Federated Satellite Systems (FSS): A Vision Towards an Innovation in Space Systems Design

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Abstract: This paper describes ongoing research efforts at the Skolkovo Institute of Science and Technology (Skoltech) in collaboration with MIT to explore an innovation in space systems design: the Federated Satellite Systems (FSS) concept. FSS are conceived to increase the sustainability, cost effectiveness, robustness, and reliability of space-based assets, and hedge demand uncertainty while creating in-orbit markets of space resources. This abstract will present an overview of the current research efforts and will describe an application example of a possible implementation of FSS. The example in the paper demonstrates access time gains obtained by a radar altimeter mission relying on services delivered by an FSS infrastructure, and demonstrate feasibility of FSS in this context. The paper ends with conclusions formulating a research roadmap for the work on FSS development including stakeholders analysis, systems architecting, backbone technology development, and applications development.

1. INTRODUCTION

The industrial revolution has been characterized, amongst others, by breakthroughs in information technology (IT) and space science and engineering. Nevertheless, these two technology areas have taken radically different evolutionary paths in the last six decades. IT developers soon realized that most of the potential of computer technology could be harnessed by allowing computers to communicate and operate through distributed networks. This idea led to the invention of the Internet, which has nowadays become indispensable to billions of people throughout the globe, and to the expansion of cloud computing services as cost-effective means to develop flexible IT virtual infrastructures [1]. In another engineering domain, energy infrastructures are undergoing similar developments with smart power energy grids [2]. Neither has such a cultural revolution happened nor has it been explored extensively by scholars and industry practitioners in space technology.

This paper intends to overview ongoing research efforts aimed at spurring innovation in space engineering similar to what has been developed with cloud computing in IT and with smart grids in energy. A vision for research development of a federated approach is here outlined, blurring the boundaries between different space missions. A new class of systems is proposed at the intersection of multiple research avenues, that of *Federated Satellite Systems* (FSS). FSS exploit the potential of underutilized space commodities by trading and sharing previously inefficiently allocated and unused resource commodities that are available in space assets at any given time.

The purpose of this paper is to present the concept of Federated Satellite Systems (FSS) to the small satellite engineering community, and foster discussion around the topic in order to identify opportunities for development and challenges associated with the proposed technology.

A federated approach to space systems architecting and spacecraft design is expected to change the way in which spacecraft missions are conceived and designed in multiple ways. It will improve sustainability of new missions by enabling use of small satellite platforms for Earth Observation and interplanetary exploration mission concepts that would not be feasible without support of a FSS infrastructure. It will improve the reliability of new space missions, by exploiting the inherent redundancy of FSS systems. It will improve cost efficiency, allowing designers to maximize utilization efficiency of space assets. Lastly, it will provide operators with significant mitigation of demand uncertainty, as it will allow them to rely on federated services to accommodate increased market demand in satellite services.

A federated approach to satellite systems design is an advanced instance of distributed satellite systems (DSS). DSS have been defined as missions whereby multiple satellites collaborate to fulfill a mission [3]. While this breakthrough concept led to the development of satellite constellations [4], satellite trains such as NASA's A-Train [5], and fractionated satellite concepts [6], its full potential has not been thoroughly explored. Much of FSS potential relies on the ability of LEO satellites to establish communications through intersatellite links (ISL). Significant work in ISL theory and technology development has been done in the last decades by the engineering community [7], but still much has to be done to realize in-space "networks of networks", such as the Internet for terrestrial applications. A posteriori collaboration of heterogenous satellite missions is not considered in the conventional ISL/DSS view, in part due to incompatibility of interfaces. As a result, a significant potential made of untapped and unused resources exists nowadays in orbit. Resources are here defined broadly as any commodity or service that could be potentially traded or shared between spacecraft. Resource underutilization is a lost opportunity in enhanced performance and reliability of space systems, as well as a lost opportunity for creating in-orbit markets of space commodities. Dormant resources are buried costs for a mission, as they translate into launch mass and development efforts.

The structure of this paper is as follows. Section 2 describes an application example of a Federated Satellite System with an application to radar altimeter satellite, describing architectural tradeoffs implied by a FSS infrastructure and new Earth Observation (EO) science opportunities enabled by the federated approach. Section 4 derives expected research challenges in the study and implementation of Federated Systems. Section 5 draws conclusions from the paper and derives a research roadmap for FSS.

2. APPLICATION EXAMPLE: FSS EARTH OBSERVATION SUPPORT INFRASTRUCTURE

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 [8] and designed from the outset as a predefined communications architecture between involved spacecraft. In the proposed application we consider ISL between heterogeneous spacecraft, which communications operate at different frequencies and using different protocols. We assume that a FSS middleware is installed in all missions, allowing intercommunications between heterogeneous standards acting as a metalayer similar to what is done in Internet communications. The objective of this example is not to define a detailed design of the FSS middleware or of the involved spacecraft, but rather to analyze a first baseline scenario to highlight architectural tradeoffs of the proposed FSS technology, and outline future work towards a more detailed definition of the required technology. Future work will entail a more extensive conceptual analysis, including comprehensive tradespace exploration coupled with the optimization of the virtual FSS infrastructure. In FSS, spacecraft act as suppliers and customers on an opportunistic basis – that is, when a win-win ISL opportunity for economic trading of resources between customers and suppliers is identified by means of FSS resource allocation algorithms. 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.

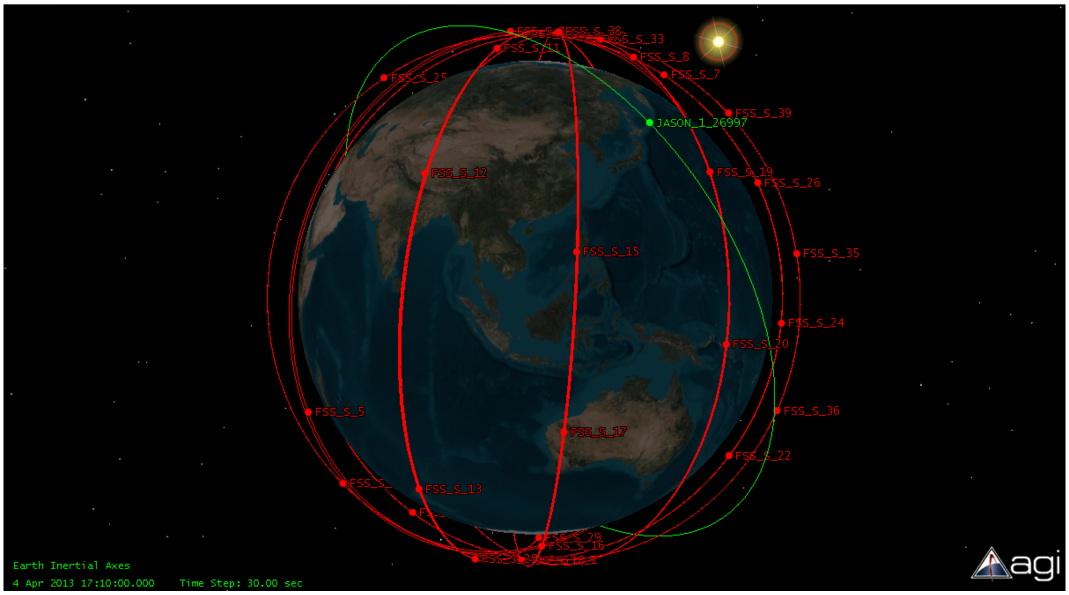

Figure 1 FSS Earth Observation Support Infrastructure Example - STK© Visual Representation

Consider the case of a radar altimetry mission for Earth Observation purposes, such as the Jason-1 mission [9] (J1), and define it as *FSS customer*. J1 is a 500kg spacecraft, whose characteristics of interest are shown in Table 1.

Table 1 Jason-1 Characteristics (data source: [9])

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

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*. In this example we consider Iridium as an example use case, but future work will generalize the concept to an arbitrary set of LEO spacecraft not designed *a priori* as a constellation. 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. Figure 1 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:

- *Total access time:* 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 other communications characteristics (as discussed later in the paper);
- *Minimum handover time*: 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.
- *Range:* 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 (as discussed later in the paper).

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 handover time. 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 architectural tradeoffs.

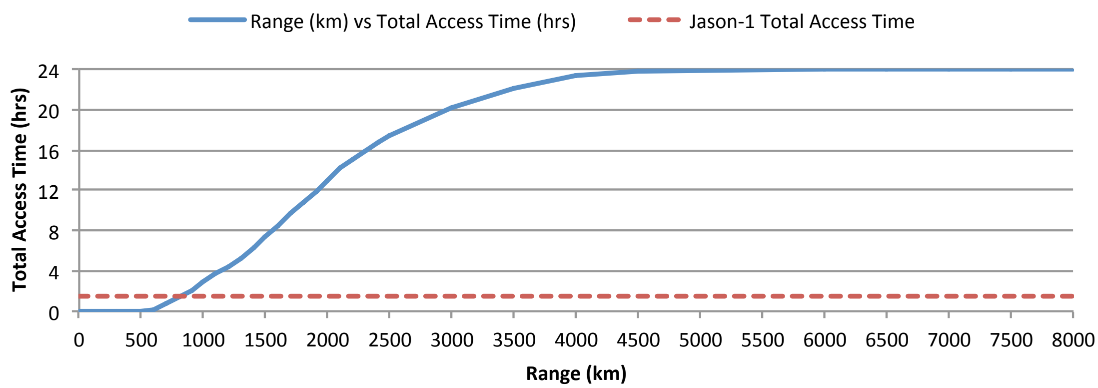

Figure 2 Maximum allowed slant range (km) versus Total access time (hrs)

Figure 2 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 minutes, total nominal access time is given by:

$$\text{total nominal access time (hrs)} = \frac{24hrs}{\text{J1 orbital period(hrs)}} \cdot \frac{7}{60} \qquad (1)$$

Figure 2 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 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 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 handover time, as shown by Figure 3.

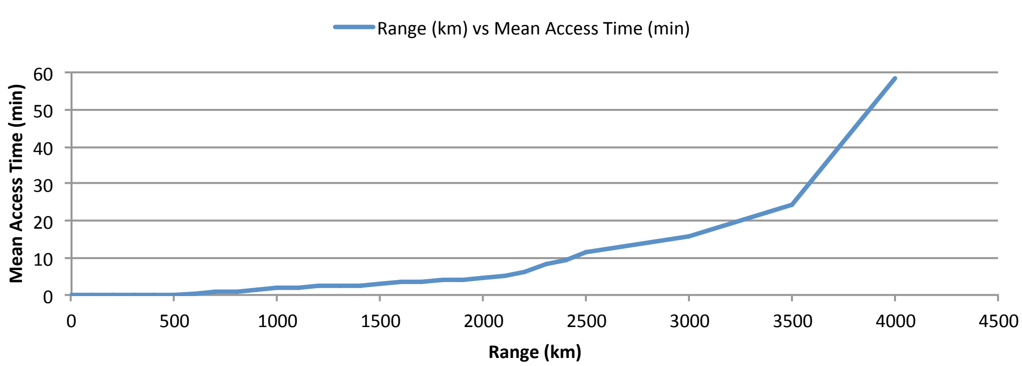

Figure 3 Maximum allowed slant range (km) versus Mean access time (min)

Low handover times represent a technological challenge for the foreseen FSS middleware payload, as technical complexity is significantly increased by the number of switching and handover operations FSS spacecraft have to perform during operations. As a baseline scenario, it is assumed that a minimum handover time of less than 2 minutes would pose too stringent challenges on the FSS technology and therefore is deemed infeasible.

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 5W transmitting power capability. We assume total implementation, atmospheric and pointing losses of 4dB, total system noise temperature of 25dBK, 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 ~33W 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 Figure 2. Data rates are evaluated as follows:

$$\text{RequiredDataVolume} = DR_{nom} \cdot \frac{24}{\Omega} \cdot 7 \cdot 60 \cdot C_{orb} \tag{2}$$

$$\text{RequiredDataRate} = \frac{\text{RequiredDataVolume}}{\text{TotalAccessTime}}, \text{TotalAccessTime=f}\left(S\right) \tag{3}$$

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

Where:

DR_{nom} = nominal customer spacecraft data rate (the data rate the customer would adopt should it rely on its own nominal ground infrastructure) [bps]

Ω = customer spacecraft orbital period [hrs]

C_{orb} = number of contacts per orbit (here assumed as unity)

S = maximum slant range [km]

P_t = FSS middleware payload transmit power [W]

G_t = customer spacecraft gain

G_r = supplier spacecraft gain

$L_s = \left(\frac{c}{4\pi Sf}\right)^2$ = free space loss, where c: speed of light [km/s], f: communications center frequency (S-band assumed 2.2 GHz).

L_l = total line loss

k = Boltzmann's constant

T_s = total system noise temperature

$\left(E_b / N_0\right)_{req}$ = required ratio of received energy-per-bit to noise-density

M = link margin

Figure 4 shows the results of the data rate calculations.

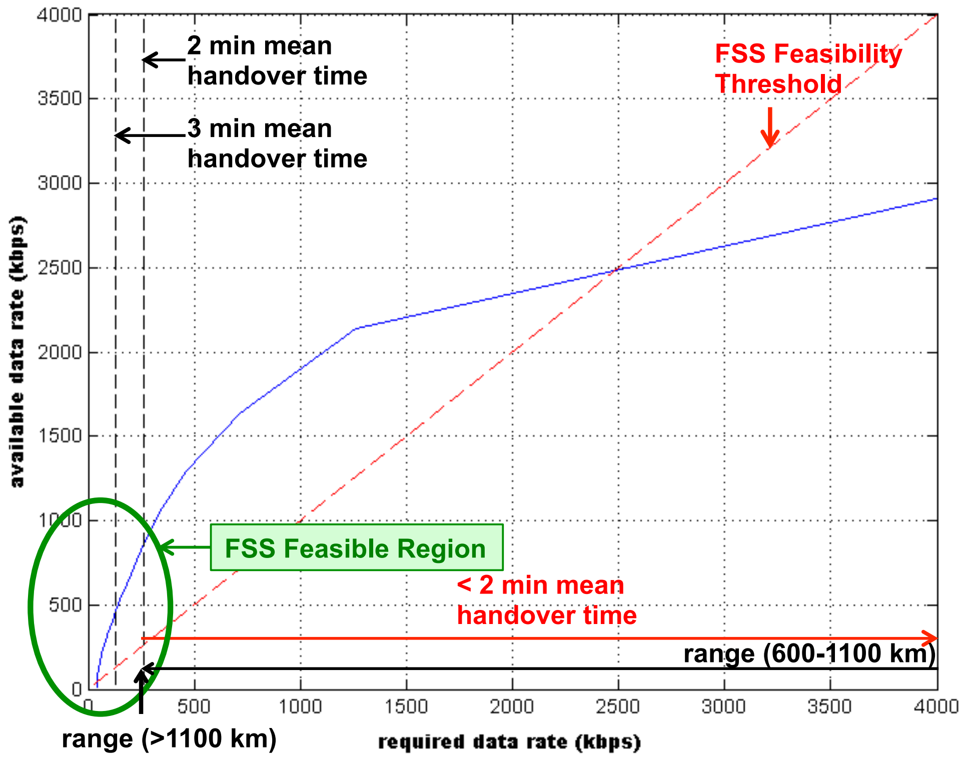

Figure 4 FSS feasible region determination by comparison of available/required data rate

For a FSS scenario to be feasible, the available data rate must be greater than the required data rate. Therefore, the resulting feasible region is represented by the curve lying on the upper triangle of the chart. 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 handover time, due to technical challenges in implementing a very large number of switches during operations.

4. CHALLENGES ASSOCIATED WITH FSS DEVELOPMENTS

While FSS hold great promise in advancing the state of the art of space systems development, several challenges need to be addressed for successful implementation and operations of Federated Satellite Systems. Research efforts in this area will identify advantages and limitations of FSS and will identify inherent tradeoffs to be considered in the systems architecting and conceptual design process. Challenges can be broadly classified in *technical challenges* and *business challenges*. Technical challenges are engineering issues that need to be analyzed and considered in the development of FSS. These include:

- **Development of backbone communications technology** supporting FSS operations;
- **Consideration of orbital mechanics implications** in FSS operations, evaluating collaborative work of space platforms operating at asynchronous orbits;
- **Management of fast switches/handoffs, bottlenecks and quality of service (QoS)** in FSS infrastructures;
- **Confidentiality issues** implied by security requirements in the FSS environment.
- **Commodity protection issues** posed by potentially malicious users operating either inside or outside the Federated Satellite Architecture.

Business challenges include all those challenges associated with stakeholders, the business case of FSS infrastructures, and related policy and regulations affecting their operations. They include:

- **Characterization of the FSS stakeholders network**, and the identification of potential threats to the development of FSS architectures;
- **Analysis of the acceptance of the FSS technology by stakeholders**. Acceptance is built by developing incentive structures from both the customer and supplier sides while addressing externalities from various stakeholders' perspectives. Incremental value delivery and hedging of demand uncertainties must be provided by means of an evolutionary development of FSS. The achievement of a critical mass of number of participating satellites – in particular for LEO applications – is an important challenge to be considered and analyzed in future work;
- **Consideration of collective action issues**, where a fine balance of customers and suppliers need to be preserved to ensure sustained FSS service;
- **Consideration of FSS development issues** due to sharing of commodities and platforms by multiple organizations, such as legal liability, and implications due to nation-specific export control regulations;
- **Consideration of collective reputation issues**, where mission failures of FSS-associated missions may be ascribed to the FSS infrastructure itself, thereby threatening market demand of successive missions joining the infrastructure.

5. RESEARCH ROADMAP AND CONCLUSIONS

Research in Federated Satellite Systems holds the promise to spur innovation in space systems design. FSS are an advanced concept of distributed satellite systems, whereby inefficiently allocated and unused in-space resource commodities are traded among heterogeneous participating spacecraft. FSS are conceived to increase the sustainability, cost-effectiveness, robustness, and reliability of space-based assets, and hedge demand uncertainty while creating in-orbit markets of space resource commodities. Notwithstanding its promises, the FSS concept requires substantial research efforts to better understand advantages and limitations of its potential implementations in future space missions. To this end, a research roadmap for the development of the conceptual backbone supporting Federated Satellite Systems is devised in this paper. Research efforts are foreseen in stakeholder analysis, systems architecture design, backbone technology development, and development of novel mission concepts.

In stakeholder analysis, questions of interest to FSS will be to analyze and characterize the stakeholders of space missions to elicit stakeholder needs and therefore derive requirements for FSS architectures. In systems architecture design, research will focus in comprehensive tradespace exploration of FSS architectures, by identifying architectural decisions, enumerating feasible FSS architectures, evaluating them through evaluation metrics derived from stakeholders analysis, and down-selecting FSS architectures of interest for more detailed study. Backbone technology development will include development of communications technology underlying FSS architectures, such commodity-sharing communications protocols, and spacecraft coordination mechanisms required to enable FSS networks. Eventually, research will focus in the identification of novel small satellite mission concepts enabled by the FSS paradigm, characterized by enhanced performance, lower cost and new concept of operations. Mission concept development will test the potential of the FSS paradigm, and provide feedback to the development of future FSS infrastructures.

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8. APPENDIX – APPLICATION EXAMPLE DATA

Range	Total Access Time (hours)	Mean Access Time (min.)
0	0	0
100	0	0
200	0	0
300	0	0
400	0	0
500	0	0
600	0.243	0.48
700	0.771	0.9
800	1.356	1.14
900	2.094	1.38
1000	2.913	1.74
1100	3.661	2.04
1200	4.445	2.28
1300	5.329	2.46
1400	6.351	2.7
1500	7.487	2.94
1600	8.556	3.3
1700	9.683	3.72
1800	10.741	4.2
1900	11.874	4.32
2000	13.025	4.68
2100	14.124	5.22
2200	15.157	6.3
2300	16.018	8.34
2400	16.849	9.36
2500	17.501	11.52
3000	20.222	15.96
3500	22.164	24.18
4000	23.366	58.44
4500	23.871	179.04
6000	24	1440
6500	24	1440
7000	24	1440
7500	24	1440
8000	24	1440