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Identifying Retrofitting Opportunities for Federated Satellite Systems

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This paper aims at identifying retrofitting possibilities to incorporate existing spacecraft into a network of federated satellite systems. The paper presents a systematic review of possible retrofitting options, such as direct modifications including replacement and addition of interfaces, and indirect modifications through the addition of intermediary federated negotiators. The paper considers existing frequency regulations for the analysis in the technical domain, but does not take into consideration how complex or time-consuming any legislative changes might be. Although the paper concludes that direct modifications of existing satellites are nonfeasible from a technical point of view, it identifies a possible scenario of retrofitting by adding intermediary negotiator satellites. The link budget for the intersatellite link between an existing satellite mission, such as SPOT-6, and a conceptual satellite negotiator was estimated. The work concludes that from a link budget point of view and existing technology, such a configuration can provide a slant range from several hundred to thousands of kilometers. The work defines models for trade-off analysis identifying correlations between satellite negotiator parameters and the number of covered satellites. The paper concludes proposing several possible satellite negotiator architectures and high-level technical requirements based on analysis of characteristics of existing and planned satellites.

I. Introduction

THE space industry has experienced an exponential evolution over the past decade; new concepts and approaches have emerged. Space business today is not anymore the exclusive prerogative of governmental agencies. New private companies have shown their ability to attract significant investments [1], and compete on new segments of the Earth observation market [2]. In parallel, due to technological progress in microelectronics, the technical abilities of small satellites to deliver services have increased significantly, along with a reduced time for development [3,4].

With an objective to reduce cost and optimize services, the idea of resource sharing through platforms has also reached the space industry. Possible applications of this concept are temporary storage of data in-space, as well as data relay (e.g., store-carry-forward techniques) [5], or multipurpose instrumentation that could be used for different mission objectives. Looking at data relay, it can be observed that data relay satellites appeared in the 1960s [6]. Today Tracking and Data Relay Satellites (TDRS) are providing near-continuous information relay service to missions such as the Hubble Space Telescope and the International Space Station [7]. At present day, there are already several existing and planned commercial systems with store-and-forward communications, such as ORB-COMM, Starsys, LEO-1, FAI, and Esat [6]. Recently, more advanced paradigms such as Federated Satellites Systems (FSS) were proposed in this field [8]. These new paradigms promise to increase robustness and maximize utilization efficiency for satellite missions. At the same time, these approaches bring technical challenges to a new level for the participating satellite missions, including challenges to regulatory

constraints that are currently in place, for instance, in the field of space communications. The benefit for participating missions, defined as synergy of cooperation in [9], depends on the number of participating missions, which makes the deployment speed of such federations crucial. Eventually, the question may arise what could be done with existing satellites, either in their current functioning or as part of cooperating satellite structures.

The purpose of this work was to investigate technical possibilities for retrofitting existing satellites into cooperating satellite structures, such as federated satellite systems. Under the term of retrofitting the paper understands the way to modify equipment that is already in-service using parts developed or made available after the time of original manufacture. The paper presents the methodology and applies it to the case of satellite federations. The paper also aims to contribute to the technology roadmap of future federated satellite system developments.

The work considers the feasibility of retrofitting options for direct modification by replacing and adding interfaces, and indirect modification by adding intermediary nodes, here defined as satellite negotiators [10]. The work presented in this paper aims at considering both retrofitting scenarios for satellite missions and building more general empirical models based on available open data such as the ITU Space Networks List (SNL) [11] for estimates in the scale of a hundred satellite missions. The paper studies the feasibility of identified options mainly from a technical point of view. The authors do not consider the economic feasibility as part of the scope of this paper, although acknowledge its high relevance for future work. The paper addresses economic feasibility in this work only insofar the comparison with state-of-the-art solutions. This paper does not address details on modulations, routing protocols, coding techniques, and data security for satellites in federations, as this goes beyond the scope of the paper; some of these topics were already addressed in [5,12,13]. Retrofitting existing satellites so to incorporate them into FSS does not only bring technological challenges; legal and political issues are likely to play a major role as well [12,14]. In particular, existing radio regulations allocate different frequency bands for downlink, uplink, and intersatellite communications. Although current legislation does not allow reuse of downlink frequencies for intersatellite links, demonstration of technical feasibility and economic

viability of new solutions may eventually trigger changes in the regulations. Both political and legal aspects for retrofitting of existing satellites primarily will depend on the deployment strategy of new satellites in federations. The paper considers the hypothetical case where both political and legal barriers do not exist. This approach allows to identify the sensitivity of the proposed solutions to existing constraints, and thereby define a roadmap for future policy and technical developments in the field.

The paper is structured as follows. Section II provides a brief literature overview of existing federated and fractionated concepts, leading to the technological requirements for FSS deployment and dissecting the issues of incorporating existing satellite missions into future federations. Section III presents possible ways to solve these problems. The paper provides an overview of limitations for direct retrofitting by replacement of existing interfaces or new interface addition. A notional candidate mission inspired by the SPOT-6 satellite is considered from a link budget point of view to be incorporated in FSS via negotiators. The frequency allocation of existing satellites is considered to define trade-offs and build empirical models correlating negotiator performance and characteristics. Additionally, the subcase of the FSS negotiator for nanosatellites is considered. Different trades are studied, and eventually several empirical models for negotiator parameters selection are proposed. The paper concludes with Sec. IV on the limited feasibility of a negotiator concept from the considered points of view and with particular configurations, discussing limitations of the current work and presenting plans for future research.

II. Related Literature: Informing the Technical Requirements for the Deployment of FSS

FSS, as other Distributed Satellite Systems (DSS) concepts, intends to share resources such as bandwidth, data storage, and data processing. Distributed computing arrays in orbit have also been proposed to enable new applications requiring reactive processing of raw data in orbit [15]. Table 1 provides a detailed comparison of federated, collaborative, fractionated concepts for satellite systems [16].

The main distinctive feature of FSS concerns voluntary and opportunistic participation, when every single participating satellite still keeps its primary mission for which it was originally designed. The key driver for participation in FSS is the agreement between the two ends of the resource transaction, based on mutual positive valuation of the opportunity. Economic metrics to financially value similar link concepts have been proposed in the literature since the late 1990s [17]. The FSS concept supposes to change the way in which spacecraft missions are conceived [8]. These include, for instance, hybrid orbit satellite constellations [18], as well as opportunistic contacts fulfilling technical constraints in terms of relative attitude pointing and orbital motion. In addition to opportunistic participation, FSS concepts include explicit design modifications to spacecraft in order to embed margins and allow extended use in federated operations in order to subsidize mission operations costs [19]. For example, traditional satellite communication service providers such as Eutelsat or SES face a reduction of the utilization

rate of their on-board capacities (73.9 and 72.8% in 2015, respectively) [20,21] due to an excess of available Ka-band frequencies provided by high-throughput satellites (wider available bandwidth and smaller size of covered zone) [22]. Prices for TPE (36 MHz transponder equivalent) are decreasing as well [23]. At the same time, Earth observation (EO) satellites experience a growth of requirements for revisit time, resolution, and coordination (multiple bands and instruments) [24]. The overall goal of FSS is to increase mission robustness for EO satellites, maximize utilization efficiency for communication satellites, and minimize demand uncertainty for both [8].

FSS requires the establishment of flexible (ad-hoc) links between satellites, meaning that participants need to have well-established mechanisms to predict location (orbit propagation), estimate benefits from the communications (through an economic model) [14], and establish the link (pointing, hand-shaking, secured data exchange, and acknowledgment protocols) [5,12].

Most of the above-mentioned technologies are already present in today's intersatellite links (ISLs). However, ISLs have seen limited application in modern commercial satellite systems. Except for a limited number of systems, such as Iridium, TDRS, LUCH, and EDRS, and several technology demonstrators, ISLs are mostly unused in today's commercial applications [25]. Even upcoming projects such as Oneweb do not plan to use ISLs [26].

Technologies such as software-defined radio (SDR) and optical communications are considered as emerging enabling technologies for FSS [16,27–29]. In particular, SDR technology provides the ability to receive and transmit various modulation techniques and to easily change operating frequencies even after system deployment using a common set of hardware [27,30].

FSS can already bring rapidly interesting benefits to users even with a federation made with as little as two or three participating satellites [9]. However, replacing an existing satellite fleet to fully benefit from the possibilities of this approach is time-consuming; this may take at least 10 to 15 years, as the cumulative utility grows with a number of participants. An option forward may be to turn attention to “retrofitting” existing satellites so to use the currently available resources to emulate an FSS-like behavior. Of course, with technology that was developed much earlier, this emulation may be only capturing part of the benefit of what new satellites can bring. But, having existing satellites able to interoperate with each other, and as such to have a faster start on FSS, is an option.

III. Approach

The term “retrofitting” has its origins in 1950s, as a blend of “retroactive” and “refit” [31]. World War II made this concept an urgent need: *weapons technology was advancing at an intense pace and airplanes and ships were becoming outdated even before their construction was complete, and the only solution was to retrofit the completed craft with brand-new technology* [32]. Systems engineering literature, however, does not use “retrofitting” as a separate instance. Retrofitting is a strategy in Systems of Systems Integration

Table 1 Comparison of DSS architectures (adapted from [16])

DSS architectures	Mission goals	Cooperation	Degree of homogeneity	Scale	Degree of autonomy
Constellations	Shared (Iridium, GPS)	Required to support mission goals	Homogeneous components, some differences possible	Regional	Autonomous
Trains	Independent, but could be shared	From optional to required	Heterogeneous components	Local	Autonomous
Clusters	Shared	Required to support mission goals	Homogeneous components	Local	Autonomous to completely co-dependent
Swarms	Shared	Required to support mission goals	From homogeneous to heterogeneous components	From local to regional	Autonomous to completely co-dependent
Fractionated Satellites	Shared	From optional to required	Heterogeneous components	Local	Autonomous to completely co-dependent
Federated Satellites	Independent	Ad-hoc, optional	Heterogeneous components	From local to regional	Autonomous

Table 2 Comparison of terminology

Term	Definition
Modernization	Adapting something to modern needs or habits [31].
Retrofitting	Adding (a component or accessory) to something that did not have it when manufactured [31].
Upgrade	Raise (something) to a higher standard, in particular improve (equipment or machinery) by adding or replacing components [31].
Update	To make something more modern or suitable for use now by adding new information or changing its design [31].
Modification	A change to something, usually to improve it [31].

(SoSI), which is the capability for systems to interoperate on demand to meet mission objectives [33]. Concepts such as “change” [34], “modernization and upgrade” [35], and “modification” [36] are related to retrofitting. “Changeability” refers to system characteristics such as flexibility, agility, and adaptability [37], concerning the opportunity for engineering systems to evolve over time to meet emerging and changing requirements. Design for changeability (DfC) can be used to estimate cost and time involved in redesign and adaptation efforts [37]. “Retrofitting” is a very specific process of adding new functionalities. Retrofitting implies risk management approaches specifically tailored to systems of systems integration [38]. While retrofitting is extensively encountered in applications, it is explicitly identified as a difficult challenge in systems engineering literature [33]. Table 2 introduces some of the existing terms and provides definitions, which are later built upon in the paper. The extensive generalization of retrofitting concepts is outside of the scope of this paper, but it is identified as a promising avenue of future research emerging from the study of system retrofitting in FSS negotiators.

For these more general cases, existing systems engineering methodology proposes to use the same processes and principles that are employed during the upfront design, development, integration, and testing [34,35,39]. In particular, [35] states that “upgrading of existing systems is a matter of following the systems engineering process, with emphasis on configuration and interface management.” The proposed framework in [35], however, does not cover a step for identification of alternatives of system design.

This work applies a morphological method [40] for identification of system alternatives. In particular, different combinations of interface modification were identified (Fig. 1). The major system interface in the satellite case is a radio transceiver; optical communications are still not mature enough and not widely spread yet. Identified retrofitting options consist of direct modifications, which include replacement and addition of interfaces, and indirect with adding a middleware (intermediary).

The approach selected for feasibility analysis is to formulate major technical requirements for each option and compare it with state-of-the-art solutions.

Although different criteria are important for establishing inter-satellite communications, the paper is focused mainly on feasibility considerations from a link budget point of view and a correspondence between frequency bands of receiver and transmitter sides, as these parameters are relatively easy to quantify, and can eliminate a significant part of unfeasible architectures. Other criteria have a limited overview in the paper. In particular, the technical need of satellite repointing is directly connected not only to Attitude Determination and Control System (ADCS) capabilities, but also to spacecraft concept of operations. The paper assumes that EO satellites have the ability to implement change of pointing from Earth to another satellite; any potential additional energy losses from repointing are not considered. Modulations, coding, and network protocols specifics require separate studies, which are out of scope of the paper.

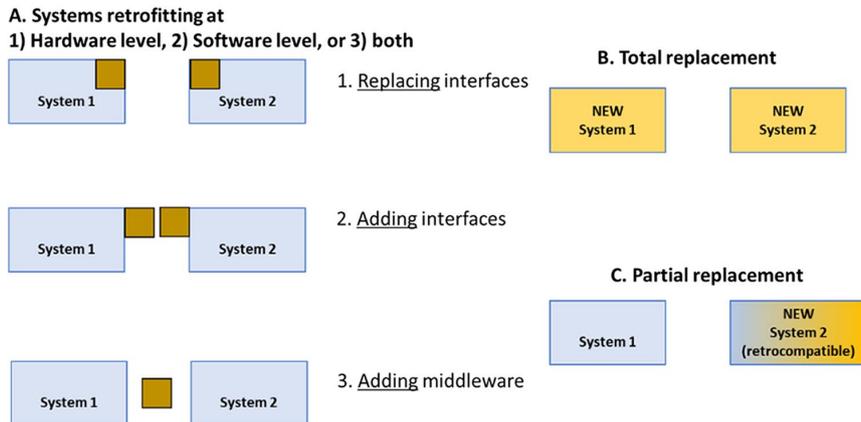
The satellite data used for analysis include key parameters of satellite transceivers such as frequencies and bandwidths (based on applications of existing and future space missions to ITU on different stages such as advance publication, notification, and coordination). The data used for the analysis were extracted data from the ITU Space Networks List (SNL), the Union of Concerned Scientists (UCS) database, the open satellites frequency list [41], and nanosatellite databases [42]. The selected missions include all missions available in the SNL database in the frequency range of interest. No differentiation according to the type of delivered data (telemetry or payload data) is considered. All available types of missions, such as EO, communications, scientific missions, and technology demonstrators, are used for the analysis.

A. Feasibility of Bringing Existing Satellites to FSS by Direct Modifications

The current use of intersatellite communications in space is represented mostly by data relay systems such as TDRS, EDRS, LUCH, the Iridium mobile communication system [25] and multiple technology demonstrators (Proba-3, EDSN, ESPACENET) [43]. Several major issues prevent most of the existing missions to be incorporated into FSS without serious modifications.

First of all, the regulatory requirements and coordination with other users impose strict limits on the operating bands and radiated power flux density; hence, spectral allocation has a direct impact on the architecture of satellite communications payloads [6]. In particular, many EO missions by design have asymmetric or even simplex data rates (downlink only); different frequency bands are used for uplink and downlink. Figure 2 shows how beam frequencies are allocated for different space missions. The frequency selection follows ITU frequency allocations, the specifics of atmospheric attenuation for different frequencies, and the relation of antenna dimensions with the wavelength [6]. ITU has also allocated frequencies for intersatellite services different from uplink or downlink frequency bands [25].

Only UHF and S-band beams are used for both transmission and reception; however, these frequencies are used mainly for telemetry

**Fig. 1 Possible options for modifications (retrofitting or replacement) of two existing systems.**

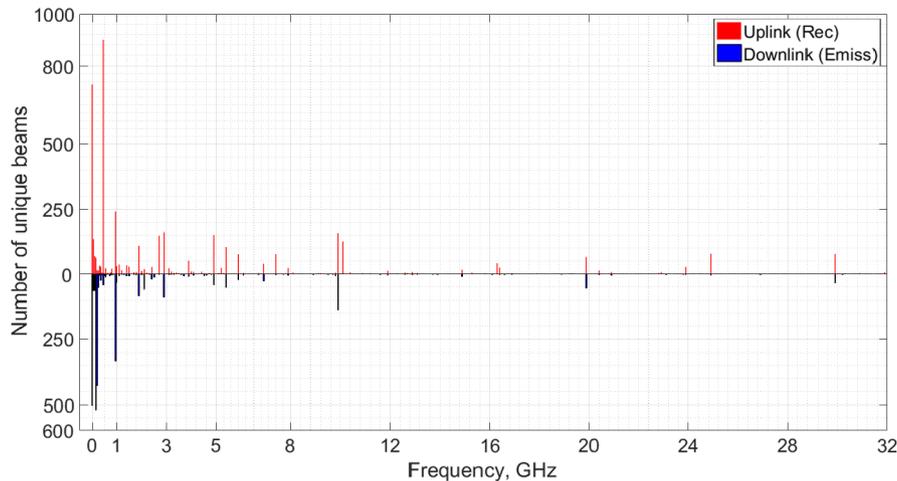


Fig. 2 Allocation of beams with unique frequencies for communication data transmission and reception (based on 1013 applications for existing and future nongeostationary space missions from ITU Space Network List) with 50 MHz step below 1 GHz and 100 MHz step after 1 GHz.

and telecommand. Only very specific cases of matches in other bands are available, such as payloads for passive radars and radiometers [44].

Second, existing missions have high level of specialization and individuality: a highly diverse number of protocols, modulation, and coding techniques exist, while conventional radio transceivers have very limited flexibility. Existing standards, such as those offered by the Consultative Committee of Space Data Systems (CCSDS), contain recommendations on modulation types and coding techniques; however, most of their standards are only recommended but not compulsory [45].

As a result, none of existing satellites can be introduced into FSS without modifications (by simple change of on-board transceiver settings) and either the replacement or addition of a new interface is required.

The addition of an interface in a satellite case would be a physical addition of radio transceiver capabilities to existing satellites, which would require a physical access to satellite and to its power and data subsystems. However, only a few in-orbit servicing missions ever took place in history (namely, Solar Max [46], Intelsat VI [47], Leasat-F3 [48], and Hubble Space Telescope [49]), when satellites were deployed or repaired during Space Shuttle missions. While research is ongoing on this subject and new projects such as Phoenix Program by DARPA, ConeXpress, and ViviSat Mission Extension Vehicle are proposed for on-orbit servicing and retrofitting, there are currently no technologically mature options available for operating an in-orbit servicing mission “off the shelf,” nor their cost-effectiveness has been demonstrated [50]. In particular, a demonstration of formation flying for the DARPA F6 program was canceled [51].

Interface replacement requires reconfiguration or reprogramming of existing on-board transponders. Although there are some examples of on-orbit reprogramming of spacecraft communication systems, such as reprogramming of Voyager spacecraft transceiver to support Reed-Solomon codes [52], usually existing space missions have very limited changes in operations over lifetime, if it was not intended so. Some existing missions, however, have been designed for on-orbit reconfigurability of communication and data processing equipment. For instance, FormoSat-7 satellites were equipped with COM DEV’s S-Band TT&C transponders [27]. Geostationary communication satellites developed by Airbus, such as Eutelsat Quantum, can reconfigure its frequencies, coverages, and/or power allocation in Ku band [53]. Another example is the use of FPGAs for both communication systems and data processing units, allowing high reconfigurability [54].

Before even considering communication protocols and modulation techniques, link budget requirements need to be met according to the desired slant ranges involved in intersatellite link operations. An excess margin of downlink throughput might not emerge, due to the identical nature of the spacecraft implemented in the missions.

In many cases, existing satellites might be considered only as black boxes due to political, security, and other nontechnical reasons.

The considerations above bring us to the conclusion that physical retrofitting of existing satellites is unlikely to be a cost-efficient solution, nor technically viable with technology that is mature at the time of writing of this paper.

B. Negotiator Scenarios for a Particular Existing Satellite Mission

Besides reconfiguration and reprogramming, there might be a way to bring existing satellites to FSS by use of an intermediate middleware, a so-called negotiator (see [10] for a concept of a special negotiator node and a testbed with the demonstration of the store-and-forward technique for CubeSat data).

The concept of hosted payloads is now common in today’s space industry. Satellite operators are constantly on the look for opportunities to diversify their businesses. An FSS negotiator could be an independent hosted payload similar to Aireon ADS-B payloads installed on the first Iridium Next Satellites [56] or a multifunctional primary payload, providing negotiation as a secondary task on nongeostationary or geostationary satellites. Figure 3 shows an OPM diagram (Object Process Methodology [55]), providing details about possible structures and key high-level functions of the envisioned negotiator. Besides communication functions (data reception and relay), FSS negotiators also need to schedule communication sessions, process, and store received data.

Key enabling technologies for FSS negotiators are SDR, multiport amplifiers, reconfigurable antennas, and so on [27]. As existing applications of SDR technology for satellite ground stations demonstrate feasibility in terms of processing power [57,58], other factors such as link budgets need to be evaluated first. The authors also assume that data processing power of on-board SDR modules on negotiator satellites is sufficient to implement any required modulation techniques and process any required volumes of data.

The main trade-offs in the negotiator satellite design include parameters such as the number of contact opportunities, contact duration, slant range, the number of participating missions, and the number of negotiators. Nevertheless, the initial number of options is narrowed down simply by link budget considerations.

Orbit type and semimajor axis define the slant range and play a principal role in determining the requirements for the communications payload architecture. For example, a geostationary orbit provides a longer access time for FSS, but requires larger communication distances, and higher launch and equipment costs. A scenario with a notional candidate remote sensing satellite mission (inspired by the SPOT-6 satellite) is here proposed in order to compare the two solutions. The envisioned scenario considers two cases: with a negotiator payload hosted on a geostationary platform, and a negotiator hosted on nongeostationary satellites, for example, in low

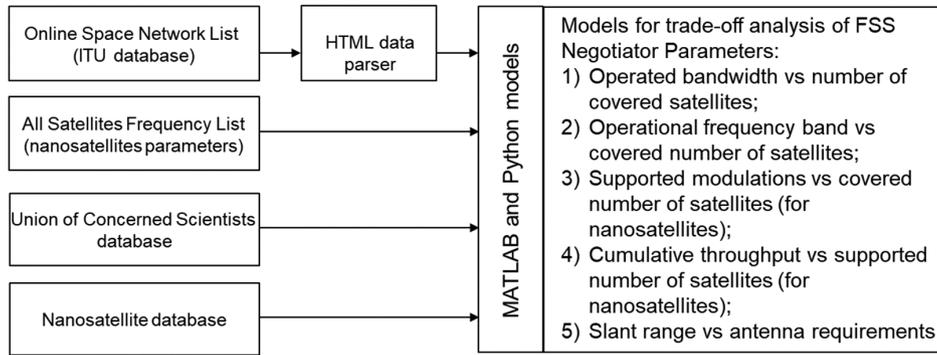


Fig. 4 Proposed models for FSS negotiator parameters evaluation.

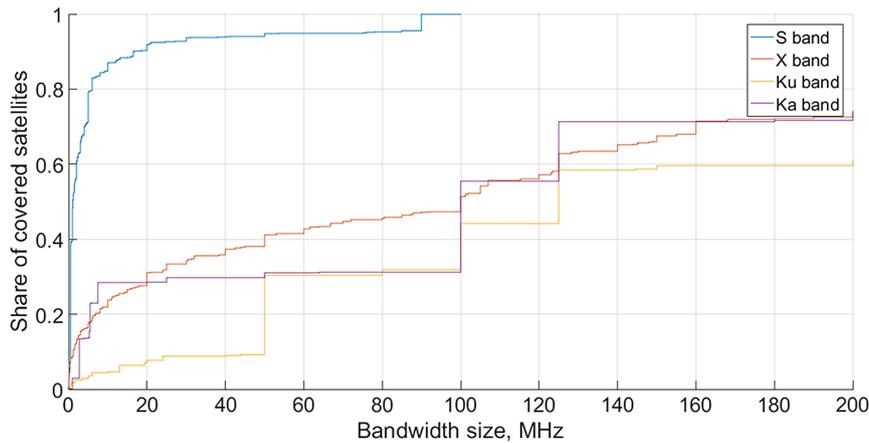


Fig. 5 Empirical cumulative distribution of channel bandwidths in S, X, Ku, and Ka bands (for 869 existing space missions and submitted applications).

mostly EO missions. In addition to this, the data were processed and filtered to exclude satellites with communication, radar, and deep-space-related payloads.

The increase of FSS negotiator parameters such as the number of supported frequencies and bandwidth size increases the supported number of satellites. However, at the same time, the technical requirements and eventually the cost of the mission go up. The characteristics of the negotiator can therefore be optimized using a statistical approach. To define requirements in terms of bandwidth and corresponding processing power, an empirical cumulative distribution functions for bandwidth in S, X, Ku, and Ka bands can be used (Fig. 5). It is observed that the largest number of license applications is submitted for S and X bands. Although the difference between bandwidth size may be several orders of magnitude, about 68% of all

submissions in X band do not exceed 170 MHz. At the same time, X band has a higher number of submitted applications than Ku or Ka band (Fig. 2). Besides the frequency bands, the compatibility of various other parameters needs to be considered. Although SDR technology promises very high flexibility in terms of modulation techniques and communication protocols, it requires significant efforts and expenses in software development. Antenna design issues, including polarization and frequency adjustment, is a topic, which as well requires separate studies.

The incorporation of traditional EO missions into FSS via negotiators may significantly change the original concept of mission operations. A detailed analysis of each mission is therefore required.

A subcase of the use of FSS negotiators for nanosatellite missions (weight less than 10 kg according to ITU classification) has lower

Table 3 Link budget evaluation for GSO and LEO negotiator scenarios for SPOT-6 satellite mission

	Geostationary negotiator	Negotiator at LEO orbit (800 km)
Maximum space-to-ground slant range for the original mission, km	2,560	2,560
Slant range at 20 deg elevation angle, km		
Atmospheric attenuation losses assumed for the original mission, dB	~2.5	~2.5
Line-of-sight distance in the new configuration, km	From 35,090 to 42,800	From 105 to 5,500
Additional free space propagation losses, dB [6]	28.7	10.9
Access time, %	Depends on the position on GSO (up to 50%)	Depends on negotiator orbit parameters (up to 100%)
Required increase in gain for negotiator, dB	$44 - 2.5 + 28.7 = 70.2$	$44 - 2.5 + 10.9 = 52.4$
Conclusion	Nonfeasible due to high requirements to negotiator (it would require a parabolic antenna with at least 40 m in diameter, comparable with the largest radio telescopes in the world)	Feasible for short distances; a constellation of negotiators is required for a full coverage

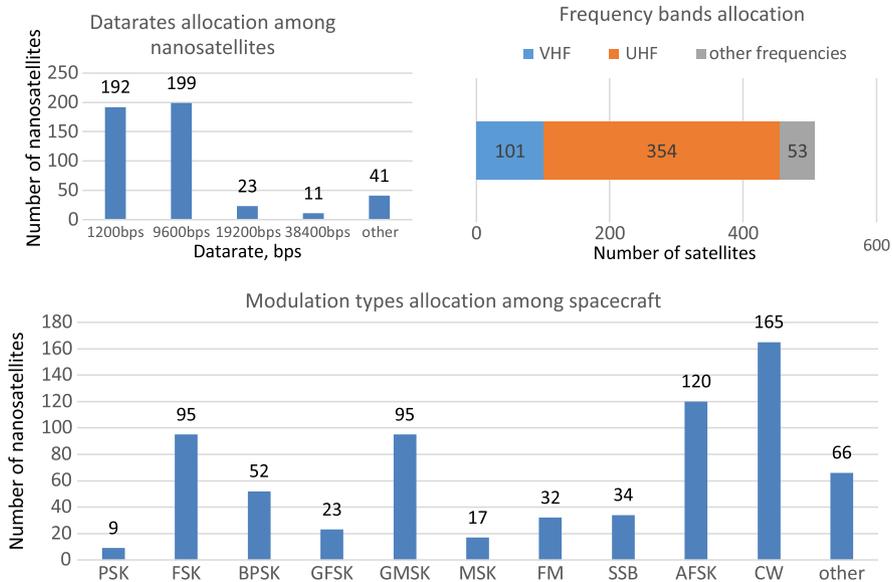


Fig. 6 Allocation of parameters of 500 existing nanosatellite missions (September 25, 2017, several frequency bands/datarates/modulation types could be supported simultaneously [31]).

impact on the original mission concept of operations. A nanosatellite case has lower requirements for the FSS negotiator, due to less diversity in terms of used frequency bands (mostly UHF and VHF) and lower technical complexity. The main scenario for nanosatellite FSS negotiators is telemetry aggregation and its relay to the ground. While telemetry has limited monetary value, especially for small satellites, the considered case is used as a technical proof-of-concept. Because of the nature of telemetry, omnidirectional or wide-beam antennas are used [6]. As a consequence, no change in the concept of operation of the participating missions is required. The analysis of parameters of existing nanosatellites brings to the conclusion that multiple AFSK/FSK/GMSK receivers would cover 60% of all nanosatellites, while at the same time a significant fraction of all existing nanosatellites (~60%) generates less than 2 Mbps of data. Most nanosatellite missions use frequencies in radio amateur and ISM bands. These bands have simpler radio spectrum regulation procedures in comparison to conventional satellite missions, and potentially can be used for ISL links without disruptive changes in the existing regulations.

From a link budget point of view, the CubeSat case has the same limitations as traditional large satellites. Most nanosatellites are orbiting the Earth at 300–700 km altitudes [42]. The orbits define the maximum line-of-sight distance between the spacecraft and the FSS negotiators. In particular, if the satellite and FSS negotiators have the same altitudes, the slant range would range between 4000 and

6000 km for 300 and 700 km altitudes, respectively (considering only line-of-sight propagation).

Assuming that nanosatellite missions are designed for stable reception at 20 deg elevation angle and higher, based on the cosine law [60], the increase in the communication path can be evaluated as 3–4.5 times in comparison with the original space-to-ground link. The corresponding additional *FSPL*, based on Eq. (3), will be 9.4–13.2 dB. However, space-to-space communications have an advantage of having no atmospheric attenuation. Figure 7 illustrates the correlation between additional *FSPL* and distance between CubeSat and FSS negotiators on orbits with different altitudes.

Existing nanosatellites and satellites operating at UHF/VHF frequencies can be divided into three different groups according to the minimum gain required for its ground station: low-gain 3–4 dB antennas with no pointing, such as quadrifilar antennas; 5–10 dB antennas with pointing; and antennas with pointing and gain of 11 dB or higher.

Using this classification, three regions can be identified in Fig. 7 for the FSS negotiator. The first region describes the case where an increase in gain in comparison to the original ground station is required, thereby increasing technical complexity (due to additional requirements in terms of pointing, scheduling, and so on). The second region covers first group of nanosatellites even if omnidirectional antennas are used on FSS negotiators. The third region covers nanosatellites from both the first group and the second group. This proposed relation can be used to evaluate the number of missions to be supported by FSS negotiators.

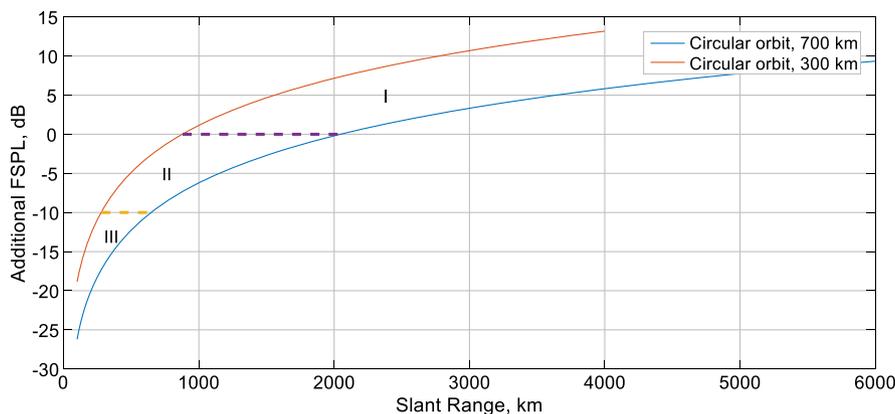


Fig. 7 Correlation between FSPL and distance between FSS negotiator and CubeSat for different orbits.

Table 4 Comparison of retrofitting options for Federated Satellite Systems

Retrofitting option	Adding interface	Replacing interface	Adding middleware
Examples of retrofitting in space missions	COSTAR and the Wide Field Planetary Camera 2 were installed during a shuttle mission, correcting Hubble's flawed vision [49]	The Voyager 1 spacecraft was reprogrammed to support Reed-Solomon codes [52]	The docking system for Apollo-Soyuz project [68]
Type of interface in FSS case	Radio transceiver	Radio transceiver	Radio transceiver
Retrofitting in FSS case	Physical addition of new radio transceiver capabilities to existing satellite	Reconfiguration or reprogramming of existing on-board transceivers	Launch of a negotiator satellite able to receive and relay data
Requirements for participating missions	A physical access to electrical and data interfaces of the satellite	Reconfigurability and flexibility of on-board transceivers; active pointing; link budget	Active pointing; link budget
Impact on the original mission operations	Change of the power budget and mission schedule	Change of the schedule; the original ground segment also needs to be updated	Change of the schedule
Conclusion (feasibility from the technical point of view)	Nonfeasible at the current moment due to high cost of on-orbital operations and cancelation of Space Shuttle program	Feasible for some missions in terms of communication standards (e.g., satellites with reconfigurable transponders [27]), requires additional studies of link budget requirements	Feasible for a LEO negotiators with communication distances limited to hundreds kilometers

IV. Results and Conclusions

The work presented in this paper considered different scenarios of retrofitting existing satellites in order to enable their participation to satellite system federations (Table 4). Different options such as a replacement of existing systems interfaces and the addition of new interfaces and middleware were considered.

The work concluded that the ideas of replacement of existing systems interfaces or addition of new interfaces are unfeasible at present time and at least for the next 5–10 years from the time of writing of this paper, due to frequency mismatches and low reconfigurability potential of most of the existing missions due to lack of technically viable and cost-effective in-orbit servicing options.

At the same time, the work demonstrated that an option of adding a middleware such as a special negotiator satellite might be feasible today from a technical point of view, while featuring several limitations. The analysis has shown that a geostationary negotiator would require a gain for the FSS negotiator on-board antenna that is far beyond most of the existing state-of-the-art space solutions and higher than the original ground stations for the selected mission. At the same time, a negotiators on LEO could benefit from free space communications while requiring lower gain. Such a scenario is realized either in the case of reduced slant range and larger number of negotiators, or in the case of spacecraft using higher-frequency bands, because of atmospheric attenuation compensation. As a reference for the feasibility evaluation of on-board antennas of a negotiator, the paper assumed the technical specifications of the existing O3B and TDRS satellites.

The work presented in this paper defines several empirical models for further trade-off analysis. The proposed models enable the analysis on how the design parameters of an FSS negotiator such as operated bandwidth and frequency, types of supported modulations, and cumulative throughput correlate with the covered number of satellites. The paper proposes several architectures of communication equipment for FSS negotiators such as X-band receivers with 170 MHz bandwidth for existing EO missions and AFSK/FSK/GMSK telemetry-receiver in UHF band for nanosatellites. Nanosatellites were considered as technical proofs-of-concept with no constraints imposed with regard to economic attractiveness.

Besides the technical challenges here mentioned, all considered retrofitting scenarios would require political efforts to modernize the existing radio regulations accordingly. The authors recognize that any changes in the current radio spectrum regulation policies would require significant efforts from the parties involved. Nevertheless, this topic is out of the scope of this paper and could be subject of dedicated future work in the area of technology policy.

The presented work might be extended in two different directions. Specifically, on the FSS negotiator use case, a tabletop demonstrator based on commercial software-defined radios can be developed as a first validation of the proposed concept. The second avenue of future work will be the development of general understanding of retrofitting in legacy systems, as an extension of the initial retrofitting principles discussed in this paper, contributing to the development of the related systems engineering methodology.

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