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Identifying retrofitting opportunities for Federated Satellite Systems

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Abstract

This work aims to facilitate deployment of novel distributed space systems architectures such as Federated Satellite Systems (FSS). In particular, the purpose of the work is to identify retrofitting possibilities to incorporate existing satellites into a network. For the satellite case, the paper presents a systematic review of possible retrofitting options such as direct modifications, which include replacement and addition of interfaces, and indirect modifications with adding an intermediary (FSS Negotiator).

While the paper concludes that direct modifications of existing satellites are non-feasible from the technical point of view, it also identifies a possible scenario of retrofitting by adding as an intermediary a Negotiator satellite. The link budget for the inter-satellite link between an existing satellite mission such as SPOT-6 and FSS Negotiator was estimated. The work concludes that from the link budget point of view with the existing communication technologies such configuration can provide a slant range limited from several hundred to thousands kilometers.

Through analysis of open data of satellite characteristics, including ITU information concerning planned or existing space stations, the work comes up with several models for the further trade-off analysis, identifying how parameters of FSS Negotiator such as an operated bandwidth and frequency, types of supported modulations and cumulative throughput correlate with the covered number of satellites. These results might be used for the tradeoff analysis for the FSS Negotiator mission design.

Eventually paper proposes several possible FSS Negotiator architectures and its high-level technical requirements based on analysis of characteristics of existed and planned satellites.

Keywords

Federated Satellite Systems; Retrofitting; FSS Negotiator

1. INTRODUCTION

The space industry has seen a revolutionary change over the past 10 years; new concepts and approaches have emerged. The 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, the technological abilities of small satellites to deliver services have increased significantly, together with a reduced time for development [3] [4].

With an objective to reduce cost and optimize services, the ideas of resource sharing have also reached space industry. Thereby one can think of temporary storage of data and its relay (store-carry-forward techniques) [5], as well as a multipurpose instrumentation used for different objectives. Looking at data relay, it can be observed that data relay satellites appeared in the 1960s [6] and today Tracking and Data Relay Satellites (TDRS) are providing near continuous information relay service to missions such as the Hubble Space Telescope and International Space Station [7]. At present day, there are already several existing and planned commercial systems with store-and-forward communications, such as ORBCOMM, Starsys, LEO-1, FAI, and Esat [6].

Recently, newer, 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 and revolutionize spaceflight industry. At the same time, these approaches bring technical requirements to a new level for the participating satellite missions. And total benefits for the participating missions defined as a synergy of cooperation in [9] depend on the number of participating missions, which makes deployment speed of Federations crucial. And, 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 possibilities for retrofitting existing satellites into cooperating satellite structures, such as Federated Satellite Systems. Under the term of retrofitting this 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 work studies feasibility of retrofitting options for a direct modification, replacing and adding interfaces, and indirect with adding an intermediary (Negotiator). The work aims to consider both retrofitting scenarios for particular satellite missions and to build more general empirical models based on available open data such as ITU Space Networks List [10] for estimations in a bigger scale of hundred satellite missions.

This paper will not address details on modulations, routing protocols, coding techniques and data security, as these topics were already addressed in [11] [5]. 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. These aspects are also not further addressed in this paper.

The paper is structured as follows. The next section gives a brief literature overview of existing federated and fractionated concepts, leading to the technological requirements for FSS deployment and revealing the problem of incorporation of existing satellites. The third section presents possible ways to solve these problems. It gives an overview of limitations for direct retrofitting by replacement of existing interfaces or new interface addition. A candidate mission is considered to be incorporated in FSS via Negotiators and the frequency allocation of existing satellites is studied in order to build empirical models of Negotiator performance and Negotiator characteristics. The paper concludes on the feasibility of a Negotiator concept with particular configurations, discusses limitations of the current work and presents future plans.

2. RELATED WORKS – 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, for mutual benefits. The table below provides a detailed comparison of federated, collaborative, fractionated concepts for satellite systems [12].

Table 1 A comparison of DSS architectures, adapted from [12]

DSS architectures	*Mission goals*	*Cooperation*	Homogenity	Inter-satellite distance	Autonomity
Constellations	Mission goals shared (Iridium, GPS)	Cooperation required to support mission goals	Homogeneous components, some differences possible	Regional	Autonomous
Trains	Independent, but could be shared	Cooperation from optional to required	Heterogeneous components	Local	Autonomous
Clusters	Mission goals shared	Cooperation required to support mission goals	Homogeneous components	Local	Autonomous to completely co-dependent
Swarms	Mission goals shared	Cooperation required to support mission goals	From homogeneous to heterogeneous components	From local to regional	Autonomous to completely co-dependent
Fractionated Satellites	Mission goals shared	From optional (service areas) to required (distributed critical functions)	Heterogeneous components	Local	Autonomous to completely co-dependent
Federated Satellites	Independent mission goals	Ad-hoc, optional	Heterogeneous components	From local to regional	Autonomous

The main distinctive feature of FSS is a voluntary way of participation, when every single participating satellite still keeps its primary mission for which it was originally designed. The FSS concept supposes to change the way in which spacecraft missions are conceived [8]. For example, traditional satellite communications services providers, such as Eutelsat or SES, face a reduction of utilization rate of their on-board capacities (73.9 and 72.8% in 2015) [13] [14], due an excess of available Ka-band frequencies provided by High-Throughput Satellites (wider available bandwidth and smaller size of covered zone) [15]. Prices for TPE (36 MHz-equivalent transponders) are also going down [16]. At the same time, Earth Observation (EO) satellites experience a growth of requirements for revisit time, resolution and coordination (multiple bands and instruments) [17]. 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 (economic model), establish the link (pointing, hand-shaking, secured data exchange and acknowledgment protocols) [6] [18]. Technologies such as software-defined radio (SDR) and optical communications are considered as emerging contributing technologies for FSS [19] [20] [21]. The network-layer protocol could be implemented in a similar fashion as proposed in [5].

With just 2-3 satellites deployed, FSS can already bring rapidly interesting benefits to the users [9]. However, replacing a complete existing satellite fleet so to fully benefit from the possibilities of this approach is time-consuming; this may take at least 10 to 15 years (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 the FSS-like behavior. Of course, with technology that was developed much earlier, this emulation may be an approximation of what new satellites can bring. But, having existing satellites able to inter-operate with each other, and as such to have a faster start on FSS, is an option.

3. APPROACH

The approach chosen in this work is to consider on a systematic way options available for retrofitting legacy systems (figure 1) and apply it to FSS case to identify a set of possible retrofitting solutions. Reviewed retrofitting options consist of direct modifications, which include replacement and addition of interfaces, and indirect with adding a middleware (intermediary).

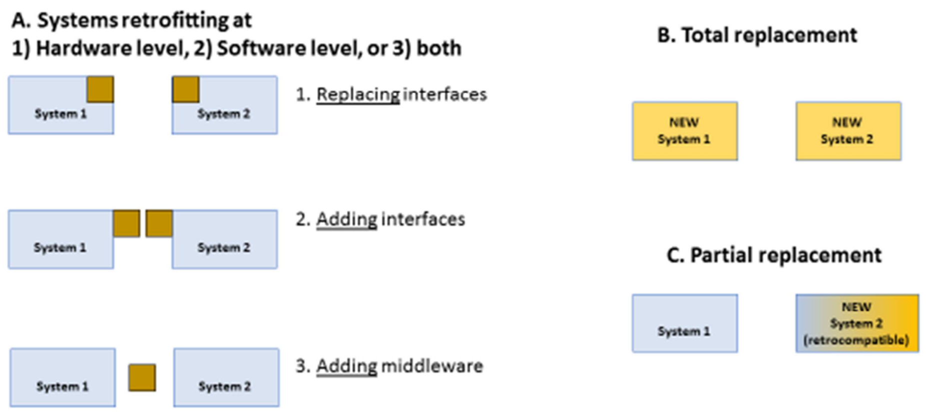

Figure 1 Possible options for retrofitting or replacement of two existing systems

The major system interface in the satellite case is a radio transceiver; optical communications are still not mature enough and not widely spread yet. The analyzed satellite data includes key parameters of satellite transceivers such as frequencies and bandwidths (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 was extracted data from ITU Space Networks List (SNL), Union of Concerned Scientists (UCS) Database, all satellites frequency list database [22].

3.1 A FEASIBILITY OF BRINGNIG EXISTING SATELLITES TO FSS BY DIRECT MODIFICATIONS

Although existing specialized satellite systems demonstrate inter-satellite communications and data relay (Iridium, TDRS, EDRS, Gonetz), 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 place 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), which is also caused by the nature of radio waves (propagation and antenna dimensions). Only in UHF and S-band matches could be found, however these frequencies are used mainly for telemetry and telecommand. Only very specific cases of matches in other bands are available.

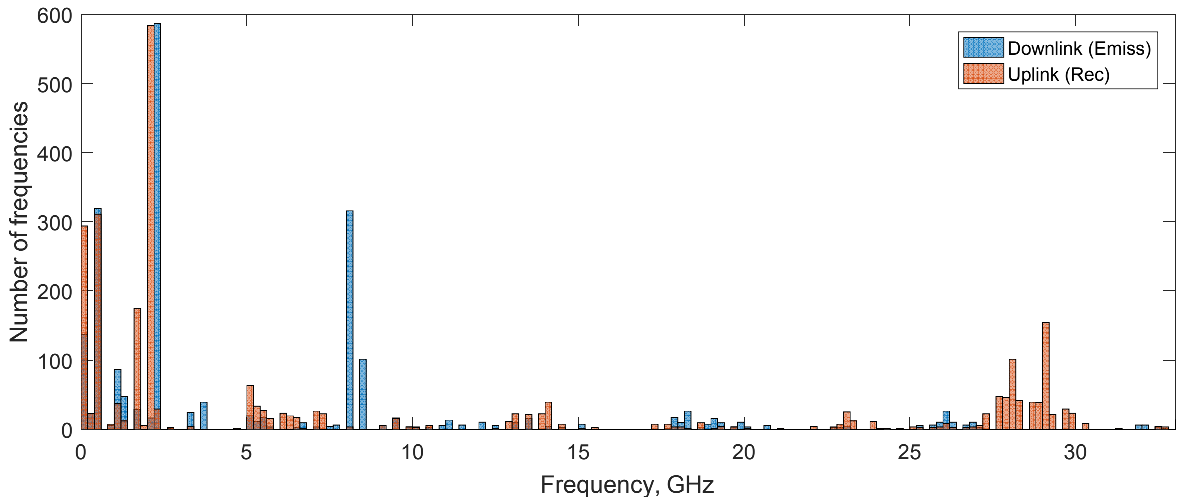

Figure 2 Allocation of frequencies for transmission and reception (869 applications for existing and future non-geostationary space missions from ITU Space Network List) with 200MHz step

Secondly, the existing missions have high level of specialization and individuality: extremely diverse number of protocols, modulation and coding techniques, while conventional radio transceivers have very limited flexibility. Existing standards, such as CCSDS books, contain recommendations on modulation types, coding techniques, etc, but still most of the standards are recommended but not compulsory [23].

In accordance with above-mentioned satellites cannot be introduced into FSS without modifications and either 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 satellite, which would require a physical access to satellite and to its power and data subsystems. But only a few missions with repairment of satellites on orbit (Intelsat VI and Hubble telescope) took place in the history. And after Space Shuttle program was shut down, this kind of projects is not feasible.

The interface replacement requires re-configuration or re-programming of existing on-board transponders. Just several existing missions have the required level of re-configurability, e.g. FormoSat-7 satellites equipped with COM DEV's S-Band TT&C transponders [24]. However, this case requires inter-satellite distances matching link budget requirements and excess of downlink throughput might not appear due to identical types of the mission.

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

All mentioned above brings a conclusion that existing satellites are not flexible to be introduced in federations by direct modifications only.

3.2 NEGOTIATOR SCENARIOS FOR A PARTICULAR EXISTING SATELLITE MISSION

Besides re-configuration and re-programming, there might be a way to bring existing satellites to FSS by use of an intermediate (middleware), a so-called Negotiator (see [25] for a concept of a special negotiator node and a testbed with the demonstration of the store-and-forward technique for CubeSat data).

A concept of hosted payloads becomes more common for today's space industry. Satellite Operators are looking for the opportunities to diversify their businesses. FSS Negotiator could be an independently hosted payload in the way like Aireon℠ ADS-B Payloads installed on the first Iridium Next Satellites [26] or a multifunctional primary payload, providing negotiation as a secondary task on non-geostationary or geostationary satellites. The picture below (Figure 3) shows an OPM diagram, providing details about possible structure and functions of Negotiator.

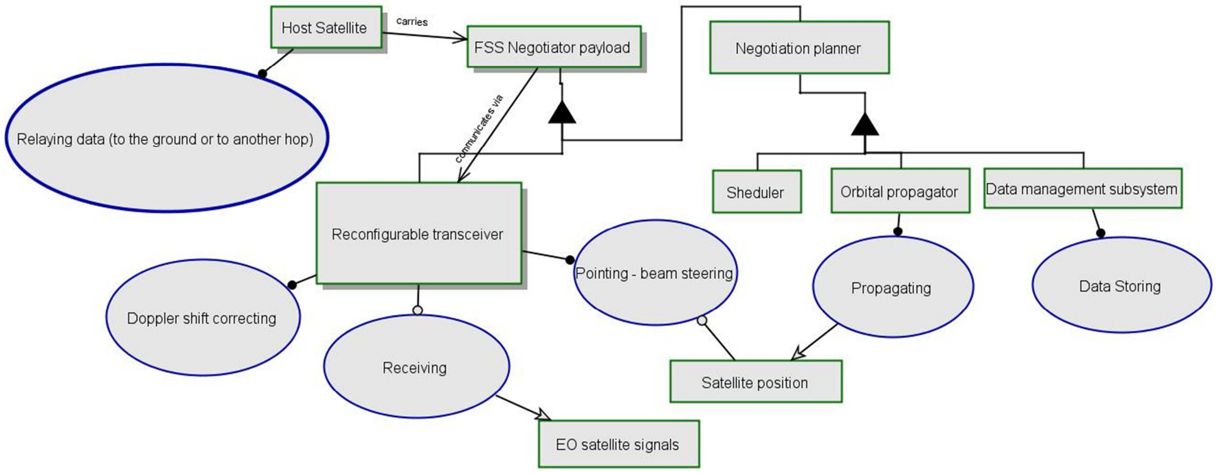

Figure 3 An OPM diagram of FSS Negotiator

Orbit type and diameter plays a principal role in determining requirements for the communications payload architecture. For example, geostationary orbit provides a longer access time for FSS, but requires greater communication distances, higher launch and equipment costs. A scenario with a candidate remote sensing satellite mission (SPOT-6), proposed below, demonstrates this difference. The studied scenario considers two cases, when Negotiator payload hosted on geostationary and non-geostationary satellites (LEO).

The required parameters for the FSS Negotiator payload could be derived from the re-calculation of the original link budget. Due to the unavailability of the original link budget information, the required data was reconstructed from parameters of UniScan ground stations with 2.4m aperture [26]. The chosen ground station has 44 dB of antenna gain and provides reception of SPOT-6/7 and TERRASAR satellite at an elevation angle of 20 degrees [26]. Altitudes of SPOT satellites are 695 km, which eventually gives about 2560 km communication distance.

Each SPOT satellite has a single Isoflux antenna to provide the necessary ground coverage. The data downlink is a standard 300 Mbit/s 2-channel cold redundant X- band, with a possibility for downlink data encryption [27].

Besides an appropriate link budget, the mission should have an active stabilization system to switch pointing from the ground to GSO or LEO. SPOT satellites have enhanced 3-axis stabilization attitude control system based 4 reaction wheels for fine-pointing with 3 magnetic torquers for off-loading [27].

However, any change in satellite behavior should be considered in order not to put in danger the original mission goals.

Table 2 Link budget evaluation for GSO and LEO Negotiator scenarios for SPOT-6 satellite mission

	Geostationary Negotiator	Non-geostationary Negotiator at LEO orbit (800 km)
Maximum slant range for original missions	2560	2560
Maximum line-of-sight distance in the new configuration, km	Up to 42800	Up to 5500
Additional free space propagation losses, dB [6]	24.5	6.6
access time, %	Depends on the position on GSO (up to 50%)	Depends on Negotiator orbit parameters (up to 100%)
Atmospheric attenuation losses assumed for the original mission, dB	~2.5	~2.5
Required gain of Negotiator on-board antenna, dB	44 + 24.5 = 60,4 dB	44 – 2,5 + 6.6 = 48.1dB
Conclusion	Nonfeasible due to high requirements to Negotiator (it would require a parabolic antenna with at least 14m in diameter)	Feasible for shorter distances; A constellation of Negotiators is required for a full coverage.

A comparison of derived Negotiator parameters with state of the art radio communication technologies (O3B and TDRS satellites characteristics) was conducted. It was assumed that on-board losses of FSS Negotiator are equivalent to the original ground station. On-board antennas of O3B and TDRSS satellites have 31.66 dBi and 23.82 dBi gain correspondingly [28] [29]. Hence, the geostationary configuration of FSS Negotiator looks unfeasible. At the same time, the LEO Negotiator concept is feasible for the selected case only when a location on the orbit selected to keep the communication distance up to several hundreds of kilometers (e.g. 300km would require ~23dB gain of FSS Negotiator antenna) and an introduction of more Negotiators.

The mission with the use of higher frequencies would also benefit more from Negotiator due to higher atmospheric attenuation of a signal. The space industry moves towards higher operating frequencies [30], mainly because of the lack of available bandwidth. New technologies such as 5G might expand on traditional satellite frequencies due extremely high demand on frequencies below 6 GHz [31]. And eventually, possible benefits in gain from the use of inter-satellite links oppose to direct downlink in the future might be even higher.

3.3 MODELS FOR FSS NEGOTIATOR PARAMETERS SELECTION

This section follows up the possibility to scale up the scenario described in the previous section for more satellites and formulate high-level architecture requirements to FSS Negotiator. It identifies correlations between parameters of FSS Negotiator and amount of supported satellites based on such parameters of existing satellites as a working frequency range, bandwidth, datarate and modulation type; however, it does not include link budget evaluation (figure 4).

The increase of such parameter of FSS Negotiator as the number of supported frequencies and bandwidth size will increase a supported number of satellites but at the same time technical requirements and eventually cost of the mission will grow up. Characteristics of Negotiator could be optimized using statistical data.

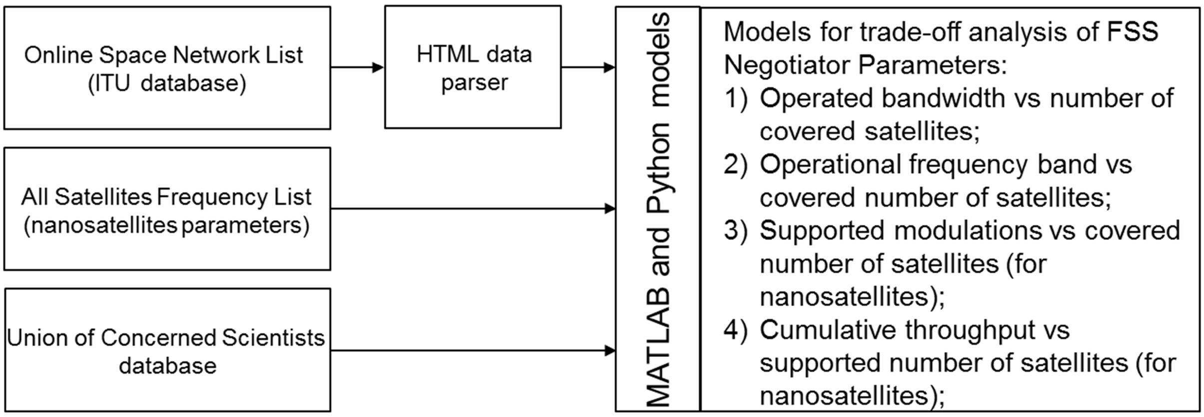

Figure 4 Models for FSS Negotiator parameters evaluation

To define requirements in terms of bandwidth and corresponding processing power empirical cumulative distribution functions for bandwidth in S, X, Ku and Ka bands can be used (figure 5). The biggest number of applications is submitted for S- and X- bands. While the difference between bandwidths sizes may be several orders of magnitude, about 67% of all submissions in X-band do not exceed 170MHz. At the same time, X-band has a higher number of submitted application than Ku or Ka band (figure 2).

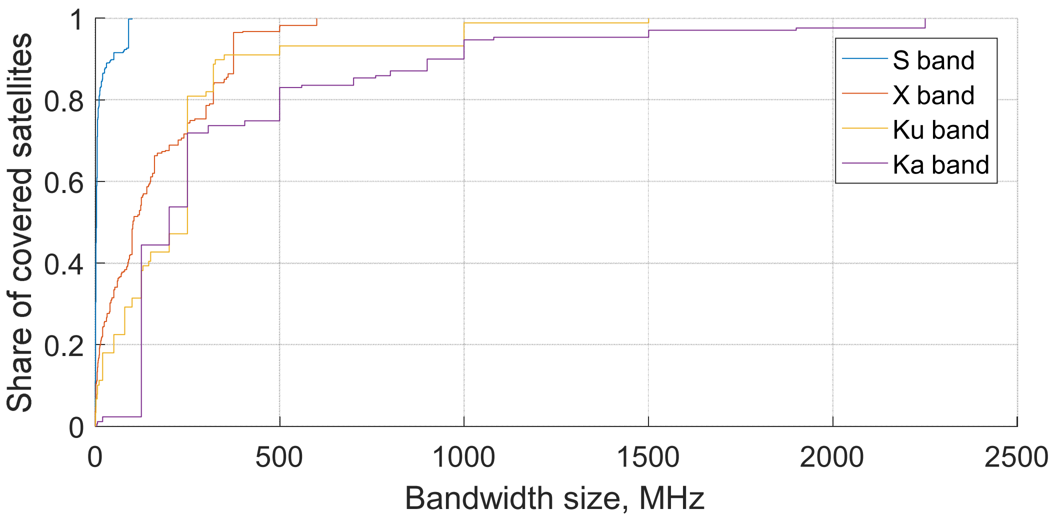

Figure 5 Empirical cumulative distribution of channel bandwidths in S, X, Ku and Ka bands (for 869 existing space missions and submitted applications)

However, the incorporation of traditional EO missions into FSS via Negotiator may significantly change original concept of mission operations, therefore a detailed analysis of each mission is required.

A subcase of FSS Negotiator for nanosatellite missions (weight less than 10 kg according to ITU classification) has less impact on original mission concept of operations.

A nanosatellite case due to less diversity in terms of utilized frequency bands (mostly UHF and VHF) and lower technical complexity has lower requirements for FSS Negotiator. The main scenario for nanosatellite FSS Negotiator is telemetry aggregation and its relay to the ground. Due to nature of telemetry, usually omnidirectional or wide-beam antennas are used [6], so no change in the concept of operation of participating missions is required.

Analysis of parameters of existing nanosatellites brings the conclusion that multiple AFSK/FSK/GMSK receiver would cover 60% of all nanosatellites, at the same time the significant part of all existing nanosatellites (~60%) generates less than 2 Mbps of data.

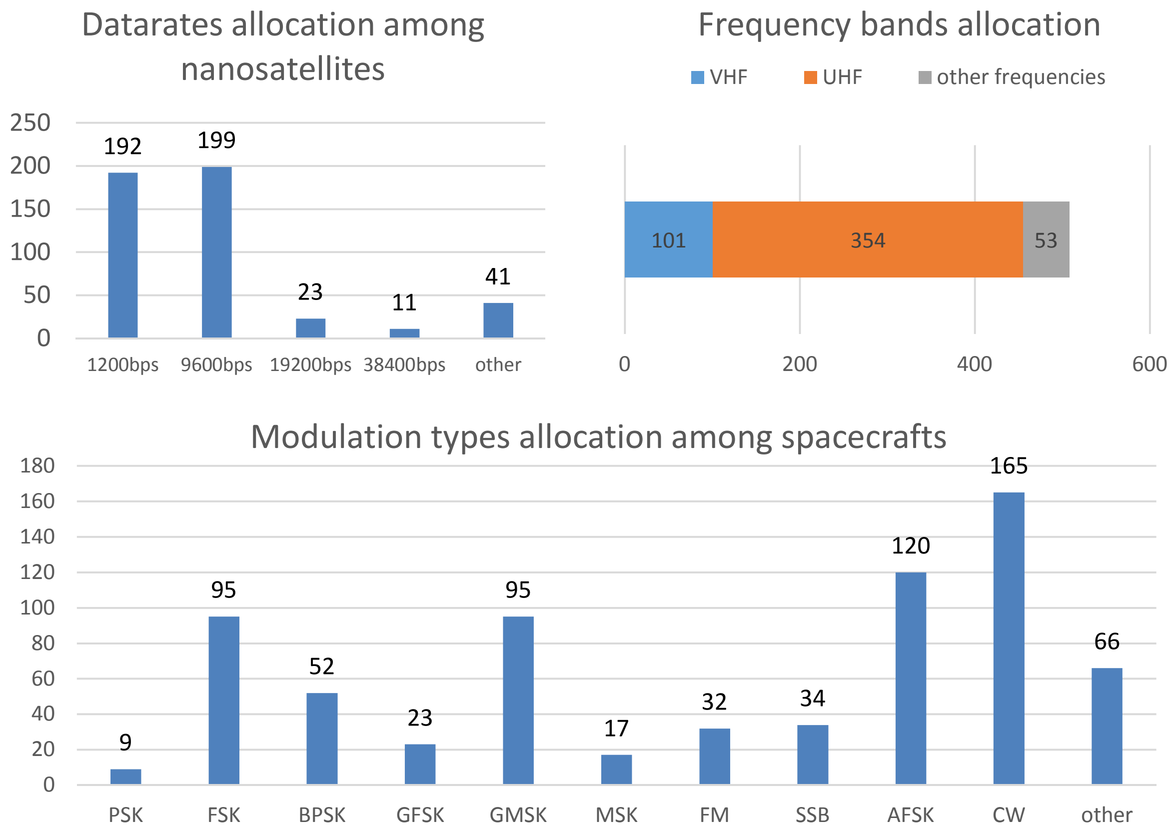

Figure 6 Allocation of parameters of 500 existing nanosatellite missions (25th September, 2017 several frequency bands/datarates/modulation types could be supported simultaneously [22])

4. RESULTS AND CONCLUSIONS

The conducted work considered different scenarios of retrofitting existing satellites in order to bring them into Federations of Satellite Systems. Different options such as a replacement of existing systems interfaces, an addition of new interfaces and an addition of a middleware were considered.

The conducted work made a conclusion that the ideas of replacement of existing systems interfaces or addition of new interfaces are unfeasible, due to frequencies mismatch and low re-configurability potential of most of the existing missions.

Table 3 A comparison of retrofitting options for Federated Satellite Systems

Retrofitting option	Adding interface	Replacing interface	Adding middleware
Existing examples of retrofitting for space missions	COSTAR and the Wide Field Planetary Camera 2 were installed during a shuttle mission, correcting Hubble's flawed vision [32]	The Voyager 1 spacecraft was reprogrammed to support Reed-Solomon codes [33]	The docking system for Apollo–Soyuz project [34]
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	Re-configuration or re-programming of existing on-board transceivers	Launch of a Negotiator satellite able to receive and relay data
Key requirements for participating missions	A physical access to electrical and data interfaces of the satellite	Re-configurability 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 need to be updated	Change of the schedule
Conclusion: feasibility from the technical point of view	Not feasible at the current moment due to high cost of on-orbital operations and cancelation of Space Shuttle program	Feasible for a limited number of satellites in terms of communication standards (e.g. satellites with re-configurable COM DEV's S-Band TT&C transponders [24]), but requires additional studies to identify cases when inter-satellite distances match link budget requirements	Feasible for a LEO Negotiators with communication distances limited to hundreds kilometers

At the same time, the work demonstrated that an option of adding a middleware, a special Negotiator satellite, might be feasible from a technical point of view with several limitations. The analysis has shown, that the geostationary Negotiator would require a gain for the FSS Negotiator on-board antenna far beyond most of existing state-of-the-art space solutions and higher than the original ground stations for the selected mission. At the same time, the Negotiator on LEO benefits from free space communications and requires less gain in case of either reduced distance of communications and a bigger number of Negotiators or in case of incorporation of satellites utilizing higher frequency bands, because of atmospheric attenuation compensation. As a reference for the feasibility evaluation of on-board antennas of Negotiator, the paper used as characteristics of existing O3B and TDRS satellites.

The work comes up with several empirical models for the further trade-off analysis, identifying how parameters of FSS Negotiator such as an operated bandwidth and frequency, types of supported modulations and cumulative throughput correlate with the covered number of satellites. And eventually, several architectures of communication equipment for FSS Negotiators such as X-band receiver with 170MHz bandwidth for existing EO missions and AFSK/FSK/GMSK receiver in UHF-band for nanosatellites were proposed.

In the future, the presented work might be extended in two different directions. A tabletop demonstrator based on commercial software-defined radios might be developed as a technological continuation of the topic. And a general Framework for Managing Retrofitting in Legacy Systems could be a generalized output for the work, complementing existing systems engineering methodology.

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