0 [dB]	C_{IP} (Mbit/s)
QPSK 1/4	−2.35	0.4	**77.65**	**47.55**
QPSK 1/3	−1.24	0.53	**78.76**	**63.4**
QPSK 2/5	−0.3	0.64	**79.7**	**76.08**
QPSK 1/2	1	0.8	**81**	**95.1**
QPSK 3/5	2.23	0.96	**82.23**	**114.12**
QPSK 2/3	3.1	1.06	**83.1**	**126.8**
QPSK 3/4	4.03	1.2	**84.03**	**142.65**
QPSK 4/5	4.68	1.28	**84.68**	**152.16**
8PSK 3/5	5.5	1.44	**85.5**	**171.18**
8PSK 2/3	6.62	1.6	**86.62**	**190.2**
8PSK 3/4	7.91	2.8	**87.91**	**213.97**
16APSK 2/3	8.97	2.13	**88.97**	**253.6**
16APSK 3/4	10.21	2.4	**90.21**	**285.3**
16APSK 4/5	11.03	2.56	**91.03**	**304.32**
16APSK 5/6	11.61	2.66	**91.61**	**317**
32APSK 3/4	12.73	3	**92.73**	**356.62**
32APSK 4/5	13.64	3.2	**93.64**	**380.4**
32APSK 5/6	14.28	3.33	**94.28**	**396.25**
32APSK 8/9	15.69	3.55	**95.69**	**422.67**
32APSK 9/10	16.05	3.6	**96.05**	**427.95**

terminals. Results are shown in Fig. 12 for Channel #16. With a high availability of 99.9%, the totality of terminals show a link budget margin above the lower threshold (related to QPSK 1/4), so that connectivity requirement is always respected, giving at IP layer a capacity of at least 28 Mbit/s. In fact, most of the terminals are in conditions to work with QPSK 1/2, thus with a net IP capacity of 38 Mbit/s. Setting a slightly lower availability requirement (i.e. 99.5%), terminals can use a MODCOD much more efficient such as the QPSK 5/6 and then exploiting a capacity of about 95 Mbit/s.

Results for Channel #18, shown in Fig. 13, are very similar to those experienced in the previous forward link configuration, in terms of SNR_0. Of course, Channel #18 allows the achievement of much higher overall rates, once fixed the SNR leaving the same overall evaluation approach unchanged.

In conclusion, the forward link does not present any particular critical issue in the considered scenario, also for applications requiring high availability values.

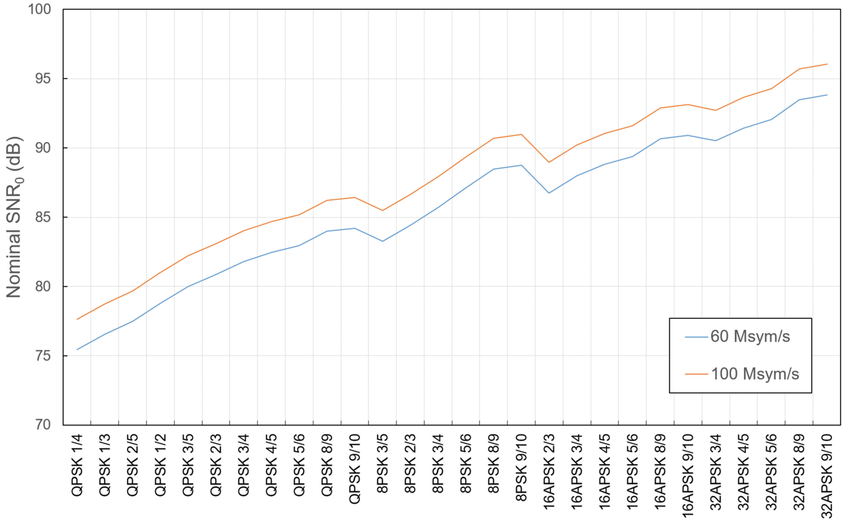

Fig. 11. Possible MODCODs in DVB-S2

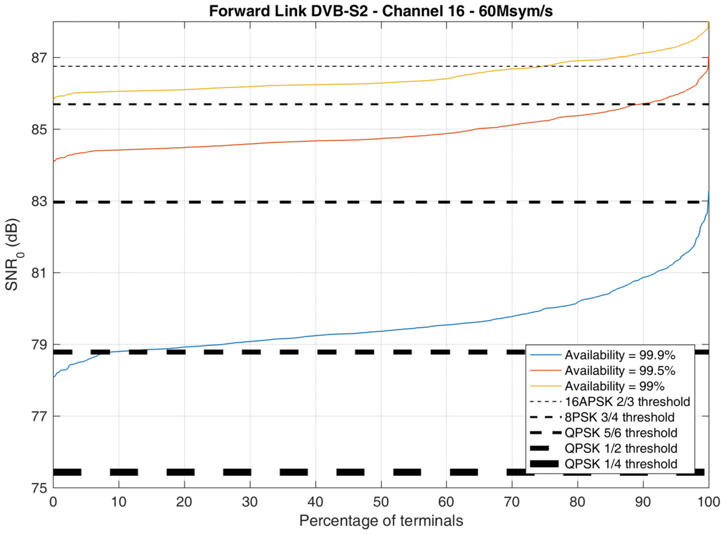

Fig. 12. Forward link ModCod configuration for Gateway - Channel #16.

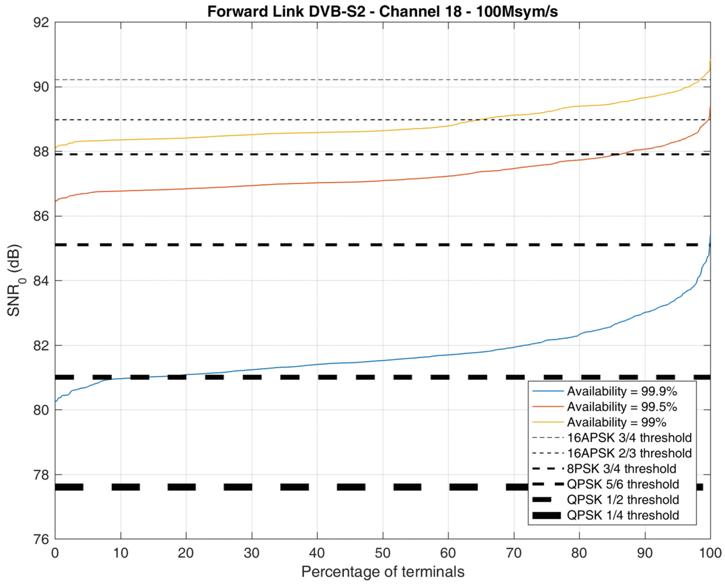

Fig. 13. Forward link ModCod configuration for Gateway - Channel #18.

6 Conclusion

In this paper we discuss in details the configuration and system specification of the Athena Fidus satellite platform, with a focus on its Italian Ka-band broadband interactive IP service. The Athena Fidus platform and its peculiar characteristics where presented and discussed in more details with regard to the previous work from the same authors [10]. Furthermore, this work represents an extension on previous works and available literature providing more details on system characteristics, and supporting with more details and additional simulations the possible system configuration for the Athena Fidus users and operators. From these outcomes, the identification of the most suitable configurations to support the provision of upcoming IP/5G services is possible. The authors are preparing an experimental campaign to compare the results presented in this paper with measures resulting by real installations. Once the analysis outcomes are confirmed, it will be important to test new transmission protocols and innovative approaches oriented to 5G communications on the real satellite links as in [22–24].

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