Preface

Space and terrestrial systems are more tightly related then anyone can suspect.

Apart from the obvious cooperation and synergy that must exist between the space and terrestrial components of an integrated infrastructure, another subtended relationship characterizes terrestrial and space activities: the virtuous osmosis of architectures and technologies adopted on Earth to space and vice versa.

It is perhaps more instinctive to expect a from-Earth-to-space osmosis of technologies and architectures and the spin-in as the natural way to go. The capability, instead, of space technologies and related architectures to pour innovations on Earth is amazing and the spin-out from space to Earth is very rewarding and surprising since at least the first Apollo mission!

A consequence of the bidirectional contamination between Earth and space is that actions and choices of Human Beings in the space realm have an impact on Earth. It is a great opportunity, a fascinating challenge but also a very strong responsibility. Selecting the suitable technology for a space system is then much more than finalising a new mission or a service in a cost and operation effective manner. To be more precise, let's say that the measure of effectiveness risks to be inaccurate in terms of predictable and unpredictable effects in the medium and long term.

This book is focused on a roadmap for future space connectivity that moves from awareness and responsibility in the use of the space domain. The above approach makes space indeed a main actor not only in the progress of knowledge and in the recognition of the recently added right of Humanity of "connecting the unconnected", but also in the capability of assuring a satisfactory future to all of us.

Despite the neutrality of technology, that is neither good nor bad by itself but that can become either one according to the use we make of it, the roadmap for future space connectivity is studded with choices on both technologies and architectures that can turn out to be right or wrong for the ambitious goal of a suitable way ahead for Mankind.

Let's be somehow disruptive here in measuring the suitability of technologies and architectures with their success of failure in passing a Glue Tech test of compliance. In fact, a Glue Technology (GT) is a powerful means of integrating various components while effectively maintaining their autonomy. By applying the GT paradigm to future connectivity infrastructures, the integration between terrestrial, aerial and space components could pave the way for very ambitious goals, including "connecting the connected" in a truly sustainable manner. The GT paradigm is so promising, that a group of experts worldwide created a technical panel of the IEEE Aerospace and Electronic Systems Society (AESS), named "Glue Technologies for Space Systems", whose focus is the conception, design, and application of Glue Technologies in space missions, infrastructures, and services under the sustainability umbrella. The editors and most of the Chapter authors of this book belong to the above AESS panel.

The holistic nature of sustainability makes it not effective to focus on Earth without caring effectively for the surrounding domain (space). Therefore, space sustainability is part of the picture and its implementation contributes to reach the more obvious goal of a green Earth. In the book space sustainability is both an underlying topic for different frameworks and a specific topic in a dedicated chapter. A powerful equation relates the capability of implementing sustainable space systems to the identification - and consequent use - of only Glue Technologies and related architectures. In fact, the horizontal ranges of application realms that a GT guarantees along with its related software-driven architectures offer to the system intrinsic pillars for its sustainable design, implementation and operations along with a good potential for its future recycling or, even better, upcycling. It is not dreamful to envisage in the future a system certification based on the use of only pure Glue Technologies and to expect a standardization activity related to the GT paradigm.

We hope the reader will be captured by the GT concept and its broad range of implications and potentials and that he/she will be stimulated to contribute to the future of space connectivity in a sustainable manner. The book is organized in four parts dedicated to satellite communications technology (Part I), systems and infrastructures (Part II), interplanetary networking (Part III) and new space applications (Part IV). Disruptive technologies, configurations, implications, design guidelines and verticals will guide the reader in the articulated domains of the GT paradigm.

Enjoy the journey. . .

Trento, Rome, Italy
Dresden, Germany
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Contents

Part III Interplanetary Networking

Part IV New Space Applications

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Acronyms

3GPP 3rd Generation Partnership Project

ACM Adaptive Coding and Modulation
ACT Adaptive Coding Transmission
ADC Analog-to-Digital Converter
AEHF Advanced Extreme High Frequency
AFC Analog Fountain Code
AHM Active Hydrogen Maser
AI Artificial Intelligence
ALOS Advanced Land Observing Satellite
AoD Age of Data
API Application Programming Interface
ARMA Auto-Regressive Moving Average
ARTES Advanced Research in Telecommunications Systems
ASI Italian Space Agency

BH Beam Hopping
BHC Beam Hopping Cycle
BHTC Beam Hopping Transmission Channel
BHTP Beam Hopping Time Plan
BSM Bell State Measurement
BSS Broadcasting Satellite Service
BW-Comp Backward Compatibility
BWG Beam Waveguide

CA Carrier Aggregation
CDM Code Division Multiplexing
CDMA Code Division Multiple Access
CEPT European Conference of Postal and Telecommunications Administrations
CF-MIMO Cell-Free Multiple Input Multiple Output
CHAMP Challenging Minisatellite Payload

CIR Carrier-to-Interference
CN0 Carrier-to- Noise Ratio
CNN Convolutional Neural Network
COMPASS Combined Observational Methods for Positional Awareness in the Solar System
CP Control Plane
CPRI Common Public Radio Interface
CRAN Cloud Radio Access Network
CRT Contention Resolution Timer
CSI Channel State Information
CSTD Concurrent Spatial and Time Division
CT Core network & Terminals
CV Continuous Variable

DAC Digital-to-Analog Converter
DAS Distributed Antenna System
DC Dual-Connectivity
DC Direct Current
DCU Digital Channelizer Unit
DD Delay-Doppler
DL Deep Learning
DRL Deep Reinforcement Learning
DROM Data Relay for Moon
DS Deep Space
DSA Dynamic Spectrum Access
DSA Deep Space Antenna
DSN Deep Space Network
DSRSS Deep Space Relay Satellite System
DSS Deep Space Station
DSS Distributed Satellite System
DSSS Direct Sequence Spread Spectrum
DST Deep Space Transponder
DT Dwell Time
DTE Direct to Earth
DTP Digital Transparent Processor

EDRSS European Data Relay Satellite System
EDSN ESA Deep Space Network
EGS Earth Ground Segment
EHF Extremely High Frequency
EIRP Effective Isotropic Radiated Power
ELFO Elliptical Lunar Frozen Orbits
eNodeB Extended Node B
EOL End Of Life
EOORT Earth-Orbiting Optical Communication Relay Transceiver

ESA European Space Agency
ESIM Earth Station In Motion
ESTEC European Space Research and Technology Centre
ESTRACK ESA Tracking Station Network

FCN Fully Convolutional Network
FDD Frequency Division Duplexing
FER Frame Error Rate
FFR Full Frequency Reuse
FHSS Frequency Hopping Spread Spectrum
FR Frequency Range
FS Fixed Service
FSO Free-Space Optics
FSS Fixed Satellite Service
FSS Federated Satellite System
FW-Comp Forward Compatibility

GaAs Gallium Arsenide
GaN Gallium Nitride
GEO Geostationary Earth Orbit
gNB-CU gNB Centralised Unit
gNB-DU gNB Distributed Unit
GNSS Global Navigation Satellite System
GOCE Gravity Field and Steady-State Ocean Circulation Explorer
GRACE Gravity Recovery and Climate Experiment
GSFC Goddard Space Flight Center
GSO Geosynchronous Satellite Orbit
GW Gateway

H/W Hardware
HAPS High Altitude Platform
HARQ Hybrid Automatic Repeat reQuest
HEMT High Electron Mobility Transistors
HEO High Elliptical Orbit
HGA High Gain Antenna
HiRISE High Resolution Imaging Science Experiment
HPA High-Power Amplifier
HTS High Throughput Satellite
HydRON High Throughput Optical Network

IAB Integrated Access and Backhaul
ICI Inter-Carrier Interference
ICT Information and Communication Technologies
IF Intermediate Frequency
ILRS International Laser Ranging Service
INS Inertial Navigation

IOAG Interagency Operations Advisory Group
IoRT Internet of Remote Things
IoT Internet of Things
IP Internet Protocol
ISFFT Inverse Simplistic Fast Fourier Transform
ISI Intersymbol Interference
ISL Inter-Satellite Link
ISS International Space Station
ITU International Telecommunications Union

JCS Joint Communication and Sensing Systems
JDRS Japanese Optical Data Relay System
JPL Jet Propulsion Laboratory

kNN k-Nearest Neighbours
KPI Key Performance Indicator

LCAWG Lunar Communications Architecture Working Group
LCNS Lunar Communication and Navigation Service
LCRD Laser Communications Relay Demonstration
LEO Low Earth Orbit
LFO Lunar Frozen Orbit
LGA Low Gain Antenna
LIDAR Light Detection and Ranging
LLCD Lunar Laser Communication Demonstration
LLO Low Lunar Orbit
LLR Lunar Laser Ranging
LMO Low Mars Orbit
LNA Low Noise Amplifier
LOLA Lunar Orbiter Laser Altimeter
LOS Line Of Sight
LPWAN Low-Power Wide-Area Network
LRD Long-Range-Dependence
LRNS Lunar Radio Navigation System
LRO Lunar Reconnaissance Orbiter
LSS Lunar Space Segment
LSTM Long Short-Term Memory
LT Luby Transform
LTE Long Term Evolution
LUCAS Laser Utilizing CommunicAtion System
LuGRE Lunar GNSS Receiver Experiment
LUS Lunar User Segment

MAC Medium Access Control layer
MarCO MarsCubeOne
MC Multi-Connectivity

MEO Medium Earth Orbit
MER Mars Exploration Rovers
MESFET MEtal-Semiconductor Field-Effect Transistor
MF Matched Filter
MGA Medium Gain Antenna
MIMC Monolithic Microwave Integrated Circuit
MIMO Multiple Input Multiple Output
MIT Massachusetts Institute of Technology
ML Machine Learning
MMIC Monolithic Microwave Integrated Circuit
MMS Magnetospheric Multiscale
MMSE Minimum Mean Square Error
mmWave millimiter waves
ModCod Modulation and Coding
MPA Medium Power Amplifiers
MPC Minimum Power Constraint
MRO Mars Reconnaissance Orbiter
MSL Mars Science Laboratory
MSPA Multiple Spacecraft Per Antenna
MSS Moon Surface Segment
MSS Mobile Satellite Service
MT Mobile Termination

NB-IoT Narrowband IoT
NCC Network Control Center
NEO Near-Earth Objects
NFV Network Function Virtualization
NGC Next Generation Core network
NGSO Non-Geosynchronous Satellite Orbit
NLOS Non Line Of Sight
NN Neural Network
NR New Radio
NTN Non-Terrestrial Network

O-RAN Open Radio Access Network
OAI Open Air Interface
OBBF On-Board Beamforming
OBP On-Board Processor
OBPU On-Board Processing Unit
ODTS Orbit Determination and Timing Synchronisation
OEC Orbital Edge Computing
OFDM Orthogonal Frequency Division Multiplexing
OGBF On-Ground Beamforming
OOBE Out-Of-Band Emissions
OTFS Orthogonal Time Frequency Space

PA Pilot Aided
PAC Per Antenna Constraint
PAE Power-Added Efficiency
PAPR Peak-to-Average Power Ratio
PDCP Packet Data Convergence Protocol layer
PER Packet Error Rate
PHY Physical layer
PIMT Propagation Impairment Mitigation Techniques
PLMN Public Land Mobile Network
PMD Post-Mission Disposal
PNT Position Navigation and Timing
PPP Precise Point Positioning
PU Primary User
PVT Position Velocity and Time

QBER Quantum Bit Error Rate
QKD Quantum Key Distribution
QND Quantum Nondemolition
QoS Quality of Service

RA Random Access
RAN Radio Access Network
RF Radio Frequency
RIS Reflecting Intelligent Surfaces
RL Reinforcement Learning
RLC Radio Link Control layer
RLM Return Link Message
RMS Root Mean Square
RN Relay Node
RNN Recursive Neural Network
RPAS Remotely Piloted Aircraft Systems
RRM Radio Resource Management
RSE Radio Science Experiment

S/C Spacecraft
SAE Society of Automotive Engineers
SAGIN Space-Aerial-Ground Integrated Network
SAR Search and Rescue
SatCom Satellite Communications
SCaN Space Communications and Navigation
ScyLight SeCure and Laser communication technology
SD Software Defined
SDAP Service Data Application Protocol
SdE Sustainability design Efficiency
SDM Space Debris Mitigation
SDN Software Defined Network

SDP Software Defined Payload
SDR Software Defined Radio
SEP Sun-Earth-Probe
SFFT Simplistic Fast Fourier Transform
SFGC Space Frequency Coordination Group
SFU Solar Flux Unit
SGD Smart Gateway Diversity
SI Study Item
SINR Signal-to-Interference-plus-Noise Ratio
SISE Signal In Space Signal Error
SISO Single Input Single Output
SNR Signal-to-Noise Ratio
SoL Safety of Life
SOOP Signals Of OPportunity
SPC Sum Power Constraint
SRI Satellite Radio Interface
SS Subsystem
SSA Space Situational Awareness
SSPA Solid State Power Amplifier
SSR Space Sustainability Rating
SST Space Surveillance and Tracking
STIN Satellite-Terrestrial Integrated Network
STK Software Systems Tool Kit
SU Secondary User
SubyD Sustainability-by-Design
SVM Support Vector Machine
SWE Space Weather

TA Timing Advance
TC Telecommand
TDRS Tracking and Data Relay Satellites
TDRSS Tracking and Data Relay Satellites System
TF Time-Frequency
TM Telemetry
TN Terrestrial Network
TSG Technical Specification Group
TT&C Tracking, Telemetry & Command
TTFF Time To First Fix
TWT Travelling Wave Tube
TWTA Travelling-Wave Tube Amplifier
TX Transmission
TZD Troposphere Zenith Delay

UAS Unmanned Aerial System
UAV Unmanned Aerial Vechile

UE User Equipment
UHF Ultra High Frequency
UL-PC Uplink Power Control
UP User Plane
UTC Coordinated Universal Time

VHTS Very High Throughput Satellite
VLBI Very Long Baseline Interferometry
VLMO Very Low Mars Orbit
VNF Virtual Network Function
VSAT Very Small Aperture Terminal

WI Work Item
WLAN Wireless Local Area Network

ZF Zero Forcing

Part I
Satellite Communication Technology

Chapter 8
Technologies and Infrastructures for a Sustainable Space

Ernestina Cianca, Simone Morosi and Marina Ruggieri

Abstract The space is going to become an unsafe place to operate. The amount of active and passive space objects (satellites and debris) that are concentrated in some orbits represents a treat. In such a crowded environment, spectrum management becomes more complex and the probability to operate with high level of interference increases. It is becoming more and more clear that actions are needed to make the space more sustainable. Much of the effort is nowadays in reducing the risk associated to the already produced "space junks". This chapter outlines the need to design future missions through a common sustainability-prone strategy that aim to stop producing further pollution. The chapter describes the proposed strategy and key technologies to enable it

8.1 Space Sustainability: the Problem

The room the sustainability concept is gaining in the design of space systems, missions and infrastructures is encouraging [1]-[9].

Until a few years ago, the progress in activities related to the space domain was mainly measured in terms of conquering destinations (planets, stars), creating larger infrastructures (for example, mega-constellations), assuring longer manned stay in the International Space Station (ISS), conceiving more and more innovative services to be provided from space, etc.

All the above matter is certainly very important and it represents in different ways a progress for Humanity. However, in the meantime, the priorities for assuring a

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decent future to Humanity were rapidly changing or, to be more precise, priorities that should have been dealt with efficiently and effectively long time ago were knocking hard at Humanity's door to be considered with the proper attention.

In the above frame, space-related activities seemed for some years out of the loop of the revolutionary change in Humanity's priorities: the knowledge to be rapidly acquired is clearly becoming how to survive to the effects of ignoring sustainability for too long.

The recent recognition from some of the space key-players that sustainability is also a matter to be considered in the development of infrastructures and services is an important step forward [4], [6], [8]. In fact, sustainability has an intrinsic holistic nature that needs attention not only on Earth but also in the whole space Earth is a small part of [3].

To give some numbers of the *problem*: together with active satellites, there are currently an estimated 330 million pieces of space debris, including 36,500 objects bigger than 10cm, such as old satellites, spent rocket bodies and even tools dropped by astronauts orbiting around Earth. This crowded situation poses several challenges such as:

- interference to astronomical observations;
- radio frequency interference to other communication systems and challenging spectrum management;
- challenges in space operations by shrinking the margin of error for maintaining separation between satellites;
- high probability of collisions, further increasing the debris.

Space soon will become an unsafe place to operate.

Caring for sustainability of the space environment implies the following actions:

- cleaning space from the junk produced by past (and most of the current) activities;
- stop polluting through a common sustainability-prone strategy for future activities.

In the following sections of the Chapter both the cleaning and the stop-polluting actions will be discussed, highlighting the current and envisaged status of their implementation and the related challenges.

Authors' aim is also to stimulate thoughts, new ideas and innovative solutions from the readers, because sustainability is not a matter of a few, but the biggest challenges ever in the history of Mankind.

8.2 Space Debris Mitigation/Removal

With more than 300 million fragments populating the orbits around Earth and about 5000 defunct satellites and large abandoned objects, space debris has become one of the most severe threats to a sustainable access to space for humanity in the next future [10]. Moreover, the density of debris in space is growing with an exponential trend as depicted by Fig. 8.1 [11].

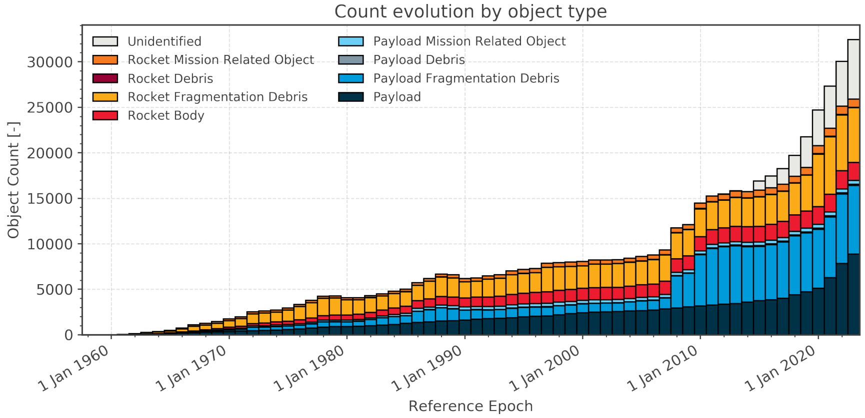


Fig. 8.1: Space Debris growing trend, courtesy of ESA, Space Environment Statistics updated to Aug.2022

All these "space bullets" are travelling at relative speeds of several kilo-meters per second and they are wondering uncontrolled, risking to collide with other operational satellites. This gives an idea on how unsustainable risky space activities are: if the satellites launched in orbit are not quickly disposed at the end of their mission, the possibility of chain collisions first predicted in the 1970s by NASA scientists that could possibly jeopardize the satellite classes around the Earth, could become real.

Current disposal practices have shown to be insufficient: many studies prove that a removal efficiency of at least 90%, in cooperation with dedicated Active Debris Removal missions is the minimum viable to keep the debris population at a steady value but the current success rate is still very far from that value, being around 50%.

The main strategies for Space Debris Mitigation/Removal are:

- SSA and Collision Avoidance;
- Space Debris Removal Techniques.

Space Situational Awareness (SSA) refers to the knowledge of the space environment, including location and function of space objects and space weather phenomena. SSA is generally understood as covering three main areas:

- Space Surveillance and Tracking (SST) of man-made objects;
- Space Weather (SWE) monitoring and forecast;
- Near-Earth Objects (NEO) monitoring (only natural space objects).

Particularly, an SST system is a network of ground-based and space-based sensors capable of surveying and tracking space objects, together with processing capabilities aiming to provide data, information and services on space objects that orbit around the Earth. As a result the SST Systems are the basis for the implementation of suitable Spacecraft collision avoidance strategies, namely to provide risk assessment of collision between spacecraft or between spacecraft and space debris by minimizing the chance of orbiting spacecraft inadvertently colliding with other orbiting objects.

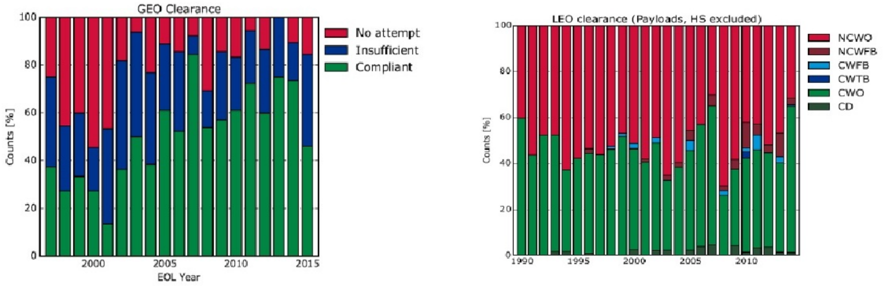
The most common subject of spacecraft collision avoidance research and development is for human-made satellites in geocentric orbits. The subject includes procedures designed to prevent the accumulation of space debris in orbit, analytical methods for predicting likely collisions, and avoidance procedures to maneuver offending spacecraft away from danger.

The removal of space debris from highly crowded orbits can be done according to the following techniques:

- de-orbiting, i.e. the forced reentry of a space object into the Earth's atmosphere usually via a propulsion system at the End of Life (EOL);
- reducing the orbital lifetime by accelerating the natural decay of spacecraft;
- moving the space object is less populated "disposal" orbits at the EOL;
- active removal of space debris.

It must be outlined that the implementation of dedicated Post-Mission Disposal (PMD) technologies is still seen by many operators and officials as a burden for space industry's competitiveness [12]-[13]. In LEO, where the removal manoeuvre is often more complicated than in GEO and the commercial exploitation of the orbits has just begun, the average level of adherence to PMD regulations and guidelines in terms of PMD manoeuvre has been about 45% over the past 10 years.

In GEO, where there is a commercial interest in removing the satellites from its operational slots, in order to replace them with the new and more performing satellite the average level of adherence to PMD regulations and guidelines in terms of PMD manoeuvre has been of about 65% over the last 10 years. Above statistics are shown in Figure 8.2.



(a) for GEO satellite (b) for LEO satellite

Fig. 8.2: Adherence to PMD regulations in terms of PMD manoeuvre.

Current solutions for implementing SDM requirements rely mostly on the propulsive system already on-board the satellites for performing station-keeping manoeuvres. However this solution has shown a lower rate of success in implementing decommissioning manoeuvres.

Active in-orbit debris removal would require some kind of space vehicle dedicated to this purpose. As a matter of fact, the cost of such a vehicle could be very high. Some studies have estimated a cost of 15 million for each piece of debris in LEO removed, not counting the cost of developing an orbital maneuvering vehicle.
Also the use of tethers have been considered for deorbit large objects, but the cost would be high in any case.

Other active removal schemes for small debris are:

- "debris sweepers" such as large foam balls or braking foils;
- ground- or space-based laser evaporation of debris surface material;

All of the proposed techniques are expensive and technically daunting. Yet it is becoming increasingly clear that this will be a necessary component of space sustainability.

8.3 Sustainable-by-Design approach: enabling technology

8.3.1 Concept of Sustainability by Design

Awareness about the space sustainability matter should translate into a focused set of actions during the conceivement, design, deployment and management of any new system, infrastructure, mission or service. If sustainability becomes a goal only in an advanced stage of development effectiveness of any action will be much lower.

Some of the readers might remember the dawn of security requirements in information systems. Caring about security needs in an advanced stage of the development was often bringing unsatisfactory results and exposing the system to risks. The criticality was increased when systems or infrastructures were integrating non-homogeneous components (for instance, terrestrial, aerial and satellite portions). If we compare the integrated system or infrastructure to a patchwork blanket, inter-patch stitching is often the most critical for the blanket lifetime. A successful approach in the design of a system or infrastructure, particularly if integrated, should then take security into account from the very beginning of the conceivement to guarantee a lasting resilience.

Sustainability has a similar impact as security in both the behaviour of the system or infrastructure and its resilience capability in time, particularly if the system or infrastructure is integrated (e.g. [14]). The sooner the sustainability requirements are in the loop, the better the system or infrastructure will perform over time and under both predictable and unpredictable circumstances.

Sustainability-by-Design (SubyD) is the approach that moves from sustainability requirements at the very beginning of the design phase and, even better, during the conceivement stage. A sustainable space system takes into account what is already available in space in order to both reduce/simplify harware and upcycle existing infrastructures. This capability allows the system or infrastructure under design a backward compatibility (BW-Comp), that is feasible when a SubyD approach is used, while it becomes quite complicate and very costly when the sustainability requirements are not in an early phase of the design chain.

Furthermore, the system under design has also to look strategically at the future and, thus, it has to be prone to be used by systems that will be in space later. This capability allows the system under design a forward compatibility (FW-Comp), that makes sense if a SubyD approach is used not only by the system under design but also by most or, in a long term vision, all systems to be deployed in space.

Both BW-Comp and FW-Comp imply that each system is a block of a multi-component integrated infrastructucture that evolves in the time domain.

As highlighted in the comparison with security requirements, sustainability requirements become more critical in an integrated infrastructure. On the other hand, the integrated infrastructure is the means to implement both BW-Comp and FW-Comp. Therefore, the SubyD approach admits no excuse because only if it is followed by most or, in a long term perspective, all space players the achievable results will be effective.

It looks pretty complicate to start the virtuous cycle of developing a sustainable space. The neutrality of technology is a good starting point.

In fact, technology is neutral and only its use can be for good or bad purposes: in the space sustainability framework, “good” or “bad” measures the capability of a given technology to easy the realization of both BK-Comp and FW-Comp.

In the next sections some technologies that are prone to the deployment of the SubyD approach and its pillar architectures based on backward and forward compatibility will be highlighted. The design based on sustainability requirements measures its effectiveness in terms of a quality parameter, the Sustainability design Efficiency (SdE) that can be expressed as:

$$SdE = \eta_{BW}\eta_{FW}\eta_{TK} \tag{8.1}$$

where η_{BW}, η_{FW} and η_{TK} are the design efficiencies related, respectively, to the use of BW-Comp, FW-Comp and *ally* technologies in the design. Each of the three factors of Eq. 8.1 can be increased by an extensive use of the existing space infrastrctures, an informed and strategic vision on future missions and services and a brave and effective use of those technologies that support the SubyD approach. The unitary values of the three η_{BW}, η_{FW} and η_{TK} efficiencies, that would imply a unitary value of *SdE*, are very unlikely to be reached in the short, medium and perhaps also long term. In fact, $\eta_{BW} = 1$ would imply that the mission or service of the system under design can be performed without the launch of any additional hardware, $\eta_{FW} = 1$ would indicate that all future missions or services could take advantage from the system under design and $\eta_{TK} = 1$ would mean that all technologies adopted in the system under design be SubyD prone.

Present values of the efficiencies in Eq. 8.1 are almost close to zero. To be optimistic, let's say that there is a wide margin of improvement that can be spent to increase the three factors and, through them, the SdE value. A coordinated effort of the various space players and focused standardization activities would easy the capability of each system under design to increase both η_{BW} and η_{FW}.

The conceptual flow of the SubyD approach is depicted in Figure 8.3. The design is based not only on the conventional set of system requirements but also on sustainability requirements that can be translated into three thresholds (A, B and C) of the three efficiencies composing the SdE quality parameter.

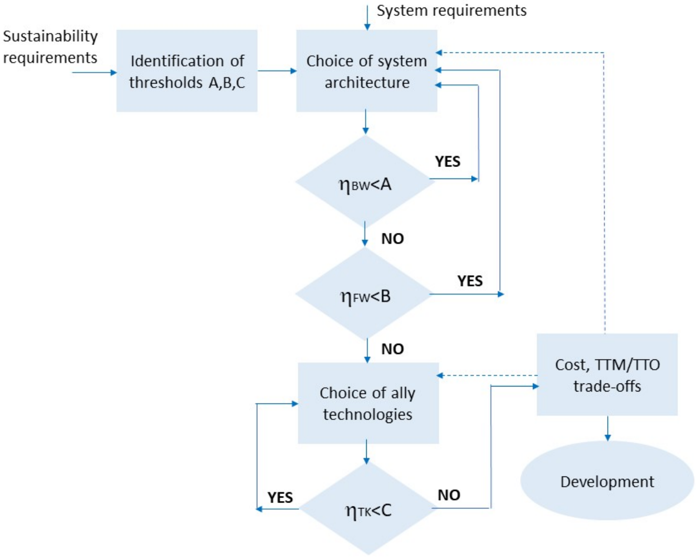


Fig. 8.3: Conceptual flow of the SubyD approach.

The three SubyD pillars are all important to meet the goal of a sustainable space, but there is a logical flux of actions that envisages a sequential check first on η_{BW}, then on η_{FW} and, after system architecture is finalized, on η_{TK}, as highlighted in Figure 8.3.

When the design meets the three thresholds, cost and time-to-market/time-to-operations might bring further trade-offs to be considered before the development phase, with eventual feedback on the choice of both system architecture and usable technologies.

The definition and the adoption of a sustainability-aware approach to the design of space networks encompass the formalization of novel and targeted Key Performance Indicators (KPIs) to effectively assess the sustainability of the integrated infrastructure in its broader sense. In 2019 the World Economic Forum has launched an initiative to develop a Space Sustainability Rating (SSR) tool, [15]. ESA and the MIT are developing the SSR tool to score the sustainability of manufacturers and operators on the basis of factors such as plans to de-orbit systems upon completion of missions; choice of orbital altitude; ability of systems to be detected and identified from the ground; collision-avoidance tools; size and number of objects left in space from the launch vehicle; and sharing of data. However, most of the considered KPIs of space sustainability are related to choices made in production phase (choice of the materials, lifetime, etc.) or they are related to the space mitigation/removal techniques that are implemented. The approach proposed in this Chapter calls for the definition of new KPIs that will have to take into account the following features:

- the level and the pervasiveness of the softwarization and virtualization of the specific technologies which are adopted in the considered systems and networks;
- the capabilities of inter-operation with previous and future technologies by means of BW-Comp and FW-Comp.

8.3.2 BW/FW Compatibility: Federated Satellite Systems

A concept that is strongly related to the need of BW/FW compatibility is the concept of Federated Satellite Systems(FSS), which is an evolution of Distributed Satellite Systems (DSS) [16]-[18].

A satellite federation consists of a group of satellites that during their mission may decide to establish opportunistic collaborations with other groups of satellites to share resources that are underutilized such as commodities, data storage, data processing, downlink capacity, power supply, or instrument time. Such collaboration should result in a benefit for the satellite operator that decide to establish it and should not lead to a degradation of performance for the main mission of satellites. Therefore, the concept of FSSs is strictly related to the capability to interoperate with other spacecrafts/constellations already deployed and or that will be deployed in the future which would allow the "reuse" of the same infrastructure to provide other services.

The concept of FSS was first introduced by Golkar [16] and mainly for Earth Observation constellations. Most of the previous works on FSS has focused on the business cases and opportunity to establish such a collaboration but not much effort has been posed to solve the challenging technical issues that are related to its implementation. In the short term, the concept of FSS could be implemented by using a negotiator node, a kind of gateway that adapts the communication protocols to enable the communication between satellites belonging to different communication systems and eventually operators. Newly designed missions should be flexible enough to intrinsically enable the establishment of opportunistic links between different satellite systems.

The feasibility of an effective FSS requires high level of flexibility both at paylaod level and at network level. On one hand, it should be possible to establish communication links between heterogeneous communication nodes, and hence the transceiver must be highly adaptable and flexible. Moreover, opportunistic links between different constellations will make the network topology highly variable and hence, high level of adaptability is also required at network level. Finally, the feasibility of FSSs is strictly related to the feasibility of stable ISLs among heterogeneous spacecrafts, characterized by different sizes, characteristics and dynamic behaviour.

8.3.3 BW/FW Compatibility: Joint Communication and Sensing

The design of Information and Communication Technology (ICT) systems that are able to jointly perform communication and sensing (and localization as a specific type of sensing), is a hot research area [19]. Such systems are referred as Joint Communication and Sensing Systems (JCS). On one hand, there is a strong interest in using LEO mega-constellations born to provide broadband communication services, to provide Positioning Navigation and Timing (PNT) services mainly in the events in which GLobal Navigation Satellite Systems (GNSS) signals become unavailable (deep urban canyons, under dense foliage, during unintentional or intentional interference). Such a solution is a key enabler of the backward compatibility and hence, of the space sustainability, as already deployed infrastructure is reused to provide novel services. Research in this field is now focused on facing the following challenges:

- satellites do transmit satellite ephemerides and using the information that can be found in the two-line-element files introduces an error of kilometers due to several sources of perturbations.
- LEO are not equipped with atomic clocks so they are not tightly synchronized.
- LEO satellites are owned and operated by private entities which use proprietary protocols and hence novel specialized receivers must be developed that are capable for extracting navigation observables.

An emerging area of research is the network/satellite-based geolocalization of Internet of Remote Things [20] devices via satellites that are used to provide them communication services [21]-[22]. The need to geolocalize IoRT terminals is not only related to the possibility to provide location-based services but also to improve the communication performance. In the release 17 of [23], when proposing adaptation of 5G NR or Narrow Band (NB)-IoT standards to the use with satellites links, the assumption is the IoT terminals are equipped with GNSS receiver. This is not always feasible if the IoT terminals are low cost, battery-powered devices. Therefore, it would be crucial to localize them from the satellite by using the communication signals. On the other hand, much effort is nowadays also focused on the design of future space systems that can, by design, provide jointly communication/navigation and sensing. Therefore, such approach is a key enabler of the FW compatibility. In this framework, lot of research activity has addressed the issue of novel waveforms. In particular, the novel waveform OTFS, which has attracted interest for high date rate communications from LEO satellites (see Chapter 1), has also interesting characteristics when joint communication and localization services must be provided [24].

8.3.4 Ally Technologies

As shown in Fig.8.4, the concept of FSS and JCS are key ingredients to make satellite infrastructure BW and FW compatible thus reducing the need to launch new nodes and infrastructure elements. The use of a negotiator node would enable the establishment of FSSs with currently deployed satellite systems and thus contributing to the BW compatibility. On the other hand, future missions should be designed with communication nodes already able to establish opportunistic links with other elements of the deployed infrastructure to provide novel services, thus enabling the FW compatibility. At the same time, the reuse of already deployed infrastructure (BW compatibility) will be enabled by the research in the field of JCS towards the use of signals transmitted by current systems (e.g., the use of communication signals for navigation purposes). On the other hand, the research on JCS aims to make future system more flexible and able to *natively* provide different services using the same signals. Moreover, in Fig.8.4 The key enabling technologies to the implementation of FSS and JCS, shown in Fig. 8.4, are presented in the rest of this Section.

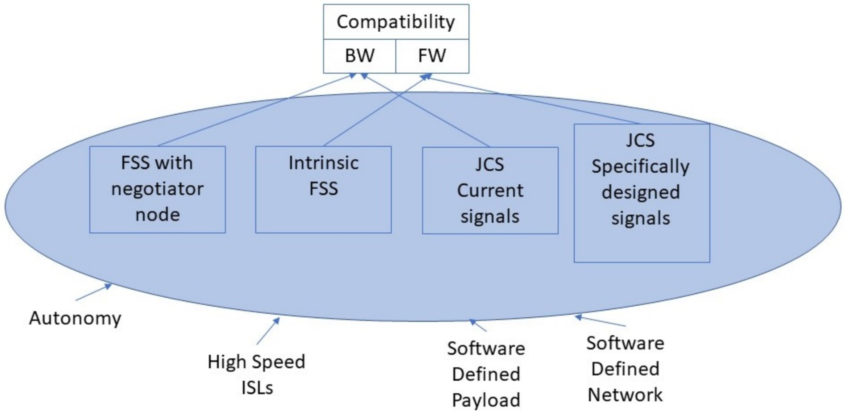


Fig. 8.4: Key technologies enagling BW/FW compatibility

8.3.4.1 Softwarization

The sustainability-driven design can take an enormous advantage from the choice of technologies that easy the development and management of system architectures being both backward and forward compatible over a long period of time.

A pervasive use of the Software Defined (SD) paradigm into the space system or infrastructure is a major ally to the easy, massive and lasting application of the backward and forward compatibility [3]. The SD approach can benefit both networking and data storage through the powerful decoupling between physical and control/service components [25]. In the last years the SD paradigm is receiving attention and focused efforts, in particular for integrated space-terrestrial frameworks (e.g. [26], [27]). In the medium and long term, architectures when even the SDN controller is in space are envisaged (Figure 8.5). Considering, then, that the FW compatibility moves the overall architecture ahead over a time sliding window, also the SDN controller could be moved from a current system to a future one, due to the flexibility of a full space-based SD approach and an effective coordinated effort among space players. Besides the obvious issues related to the pervasive implementation in space of new paradigms, like the SD approach, there is a further important aspect that relates to all sustainability ally technologies. Any technology that supports sustainability-prone design and architectures has to be sustainable itself. This, perhaps, is the most challenging aspect.

To understand the problem, let's focus for a moment on what is happening on the effort of terrestrial connectivity infrastructures to become "green". On one hand, the pervasiveness of connectivity is the key to render "green" most of the vertical domains, from energy to heath to industry, just to mention some very popular application realms. On the other hand, the pervasiveness and its consequences, like for instance the spreading of edge computing, the amount of small and spread around data centres, the increased transport and computational capacity related to the cloud operations need to become truly energy efficient so that pervasive connectivity be indeed a relief for the vertical sectors and, thus, for the Planet from the sustainability viewpoint [28]-[30]. Similarly, when dealing with space sustainability ally technologies, in particular with SDN, focused efforts are needed to render them energy efficient (e.g. [31],[32]).

8.3.4.2 Autonomy and AI tools

Automated systems are systems where the system knows exactly how to react for any situation that is predicted. When unpredicted situations occur the system gets stuck. On the other hand, an autonomous system is able to to react at its best in any possible situations. Historically, the work on spacecraft autonomy has been focused on deep-space exploration missions. In the framework of space sustainability, the introduction of some level of autonomy could be crucial for: i) prevention of collisions due to space debris; ii) spectrum and interference management [33]. Deep learning tools have been proposed to detect external threats (space debris) and react to avoid

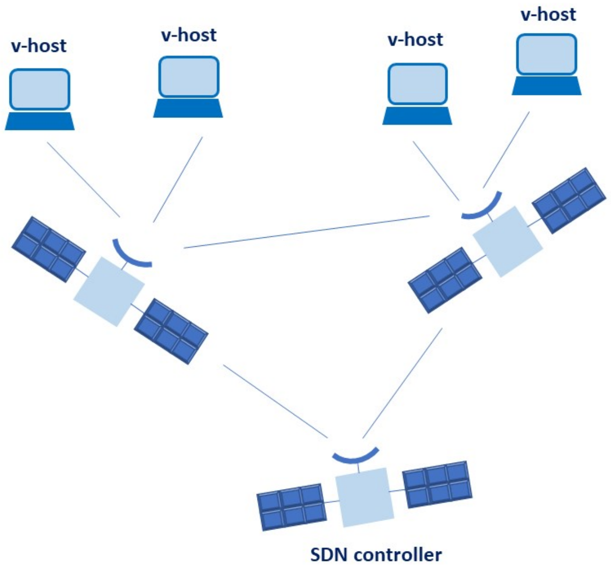


Fig. 8.5: Full space SDN approach.

collisions by replanning the route [34]-[36] to maximise mission efficiency and minimise the risk of collision with resident space objects. Moreover, autonomy could be used also for establishing more quickly, only based on local information, opportunistic connections with heterogenous spacecrafts to support the introduction of new missions [36]-[37]. In [37], a predictive algorithm was developed to estimate future satellite contacts and predict routes overtime in which federations can be established.

8.3.5 Very High-Speed Inter-Satellite/Inter-Layer Links

In such a highly softwarized space infrastructure, with many decentralized functions and high level of autonomy, higher volumes of signalling and control data will have to be exchanged by network nodes, besides the user data. It must be outlined, that space systems are part of a multi-layered architecture whose non terrestrials nodes are not only the satellites in different orbits, but also High Altitude Platforms (HAPs) and Unmanned Aerial Vehicles (UAVs). Therefore, high throughput links between space nodes and more in general space and aerial nodes are needed and the use of mmWave/optical links and more recently also of Terahertz links [38], become a key enabler of such a vision. As presented in Chapter 1, the use of Q/V bands in the feeder link of HTS systems for broadband services is a consolidated concept. Their use for ISLs but also inter-layer links between satellites (also in different orbits) and HAP/UAVS poses many challenges such as lack of channel models considering platform vibrations, related mispointing and tracking losses, high Doppler shifts besides the atmospheric attenuation. Novel waveforms and error correcting mechanisms should be investigated [39]. Another key issue that have an impact of the feasibility of mm-waves/THz links and on the trade-off between HW and SW implementation, between flexibility and number of nodes that are needed to cover a given service area, is the antenna design and beamforming architectures [40]. Some recent papers have proposed hybrid analog-digital implementation for beamforming in mm-waves UAV-ground links as a good trade-off between the flexibility offered by the full digital implementation and the lower power consumption associated to an analog implementation [41]. An important challenge for THz links is the need to fine alignment of pencil-beams in presence of high Doppler and relative speeds. In [42], the use of Reconfigurable Intelligent Superfaces (RISs) is proposed as a highly energy efficient fashion to facilitate the beam alignment.

8.4 Conclusions

The way for a truly sustainable space is paved with challenges and brave decisions as well as with a high degree of coordination among key players. It looks very hard, but the result would be very rewarding: an unprecedented growth in the ability of deploying and managing systems and infrastructures able to last much more than usual, due to the sliding time window of the forward compatibility that, in turns, moves from a convincing backward compatibility. It should be also noted that the efforts for energy efficiency reported in the literature are named “green” even if they are referred to the space realm. Perhaps, space sustainability could bring to a new two-dimensional colour definition: “green” and “blue”. In fact, “green” is the goal for the impact on Earth of producing a given technology, while “blue” is the goal of the impact that technology should have in terms of space sustainability. The holistic nature of sustainability suggests that a sustainable space needs only “green-blue” technologies. What a fascinating and coloured goal!

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