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Resource Balancing for Federated Satellite Systems

Ignasi Lluch[1] and Alessandro Golkar.[2]
Skolkovo Institute of Science and Technology, Skolkovo, Moscow Region, 143025 Russian Federation

The amount of available resources on board a spacecraft determine the extent of its potential participation in Federated Satellite Systems (FSS). FSS are a new approach to space missions with the goal of enhancing mission sustainability, performance and reliability by the exchange of resources such as data storage, processing and relay among participant spacecraft. This work quantifies the design impacts for spacecraft willing to offer or use its data relay through the federation. Participation of spacecraft in a FSS ranges from sharing its unused resources (FSS operations on design margins) to partial or full spacecraft redesign reallocating part of mission functionality to the federated network (full FSS operations). Spacecraft in a FSS may act as suppliers of resources, customers of resources, or any hybrid role in the middle where satellites could be suppliers and customers of the network at the same time. This paper conducts a first design exploration of this tradespace assuming a dual supplier/customer nature of spacecraft (no hybrids), and assuming FSS operations on design margins. The paper develops a spacecraft model to study resource balancing in federations, including power, attitude control, communications and ISL subsystems. The goal is to quantify the necessary changes in the federated spacecraft in terms of system-level mass as a function of benefits obtained by participating in the federation. Impacts for small, medium and large spacecraft in Low Earth Orbit (LEO) offering a relay service on design margins are shown to be 12% (small platforms), 1.1% (medium platforms) and 0.6% (large platforms) in loaded mass. This results thus reveals that a relatively small mass overhead is required to participate in spacecraft federations to operate at design margins. Spacecraft relaying data through the federation may substitute space-to-ground link capabilities for FSS Inter-Satellite Links leading to mass savings up to 4.5% of loaded spacecraft mass. Finally, an analysis through lifetime shows that current power margins on spacecraft allow for a connection to the federation of 500s/orbit up to the 70% of spacecraft lifetime. The paper paves the way towards more sophisticated modeling of FSS operations aimed at addressing more general cases of participation schemes in FSS in hybrid/customer roles, and allowing designers to identify sweet spots in the level of participation to spacecraft federations.

Nomenclature

$\alpha_{steering}$	=	Acceleration of the steering mechanism
ε_{wheel}	=	Electric to kinetic energy momentum wheel conversion efficiency
η	=	Efficiency of the solar array
$\omega_{0\,wheel}$	=	Nominal speed of the momentum wheels
E	=	Energy requirement of momentum wheels
$I_{antenna}$	=	Inertia of the inter-satellite link antenna
$I_{\omega heel}$	=	Inertia of momentum wheel
t	=	Duration of the steering maneuver
T	=	Temperature of the solar array
ACDS	=	Attitude Control and Determination System
BOL	=	Beginning of Life
DOD	=	Depth of Discharge

[1] Graduate Research Assistant, Skoltech, Novaya St., 100, 143025 Russian Federation, AIAA Student Member.
[2] Assistant Professor, Skoltech, Novaya St., 100, 143025 Russian Federation, AIAA Member.

EIRP	=	Equivalent Isotropic Radiated Power
EO	=	Earth Observation
EOL	=	End of Life
EPC	=	Electronic Power Conditioner
FSS	=	Federated Satellite Systems
ISL	=	Inter-Satellite Link
LEO	=	Low Earth Orbit
LEOP	=	Launch and Early Orbit Phase
P2P	=	Peer to Peer
PTT	=	Peak Power Tracking
RF	=	Radio Frequency
SSPA	=	Solid State Power Amplifier
TT&C	=	Telemetry, Tracking & Control
TWTA	=	Travelling Wave Tube Amplifier

I. Introduction

FEDERATED Satellite Systems (FSS) are an emerging concept[1-4] proposing the exchange of space-based resources such as data relay, storage and processing among participant spacecraft. The goal of FSS is to enhance sustainability, reliability and performance of new and existing space missions. The implementation of a distributed architecture of this type requires the realization of a Peer-to-Peer (P2P) communications network. Space-based networks have been implemented and extensively discussed[5] to achieve a variety of mission goals, such as deep-space communications[6] terrestrial mobile communications[7] and others.[8] The space network concept enabling the deployment of FSS differs from the former by supporting opportunistic links between heterogeneous spacecraft,[9] as opposed to pre-defined constellation networks. Such links are established on a voluntary basis subject to the needs of participating spacecraft, following similar processes observed in smart grids of terrestrial electrical distribution systems.

Seeking the most advantageous conditions to engage in this space-based market requires to understand the complex interplay - *balance* - between the gains in resources and capabilities achieved by operating within FSS, and the system-level impacts in spacecraft design for operating in a federation. The goal is to support mission designers to identify optimal sweet spots between participating to a spacecraft federation to achieve part of required mission functionalities, and implementing the rest of functionalities in their spacecraft design. This paper is a first step towards the direction of assessing design impacts at system level when a spacecraft acts as a node in an FSS network. Specifically, this paper attempts to quantify **what are the design impacts in mass and power of operating an FSS ISL subsystem to engage in a federation of satellites, assuming that spacecraft are willing to trade in the federation their unused resources (FSS operations at the margin) without significantly affecting their design.**

Participating spacecraft in FSS choose to what extent they wish to engage in exchange of resources, depending on their needs or the availability of on-board spare capacity. Their commitment can range from occasional to full time connection, depending on needs, orbital geometry and spacecraft power constraints. The focus in this paper is on analyzing occasional participation of spacecraft in a federation, that is, the minimum spacecraft design impact case.

Performing a relay function or carrying out any of the envisioned data-based exchanges requires a data transfer system, implemented as an Inter-Satellite Link (ISL) communications payload onboard participating spacecraft. Adding this ISL communications payload to a spacecraft (from now on referred as *FSS ISL*) requires an overhead in mass and volume, that constitutes part of the entry cost of joining the space-based market proposed by FSS. Another significant design impact to be addressed in future work concerns spacecraft configuration changes to ensure an unobstructed field of view to the primary payload and avoid electromagnetic compatibility issues with the FSS ISL. The FSS ISL requires an amount of power to be operated, being this equivalent to the operation costs of participating in the market. Besides from the power subsystem, other subsystems such as communications and Attitude Control and Determination System (ACDS) also experience changes when introducing FSS ISL payload in the spacecraft.

The system level impacts and subsystem impacts of operating within an FSS are explored in this paper by the development of a bespoke spacecraft model that accounts for the interrelations and dependencies of the spacecraft subsystems with the FSS ISL.

The remainder of this paper is structured as follows: Section 2 defines the design and operational approaches for spacecraft participating in FSS. Section 3 describes the spacecraft model assembled to analyze the impacts of such design and operational approaches. Section 4 highlights the impacts and resource optimal balances attainable by different platform classes. Section 5 draws conclusions from this research and outlines the future work in the area.

II. Design and operational approaches to FSS

The schedule of operations of the ISL payload drives the design impacts on spacecraft. This schedule is very dynamic in nature and depends on the market role and strategy of participating spacecraft. Operations are constrained by spacecraft resource limitations (available power, data storage, adequate attitude) and by orbital geometry constraints.[2] Furthermore, the strategy of participating spacecraft may also change in time, if the FSS market adopts dynamic pricing policies. Considering FSS from the perspective of a data relay service two representative roles can be defined[4] for the federated spacecraft. One option is to be a **Supplier**; a supplier spacecraft engages in the federation to offer resources such as data relay to the ground. For the purposes of this paper, this translates into a direct requirement for the space-to-ground link to download the additional amount of data acquired from the ISL subsystem. The supplier has a positive FSS data flow balance, receiving more data than it sends, and therefore obtaining positive revenue from the FSS operation. Another option is to be a **Customer**; a FSS customer spacecraft relays data through the system to achieve enhanced reliability, performance, or to relieve the space-to-ground communications subsystem. The customer has a negative data flow balance, sending more data than it routes through itself.

Note that these roles are interchangeable and encompass a variety of hybrid approaches, where spacecraft are customers and suppliers at the same time, and changing their role balance at different phases during their mission lifecycle. A possibility for a customer spacecraft is to completely outsource all of its data-based functions (processing, storage, relay) to the federation. Hybrid participation roles and full FSS engagement are not considered in this paper, which instead focuses on more fundamental analysis of spacecraft acting as customers or suppliers, operating in the federation with their unused resources (available design margins).

For the purposes of this paper, the customer is always assumed to be a **network data source** and can downsize its space-to-ground communications subsystem by routing the data via the federation. Reciprocally, the supplier spacecraft always acts as a **network data sink**, and this introduces important design changes. The space-to-ground link has to be oversized to manage the additional data relay to ground. Note that in the case of multiple-hop connections, one or more participant spacecraft may act as data routers, buffering data and retransmitting it when the supplier is available. When the data reaches a supplier, it has to be transmitted to the ground. Figure 1 exemplifies the evolution of the downlink data rate requirement on the supplier spacecraft offering a relay service, depending on the data volume acquired via ISL. For this example, the supplier is assumed to be at 800 km altitude and downlink the data via a single ground station contact per orbit. Realistic limits to the achievable downlink data rate are around 500 Mbit/s on X-band for Low Earth Orbit (LEO).[10]

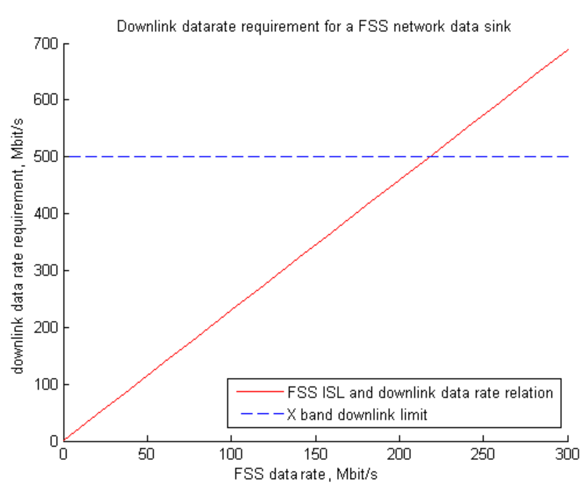

Figure 1. Downlink data rate requirement for a FSS network data sink. *The downlink data rate requirement on the supplier is a function of the ISL data rate. Results obtained assuming 10 ISL contacts of 120 sec per orbit.*

The transmission and data relay operations are limited by the spacecraft's operational approach to FSS. Two situations can be distinguished. A first operational approach is to **operate the ISL subsystem by using spacecraft design margins**. This approach seeks to participate in the federation in an opportunistic way with the minimum impact on spacecraft design. In this approach, the extra capabilities originated by spacecraft design margins support the participation in the federation. One of the most significant design margins is found in the power subsystem. Solar-powered missions present a significant difference on power production at the Beginning of Life (BOL) and at the End of Life (EOL) due to solar cell degradation.[11,12] The amount of excess power produced will progressively decay towards 0 at EOL. The FSS ISL subsystem can exploit this power excess, resembling a non-critical mission payload with a progressively less frequent activation. A second operational approach is to **re-design the spacecraft** to allow for the full use of the FSS ISL subsystem in a constant fashion through lifetime, that is, operate the FSS ISL *by design*. This implies increasing the power provision for EOL and modifying the communications and ACDS if needed.

Figure 2 illustrates the different approaches explained in this section, ranging from customer to supplier-based approaches and from marginal to fully capable FSS engagement, which requires the redesign of power, ACDS and communications subsystems.

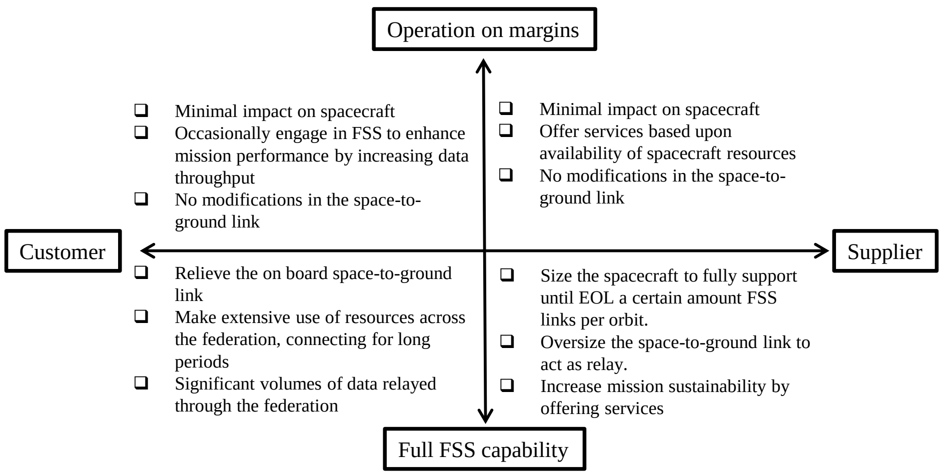

Figure 2. Notional classification of different engagement regimes on the federation.

The next section describes the spacecraft model developed to estimate the design impacts of the operation regimes described above.

III. Spacecraft Model

The approach chosen is to develop a spacecraft model, including the subsystems most affected by adding an ISL subsystem and deriving the impacts up to system-level mass and power. Spacecraft bus power is the first noticeable spacecraft resource being directly used as in the spacecraft federation through the operation of the ISL. Ultimately, any change in the onboard power consumption profiles has an impact on spacecraft mass and the mission's concept of operations. The change in spacecraft loaded mass is recognized as the proxy metric for system-level spacecraft impacts.

The model captures the main interactions between key subsystems and the FSS ISL with an adequate level of fidelity given the purpose of the analysis. The chosen level of fidelity goes beyond general purpose spacecraft sizing literature[13] while avoiding specificities that are exclusive to second-level subsystem design details. The spacecraft model here developed describes system changes relative to a reference design, rather than attempting to give absolute sizing estimations. The next sections describe which subsystems are to be considered and how are they modeled.

A. Subsystems considered

The model considers the following subsystems: *Power*, *Telemetry, Tracking and Control (TT&C)*, *FSS Inter-Satellite Link*, and *Attitude Control and Determination Subsystem (ACDS)*. The Power subsystem is directly affected by the additional consumption of operating an ISL module. An accurate modeling of this subsystem is key to understand the evolution of power margins on the spacecraft through lifetime. The communications to ground are enabled by the TT&C subsystem. TT&C is one of the key elements which capacity can be scaled upwards or downwards depending on the role and intensity of engagement of the spacecraft in the federation. The FSS ISL communications subsystem and the space-to-space RF link are included in the spacecraft model to assess its system-level impacts in terms of mass and power consumption. Lastly, as the FSS payload is assumed to use a steering mechanism to orientate the antenna,[2] extra loads to the ACDS and associated design impacts need to be considered in the modeling effort.

The additional volume of data management and steering mechanism is assumed by the FSS ISL model, hence the data handling and mechanisms/structures subsystems is not explicitly modeled. The influence of the FSS ISL on the propulsion subsystem would appear as an increased wheel de-spin requirement, but this is ruled out due the acceleration-neutral movements of the steering mechanisms (see section 3C). Thermal subsystem is not included since this system is very sensitive to particular spacecraft configurations and no general trends can be outlined. This paper does not analyze the data storage and payload data handling requirements on the ground segment, which are included in future work.

The interfaces between subsystems taken into account are shown on Figure 3. The interrelations between FSS module and communications subsystems are expressed by data relay requirements. The amount of operations performed by the FSS module steering antenna poses a load on the ACDS system, which in turn translates into a power requirement. The modified power requirements of the ACDS, FSS and Communications subsystem are fed into the power subsystem. Lastly, the mass variation of these subsystems is added to obtain a system-level impact on the spacecraft mass budget.

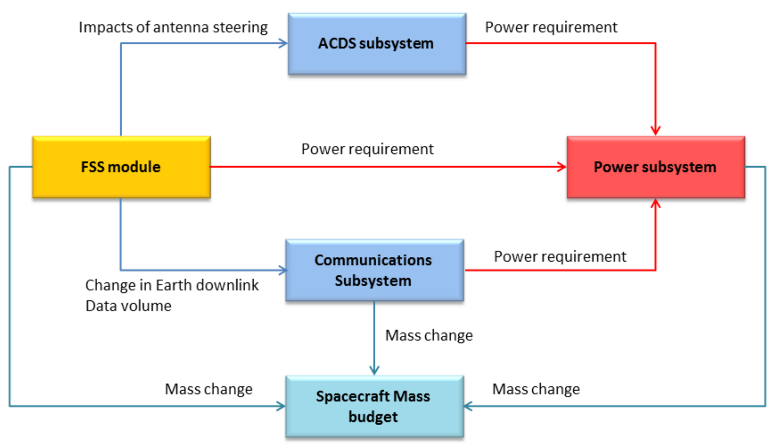

Figure 3. Flow of design impacts across the considered subsystems.

A.Power subsystem model

Overview

The power subsystem sizes the solar array and battery taking into account the load profile of the spacecraft, with the requirement to meet all subsystems consumption until End of Life (EOL). The model makes four main assumptions in regards to the power subsystem. The first assumption of the model is to assume a solar-powered spacecraft with three-axis stabilization and sun-pointing array mechanism. The solar array energy transfer system is considered to be peak-power tracking (PTT). [11,14]. For excess power computation purposes, the output power generated corresponds to maximum power achieved by operating always at the maximum output point on the array V-I characteristic curve.[14] The second assumption being made regards the evolution of solar panel efficiency over the course of the orbit. It is assumed that solar array efficiency evolves as a function of its temperature: [15]

$$\eta(T) = \frac{\partial \eta}{\partial T}(T - 28) \tag{1}$$

Where, in Eq. 1, T is temperature in Celsius degrees; data on the gradient dη/dT is found in Ref. 15, Table 10.5, as a function of cell technology type. The temperature on the solar array is evaluated by solving a centered finite differences numerical approximation of the transient-state thermal balance of the array.

The third assumption considered regards the modeling approach of the pointing misalignment between solar array and the sun vector, which affects the power production of the array. This factor is modeled as white noise centered on 0 degrees (no misalignment) and a default standard deviation of 3 degrees.

Lastly, the model makes a fourth assumption on solar cell degradation over time. This degradation ranges from 0.5%% to 5% per year[13,16] depending on the orbital environment. The model uses cell manufacturer data[17] to estimate this value.

In addition to sizing the power subsystem, the model is capable of assembling a continuous power generation profile for the entire lifetime of the spacecraft, taking into account power generation dynamics including battery charging and discharging. Figures 4 to 7 show the evolution of the power generation, battery characteristics and spare power produced based on an assumed End-of-Life (EOL) required power consumption profile, of 1760 W on average. The spacecraft orbits at 700 km altitude and is powered by triple junction solar cells[18] that degrade the 2.75% per year. Eclipse time is taken as 35 minutes, and the design lifetime is 10 years. The figures correspond to 5 orbital revolutions at Beginning-of-Life.

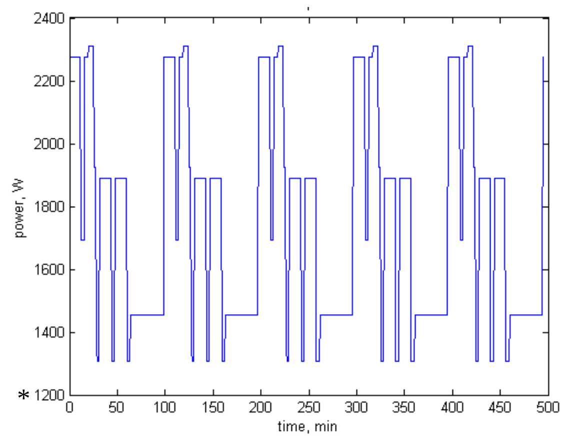

Figure 4. **Load profile.** *Assumes one ground station contact, payload 80% duty, heaters on in eclipse.*Note y-axis origin is 1200W.*

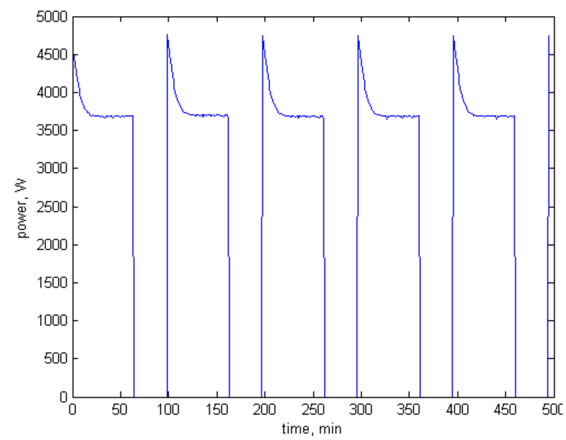

Figure 5. BOL array power output. *This output is sized to meet the average EOL consumption of 1760W.*

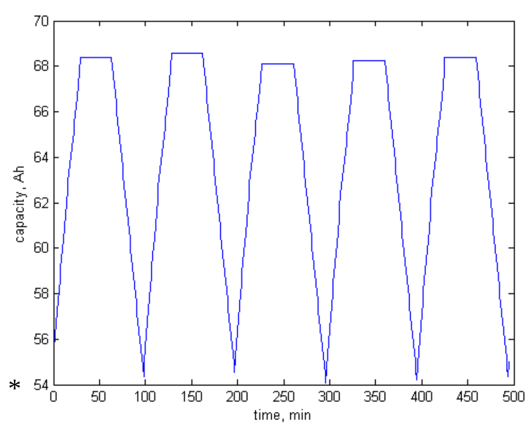

Figure 7. Battery state of charge. *20% Depth-of-Discharge limit set.*Note y-axis origin is 54A*

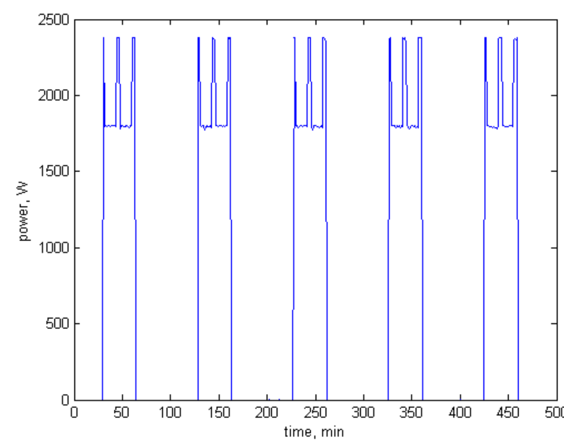

Figure 6. Excess power generated at BOL after battery charging.

Figure 5 shows that the BOL peak power production of the array is 2 to 3 times larger than the average power consumption requirement at EOL (1760 W). This is not only due to different system efficiencies and the need to provision power for the eclipse time; this over-sizing is indeed required to account for solar panel degradation through lifetime. An additional power margin that is typically found is due to the beneficial effect of post-eclipse colder temperatures on the array providing extra power production. This factor is typically overlooked in conservative sizing of the solar array. All these effects originate the BOL excess power shown on Figure 6, which shows the amount of the additional power that could be gathered after battery charging. Figure 7 exemplifies the simulation of battery cycles and how a healthy system is able to keep the batteries above the Depth-of Discharge (DOD) limit set, as opposed to the process on Figure 9. If profiles are run through a 10 year simulation, the progressive degradation of the array brings this excess power close to 0 as expected. Figure 8 illustrates this evolution.

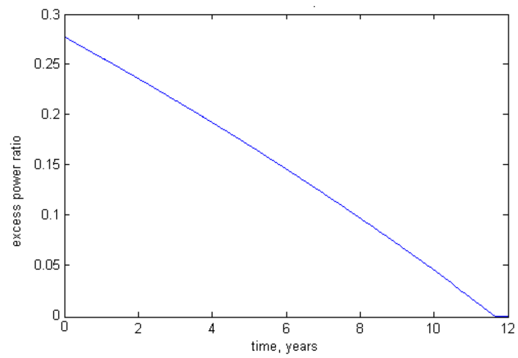

Figure 8. Excess power to total power available on bus through lifetime.

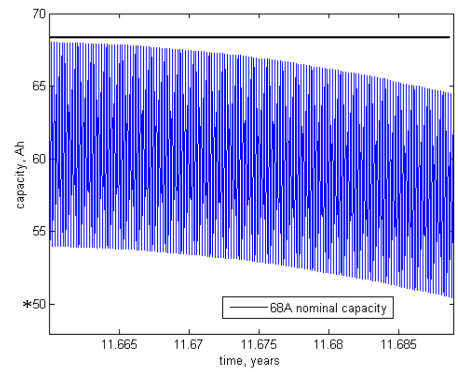

Figure 9. Battery charge-discharge cycles during a week at EOL. *Note how the full charge (68 A) is not achieved due shortage of power and the battery is progressively drained. *Note y-axis origin is 50A.*

During and after controlled battery charge, spacecraft with Peak Power Tracking eliminate excess power by changing the operation point of the array in a dynamic way, always to match the power output to the load need. Indeed, this power margin (shown in Figure 8 as a function of mission lifetime) could be otherwise used instead of being dissipated. As Figure 8 exemplifies, the excess power will eventually reach zero at EOL, meaning that when the array is working at its full capability the loads are exactly matched as per the original criteria adopted by spacecraft designers. In the example regarded, this happens after the design limit (10^{th} year) because of temperature effects and conservative dimensioning of the pointing loss. From that point, the system is not generating enough energy to cope with the load requirement, and the loads will start draining the battery capacity unless they are reduced. The model reflects this process as shown on Figure 9.

Validation

The accuracy of the power-sizing computation has been checked against two cases for which detailed data was available. Table 1 illustrates the main parameters being used for the sizing of the COSMO-Skymed satellite[19] and compares its final design specifications with the model outcomes.

Table 1. Model validation with COSMO-Skymed data. Data courtesy of TAS-I and Refs. 18,20.

Orbit	619 km, 97.1 min period, 35.5 min eclipse	Cell efficiency	0.27
Lifetime	5 yr	Array assembly efficiency	0.85
EOL bus power	3871 W	Array cover loss factor	0.99
Battery Discharge voltage	32 V	Array calibration factor	0.97
Design solar aspect	21 degrees	Yearly degradation	2.5 %
Array Area (model)	**18.02 m^2**	**Array Area (specs)**	**18 m^2**
Battery capacity (model)	**333 Ah**	**Battery capacity (specs)**	**338 Ah**

The same validation has been performed on the data available of the Göktürk-2 satellite.[19] Since this sun-synchronous EO spacecraft does not have tracking arrays, the solar aspect angle on the arrays keeps changing through the orbit. Nevertheless, this can be simulated in the model by taking the average of the solar aspect angle as the design solar aspect angle.

Table 2. Model validation for Göktürk-2[21,22]

Orbit	680 km, 98.1 min period, 50 min eclipse[22]	Cell efficiency	0.28
Lifetime	5 yr	Array assembly efficiency	0.86
Average bus power	181 W	Number of cells	720
Battery DOD	20%	Cell area	3200 mm^2
Average solar aspect	48.5 deg	Yearly degradation	0.5 %
Array Area (model)	**2.33 m^2**	**Array Area (specs)**	**2.30 m^2**
Battery capacity (model)	**37.7 Ah**	**Battery capacity (specs)**	**34.8 Ah**

Notwithstanding the limited amount of complete spacecraft data available, the validation shows that the model dimensions the power subsystem within 8% accuracy, approximately.

A. Attitude Control and determination model

The operation of the FSS ISL may require the use of antenna steering mechanisms to acquire the adequate pointing before the satellite-to-satellite data exchange. If this is the case, the recurrent operations of the FSS payload pose additional requirements on the ACDS. Such design impacts are three-fold. First, it is possible to identify **impacts on global platform accuracy and jitter-tolerance**. In the current analysis scenario, the requirements on accuracy are assumed by the antenna steering mechanism that will work in a closed-loop. Space-proven ISL RF pointing systems have positively dealt with spacecraft jitter and attitude determination error since the sixties.[23] The present paper work focuses on Radio-Frequency (RF) based ISL links. The ensuring of proper steering accuracy shall prove more challenging for optical links, which also have been proposed for FSS.[2] Second, designers **impacts on torque authority requirements** may also occur. The model assumes the attitude control is based on momentum-wheels which have to provide enough torque authority to deal with antenna steering. This is typically not a problem given the dimensions of the ISL subsystem compared to the spacecraft. Lastly, FSS operations may imply **impacts on management on-board momentum**. In order to acquire a new contact, the steering mechanism will accelerate, move at constant speed and decelerate the antenna in a symmetric process. Disturbance torques are a product of accelerations. Even though a whole movement cycle of the steering mechanisms of the antenna is acceleration-neutral (and could be entirely disregarded), in a worst case scenario the ACDS would immediately counter the accelerations of the steering mechanisms without leaving time for its own cancelling deceleration. Hence, extra power is required to accelerate and decelerate the momentum wheels accordingly.

This ACDS subsystem model captures the aforementioned behavior. A reference momentum wheel is spun and despun according to the inertia ratios of the wheel and the antenna every time the FSS ISL operates. The energy required to change the rotational state of the momentum wheel is translated into a power subsystem requirement through a wheel efficiency coefficient $\varepsilon_{\text{wheel}}$:

$$\mathrm{E} = \frac{\alpha_{\text{steering}} \cdot I_{antenna}}{\varepsilon_{wheel}} \left(\omega_{0_{wheel}} \cdot t + \frac{1}{2} \cdot \frac{I_{antenna} \cdot \alpha_{steering}}{I_{wheel}} t^2\right) \tag{2}$$

Where, in Eq. 2, t is steering time, α_{steering} the acceleration of the steering mechanism (chosen to cover 45 deg displacement in time t), I stands for the inertias of the antenna and the reaction wheel, and $\omega_{0\ \text{wheel}}$ is the initial spinning speed of the momentum wheel. The value for this parameter is averaged from the nominal range of operations of commercial momentum wheels.[24] $\varepsilon_{\text{wheel}}$ is taken 0.8 as a reasonable electric to kinetic energy conversion factor for brushless motors.

B. Communications subsystem model

The communications subsystem model aims to capture the relations between downlink data rates and the power and mass associated to the spacecraft communications subsystem. Since the models available are either outdated, inaccurate, or hardly applicable to EO low earth orbiting spacecraft,[13,25,26] this work relies in tailored communications subsystem mass and power model. In accordance to the goals of FSS, the model of the communications subsystem focuses on sizing the hardware required for the most voluminous mission data downlinks. Therefore, the model represents a mission data downlink, that is the main element that can be influenced by the use of FSS ISL as an alternative data relay. It includes the components of the communications subsystem considered data rate sensitive and mass/power-intensive. This incorporates the signal generation hardware (modulators, coders), the amplifier units such as Travelling Wave Tube Amplifiers (TWTA) or Solid-State Power Amplifiers (SSPA) and the mission antenna. The masses and consumptions of the harness, multiplexers, filters, and other auxiliary hardware are not included as its dependence on final data rate is not direct. Moreover, the low data rate equipment for the telecommanding link and the LEOP omnidirectional antenna is left aside. It is a critical equipment that would hardly be suppressed in favor of FSS telecommanding, and has to be flown anyway for the commissioning phase of the original mission. The model allows to specify the amount of fully redundant amplifier and antenna units included in the communication subsystem design.

Said model uses flight hardware data on S,C,X and Ku band equipment to represent the transmitter equipment, and a parabolic antenna model[27] to describe the antenna gain and mass. The transmitter is embodied by an assembly of space-qualified equipment consisting of a signal generator generally managing the data formatting, coding and modulation such as exemplified on Ref.28, a RF amplifier, and an Electronic Power Conditioner unit (EPC) for those TWTA amplifiers not including its own conditioner. This assembly is depicted on Figure 10.

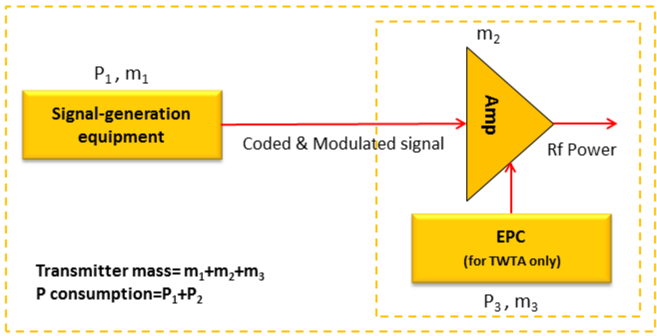

Figure 10. Model of the transmitter equipment composed of a coder/modulator device, amplifier and a its Electronic Power (EPC).

With the data available from several manufacturers, up to 20 transmitter equipment combinations in X band have been assembled: 8 in S band, 6 in C band and 23 in Ku band. Each of these transmitters has a RF power grading, a consumption and a mass sum of the masses of its components. Figure 12 shows a tridimensional tradespace where each transmitter is plotted on these coordinates. Pareto-optimal[29] transmitters are chosen, representing more modern transmitters or a better combination of the components on the database as shown in Figure 12. Over theses Pareto-optimal points a surface is adjusted providing a mass and power consumption tradeoff for a given RF power requirement. In addition, the sizing of the transmitter is based upon a minimal mass requirement that leads to using the black dashed spline shown in Figure 12.

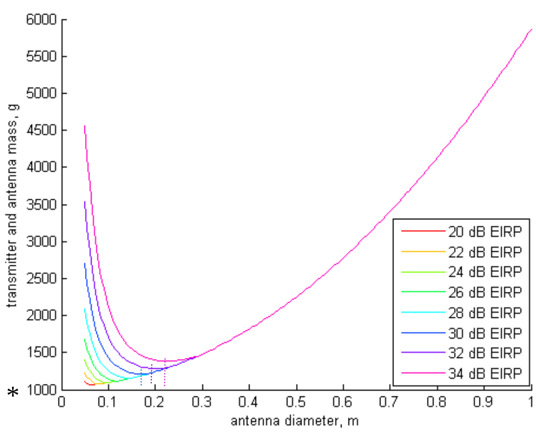

Figure 11. Transmitter and antenna mass evolution with parabolic antenna diameter, given EIRP requirement. *Minimal communications equipment points underscored.*Note y-axis origin is 1000g.*

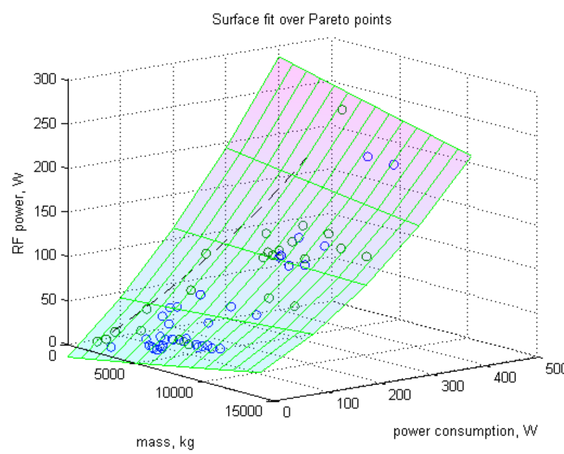

Figure 12. Transmission equipment assemblies plotted by RF power, consumption and mass. *Green points belong to the pareto-optimal surface. The black dashed spline is the mass-optimal limit.*

Subsequently, the model runs a search for the minimum communications equipment mass compliant with a given an Effective Isotropic Radiated Power (EIRP) requirement. A parabolic antenna with the suitable aperture is added to each to the transmitter to reach the set EIRP. Their added masses are computed against antenna diameter and plotted on Figure 11. The trend reflected is analogous as the one found in Ref.28. These sizing laws are independent of operating frequency as reported in Ref. 13.

The EIRP requirement is derived from a data rate requirement, through a link budget model that uses the set of values shown in Table 3.

Table 3. Space to Ground link default parameters.

Ground Antenna diameter	2 m
Link elevation constraint	10 deg
Atmospheric gas attenuation losses (11 Ghz)	0.3 dB
Receiver system temperature (at 11 Ghz)	386 K
Maximum Bit error rate	10-5
Link margin to be achieved	6 dB
No coding gain added	

The atmospheric attenuation and antenna temperature component of system temperature is estimated for to different frequencies according to ITU recommendations.[30] The model sizes the data rate for the contact at the largest range given by the spacecraft height and link elevation constraint.[13] Contact times to ground station are derived from spacecraft height following the tables in Ref.13.

C.FSS ISL subsystem model

The ISL communications model uses the same procedure as described in section 3.D to size the ISL equipment given a data rate requirement. However, the link model is modified accordingly to a space-to-space link: there are no atmospheric losses, the ISL range chosen for analysis on Low Earth orbit is 4500 km[4] and the antennas at both sides of the transmission are assumed identical. An arbitrary idle consumption of 5W is assigned to the ISL hardware when not operating. Future work on the model includes relating this idle consumption to the ISL capability and type of components. The minimal mass of a communications subsystem following the model described on section 3.D is slightly over 1000 grams, and this is also the minimal mass of the FSS module.

IV. Results

This section analyzes the spacecraft impacts of adopting different roles in the satellite federation as supplier or customer for different spacecraft types at different orbital environments. First, the analysis shows the impacts of supplying a relay service for tradeoff in three classes of Earth Observation (EO) spacecraft in LEO, and a large platform in Geostationary Earth Orbit (GEO). The supplier spacecraft are oversizing their space-to-ground link to provide this service and modifying the ACDS and power subsystem. Then, the analysis quantifies the loaded mass (dry mass and propellant mass at separation from launcher)[31] for customer spacecraft engaging in the federation, who are exchanging space-to-ground link capabilities for ISL capabilities and also receive impacts across subsystems. Lastly, it analyzes the potential of the usage of FSS on margins -with no subsystem modifications- on the selected spacecraft.

A.Impacts on supplier spacecraft

Three different spacecraft in Low-Earth orbit have been simulated. These spacecraft represent large, medium and small class missions (2000,900 and 100 kg) with different space to ground link capabilities. Their characteristics, inspired in COSMO-Skymed, Enmap, [19] and SN microsatellite platform,[32] are summarized in Table 4.

Table 4. LEO spacecraft characteristics

Large platform			
Loaded mass	2000 kg	Mission space-to-ground data rate	150 Mbit/s
Average EOL power	3500 W	Space-to-ground link frequency	11 Ghz
Mission lifetime	10 yr	Space-to-ground link redundancy	4 amplifiers, 2 antennas
Orbit	SSO 619 km		
Medium platform			
Loaded mass	900 kg	Mission space-to-ground data rate	320 Mbit/s
Average EOL power	800 W	Space-to-ground link frequency	8 Ghz
Mission lifetime	7 yr	Space-to-ground link redundancy	2 amplifiers, 1 antenna
Orbit	SSO 643 km		
Small platform			
Loaded mass	100 kg	Mission space-to-ground data rate	50 Mbit/s
Average EOL power	400 W	Space-to-ground link frequency	8 Ghz
Mission lifetime	5 yr	Space-to-ground link redundancy	2 amplifiers, 1 antenna
Orbit	SSO 700 km		

The solar cell performance data is kept constant for all platforms, and based upon the parameters shown on Table 1. The FSS module sized to provide a link capability with the characteristics shown in Table 5.

Table 5. FSS ISL characteristics

Frequency	27 Ghz	Typical ISL contact time	120 sec
Data rate	100 Mbit/s	BER	10^{-5}
Link Range	4500 Km	Link Margin required	6 dB

The requirements shown in Table 3 are met, according to the ISL subsystem model, by a 50W consumption transmitter and 0.4 m diameter parabolic antenna for a total EIRP of 50.2 dBW and 6 dBW margin. In the simulations, the ISL operates with an increasing number of contacts per orbit and the corresponding mass impacts to design for this operation regimes is shown on Figure 13. Each of the data points on Figure 13 corresponds to a number of ISL contacts, ranging from 1 to 15. Contacts last 120 seconds and are evenly distributed in the sunlight period of the orbit. The volume of data received via these contacts has to be relayed to the ground, and the capability of the space-to-ground communications equipment is increased accordingly.

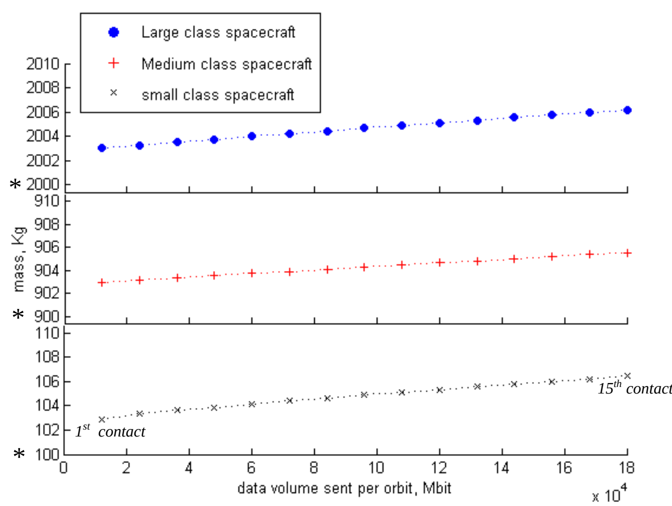

Figure 13. Evolution of spacecraft mass as a function of data volume relayed. One orbit period. **Note each subplot is referred to a different spacecraft class and presents a different mass range.*

The system-level mass impacts on the three spacecraft are very similar, on the range of the 3-6 kilograms. A constant mass shall be added to this value, to account for the passive equipment needed to operate the FSS ISL, such as harness, casings, filters, multiplexers, etc. as explained in section 3.D. If these elements were accounted for total of 5 kilograms, then the relative mass impact of adquiring and relaying to ground 180 Gbits per orbit for the large, medium and small spacecraft is 0.6%, 1.1%, and 12% respectively.

However, not only the available mass may limit the data volume to be relayed. The short ground station passes in LEO imply large downlink data rates that may not be achievable due to bandwidth limitations. For instance, the medium class mission needs a large data rate to downlink its own mission data (320 Mbit/s) and the model shown this leads scenario where the increased data rate required to act as a data sink surpasses the achievable data rate. This situation could be overcome by adding a second X-band transmission system, at the cost of doubling the mass impacts on the spacecraft.

In addition to the three LEO platforms, a very large GEO spacecraft based upon Alphasat[19] of 6500 kg loaded mass and 12 kW has also been simulated as a supplier. The FSS ISL in the GEO spacecraft is required to support a 100 Mbit/s data rate when receiving the signal from a LEO spacecraft which uses the relatively small LEO-to-LEO ISL equipment. Therefore the GEO spacecraft must equip a large FSS ISL antenna (2.5 m dish) to be able to close the link, constituting a significant mass - and platform configuration- impact. A GEO spacecraft can relay data to the ground continuously, but in this analysis, a period of 100 minutes (roughly corresponding to the LEO orbit period) has been set as the time window for the relay to send the data to the ground after receiving it via ISL. That is, the data received from a LEO spacecraft has to be relayed to ground before the next ground station pass. In addition, a dedicated Space-to-Ground X-band transponder has been added to relay the FSS data to the ground station. The ISL contacts are, as before, limited to 120 seconds, and up to a 100 of them are tracked on Figure 14.

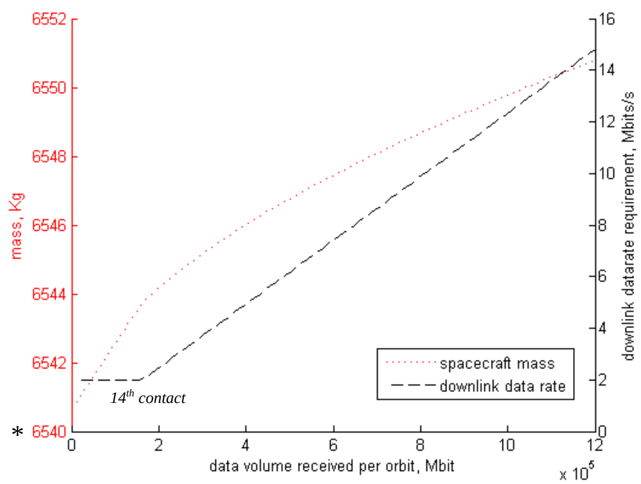

Figure 14. Mass impacts on 6500 kg GEO Spacecraft of operating 1 to a 100 times the FSS ISL to relay data from LEO. **Note y-axis origin is 6540 kg.*

As Figure 14 illustrates, the starting impact of adding a FSS ISL payload is over 40 kilograms, and operating it to relay 1.2 Tbits per 24h period implies adding approximately 50 kilograms over the spacecraft baseline mass. This is an impact of 0.8% over loaded mass. Note that from 1 to 14 contacts, the driving constraint dimensioning the downlink is the 100 minutes time window, over which a constant 2 Mbit/s data rate is maintained (100 minutes at 2 Mbit/s to relay 120 seconds worth of data at 100 Mbit/s). After each contact, the downlink is powered by 100 minutes. After fourteen contacts, the number of contacts is too frequent and the communications downlink has to be permanently on, increasing progressively the downlink data rate. This increase is less mass costly than increasing the transmission time. This result suggests that increasing data rates rather than transmission times is mass-beneficial in satellite communication systems.

B. Impacts on a customer spacecraft

Considering the same set of LEO spacecraft illustrated in Table 4, this section analyses the impacts of operating the FSS ISL from a customer perspective. The FSS customer relays its mission data via the federation, and downsizes accordingly its communications subsystem. This process is shown in Figure 15.

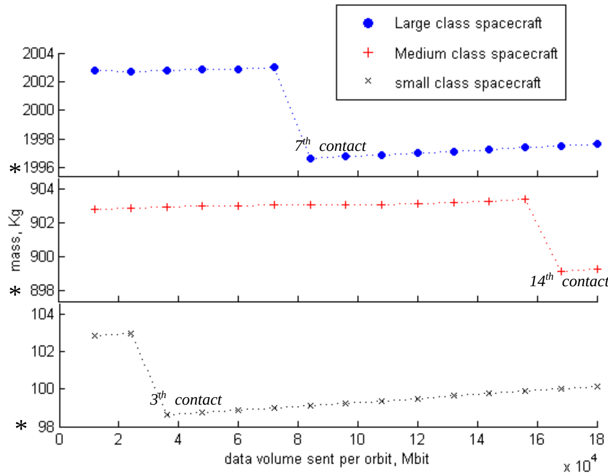

**Figure 15. Evolution of spacecraft mass as a function of data volume sent. One orbit period. ****Note each subplot is referred to a different spacecraft class and presents a different mass range.*

As more contacts are made, more of the mission data can be relayed through the ISL and the downlink data rate requirement on the space-to-ground link is reduced. With enough contacts, all of the data can be relayed and the mission data downlink equipment can be completely suppressed, leading to a significant mass reduction. This occurs at the seventh contact on Figure 15 for large spacecraft (0.35% reduction), at the fourteenth on the medium (0.5% reduction), and at the third contact on the small spacecraft (4.5% mass reduction). Note that such a reduction is a product of substituting a fully redundant communications subsystem for a single ISL link. Mission designers may hence prefer an approach retaining a minimal space-to-ground link capability as on the left of Figure 15, leading to a slight mass increase and the capability to use both the ISL and the downsized space-to-ground link.

The spacecraft mass increment is a result of increasing the capabilities of the ISL and decreasing those of the downlink. Figure 15 shows that the progressive mass increase at the left of the plot presents a slight change of trend. This can be observed for the medium and large spacecraft due their larger starting data rates. This is originated by the reduction of the data rate requirement on the downlink, which leads the communications subsystem to first hit the point of a minimal amplifier power need, and from that point the downsizing can only be applied to the mission parabolic antenna. The particular position of the change of trend will depend on the built-in data of the space-to-ground communications model and the link model assumptions.

C.Operation of the FSS ISL on spacecraft power margins

In the discussion that follows, the only design modification introduced to the spacecraft is the addition of the ISL FSS module, adding 5 to 10 kg to the baseline spacecraft loaded mass. No other changes are introduced on any other subsystem, therefore it is indifferent whether the spacecraft role in the federation is biased towards a supplier or customer approach. Figures 16 to 18 give an estimate on potential connection periods of each spacecraft to the network; provided there is another node available to connect to via ISL.

The spacecraft analyzed are LEO residents as shown on Table 4, with orbital periods of approximately 5800 seconds. Eclipses are assumed to be worst case through the whole time, lasting approximately 2100 seconds. The ISL connection supported features 100 Mbit/s corresponding to Table 5. The FSS ISL is not operated during eclipse times to avoid any impacts on battery sizing. During sunlight, the spacecraft perform a standardized typical load profile consisting of 1 communications contact per orbit, payload operation with 0.8 duty cycle, constant thermal and mechanical loads and 0.5 duty cycle ACDS operations. The operations are profiled such that their average at EOL for each spacecraft corresponds to the data on Table 4.The resulting pattern of these profiles is analogous to the one shown in Figure 5.

The simulations depicted on figures 16-18 run in 60 seconds time steps through the whole spacecraft lifetime of 10,7 and 5 years for the different spacecraft. Each and every time the solar arrays could produce more power than the current total load requirement this excess power, if enough, feeds the FSS ISL. The load of the batteries is prioritized. Note that at BOL the large spacecraft can generate excess peaks on the order of 1000W, but only 50W are needed to switch on the FSS ISL (Table 5). The decay of power production during lifetime impacts the amount of excess power produced as shown on Figure 8. This reduces the total time per orbit the spacecraft can be connected to the federation as shown on Figures 16-18. Due to the simulation time discretization, the potential FSS operation time per orbit decreases in discrete amounts. All the platforms can support a significant connection time as shown on the plots. As a general guideline, 500 seconds/orbit can be sustained for more of 70% lifetime. This analysis shows that minimal changes at spacecraft level could enable future space missions to reap the benefits of participating in satellite federations.

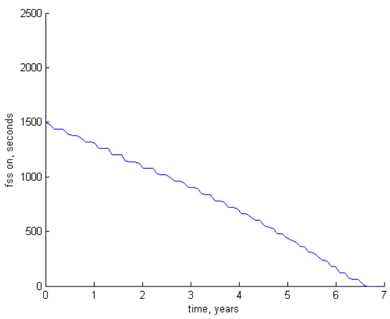

Figure 16. Seconds per orbit of supported FSS ISL operation through lifetime, 100 kg class spacecraft.

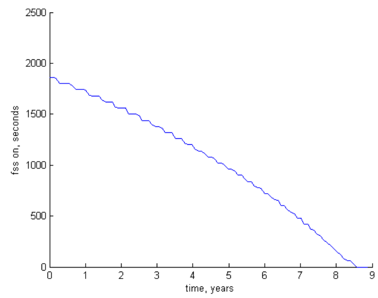

Figure 17. Seconds per orbit of supported FSS ISL operation through lifetime, 900 kg class spacecraft.

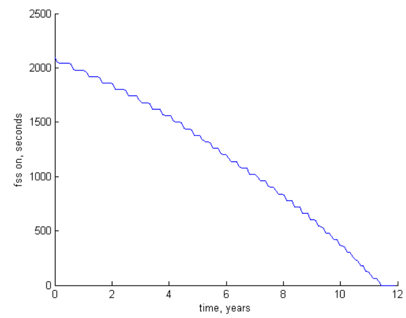

Figure 18. Seconds per orbit of supported FSS ISL operation through lifetime, 2000 kg class spacecraft.

V. Conclusion

This work has analyzed the mass impact on spacecraft participating in satellite federations through the development of a tailored spacecraft model. The work has focused on the data relay between participating spacecraft. First, such impacts have been shown for supplier spacecraft, which act as data sinks. The spacecraft in LEO orbit with this role present a nearly linear increase on their baseline loaded mass, as more ISL contacts per orbit are established. For a total of 15 contacts of 120 seconds, corresponding to a total data volume of 180 Gbits per orbit , small, medium and large spacecraft present 12%, 1.1% and 0.6% of loaded mass increase, respectively. Large spacecraft are subject to smaller design impacts of including FSS capabilities, presenting an economies of scale effect. However, for any size of platform, the need of augmented space to ground data rate can reach the bandwith limits if supplier spacecraft is also generating itself a high volume of data.

For the particular case of a GEO spacecraft acting as a supplier, the absolute mass increase can exceed 50 kilograms, meaning a 0.8% mass increase for a 6500 kg platform. In addition, a 2.5 meter antenna is required to acquire signals transmitted from LEO customers using the LEO-sized ISL. This suggests that the hops between altitude belts in a multi-layered network[33] are severely constrained by the physical layer and shall only occur between designated spacecraft using a more capable ISL transmitter. Another option is to link to the GEO suppliers at a lower data rate, or use them to broadcast low data volumes with auxiliary data such as routing tables or node positions. MEO satellites could represent an intermediate solution that has to be explored in the future work.

Next, this work has shown the evolution of the mass impacts on spacecraft acting as customers. Such spacecraft may choose to downsize their space-to-ground communications equipment and progressively substitute it by ISL contacts to other federated spacecraft. For a limited loaded mass increase consisting on 3 kilograms worth of active ISL components (antenna and amplifiers), plus any other ancillary components needed (estimated on 5 kg), the customer spacecraft can relay all their mission data via the federation, and retain at the same time a minimal space-to-ground communications subsystem. Going a step further, the customers may completely drop their space-to-ground link capacity for increased mass savings. However, this option may come with effects on mission reliability and would ultimately depend on the amount of suppliers available in the Federation and the perception of risks by the mission designer.

A third case study has been presented, analyzing the potential of participating in an FSS without any subsystem modifications, only adding to the spacecraft the said 3-8 Kg ISL providing 100 Mbit/s data rate, and operating it on power margins. The results show, for small, medium and big LEO spacecraft classes, the capability to sustain a significant amount of ISL operations through lifetime based upon the extra power generated before EOL. For all spacecraft types, the operations' potential duration exceeded 500 seconds/orbit for more of 70% of mission life.

This work supports the concept of Federated Satellite systems by showing how participant spacecraft can access to the Federation with very small operational and design impacts and exchange resources in an opportunistic, ad-hoc fashion, based upon marginal on-board resources. Future work includes analyzing the full scale design impacts for customer spacecraft of allocating all of the data-based spacecraft functions to the federation, not only the data relay as described in this work. Moreover, the potential of FSS for new missions has to be assessed in conjunction with thorough assessment of its business case.

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