Benchmarking the Future of RF in Space Missions: From Low Earth Orbit to Deep Space

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***Abstract*— This paper reports on an internal study carried out at the European Space Agency (ESA) for assessing the reference performance of Payload Data Transmitters achieved in the mid-term. This assessment is meant to provide input to the ESA roadmaps for the 2023 time frame. The assessment is carried out for various space missions, from low Earth to deep space orbits.**

Taking advantage of technology evolution combined with innovative architectures and advanced digital signal processing, the paper shows how the data return in several space missions can be dramatically increased by reasonably extrapolating existing RF technology.

***Index Terms*—benchmarking, low Earth orbit, deep space, data return.**

I. Introduction

Space missions target the exploration of our solar system (e.g. BepiColombo and JUICE), or astrophysics, either solving mysteries of our galaxy or of extragalactic matter (e.g. Gaia and Euclid), or even related to fundamental physics (e.g. LISA). Regardless of the scientific objective of a mission, over the years more complex experiments have been designed and the possibility of collecting an increasing volume of data is a general trend in user needs [1] .

The purpose of this paper is to report on an internal study carried out by the European Space Agency (ESA) for assessing the reference performance of Payload Data Transmitters (PDT) achieved in the mid-term. Different scenarios based on plausible/existing mission concepts are defined. Based on these concepts, an assessment of how much the performance can be improved employing new communications techniques and technologies available in two different time frames is presented. The selected time frames are: **'2017 frame'**, representing today's capabilities and **'2023 frame'**, as a predicted medium-term evolution. Those dates should be understood as the year of availability for the needed technology, therefore at a Technology Readiness Level (TRL) ≥6 [2]. They should not be understood as intended mission launch dates. This assessment is carried out for various space missions, from low Earth orbits to deep space orbits.

A secondary objective of this paper is to better appreciate the potential and the limitations of RF technologies with respect to each mission and system scenario in comparison with alternative technologies, e.g. optical communications.

The following techno-economic criteria are used to assess each mission:

a. Data rate (e.g. Megabits/second)
b. Volume of data transferred in a given time (e.g. Terabit/day).
c. On-board resources in terms of spacecraft power, size and mass.
d. Link availability
e. Reliability of equipment.

II. Methodology of the Study

A. System Assumptions

Most of the RF system assumptions considered in this study are the result of either prior ESA industrial activities or internal work. In terms of frequency bands, depending on the service, various allocations of Ka-band have been considered in order to offer competitive link performance.

B. Ground & Space Terminals

The choice of characteristics for the space and ground RF terminals available in the 2017 frame are derived by the manufacturers' data sheets and specifications where available and by using planned or existing ESA missions. For the capabilities and characteristics of terminals of the 2023 frame, reasonable extrapolations based on technology trends and ESA roadmaps are provided.

C. Transmission Channel

The availability of RF links above 10 GHz is limited mainly by rain attenuation and, to a much lesser extent, by cloud attenuation and scintillations. For all the categories of space missions studied in this paper, the atmospheric phenomena impairing the RF channel are modelled employing ITU-R prediction models, predominantly the ITU-R Recommendation P.618 [3] as well as its underlying recommendations.

D. Advanced Physical Layer Techniques

A key enabler for some RF communication systems exhibiting a large dynamic ranger of received power (e.g. in the case of a LEO pass) are link adaptation strategies such Variable Coding and Modulation (VCM) and Adaptive Coding and Modulation (ACM) [4]. These techniques are used to adapt the physical layer configuration to the current channel conditions thus maximizing the data return during favourable conditions while minimizing the outage during unfavourable conditions.

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Apart from link adaptation, to push the limits of RF systems, transmitter and receiver techniques are needed to counter the effects of linear and non-linear distortions. Such modules are already available with existing technology even within telecom consumer equipment. They fall under the various flavours of *pre-distortion* at the transmitter and *equalization* at the receiver [5].

III. High Rate LEO-to-Ground Telemetry

A. Mission Concept

The new generation of scientific LEO satellites for Earth Exploration Satellite Services (EESS) provide high data rate telemetry links for the data collected from on-board Earth observation instruments. Exemplary systems are the ESA Sentinels.

B. Assumptions & Results (2017 & 2023 Frame)

In this paper, the system is assumed to be operating at the K frequency band (26 GHz) within the 1.5 GHz spectrum assigned to EESS. A two-channel PDT is considered using two high power amplifiers (HPAs), as shown in Figure 1.

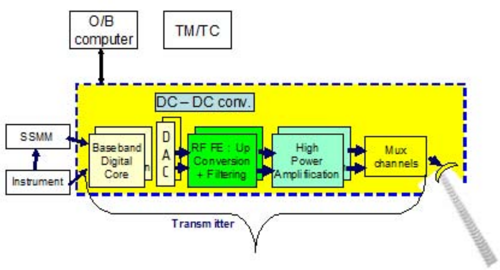

Fig. 1. Transmitter for two parallel RF channels on board the LEO spacecraft.

Three locations are considered for the RF ground terminal, namely Svalbard, Norway, McMurdo, Antarctica and Matera, Italy. Given the orbit at hand (polar orbit of Sentinel 1A), for Svalbard there are 136 min/day visibility for a minimum elevation of 5^{o}. The assumptions for the 2017 frame are as follows: The ground station is assumed to have an antenna of 5.8 m aperture. In terms of physical layer waveform, the complete set of 27 possible combinations of modulation & coding (ModCods) foreseen in the CCSDS SCCC standard [6]. The symbol rate per channel is 500 Msym/s. During a LEO pass over any ground station, the changing link geometry varies substantially the link margin. To exploit this fact, for each sector the most suitable out of the available ModCods is selected. This concept is referred to as VCM. For the 2023 frame, the adaptation technique is based on real time channel info (ACM), the ground station antenna is increased to 7.2 m and the channel bandwidth to the whole 1500 MHz allocation (single carrier). Thereby, two channels imply also the use of the second polarization.

Extensive computer simulations have been carried out with a system simulator by emulating the VCM/ACM principles for the three ground station locations over an orbit propagator. The summary of results in provided in Table I.

TABLE I: Summary of High-Rate LEO-To-Ground Telemetry Mission Scenario

	RF (2017 Frame) 2 channels	**RF (2023 Frame) High Data Rate 2 channels**
Data Rate	Variable (VCM) 2x (360 Mbps-2.2 Gbps)	Variable (ACM) 2x (691 Mbps-4.2 Gbps)
Data return	30.0 Tb/day (Svalbard, availability 99.5%) 31.4 Tb/day (Svalbard, availability 95%) 41.5 Tb/day (Svalbard + Matera, availability 95%)	84.3 Tb/day for ACM (Svalbard, availability 95%) 208.4 Tb/day for ACM (95%), 254.5 Tb/day for ACM (Svalbard+ Matera+ Mcmurdo,)
Space terminal power	~154 W	~ 250 W
Space terminal Mass - Reliability	26 kg (with redundancy)- 0.97 reliability	21 kg (with redundancy)- 0.97 reliability
Space terminal volume	~9.0 lt (inside platform) + antenna)	~9.0 lt (inside platform) + antenna)
Space terminal aperture	15 cm	15 cm
Ground network	Single station (5.8 m antenna) Two stations as an option for an increased data return	Single station (7.2 m antenna) Three stations as an option for an increased data return
Lifetime	7 years	7 years

IV. Lunar & L2 Missions

A. Mission Concept

The Lunar scenario refers to a system providing communications from a lunar orbiting satellite to a ground station on the Earth's surface. This scenario became interesting after the 2013 launch of the NASA's LADEE mission. ESA has no Lunar mission, therefore only the 2023 frame is considered.

The L2 orbit consists of a halo around the Second Sun Earth Lagrange point with the distance from Earth ranging between 1.5 and 1.7 million km (during orbital period). The mission concept in this case consists of a telescope in L2 orbit to perform science observations of deep space. A typical example of an L2 science mission is the ESA Euclid mission.

B. Assumptions & Results (2017 & 2023 Frame)

An on-board PDT of a class similar to Euclid is assumed for both Lunar and L2. The following parameters are used for the results reported in Table II: Frequency band: K-band (26 GHz), RF bandwidth occupied: 500 MHz (2017)/650 MHz (2023), spacecraft antenna: 65 cm (2017)/ 1.0 m (2023), transmit power at saturation: 50 W, ground station antenna: 35 m (Cebreros), metasurface antennas (to reduce on board mass in 2023), and use of current cryo-LNA and feed technology. In all cases the CCSDS SCCC waveform is used.

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TABLE II: SUMMARY OF LUNAR & L2 MISSION SCENARIO

	Lunar mission (2023 Frame) 35 m antenna	**L2 mission (2017 Frame) 35 m Antenna**	**L2 mission (2023 Frame) 35 m Antenna**
Data rate	2154 Mbps	762 Mbps	1467 Mbps
Data return	5.72 Tbit in 44 mins	7.5 Tbit in 164 min	7.5 Tbit in 85 min
Space terminal power	~110 W	~110 W	~110 W
Space terminal mass - reliability	18 kg – 0.97 reliability	29 kg (Euclid) – 0.97 reliability	18 kg – 0.97 reliability
Space terminal volume	9 ltr (inside platform) + antenna	9 ltr (inside platform) + antenna	9 ltr (inside platform) + antenna
Ground network	2 stations in different hemispheres with 35m antennae		
Lifetime	6 years	6 years	6 years

V. DEEP SPACE MISSIONS

A. Mission Concept

The deep space scenario refers to a system providing communications to a spacecraft beyond the 2 million kilometer range. In this section, two such links are examined, namely a mission to Mars (far range) and a mission to Jupiter (far range).

As the PDT characteristics of deep space science missions are very mission dependent, it was decided to carry out simple link budget exercises along with an assessment of the needed resources, without entering into the specifics of the science objectives of the mission.

B. Assumptions & Results (2017 & 2023 Frame)

Table III is using Mars Express and Juice for the Mars and Jupiter 2017 frame. For the 2023, the deep space allocation at Ka band (32 GHz) is adopted, on board antenna 3 m, on board HPA of 75 W, 50 mdeg. 3 sigma pointing accuracy, 35 m ground station at Cebreros and CCSDS turbo FEC coding scheme.

TABLE III: SUMMARY DEEP SPACE (MARS, JUPITER) MISSION SCENARIO

	Mars mission (MEX X-Band) 35 m Antenna	**Mars mission (2023 Frame, Ka-Band) 35 m Antenna**	**Jupiter mission (2017 Frame, JUICE X/Ka-Band) 35 m Antenna**	**Jupiter mission (2023 Frame, Ka-Band) 35 m Antenna**
Data rate at far range	0.033 Mbps	2.65 Mbps	0.025 Mbps	0.370 Mbps
Space terminal power	140 W	160 W	175 W	175 W
Space terminal mass - reliability	37 kg	45 kg	78 kg	45 kg
Space terminal volume	TBD	TBD	TBD	TBD
Ground network	2 stations in two different hemispheres, 35 m antenna			
Lifetime	TBD	TBD	TBD	TBD

VI. CONCLUSION

A number of space missions (LEO, Lunar, L2, Mars, Jupiter) have been extrapolated to the mid term considering realistic assumptions on the available technology. In some case, the RF technology can provide a significant improvement in offered data return for a reasonable on board PDT burden.

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