Satellite Communications in the New Space Era: A Survey and Future Challenges

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***Abstract*—Satellite communications (SatComs) have recently entered a period of renewed interest motivated by technological advances and nurtured through private investment and ventures. The present survey aims at capturing the state of the art in SatComs, while highlighting the most promising open research topics. Firstly, the main innovation drivers are motivated, such as new constellation types, on-board processing capabilities, non-terrestrial networks and space-based data collection/processing. Secondly, the most promising applications are described, i.e., 5G integration, space communications, Earth observation, aeronautical and maritime tracking and communication. Subsequently, an in-depth literature review is provided across five axes: i) system aspects, ii) air interface, iii) medium access, iv) networking, v) testbeds & prototyping. Finally, a number of future challenges and the respective open research topics are described.**

***Index Terms*—Satellite communications, space-based data collection, 5G integration, non-terrestrial networks, new constellations, on-board processing, air interface, MAC protocols, networking, testbeds.**

I. INTRODUCTION

SINCE their inception, Satellite Communications (SatComs) have found a plethora of applications, including media broadcasting, backhauling, news gathering etc. Nowadays, following the evolution of Internet-based applications, SatComs are going through a transformation phase refocusing the system design on data services, namely broadband SatComs. The main motivation is a) the rapid adoption of media streaming instead of linear media broadcasting and b) the urgent need to extend broadband coverage to underserved areas (e.g., developing countries, aero/maritime, rural). Furthermore, a major milestone of the 5th generation of communication systems (5G) is the integration and convergence of diverse wired and wireless technologies. In this context, SatComs pave the way for seamless integration targeting specific use cases which can take advantage of their unique capabilities. In parallel, private ventures have led the development of a multitude of manufacturing and launching options, previously only reserved for governments and a handful of large international corporations. This initiative named New Space has spawned a large number of innovative broadband and earth observation missions all of which require advances in SatCom systems.

The purpose of this survey is to describe in a structured way these technological advances and to highlight the main research challenges and open issues. In this direction, Section II provides details on the aforementioned developments and associated requirements that have spurred SatCom innovation. Subsequently, Section III presents the main applications and use cases which are currently the focus of SatCom research. The next four sections describe and classify the latest SatCom contributions in terms of 1) system aspects, 2) air interface, 3) medium access techniques, and 4) networking and upper layers. When needed, certain preliminaries are provided in a tutorial manner to make sure that the reader can follow the material flow without reverting to external sources. Section VIII surveys communication testbeds which have been developed in order to practically demonstrate some of the advanced SatCom concepts. The last section is reserved for highlighting open research topics that are both timely and challenging. To improve the material flow we provide the structure of the paper in Fig. 1 and the list of acronyms in Table I.

II. MOTIVATION

A. New Constellation Types

Traditionally, Geostationary (GEO) satellites have been mainly used for SatComs since they avoid fast movement

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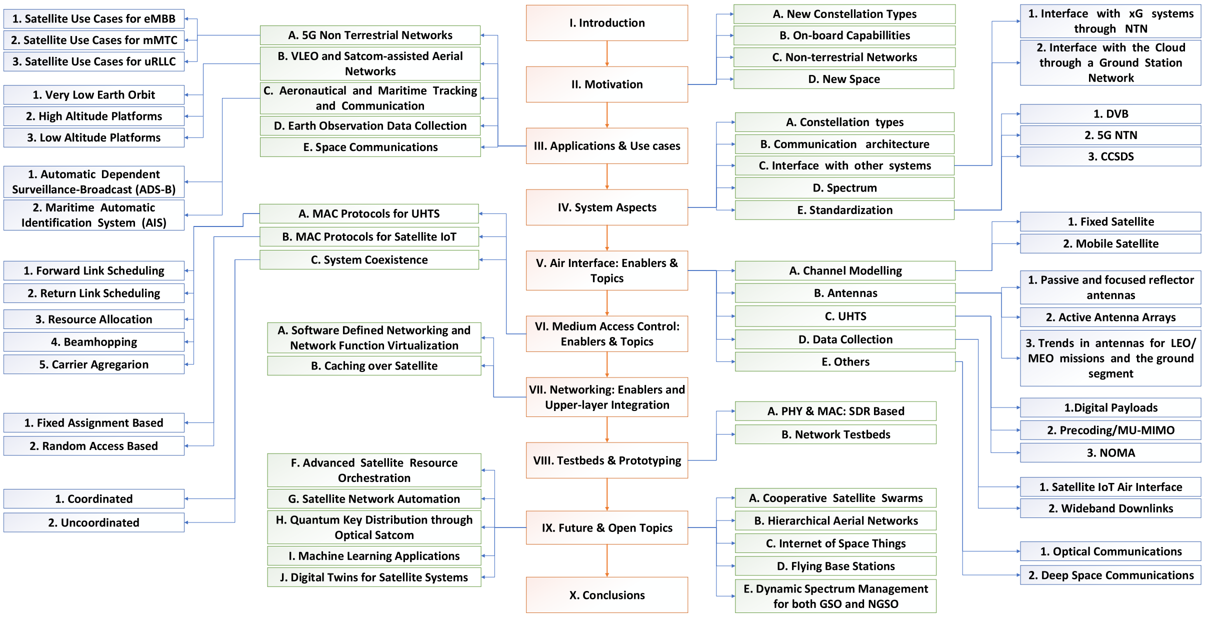


Fig. 1. Structure of the paper and topic classification.

between the terminals and the satellite transceiver, and they allow for a wide coverage using a single satellite. Multibeam satellite systems have been specifically developed to allow efficient frequency reuse and high-throughput broadband rates across the coverage area, not unlike their terrestrial cellular counterparts. However, new more ambitious constellation types are currently being developed, motivated by advanced communication technologies and cheaper launch costs.

In this direction, there has recently been a tremendous interest in developing large Low Earth Orbit (LEO) constellations that can deliver high-throughput broadband services with low latency. This constellation type has been the holy grail of SatComs since Teledesic first proposed it 25 years ago [1]. However, it appears that now the relevant manufacturing and launching processes have matured and a viable implementation and deployment may be within grasp. Multiple companies, such as SpaceX, Amazon, OneWeb, and TeleSAT, have already announced large LEO plans including thousands of satellites and some have already launched demo satellites. As of January 2020, SpaceX has deployed 242 satellites to build its Starlink constellation, with the goal to reach nearly 12000 satellites by mid-2020 [2].

Moreover, we turn our focus to Medium Earth Orbit (MEO) where a constellation of 20 satellites (O3B) has been placed in a circular orbit along the equator at an altitude of 8063 km. Each satellite is equipped with twelve mechanically steerable antennas to allow tracking and handover of terminals. The next generation of O3B satellites is planned to use an active antenna (see Section V-B2) which can generate thousands of beams along with an on-board digital transparent processor (see Section V-C1). This constellation type is unique since it manages to hit a trade-off between constellation size and latency.

Finally, the proliferation of new constellation types has given rise to hybrid constellations which combine assets in different orbits. One such example is the combination of MEO and GEO connectivity, where the terminals can seamlessly handover between the two orbits [3]. Another example is the backhauling of LEO satellite data through higher orbit satellites [4], [5].

B. On-Board Capabilities

Traditionally, the on-board processing capabilities have been the limiting factor for advanced SatCom strategies. Firstly, the majority of satellites operate as a relay which frequency-converts, amplifies, and forwards, and thus, the on-board processing has to be waveform-agnostic. Secondly, there is usually a large path loss to combat and a limited power supply which is tightly correlated with the satellite mass and launch cost. Thirdly, employed on-board components and technologies have to be ultra-reliable and robust since there is very little chance of repairing/replacing after the asset is put in orbit. Nevertheless, recent advances in the efficiency of power generation as well as the energy efficiency of radio frequency and digital processing components have allowed for enhanced on-board processing which can enable innovative communication technologies, such as flexible routing/channelization, beamforming, free-space optics and even signal regeneration (see Section V-C). Furthermore, space-hardened software-defined radios can enable on-board waveform-specific processing which can be upgraded during the satellite lifetime. Finally, cheap launching cost and conveyor-belt manufacturing allow for deploying more risky/innovative approaches while keeping up with the latest evolutions in communication technology.

C. Non Terrestrial Networks

Non Terrestrial Networks (NTN) is a term coined under 5G standardization to designate communication systems that include satellites, Unmanned Aerial Systems (UAVs) or High

TABLE I
LIST OF ACRONYMS

Acronyms	Definitions	Acronyms	Definitions
3GPP	The 3rd Generation Partnership Project	LLO	Low Lunar Orbit
5G	The 5th Generation of Mobile Communication Systems	LoRa	Long Range
ACM	Adaptive Coding and Modulation	LoS	Line of Sigh
ADC	Analog to Digital Converter	LPWAN	Low-power Wide Area Networks
ADS-B	Automatic Dependent Surveillance-Broadcast	LSA	Licensed Shared Access
AFR	Array Feed Reflector	LTE	Long Term Evolution
AIS	Automatic Identification Systems	LUT	Look up Table
ATC	Air Traffic Controller	MAC	Medium Access Control Layer
ATCRBS	Air Traffic Control Radar Beacon System	MBAs	Multibeam Antennas
ATM	Air Traffic Management	MEO	Medium Earth Orbit
ATSC	Advanced Television Systems Committee	MFPB	Multi Feed per Beam
AWGN	Additive White Gaussian Noise	MF-TDMA	Multi-Frequency Time Division Multiple Access
BS	Base Station	MIMO	Multiple Input Multiple Output
BATF	Backhauling and Tower Feed	mMTC	Massive MAchine Type Communications
CA	Carrier Aggregation	ML	Machine Learning
CCSDS	Consultative Committee for Space Data System	MSS	Mobile Satellite Services
CoMP	Coordinated Multipoint	MU-MIMO	Multi-User Multiple-Input Multiple-Output
COOM	Communication on The Move	MUI	Multi-User Interface
CR	Cognitive Radio	NB-IoT	Narrowband Internet of Things
CSI	Channel State Information	NCC	Network Control Center
CSS	Chirp Spread Spectrum	NFV	Netowrk Function Virtualization
D2D	Device-to-Device	NGSO	Non Geostationary Orbit
DRA	Direct Radiating Array	NOMA	Non-orthogonal Multiple Access
DSP	Digital Signal Processing	NTN	Non Terrestrial Network
DSS	Dynamic Spectrum Sharing	OBP	On-board Processing
DVB	Digital Video Broadcasting	OFDM	Orthogonal Frequency Division Multiplexing
DTPs	Digital Transparent Processors	OMA	Orthogonal Multiple Access
EBU	European Broadcasting Union	PAPR	Peak to Average Power Ratio
EDRS	European Data Relay System	PHY	Physical Layer
EPC	Evolved Packet Core	QoS	Quality of Service
EHF	Extremely High Frequency	RC	Repetition Coding
eMTC	enhanced Machine Type Communication	RF	Radio Frequency
eMBB	Enhanced Mobile Broadband	RN	Relay Node
EO	Earth Observation	RTT	Round Trip Time
ESA	European Space Agency	SatComs	Satellite Communications
ETSI	European Telecommunications Standards Institute	SC-FDM	Single Carrier Frequency Division Multiplexing
FAA	Federal Aviation Administration	SDMA	Space Division Multiple Access
FEC	Forward Error Correction	SDMB	Satellite Digital Multimedia Broadcasting
FPGA	field programmable gate arrays	SDN	Software Defined Networking
GEO	Geostationary Orbit	SDR	Software Radio
GNSS	Global Navigation Satellite System	SFPB	Single Feed per Beam
GPS	Global Positioning System	SIC	Successive Interference Cancellation
GW	Gateway	SLP	Symbol Level Precoding
HAPs	High Altitude Platforms	SINR	Signal to Interference plus Noise Ratio
HEO	Highly Elliptical Orbit	SNR	Signal to Noise Ratio
HTS	High Throughput Satellite	SOTM	Satellite on The Move
HYMP	Hybrid Multiplay	TDRSS	Tracking and Data Relay Satellite System
IETF	Internet Engineering Task Force	THEF	Trunking and Headend Feed
IFF	Identification Friend or Foe	TT&C	Telemetry, Tracking and Control
IMO	International Maritime Organization	TWTAs	Traveling Wave Tube Amplifiers
IMT	International Mobile Telecommunications	UAT	Universal Access Transceiver
IOT	In Orbit Testing	UAVs	Unmanned Aerial Vehicles
IoT	Internet of Things	UCSS	Unipolar Coded Chirp Spread Spectrum
ISL	Inter-satellite Link	UE	User Equipment
ISS	International Space Station	UHTS	Ultra High Throughput Satellite
ISTB	Integrated Satellite-Terrestrial Backhaul	UNB	Ultra Narrowband Signal
KPI	Key Performance Indicators	uRLLC	Ultra Reliable and Low Latency Communications
LAPs	Low Altitude Platforms	USRP	Universal Software Radio Peripheral
LDM	Layered Division Multiplexing	UT	User Terminal
LDPC	Low Density Parity Check	VLEO	Very Low Earth Orbit
LEO	Low Earth Orbit	VNE	Virtual Network Embedding

Altitude Platforms (HAPs). The main objective of this initiative is to seamlessly integrate these assets into the 5G systems by studying their peculiarities in terms of architecture and air interface. More importantly, the relevant stakeholders would like to valorize unique characteristics of NTNs, such as their wide coverage, multicast capabilities and complementarity with local terrestrial infrastructure. Furthermore from a deployment point-of-view, the cost can be largely decreased by using 5G chipsets/systems and tapping into economies of a larger scale. In this direction, a number of promising use cases have been put forward (see Section III-A) and specific adaptation points of the current 5G standards have been suggested through the relevant working groups, focusing on air interface compatibility and architectural integration (see Section IV-C1).

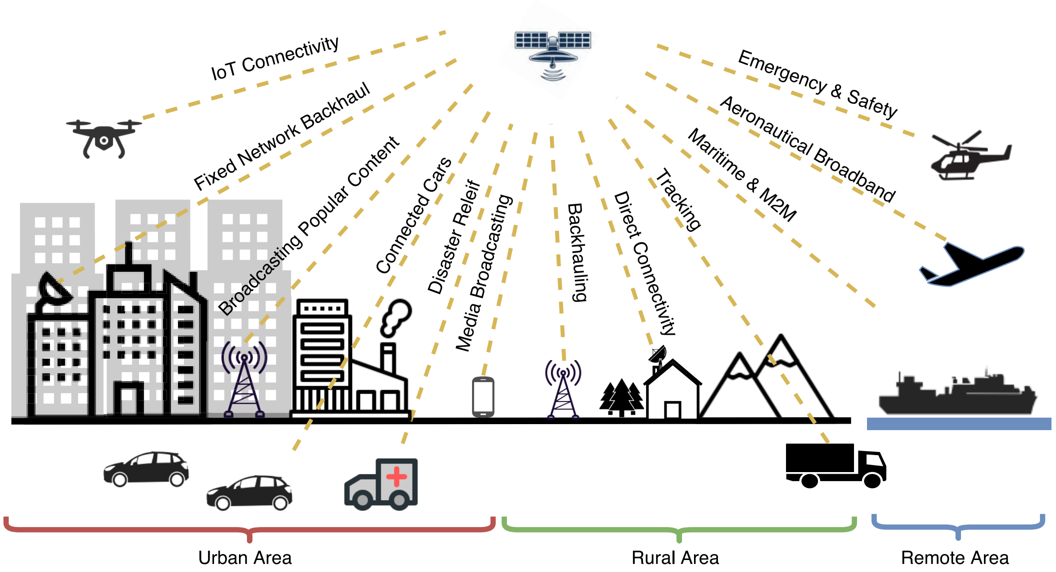


Fig. 2. The role of satellites in the 5G ecosystem.

D. New Space

New Space does not refer to a specific technology, but it rather implies a new mentality towards space. It originated from three main aspects: 1) space privatization, 2) satellite miniaturization, 3) novel services based on space data. Privatization refers to the manufacturing and especially the launching of satellites by private companies, such as SpaceX and Rocket Lab, in contrast to the traditional institutional approach. In parallel, satellite and component miniaturization allowed easy access to space by multiplexing multiple cube/micro/nano-satellites into a single launcher. The combination of the two first aspects has led to the latter, by allowing quick and relatively inexpensive access to space. In this direction, a wealth of data collection constellations have made it into orbit, spanning a wide range of services, e.g., earth observation, radio frequency (RF) monitoring, asset tracking, sensor data collection etc. Bringing our focus back to communication aspects, New Space has inspired new opportunities in terms of collecting data from ground sensors directly via satellites, i.e., Satellite Internet of Things. Currently, tens of private companies are building demonstrators and competing to launch a viable commercial service. Almost all these ventures rely on low earth orbits which raises additional communication challenges in efficiently downlinking the collected data back to the ground for processing. Conventionally, each such venture would require an extensive network of earth stations for high availability. However, cloud-based services (e.g., Amazon Web Services) have rolled out ground station networks that can be shared among the various constellations, while providing easy access to high performance computing for the data processing (see Section IV-C2).

III. APPLICATIONS & USE CASES

The aim of this section is to outline and briefly describe some of the most relevant applications and use cases where SatComs can play a significant role.

A. 5G Non Terrestrial Network

5G will be more than just an evolution of the previous standards, embracing a wide new range of applications so as to satisfy future important market segments, such as the automotive and transportation sectors, media and entertainment, e-Health, Industry 4.0, etc., [6], [7]. Three major groups of 5G use cases are defined by ITU-R for International Mobile Telecommunications (IMT) for 2020 and beyond (IMT-2020) [8]: enhanced mobile broadband (eMBB), massive machine-type communication (mMTC) and ultra-reliable and low latency communications (uRLLC). The role that the satellites can play in the 5G ecosystem is crucial and has been widely recognized. The 3rd Generation Partnership Project (3GPP) initiated new activities in March 2017 to study the role of the satellites in the 5G, and two study items (SI) have already been concluded [9], [10]. After two years of a study phase, it is now approved that NTN will be a new key feature of 5G and a work item (WI) will start from January 2020 [11].

Three major groups of use cases for NTN 5G systems have been defined by the 3GPP [12]. Firstly, NTN can significantly enhance the "5G network reliability" by ensuring service continuity, in cases where it cannot be offered by a single or a combination of terrestrial networks. This is especially true in case of moving platforms (e.g., car, train, airplane etc.) and mission-critical communications. Secondly, NTN can guarantee the "5G service ubiquity" in un-served (e.g., desert, oceans, forest etc.) or underserved areas (e.g., urban areas), where a terrestrial network does not exist or it is too impractical/cost-ineffective to reach. Last but not least, NTN can enable the "5G service scalability" due to the efficiency of the satellites in multicasting or broadcasting over a very wide area. This can be extremely useful to offload the terrestrial network, by broadcasting popular content to the edge of the network or directly to the users. A more detailed list of the satellite use cases for each 5G service group can be found below and an illustration is shown in Fig. 2.

1) Satellite Use Cases for eMBB: The authors in [13] come up with a consolidated list of satellite-based 5G uses cases for the eMBB service, as listed hereafter.

- *Backhauling and tower feed (BATF):* In this use case the satellite provides a complementary role by backhauling the traffic load from the edge of the network or broadcasting the popular content to the edge, hence optimizing the operation of the 5G network infrastructure;
- *Trunking and head-end feed (THEF):* The satellite ensures a direct 5G connectivity in remote areas where a terrestrial infrastructure is difficult or impossible to implement;
- *Hybrid multiplay (HYMP):* The satellite enables 5G service into home/office premises in underserved areas via hybrid terrestrial-satellite broadband connections;
- *Communications on the move (COOM):* The satellite provides a direct or complementary connectivity to support 5G service on board moving platforms, such as aircraft, vessels, and trains.

2) Satellite Use Cases for mMTC: The massive machine-type communication, also known as Internet of things (IoT), includes low complexity and extremely cheap devices (sensors/actuators) able to generate and exchange information. Even though small in nature, the traffic generated by these IoT devices will have a significant impact on the network load. Therefore, the satellites can help to offload the terrestrial IoT network through backhauling, or provide service continuity in cases where a terrestrial network cannot reach. Naturally, one might think that such low-cost and low-power devices will be unable to close the link due to the large distance to the satellite. Nevertheless, some link budget analysis in the literature [14], [15] demonstrate that the direct access is possible from the power perspective, at the cost of a significant decrease of the achievable data rate. This group of uses cases can be categorized into two smaller subgroups depending on the type of application that the satellite can support and on how the IoT sensors are distributed on Earth.

- *Wide area IoT services:* This use case has to do with applications based on a group of IoT devices distributed over a wide area and reporting information to or controlled by a central server. Typical applications where the satellite can play a role include:
  - *Energy:* Critical surveillance of oil/gas infrastructures (e.g., pipeline status)
  - *Transport:* Fleet management, asset tracking, digital signage, remote road alerts
  - *Agriculture:* Livestock management, farming
- *Local area IoT services:* The IoT devices in this kind of applications are used to collect local data and report to the central server. Some typical applications can be a smart grid sub-system (advanced metering) or services to on-board moving platforms (e.g., container on board a vessel, a truck or a train).

3) Satellite Use Cases for uRLLC: This 5G use case is expected to support services where the availability (99.99%), delay in the communication link (lower than 1 ms) and the reliability (1 packet loss in 10^5 packets) is of utmost importance. Some typical application examples include autonomous driving, remote surgery, factory automation, etc. It is clear that the satellite, regardless of the selected orbit altitude, is not able to fully support this service category due to the increased latency in the communication link. In fact, uRLLC requirements can be quite challenging even for a terrestrial network alone, due to either missing infrastructure in certain areas or network congestion in the extremely crowded ones. In this context, an integrated satellite-terrestrial network may take advantage of both, terrestrial and non-terrestrial infrastructures, in achieving the demanding uRLLC requirements. For example, in an autonomous vehicle scenario, the non-critical data, such as the traffic/software updates, may be re-routed through the satellite in order to benefit from its unique broadcasting capabilities over a wide area. This may substantially reduce the congestion that would otherwise be put on the terrestrial network, leaving it only for critical data exchange. Another example is the mobile edge caching, which enables the processing of ultra low-latency services at the edge such that only aggregated delay-tolerant information need to be transmitted through the satellite. Notably, in this service category the satellites would play a secondary/complementary role.

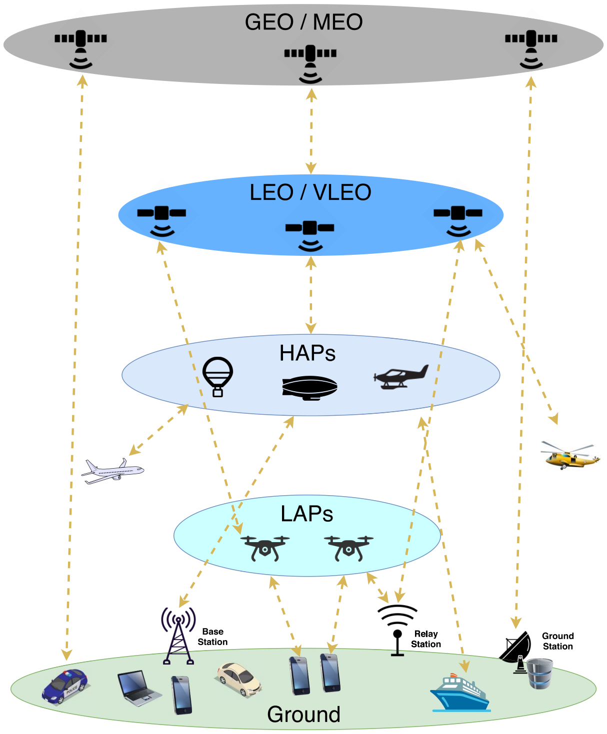


Fig. 3. Multi-layer communications architecture.

B. VLEO and SatCom-Assisted Aerial Networks

During the last years, intermediate layers of communications systems between terrestrial and traditional satellite segments have emerged thanks to the technological advance of the aerial and miniaturized satellite platforms. Regardless of the application, these new platforms can be classified according to their operation altitude. Three major groups can be distinguished: Very Low Earth Orbit (VLEO) satellites, High Altitude Platforms (HAPs), and Low Altitude Platforms (LAPs). Their respective altitude ranges are [16], [17] 100 to 450 km for VLEO, 15 to 25 km for HAPs, and 0 to 4 km for LAPs. The advent of these new platforms enables a new multi-layer communications architecture [18] with multiple inter-layer links capable to overcome the most challenging scenarios. Fig. 3 shows a schematic approach of this new multi-layer communications paradigm. The following subsections summarize the benefits ad challenges of LAPs, HAPs and VLEO satellites.

1) Very Low Earth Orbit: VLEO platforms operate closer to the Earth than LEO satellites. This allows them to be simpler, smaller, and, thus, cheaper [16]. However, such low altitudes contain a denser part of the atmosphere, and therefore, larger aerodynamic forces. This can be seen as a challenge, but they can also represent an opportunity for orbit and altitude control [19]. Moreover, the increased drag represents a shortening of the orbital lifetime, which also means a more frequent fleet replacement of smaller and cheaper spacecrafts, thus, becoming more responsive to technology and market changes [20]. Several private companies such as SpaceX, OneWeb or Telesat are planning to launch their Mobile Satellite Services (MSS) at VLEO.

2) High Altitude Platforms: HAPs have the potential to complement conventional satellite networks. Indeed, they are also known as High Altitude Pseudo-Satellites [21], [22]. Due to their working altitude, HAPs have the potential to provide communications services at a regional scale. There are two main ways of cooperation between satellites and HAPs according to [21], [22]:

- *Backhauling:* HAPs can be an intermediate element between the satellite and the ground receiver. This two-step downlink communication will have a first hop between satellite and HAPs, and a second hop between HAPs and ground. The former is prone to the use of high bandwidth optical links, as it suffers little atmospheric effects, whereas the latter has a much shorter path than the satellite height, which improves the link budget enabling smaller antennae (cost-saving) or wider bandwidth (revenue increase).
- *Trunking:* HAPs have a good balance between regional coverage and reduced signal degradation. This triggers their use as a low-cost deployment solution for broadcast or multicast services, allowing the users to directly connect within its coverage area and going to the satellite for inter-coverage communications.

Despite their promising applications, HAPs are still facing some major challenges for their deployment at a global scale, although they have been successfully deployed in emergency scenarios [23], [24]. One of the main challenges is the limited autonomy, especially in higher latitudes due to the reduced amount of daylight hours. Another is the weather conditions since high wind speeds may drag HAPs away from their operating area and low temperatures reduce the lifetime of the batteries. However, despite of the above-mentioned challenges, they offer crucial benefits, which have been studied in depth in [17], [21], [22]. The following list highlights the main advantages of the use of HAPs in communication networks:

- *Geographical coverage:* HAPs provide an intermediate coverage range between terrestrial and satellite systems.
- *Fast deployment:* aerial base-stations can be deployed for operation within hours. They can be a supplement or complement to the existing terrestrial and satellite communications networks when they are overloaded or in case of failure.
- *Reconfiguration:* HAPs can be operated for long periods, but they can also return to the ground for reconfiguration.
- *Propagation delay:* the propagation delay ($\sim$50-85 μs) is significantly lower compared to the GEO ($\sim$120 ms), MEO ($\sim$15-85 ms) and even LEO satellites ($\sim$1.5-3 ms), offering important advantages for delay-sensitive applications.
- *Less infrastructure:* a simple aerial platform can serve a large number of terrestrial cells, limited by its antenna technology.

3) Low Altitude Platforms: Unmanned Aerial Vehicles (UAVs) are the most prominent example of LAPs, but other systems, such as tethered balloons [25], have been also used for communication purposes. UAVs are expected to be an important component of the near-future wireless networks. They can potentially facilitate wireless broadcast and support high rate transmissions [26], [27]. The main benefits of UAVs (and LAPs) are similar to the HAPs ones, but at a cellular level: fast and flexible deployment, strong line-of-sight (LoS) connection links, and additional design degrees of freedom with the autonomous and controlled mobility. Moreover, UAV-enabled aerial base stations may establish, enhance, and recover cellular coverage in real-time for ground users in remote, densely populated, and disastrous areas.

Despite the technological maturity of UAVs, UAV-based communication networks have not been widespread because of several limiting factors such as cost constraints, regulatory frameworks, and public acceptance [17]. The use of autonomous UAVs as 5G aerial base stations or as relays in a multi-layer vertical architecture is also a major research topic [28]. The technical challenges to be overcome are:

- Improve the operation range and safety of the drones.
- Integrate trustfully beyond-visual-line-of-sight communication.
- Assess the applicability of all 5G capabilities in UAV base stations.

Further work related to wireless communications using HAPs and LAPs may be found in [29] and [30].

C. Aeronautical and Maritime Tracking and Communication

In addition to the above-mentioned uses cases, satellites can also play an important role in the aeronautical and maritime tracking systems. These systems share many similarities with other kinds of Device-to-Device (D2D) communications and the IoT. Such similarities are the very low data rates, the sporadic nature of the communications, and the simplicity of the protocols.

1) Automatic Dependent Surveillance-Broadcast (ADS-B): The ADS-B system is based on the capability of the aircraft to navigate to a destination (typically using Global Navigation

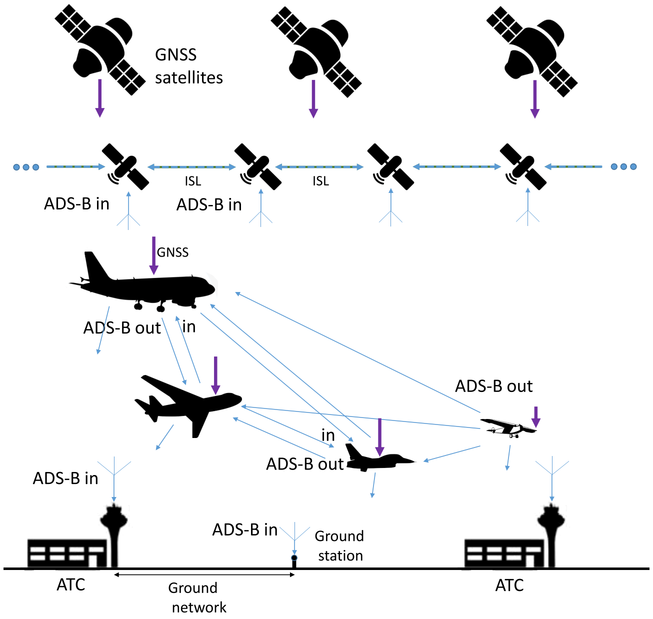


Fig. 4. ADS-B hierarchy, with integration of the satellites in low orbit into the scenario performing ADS-B reception.

Satellite System (GNSS) data and barometric altitude), communicate with an Air Traffic Controller (ATC), and participate in cooperative surveillance with ATC for separation and situational awareness services. ADS-B is automatic as it requires no human intervention, and it is dependent on the data coming from the aircraft navigation system. The ADS-B signals are received by the available sensors, which are connected in the Air Traffic Management (ATM) network. These sensors are usually deployed on ground in the proximity of the ATC. However, as the under-the-horizon transmission is not feasible, ground-based ADS-B receivers cannot accurately receive signals from flights passing over areas without ground stations, such as in the middle of the oceans or in the Arctic regions. As a result, a large part of the airspace still remains unsupervised [31], [32] and the ground stations become congested by the workload they are required to process. For these reasons, during the last years, it has been proposed to implement space-based ADS-B receivers using a LEO constellation of small satellites which become part of the complete ATM relay network. In this way it is possible to achieve a low latency and secure global ADS-B coverage [31], [33]. An illustration of a satellite-based ADS-B system is shown in Fig. 4. Some specialized companies offer the services of satellite based ADS-B reception and networking, such as SPIRE [34] and Aireon [35].

2) Maritime Automatic Identification System (AIS): The AIS is currently used on ships as a short-range tracking system and it is regulated by the International Maritime Organization (IMO) [36]. It provides the vessels and the shore stations with information on identification and positioning in real-time in order to avoid ship collision accidents. Despite having been specified in the late part of the twentieth century, it has only gained popularity over the last decade due to the use of satellite-based receivers which provide global coverage, improved response times and more reliability [37]. Space-based AIS receptions open the possibility of unmanned transoceanic journeys, convenient for the transport of hazardous materials, which consequently enables the elongation of the duration of non-time-critical journeys, optimizes the fuel consumption or even allows the direct use of electrical or solar power [38], [39]. Additionally, these satellites serve as supplementary data sources for vessels and coastal authorities in busy port areas where conventional AIS receivers may not be able to cope with the large volume of ocean traffic [40]. Satellite-based AIS provides an easy way for collecting AIS data on a global scale in almost real-time [41]. Commercial exploitation of space AIS has been carried out during the last decade by companies such as SpaceQuest, Elane, ExactEarth, Marine Traffic, ORBCOMM, and SPIRE [34]).

D. Earth Observation Data Collection

Traditionally, Earth Observation (EO) has been used by Governmental or International agencies to report the weather, monitor the oceans, detect changes in vegetation and analyse the damage done by natural disasters, like earthquakes or hurricanes. It provides objective data on what really happens, showing trends and changes over time in a way that can never be observed from the ground.

However, in the last few years, the space industry is experiencing a trend towards investment in so-called “agile” space activity as opposed to traditional “big space” governmental programs. Agile space has the potential to open up the space program to a wider, more flexible range of players, such as universities, companies and developing countries. The agile space sector is broadly split into two segments: upstream and downstream. The upstream space is focused on hardware, launchers, rockets and satellites, whereas the downstream space data activities take information from the upstream and turn it into useful applications for business.

Private space data collection and space data analytic companies, like SPIRE [34], are proposing new types of services by combining together satellite technology to collect information and modern data analysis techniques (e.g., machine learning). A field where satellite information collection and machine learning data analytics can be very effective is the field of logistics. Consider, for instance, the task of monitoring the number of containers that are moved in a harbor during the day. An effective way to accomplish this objective is to take pictures of the harbor container storage zone trough a fleet of small LEO satellites. Then, these pictures are sent back to Earth, where they are processed using some machine learning technique in order to efficiently count the number of containers that have been moved between the different satellite passages. This allows to get a count of the total number of containers moved in that harbor during the day [42].

While the LEO orbits guarantee some advantages for EO purposes, they also pose some challenges from the telecommunication point of view. First of all, satellites in LEO orbit move relatively fast and because of this they can guarantee coverage of a certain area only for a few minutes each of several hours. Hence, to guarantee continuous coverage a large fleet of satellites is needed. For the same reason, a Gateway (GW) can stay in contact with the satellite for a very limited amount of time. To guarantee full-time connectivity between the ground and the satellites' fleet either a large number of GWs must be built all around the globe, or inter-satellite link (ISL) capabilities must be implemented in the satellites. More details on this matter can be found in Section IV-B.

E. Space Communications

Telecommunications play a fundamental role in space exploration. Seeing Apollo 11 land on the Moon, downloading Pluto's pictures from New Horizon, receiving scientific data on 67-p/Churyumov-Gerasimenko comet from Rosetta, commanding Voyager 1 to turn its camera and take a photograph of Earth from a record distance of about 6 billion kilometers- all these and many other incredible achievements would have been impossible without very efficient communication systems between us and our space explorers.

The Space Exploration age began in 1957 with the launch of the Sputnik, and until now it has been carried out mainly by either robotics missions or by very short human missions outside the Earth orbit, as in the case of the Apollo Program. The paradigm shift that we see today in space activities is best encapsulated by the term 'Space 4.0,' where the different space agencies are planning to have a stable human presence in other celestial bodies of our solar system. One of the most promising in this sense is the 'Moon Village' concept developed by ESA [43], which seeks to transform this paradigm shift into a set of concrete actions and create an environment, where both international cooperation and the commercialisation of space can thrive.

Such an ambitious goal can only be achieved, if high-capacity and very reliable communication links between Earth and these human outposts in the solar system are established. For this, novel techniques are needed from the telecommunications perspective, in order to overcome the specific telecommunication challenges that arise in Deep Space Communication scenarios, as a result of the tremendous distance between the Earth and the spacecraft. This, together with the limited power that a spacecraft is able to generate far from the sun, bring new telecommunication needs, which are quite different from the ones on Earth. More details regarding the challenges of Deep Space Communications and their respective solutions are provided in Section V-E2.

IV. SYSTEM ASPECTS

This section covers the system aspects of a satellite communication system. Some preliminaries regarding SatComs are included, especially related to the constellation types and communication architecture, in order to introduce terminology and facilitate the reader to follow the material flow. Then we focus on other relevant topics, such as the interface of SatComs with other systems, spectrum utilization and standardization.

A. Constellation Types

A fundamental aspect of satellite constellations is the orbit's altitude, which severely affects the latency of the communication, the signal attenuation and the coverage. As anticipated, three basic orbit configurations are LEO, MEO, and GEO. The respective altitude ranges are 500 to 900 km for LEO, 5,000 to 25,000 km for MEO, and 36,000 km for GEO [45]. A GEO satellite can cover about one third of the Earth's surface, with the exception of the polar regions. This coverage includes more than 99% of the world's population and economic activity. The LEO and MEO orbits require more satellites to achieve such global a coverage, since non-GEO satellites move in relation to the surface of the Earth, hence a higher number of satellites must be operating to provide continuous service.

Another relevant characteristic of satellite orbits is the eccentricity. While for most SatCom services the orbits are circular, there are cases of elliptical orbits with high eccentricity, typically referred to as highly elliptical orbits (HEO). Examples of inclined HEO include Molniya orbits and Tundra orbits. Such extremely elongated orbits have the advantage of long dwell times at a point in the sky during the approach to, and descent from, apogee. Bodies moving through the long apogee dwell appear to move slowly, and remain at high altitude over high-latitude ground sites for long periods of time. This makes these elliptical orbits useful for communications towards high latitude regions.

In general, in the design of a satellite constellation for SatCom services, it is important to assess a number of parameters and to evaluate their respective trade-offs. While high altitude constellations, such as the GEO ones, allow a wide coverage, they suffer a much higher latency and propagation path loss compared to the lower altitude ones. Furthermore, satellites at lower altitudes move faster, which leads to higher Doppler frequency offset/drift and can be crucial for the design of the user equipment, especially for wideband links, as described in Section V-D2. Concerning the cost of constellations, the principal parameter is clearly the number of satellites, thus it is important to achieve the desired performance keeping this number as low as possible. Also, the number of orbital planes affects the overall cost, as changes require large amounts of propellant. Ultimately, once the constellation altitude is selected based on the specific service to be provided, the constellation design aims at guaranteeing coverage in the regions of interest, using the lowest possible number of satellites and orbital planes. After that, the satellite payload and architecture are designed by taking into account the system requirements.

B. Communication Architecture

The basic structure of a satellite communication system consists of a space segment that includes the satellite constellation, a ground segment including GW stations and large ground facilities for control, network operations and backhauling, and a user segment with the user terminals deployed on fixed and mobile platforms (e.g., airplanes and ships), see Fig. 5.

The control of the satellites is performed by the so-called Telemetry, Tracking and Control (TT&C) stations. The main task of TT&C stations is to monitor the status of the satellite sub-systems, run tests and update the configuration. Such control mechanisms are needed for maintenance purposes and in order to keep the satellites on the respective orbits. Correspondingly, the operation of TT&C stations falls into the responsibility of the satellite operator. In contrast, the GW

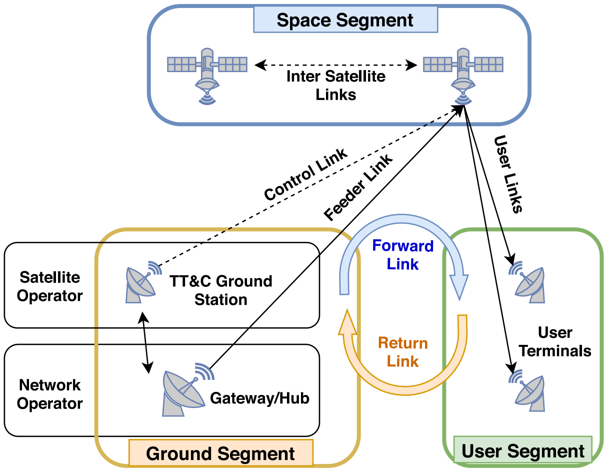


Fig. 5. SatCom System Architecture.

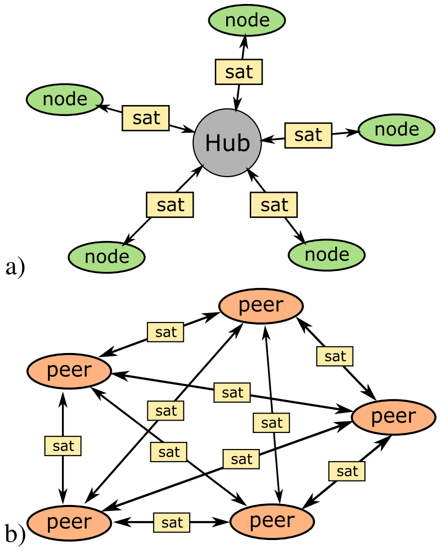


Fig. 6. Communication topology: a) star; b) mesh.

stations are run and maintained by the network operator, since they manage the network access and backhauling. For more information on the ground segment, we refer to [46].

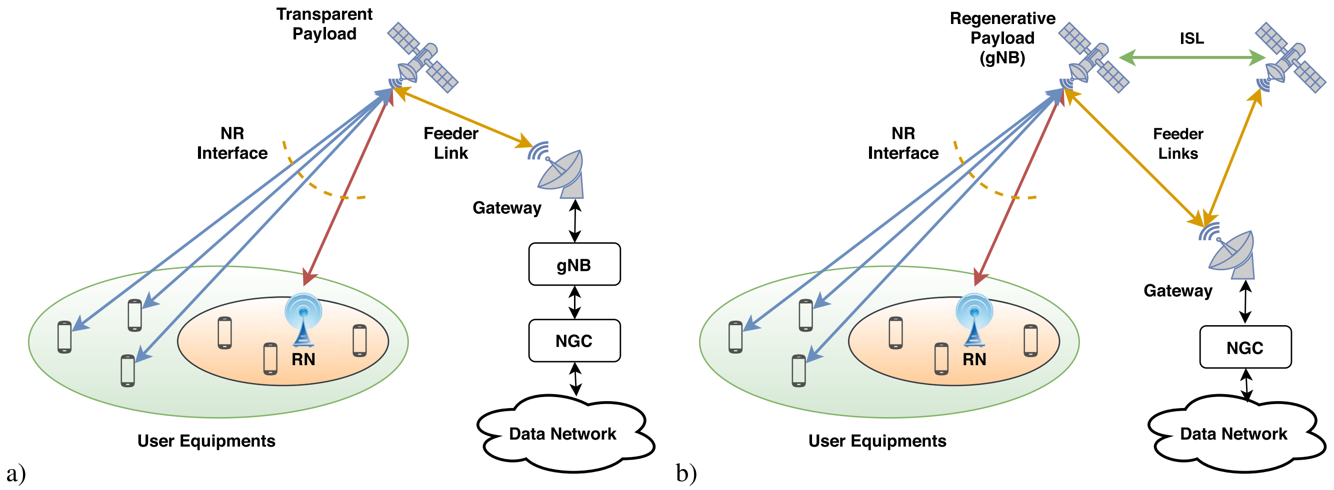
The two typical topologies are star and mesh. In both cases, the satellite acts as a relay between each node and the hub (backhaul) or between multiple peer nodes, respectively. Here, we differentiate between point-to-point and point-to-multipoint transmissions. The point-to-multipoint connectivity as in traditional broadcast services, Internet connections via satellite and data collection from the sensors deployed on the earth surface, the star topology is used, where each terminal is connected to the hub via a satellite on a single-hop basis, see Fig. 6a). The data collection from the sensors deployed on board the satellite (e.g., in earth observation applications), can be viewed as a special case of star topology, since the satellite acts both as a relay and as a signal source. For point-to-point connectivity as in video conferencing, the star topology would imply two-hop transmissions, which might be crucial with respect to the end-to-end packet transmission latency. Hence, the mesh topology is usually preferred, where each peer node can communicate with another peer node via a satellite relay, see Fig. 6b). However, this topology may require an intelligent routing of data packets by the satellite. As an example, the mesh topology is employed by AIS (see Section III-C2).

In order to enhance the performance of satellite constellations, ISLs can be created, such that multiple satellites can cooperatively accomplish complicated missions. The implementation of the ISLs can be done using traditional RF antennas or optical wireless technology. The latter is beneficial due to the narrower beams generated by the employed lasers. A distinct advantage of this technique is the substantially reduced antenna size. The link can be established between multiple satellites of the same orbit (e.g., LEO-LEO) as well as between satellites of different orbits (e.g., GEO-LEO). The coexistence of multiple satellites belonging to different orbital planes with coordinated and uncoordinated access is very challenging and, therefore, plays an important role in the system design/operation. We will discuss the inter-plane access technology in more detail in Section VI-C.

C. Interface With Other Systems

1) Interface With xG Systems Through NTN: From the system level point of view, in order to create an interface between the satellite and the 5G network, various architecture options have been identified within the 3GPP studies for NTN [10]. The different architecture options are categorized based on the payload type (e.g., transparent or regenerative) and the user access link type (direct or non-direct), as illustrated in Fig. 7. In case of a transparent payload, the satellite provides connectivity between the users and the base station, which is on ground. On the other hand, in case of a regenerative payload, the base station functionalities can be performed by the satellite. This option, even though it is more complex, would improve significantly the round trip time (RTT) of the communication. In addition, due to the regenerative payload, an ISL can be also established, which would be beneficial for hand-over procedures in case of a satellite constellation. Both architecture options can ensure direct or non-direct access to the user equipment (UE) on ground. In the latter case, the access link to the users is provided by the relay nodes (RN), which are then connected to the base stations through the satellite link. The functionality of the RN and the air interface for the link between base stations and the RN is still under definition in the 3GPP. However, assuming that they would have a similar role as the RN in the Long Term Evolution (LTE) network, they can simplify the integration of the satellites in the 5G network, by aggregating the traffic coming from many users on ground. For interested readers, [47] provides a more detailed explanation of each component in these architecture options, whereas the challenges of a 5G satellite-terrestrial network integration and possible solutions can be found in [48], [49].

2) Interface With the Cloud Through a Ground Station Network: As already mentioned in Section II-A, it is expected that in the near future thousands of satellites will be in the LEO orbit. Therefore, the amount of data to be collected by these satellites will be tremendously high. In order to have access to this data, the interested customers must either build their own ground stations and antennas, or lease them from ground



a)

b)

Fig. 7. 5G-NTN architecture options with a) transparent payload; b) regenerative payload.

station providers. In addition, servers, storage and routing capabilities are needed in order to store, process and transport the data coming from the satellite. This requires a significant investment since the cost of each of the above-mentioned components is high. Through a Ground Station Network that can be shared among the various constellations, the data can be collected from the numerous satellites orbiting the Earth and stored in a central cloud. In such a case, the interested customers will only need to access the cloud, without the need for a long-term investment towards a personal ground station infrastructure. A typical example of such a system is the AWS Ground Station, which is an initiative launched by Amazon. An illustration of the system architecture is shown in Fig. 8. Such a cloud based service solution not only lowers the cost of sending data from space to Earth, but also it significantly reduces the data access delay [50].

D. Spectrum

Satellite communications operate in the Extremely High Frequency (EHF) band, in particular between 1-50 GHz. Different frequency bands are suitable for different climate conditions, types of service and types of users. For simplicity, the frequency bands used for satellites are identified by simple letters: (i) Lower frequencies (L, S, X and C-bands), and (ii) Higher frequencies (Ku, K, Ka, Q/V bands). A schematic illustration of the satellite spectrum is provided in Fig. 9.

Radio navigation systems, like GPS or Galileo, operate in the L-band. The S-band is used for weather radar, surface ship radar, and some satellites, especially those of NASA for communication with the International Space Station (ISS) and the Space Shuttle [51]. L and S bands are also used for TT&C. In particular, the frequency bands between 2-2.3 GHz are shared co-equally by the space research, space operation, and EO satellite services [52]. Clearly, there is not much bandwidth available in the lower bands, so it has become a costly commodity.

Satellite communications, especially TV broadcasting, predominately operate in the C and Ku bands. Because of recent developments in satellite communications [53], [54] together with the conventional fixed spectrum allocation policy, the congestion of C and Ku bands has become a serious issue. To enhance the spectral efficiency and leave room for new broadband applications, satellite systems have moved from single-beam to multi-beam satellites with smaller beam spots. Aggressive frequency reuse schemes have been shown to be a promising approach towards enhancing the spectral efficiency of satellite communications (see Section V-C2).

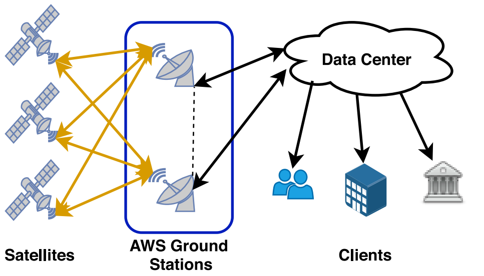


Fig. 8. AWS Ground Station System Architecture.

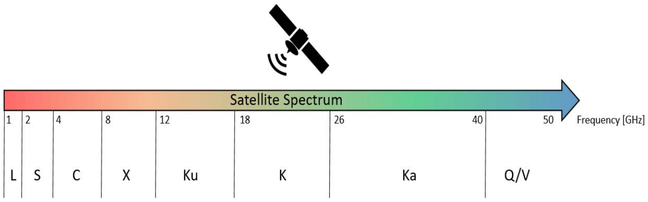


Fig. 9. Satellite spectrum.

Due to the spectrum scarcity, satellite operators are moving from the conventional C-band and Ku-band to the Ka-band, which offers much greater signal bandwidth than the C and Ku bands altogether. However, the Ka-band systems are much more susceptible to adverse weather conditions than the Ku-band ones and especially C-Band ones. On the other hand, moving to higher frequencies allows for smaller antenna sizes, thus promoting the use of multi-antenna systems (Section V-B).

The success of 5G heavily depends on national governments and regulators, as they are responsible to provide the new spectrum bands and operational guidelines for 5G deployment. The main representatives of the digital technology industry have released a list of recommendations on the commercial spectrum for 5G in Europe [55], where the frequency band 3400-3800 MHz (C-band) is identified as a potential candidate for the initial deployment of 5G mobile service. The C-band spectrum has been traditionally reserved exclusively for satellite use and the reallocation of C-band spectrum to other telecommunications would inevitably have an impact on the satellite systems. In this regard, the C-band should be carefully assigned to new 5G systems so as to ensure the continuity of vital satellite communication services. In this context, it is worth citing the recent developments in EEUU, where a satellite alliance is proposing ways to clear the C-band spectrum and to accommodate the 5G wireless services [56].

Regarding the feeder link, moving from the Ka-band to the Q/V-band (40/50 GHz) has been investigated as a solution to the Ka-band congestion [57]. This migration not only frees-up the whole Ka-band spectrum for the user link, but also provides higher bandwidth for feeder links that can accommodate a broadband High Throughput Satellite (HTS) system. Unfortunately, weather impairments heavily affect the Q/V band, claiming for the use of GW diversity techniques to ensure the required availability [58], [59].

To solve the spectrum scarcity, Cognitive Radio (CR) is a well-known spectrum management framework, as it enables unlicensed systems to opportunistically utilize the underutilized licensed bands. Within the satellite communications context, CR has been considered in [60], [61], where the non-exclusive Ka-band (17.7-19.7 GHz for Space-to-Earth and 27.5-29.5 GHz for Earth-to-Space) is considered for spectrum coexistence between incumbent terrestrial backhaul links and the non-exclusive satellite links. In order to further improve the capacity and reliability of mobile wireless backhaul networks, the concept of a seamlessly Integrated Satellite-Terrestrial Backhaul Network (ISTB) has been proposed in [62]–[64]. In ISTB, the satellite and the terrestrial system intelligently collaborate not only to enhance the backhaul network capacity but also to overcome the current spectrum scarcity while reducing the spectrum licensing costs. In both CR and ISTB scenarios, spectrum coexistence results in undesired interference which needs to be carefully addressed to truly leverage the full potential of such schemes (e.g., [65]–[67]). For more information on system coexistence scenarios, the reader is referred to Section VI-C.

E. Standardization

Standardization is also an important aspect of all the telecommunication systems. The usage of common open standards is fundamental to guarantee interoperability between devices from several manufacturers on both the transmitter and the receiver side. This reveals an open market with different manufacturers competing to offer the best possible devices in order to acquire more market shares. Apparently, this is hugely beneficial for the development of the technology and also for consumers. The main set of standards for SatComs can be found hereafter.

1) DVB: Digital Video Broadcasting (DVB) [68] is a set of international open standards for digital television. DVB standards are maintained by the DVB Project, an international industry consortium, and are published by a Joint Technical Committee (JTC) of the European Telecommunications Standards Institute (ETSI), the European Committee for Electrotechnical Standardization (CENELEC) and the European Broadcasting Union (EBU). The DVB standards are recognized as the most important set of standards for Television Broadcast and are widely used around the World, well beyond the European Border where the standards were originally developed. The DVB standards cover different TV broadcasting technologies from satellite to cable to terrestrial television. They cover both the physical and the data link layer of the ISO-OSI stack. The most important standards developed by DVB for the Physical Layer are: i) DVB-S, DVB-S2 and DVB-S2X for Satellite TV; ii) DVB-C and DVB-C2 for cable TV; iii) DVB-T and DVB-T2 for terrestrial TV. For the second layer of the ISO-OSI stack, the most important DVB standards are: i) DVB-MPEG and ii) DVB-GSE.

2) 5G NTN Standardization: The standardization of 5G, like the previous mobile communications generations, is led by the 3GPP. Traditionally, satellite and terrestrial standardization have been separate processes. However, in the recent years, there has been an increasing interest from the satellite communication industry in participating in the 3GPP standardization effort for 5G, due to the market potential of an integrated satellite-terrestrial network. As a matter of fact, 3GPP initiated in March 2017, as part of Release 14, a study item in order to analyse the feasibility of satellite integration into the 5G network [12]. Two study items have already been concluded [9], [10], where the role that the satellites can play in the 5G ecosystem has been studied. In addition, the challenges of a satellite-terrestrial network co-existence have been analysed taking into account different architecture options and all the layers of communication. After two years of a study phase, it is now approved from the 3GPP that NTN will be a new key feature of 5G and a work item (WI) will start from January 2020 [11]. It is agreed that as a starting phase only the LEO and GEO satellite orbits will be considered having a transparent payload. Last but not least, initial studies on the support of IoT technologies, such as Narrowband Internet of Things (NB-IoT) and enhanced Machine Type Communications (eMTC), will be performed.

3) CCSDS: The Consultative Committee for Space Data System (CCSDS) was established in 1982 by the major space agencies of the world to provide a forum for solving common problems in the development and operations of space data systems. CCSDS develops recommended standards and practices for data and communications systems with two main aims: to promote interoperability and cross support among cooperating space agencies, so reducing operations costs by sharing facilities, and also reduce the costs performing common data functions, by eliminating unjustified project-unique design and development within the various agencies. On the official CCSDS website, [69], all the standards and practices developed by the CCSDS are published and they are available for free. The Architectural Overview in Fig. 10 shows

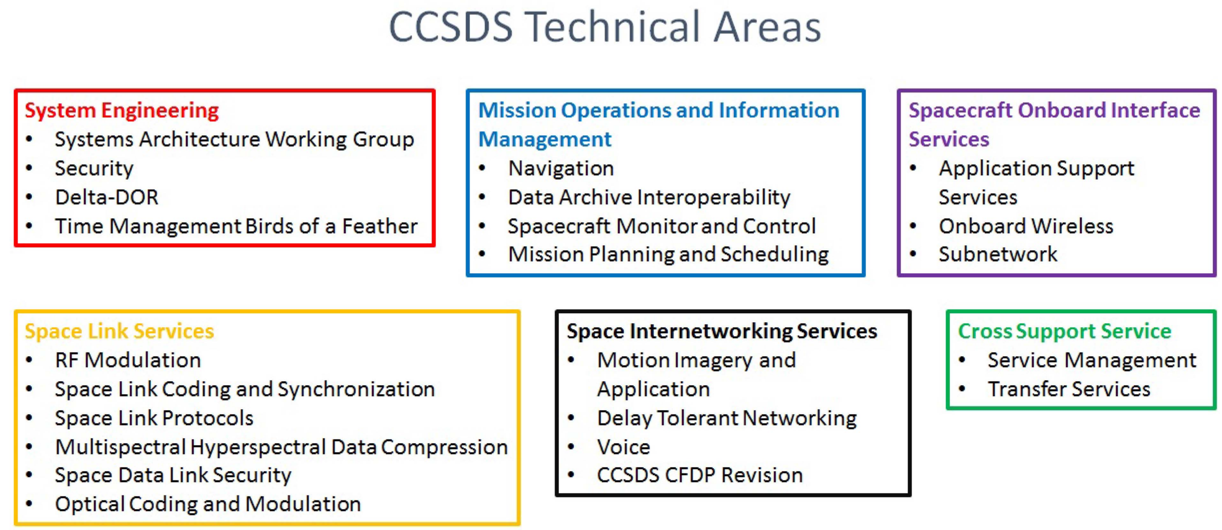


Fig. 10. Areas and Working Groups (topic) that are currently developing new standards in CCSDS.

the Areas and Working Groups (topics) that are currently developing new standards in CCSDS.

V. AIR INTERFACE: ENABLERS & TOPICS

This section covers the main technical features related to the air interface of SatComs, including channel modelling, antenna design, and PHY layer aspects enabling ultra high throughput satellite systems and data collection. Lastly, other relevant topics are considered, covering optical and deep space communications.

A. Channel Modelling

Channel and propagation characteristics play a key role in dictating the system design. These aspects are typically determined by the frequency of operation in addition to the system configuration. As analyzed in Section IV-D, the satellite communication systems utilize a wide range of frequencies, hence resulting in different channel models [70]. In the following, we present a canvas of the channel models encountered in satellite communications.

1) Fixed Satellite: The next generation satellite systems would be typically operating at frequencies higher than 10 GHz. According to [70], such channels are characterized by line-of-sight (LoS); the satellite channel essentially corresponds to an Additive White Gaussian Noise (AWGN) channel. However, on top of this, the propagation at the Ku and, especially, at the Ka-band is subjected to various atmospheric fading mechanisms (see [70] for details). These effects can be modelled as,

- *Long Term Channel Effects:* The key constituents to this category include, attenuation due to precipitation, gaseous absorption and clouds, tropospheric scintillation and signal depolarization among others. The models for such effects typically involve *first-order statistics* [70].
- *Dynamic Channel Effects:* These effects determine the temporal properties of the AWGN channel when impacted by rain. Such models allow for the calculation of several second-order statistics, such as fade slope and fade duration.

Clearly, the distance between the user terminal and the satellite is quite large compared to the distance between the antennas (either on-board or on the ground). This fact and the absence of scatterers near the satellite antennas, tend to make the fading among all the channels between the satellite and the user terminal correlated. This spatial correlation negatively impacts the use of Multiple Input Multiple Output Multiple Input Multiple Output (MIMO) for Fixed Satellites [70], [71]. Further, with regard to rain-fading, the ground terminals need to be several miles away to ensure a significant decorrelation of fading.

2) Mobile Satellites: As mentioned in [70], the channel characteristics in mobile satellite systems differ from their Fixed Satellite counterparts since mobility implies the presence of diffuse multipath components in addition to the direct path. The direct path is due to the tracking of the satellite by the mobile terminal and the multipath arises due to enhanced quantum of scatterers in mobility-induced changing environments e. g., foliage scattering, building reflection. Narrowband and Broadband channel models have been proposed in the literature. Typically, these models involve a multi-state Markov model, with each state determining the parameters and the nature of the distribution of the corresponding channel. As a case in point, ITU Recommendation P.681 [72] presents a narrowband 3-state Markov model with related state statistics. The states represent (i) a Deep shadow state, (ii) an Intermediate shadow state, and (iii) a good state with very slow variations. The severity of the mean attenuation increases with the shadow strength. Another approach for a narrowband 2-state land-mobile satellite channel model at 2.2 GHz is presented in [73]. This approach assumes a Loo distributed RX signal defined by a parameter triplet and the channel state statistics are determined by the User Terminal (UT) (vehicle) speed. Further, a wideband satellite channel model comprises the 2-state semi-Markov model for shadowing and the ITU multi-tap model [74] for the multipath propagation. Typically, the channel properties are assumed quasi-stationary over short-time periods, and during these periods they are represented by stationary stochastic processes.

B. Antennas

Antenna design is also an important aspect worth analyzing. Here we describe the main features of the passive and active antennas, while highlighting future trends on antenna design for satellite communication systems.

1) Passive and Focused Reflector Antennas: The shift from broadcast to broadband missions marks a transition from contour beam coverage, which is designed to serve a given geographical region, to multibeam antennas (MBAs) that by virtue of their narrower beams enable both higher gains and frequency reuse, thereby maximising the spectral efficiency. The corresponding evolution of traditional passive antenna architectures for GEO missions has driven the shaped reflector antennas towards single feed per beam (SFPB) and multiple feeds per beam (MFPB) MBAs [75], [76].

In SFPB antennas, each beam is produced by the illumination from a single feed. SFPB MBAs provide high gain and low side-lobe level thereby leading to an advantageous carrier to interference ratio. On the other hand, the SFPB architecture typically requires 3 or 4 reflectors to achieve contiguous coverage [75], [76], leaving little or no space to accommodate additional missions on the satellite.

In the alternative MFPB architecture, each beam is produced by a cluster of feeds. An advantage of MFPB is therefore that contiguous coverage can be achieved with one or two main reflectors [75], [76]. On the other hand, MFPB antennas require a more complex beam-forming network and can give rise to challenges in terms of, e.g., the operating frequency bandwidth or the lower aperture efficiency. Consequently, MFPB does not always represent the choice of preference within passive antenna architectures [77].

The SFPB and MFPB architectures outlined above have so far been the most widely used architectures for GEO High Throughput Systems [78]. The use of multiport amplifiers [79] is increasingly being deployed in these architectures to add flexibility in power allocation (e.g., Eutelsat 172B [80]). Larger reflectors enabled by deployable technologies are also being developed for delivering more directive beams for telecommunications and other missions [81]. Meanwhile, the pressing needs for flexibility in coverage and an ever-increasing number of beams is driving major efforts for the development of active array solutions [78], [82], [83].

2) Active Antenna Arrays: By definition, in active antennas the amplifiers are integrated with the radiating elements. A marking difference from passive antennas is, thus, the distributed amplification of the radiating signal. The spatial RF power distribution and the reduced peak RF power levels in active arrays improve reliability (including reducing multipaction thresholds [84]) and provide a graceful degradation. Recent developments in wide bandgap semiconductor technologies (e.g., GaN) are promising to improve the relatively low power and thermal efficiencies of MMIC amplifiers at the Ku-band and beyond [85], which is otherwise a natural choice for active arrays in place of the more traditional vacuum (travelling wave tube) amplifiers due to their advantageous integration.

Active antennas can be deployed in either direct radiating array (DRA) or array fed reflector (AFR) architectures. The choice and the associated trade-offs strongly depend on the system requirements. For LEO and MEO systems, the large field of view coupled with the reduced demands on gain favor DRA solutions. For GEO HTS missions, the large electrical sizes required to achieve the gain targets are preferentially achieved with reflector-based geometries that provide a magnification of the radiating aperture [82]; the best active array architecture for GEO thus remains an open question [78].

Reducing the number of active elements in an array provides advantages in terms of cost, complexity, thermal management as well as of digital demands for the control of the phased array. Since the gain of an antenna is strongly linked with the size of the illuminating aperture, one technique to reduce the number of elements in an array without reducing the overall surface area is to increase their size. The antenna array theory suggests that in this case grating lobes are likely to appear [86]. In multibeam satellite systems, grating lobes can be tolerated as long as they do not compromise the system performance, primarily due to causing unwanted interference (e.g., typically by being kept outside the field of view of the Earth [78]). Depending on the orbit, this can provide some margin to increase the size of the radiating elements and thereby reduce their number for a fixed size of the illuminating aperture. An alternative approach for reducing the number of elements in an active antenna is based on array thinning techniques. The latter relies on sparse and aperiodic arrays, which provide opportunities for a trade-off between the side-lobe levels and the number of elements [87], [88]. A drawback of this approach is that the antenna development is in general bespoke to a mission and, thereby, complexity and costs do not necessarily scale down.

The realisation of lightweight and efficient reconfigurable antennas can also benefit from quasi-optical beamforming (QOBF) networks [90]–[92]. An example of this is the Rotman lens, where beamforming is achieved by virtue of the phasing propagated waves in a parallel plate waveguide [90]. A single Rotman lens offers beam steering along one axis, whereas two layers of stacked Rotman lenses offer the possibility to generate pencil beams that can be steered along 2 principal axes (see Fig. 11. a). An example of Rotman lens development for the GEO VHTS mission is presented in [91]. In order to remediate the complexities associated with the discrete antenna ports of the Rotman lens as well as the losses from the dielectric substrate, a continuous parallel plate waveguide lens-like multiple-beam antenna is presented in [92] (see Fig. 11. b). A prototype involving this beamformer targeting LEO/MEO missions (see Fig. 11. c) is presented in [89] and an analysis of the performance of this solution in the presence and absence of beam-hopping under varying traffic scenarios is presented in [93].

3) Trends in Antennas for LEO/MEO Missions and the Ground Segment: MEO and LEO satellites experience a

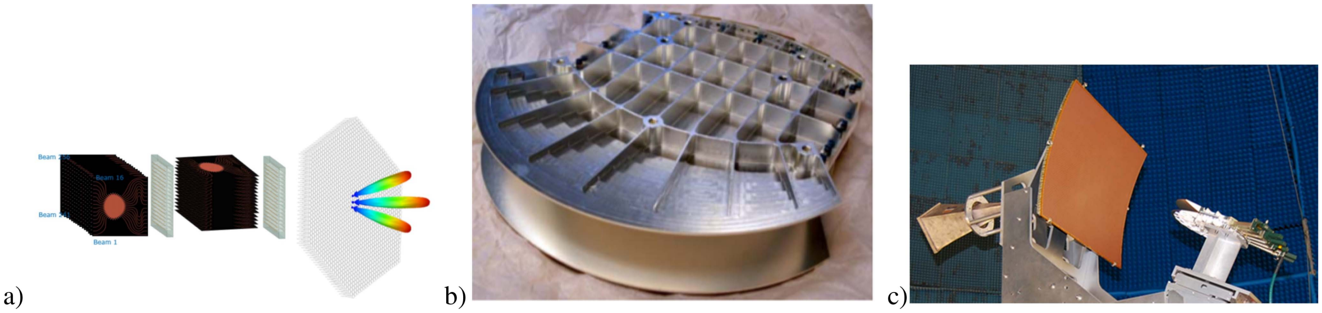


Fig. 11. a) Double layers of Rotman lenses producing pencil beams in two directions; b) Continuous parallel plate waveguide lens-like antenna; c) Prototype of a QOBF antenna [89].

spatial evolution of the traffic along the satellite orbit. Therefore, a reconfigurable antenna is needed to match the satellite coverage with the spatial distribution of the traffic. The LEO constellations by Telesat, Starlink and Akash are aligned with this approach [94]. The MEO constellation by O3B is also adopting a steerable beam approach [95]. For smaller platforms, such as cubesats, the priorities in terms of the antenna selection are defined by the mission specifics, such as the limited capacity for on-board accommodation. A review of antenna solutions for smaller satellite platforms (e.g., cubesats) can be found in [96].

The antenna design for ground terminals is also a rapidly evolving area of technology development. Of particular commercial interest remains the development of flat panel antennas with beam steering capability that enables satellite on the move (SOTM) applications as well as connectivity to non-GEO platforms [97]. A number of mechanical, electronic and hybrid approaches are reported in the literature, which are actively being pursued by a vibrant academic and industrial research community. They typically use two narrow-width arrays on a 2-axis positioner for tracking in azimuth and elevation. A significant disadvantage with this type of antennas is the broad beamwidth along the narrow plane of the aperture, which can lead to interference problems [98]. A mechanically steerable flat panel antenna product that overcomes the aforementioned high skew angle problem [98] and has successfully been deployed in the avionic industry is provided by [99]. Alternative approaches that target to maintain performance while reducing costs include the use of nematic liquid crystals [100].

C. Ultra High Throughput Satellites (UHTS)

In this section, we cover the key enablers of the UHTS system from the PHY layer perspective, including digital payloads, precoding techniques and non-orthogonal multiple access.

1) Digital Payloads: Due to the diversification of markets, satellite communications need to meet the increasing demand for a reliable and flexible connectivity at higher throughputs. Novel architectures like multibeam systems, migration to higher frequencies and novel techniques such as precoding, predistortion, interference and resource management have already been considered [54]. To fully exploit these developments in the emerging contexts, and to impart flexibility in the design, additional resources need to be considered. In this context, space-based assets are considered with on-board processing (OBP) being the widely accepted methodology.

Providing digital processing on-board the satellite is not a new concept; it has been discussed for many decades [101]–[103]. A perusal of the literature indicates two key OBP paradigms.

- *Digital Transparent Processors (DTPs):* These processors sample the waveform and operate on the resulting digital samples; neither demodulation nor decoding is implemented [102]. DTP based processing results in payload designs agnostic to air-interface evolutions. DTPs have been used in a number of missions including INMARSAT-4, SES 12 [104]. Typical applications include digital beamforming and broadcasting/multicasting based on single channel copies.
- *Regenerative Processing:* This methodology operates on the digital baseband data obtained after waveform digitization, demodulation and decoding. Missions, like Iridium, Spaceway3 and HISPASAT-AG1, incorporate regenerative processing mainly for multiplexing different streams, switching and routing. While regeneration generalizes DTPs and decouples the user and feeder links, the additional processing comes at a higher cost. Further, regenerative processing limits the flexibility to use newer transmission modes and can suffer from obsolescence of technology unless reprogrammable payloads are considered [102].

An interesting hybrid processing paradigm involves digitizing the entire waveform, but regenerating only a part for exploitation. In this context, the header packet is regenerated to allow for on-board routing [102]. This capability would radically change satellite networks and the services they can deliver.

For the sake of exposition, in the following, we briefly present the structure of a DTP. It is based on the detailed work in [105] and extended to cover novel processing.

Fig. 12 presents a payload transponder employing DTP. Standard analog front-end receiver processing including antenna systems, analog beamforming network, low noise amplifiers, down conversion (mixer, filter) and automatic gain control that appear before the digital processing are not detailed. The key components in OBP are listed below; the reader can refer to [54], [105] for further information.

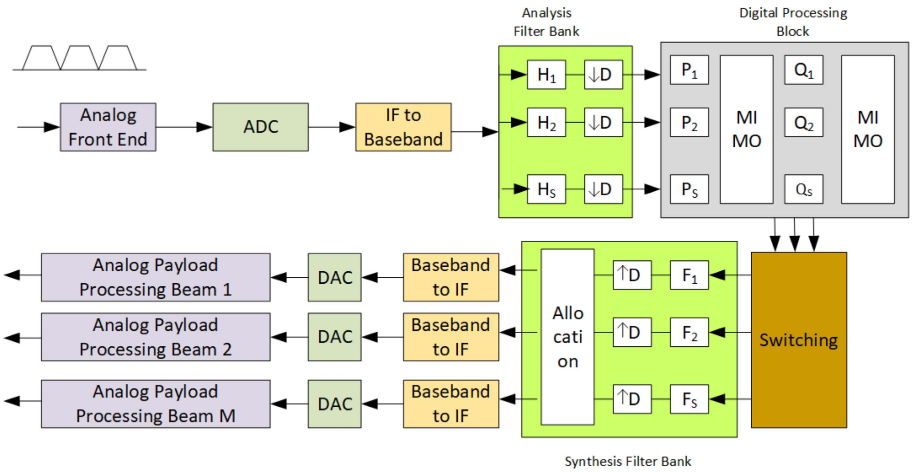


Fig. 12. On-board processing architecture [54].

- High Speed Analog to Digital Converters (ADC) and Baseband/IF Conversion.
- Channelizers comprising an analysis filter bank for demultiplexing uplink signals and a synthesis filter bank to regenerate appropriate bands.
- A processing block that includes processing of individual streams like (de)modulation, decoding/ encoding as well as joint processing using the MIMO technique. It also includes a Look-up Table (LUT) for predistortion, beamforming, precoding and spectrum calculation.
- A switching block affects routing in spatial (e. g., from one beam to another), temporal (e.g., store and forward) and spectral (e.g., frequency hopping) domains.

As mentioned earlier, on-board processing with digital payloads are being considered by satellite manufacturers and operators. With the emergence of novel signal processing and digital communication techniques, digital payloads offer an ideal platform to overcome many of the shortcomings of traditional on-ground processing. This includes reducing the latency and the inefficient use of resources, as well as enabling additional flexibility among others [54]. Some examples of application involve on-board predistortion [106] and energy-detection [107].

The payload is often seen as part of the end-to-end channel and its behaviour should be regularly measured. The so-called In-Orbit-Test (IOT) operation of the satellite payload consists in transmitting and receiving to and from the satellite a specifically designed test signal, mainly a spread spectrum signal, for the measurement and extraction of some key payload parameters such as, on-board filter responses, high power amplifier response, G/T, etc. The IOT operation is fundamental in several situations during the life-time of the satellite to verify and monitor the performance and functional requirements of the satellite payload.

Techniques to effectively monitor the on-board amplifiers and to identify possible degradation effects are open research topics with no definite solution at the moment, in particular when dealing with wideband applications. In the latter, reducing the testing time and improving the accuracy of existing narrow-band-based techniques are of key importance. Because conventional IOT methods require the interruption of the main customer service [108], novel cognitive techniques based on spread spectrum signals are gaining momentum [109]–[111].

2) Precoding/MU-MIMO: The state-of-the-art in high throughput SatCom relies on multi-beam architectures, which exploit the spatial degrees of freedom offered by antenna arrays to aggressively reuse the available spectrum, thus realizing a space-division multiple access (SDMA) scheme [113]. As a matter of fact, aggressive frequency reuse schemes are possible only if advanced signal processing techniques are developed, with the objective of handling the multi-user interference (MUI) arising in multi-beam systems and deteriorating their performance. Such signal processing techniques are commonly referred to as multi-user multiple-input multiple-output (MU-MIMO) and, in the satellite context, also as multi-beam joint processing [54]. In this context, linear precoding (or beamforming) techniques have been a prolific recent area in the recent years, showing to be an effective way to manage the MUI while guaranteeing some specific service requirements [114]–[118]. The benefits of using precoding techniques for managing the interference at the gateway in SatComs are also considered in the most recent extensions of broadband multi-beam SatCom standards [119]. The conventional precoding approach exploits the knowledge of the channel state information (CSI) in order to design a precoder to be applied to the multiple data streams, thus mitigating the MUI. With the aid of precoding, a satellite user terminal can obtain a sufficiently high signal-to-interference-plus-noise ratio (SINR), even though the same bandwidth is reused by adjacent beams. This is possible because the precoder uses the channel knowledge to mitigate the interference toward the user terminals, and, therefore, a certain SINR value can be guaranteed for the users. Typically, the precoding matrix is computed at the satellite gateway. After that, the beam signals are precoded (by multiplying the data streams by the precoder matrix) and transmitted through the feeder link using a frequency division multiplexing scheme. A schematic representation of the precoding operation, taking place at the gateway, is shown in Fig. 13. Then, the satellite payload performs a frequency shift and routes the resulting radio signal over an antenna array that

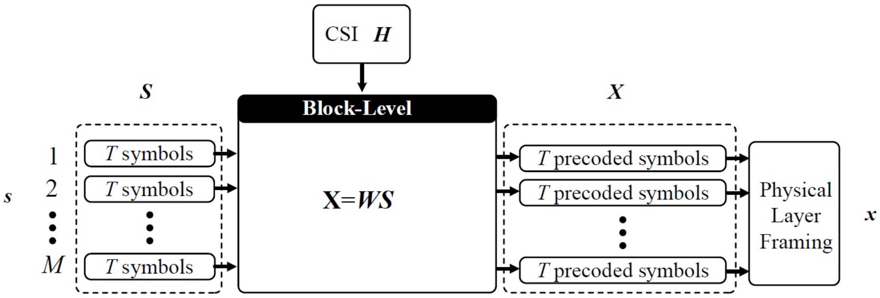


Fig. 13. Schematic diagram for conventional linear precoding [112]. The CSI is used to compute the precoding matrix, denoted as *W*. The precoding matrix is then used to filter the input data streams.

transmits the precoded data over a larger geographical area that is served by the multiple beams in the user link. It should be stressed that the signals transmitted for different beams in the downlink (i.e., from the satellite to the user terminals) use the same bandwidth in a full frequency reuse fashion. This is made possible by the described precoding operation which counteracts the interference across multiple beams.

The computational complexity that is required to implement multibeam satellite precoding techniques can be considerable when the dimensions of multibeam satellite systems are high. This is often the case, as many current systems are characterized by several hundreds of beams. This complicates the precoding implementation because of the extremely large size of the precoding matrix that must be calculated. In this regard, low-complexity linear precoding techniques are of great interest, and this is a problem that deserves further attention and research.

A different precoding strategy, known as symbol-level precoding, has been considered more recently in the literature [120]. In this approach, the transmitted signals are designed based on the knowledge of both the CSI and the data information (DI), constituted by the symbols to be delivered to the users. Since the design exploits also the DI, the objective of symbol-level precoding is not to eliminate the interference, but rather to control it so as to have a constructive interference effect at each user. This approach has been shown to outperform the conventional precoding schemes in terms of reduced power consumption at the gateway side for a given quality of service in terms of SINR at the user terminals.

A fundamental assumption of conventional precoding schemes is that independent data is addressed to each user, thus dealing with multiuser unicast systems. However, the physical layer design of the DVB-S2X SatCom standard [119] has been optimized to cope with the noise-limited satellite channel, characterized by excessive propagation delays and intense fading phenomena. Therefore, long forward error correction (FEC) codes and fade mitigation techniques that rely on an adaptive link layer design, e.g., adaptive coding and modulation (ACM), have been employed. This implies that each frame accommodates several users, and therefore the communication system becomes a multicast one. Accordingly, the multicast framing structure hinders the calculation of a precoding matrix on a user-by-user basis, and ad-hoc precoding schemes need to be employed to address multicast systems. Precoding schemes for physical layer multicasting have been proposed in [121]–[124].

Another relevant challenge for the application of precoding in practical satellite systems is related to non-linearities. In fact, the on-board per-antenna traveling-wave-tube amplifiers (TWTAs) usually introduce non-linear effects, which result in a distortion on the transmitted waveforms. A typical solution to this problem in single-user links relies on predistortion techniques, but their extension to multi-beam systems relying on precoding is not straightforward, because of the mutual correlation between the data streams induced by the precoding schemes. In this context, various precoding schemes have been proposed in the literature [120], [125]–[127], with the aim to enhance the dynamic properties of the transmitted signals, such as the peak-to-average power ratio (PAPR), and therefore, to improve the signal robustness to non-linear effects. In particular [120], [127] are based on symbol-level precoding.

Overall, the research on precoding has been developing quite fast in the recent years, and a number of practical challenges [112] have been addressed, with the aim of exploiting full frequency reuse in the current communication systems. In this direction, besides the pure research, it is of particular importance the development of ad-hoc testbeds that allow in-lab implementation and validation of precoding schemes. Considerable advances have been made in this regard, as further discussed in Section VIII.

3) Non Orthogonal Multiple Access:

As one of the promising 5G new radio techniques, the non-orthogonal multiple access (NOMA), has attracted considerable research attention from both industry and academia over the past few years [128]. NOMA breaks the orthogonality in conventional orthogonal multiple access (OMA) such that multiple terminals can access the same time-frequency resource simultaneously, which improves the efficiency of spectrum utilization. The resulted co-channel interference can be alleviated by performing multi-user detection and successive interference cancellation (SIC) at the receiver side. In various 5G terrestrial scenarios, NOMA has demonstrated performance improvements over conventional OMA schemes [128]–[131]. By observing its advantages in aggressive frequency reuse and suppressing interference, it is natural to further extend the NOMA applications beyond the cellular systems. For instance, the advanced television systems committee (ATSC) has proposed a new type of multiplexing scheme, i.e., layered division multiplexing

(LDM) which adopts the NOMA principle, in the physical layer protocol standard ATSC 3.0 for terrestrial digital TV broadcasting systems [132].

In NOMA-based multi-beam satellite systems, [133] analyzed the applicability of integrating NOMA to satellite systems from a system-level point of view, and provided general approaches for cooperating NOMA with precoding. In [134], two suboptimal user-scheduling algorithms were proposed to maximize the capacity for overloaded satellite systems. The numerical results showed that an appropriate user-grouping strategy is to pair the users with high-correlation channels. In [135], a max-min fairness optimization problem was studied to apply NOMA to achieve a good match between the offered and the requested capacity among satellite beams. The authors in [136] proposed an overlay coding strategy to utilize the cooperative NOMA to mitigate interference in multi-beam satellite systems.

In NOMA-enabled 5G terrestrial-satellite networks, [137] investigated a joint resource optimization problem for user pairing, beamforming design, and power allocation. In [138], joint beamforming and power allocation for NOMA-based satellite-terrestrial networks were studied. Optimal solutions of beamforming weight vectors and power coefficients were developed. In both works, the satellite component is viewed as a supplement part to the terrestrial networks. NOMA is applied within the terrestrial component. In [139], a cooperative NOMA scheme was proposed for satellite-terrestrial relay networks, where the user with a better channel gain is viewed as a relay to help transmit data to the user with a poorer channel condition. The outage probability and the ergodic capacity were analyzed mathematically and a performance improvement of NOMA over OMA was shown.

In general, the solutions developed for terrestrial NOMA systems might not be directly applied to satellite systems, mainly due to the following reasons. Firstly, different channel propagation models may lead to different user grouping strategies. Unlike the cellular system, the users located in a beam typically undergo similar path losses towards the satellite [54]. The user paring in terrestrial NOMA is performed by grouping the users with large gaps of their channel gains [128]. However, this paring strategy could be challenging to implement in satellite scenarios [134]. Secondly, simply applying the solutions developed for terrestrial NOMA may result in high complexity for the satellite systems due to the presence of a large number of beams. Thirdly, compared to cellular systems, some distinctive characteristics in satellite systems can introduce new constraints and challenges, e.g., on-board power constraints, limited power supply, longer propagation delays, signal distortion, and mobility issues. Fourthly, the capability of flexibly allocating on-board resources is typically limited, which introduces new dimensions in the NOMA-satellite resource management [135].

D. Data Collection

The PHY layer technologies that enable data collection from Earth (e.g., IoT sensors) or from space (e.g., EO) are also an important aspect worth considering.

1) Satellite IoT Air Interface: As mentioned in Section III, the satellite can play an important role in the IoT services, more specifically in the so-called long-range IoT or low power wide are networks (LPWANs), by ensuring global connectivity and service continuity. The three main technologies in the LPWAN family are NB-IoT, Long-Range (LoRa) and Sigfox [140]. Their PHY layer is quite different from each other and mostly driven by the need to satisfy important requirements, such as extended coverage, low power consumption and high network capacity. More specifically, NB-IoT uses a multicarrier modulation (OFDM in downlink and SC-FDM in uplink) for data transmission [141], SigFox utilizes an ultra-narrowband signal (UNB) with a differential binary phase shift keying (DBPSK) modulation [142] and LoRa employs a chirp spread spectrum signal (CSS) [143]. Since the satellite channel impairments are quite different from the terrestrial one, using the air interface of the terrestrial IoT over a satellite link in order to collect the tremendous amount of data generated by the IoT devices is not a trivial task. The increased delay in the satellite channel and the high amount of Doppler effects experienced, especially in the LEO orbit, imposes new challenges to the PHY interfaces of these technologies.

In this context, the authors in [144] stress out the impact of the Doppler effects on a LEO satellite-based NB-IoT system, while in [145] the LoRa CSS signal over a LEO satellite is analyzed. To overcome the Doppler effects in such systems, the authors in [146] come up with a new air interface for NB-IoT based on Turbo-FSK modulation, which was firstly introduced in [147]. Regarding LoRA, in [148] a new acquisition method under increased Doppler effects is analyzed, while in [149] a folded chirp-rate shift keying (FCrSK) modulation with strong immunity to Doppler effects is proposed. Other works in the literature focus on IoT over GEO orbits, where the main issue is the increased RTT. In [150] a new air interface for such a system is proposed while in [151] and [152] the authors present a novel waveform called Unipolar Coded Chirp Spread Spectrum (UCSS) that enables ultra-narrowband (uNB) communications of IoT nodes using a GEO satellite.

2) Wideband Downlinks: The commercial applications of satellite communication, such as observation satellites and LEO sensors, rely on extremely high data rates available during a short passage of the satellite. Hence, there is a recent trend of developing novel terminal modems capable of efficiently operating at very high symbol rates. One of the main challenges for the modem design results from the assumed very large signal spectrum, which can be, e.g., up to 1.5 GHz, if the whole Ka-band is utilized. Currently, the proposed terminal modems support up to 500 MHz for commercial high data rates, see [153]–[155]. In order to enhance the symbol rate even further, the following design challenges need to be circumvented:

- parallel processing with a very high factor of parallelism, which can lead to access conflicts and performance degradation;
- frequent trade-offs between performance, latency and complexity for the selection of signal processing and synchronization algorithms. In this context, the high

complexity may also lead to processing delays, which negatively affects the performance of the algorithms;

- high frequency selectivity of the wideband communication, which may result from the limitations of the hardware, in particular cables and transponders. The magnitude of this effect typically increases with the signal bandwidth;
- additional impairments due to the large difference between the minimum and the maximum employed frequencies. In particular, the clock frequency offset and drift due to the Doppler effect become substantial in wideband scenarios.

These challenges have been recently tackled in [156], where a novel modem architecture for terminal modems with a substantially wider target signal bandwidth of up to 1.5 GHz has been proposed. The potential peak symbol rate can reach up to 1.4 Gsps, such that peak data rates of 5 Gbps and higher seem to be possible in future.

E. Others

In this section, we discuss some other relevant technologies and enablers related to the SatComs air interface. Particularly, the topics included are the optical and the deep space communications.

1) Optical Communications: A potential solution for solving the high bandwidth requirements on the feeder link is to move them to the Q/V-band (40/50 GHz) [58], [59], or even to the W-band (70/80 GHz) where bandwidths up to 5 GHz are available. However, given the demand trends, it would be a matter of short time before which these links also fall short of the bandwidth requirement. A revolutionary solution is to move the feeder link from RF to optical frequencies [157]–[159]. Nevertheless, the high frequency RF and optical approaches are challenging due to the attenuation by atmospheric phenomena (e.g., rain, clouds) whose severity increases with the frequency. In either case, a network of multiple gateways with appropriate switching capabilities is thus envisaged [158], [160]. Although optical communications are highly impaired compared to their RF counterparts, they only need a few gateways to achieve a very high throughput [160]. This directly relates to a reduction in the cost of the ground-segment motivating the use of optical communications for feeder links. In addition, Free Space Optics (FSO) communications benefit from the absence of frequency regulation constraints, small systems with lower power requirements and enhanced security.

Optical links are impaired by several atmospheric phenomena like clouds, aerosols and turbulence [161]. The two main categories of propagation impairments are

- *Blockage Effects:* Cloud coverage constitutes the predominant fading mechanism, resulting in the blockage of the link [161]. This impairment is not localized but it is spread over a large geographical area. A cloud-blockage typically introduces significant attenuation on the link, potentially breaking the link. In order to maintain an optical link, the ground system design involves choosing ground-based optical stations at places with a high cloud free line of sight (CFLOS) joint probability [162], [163].
- *Turbulence and other small-scale fading effects:* Even under CFLOS conditions, the optical systems are severely affected by the atmospheric turbulence. This phenomenon leads to small-scale fading and impacts the link budget [164]. The estimation of this phenomenon taking also into account the beam wander, beam spread and amplitude scintillation is of critical importance [165]. In addition to turbulence, aerosols and cirrus clouds impact the signal amplitude as well [166].

Fade mitigation techniques are considered to mitigate the aforementioned impairments. These are categorized as:

- *Macro-Diversity:* For cloud coverage, multiple Optical Ground Stations (OGS) constituting a network are employed [162]. These stations are separated by hundreds of miles, so that a certain desired CFLOS probability of the whole network is achieved. Unfortunately, this requires several ground stations increasing the cost of the ground segment.
- *Micro-diversity:* The mitigation techniques for turbulence are termed as micro-scopic diversity techniques. For the optical feeder uplink, multiple apertures are placed in a distance higher than the coherence length of turbulence; this configuration is used to combat turbulence [167]. While several works have focused on exploiting the diversity gain achievable from MIMO optical setups, e.g., [168]–[170], they are typically used in terrestrial optical networks and have certain shortcomings for FSO. The Repetition Coding (RC) is considered, for example, in [167], [171], [172], where identical information is transmitted over multiple transmitters from different wavelengths.

The design of the optical feeder link depends on the on-board processing capabilities. Fully regenerative payloads offer the best performance due to their additional processing, partly because of their ability to include a strong FEC to enhance the optical link. However, the complexity of such payloads is rather high. On the other hand, transparent processing offers a simple, yet effective, solution to enable FSO. Two architectures have been considered in the literature for transparent satellites [160]; these are:

- *Analog Transparent:* In this architecture, the RF signal is used (after appropriate biasing) to modulate the intensity of the optical source. It offers a very simple modulation onto the optical carrier and demodulation on-board the satellites. However, it offers no protection to the optical link and can exhibit poor performance.
- *Digital Transparent:* Herein, the baseband radio signal is sufficiently oversampled (both the I/Q channels), quantized and the resulting sequence of bits modulates an optical source digitally, e.g., using pulse position modulation or On-Off keying. This architecture offers the possibility to include Forward Error Correction (FEC) to mitigate impairments on the optical channel; however, it suffers from bandwidth expansion, additional noise injection and higher complexity

A comprehensive study of optical feeder links has been pursued in [173]. Herein, the nuances of the optical and RF links were modelled and included in an end-to-end simulator with

Fig. 14. Locations of the NASA Deep Space Network and the ESA ESTRACK sites.

TABLE II
ADDITIONAL FREE SPACE LOSS AND TRANSMISSION DELAY FOR DIFFERENT LOCATION IN THE SOLAR SYSTEM WITH RESPECT TO A GEO SATELLITE

Place	FSPL (wrt GEO sat)	Delay
Moon	+20.9151dB	1.2 sec
Mars	+78.4164dB	12.5 min
Jupiter	+86.9357dB	44 min
Pluto	+102.8534dB	4h 37min

optical feeder links and RF user links. Both micro and macro diversities were considered. The results provide directions on the development of future FSO systems.

2) Deep Space Communications: Because of their very specific nature, Deep Space Communications pose specific telecommunication challenges that require specific solutions. The first and most important cause of challenges in Deep Space Communications is the huge distance between the spacecraft and the Earth. According to the ITU definition, we refer to Deep Space Communications when the spacecraft is at least 2 Million km away from the Earth. The first challenge imposed by such a huge distance is the very low available SNR. As an example, let us consider only the free space loss degradation. The increase of the FSPL with respect to the case of a GEO satellite for different objects of our solar system is reported in Table II.

This limitation is particularly challenging for the downlink (from the spacecraft to Earth). While, in fact, in the uplink the signal is generated on Earth with basically no limitation on the available transmitted power, the situation is totally different for the downlink where the transmitted power is strongly limited by the power that the spacecraft is able to generate. Power generation is very difficult for a spacecraft far from the sun. We have to keep in mind that the solar flux goes down by a factor of four each time the distance from the Sun doubles, so a solar panel at Jupiter can only generate a billionth of the power as at Earth. A more efficient alternative is to generate the onboard power through a radioisotope thermoelectric generator (RTG). An RTG uses the fact that radioactive materials (such as plutonium) generate heat as they decay into non-radioactive materials. The heat is converted into electricity by an array of thermocouples which then power the spacecraft. While this power generation method is very effective from a technical standpoint, nuclear-based generators are expensive (due to the limited amount of nuclear material available), politically sensitive and they pose a security problem. If, in fact, an accident happens on the rocket during the launch of the spacecraft the radioactive material can be spread in the atmosphere.

To overcome the limitation in terms of SNR, the space agencies have dedicated transmitting/receiving sites [174], [175]. These sites constitute what is generally known as the Deep Space Network. In the Deep Space network sites, huge antennas (e.g., 35 and 70 meters diameter dishes) are combined with cryogenic cooled antenna feeds [176]–[178]. As shown in Fig. 14, for the ESA and NASA Deep Space Network, these sites are separated on the Earth surface by approximately 120 degrees, in order to guarantee 24/7 coverage, independently of the relative position between the Earth and the spacecraft. In addition, these locations have been selected in order to guarantee a minimum amount of interference and rain fading.

Another telecommunication challenge in the case of Deep Space Communications is related to delay. As for the previous challenge, we report some numbers for different locations in our solar system in Table II. Because of the huge transmission delay, it is evident that the spacecrafts cannot be operated in real-time. On the contrary, spacecrafts are usually “sequenced”, meaning that a long list of commands is prepared in a program that is then transmitted to the spacecraft well in advance, in order to operate the spacecraft for long periods without commands from Earth. It is evident that the huge

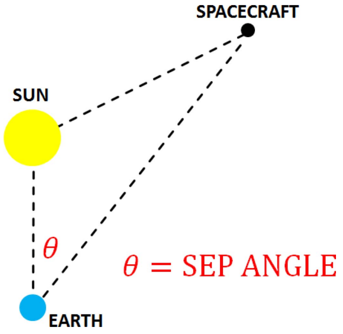


Fig. 15. Solar conjunction geometry.

delay prevents the usage of any Automatic Repeat reQuest (ARQ) mechanism, so the transmission scheme must be very reliable in order to guarantee that the transmitted message is correctly received. This high-reliability level is accomplished through the use of very powerful error-correcting codes and low order modulations as specified in the CCDSD standard for both the downlink (aka Telemetry link) [179] and the uplink (aka Telecommand link) [180].

A potentially dangerous effect on communications between Earth and space probes is scintillation, due to propagation through the solar corona, when the signal encounters solar conjunction. This event might, in fact, cause error rate degradation and eventually residual carrier unlock. The amount of scintillation depends on the solar elongation (i.e., minimum distance of the signal ray path from the sun), solar cycle and the sub-solar latitude of the signal path. The scintillation channel can be modelled as a multipath fading channel with a Rice distribution.

The Rician statistics depend on the carrier frequency, as well as on the geometry of the Sun, Earth and Probe, i.e., the SEP angle shown in Fig. 15. Usually, the Rician fading distribution is specified in terms of the scintillation index, noted by m, which is the ratio of the standard deviation of the received signal power to its mean. This topic has been recently investigated in the context of a research project funded by the ESA. Several solutions have been proposed for this scenario in [181], [182] and [183].

VI. MEDIUM ACCESS CONTROL: ENABLERS & TOPICS

The aim of this section is to address some fundamental developments related to the Medium Access Control (MAC) layer of a satellite communication system. We divide the analysis focusing on three main directions: MAC protocols for UHTS systems, MAC protocols for IoT via satellite communications and system coexistence aspects.

A. MAC Protocols for UHTS

Hereafter, we cover the key enablers of an UHTS system from the MAC layer perspective, including forward and return link scheduling, resource allocation, beamhopping, and carrier aggregation.

1) Forward Link Scheduling: Forward packet scheduling has been studied since the birth of the DVB-S2 standard to fully exploit its new features. The packet scheduling mechanism in particular plays a key role in guaranteeing an efficient resource management, through varying the time distribution of satellite resources among different beams and receivers, based on the channel conditions and quality of service (QoS) requirements. In this context, the adaptation loop, which comprises the set of operations starting by the channel estimation at the satellite terminal and ending with the reception of the information encoded/modulated according to the reported channel status, plays a fundamental role. On the other hand, the packet traffic in broadband services is bursty (i.e., the data rate needed to support the different services is not constant). Therefore, the goal of the forward link satellite scheduler is to optimize the bandwidth (capacity) utilization and QoS in the presence of traffic flows generated by services with different requirements. In general, the satellite scheduler can consider the following parameters for the design of the scheduling strategy:

- *Channel status:* The channel status information reported by the satellite terminals is essential in order to combine packets in a single frame according to the propagation conditions. This includes changes in the link quality experienced by each terminal due to weather conditions, mobility, jamming, and other factors.
- *Packet priority:* Lower priority packets can be delayed (or even dropped) in favor of high priority packets. For instance, emergency real-time packets, including emergency medical communications, rescue and natural disaster management related services, should be served with a high priority.
- *QoS requirements:* Various services have different QoS requirements and priority should be given to the ones with a higher QoS.
- *Buffer occupation:* Scheduling algorithms are strictly related to the buffer management problem. Priority must be given to packets coming from highly congested buffers.

We can distinguish two scheduling cases, which are detailed in the following paragraphs:

a) Unicast scheduling: One user (per beam) is scheduled within each frame. There are two design aspects that must be taken into account:

- *Demand satisfaction:* We do not need to schedule a user which has an empty queue. We need to schedule users which have large pending data volumes first. But this depends on the Service-Level Agreement (SLA) each user has signed with the satellite operator. An SLA may define a minimum rate over time, a maximum rate over time, an average rate over time, latency, etc.
- *Interference avoidance:* Whenever frequency is reused across beams, interference appears. Users scheduled in adjacent synchronous frames should be located far away from each-other to minimize interference. “Far distance” can be translated as “different channels”, or sometimes called “channel vectors that are as orthogonal as possible”. This means that the users served simultaneously over different beams should have orthogonal (ideally) channel vectors. This is essentially the basis of the semi-orthogonality criteria originally proposed in [184].

b) Multicast scheduling: Serving a single user within a single frame is not a practical assumption as this rarely happens in real systems. Before, we observed that minimizing the inter-beam interference can be achieved by scheduling users within adjacent synchronous frames according to orthogonal channel conditions. When considering multiple users within a frame, another design constraint applies. Since all the packets in a frame are served using the modulation and coding scheme (MODCOD) imposed by the worst user contained in that frame, significant performance gains are expected from a scheduler that groups the terminals according to similar propagation conditions.

The satellite traffic scheduling has been widely addressed in the literature [185]–[192]. In [185]–[187], a new scheduling approach suitable for DVB-S2 systems characterized by a two level architecture is proposed. This structure is able to take into account QoS requirements (i.e., buffer congestion, buffer size, dropped packets, queue waiting time) and MODCOD parameters. In [188], a scheduler for DVB-S2 based on the Weighted Round Robin (WRR) mechanism is proposed, whose weighting takes into account the traffic class as well as the available capacity. In [189], [190], the capacity region of a multi-beam satellite with N time-varying downlink channels and N on-board output queues is established. In [191], the Satellite Digital Multimedia Broadcasting (SDMB) is investigated. Given the unidirectional nature of SDMB and the point-to-multipoint services it provides, the authors in [191] propose a novel adaptive multidimensional QoS-based (AMQ) packet scheduling scheme for provisioning heterogeneous services to provide better QoS guarantee while achieving more efficient resource utilization via an adaptive service prioritization algorithm. In [192], a novel channel-aware scheduler scheme compliant with DVB-S2 is proposed which also considers the expedited delivery requirements for delay-sensitive packets.

The above-mentioned works are focused in cross-layer scheduling without considering aggressive frequency reuse. Introducing precoding techniques, the functionalities of the PHY, MAC and NET layers become even more intertwined. The main reason is that the achieved user rates at PHY are dependent on the packet scheduling due to the non-orthogonal access of the medium [123], [193]–[196]. The works in [123], [193], [194], assume that the number of users to be grouped into the same frame is fixed and constant across the beams. In addition, [123], [193], [194] follow a two-step approach where first a single user is classified in each group, and next the rest of the users are classified. In particular, [193], [194] randomly choose a user as a reference and then define the remaining group members associated with that user, while [123] selects the first user per group according to the semi-orthogonality criteria originally proposed in [184]. The works in [195], [196] try to avoid the two-step approach and perform the user-per-group classification at once. The work in [195] makes use of a geographical strategy, by sectorizing the beam. The work in [196] considers a graph-based partitioning approach using conventional spectral clustering. While [196] assumes a fix number of users per frame, [195] does not impose any constraint on that. On the other hand, [196] proposes a second step to orthognalize as much as possible the adjacent synchronous beam transmissions.

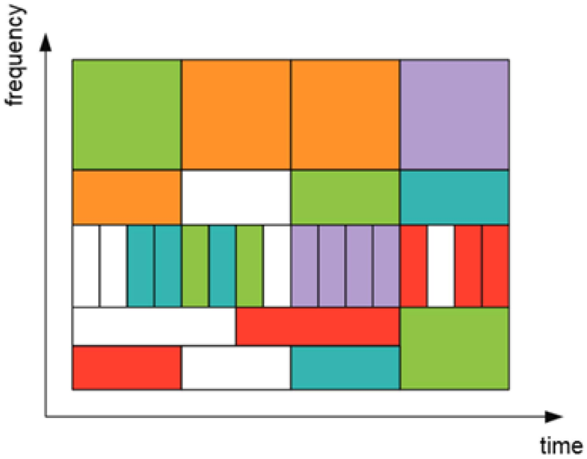


Fig. 16. MF-TDMA scheme used in satellite uplink.

2) Return Link Scheduling: In current satellite systems, the Network Control Center (NCC) is the entity that collects the traffic demands of the Return Channel Satellite Terminals (RCSTs) and distributes the available resources accordingly. The return link access is based on the Multi-Frequency Time Division Multiple Access (MF-TDMA) scheme, which provides high bandwidth efficiency for multiple users. Fig. 16 shows the frequency-time distribution of a sample MF-TDMA scheme. MF-TDMA is a system of access control to a set of digitally modulated carriers whereby the RCSTs are capable of frequency hopping among those carriers for the purpose of transmitting short bursts of data within assigned time slots. It is noteworthy that the return link can optionally use a continuous carrier (CC) instead of MF-TDMA. The advantage of this scheme is the more efficient adaptation to widely varying transmission requirements, typical of multimedia, at the expense of slightly more complex RCSTs. The NCC periodically broadcasts a signaling frame, the TBTP (Terminal Burst Time Plan), which updates the timeslot allocation within a super-frame between every competing RCTS.

However, the MF-TDMA proposed in the DVB standard has been shown to perform non optimally for bradband satellite systems [197]. In situations where the traffic is bursty, fixed assignment mechanisms lead to an inefficient use of the resources. Random access (RA) protocols are an interesting alternative. In random access, data packets are instantly transmitted, independent of other node activities. There is no prior coordination, which is translated into possible packet collisions. Unlike DVB-RCS, DVB-RCS2 optionally supports RA in the return link. For more details on uplink scheduling and RA, the reader is referred to Section VI-B.

3) Resource allocation: Satellite resources are expensive and, thus, it is necessary to optimally assign them.

a) Power assignment: In [199], a power allocation and packet scheduling technique based on traffic demands and channel conditions is proposed. However, interbeam interference is neglected by assuming non-adjacent active beams. Interbeam interference is dependent on the power allocated to each beam and therefore, affects the total system

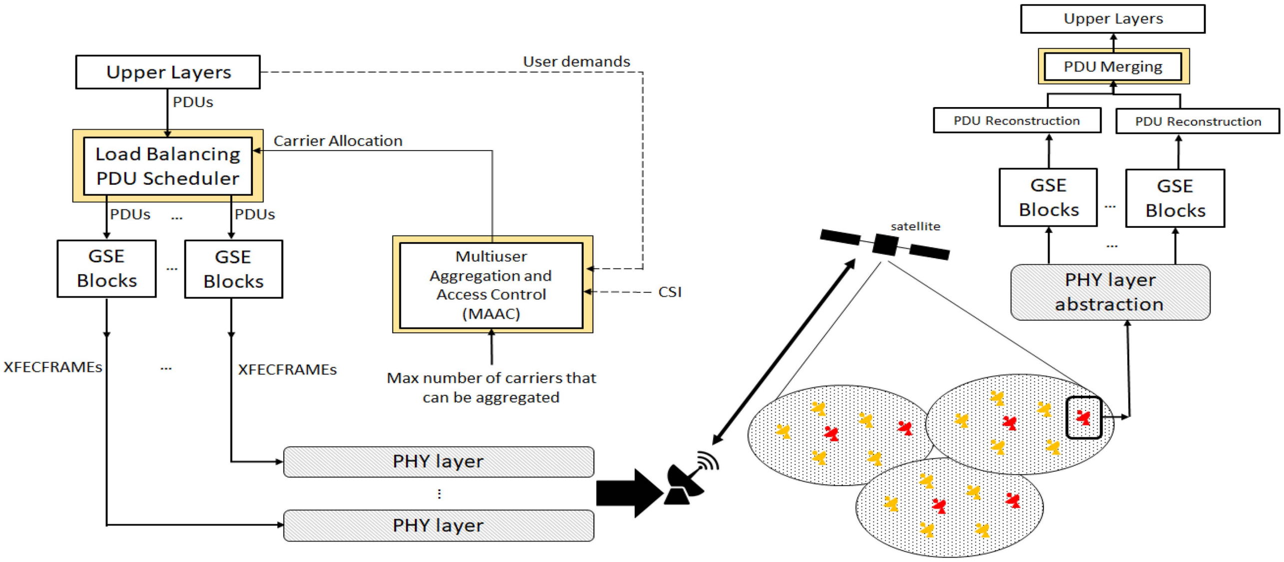


Fig. 17. CA Architecture as proposed in [198].

performance [200]. If not considered, it limits the flexibility of the system and can be a problem when a hot-spot requires coverage from multiple adjacent active beams. The benefits of power allocation are explored in [201], where a sub-optimal solution is proposed providing some insights about the relation between assigned power and offered capacity. However, the complexity of the solution in [201] limits its applicability.

Sometimes, however, power flexibility is not enough and the channelization (e.g., bandwidth and frequency) should also be adapted to provide another degree of flexibility.

b) Channelization carrier and bandwidth assignment: Dynamic bandwidth allocation techniques can be classified into three groups depending on the amount of spectrum that is shared: (i) Orthogonal but asymmetric carrier assignment across beams, with no inter-beam interference, (ii) Semi-orthogonal asymmetric carrier assignment, where a certain overlap between the spectrum of different beams is allowed, and (iii) Complete full frequency reuse, where all the beams share the total spectrum resource. Because (i) seems to not provide enough capacity, (ii) and (iii) have been identified as most promising. The semi-orthogonal scenario has been considered in [199]–[203]. In [203], a very simple sub-optimal iterative bandwidth assignment is considered to deal with the demand-matching problem. More computationally expensive algorithms have been proposed in [200]–[202] with similar objective. However, scenario (ii) and (iii) together with precoding have been overlooked as the introduction of makes the problem much more challenging, but at the same time with very high potential in terms of system performance. While in (iii) precoding is mandatory, in (ii) one can design which carriers to be precoded and which not, depending on the requested demand

4) Beamhopping: In conventional broadband multibeam HTS systems, all the satellite beams are constantly illuminated, even if there is no demand to be satisfied. It is widely accepted that the beam data demand is not homogenous, shifting from beam to beam over the course of a day or seasonally. Clearly, such uneven beam traffic patterns claim for a more efficient resource allocation mechanism. This has given rise to the beam hopping concept, a novel beam-illumination technique able to flexibly allocate on–board resources over the service coverage [204]. With beam hopping, all the available satellite resources are employed to provide service to a certain subset of beams, which is active for some portion of time, dwelling just long enough to fill the demand in each beam. The set of illuminated beams changes in each time–slot based on a time–space transmission pattern that is periodically repeated. By modulating the period and duration that each of the beams is illuminated, different offered capacity values can be achieved in different beams.

The beam hopping procedure, on one hand, allows higher frequency reuse schemes by placing inactive beams as barriers for the co–channel interference, and, on the other hand, allows for the use of a reduced number of on–board power amplifiers at each time slot. Beam hopping uncovers entirely new problems that were never considered before in satellite communications: the challenge of designing an illumination pattern able to perfectly match the demands [205], [206], the acquisition and synchronization of bursty transmitted data [207], and the exploitation of extra degrees of freedom provided by the fact that certain regions of the coverage area are inactive.

In addition, in certain scenarios (like the high throughput full frequency reuse scenario) the performance of Beam Hopping is heavily degraded by the self–interference generated by the system, particularly when neighboring co–channel beams are activated at the same time [208].

5) Carrier Aggregation: Carrier Aggregation (CA) is an integral part of current LTE terrestrial networks. Its ability to enhance the peak data rate, to efficiently utilize the limited available spectrum resources and to satisfy the demand for data-hungry applications has drawn the attention of the satellite communications community as well. In [198], several potential scenarios have been discussed and analyzed based on market, business and technical feasibility. The CA architecture is illustrated in Fig. 17.

CA represents an improved version of Channel Bonding (CB). According to the DVB-S2X standard, CB combines multiple adjacent channels to constitute larger transmission bandwidths, while CA can aggregate both contiguous and non-contiguous carriers in different spectrum bands [209]. Most importantly, CB is primarily designed for broadcast applications and employs constant coding and modulation, while CA is tailored to the emerging broadband traffic and is compatible with the ACM functionality [210]. Using CA technology has the following advantages:

- More efficient match of capacity demand distribution over satellite coverage,
- More users can be accommodated on a satellite,
- Commercial potential with higher revenues for broadband satellite operators.

Compared to conventional non-CA systems, CA is implemented by means of 3 main blocks. From the GW side, there is a block called "Multiuser Aggregation and Access Control" (MAAC) which represents the main intelligence of the system and which is in charge of designing the carrier allocation strategy for all the user terminals of the system as well as the multiplexing of each carrier. Then, a "Load balancing and PDU scheduler" module is in charge of implementing the decisions of the MAAC by distributing the incoming protocol data units (PDUs) across the available carriers. The "Load balancing and PDU scheduler" block needs to be carefully designed such that the PDUs are distributed across the selected carriers based on the link capacities so that, at the receiver side, the PDU disordering is minimized. At the receiver side, the most important block is the "Traffic merging block", which takes as input the PDU streams of the aggregated carriers and converts them into a single stream of received PDUs.

In [210], most of the implementation effort is assigned to the gateway side, so that the user terminal is as simple as possible with the minimum required changes to support CA. Following this approach, the "Traffic merging block" consists of a simple First-In First-Out (FIFO) system. Therefore, it is of extreme importance that the "Load balancing and PDU scheduler" module at the gateway side makes sure to schedule the PDUs in a proper way such that they can be easily merged in a single stream with a simple FIFO buffer.

B. MAC Protocols for Satellite IoT

Designing a MAC protocol for IoT communications over satellite is crucial and challenging, mainly driven by the low-complexity requirements and the need to support an enormous number of IoT devices generating a sporadic traffic to the network. There exist two main groups of MAC protocols in the literature for satellite-IoT applications,

1) Fixed Assignment Based: Protocols in this category ensure that each device in the network has separate resources in time, frequency, or both, for data transmission, hence avoiding data packet collisions. A leading IoT technology which uses a fixed assignment based protocol is NB-IoT. More specifically, in the downlink transmission OFDMA is used whereas the uplink is based on SC-FDMA. In an OFDMA (SC-FDMA) system, the time-frequency resources allocated to the users are different. Therefore, even in the case that many nodes transmit at the same time, data packet collisions do not happen. Of course, in order to achieve this time-frequency separation, the users should be informed apriori on the resources to use for data transmission. It is also worth highlighting here that a system based on OFDMA (SC-FDMA) requires a strict synchronization in order to maintain the orthogonality both in time and frequency in order to avoid inter-channel interference. The higher RTT delay in the satellite channel and the increased Doppler effects, especially in the LEO orbit, impose a significant challenge from the MAC layer perspective of such systems. As a matter of fact, [211] and [144] study the impact of the Doppler effects in a satellite-based NB-IoT system and come up with a new resource allocation approach to handle this problem, without modifying the existing fixed assignment based MAC protocol.

2) Random Access Based: RA based protocols are a natural solution for IoT over satellite communications since they match well with the traffic demand characteristics coming from the IoT devices. It is shown in [197] and [212] that the traditionally used demand assignment multiple access (DAMA) protocol for the satellite return link does not perform well under sporadic IoT traffic with low duty-cycles and very short packet length. In the case of RA protocols, the devices transmit the data using the same channel without prior coordination. Due to the fact that the allocation of resources is random, possibly many devices will use the same resources for data transmission, hence causing packet collisions. The most representative and well-known RA protocol is Aloha. Even though it is quite old, leading IoT technologies such as LoRa and SigFox use a variation of this protocol [213]. An Aloha based protocol, named time frequency ALOHA (TFA), is also proposed for the NB-IoT in [214]. Basically, when the nodes have some data to transmit, they do it without any prior coordination. In case an acknowledgment (ACK) is not received from the network, the device goes to sleep and tries again to retransmit the same packet after a random time. Despite being a simple protocol and performing well at very modest traffic, the increased propagation delay in the satellite channel creates potential network stability issues, making it an unattractive solution for modern IoT satellite applications [215]. In the last decade, there has been an effort in investigating more advanced RA schemes for satellite IoT; a survey can be found in [216]. A comparative study of RA techniques for satellite-IoT [217] shows that the most attractive ones in terms of spectral and energy efficiency are Enhanced Spread-Spectrum ALOHA (E-SSA) [218], Contention Resolution Diversity ALOHA (CRDSA) [219], and Asynchronous Contention Resolution Diversity ALOHA (ACRDA) [220]. The above mentioned best-performing techniques adopt iterative successive interference cancellation to increase the detection probability of the received packets. In [215], the performance of single-frequency and multifrequency CRDSA and ACRDA [221] is investigated, under realistic parameters and for a number of system scenarios of practical interest. In [222], the phase noise impact on the performance of CRDSA is analyzed.

C. System Coexistence

One of the promising solutions to address the spectrum scarcity problem caused due to spectrum segmentation and to the dedicated assignment of the available usable radio spectrum, is to enable the spectral coexistence of two or more wireless systems over the same set radio frequencies. The spectral coexistence of heterogeneous wireless networks, i.e., coexistence of satellite and terrestrial networks [223] or the coexistence of two satellite networks [224], [225] is challenging due to several aspects. In spectral coexistence scenarios, there may be multiple secondary users trying to access the same portion of the radio spectrum. In this situation, the network access should be coordinated in a way that multiple cognitive users do not seek the same portion of the radio spectrum. The effective sharing of the available radio spectrum among two or more wireless systems can be obtained by utilizing suitable Dynamic Spectrum Sharing (DSS) techniques. It can be divided into coordinated and uncoordinated, based on whether the primary and secondary systems exchange the spectrum usage information, i.e., TV WhiteSpace database, or they can operate without any coordination between them, i.e., spectrum sensing. Also, the DSS models can be broadly classified into three types, namely, commons model, exclusive-use model and shared-use model [226]. In the first model, i.e., the spectrum commons model, all the unlicensed or secondary users can access the spectrum with equal rights while in the exclusive-user model, the secondary users acquire the exclusive rights of using the radio spectrum either by being provided a cooperation award from the primary system or by purchasing a certain portion of the radio spectrum from spectrum licensees or primary service providers, also known as spectrum trading. On the other hand, the shared-use DSS model utilizes the underutilized or vacant spectrum either in an underlay (interference-avoidance) or interweave (opportunistic) manner [227]. Furthermore, several advanced mechanisms which can be employed to enable the spectrum sharing of heterogeneous networks include Licensed Shared Access (LSA), Licensed Assisted Access (LAA), CA and CB (as in Section VI-A5), and Spectrum Access System (SAS) [228], [229].

1) Coordinated: Two multibeam satellites may coexist in the same orbital position by utilizing different architectures, namely, conventional frequency splitting, cooperation, coordination and cognition [230]. In the first approach, the total available bandwidth in the forward link is divided into two equal portions, with each segment assigned to one satellite system. In the second approach, two satellites having multibeam communications payloads using aggressive frequency reuse are interconnected and synchronized with a high-speed link between the gateways. With the help of advanced signal processing techniques such as precoding, two transmitters located in two different satellites will behave like a large satellite with the equivalent payloads of two satellites. Two interconnected gateways have to exchange the channel state information and data reliably to enable the implementation of precoding techniques. The main challenge in this architecture is to meet the stringent synchronization demand between two physically separated satellites. To reduce the overhead of data exchange and to lower the system complexity, instead of full coordination, partial cooperation between the two coexisting transmitters can be employed. Such coordination will require the exchange of a smaller amount of information, i.e., CSI, and does not need to perform symbol level synchronization, thus leading to a reduced system complexity. Although intra-satellite multiuser interference in the coordinated dual satellite architecture can be completely mitigated by employing precoding techniques, interference arising from the adjacent satellite limits the system performance [230].

2) Uncoordinated: Another approach for the system coexistence is cognition via high-speed links between the satellite gateways on the Earth. Two satellite systems operating in the same or different orbits may operate over the same set of radio frequencies, with one satellite system being primary and another as secondary by utilizing various techniques such as cognitive interference alignment and cognitive beamhopping. In the cognitive interference alignment approach [224], the secondary terminals can employ precoding in a way that the received secondary signals at the primary receiver become aligned across the alignment vector, which can then be filtered by sacrificing some part of the desired received energy at the primary receiver. Based on the level of coordination between primary and secondary systems, the IA techniques can be static, uncoordinated and coordinated.

In the cognitive beamhopping approach [231], the secondary satellite having smaller beams can adapt its beamhopping pattern based on the prior knowledge of the beamhopping pattern of the primary satellite in way that the operation of the primary (incumbent) satellite does not gets impacted. To enable this, the beamhopping pattern of the primary satellite as well as the timing information can be shared with the secondary satellite via a high-speed signaling link between their gateways.

For the coexistence of Non Geostationary Orbit (NGSO) and Geostationary Orbit (GSO) satellites, the inline interference, which arises when an NGSO satellite passes through a line of sight path between an earth station and a GSO satellite, may become problematic [232]. To this end, ITU-R recommendations ITU-R S.1431 [233] and ITU-R S.1325 [234] provide recommendations for various static and uncoordinated solutions to mitigate inline interference including the following.

1) *Satellite diversity:* The traffic of the impacted satellite can be switched to an alternative satellite to avoid the main beam to the main beam interference whenever inline events occur.
2) *Transmission Ceassation:* The link budget design can be designed to accept some outage without switching to another satellite.
3) *GSO arc avoidance based on the latitude:* With this approach, the coupling of the main beam of the NGSO satellites and the main beam of the GSO earth station can be avoided by providing a sufficient angular separation with respect to the equatorial plane.

4) *GSO arc avoidance based on discrimination angle:* By switching off the beams when the point of interest in the Earth observes an angular separation (between an NGSO satellite's main beam and GSO arc) less than a predefined angle.
5) *Sidelobe design of NGSO satellite and terminal antennas:* The amount of harmful interference from/to satellites and GSO terminals can be minimized by designing the low side-lobe antennas on the terminals and the NGSO satellite, respectively.
6) *Satellite selection strategies:* Interference scenarios can be avoided by selecting a satellite that has the highest angular discrimination with respect to other GSO and NGSO and GSO satellites.
7) *Frequency channelization:* The carrier-to-interference levels can be enhanced by dividing the frequency band into smaller sub-bands and assigning these sub-bands to distinct beams.

VII. NETWORKING: ENABLERS & UPPER-LAYER INTEGRATION

The aim of this section is to cover the main technical advances related to networking and the upper-layer integration of SatComs with the 5G network.

A. Software Defined Networking and Network Function Virtualization

During the last decade, the networking community has witnessed a paradigm shift towards more open architectures based on Software Defined Networking (SDN) in a quest for improved agility, flexibility and cost reduction, in the deployment and operation of networks. The General reference of SDN architectures have been specified by the Open Networking Foundation (ONF) and the Internet Engineering Task Force (IETF) in [235], [236] respectively, reflecting the key principles of SDN: (1) separation of data plane resources (e.g., data forwarding functions) from control and management functions; (2) centralization of the management-control functions and; (3) programmabillity of network functionality through device-neutral and vendor-neutral abstractions and Application Programming Interfaces (APIs).

Mobile networks have been progressively embracing SDN concepts and technologies to decouple the control plane from the user plane. In this regard, a variety of proposals for adopting SDN concepts in mobile network architectures have been presented [237], [238]. Likewise, some standardization works, such as the Control and User Plane Separation (CUPS) architecture, have been developed as an enhancement of the 4G/LTE standards to fully split the control and user plane functions within the Evolved Packet Core (EPC) [239], or the new 5G Core Network [240]. On the other hand, while until recently the SDN scope has been focused on the packet-oriented Layers 2 and 3 (e.g., Ethernet, IP/MPLS), various extensions are underway for covering the abstractions necessary for the applicability of SDN in mobile networks [237], for example, for the management of optical transmission (Transport SDN [241]) or wireless transport devices (Wireless Transport Networks [242]).

As satellite networks are expected to be an integral part of the 5G service deployment [243]–[244], the evolution of satellite technology must also follow the guidelines towards more open architectures based on the SDN technology that are being consolidated within the 5G landscape, not only to bring the SDN benefits to the satellite technology, but also to greatly facilitate the seamless integration for combined satellite and terrestrial networks [245]–[246]. In this context, the satellite networks must also be outfitted with a set of control and management functions and interfaces (API and/or network protocols) compatible with the mainstream SDN architectures and technologies in order to realize a full end-to-end (E2E) networking concept where the whole satellite-terrestrial network behavior can be programmed in a consistent and interoperable manner [247]. In this regard, although the satellite technology has not adopted the SDN concepts at the pace that terrestrial communications networks have, important advances have been carried out in the recent years regarding the analysis of the potential use cases, requirements, and definition of functional frameworks for the exploitation of SDN technologies in satellite networks.

It should be noted that one of the most notable use cases of SDN applied to satellite networks has been Network Function Virtualization (NFV). Reference [248] investigated the advantages of introducing network programmability and virtualization using SDN and/or NFV by analyzing four use cases as well as their impacts on a typical satellite system architecture while [249] presented a satellite network architecture based on the idea of decoupling the data and control planes to gain high efficiency, fine–grained control and flexibility. Subsequently, a variety of works have been presented, aimed at the research of benefits and technical challenges brought by introducing SDN/NFV into the satellite networks, detailing a set of use cases, opportunities, scenarios and research challenges, but especially, identifying the SDN as a promising enabler in the evolution of service delivery over the integrated satellite-terrestrial networks [246], [250]–[251]. Other works, aimed at the development of platforms and architectures [245], [249], [252]–[253]. For example [245] presented a generic functional architecture for satellite ground segment systems embracing SDN/NFV technologies, detailing the interaction of the SDN controller with the satellite network control plane functions (e.g., network control centre [NCC] functions), as well as the characteristics of both externally exposed and internal interfaces, including a study of the pros and cons of several interfaces and data models that could be leveraged. Likewise, other works aimed at investigating SDN and its integration into satellite networks through several applications [248], [254]–[255]. For example, the applicability of the functional architecture in a combined satellite-terrestrial backhauling scenario presented in [245] was further developed in [254], [256] with a focus on the use of SDN technologies for the realization of end-to-end Traffic Engineering (TE) applications across the terrestrial and satellite segments. The benefits of such an architecture were assessed in [257] in terms of improved network resource efficiency achieved through the centralized and more fine-grained control of traffic routing enabled by the SDN-based TE applications. In this context, other research works have further progressed in this research area presenting some experimental proof of concepts (PoC) and testbeds for validations on the use of SDN technologies, as will be discussed in detail below (see Section VIII-B).

Despite being a key facilitator to enhance the delivery of satellite communications services and to achieve a better integration of the satellite component within the 5G ecosystem, SDN is still an emerging technology and its development and maturity are still in process. In the field of satellite communications, while important progress has been achieved so far on network architectural and functional aspects, as well as on the assessment of their benefits mainly via mathematical modelling and more or less sophisticated simulation environments, further research is still needed towards the practical implementation of integrated satellite-terrestrial solutions and their assessment under more realistic conditions.

B. Caching Over Satellite

One of the challenges in the edge caching is how to effectively prefetch popular content to the caches considering the high volume of data [258]. In order to overcome this issue, satellite backhauling has attracted much attention as a promising solution for the cache placement phase to exploit the large coverage of the satellite beams. Satellite systems have the ability to provide high throughput links and to operate in multi/broad-cast modes for immense area coverage.

Due to its multi-hop unicast architecture, the cached content via terrestrial networks has to go through multiple links and has to be transmitted individually towards each base station (BS). On the other hand, with wide area coverage, the satellite backhaul can broadcast content to all the BSs or multi-cast contents to multiple groups of BSs. Therefore, bringing these two technologies together can further off-load the network. The main idea is to integrate the satellite with the terrestrial telecommunication systems in order to create a hybrid federated content delivery network, which can improve the user experience [259]–[262]. The application of satellite communications in feeding several network caches at the same time using broad/multi-cast is investigated in [259], [263], [264]. Online satellite-assisted caching is studied in [259]. In this work, satellite broadcast is used to help placing the files in the caches located in the proxy servers, which use the local as well as the global file popularity, to update the cache.

Recent works on caching over satellites are presented in [265]–[271]. A two-layer caching algorithm is studied in [266], where the cache on the satellite is the first caching layer and the cache in the ground station is the second one. The optimal joint caching is carried out via a generic algorithm of the original mixed integer linear programming. In [267], a service model is proposed for hybrid terrestrial/satellite networks in order to identify viable alternatives to deploy converged satellite-terrestrial services. Two caching policies, namely the pull-based and the push-based, are studied.

In [268], a back-tracing partition-directed on-path caching mechanism is proposed for a hybrid LEO constellation and terrestrial network. By reducing the intermittent connectivity as much as possible, it is shown that the redundant transmissions of data access for different users can be largely reduced since the requested files are favorably fetched from intermediate caching nodes, instead of directly from the source. Reference [269] proposes a resource allocation strategy for cache filling in hybrid optimal-satellite networks. It is shown that the placement time can be notably reduced in a hybrid terrestrial-satellite backhaul network, particularly in case of bad weather that impacts the data rate of the wireless optical links. Reference [270] proposes a novel caching algorithm for optimizing content placement in LEO satellite networks based on many-to-many matching game. In [271], the performance of hybrid satellite-terrestrial relay network (HSTRN) under different caching policies is investigated. Analytical closed-forms are derived for the outage probability under the most popular uniform content based caching schemes.

Equipped with some computation capabilities in addition to storage capacity, satellite communications have shown potential applications in mobile edge computing (MEC) as well. Thanks to the wide coverage, satellites can be used for task off-loading from mobile users which are out of range from terrestrial MEC servers. It is shown in [272], [273] that with a proper network virtualization algorithm, a satellite MEC can significantly reduce latency and improve the energy efficiency compared to a stand-alone 5G terrestrial network.

VIII. TESTBEDS & PROTOTYPING

This section focuses on communication testbeds which have been developed for different communication layers in order to practically demonstrate some of the advanced SatCom concepts.

A. PHY & MAC: Software Defined Radio (SDR) Based

An SDR platform consists of a hardware RF front-end, and a digital signal processing DSP unit implemented in signal processors, Field Programmable Gate Arrays (FPGA), or GPUs. These platforms are designed to be highly flexible, and all the receiver and transmitter functionalities can be updated by a simple modification of the software code of the DSP devices [274].

In the field of satellite communications, many of the specific SDR implementations are focused on channel coding aspects [275]–[277]. Low-Density Parity-Check (LDPC) codes, which are the core of the FEC functionalities in the DBV-S2 and DVB-S2X standards, gained much of the interest in the community because their outstanding BER performance; close to Shannon limit at relatively low complexity and latency. The implementation of such type of coding was a technological challenge that was solved with the help of the flexibility of SDR approaches.

There are also several works regarding the waveform design and synchronization aspects of a satellite communication system. One example of SDR prototyping for pulse shaping optimization and multi-component signaling (MSC) is found in [278], whereas in [279], [280], the implementations of DVB-S2 transmitter and receivers are shown.

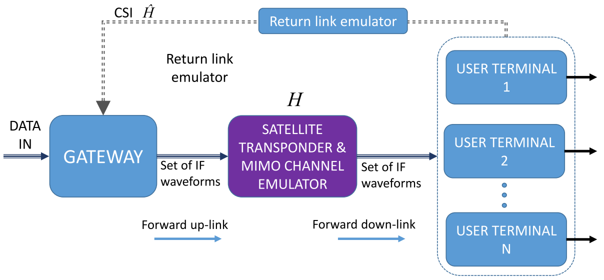


Fig. 18. General diagram of end-to-end satellite forward link hardware testbed.

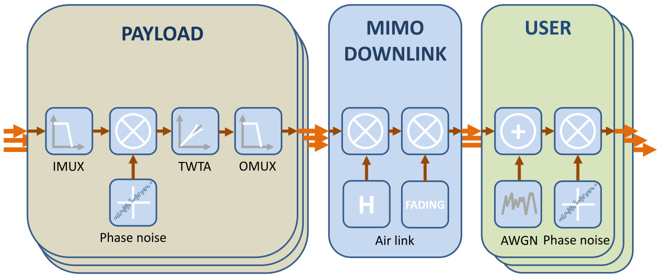


Fig. 20. Satellite payload and MIMO downlink channel emulator.

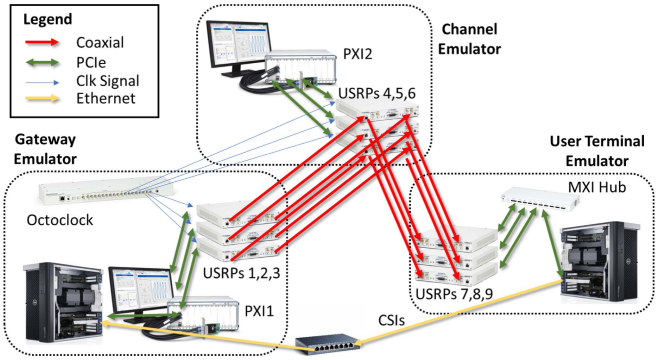


Fig. 19. SDR infrastructure of end-to-end satellite forward link hardware testbed.

There are other aspects that have grab some attention from the research community on top of the waveform design and channel coding. These aspects are the interference mitigation and the MU-MIMO schemes in multi-beam satellite systems. For the prototyping of such complex systems in emulation environments, the SDR techniques were the only alternative. Reference [281] describes an emulation system of geostationary satellite channels by means of SDR techniques. The emulator is based on the National Instruments Universal Software Radio Peripheral (USRP) [282], and uses the LabVIEW programming environment. The emulator is able to process a 1.6 MBaud signal stream in real-time, while adding thermal noise, phase noise, and propagation delay according to the system which is modelled.

The LASSENA group [283] at the University of Quebec has been developing an SDR infrastructure for interference mitigation in satellite communications. The objective of these developments aims to create a technical framework for the detection, measurement and mitigation of RFI to resolve satellite link interference issues and increase the global robustness. The infrastructure uses several devices in a hybrid approach. The GEO channel emulation is based on the commercially available single-link satellite channel emulator RT Logic T400CS [284]. The payload emulation is based on the BEECube BEE4 SDR platform, which uses multiple FPGA for high-bandwidth real-time signal processing. Finally, the transmitters and receivers are implemented by means of the SDR platforms, in particular, the Nutaq PicoSDR, and, the Nutaq ZeptoSDR [285]. This SDR infrastructure has been used to test radio frequency interference excision schemes [286], [287], and also the evaluation of scenarios for airplane connectivity [288]. [289]–[291] describe an end-to-end multi-beam satellite communication system emulator, called SERENADE, which is used for the evaluation of precoding and interference mitigation techniques [292]. The full testbed is based on a National Instruments (NI) infrastructure, which uses the NI USRP. The end-to-end testbed is hosted at the University of Luxembourg, and emulates the complete forward link for different of transponder orbits from LEO to GEO. The forward link includes a multi-beam satellite ground-based gateway transmitter using the DVB-S2X standard, a multi-beam channel and transponder emulator, and a set of UT receivers. Fig. 18 shows a functional block diagram of the SERENADE forward satellite link hardware testbed emulator.

Fig. 19 shows a generic description of the SERENADE SDR infrastructure, which is flexible and scalable for different number of channels. The infrastructure consists of the NI PXI (PCI EXtension for Instruments) 1085 chassis, which allows centralized connection of the set of USRPs, and FPGA processing units. The FPGA processing units, model NI FlexRIO 7976R, are inserted in the PXI chassis slots to increase to real-time processing capabilities, and consist of the Xilinx FPGA Kintex-7 410T. The complete testbed can be configured to have MIMO sizes of up to 16x16 using a modular satellite payload and channel emulator as the one shown in Fig. 18.

A detailed functional diagram of the payload and the MIMO channel emulator is shown in Fig. 20. The channel emulator receives the transmitted signals, applies the payload impairments, and applies the MIMO linear interference pattern to generate the signal provided towards the users. The payload impairments include:

- IMUX and OMUX frequency response.
- Phase noise emulation. This includes the phase and frequency drifts over time, and can be controlled independently at each of the transponder channels [294].
- Amplifier non-linearities, with re-configurable parameters.

The MIMO downlink applies the channel matrix, a fading pattern and a re-configurable delay. The user emulators apply Gaussian noise and the phase noise of a typical UT hardware. The UT emulators receive the output signal of the channel emulator, and perform synchronization, channel state estimation, and decode the information stream. The CSI is feedbacked to the Gateway using a return link emulator over an Ethernet link. The transmitter uses this CSI to compute the precoding signals. This infrastructure has been used to experiment with novel optimized precoding techniques, such as symbol-level precoding treated in Section V-C2 [295]–[298].

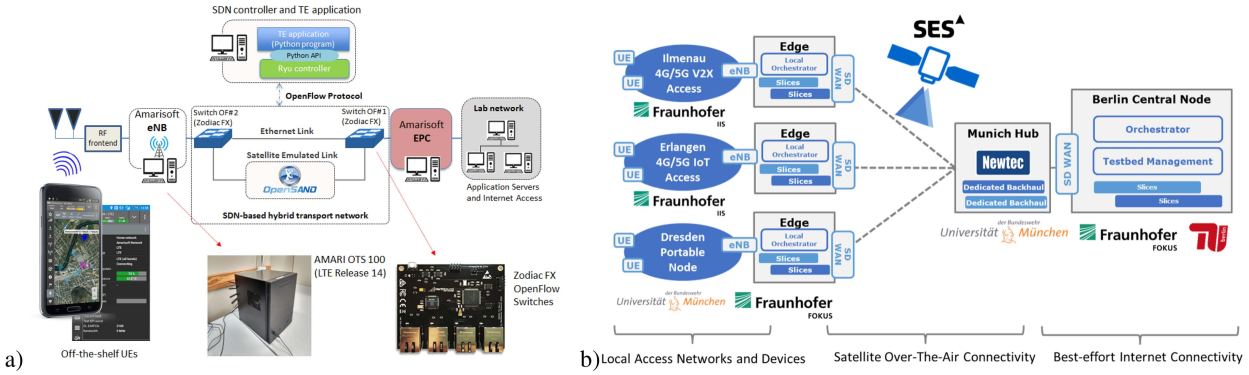


Fig. 21. High level view of the experimental test bed components a) SDN-based traffic engineering solution PoC [247]; b) SATis5 [293].

B. Network Testbeds

Due to the difficult access to satellite systems and its high costs, tools such as satellite system simulators/emulators, which in turn play a vital role in the development of PoCs/testbeds are becoming increasingly relevant in satellite technology research. In this regard, PoCs/testbeds can play an important role in conducting demonstrations and rigorous evaluations of feasibility, performance and manageability for new architectures, strategies, protocols, and algorithms, under low cost schemes, realistic and reproducible network scenarios.

In the case of the DVB-S2/RCS systems, the emulators/simulators must reproduce at least some of the important features of these systems as some Network access and Radio Resource Management (RRM) functions (e.g., the adaptability of channel conditions by modulation and coding schemes, etc). Furthermore, the satellite simulators/emulators must have other types of features that are very important for a successful implementation and analysis, such as performance, interfaces, system interconnections capabilities with real equipment and applications, performance analysis tools and ease of operation/configuration. There is a variety of satellite system simulators/emulators on the market as iTrinegy's Network Emulators [299] or the DataSoft Satellite Network Simulator [300], among others. Likewise, there are some OpenSource options among which we can highlight OpenSAND [301] initially developed by Thales Alenia Space, and the Satellite Network Simulator 3 (SNS3) [302] initially developed by Magister Solutions Ltd in the frame of the ESA ARTES projects. Others are still under development as the Real-Time Satellite Network Emulator [303] by the European Space Agency (ESA).

Regarding the satellite integration into the 5G networks, some PoC/testbed developments are presented in [64], [247], [293], [304]. For example, in [247], following the outcomes delivered by the VITAL project [245], the authors present an experimental PoC and validation based on the use of SDN technologies for the realization of E2E TE applications in integrated hybrid terrestrial-satellite backhaul mobile scenarios (Fig. 21a). Other three remarkable examples can be found in the still-in-progress projects SATis5, 5G-ALLSTAR and SAT5G [293], [304], [305]. The SATis5 project [293] aims to build a large-scale real-time live end-to-end 5G integrated satellite terrestrial network proof-of-concept testbed (Fig. 21b) in order to implement, deploy and evaluate an integrated satellite-terrestrial 5G network, showcasing the benefits of the satellite integration with the terrestrial infrastructures as part of a comprehensive communication system. The 5G-ALLSTAR project [304] aims to develop selected technologies targeting a set of PoCs to validate and demonstrate in the following heterogeneous real setup, such as new radio-based feasibility of satellite access for providing broadband and reliable 5G services, multi-connectivity support based on cellular and satellite access, and spectrum sharing between cellular and satellite access. Finally, the SAT5g project [305], is focused in the validation of technical challenges for cost effective satcom solutions for 5G as: virtualisation of satcom network functions to ensure compatibility with the 5G SDN and NFV architecture; cellular network management system to control satcoms radio resources and service; link aggregation scheme for small cell connectivity mitigating QoS and latency imbalance between satellite and cellular access; leveraging 5G features/technologies in satcoms; and optimising/harmonising key management and authentication methods between cellular and satellite access technologies.

As an important tool in the development and innovation of satellite technology by academia and industry, the development of satellite systems simulators/emulators as well as the development of PoCs/testbeds have taken on great relevance in the recent years. However, as justified in [303], the development of such tools must include new and better capabilities such as a highly configurable real-time network (e.g., time-varying topology and link characteristics in satellite constellation networks) and highly accurate models at low-cost equipment, allowing fast developments and simplicity in design. Furthermore, as SDN is also seen as a key facilitator to enhance the delivery of satellite communications services and to achieve a better integration of the satellite component within the 5G ecosystem (see Section VII-A), the new developments require the introduction of the additional SDN components as key enabling technologies.

IX. FUTURE AND OPEN TOPICS

This section aims to cover the open research topics and the future trends of satellite communication systems, while highlighting the challenges to be addressed.

A. Cooperative Satellite Swarms

The explosive progress in the field of small satellite technologies, mainly driven by the advances in electronics miniaturization and the decrease of costs [306], [307], have caused a paradigm shift from large and costly spacecraft carrying multiple payload capabilities, to decentralized distributed space systems (DSS). Some implementation of DSS, such as constellations and satellite trails, are relatively well-established, whereas satellite swarms are still in an active research and development area [308].

Unlike a constellation, where a set of satellites aim for a coordinated ground coverage with the help of a common ground control, a swarm is a group of identical and self-functioning satellites in space that achieve a common objective with their collective behavior [309]. The set of spacecraft can be nano-satellites and even femto-satellites with a mass of a few grams, with restricted capabilities. These satellites fly in close formation, and require an accurate observability and controllability of the satellite positions and attitudes to coordinate their operations. This accuracy can be in the order of micrometers and is only achievable with powerful propulsion and actuator systems [310], [311]. The complete swarm spacecraft can potentially produce a very capable system addressing complex problems that could not be solved with monolithic missions. As an example, the implementation of Synthetic Aperture Radar missions from higher orbits (MEO or GEO) can only have a realistic power budget using swarm multi-static configurations [312], [313]. Similarly, a wide variety of applications in the remote sensing area may take advantage of satellite swarms, such as the characterization of planetary atmospheres, the estimation of the composition of asteroids, the deep-space exploration and the investigation on Earth's ionosphere [314]. In these applications, the designers can use sensor fusion and offline processing.

However, the implementation of data link communications using satellite swarms has not been so popular, due to the stringent technical requirements, and in particular the strict synchronization requirements. The synchronization of the swarm nodes is a very challenging task due to the dynamic characteristics of the transmission channel between the nodes, and the limited accuracy of the time and frequency references available at the small satellites [308], [315]. In order to achieve a proper synchronization, the nodes must implement ISLs [306], [316] to obtain an accurate reference from an external source. Nevertheless, the implementation of the ISL requires additional transceivers which add to the weight and power consumption in each of the satellites [317], [318]. For this reason, how to facilitate the ISLs among satellite nodes in a swarm is still an open research topic.

B. Hierarchical Aerial Networks

As we saw in Section III-B, various intermediate layers of communications systems between terrestrial and traditional satellite segments have emerged thanks to the technological advances of the aerial and miniaturized satellite platforms. Such hierarchical area networks with multiple types of flying layers are a promising solution to provide extended coverage and to improve the security in the new space era of communications. In this architecture, multiple types of flying layers cooperate to improve the space-to-ground link reliability and capacity [319]. The UAVs have the potential to serve the ground users at the low and the medium layer, while HAPs can serve both, UAVs and ground users from high altitude, and act as relaying nodes from the satellites when necessary. However, due to the difference in the height and velocity, link connections between intermediate layers are directly affected, e.g., the HAPS and the UAVs may be frequently disconnected. Therefore, how to harmonize the flight of the UAVs and the HAPS to maintain reliable connections is of great importance, as the current routing protocol is not applicable to vertical space networks. One should note that the desired routing protocol for vertical area networks should take into account the heterogeneous connects between the links, e.g., free space optical among the HAPS, hybrid radio frequency/free space optical between the HAPS and UAVs. Another open problem is how to efficiently deploy the hierarchical area network [22]. A joint design of communications and HAPS/UAV flights is expected to achieve the required global performance and it still represents an open research topic. This includes not only UAVs and HAPs placement design but also trajectory optimizations.

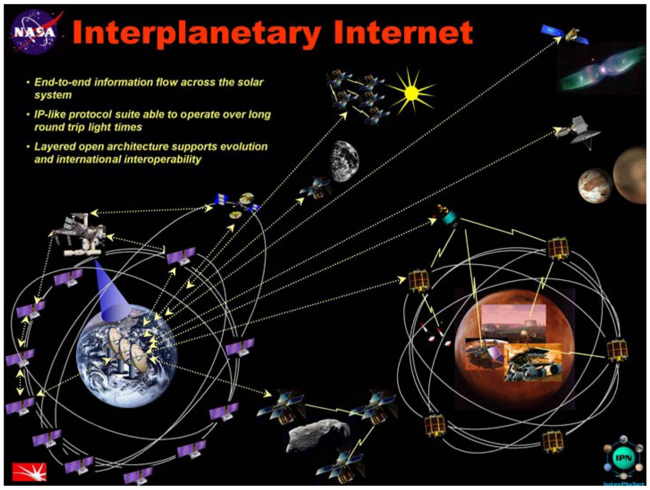


Fig. 22. Interplanetary Internet Network Concept. Credits: NASA.

C. Internet of Space Things

Space communication technology has steadily evolved from expensive, one-of-a-kind point-to-point architectures, to the re-use of technology on successive missions, to the development of standard protocols agreed upon by space agencies of many countries. This last phase has been going on since 1982 through the efforts of the Consultative Committee for Space Data Systems (CCSDS). As we emphasized in Section III-E, recently, there has been a paradigm shift on space activities where various space agencies are planning to have a stable human presence in other celestial bodies of our solar system. With the current rate of astronomy and space exploration, it is clear that a Space Wide Web network will spread to all over the solar system in the near future. As depicted in Fig. 22 the vision of NASA [320] for the future of space communications is a huge network of communications nodes so that messages can hop between different intermediate nodes to reach their final destination. This architecture completely matches the architecture used on Earth for the World Wide Web and this is the reason why this new path for space communication is commonly referred to as the Space Wide Web.

While IP-like network layer protocols are feasible for short hops, such as from the ground station to the orbiter, from the rover to the lander, from the lander to the orbiter, and so on, delay-tolerant networking (DTN) is needed to get information from one region of the Solar System to another. DTN has the potential to enable standardized communications over long distances and through time delays. At its core is the Bundle Protocol (BP), which is similar to the Internet Protocol (IP) that serves as the heart of the Internet here on Earth. Several research groups are currently working on the development of such a new network layer protocol for the Space Internet.

Although it was first conceived having space applications in mind, DTN can tackle the challenges of future satellite communications as well [321]. In particular, DTN can cope well with intermittent channels, typical for LEO, and high delay communication links, especially in a GEO satellite [322]. As satellite networks will become larger in upcoming years, a DTN protocol will allow for the seamless inter-operation and cost reduction, making the satellite just a component of the overall future Internet [323]. Open research topics in this direction include network modeling, routing, and congestion control.

D. Flying Base Stations

As we discussed in Section III-A, the next generation of mobile networks aim to satisfy various use cases with distinct types of traffic originating from a multitude of devices. Consequently, there is a need for network flexibility and scalability. To realize this, micro-cell and small-cells with certain operational autonomy and ease of deployment have been considered. These deployments involve static base-stations. A next step in achieving flexibility in this direction is the use of mobile infrastructure to provide necessary services; in this context, the Flying base-stations have been considered [324]. Flying base stations can be mounted on general-purpose UAVs, and these UAVs can be further integrated into the wireless network. It has been shown in [324] that the integration of such systems into mobile networks can be an efficient alternative to ultra-dense small cell deployment, especially in scenarios with users moving in crowds. The challenges and opportunities for assisting cellular communications with UAV-based flying relays and BSs have been surveyed in [325].

With the envisaged deployment of low latency LEO satellites supporting terrestrial communication waveforms, an additional design flexibility can be incorporated in the system by developing base-station capabilities into the satellites. The extensive use of on-board processing in the emerging satellite systems paves the way for the realization of a flying base-station on-board a satellite. On-board regeneration is essential for implementing this capability; the processing is not only restricted to PHY, but MAC and NET layer functionalities need to be added as well. Key aspects include serving a terminal using multiple satellites and appropriate routing of the packets over ISLs. This would be similar to the Coordinated Multipoint (CoMP) scenario in a cellular network where the capabilities of several base stations are utilized for data transmission, resulting in improved performance and better utilisation of the network. Also, another crucial aspect worth considering is the power budget analysis. Initial studies in this direction have been already performed in 3GPP for 5G over LEO satellite systems [10], [326].

E. Dynamic Spectrum Management for Both GSO and NGSO

Due to the several advantages of the NGSO satellites over the GSO satellites, such as less free space attenuation, small propagation delay and the reduced in-orbit injection cost per satellite [327], the trend of deploying NGSO satellites has been increasing over the recent years but the available usable radio spectrum is limited and is costly for the satellite operators. This has led to the need of spectrum coexistence of LEO/MEO satellites with the already existing GSO satellites and/or the spectral coexistence between different NGSO satellites [232], [328]. The interference analysis between GSO and NGSO systems operating over the same set of radio frequencies becomes challenging as the relative position of the co-channel spots changes over time in NGSO systems [327], [329]. The main issue for the coexistence of GSO and NGSO satellites is in-line interference, which may be challenging mainly in the equatorial region [232]. In such a scenario, an earth station that is in-line with GSO and NGSO satellites may create and receive interference through its main beam. Furthermore, in the uplink, besides the inline interference from the main lobe of the NGSO terminal, the aggregate interference caused by the side-lobe gains of the beampatterns of many NGSO terminals in the ground may cause considerable harmful interference to the GSO satellite.

As highlighted earlier in Section VI-C, the inline interference can be predetermined and avoided by using one of the static and coordinated methods suggested by ITU-R recommendation S.1431 [233] and ITU-R S.1325 [234]. However, the performance of the primary system (GSO or NGSO depending on the coexistence scenario) may be impacted due to limited dynamicity of these methods. Also, the QoS of the secondary NGSO system may not be guaranteed while utilizing these static approaches. In this regard, there arises the need to investigate more dynamic/flexible approaches for the real-time mitigation of inline interference events, which may occur while operating GSO-NGSO or NGSO-NGSO satellites over the same frequency band.

One promising flexible approach for interference mitigation could be to employ the beamhopping principle at the secondary satellite so that the interference to the primary GSO or NGSO satellite can be avoided by adapting the beamhopping patterns in the real-time by utilizing the principle of cognitive beamhopping framework proposed in [231]. Another promising solution could be to employ adaptive power control mechanisms [328] at the NGSO terminal to mitigate the harmful interference towards the GSO satellite in the uplink coexistence scenario, and at the NGSO satellite to mitigate the harmful interference towards the GSO terminal in the downlink coexistence scenario. Furthermore, another dynamic approach is to incorporate sensing mechanisms with the help of intelligent sensors at the NGSO terminals in a way that the inline interference can be detected during the reception mode. Moreover, terminal-side beamforming [330] can be employed at the secondary NGSO terminal to mitigate harmful interference towards/from the primary GSO or NGSO satellite.

F. Advanced Satellite Resource Orchestration

As already discussed, one of the concepts that is revolutionizing the infrastructure of current communication systems is the SDR technology. The advances in this software disruptive paradigm is currently reinventing future network architectures, accelerating service deployment, and facilitating infrastructure management. Satellite communications are not an exception. The ability to reprogram beam patterns, allocate frequency and power dynamically anytime during the satellite mission, makes SDR technology very attractive in the forthcoming day where the data markets are more uncertain. Such software defined payloads, being much more flexible and automatically reactive, are able to deliver cost-competitive connectivity, and face the dynamicity envisaged in the forthcoming wireless traffic.

While the aforementioned capabilities posses relevant advantages for satellite communications in general, they bring new research challenges. In particular, the new on-board processing capabilities combined with the emerging role of active antenna systems, require advanced resource management techniques. These novel techniques should be capable of maximizing the satellite resource utilization while maintaining QoS guarantees, and dynamically match the geographic distribution of the traffic demand by following its variations in time.

In addition, the cost-effective plug-and-play satellite solutions for 5G require the virtualization of satellite network functions. SDN and NVF are, thus, key aspects to augment the flexibility at the network management level, intelligence of which is handled at the Network Operational Center (NOC) in close collaboration with the Satellite Operations Center (SOC). In this context, the vendor-neutral Open-RAN architecture [331] has emerged in the terrestrial community as a solution to allow smaller vendors to introduce their own services and allow operators to customize the network as needed. With the low-cost small satellites rapidly gaining popularity and with the advent of small satellite companies entering the telecom industry, the standardized and open interfaces of Open-RAN emerge as the perfect solution for a competitive ecosystem.

G. Satellite Network Automation

The upcoming integrated 5G-satellite networks will largely increase in size and complexity due to the wide adoption of heterogeneous mobile devices and wireless access. In many use cases, the optimal solutions for the terrestrial-satellite network management can be difficult to model due to the complex environment and the presence of too many uncertainties. With the growing complexity and reliability requirements, the conventional test-and-verification methods for network management will be challenging. This is because the network operators are not comfortable at deploying live traffic on untested/unoptimized configurations. The concepts of self-optimization and of self-organization networks (synonymous with network automation) are highly suited for such complex problems.

As analyzed in Section VII-A, a promising architecture and implementation comes from SDN, where the networks can be dynamically programmed through centralized control points and from NFV enabling the cost-efficient deployment and runtime of network functions as software only. Based on NFV and SDN, network slicing (NS) is a service-oriented construct providing "Network as a Service" to concurrent applications. The slices will deliver different SLAs based on a unified pool of resources. The envisioned satellite-terrestrial network will be capable to support end-to-end services (and their management) across heterogeneous environments by means of a single (converged) common network. Through this paradigm, the specific services can be highly customized, enabling the seamless integration of heterogeneous networks in a 5G-satellite ecosystem. Unlike the conventional one-type-fits-all network, network slicing presents not just a cutting-edge technique, but opens new horizons for efficient and intelligent resource configuration for integrated terrestrial-satellite systems.

In this context, the combination of terrestrial and non-terrestrial links, e.g., satellite, in transport networks has introduced new dimensions of network heterogeneity and dynamicity. Nevertheless, several open issues have to be addressed. Firstly, one of the main challenges is to devise network-slicing algorithms, e.g., slicing configuration, virtual resource isolation, that can efficiently and autonomously configure the large number of parameters present in a virtualized dynamic graph representing an integrated satellite-terrestrial transport network. Secondly, one should note that most of the works on virtual network embedding (VNE) are based on a static design, i.e., based on a snapshot of a deterministic network graph, but a realistic integrated NGSO satellite-terrestrial network is highly dynamic, resulting in fast variations of the virtual network topology over time. Also, multi-orbit systems, where terminals with advanced beamforming capabilities can connect to multiple orbits at the same time, represent another highly dynamic scenario. Dealing with the graph dynamics in the context of online network-slice management is an essential challenge. Thirdly, the de facto standard protocol between the data and control planes, i.e., OpenFlow, in SDN/NFV networks has to be extended and become compatible to satellite-terrestrial networks by considering satellite characteristics, e.g., LEO and MEO satellites' motion, available on-board energy, storage capacity, and computational power.

H. Quantum Key Distribution Through Optical Satcom

The RSA protocol has been the cornerstone of cryptographic systems due to the large computational power needed to break it. However, with the advent of significantly large increases in computing power, alternative options whose performance is not vulnerable to computing power have been considered. In this context, the Quantum key distribution (QKD), first proposed in [332], involves establishing a private encryption key between two parties. QKD is inherently an optical technology, and has the ability to deliver encryption keys between any two points that share an optical link automatically. However, the use of QKD over the mature optical fibre networks for long-range, long-scale applications is limited by the transmission losses that increase exponentially with distance. In this context, QKD over satellites is being increasingly considered [333].

Key to the success of QKD over satellites is the ability to set-up stable optical links by overcoming the various impediments in transmission. The links should ensure a certain minimum quantum bit error rate (QBER), which is the QKD counterpart of signal-to-noise ratio, is met. This requires an appropriate selection of optical frequencies, components and mechanisms for pointing, acquisition and tracking. Also of significant interest is the transmit and receive processing to ensure a high fidelity link while satisfying constraints on size (e.g., on-board receiving lens cannot be large), power (e.g., constraints imposed not to harm existing links/ equipment etc) and possibly computational power. Thus, in addition to its consideration for solving the spectrum crunch, optical satellite communications will enable QKD in the coming years. This motivates further investigations into optical satellite communications focusing on QKD scenarios.

I. Machine Learning Applications

Machine Learning (ML) techniques in the literature can be broadly categorized into supervised, unsupervised and Reinforcement Learning (RL) [334]. Out of these, supervised learning requires the labelled training data-set while the unsupervised learning does not require the labelled data-sets. In contrast to these approaches which require training data-sets, the RL does not need a training data-set and enables a learning agent to learn from the prior experience, and seems more suitable for dynamic wireless environments [335], [336].

In the context of satellite systems, the application of ML has been already being explored in several scenarios including opportunistic weather monitoring, earth observation applications, satellite operations and sensor fusion for navigation. Furthermore, with the growing trend of investigating the applicability of ML in wireless communications, investigating its applications in the satellite communications has recently received an increasing attention from the academia as well as from the SatCom industries/agencies. The ML/AI techniques can find potential applications in addressing various issues in satellite communications including interference mitigation to enable the coexistence of satellite systems with terrestrial systems, the optimization of radio resources (spectrum, power), the optimization of SatCom network operations, and the management of large satellite constellations.

In the above context, some promising use-cases to investigate the applications of ML techniques include: (i) adaptive allocation of carrier/power for the hybrid satellite-terrestrial scenarios, (ii) adaptive beamforming to enhance the performance of multibeam satellites with non-uniform demand, (iii) scheduling and precoding to mitigate interference in multibeam satellites, (iv) beamhopping and resource scheduling in multi-beam satellite systems with heterogeneous traffic demand per beam, and (v) detection of spectrum events in spectrum monitoring applications [337]–[339].

J. Digital Twins for Satellite Systems

As described in the aforementioned sections, the next generation SatCom systems are envisioned to support various new features/paradigms including demand-based coverage, onboard processing, active antennas, dynamic resource management, mega-LEO constellations, nano-satellites, hybrid constellations, network virtualization and slicing. Towards incorporating these advanced features in future SatCom and managing the ever-increasing complexity of satellite networks, digital twins are considered as a potential solution. A digital twin, in general, represents the digital replica of physical objects, places, system, people and devices, which can be utilized for better design, manufacturing and actual operation of digital products (i.e., IBM Watson IoT) in the realistic environments with the help of sensor/IoT, data analytics and Artificial Intelligence (AI)/Machine Learning (ML) technologies [340]. Digital twins mainly comprises three components, physical product, virtual product and data transmission between physical and virtual products [341]. However, current data-driven designs are mainly based on the analysis of physical data, which within a product lifecycle are usually fragmented, isolated and static. In addition, the lack of convergence between physical and virtual worlds is leading to several issues in terms of low-efficiency, sustainability and adaptability during the aforementioned three phases (i.e., design, manufacturing and operation) of a product lifecycle [341]. In this regard, efficient data transmission between physical and virtual systems is crucial in order to effectively support the operational monitoring, maintenance and performance optimization of a physical system. For example, this is important for the high bandwidth TT&C sub-system of a satellite system to exchange data between the physical satellite and its virtual counterpart on the ground.

In addition to the aforementioned operations, the digital twin is expected to play a crucial role in integrating historical and fleet data, maintenance history and sensor data from the satellite on-board integrated health management system to enhance the safety and reliability of satellites/space vehicles [342]. By processing and analyzing all the available information, the digital twin helps to forecast different attributes such as response to critical events, the health of a satellite/vehicle system, the probability of mission success and the remaining useful life, and to activate self-healing mechanisms whenever needed. Another promising future application of the digital twin is to enable space-based monitoring and communication services since the cost and time needed to provide space-based services can be drastically reduced by utilizing software-defined components in the satellites, which can be remotely configured from the Earth [343]. Also, digital twins can enable the creation of autonomous swarms, which has been described in Section IX-A, by incorporating the intelligent sensing and communication capabilities to the satellite systems.

However, the introduction of digital twins for satellite industries is relatively new and several challenges need to be addressed to effectively implement this in practical systems. Some promising applications of digital twins in future SatCom systems include autonomous management and monitoring, software-driven transformation, end-to-end service orchestration, and network/service automation of complex satellite networks. Also, data management being a crucial aspect for the digital twin implementation, one important issue to be addressed is to ensure the privacy of individual entities and to prevent the information misuse. To address this, the combination of the emerging blockchain technology with the digital twin could be promising [344]. Another issue in the digital twin-enabled nano-satellite systems is to properly track, control and decommission nano-satellites in order prevent any threats to the ground or other satellites [343]. Other future issues include how to manage the space debris and pollution by removing the failed or inoperative satellites and how to regulate the digital twin-enabled infrastructure in terms of preventing data misuse by the governments, criminals or terrorist bodies.

X. CONCLUSION

Satellite communications have recently entered in a crucial phase of their evolution, mainly motivated by the explosive growth of various Interned-based applications and services, which have triggered an ever increasing demand for broadband high-speed, heterogeneous, ultra-reliable and low latency communications. Due to their unique features and technical advances in the field, satellites can be a cornerstone in satisfying this demand, either as a stand-alone solution, or as an integrated satellite-terrestrial network.

To this end, this article has captured the latest technical advances in scientific, industrial and standardisation analyses in the domain of satellite communications. In particular, the most important applications and use cases under the current focus of SatCom research have been highlighted. Moreover, an in-depth literature review has been provided covering the latest SatCom contributions in terms of system aspects, air interface, medium access control techniques and networking. The communication testbeds which have been developed in order to practically demonstrate some of the advanced SatCom concepts are shown. Finally, some important future challenges and their respective open research topics have been described.

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