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The Federated Satellite Systems paradigm: Concept and business case evaluation

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A B S T R A C T

This paper defines the paradigm of Federated Satellite Systems (FSS) as a novel distributed space systems architecture. FSS are networks of spacecraft trading previously inefficiently allocated and unused resources such as downlink bandwidth, storage, processing power, and instrument time. FSS holds the promise to enhance cost-effectiveness, performance and reliability of existing and future space missions, by networking different missions and effectively creating a pool of resources to exchange between participants in the federation. This paper introduces and describes the FSS paradigm, and develops an approach integrating mission analysis and economic assessments to evaluate the feasibility of the business case of FSS. The approach is demonstrated on a case study on opportunities enabled by FSS to enhance space exploration programs, with particular reference to the International Space Station. The application of the proposed methodology shows that the FSS concept is potentially able to create large commercial markets of in-space resources, by providing the technical platform to offer the opportunity for spacecraft to share or make use of unused resources within their orbital neighborhood. It is shown how the concept is beneficial to satellite operators, space agencies, and other stakeholders of the space industry to more flexibly interoperate space systems as a portfolio of assets, allowing unprecedented collaboration among heterogeneous types of missions.

1. Introduction

The last five decades have seen important breakthroughs in the field of Information Technology (IT). Together with the miniaturization and integration of electronics, one of the most prominent features of the field is the networking approach adopted by IT developers, which allows harnessing the full potential of computers by connecting and operating them in networks, creating virtual, flexible cloud infrastructures [1] and emerging capabilities transparent to hardware. Nowadays, the global implementation of this concept is the Internet, used worldwide and indispensable to billions of people around the globe. Nevertheless, the field has not reached its full potential, with the Internet of Things (IoT) concept [2] promising to be the next revolution in the way we generate and manage information about the world. The ideas about distribution, virtualization and scalability behind these successful technical breakthroughs have been spread to other domains, notably electric power distribution systems in the form of smart grids [3]. These ideas have not, to the date, been adopted nor extensively discussed by Space mission designers, operators nor scholars.

Drawing from ideas in cloud computing and changes already underway in other fields, in this paper we propose the Federated Satellite Systems (FSS) paradigm. Likewise to

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cloud computing nodes, FSS consists in spacecraft networks trading previously inefficiently allocated and unused resource commodities such as downlink bandwidth, storage, processing power, and instrument time. FSS hold the promise to enhance cost-effectiveness, performance and reliability of existing and future space missions, by networking different missions and effectively creating a pool of resources to exchange between participants in the federation. This exchange improves the overall welfare of the federation by improving overall cost efficiency or by creating business opportunities, implementing usage-based pricing policies in the network. FSS envisions a space-based resources market, where missions dynamically offer to the federation any underutilized capabilities such as bandwidth, processing power or data storage, and access to such resources depending on their needs. FSS are a new space mission paradigm, aiming to switch from independent, isolated space missions to a highly dynamic, constantly evolving in-orbit infrastructure capable of supporting different missions and even deploying software-based, virtual missions. FSS constitute the dawn of cloud computing environments in space, which will significantly change the way space missions are conceived and operated.

This paper introduces and describes the FSS paradigm, and develops an approach integrating mission analysis and economic assessments to evaluate the feasibility of the business case of FSS. The approach is demonstrated on a case study on opportunities enabled by FSS to enhance space exploration programs sustainability, with particular reference to the International Space Station (ISS). In previous papers [4,5], we introduce and analyze some of the key technical aspects for the implementation of FSS, and identify the major challenges for technological development required for the development of satellite federations in space.

The remainder of this paper is structured as follows. Section 2 provides background to FSS, and provides context through a literature review. Section 3 describes in more detail the idea of FSS, providing definitions that will be used throughout the paper and describing a market assessment exercise to demonstrate the opportunities enabled by FSS. Section 4 illustrates the proposed federation idea illustrating a case study in Earth Observation. Building on this example Section 5 presents a structured approach for the evaluation of the business case of a satellite federation and describes a second case study on the implementation of federations in space exploration. Section 6 summarizes the results achieved by this paper, and draws conclusions from the research.

2. Background

FSS can be considered as a new instance of distributed satellite systems [6,7]. Distributed systems have already been implemented in space as satellite constellations. Typical space constellations feature identical type of spacecraft designed to carry out the same tasks, whose aggregation support the primary mission goal pursued by the constellation [8]. The idea behind distributed systems is to allocate mission functionality to multiple elements, as means to enable new functionality (such as space-based geo-localization [9]), to mitigate programmatic constraints or risks (such as the case of NASA's 3-element Mars Sample Return campaign [10]), or to reduce the size of the required space platforms (like fractionated spacecraft elements deployed on service areas) [11].

FSS are composed of heterogeneous spacecraft, with different goals and capabilities. The technical developments needed for networking heterogeneous missions have recently been explored in [12], and in [13] as ways to enhance CubeSat capabilities. FSS envision opportunistic collaboration across spacecraft, much alike what is done in peer to peer networks [14] and in cloud computing [1]. The ideas of the space internet [15,16], solar system internetworks [17], and sensor webs [18] can be considered as precursors to the idea of satellite federations. All these are system concepts that make use of spacecraft interoperability to enable their functions, allocated within spacecraft operated by a single set of stakeholders (a space agency, or a nation). Several space agencies around the globe started investigating interoperability for different aspects of space missions, including the establishment of a Consultative Committee for Space Data Systems (CCSDS) [19] for data product standard development and ground segment interoperability, and the IOAG Space Internetworking Strategy Group (SISG) for the development of the concept of Solar System Internetwork [20]. Researchers started looking at disruption-tolerant protocols as means to enable these novel space network concepts in distributed satellite systems [21]. Interoperability within spacecraft components has also been of interest to the community, with standards such as SpaceWire developed for this purpose [22]. Yet, all the above-mentioned concepts lack of a vision of the establishment of a commercial market of on-orbit resources, which this paper intends to propose as a contribution to the state of the art.

One of the notable research efforts in this direction was DARPA's F6 program, exploring the concept of Fractionated Spacecraft [23]. This advanced system concept disaggregates and reallocates the functionality of a spacecraft into multiple smaller units, networked and operating together to achieve mission objectives. Despite the ambitious goals of F6, the program was terminated in early 2013 due to a cut in funding from the sponsoring agency [24]. Instead of allocating mission functionality to smaller units, FSS attempts to establish a peer-to-peer network for the opportunistic sharing of resources among participant spacecraft. Table 1 illustrates the different distributed mission types discussed in this section. Fig. 1 shows a graphical representation of the differences between constellations, FSS and Fractionated Systems in their autonomy and mission goals dimensions.

The peer-to-peer network concept proposed by FSS could be extended to spacecraft anywhere to the solar system, converging with the interplanetary data relay system of systems proposed by NASA with SCaN [25]. Space-based networks have been implemented and extensively discussed [26–28] to achieve a variety of mission goals not only limited to deep-space communications, but most notably terrestrial mobile communications [29]. The space network concept enabling the deployment of FSS differs from the former by supporting ad-hoc, opportunistic links between heterogeneous

Table 1
Types of distributed mission architectures.

Distributed architecture type	Mission goals of components	Type of cooperation	Uniformity of components	Autonomy of components
Constellation	Mission goal shared (Iridium, GPS) One ore several mission goals, but not all, shared (A-train)	Cooperation required to support mission goals	In general homogeneous components, some differences possible (GPS generations)	Autonomous
Federated Satellite System	Independent mission goals	Ad-hoc, optional	Heterogeneous components	Autonomous
Fractionated System	Mission goals shared	From optional (service areas) to required (distributed critical spacecraft functions)	Heterogeneous components	From autonomous to completely co-dependent

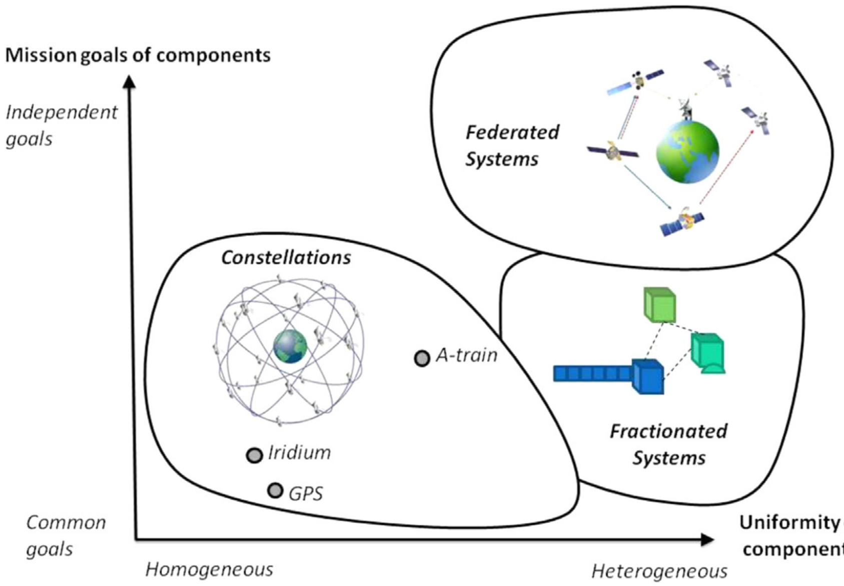

Fig. 1. Notional map of distributed mission architectures, represented on the component uniformity and mission goal dimensions.

spacecraft as opposed to pre-defined constellation networks. The different capabilities of the spacecraft acting as network nodes, the mobility of those and the engagement on voluntary basis pose a very dynamic network problem, that challenges state-of-the-art space network protocols [30,31].

The links among participants of the federation enable the data exchange and remote information relay. The most notable currently operative data relay system is NASA's TDRSS, which offers data relay from Geostationary Earth Orbit (GEO) [32]. TDRSS was initially designed to serve time-critical manned missions and is not commercial in nature. Nevertheless, the deployment of the European EDRS system [33] may spur competition and consolidate a commercial market of in-space data relay services. TDRSS and EDRS are deployed in GEO to experience enhanced coverage and link availability. However, using GEO relay satellites implies long link distances in relation to LEO–LEO and direct downlink, thus a high burden for customers in LEO, leading to high cost per unit of information sent (LEO to GEO and GEO to ground data path), long round-trip delay, and a high cost per deployed relay satellite. FSS is an option to enable the establishment of non-geosynchronous, dynamic LEO-to-LEO data relays and to supply on-board spare resources to enhance the sustainability of participating mission. In addition to relaying data, other data-based commodities such as storage or processing power can be traded within the federation, and even electrical power exchanges through wireless power transfer technology [34] – or other means – can be envisioned when the appropriate level of technology maturity is reached. Section 3 discusses all these possibilities providing a more detailed description and giving formal definitions to the idea behind the FSS concept.

3. FSS idea description, definitions, and market assessment

Satellite Federations are in-space cloud-computing environments in which all types of space missions can join to contribute. Any type of space mission may benefit from the resources exchange: data-intensive missions such as Synthetic Aperture Radar (SAR), hyperspectral and high resolution imaging missions, for instance, may enhance the platform's total data volume downloaded, and latency, through the federation. Spacecraft with very dynamic or irregular workload such as military telecommunications and emergency satellites may offer, when idle, their link and processing capacity to other spacecraft, and spacecraft with payload failures could be reused as a resource pool for other missions or services – such as the repurposing case of the Russian Express AM4 spacecraft [35]. Instead of being developments designed under minimum cost or best performance/cost criteria, satellite federations are designed to maximize value – such as economic profit – for both parties engaging in business transactions, as any other conventional terrestrial business [36]. A resource transaction within the FSS network occurs on an opportunistic basis, when both the recipient and the provider of the service see value in the transaction, that is, when the utility of both parties is increased by the transaction. For a recipient, a service rendered by a satellite federation must be less expensive than what could be achieved by launching and operating an internal capability for that service; that is, the federation must provide an advantage in terms of opportunity cost. For a supplier, rendering services to the federation needs to translate into profit. Alternatively, suppliers can add value to their missions by becoming customers for a resource type different from the one they are offering. In our concept, missions interact with a federated infrastructure on an "*as-needed*" or "*as-afforded*" basis. Virtual space missions could be developed by purchasing a collection of services from a satellite federation, and operate them concurrently in order to meet desired system-level requirements and outcomes.

The resource sharing within a satellite federation requires the implementation of a Peer-to-Peer (P2P) communications network. The physical layer of this network consists of Inter-Satellite Links (ISL) among participant spacecraft, enabled by dedicated equipment, from now on referred as *FSS ISL*. In the frame of FSS, an ISL device is comparable to the network adapter found in terrestrial computer networks. Adding this equipment to a spacecraft requires an overhead in mass and volume, which constitutes part of the entry cost of joining the space-based market proposed by FSS.

The schedule of operations of the FSS ISL drives the design impacts on spacecraft, which are discussed in another publication [5]. The FSS operations 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 as discussed in [4]. Furthermore, the strategy of participating spacecraft may also change in time, if the FSS market adopts dynamic pricing policies. In order to frame this following discussion and propose an approach for the assessment of the related business case, we now formulate definitions to the terms and concepts introduced in this paper.

3.1. Definitions

We define *satellite federation* as a set of spacecraft that engages in opportunistic collaboration with each other during their mission lifecycle. In opposition to identical or *homogeneous* sets of spacecraft designed from the outset to work in collaboration (as in the case of constellations and swarms), FSS is based upon *heterogeneous spacecraft*, that is, distinct spacecraft for which interoperability has been enabled but not been scheduled *a priori*. The term *opportunistic* means that federated spacecraft engage in collaboration only if all involved parties deem the latter beneficial, where benefit is defined as either economic profit, or generic value. We define as *federates* all the members of a satellite federation. Federates collaborate by engaging in commodity transactions within the federation. *Resources* are all the assets that can be traded among federates – in principle both tangible (e.g. propellant) and intangible (e.g. data and power) resources. For the remainder of this paper we focus on the data-based resources of downlink bandwidth, storage, and processing. These resources are considered opportunities for earlier implementation as opposed to more advanced concepts. The FSS approach here presented is generalizable to all types of intangible resources. Spacecraft supplying resources as providers of the satellite federation are defined as *suppliers*. When instead a federate is seeking to request FSS services as a recipient, it plays the role of a *customer* in the federation. Federates can switch their role over their lifetime, and also act as both customers and suppliers at the same time. The joint set of customers and suppliers makes a satellite federation.

The transmission and data relay operations are limited by the operational approach of spacecraft as customer and supplier operators in a federation. Different design and operational approaches to FSS can be distinguished. A first operational approach is to operate using spacecraft design margins – which we define as *operations on 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. Another approach is to re-design the spacecraft to allow for the full use of federations during the mission's lifecycle, for instance by relaying entirely on the federation for the provision of certain services, or oversizing certain capabilities in order to provide extra service to the federation in exchange of service fees or other resources of interest. We call this approach *full FSS capability*. These definitions give rise to a whole range of hybrid options, which are illustrated in Fig. 2.

Federations enable two high-level functions for interoperability among federates: *transacting*, and *negotiating*. Transacting refers to the ability of federates to exchange resources among each other, such as distributing computing tasks, relaying data to ground stations, or storing data for subsequent downlink. Negotiating refers to the ability of federates to receive customer requests and allocate them efficiently among suppliers, while coping with demand and resource uncertainties over time. While transaction is effectively performed in-space, directly or through a middleman federate, negotiation is a distinct function that could even be implemented on the ground via diverse auction mechanisms and task scheduling.

The above-mentioned interoperability functions define three families of architectures for federated spacecraft, as

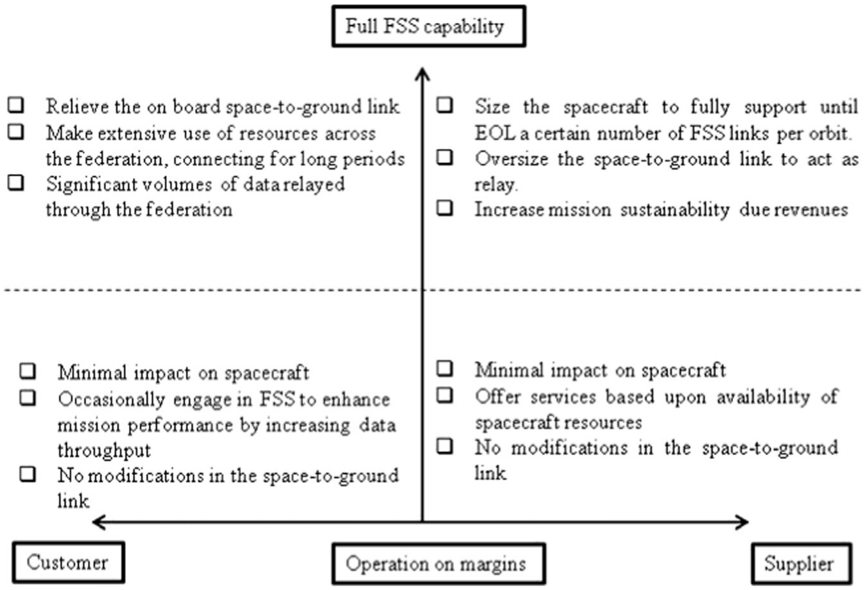

Fig. 2. Notional classification of different engagement regimes in a satellite federation.

illustrated in Fig. 3. These families are distinguished by the different allocations of functions to federation elements.

Firstly, we define *centralized federations* (centralized FSS), in which all resource transactions are regulated and negotiated by dedicated spacecraft acting as *negotiators*. In this scenario, negotiating spacecraft also act as hubs for service provision. Negotiators may or may not interoperate among them. Such architectures give rise to new mission concepts, such as the development of generic service spacecraft operated with the sole purpose to support other missions providing functionalities for a profit; to this end, Palermo and colleagues recently developed the idea of Earth Orbiting Support Systems [37]. Negotiators could be fitted to perform multi-protocol communications translation among federates, track them and contact multiple federates at the same time. It is of interest to centralized federations to determine which orbits can be considered as most profitable for operating commercial negotiators. Lluch and Golkar proposed a novel satellite-to-satellite coverage optimization approach to answer this question [4]. Their analysis shows that quasi-polar orbits appear to be of particular interest, due to the optimal access schedules achieved with customers in Sun Synchronous Orbit, in particular Earth Observation satellites. This category of customers is of particular interest to centralized FSS architectures in Low Earth Orbit, as their data volume demands are steadily increasing over time. Compare for instance the 0.3 Tb/day data volume that were produced by Envisat [38], with the 1.3 Tb/day of data produced nowadays by the Sentinel-1 remote sensing mission [39]. Data throughput in the next decade is estimated to be in the order of tens of Tb/day [40]. Access time to ground stations of Earth Observation platforms remains limited and geostationary data relays are out of their reach due to the impossibility to close the corresponding link budgets with their typical equipment at the desired data rates. Secondly, we define *negotiated federations* (negotiated

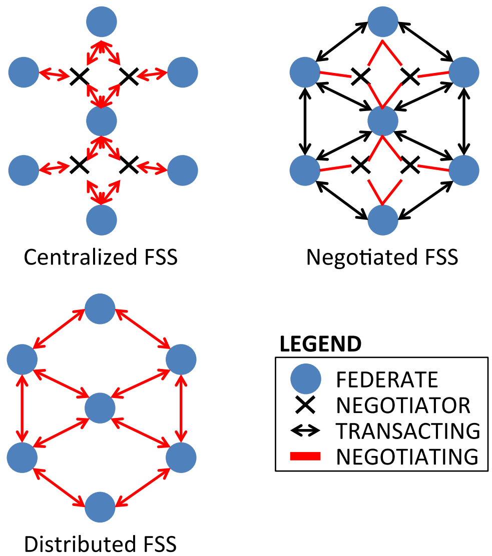

Fig. 3. Families of architectures for satellite federations.

FSS), differing from centralized FSS in that negotiators only fulfill their negotiating role, while resource transactions are conducted directly by federates. This architecture is of particular interest to scenarios in which operators envision to repurpose existing assets to working within a federation; in this case, however, negotiators must face the challenge of coordinating operations of federates operating under different standards and using different types of interfaces.

Thirdly, we define *distributed federations* (distributed FSS), where both the transacting and negotiating functions are handled by federates, in a similar concept of operations as the Internet or terrestrial peer-to-peer networks [14]. This architecture assumes full integration of the FSS concept in spacecraft design, therefore representing the final goal for satellite federations.

Several *hybrid federations* can also be conceived by coordinating sub-federations of spacecraft each operating using different centralized, negotiated, or distributed schemes.

A satellite federation can be deployed in orbit via diverse implementations. One can envision a FSS architecture where resources are traded by spacecraft with hosted communication payloads willing to lease their spare capacity. Another option is to deploy dedicated FSS supplier spacecraft. Other orbital resources, such as payloads hosted on the ISS, could also be included in an FSS network as discussed in Section 5. Note that there is no conceptual impediment to imagine an FSS network based upon a mixture of nodes from different nature, as illustrated in Fig. 4, since resource diversification is in the core itself of the FSS concept.

With these definitions, this section provided a common dictionary to describe and analyze satellite federations. We now conduct a first-order market assessment to demonstrate the opportunities associated with satellite federations, characterizing the distribution in Earth orbit of potential customers and suppliers for FSS-enabled services.

3.2. *Market assessment: distribution in earth orbit of potential FSS customers and suppliers*

In order to understand the potential market achievable and the topology of the FSS network, we analyze the orbital distribution of spacecraft that could collaborate in a federation. A satellite database based upon the population of active satellites has been developed using Two-Line Elements (TLE) data from a TLE database derived from NORAD available from public online sources. Most Earth-orbiting satellites are deployed either in LEO, Medium Earth Orbit (MEO) or GEO orbit. Fig. 5 shows the distribution of inclination of the satellite population of these three groups.

The increasing data generation rates of new Earth Observation Satellites in LEO and their ground station access time constraints make them suitable candidates for engaging in a satellite federation. LEO satellite population presents a wider scatter in inclination than the other altitude belts, with only

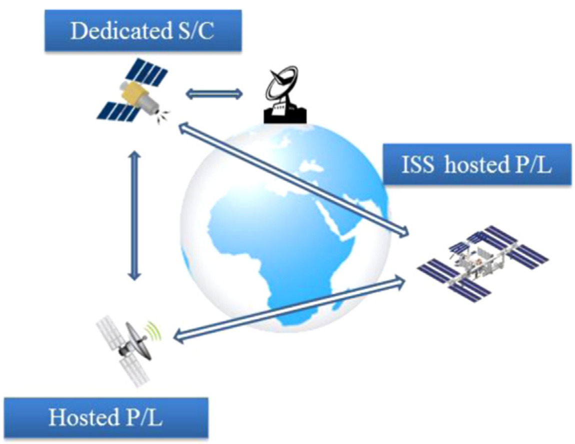

Fig. 4. Notional FSS featuring different types of supplier nodes.

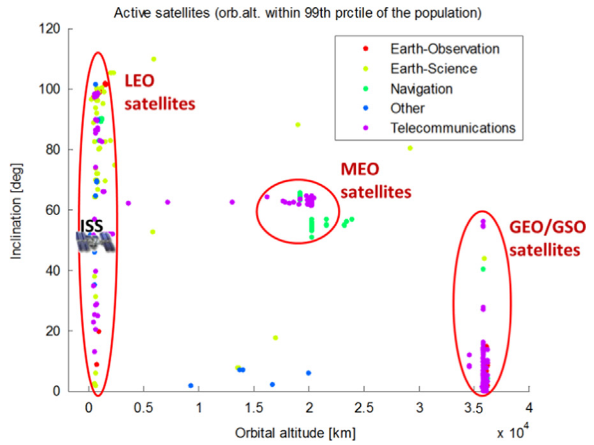

Fig. 5. Population of active satellites classified by orbital altitude and inclination, with altitude within the 99% percentile of the total population.

a higher population density in Sun Synchronous Orbits (SSO). Considering the emergent use of commercial Earth Observation satellites for imaging purposes in recent years, such as for instance the GeoEye-1 high resolution commercial satellite [41], a LEO-based FSS network is of particular interest. In order to better understand the market potential of FSS, the following section describes a case study of FSS in Earth Observation.

4. First case study: an implementation of FSS in support of earth observation

We now consider a technically challenging yet promising application of FSS, that of opportunistic FSS intersatellite links (ISL) between spacecraft in Low Earth Orbit (LEO). Traditionally, ISL has been implemented in satellite constellations such as Iridium [42] and designed from the outset as predefined communications architecture between involved spacecraft. We assume that a FSS ISL payload is installed in all missions in this example, allowing intercommunications between heterogeneous standards acting as a meta-layer similar to what is done in Internet communications. The objective of this example is not to define a detailed design of the FSS ISL payload or of the involved spacecraft, but rather to analyze a first baseline scenario to highlight architectural tradeoffs of the proposed FSS technology. This example shows an instance of this win–win FSS strategy, while at the same time it exemplifies some of the technical challenges that are inherent to opportunistic FSS infrastructures operating in Low Earth Orbit.

Consider the case of a radar altimetry mission for oceanography purposes, such as the Jason-1 mission (J1) [43], and define it as *FSS customer*. J1 is a 500 kg spacecraft, whose characteristics of interest are shown in Table 2.

We now consider a series of communications satellites in LEO, such as ~60% of the Iridium constellation (41 satellites), and define them as FSS suppliers. This number of satellites is chosen to reflect a representative size of a satellite federation, which is assumed for the purposes of this illustrative example. While this example builds on existing satellite systems, it does not consider the specificities of the design changes required on those satellites to accommodate FSS technology; a preliminary assumption is made that changes can be accommodated by a more detailed design analysis. Fig. 6 shows a snapshot of the orbital configuration of the satellites here considered. In considering opportunistic FSS exchanges between customer and suppliers, we evaluate three metrics. The first metric is *total access time*, that is, the total time in which customers and suppliers are in line of sight, therefore enabling potential ISL should the link budget close for given transmit power and communication parameters. The second evaluation metric considered is *minimum contact duration*. This is the minimum time in which the customer and a supplier are in direct line of sight with each other. This metric is used as a proxy for the handover rate at which the customer would have to switch from an FSS supplier to the next one. If this rate is too elevated then the customer could incur in a high probability of handover dropout. The last metric being considered is the *maximum slant range* distance allowed between customer and suppliers. We evaluate different ranges in order to identify a feasible FSS region for which link budgets close for given communication constraints.

Table 2
Jason-1 characteristics (data source: [43]).

Parameter	Jason-1
S/C mass	500 kg
S/C power	450 W
Orbit type	Circular non-sun-synchronous
Orbital period	~2 h
Orbital inclination	66.038°

We wish to maximize total access time in order to improve access to payload data for users and reduce latency time at the same time. We also wish to minimize maximum range and maximize minimum contact duration. The goal is to allow FSS ISL with minimal impact on customers' and suppliers' link and power budgets. These objectives are naturally conflicting with each other, therefore they determine tradeoffs in the architecture.

Fig. 7 shows total access time versus maximum allowable range for the FSS example here being considered. The resulting S-curve is plotted against the nominal J1 total access time, i.e. the total access time J1 is assumed to have without support of the FSS infrastructure. Assuming one ground contact per orbit of mean duration of 7 min, total nominal access time is given by:

$$\text{total nominal access time }(h) = \frac{24\text{ h}}{\text{J1 orbital period }(h)} \cdot \frac{7\text{ min}}{60\text{ min }/h} \quad (1)$$

Fig. 7 therefore shows the increase in total access time achieved by virtue of FSS communications as a function of increasing maximum allowable range. It is shown that access time is greatly improved by the FSS infrastructure, allowing up to “round the clock” access to near-real-time J1 data. In the example shown here, this would be very valuable as it would presumably enable, among other

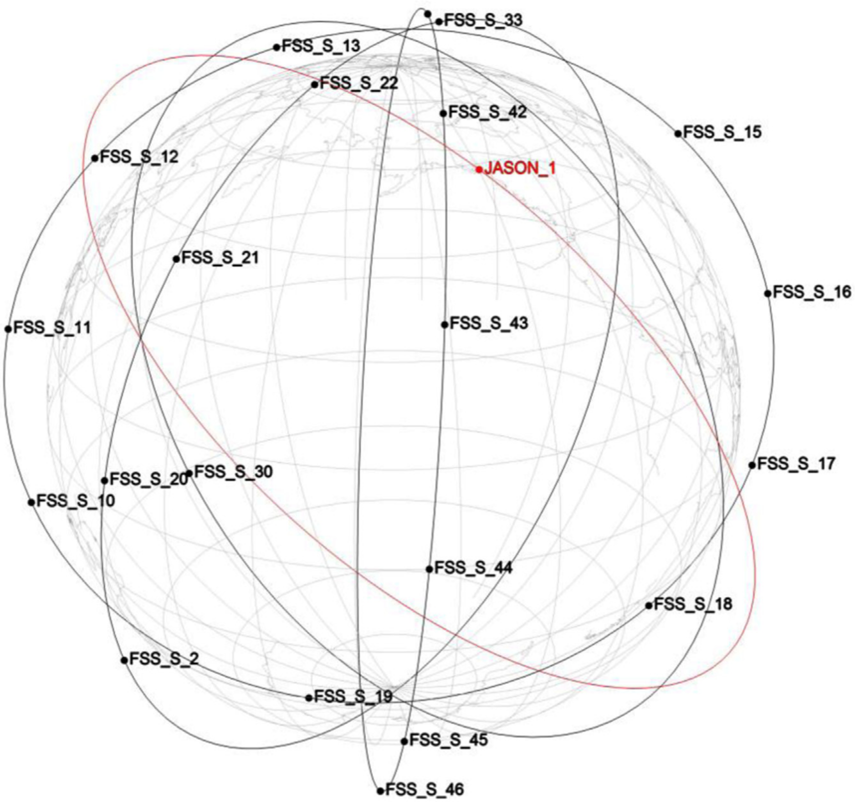

Fig. 6. FSS Earth Observation Support Infrastructure example – STK© visual representation.

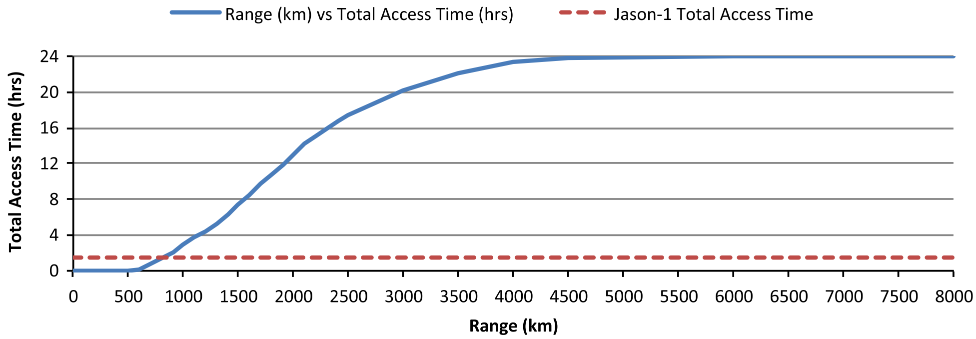

Fig. 7. Maximum allowed slant range (km) versus total access time (h) in the J1-Iridium case study.

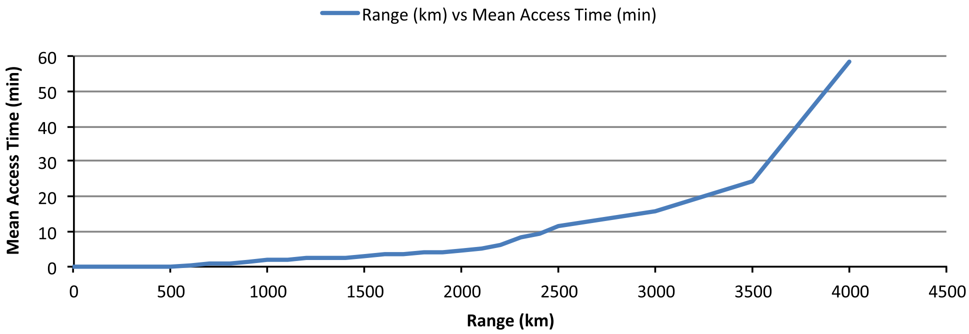

Fig. 8. Maximum allowed slant range (km) versus mean access time (min) in the J1-Iridium case study.

potential applications, the improvement of numerical weather modeling and tidal predictions based on near real-time access to radar altimeter data. This assumes an appropriate closure of power and link budgets, accommodated by appropriate transmitter and receiver design choices on the involved spacecraft. Minimum range is desired to minimize link and power budget requirements on participating spacecraft. However, minimum range also implies lower minimum contact duration, as shown by Fig. 8.

Low contact times represent a technological challenge for the foreseen FSS ISL payload, as the number of switching operations significantly increases technical complexity. As a worst-case scenario, it is assumed that a minimum contact duration of less than 2 min would pose too stringent challenges on the FSS technology and therefore is deemed infeasible. This conservative assumption is drawn from the TDRSS system user manual [44], which recommends preparing the user spacecraft for the link up to 2 min before actual data transmission starts.

Finally, link feasibility is determined by technical assumptions on the FSS middleware being conceived at the customer and supplier ends of the FSS infrastructure. We assume that both the customer and supplier spacecraft mount small patch antennas operating at S-band with a gain of 12 dB each, with a 5 W transmitting power capability. We assume total implementation and pointing losses of 4 dB, total system noise temperature of 25 dB K, a required $E_b/N_0 = 9.6$ dB (QPSK modulation with BER = 1E − 05), and a link margin of 1.5 dB. Assuming a ~15% efficiency of the associated amplifier technology, this translates into a ~33 W load on the customer and supplier FSS spacecraft – amounting to about 7.3% of J1's total power budget. With these assumptions in mind, we now evaluate available and required data rates for each scenario represented by all maximum range values assumed previously in Fig. 7. Data rates are evaluated as follows:

$$\text{Required Data Volume} = \text{DR}_{\text{nom}} \frac{24}{\Omega} \times 7 \times 60 \times C_{\text{orb}} \tag{2}$$

$$\text{Required Data Volume} = \frac{\text{Required Data Volume}}{\text{Total Access Time}};\ \text{Total Access Time} = f(S) \tag{3}$$

$$\text{Available Data Rate} = \frac{P_t G_t G_r L_s L_l}{kT_s \cdot (E_b/N_0)_{\text{req}} M} \tag{4}$$

$$L_s = \left(\frac{c}{4\pi \times S \times f}\right)^2 \tag{5}$$

where c is the speed of light (in km/s), C_{orb} is the number of contacts per orbit, DR_{nom} is the nominal customer spacecraft data rate (in bps), $(E_b/N_0)_{\text{req}}$ is the required ratio of received energy-per-bit to noise-density, f is the communications center frequency (in Hz), G_t is the customer spacecraft gain, G_r is the supplier FSS ISL antenna gain, k is the Boltzmann's constant (in J K^{-1}), L_s is the free space loss, L_l is thetotal line loss, M is thelink margin, P_t is the FSS ISL payload transmit power (in W), S is the maximum slant range (in km), T_s is the total system noise temperature (in K), and Ω is the customer spacecraft orbital period (in hours).

In the analysis that follows, we assume a S-band center frequency (f=2.2 GHz) and one contact per orbit (C_{orb}=1) Fig. 9 shows the results of the data rate calculations. For a FSS scenario to be feasible, the available data rate must be

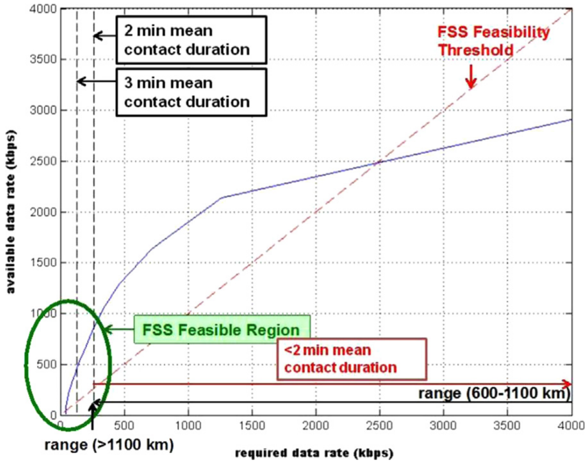

Fig. 9. FSS feasible region determination by comparison of available/required data rate.

greater than the required data rate. Therefore, the resulting feasible region is represented by the curve lying on the region above the dotted line in Fig. 9. This result shows therefore that FSS is indeed feasible for a variety of maximum range assumptions in this example. Infeasibility is determined by too large maximum range, not allowing link budgets to close for the assumed FSS middleware technical characteristics. A second infeasibility criterion is given by a too low minimum contact duration, due to technical challenges in implementing a very large number of switches during operations. Moreover, final implementations should also comply with frequency allocation regulations.

This case study has demonstrated an application of FSS to enable new capabilities in Earth Observation; however, what is also important to evaluate is the business opportunity associated with FSS operations. Building on this example, therefore, Section 5 describes an integrated approach to evaluate the business case of FSS, and applies it to the case of space exploration – to show how the proposed FSS development could help to enhance the sustainability of space exploration, traditionally, a cost-intensive endeavor.

5. Second case study: enhancing sustainability of space exploration

This section describes a case study that shows the financial profit that could be achieved applying the FSS paradigm to the ISS. The ISS is here thought as a supplier of resources such as downlink bandwidth, data storage, computing power, and so forth. In this scenario, the ISS is a supplier node in a federation with other customer spacecraft that trade such resources in an in-space market where resource price is determined by the balance of supply and demand. This constitutes a creative way of adding value to the business case of manned exploration programs, considering the ability of manned spaceflight infrastructures to generate financial profit as a secondary objective for their missions, by exploiting synergies with non-manned programs.

Manned exploration is an expensive business, with programs often running on the order of hundreds of billions of dollars during the course of their lifecycle, such as the case of the ISS, a large investment on the order of 100 billion Euros [45]. Manned space exploration programs are facing years of uncertainty, due to increasing financial pressures and diverging view of stakeholders on the value proposition of the exploration enterprise. While the discussion of the rationale supporting manned exploration is outside of the scope of this paper, a more compelling case for manned exploration can be made if the ISS generates profit by supplying resources in a satellite federation. The ISS is a massive infrastructure with a significant endowment of size, mass, and power. As such, mass and power constraints for payloads onboard the ISS are much less stringent than what experienced on conventional satellites, making it therefore possible to consider the development of hosted payloads at relatively lower complexity, hence cost, of what experienced with typical satellite developments. The resources offered by the ISS makes it interesting to explore whether the Station could be put to commercial use as a secondary objective for its mission.

The methodology to assess the business potential of this proposition includes 1) the identification and ranking of potential customers from a supplier perspective, 2) the sizing of the market and the required capabilities of resource-trading FSS payloads, and 3) the evaluation of the business case from both customer and supplier perspectives to assess whether the introduction of FSS technology on the supplier spacecraft gives rise to a win–win proposition, and therefore to a viable market. The overview of the proposed assessment methodology is shown in Fig. 10. The approach combines business assessments with systems engineering and technical feasibility analysis in order to provide a holistic assessment of the business value proposition.

5.1. Step1: customers identification

First, potential customers of an ISS-based resource supply are identified among the active satellites surveyed in the market assessment presented in Section 3. Given this broad survey, six categories of representative customers have been formulated, as shown in Table 3. Representative customers range from LEO to GEO altitudes, with varying inclinations across mission categories to assess the sensitivity of the business proposition to varying orbital parameters. The next step, therefore, is to assess the accessibility of those customers from the ISS, where accessibility is defined by the combination of number of accesses, slant range, and access duration for each mission, for a given timeframe of interest.

5.2. Step 2: ISS customers accessibility analysis

In the following, accessibility analysis is conducted on the set of representative customers identified in Table 3. The number of opportunities available to the supplier to trade resources defines accessibility to customers. Accessibility depends on number of contacts, their duration, and is affected by slant range.

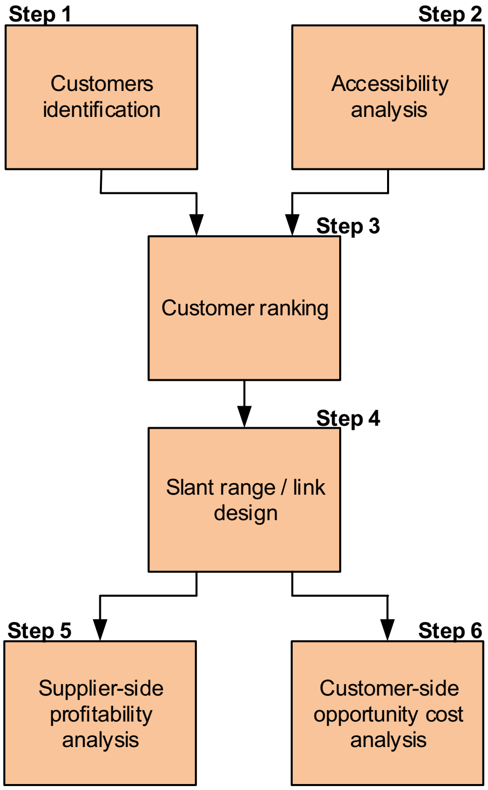

Fig. 10. Proposed assessment methodology for FSS suppliers.

Table 3
ISS case study representative customers.

ID	Orbit Type	Altitude (km)	Inclination (deg.)	Typical customer
1	LEO/SSO	600	97.79	EO/Tlc.
2	LEO/SSO	800	98.61	EO/Tlc.
3	LEO	600	20	Tlc.
4	LEO	600	40	Tlc.
5	MEO	20,000	60	Tlc./Nav.
6	GEO	35,786	0	Tlc.
7	GSO	35,786	18	Tlc.

In order to compute such parameters, access durations and slant ranges are calculated for all access opportunities by propagating the orbits of representative customers over a timeframe large enough to represent all orbital configurations of interest. A one-year propagation time-period has been considered in this case study, and slant range and accesses evaluated using a commercial orbital propagator. The results on the selected customer sets are illustrated in Figs. 11–14, showing mean access range versus access duration for each access opportunity. Figures are color and marker coded according to the representative customer being accessed. As also shown in customer identification, Fig. 11 reflects the three-tier market segmentation between LEO, MEO, and GEO/GSO satellites as seen from Station, defined by mean slant ranges. It is interesting to notice how significant access opportunities from the ISS are provided for LEO satellites at inclinations that are dissimilar to the ISS', namely 20° and SSO orbits. On the other hand, accessibility simulations to LEO satellites appeared less sensitive to variations in orbital altitude than to in inclination changes, as shown comparing LEO access durations between Fig. 11 and Fig. 12. Fig. 13 shows access opportunities to MEO constellations, whereas Fig. 14 shows accesses to GEO/GSO assets.

By visual inspection of the results in Fig. 11 one would rank customers based on the total number of access opportunities, and therefore rank MEO satellites as priority customers (central magenta cluster in Fig. 11), followed by LEO assets (left clusters in Fig. 11), and ultimately by GEO/GSO satellites (red/yellow clusters on the right side). However, cost of accessing those customers should be considered in a holistic evaluation of both supplier and customer benefits derived by engaging in resource transactions. The following steps will therefore provide criteria for customer ranking from the supplier side, and business evaluation approaches from both customer and supplier perspective.

5.3. Step 3: customer ranking

Ranking is required to prioritize customers and to define thresholds in selecting customers in the market. This step implements a ranking by considering both benefits and costs associated with customers, proposing an overall accessibility metric. Accessibility for customer i is defined as the sum of the ratios between time duration (i.e. benefit) and the square of slant range (i.e. cost) of each access:

$$\text{Accessibility}_i = \sum_j \frac{\text{Duration}_{ij}}{\left(\text{Mean Range}_{ij}\right)^2} \tag{6}$$

The accessibility metric defined in Eq. (6) assumes that all customers are equally important. Moreover, does not reflect the costs effects of requiring many handovers to achieve a longer contact times. These assumptions are deemed acceptable in this preliminary analysis. Ranking of the customers leads to the assessment show in Fig. 15. The

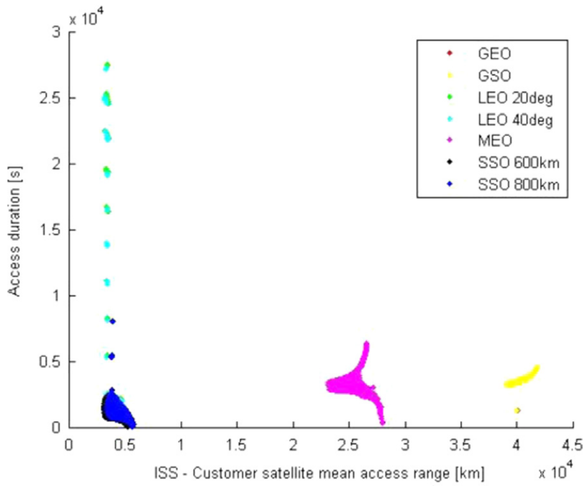

Fig. 11. Accessibility analysis, all customers.

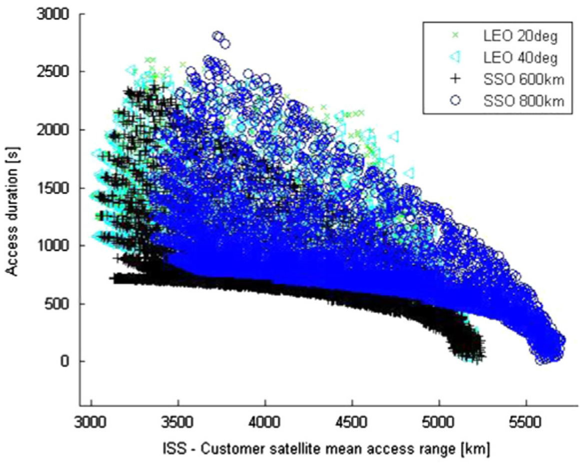

Fig. 12. Accessibility analysis, zoom on LEO customers (access time 0–3000 s).

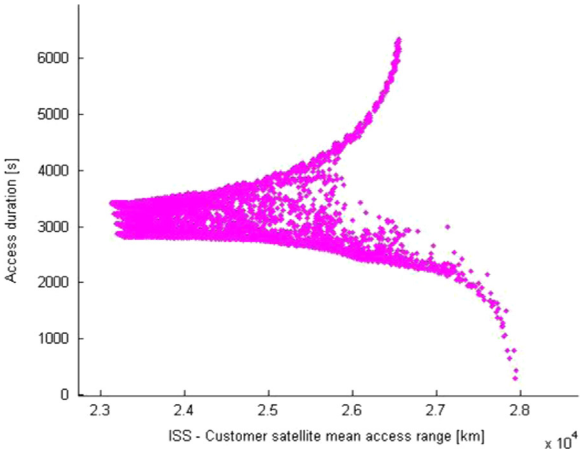

Fig. 13. Accessibility analysis, MEO customers.

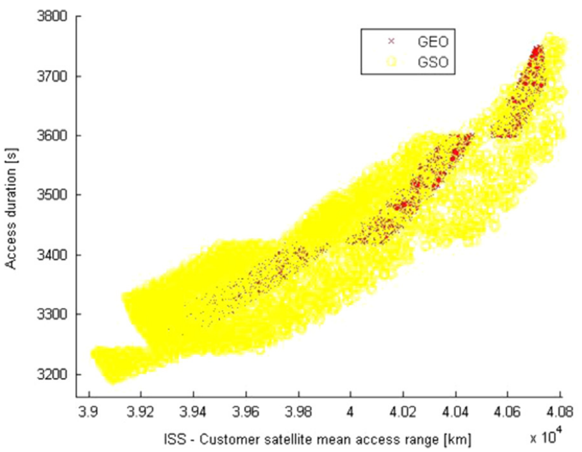

Fig. 14. Accessibility analysis, GEO/GSO customers (detail on 39,000–40,800 km slant range).

figure identifies all LEO assets as the customers with the best benefit-cost ratios. As free space loss goes with the inverse square of slant range, link requirements are expected to rank analogously, hence the square range in Eq. (6) providing an evaluation metric that is reflective of the link budgets associated with customers.

As a result of the ranking, all LEO customers (IDs 1–4 in Table 3) are considered as core customers for which FSS supplier payloads need to be sized. The following step provides the criterion to define the slant range for FSS payload design, based on percentile criteria of the overall population of best benefit/cost customers.

5.4. Step 4: slant range/link design

Customer ranking results are used to determine a design slant range for the FSS ISL payload. A percentile criterion on highest-ranking customers, as defined in Step 3, is adopted. Fig. 16 shows the distribution of slant ranges across the top 4 best benefit/cost customer population. A 90% percentile cutoff criterion is adopted, setting a threshold range large enough to include most accesses and discard outliers and the upward tail of the range distribution. The resulting design slant range for the ISS case study is 5123 km, as shown in Fig. 16.

Slant range selection determines the cost to be borne by suppliers, driven by FSS supplier payload sizing, and the opportunities available to customers for resource trading. The following steps provide approaches to estimate the business proposition from both supplier and customer perspective, and assess the emergence of win–win opportunities by the introduction of FSS. In these steps, answers are provided to the three research questions set out in this case study: 1) is the number of customers reachable from ISS enough to create a compelling business case? 2) Would the FSS service from ISS be an attractive opportunity to customers? And finally, 3) how much profit can be made interfacing the ISS in a FSS infrastructure? Profitability analysis and opportunity cost analysis are proposed to investigate such questions, examining the business case for two different Inter-Satellite Link (ISL) technologies: RF-based and Optical-based FSS ISL hosted payloads.

5.5. Step 5: supplier-side profitability analysis

A two-step approach is adopted for the assessment of the business proposition from a market perspective: first a cost analysis from the supplier perspective is conducted, estimating a financial break-even point and a selling price to the market. Successively, an analysis from a customer perspective is conducted, in order to verify that the set price point leads to a financial incentive to customers to adopt the service.

Capacity and cost estimates are made assuming an equivalent number of 36 MHz C-band transponders, adopting a Digital Video Broadcast Second Generation (DVB-2S) standard, and 8-Phase Shift Keying (8PSK) modulation with 3/4 forward error correction (FEC). This assumption sets the technical currency with which throughput rates are estimated. Thereon, a throughput efficiency of 1.875 Mbps/MHz is assumed (67.5 Mbps maximum throughput per 36 MHz bandwidth) [46]. “Exchange rates” from other types of transponders, modulation schemes, center frequencies, and standards, can be easily determined by considering equivalent

Fig. 15. Customer ranking results.

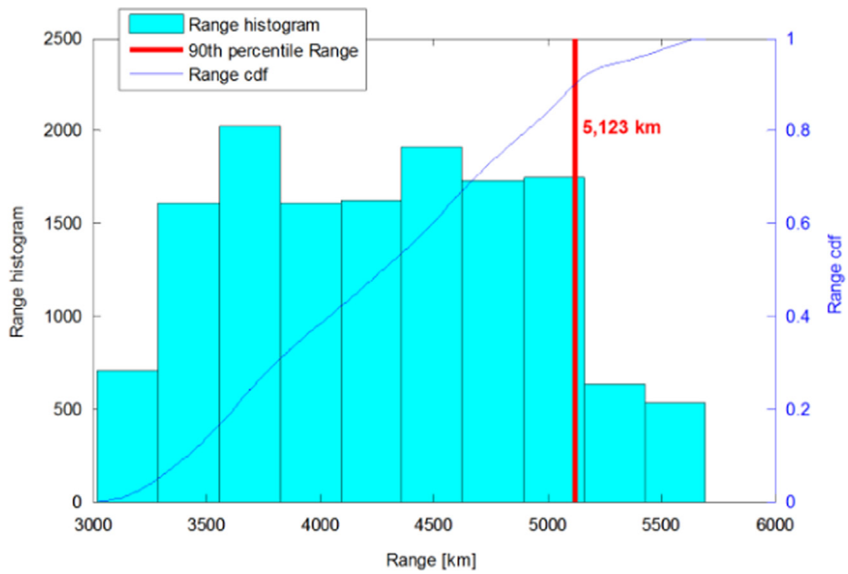

Fig. 16. Top 4 customers (LEO 20°, SSO 600 km, SSO 800 km, LEO 40°) slant range/link design results. Red line indicates 90th percentile of slant range. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

throughput efficiencies (Mbps/MHz), which are functions of the above mentioned transponder parameters.

The goal of the profitability analysis is to determine the marginal cost per equivalent transponder that allows the operator to break even from supplying FSS services, and to estimate the selling price to the market.

5.5.1. Determine number of equivalent transponders

To ensure a conservative estimate for all kind of suppliers, it is assumed that the marginal cost of a FSS equivalent transponder is equivalent to the marginal cost of one equivalent transponder on a telecommunications satellite such as NASA's Tracking and Data Relay Satellite (TDRS) [47]. This is a conservative estimate because TDRS is a GEO satellite (GEO being the highest altitude assumed for an Earth-orbiting FSS operator), radiation-hardened to ensure operations for at least 15 years [48]. LEO transponders have, in general, lifecycles shorter than 15 years, and lower costs due to less stringent radiation-hardening requirements. This assumption holds even stronger for hosted FSS payloads on the ISS, since those are not subject to stringent mass and size requirements imposed by satellites driving up complexity, hence cost.

A Second Generation TDRS satellite is reported to have 3900 MHz of total Ka-band capacity [49]. Ka-band transponders on TDRS 2nd generation have a 650 MHz bandwidth, and have been demonstrated to operate at 800 Mbps [50], hence setting a throughput efficiency of 1.23 Mbps/MHz. Therefore, the power and ground link-unconstrained equivalent maximum throughput of a TDRS 2nd generation satellite equals to $3900 \cdot 1.23 = 4797$ Mbps. The number of equivalent

36 MHz transponders is calculated dividing this throughput by the maximum throughput of a 36 MHz unit: 4797 / 67.5 = 71 equivalent transponders.

5.5.2. Estimate net present value of TDRS LCC

Marginal total lifecycle costs (LCC) attributed to an individual TDRS unit are then estimated. Development cost of two TDRS 2nd generation satellites has been reported at 700 MUSD FY2009 [51]. Considering an equal cost split among spacecraft, this amounts to 350 MUSD FY2009 for TDRS marginal unit development cost. Ground segment and operation cost estimates are assumed by estimating ground segment development cost as 9% of total development cost (31.5 MUSD FY2009), and annual operations cost as 5% of total development cost (17.5 MUSD/yr FY2009) [52], for 15 years of nominal operations. As public data on TDRS launch cost is not publicly available, an estimate is made by assuming a specific launch cost to geostationary transfer orbit (GTO) of 21 kUSD/kg FY2000 [53]. A TDRS unit has a wet mass of 3454 kg [54]. Hence, launch cost is estimated at 72.5 MUSD FY2000.

Therefore, the Net Present Value (NPV) of the total TDRS marginal lifecycle cost is calculated assuming a constant 4% annual inflation rate, and converted into Euros assuming a 1.3 EUR/USD exchange rate – hence leading to a total TDRS marginal NPV of 701.6 MEUR FY2013.

5.5.3. Estimate equivalent transponder marginal NPV

Using the results from previous sections, the minimum marginal NPV of 36 MHz equivalent transponders on TDRS 2nd generation is then estimated as 701.6/71 = 9.88 MEUR FY2013. This is a minimum marginal cost estimate, as it does not consider power constraints and ground segment downlink constraints that limit throughput capacity of a TDRS satellite.

Assuming a symmetric 30% uncertainty due to these factors, a likely estimate of marginal unit cost for equivalent transponders equals is hence defined at 11.4 ± 15% MEUR FY2013 corresponding to 168.9 ± 15% kEUR-FY2013/Mbps.

5.5.4. Estimate market selling price and associated maximum profit

Selling price for an equivalent transponder is estimated adding markups to the breakeven cost estimates that have been conducted above. Two scenarios for markups are here considered for the ISS case study: 1.5 MEUR/yr, and 3.5 MEUR/yr. If the transponder marginal cost estimated above is to be recovered in one year of operations, these markups would lead to a nominal 13% and 31% profit margin, respectively. The coherence of markups and resulting selling prices with the market is verified in Step 6 of the approach as illustrated previously in Fig. 10 – opportunity cost analysis-, and iterations between these processes are implemented if needed. Maximum profit is estimated by first calculating the maximum data rate achievable between suppliers and customers. In the ISS case study, the nominal customer at 5123 km slant range is assumed, as determined in Step 4. Different scenarios are considered, assuming both RF-based and optical-based link technologies, varying diameters for supplier antennas, and varying transmit powers for customers. Small antenna diameters impose small burdens to customer missions: 0.25 cm diameter customer antennas in the RF case, and 0.05 cm for Optical. The relevant equations for the RF link budgets are Eqs. (2)–(5). The performance of the optical links is computed as [55]:

$$P_s = P_t\left(\eta_t \eta_A \frac{4\pi A_t}{\lambda^2}\right) L_{pt} L_{pr} L_{pol} L_{misc}\left(\eta_r \frac{A_r}{4\pi z^2}\right) \tag{7}$$

$$\eta_A = \frac{2S}{\alpha^2}\left(e^{-\alpha^2\gamma^2} - \left(e^{-\alpha^2}\right)\right)^2 \tag{8}$$

$$R = \frac{M \times \lambda \times \eta_{quant}}{ns \times h \times c}\left(P_s \times c_{margin}\right) \tag{9}$$

where in Eq.(7), P_s is the power received, η_t and η_r are the transmitter and receiver power efficiencies, A_t and A_r are the transmitter and receiver apertures, z is the link distance, L_{pt} and L_{pr} are transmitter and receiver pointing losses, L_{pol} are the polarization losses, and L_{misc} includes miscellaneous losses such as bit synchronization and pulse amplitude variation losses. η_A is the illumination aperture efficiency, computed via Eq. (8) based on the Strehl ratio S, obscuration ratio γ and the ratio between aperture diameter and Gaussian beam α. The achievable rate R in Eq. (9) depends on modulation format M, wavelength λ, quantum efficiency η_{quant}, the planck constant h, speed of light c, the receiver sensitivity ns in photons/bit and the margin chosen C_{margin}.

Using this formulation, Tables 4–9 report the resulting maximum data rate estimates for RF-based and Optical-based communications payloads for the ISS case study, with working assumptions for the link budgets (such as assumed signal to noise ratios, efficiencies, link margins, and so forth) included at the bottom of each table. Data rates from Station to the nominal customer vary from 3 Mbps to 1088 Mbps in the RF case, and from 611 Mbps to approximately 73 Gbps in the Optical case, for the ranges of supplier antennas considered (1–8 m for RF, 5–10 cm for Optical).

Corresponding maximum profits *Pf* are estimated by computing the number of equivalent transponders and multiplying by the assumed markups as shown in Eq. (10):

$$Pf = \frac{R}{\eta_{eff} \times \mathrm{BW}_{eq}} \times \mathrm{Markup} \tag{10}$$

where R are the achieved data rates. The equivalent transponder for which the NPV has been previously estimated features a throughput efficiency of η_{eff} 1.875 Mbps/MHz and a bandwidth BW of 36 MHz.

Results for the ISS case study and for the two markup scenarios considered are shown in Tables 4–6 (RF FSS payload), and Tables 7–9 (Optical FSS payload). Estimated maximum profits range from 0.1 to 56.4 MEUR/yr in the RF payload case, and from 13.6 to 3805 MEUR/yr in the optical payload case – accounting for all financial and technical assumptions described previously. Indeed, these assumptions are to be considered as maximum boundaries, as likely profit analysis needs to consider actual market demand, estimated with knowledge on customer specifications and requirements. The analysis highlights the dominance of optical-based payloads over the RF-payloads in the ISS case study,

Table 4
Maximum achievable data rate, Ku-band ISL capacity, ISS to customer at 5123 slant range.

	Ku-band ISL capacity ISS to customer at 5123 km range Maximum data rate [Mbps]				
Supplier antenna diameter (TX) [m]	Tx power 1 W	Tx power 5 W	Tx power 10 W	Tx power 15 W	Tx power 20 W
1	3	4	9	13	17
2	3	17	34	51	68
3	8	38	76	115	153
4	14	68	136	204	272
5	21	106	212	319	425
6	31	153	306	459	612
7	42	208	416	625	833
8	54	272	544	816	1088

Assumptions:
(1) 0.25 m diameter transmit antenna, 70% efficiency, 2 dB total line losses, 29.6 dB K system noise
(2) 55% gateway efficiency, 6 dB total line losses, BER = 1E − 5
(3) Required $E_b/N_0 = 9.6$ dB
(4) Link margin = 3.0 dB

Table 5
Maximum annual profit (MEUR 2013), Ku-band ISL capacity, ISS to customer at 5123 slant range, equivalent 36 MHz transponder cost = 1.5 MEUR/yr.

	Ku-band ISL capacity ISS to customer at 5123 km range Max annual profit (MEUR 2013), equivalent 36 MHz transponder markup = 1.5 MEUR/yr				
Supplier antenna diameter (TX) [m]	Tx power 1 W	Tx power 5 W	Tx power 10 W	Tx power 15 W	Tx power 20 W
1	0.1	0.1	0.2	0.3	0.4
2	0.1	0.4	0.8	1.1	1.5
3	0.2	0.8	1.7	2.5	3.4
4	0.3	1.5	3.0	4.5	6.0
5	0.5	2.4	4.7	7.1	9.4
6	0.7	3.4	6.8	10.2	13.6
7	0.9	4.6	9.3	13.9	18.5
8	1.2	6.0	12.1	18.1	24.2

Table 6
Maximum annual profit (MEUR 2013), Ku-band ISL capacity, ISS to customer at 5123 slant range, equivalent 36 MHz transponder cost = 3.5 MEUR/yr.

	Ku-band ISL capacity ISS to customer at 5123 km range Max annual profit (MEUR 2013), equivalent 36 MHz transponder markup = 3.5 MEUR/yr				
Supplier antenna diameter (TX) [m]	Tx power 1 W	Tx power 5 W	Tx power 10 W	Tx power 15 W	Tx power 20 W
1	0.1	0.2	0.4	0.7	0.9
2	0.2	0.9	1.8	2.6	3.5
3	0.4	2.0	4.0	5.9	7.9
4	0.7	3.5	7.0	10.6	14.1
5	1.1	5.5	11.0	16.5	22.0
6	1.6	7.9	15.9	23.8	31.7
7	2.2	10.8	21.6	32.4	43.2
8	2.8	14.1	28.2	42.3	56.4

where dominance is defined by the broader range of maximum allowed profits. This consideration, in addition to the much smaller antenna diameters and mass/power requirements of optical solutions, give strong indicators that optical payloads are preferred solutions, should ISS consider joining an FSS infrastructure, and if customer satellites adopt optical link technology over the incoming years. Technology developments in the European market of Earth Observation [39], together with a strong interest from the US interplanetary exploration community [55], give strong pointers towards this direction.

As profitability has been assessed, coherence of foreseen selling prices with the market needs to be ensured. This is done in the following step, opportunity cost analysis, looking at cost estimates from a customer satellite perspective, willing to use FSS, and in particular the ISS node, as its primary infrastructure for space-to-ground link, and other on-orbit services such as data processing, storage, handling, and distribution.

5.6. Step 6: customer side opportunity cost analysis

While profitability analysis determines a selling price to market that incentivizes suppliers to join the FSS infrastructure, opportunity cost analysis looks at the other side of the coin – that is, whether customers have incentives in preferring FSS services to conventional business-as-usual (BAU) operations.

Incentives to customers are represented by cost savings realized implementing a FSS hosted payload on their

Table 7
Maximum achievable data rate, Optical ISL capacity, ISS to customer at 5123 slant range.

	Optical ISL capacity, ISS to customer at 5123 km range Maximum data rate [Mbps]				
Supplier antenna diameter (TX) [cm]	Tx power = 0.5 W	Tx power = 1 W	Tx power = 5 W	Tx power = 10 W	Tx power = 15 W
5	611	1223	6615	12,232	18,348
6	880	1761	8806	17,614	26,421
7	1198	2397	11,987	23,975	35,962
8	1565	3131	15,657	31,314	46,970
9	1981	3963	19,816	39,631	59,447
10	2246	4892	24,464	48,928	73,391

Assumptions:
(1) Receiver antenna diameter = 5 cm, 10% obscuration, 36 photon/bit sensitivity
(2) BER = 1E − 12, 16-PPM Modulation, 1550 nm wavelength, 0.8 quantum efficiency
(3) 50% TX and RX power efficiency, 72% TX illumination aperture efficiency
(4) Link margin = 5.0 dB, 2 dB pointing losses at both ends, 1 dB polarization losses.

Table 8
Maximum annual profit (MEUR 2013), Optical ISL capacity, ISS to customer at 5123 slant range, equivalent 36 MHz transponder cost = 1.5 MEUR/yr.

	Optical ISL capacity ISS to customer at 5123 km range Max annual profit (MEUR 2013), equivalent 36 MHz transponder markup = 1.5 MEUR/yr				
Supplier antenna diameter (TX) [cm]	Tx power 0.5 W	Tx power 1 W	Tx power 5 W	Tx power 10 W	Tx power 15 W
5	13.6	27.2	147.0	271.8	407.7
6	19.6	39.1	195.7	391.4	587.1
7	26.6	53.3	266.4	532.8	799.2
8	34.8	69.6	347.9	695.9	1043.8
9	44.0	88.1	440.4	880.7	1321.0
10	49.9	108.7	543.6	1087.3	1630.9

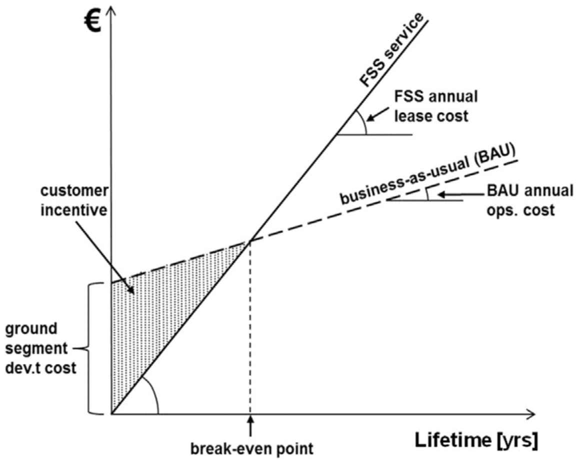

Fig. 17. FSS Opportunity cost analysis concept.

Table 9
Maximum annual profit (MEUR 2013), Optical ISL capacity, ISS to customer at 5123 slant range, equivalent 36 MHz transponder cost = 3.5 MEUR/yr.

	Optical ISL capacity ISS to customer at 5123 km range Max annual profit (MEUR 2013), equivalent 36 MHz transponder markup = 3.5 MEUR/yr				
Supplier antenna diameter (TX) [cm]	Tx power 0.5 W	Tx power 1 W	Tx power 5 W	Tx power 10 W	Tx power 15 W
5	31.7	63.4	343.0	634.2	951.4
6	45.6	91.3	456.6	913.3	1370.0
7	62.1	124.3	621.5	1243.1	1864.7
8	81.1	162.3	811.8	1623.7	2435.5
9	102.7	205.5	1027.5	2055.0	3082.4
10	116.5	253.7	1268.5	2537.0	3805.5

spacecraft. Cost savings are evaluated estimating the opportunity cost, which is done comparing the cost difference between FSS services and developing the system using business as usual practices. A notional depiction of opportunity cost analysis is shown in Fig. 17. For simplicity of illustration, the figure represents undiscounted cash flows; however, a discount rate can be introduced in the evaluation to value the time component of expenditures and therefore determine the Net Present Value of the customer incentive.

Cost savings are associated with the conversion of fixed costs associated with ground segment development costs (the fixed cost at time 0 for the dashed BAU curve shown in Fig. 17 in recurring costs associated with annual lease fees for capacity on the FSS network). It is here assumed that development cost remains unchanged between implementing and not implementing a FSS hosted payload on a customer spacecraft; this assumption likely results in a conservative estimate, as introduction of FSS technology (once at Technology Readiness Level 9) will lead to overall complexity reduction of space missions, as participating

Table 10
ISS case study – opportunity cost analysis.

Customer size	Dev. cost [MEUR FY13]	Avg data volume [Tb/d]	FSS TX Power [W]	required FSS transp.	Lifetime [years]
S	150	1	0.5	1	5
M	500	5	1	1	7
L	1000	20	5	1	15
Customer size	**Gnd. cost [MEUR FY13]**	**Ops. cost [MEUR-FY13 /yr]**	**(Gnd+Ops) NPV per year – BAU**	**(Gnd+Ops) NPV per year – FSS / 1.5 M markup**	**(Gnd+Ops) NPV per year – FSS / 3.5 M markup**
S	14	8	10.8	14.0	16.1
M	45	25	48.5	20.4	23.5
L	90	50	218.2	51.7	59.7

Assumptions:
(1) Optical FSS Payload
(2) Customer antenna diameter 5 cm
(3) Supplier antenna diameter 7 cm
(4) All other assumptions shown in Table 7

spacecraft will not need anymore to perform all functionality required by system requirements on their mission, relying on FSS network-provided services instead.

A pure recurring cost structure is a hedge against uncertainty, where uncertainty is chiefly represented by early spacecraft failure, and changing market demand for customer payload services. Such hedge corresponds to a premium in annual FSS lease fee, which may result higher than annual operations cost associated with business as usual operations.

The overall customer benefit is shown by the shaded triangle in Fig. 17. As shown in the figure, customer benefit is a function of the break-even point between the introduction of FSS and business-as-usual practice. Therefore, customer incentive is a function of customer spacecraft nominal lifetime, for a fixed FSS annual lease cost.

Table 10 shows the results of opportunity cost analysis, assuming the most convenient case of an optical FSS hosted payload; three customer categories are considered: small (S), medium (M), and large (L), with associated development costs, average data volume, FSS hosted payload transmit power, and varying mission lifetimes. Ground segment and operations cost are estimated as done previously in this paper using fraction estimates from the NASA QuickCost model [56]. For all cases considered, a single optical transponder is sufficient to meet the needs of all customer categories. The second portion of the table shows NPV calculations of ground and operations cost for both BAU and FSS cases, where the two different markup assumptions are considered. A 4% constant annual discount rate has been assumed. Under these assumptions, the customer incentive defined by the difference in NPV between the BAU and FSS cases solely depends on the development cost of the mission, which is a rough proxy of mission size and complexity. Small satellite missions (representing a low business volume for the FSS infrastructure) seem not to have a financial incentive in securing FSS services. Nevertheless, such missions shall not be neglected in future evaluations, as non-tangible incentives may also be designed by considering the overall stakeholder network supporting and funding satellite projects [57]. Significant incentives, with large margins, are realized for medium and large missions for both markup cases considered. Large margins found in this evaluation

Table 11
ISS case study – customer breakeven points.

Markup [MEUR FY13]	**Customer break-even points** Lifetime [years]		
	5	7	15
1.5	194	210	237
3.5	224	243	273

Assumptions:
(1) 4% annual discount rate

provide confidence in the robustness of the result, and also provide additional leeway to improve profitability towards suppliers (increasing markup), or to hedge cost uncertainty in the development of the FSS infrastructure. In order to better understand this result, Table 11 shows customer breakeven points for all cases considered; that is, development costs for which the customer is indifferent between choosing FSS versus BAU are calculated for all combinations of mission lifetime and markups considered. It can be found that the threshold lies roughly in the 200 MEUR FY13 ballpark, which is coherent with the results found so far in the opportunity cost analysis. Therefore, as a result, it is found that selling prices set by profitability analysis are coherent with the market, and provide large margins for further markup increase following a more detailed market sizing exercise. It is clear that further market research is required in order to understand how much of the market opportunity that is here identified is supported by the existing and future market of satellite systems – in particular, considering technology adoption estimates for optical payload systems, which seems to be ramping up at the moment of writing of this paper, but still lies at the experimental/technology demonstration level.

6. Conclusion

Space missions have been predominantly developed and operated as self-standing efforts. Only in recent years have missions been designed in a more synergistic fashion, with standardized design processes and shared components.

Interoperability has become more and more of interest to share costs and enhance sustainability, and to open new possibilities that are enabled by the collaboration of multiple missions. The space community has been developing standards and initiating working groups towards increased spacecraft and mission interoperability; however, to date no research effort in the public domain has addressed the commercial opportunities that could arise by interoperability, and how the latter could be exploited by operating heterogeneous missions as a cloud infrastructure.

This paper defines a new paradigm in distributed satellite systems: Federated Satellite Systems, as means to create new commercial opportunities enabled by opportunistic spacecraft interoperability. The paper provides formal definitions of the elements involved in satellite federations, providing a taxonomy that defines a whole range of options for spacecraft to be engaged in satellite federations. The proposed federated approach is then demonstrated with a technical assessment on an case study for Earth Observation platforms. The paper then proposes an integrated approach to evaluate the business case of satellite federations dealing with intangible resources; the approach is demonstrated with the exploration of possible opportunities to enhance sustainability of human space exploration systems, such as the ISS. This second case study demonstrated an assessment methodology for comprehensive evaluation of market opportunities for a given supplier. In this case, it has been found that potential is identified for enough customers to support FSS operations onboard Station; in particular, optical communications hosted payloads seem to be preferred solutions, as they provide simpler, lighter, and more effective data relay and processing systems when compared to traditional RF-based alternatives. The application of the proposed methodology has shown that market opportunities are potentially able to create markets of in-space resource sharing from ISS ranging from millions to hundreds of millions of Euro, depending on market interest and future adoption of optical communication systems among potential customer spacecraft. Potential markets of interest to the ISS include most LEO spacecraft, including those operating in SSO orbits, chiefly for Earth Observation, and Telecommunication purposes. The magnitude of customer incentives are driven by mission size and requirement for data processing, with medium-sized (approximately 500 MEUR-FY13 total development cost) and large-sized (approximately 1000 MEUR-FY13 total development cost) missions being preferred customers.

The case studies presented in this paper are a first step to illustrate and analyze the technical and business challenges that stand in the way of the successful implementation and operation of FSS. On the technical side, the management of fast switches and communication handoffs among spacecraft in heterogeneous orbits, the data confidentiality, and the commodity protection issues are key areas to be addressed by designers of the FSS architecture. On the business side, key challenges include stakeholder acceptance, the achievement of a critical mass of participants on a progressive deployment, and legal implications of sharing systems among several nations and organizations. However, these topics are not completely particular to FSS, being also present in the deployment of internet connectivity or terrestrial smart grids. As heterogeneous, interconnected systems are more and more common, technical and business solutions to the aforementioned challenges appear.

The concept of FSS is beneficial to satellite operators, space agencies, and other stakeholders of the space industry on several fronts. It allows them to more flexibly interoperate their systems as a portfolio of assets, allowing unprecedented collaboration among heterogeneous types of missions. For instance, one could envision opportunistic collaboration between Earth Observation, Navigation, Telecommunications missions, and manned spacecraft. The FSS concept gives the opportunity of developing opportunistic intra-agency collaborations, which are particularly beneficial in budget-constrained environments. A benefit of particular interest is the unique opportunity of generating revenue for non-profit missions, such as science and exploration missions. These would strengthen their business case by self-sustaining part of their program through commercial collaboration with other assets. Lastly, we envision how FSS could benefit partially failed or otherwise unused spacecraft. Consider for instance the case of payload failures, that can amount up to 34% of spacecraft failures depending on the platform [58]. A spacecraft with a partial or total payload failure, but otherwise healthy subsystems, could supply resources to other missions, making possible the recovery of part of the mission value. This option would have been interesting for some real missions like the European Herschel telescope [59], for which the end of mission was determined by the depletion of the helium reservoir used to cool the optical instrument, rather than for a sheer failure of a spacecraft subsystem.

Lastly, FSS represents an invaluable opportunity to develop innovative small satellite system concepts. Small satellite mission architectures are constrained by their ability to gather, store, process, and relay data to the ground. Such limitations would be overcome in part or in their entirety by federating those spacecraft as customers of a Space Cloud, thus relying on other federates to accomplish some mission critical functions such as those previously mentioned. This could therefore allow agencies to develop unprecedented low-cost satellite missions, while establishing new infrastructures in space which functionality and capacity are set to grow over time, as more spacecraft join the federation, making the overall infrastructure more robust and enjoying increasingly positive economies of scale.

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References

[1] M. Armbrust, A. Fox, R. Griffith, A.D. Joseph, R. Katz, A. Konwinski, G. Lee, D. Patterson, A. Rabkin, I. Stoica, I. Stoica, M. Zaharia, A view of cloud computing, Commun. ACM 53 (2010) 50–58.

[2] L. Atzori, A. Iera, G. Morabito, The internet of things: a survey, Comput. Netw. 54 (2010) 2787–2805.

[3] S.M. Amin, B.F. Wollenberg, Toward a smart grid: power delivery for the 21st century, in: IEEE Power and Energy Magazine, 2005, pp. 34–41.

[4] I. Lluch, A. Golkar, Satellite-to-satellite coverage optimization approach for opportunistic inter-satellite links, in: Proceedings of the IEEE Aerospace Conference, 2014, pp. 1–13.

[5] I. Lluch, A. Golkar, Resource Balancing for Federated Satellite Systems, in: Proceedings of the AIAA SPACE Conference, AIAA, San Diego CA, 2014.

[6] S.L. Graeme, D.G. Vane, R.J. Boain, G.G. Mace, K. Sassen, Z. Wang, A.J. Illingworth, E.J. O'Connor, W.B. Rossow, S.L. Durden, S.D. Miller, R.T. Austin, A. Benedetti, C. Mitrescu, The CloudSat Mission and the A-Train, Bull. Am. Metereol. Soc. 83 (2002) 1771–1790.

[7] G.B. Shaw, The generalized information network analysis methodology for distributed satellite systems, in: Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge MA, 1999.

[8] J. Walker, Satellite constellations, J. Br. Interplanet. Soc. 37 (1984) 559–572.

[9] B. Hoffmann-Wellenhof, H. Lichtenegger, E. Wasle, GNSS Global Navigation Satellite Systems: GPS, GLONASS, Galileo & more, Springer, New York, 2008.

[10] R. Mattingly, L. May, Mars Sample Return as a Campaign, in: Proceedings of the IEEE Aerospace Conference, 2011.

[11] D. Selva, Rule-based System Architecting of Earth Observation Satellite Systems, in: Aero/Astro, Massachusetts Institute of Technology, Cambridge, MA, 2012.

[12] Y. Nakamura, N. Faber, D. Mauro, S. Ghaffarian, R. Alena, C.R. Frost, G. Bhat, J. McNair, Heterogeneous Spacecraft Networks: Performance analysis for low-cost Earth Observation missions, in: Proceedings of the IEEE Aerospace Conference, 2014, pp. 1–14.

[13] P. Muri, J. McNair, J. Antoon, A. Gordon-Ross, K. Cason, N. Fitz-Coy, Topology design and performance analysis for networked earth observing small satellites, in: Proceedings of the IEEE Military Communications Conference, 2011-MILCOM, 2011, pp. 1940–1945.

[14] R. Schollmeier, A Definition of Peer-to-Peer Networking for the Classification of Peer-to-Peer Architectures and Applications, in: Proceedings of the IEEE (Ed.) First International Conference on Peer-to-Peer Computing (P2P'01), IEEE, Linkoping, 2001, pp. 101–102.

[15] K. Bhasin, J.L. Hayden, Space Internet architectures and technologies for NASA enterprises, in: Proceedings of the IEEE Aerospace Conference, vol. 2, 2001.

[16] J.R. Budenske, K.S. Millikin, J.C. Bonney, R.S. Ramanujan, O. Scott Sands, Space Network Architecture Technologies, in: Proceedings of the IEEE (Ed.) Aerospace Conference, IEEE, Big Sky, MT, 2002, pp. 3–1061 – 1063–1069.

[17] C.D. Edwards, M. Denis, L. Braatz, Operations concept for a Solar System Internetwork, in: Proceedings of the 2011 IEEE Aerospace Conference, 2011, pp. 1–9.

[18] K.A. Delin, S.P. Jackson, Sensor web: a new instrument concept, in, 2001, pp. 1–9.

[19] S.A. Lucord, CCSDS Spacecraft Monitor and Control Mission Operations Interoperability Prototype, in: Proceedings of the SpaceOps 2010, AIAA, Huntsville, Alabama, 2010.

[20] C.D. Edwards, M. Denis, L. Braatz, Operations Concept for a Solar System Internetwork, in: NASA (Ed.), NASA, 2014.

[21] K. Schilling, M. Schmidt, Communication in distributed satellite systems, in: M. D'Errico (Ed.), Distributed Space Missions for Earth System Monitoring, Springer, New York, 2013, pp. 345–354.

[22] S.M. Parkes, P. Armbruster, SpaceWire: a spacecraft onboard network for real-time communications, in: Proceedings of the 14th IEEE-NPSS Real Time Conference, 2005, pp. 6–10.

[23] O. Brown, P. Eremenko, The Value Proposition for Fractionated Space Architectures, in: AIAA (Ed.) AIAA Space 2006, AIAA, San Jose, CA, 2006.

[24] W. Ferster, DARPA Cancels Formation-flying Satellite Demo, in: Space News, 2013.

[25] M. Sanchez, D. Selva, B. Cameron, E. Crawley, A. Seas, B. Seery, Results of the MIT Space Communication and Navigation Architecture Study, in: Proceedings of the IEEE Aerospace Conference, 2014.

[26] M.T. Lee, Feasibility and performance analyses of adapting Ethernet-based protocols in space-based networks, in: Proceedings of the Military Communications Conference, 2011 MILCOM, 2011, pp. 1845–1852.

[27] J. Li-zheng, M. Xin, H. Sheng-bo, L. Shu-qian, Research on Mobile IP Routing of Space Network that Based on IP over CCSDS, in: Proceedings of the Eighth ACIS International Conference on Software Engineering, Artificial Intelligence, Networking, and Parallel/Distributed Computing (SNPD), 2007, pp. 517–520.

[28] T.O. Walker, M. Tummala, J. McEachen, A system of systems study of space-based networks utilizing picosatellite formations, in: Proceedings of the 2010 5th International Conference on System of Systems Engineering (SoSE), 2010, pp. 1–6.

[29] M. Ibnkahla, Q.M. Rahman, A.I. Sulyman, H.A. Al-Asady, Y. Jun, A. Safwat, High-speed satellite mobile communications: technologies and challenges, in: Proceedings of the IEEE, vol. 92, 2004, pp. 312–339.

[30] P. Puri, M.P. Singh, A survey paper on routing in delay-tolerant networks, in: Proceedings of the 2013 International Conference on Information Systems and Computer Networks (ISCON), 2013, pp. 215–220.

[31] L. Wood, W.M. Eddy, P. Holliday, A bundle of problems, in: Proceedings of the 2009 IEEE Aerospace Conference, 2009, pp. 1–17.

[32] J. Teles, M.V. Samii, C.E. Doll, Overview of TDRSS, Adv. Space Res. 16 (1995) 67–76.

[33] F. Heine, H. Kämpfner, R. Lange, R. Czichy, M. Lutzer, R. Meyer, Laser communication applied for EDRS, the European data relay system, CEAS Space J. 2 (2011) 85–90.

[34] A. Kurs, A. Karalis, R. Moffatt, J.D. Joannopoulos, P. Fisher, M. Soljačić, Wireless power transfer via strongly coupled magnetic resonances, Science 317 (2007) 83–86.

[35] C. Gramling, Second Life for Failed Russian Satellite?, in: Science News, AAAS, 2012.

[36] P.D. Collopy, P.M. Hollingsworth, Value-driven design, J. Aircr. 48 (2011) 749–759.

[37] G. Palermo, A. Golkar, P. Gaudenzi, Earth Orbiting Support Systems for Commercial Low Earth Orbit Data Relay: Assessing Architectures through Tradespace Exploration, in: 20th Ka and Broadband Communications, Navigation and Earth Observation Conference, Vietri, Italy, 2014.

[38] J. Louet, S. Bruzzi, ENVISAT mission and system, in: Proceedings of the IGARSS '99, IEEE (Ed.), Geoscience and Remote Sensing Symposium, 1999, pp. 1680–1682.

[39] G. Taini, A. Panetti, F. Spataro, C. Bruno, Sentinel-1 Satellite System architecture: Design, performances and operations, in: Proceedings of the 2012 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), IEEE, Munich, Germany, 2012, pp. 1722–1725.

[40] A. Gunderson, T. Tao, X-band telecommunications design for large data volume earth observing missions, in: Proceedings of the 2010 IEEE Aerospace Conference, 2010, pp. 1–18.

[41] M. Madden, GeoEye-1, the world's highest resolution commercial satellite, in: Proceedings of the Conference on Lasers and Electro-Optics and Conference on Quantum Electronics and Laser Science, 2009, (CLEO/QELS 2009), IEEE, Baltimore, MD, 2009.

[42] M. Werner, G. Berndl, B. Edmaier, Performance of optimized routing in LEO intersatellite link networks, in: Proceedings of the IEEE 47th Vehicular Technology Conference, vol. 241, 1997, pp. 246–250.

[43] H.J. Kramer, Observation of the Earth and its Environment: Survey of Missions and Sensors, Springer, Berlin, 2002.

[44] NASA, Space Network Users' Guide (SNUG), in, Goddard Space Flight Center, NASA, 〈http://esc.gsfc.nasa.gov/assets/files/SN_UserGuide.pdf〉, 2007.

[45] E.S. Agency, How much does it cost?, in, 〈http://www.esa.int/Our_Activities/Human_Spaceflight/International_Space_Station/How_much_does_it_cost〉, September 3, 2013.

[46] Intelsat, Digital Compression – is there a better way to maximize the throughput of my satellite capacity?, in, 〈http://www.intelsat.com/tools-resources/satellite-basics/digital-compression/〉, September 3, 2013.

[47] NASA, Tracking and Data Relay Satellite, in, 〈http://tdrs.gsfc.nasa.gov/tdrs/136.html〉, September 3, 2013.

[48] Boeing, Generation to Generation, a Lower Risk Relay, in, 〈http://www.boeing.com/boeing/defense-space/space/bss/factsheets/601/tdrs_kl/tdrs_kl.page〉, September 3, 2013.

[49] SpaceData, NASA Satellites with SpaceData, in, 〈http://www.spacedata.us/index_page0009.htm〉, September 3, 2013.

[50] S. Vaughn, R. Sorace, Demonstration of the TDRS Ka-band transponder, in: Proceedings of the 21st Century Military Communications Conference, IEEE (Ed.), MILCOM 2000, IEEE, Los Angeles, CA, 2000, pp. 1055–1065.

[51] AGI, Spacecraft Digest – Tracking and Data Relay Satellite 11, in, 〈http://www.agi.com/resources/downloads/data/spacecraft-digest/display.aspx?i=3959〉, September 3, 2013.

[52] W.J. Larson, J.R. Wertz, Space Mission Analysis and Design, Microcosm, 1999.
[53] D.E. Koelle, R. Janovsky, Development and transportation costs of space launch systems, in: Proceedings of the DGLR/CEAS European Air and Space Conference, 2007.
[54] G.s.S. Page, TDRS 11, L, M, in, 〈http://space.skyrocket.de/doc_sdat/tdrs-11.htm〉, September 3, 2013.
[55] H. Hemmati, Deep Space Optical Communications, John Wiley & Sons, Inc., Hoboken, New Jersey, 2006.
[56] J. Hamaker, NASA QuickCost 5.0, in: Proceedings of the Society of Cost Estimating and Analysis (SCEA) and International Society of Parametric Analysts (ISPA) Joint Annual Conference, Albuquerque, NM, 2011.
[57] A. Golkar, Architecting Federated Satellite Systems for Successful Commercial Implementation, in: Proceedings of the AIAA Space 2013, AIAA, San Diego, CA, 2013.
[58] M.A. Wise, J.H. Saleh, R.A. Haga, Health scorecard of spacecraft platforms: Track record of on-orbit anomalies and failures and preliminary comparative analysis, Acta Astronaut. 68 (2011) 253–268.
[59] G.L. Pilbratt, J.R. Riedinger, T. Passvogel, G. Crone, D. Doyle, U. Gageur, A. M. Heras, C. Jewell, L. Metcalfe, S. Ott, M. Schmidt, Herschel Space Observatory – An ESA facility for far-infrared and submillimetre astronomy, arXiv:1005.5331 [astro-ph.IM], 2010.