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Review Article

From Connectivity to Advanced Internet Services: A Comprehensive Review of Small Satellites Communications and Networks

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Recently, the availability of innovative and affordable COTS (Commercial Off-The-Shelf) technological solutions and the ever-improving results of microelectronics and microsystems technologies have enabled the design of ever smaller yet ever more powerful satellites. The emergence of very capable small satellites heralds an era of new opportunities in the commercial space market. Initially applied only to scientific missions, Earth observation and remote sensing, small satellites are now being deployed to support telecommunications services. This review paper examines the operational features of small satellites that contribute to their success. An overview of recent advances and development trends in the field of small satellites is provided, with a special focus on telecommunication aspects such as the use of higher frequency bands, optical communications, new protocols, and advanced architectures.

1. Introduction

In the short span of the first two decades of the new millennium, a revolution has taken place in the field of satellite systems: the availability of innovative and affordable COTS technological solutions and the ever-improving results that are produced by microelectronics and microsystems technologies have paved the way to a process of size reduction for the satellite components and to the design of smaller and smaller satellites that have been defined as small satellites (whose weight is less or equal to 1000 kg), microsatellites (from 10 to 100 kg), nanosatellites (1 – 10 kg), and picosatellites (0.1 – 0.99 kg) [1].

These technological trends have allowed new opportunities in the space market and the implementation of long-awaited projects that have been postponed or suppressed for years due to high inherent costs. More importantly, a new space rush has been originated by these technological achievements with hundreds of small satellites being launched in the last few years and even more envisaged to be commissioned in the near future.

So far, the main drivers of small satellites developments have been Earth observation and remote sensing, as they may greatly contribute to filling the gap of *data poverty* in many industry verticals (e.g., agriculture, disaster management, forestry, and wildlife). Nevertheless, new investments in developing mega-constellations (hundreds) of pico/nanosatellites [1] for providing global communications, the increased role of satellites in Machine-to-Machine (M2M) communications [2], and the interest in taking advantage of one of the main possibilities enabled by small satellites, which is the development of distributed systems with interconnected satellites, are moving the attention also towards the telecommunication aspects. Therefore, this paper provides an overview of recent advances and development trends in the field of small satellites, with a special focus on

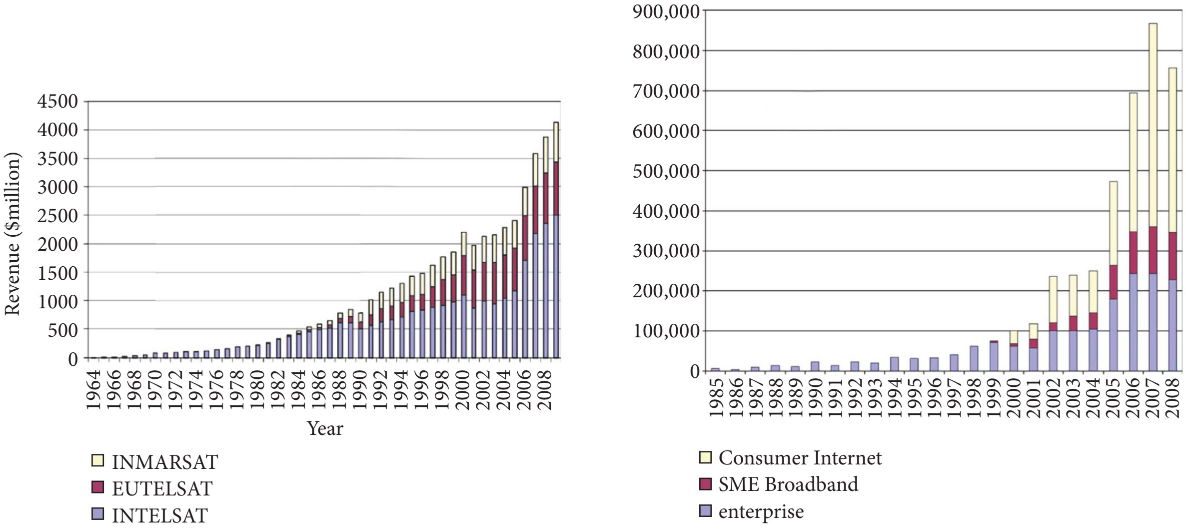

Figure 1: INTELSAT, EUTELSAT, and INMARSAT annual revenues (left). Annual sales of VSAT terminals by type (right) [7].

the telecommunication aspects such as the use of higher-frequency bands and optical communications, protocols, and architectures.

It is worth outlining that some surveys about small satellites have been published recently [3–6]: whereas [5] focuses on the evolution of the antennas for small sats, [6] concentrates on intersatellite link and related communication protocols for small sat constellations. On the other hand, [4] reviews the history of small satellite development and summarizes its capabilities and applications. A rather comprehensive review is provided in [3], which deals with many aspects, from hardware components and structures, to network topology and communication protocols; moreover, [3] focuses on Cubesat class of small sats. With respect to previous surveys, this paper provides a more extensive overview on telecommunication aspects and aims at describing this rapid evolving field, giving more insights into new protocols, architectures, and technology developments.

The paper is organized as follows: in Section 2, a brief history of the evolution of the small satellites is provided, trying to unveil the commercial reasons of their success. An overview of the services and applications which are enabled by the small satellite is given in Section 3. Section 4 is devoted to a description of the evolution of the payloads, focusing on the used frequencies and the Software Defined Radio (SDR) concept. New telecommunication architectures and the suitable protocols for small satellites based systems are described in Sections 5 and 6, respectively. Finally, the perspectives and the open challenges are discussed in Section 7 and the conclusions are drawn in Section 8.

2. A Brief History of Small Sats Evolution

From the dawn of the space era to their latest developments, satellite communications have been one of the most reliable indicators of the technical and societal evolution: as a matter of fact, in the last of few decades, amazing and unexpected progresses and changes have been obtained in the diverse fields of broadcasting, mobile communications, Earth observation and remote sensing, interplanetary exploration, transport, and remote monitoring, so encompassing commercial, civil, and military applications [7]. However, it is worth stressing that starting from the postwar times to the today scenarios, satellite systems have undergone themselves a radical and systemic evolution which proves the fact that their abilities perfectly adapt to the ever-changing needs of both the society and the market; particularly, while in the first decades, governments and national agencies were the main players in the start of space race, in the design of satellite missions, and in the development of satellite-based systems, more recently private companies have largely increased their role in this strategic industry [8].

This trend has also been enforced by the privatization of the main international satellite organizations which has taken place at the end of the last century and produced high revenues as shown by Figure 1 [7]. As far as the VSAT and broadband satellite systems are concerned, the same trends of deregulation and stimulation of the market forces have been experienced from their launch to the final successful spreading as reported by the graphs in Figure 1 [7].

On the other hand, the end of the twentieth century has also seen the birth and the first steps of a new paradigm that is based on the exploitation of the so-called small satellites, whose size and weight are much smaller than the huge geostationary orbit (GEO) or the big medium Earth orbit (MEO) and low Earth orbit (LEO) ones. These new systems are identified as micro-, nano-, and picosatellites according to their dimensions [3]. The early missions of small satellites were mainly organized and performed by research groups of Universities and Research Organizations with the goals of enabling a technology demonstration or an application validation [9].

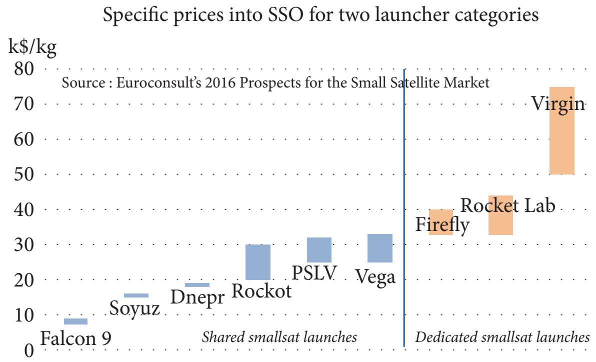

FIGURE 2: Specific prices for two launcher categories [10].

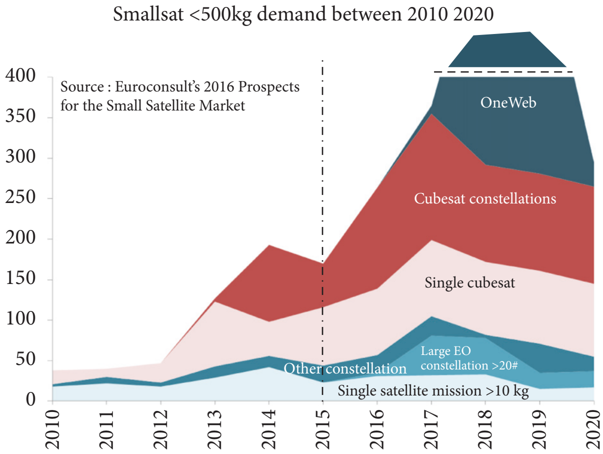

FIGURE 3: Number of small satellites in the last 15 years. [10].

More interestingly, these early attempts have paved the way to a new philosophy which has been aimed at implementing and exploiting very-low-cost satellites [10]. As reported in [3], the estimated production and launch cost for a single small satellite can be approximately assumed to span from $100,000$ to $200,000$ USD: particularly, in the case of shared small satellite, the launch unitary costs per kg can lower down to few kEuros, as sketched in Figure 2.

As a result, these unprecedented features of small satellites have been favourably considered by market forces which have been largely stimulated in the last thirty years and pushed to start a new gold rush in space, with original objectives and well-targeted applications such as Earth observation and communications, in the civil, military, and commercial dominions. Since the possible applications will be reviewed in the following section, it is now important to provide some rough numbers that can give the idea of how strong the new race to the space exploitation is.

Overall, 551 satellites ($< 400kg$) have been launched between 2010 and 2015, while the expectations for the successive five years are targeted on other 1380 launches [10]: these trends are shown in Figure 3. These numbers are confirmed by the 300 launches of nano/microsatellites which have been recorded in 2017 [1].

Moreover, three constellations for satcom and Earth observation accounted for 38% of the total and this share should grow up to 68% in the next 5 years driven by several large projects. As a result, this analysis unveils the main booster of the massive development of the small satellites: the ability to relatively easily build a constellation. This peculiar aspect will be considered in the following sections with a specific focus on the intersatellite communications.

Finally, it is worth introducing the main player of the massive increase of the number of small satellites: the CubeSat. The CubeSat has been designed as the goal of a Stanford University program which was started in 1999 to obtain a very low-cost/weight satellite which could be quickly developed and used for educational purposes [3]. Together with the California Polytechnic State University, Stanford University developed CubeSat specifications with the goal to obtain a customizable satellite, but with standard shape and weight, in order to simplify launch and deployment operations. As it is known, a CubeSat is made by one (1U) or more (nU) 10 cm X 10 cm X 10 cm units, with a mass of up to 1.33 kg per unit [11]. The nature of CubeSats has enabled the standardised production of subsystems that can even be purchased as a COTS product from online shops, so keeping the mission cost very low [9].

These peculiar features of the CubeSat solution have been very important in the fast increase of the small satellite missions and in the huge development of companies whose main core is in the new space market, such as Terra Bella (formerly Skybox Imaging), Spire, Planet Labs, and OneWeb, who are developing mega-constellations of small spacecrafts in LEO orbit [9].

3. Overview of Services and Applications

Around the year 2000, the SmallSats were able to properly exploit innovative COTS technological solutions (hardware and software), achieving the ability to compete effectively and to make profit. The successful growth of the modern SmallSats services, encompassing a large variety of application contexts, shall be analysed also based on a new management approach the small satellite organizations started to adopt: the agile methodology. This paradigm comes from the IT industry and it is based on a highly iterative design technique: well-defined objectives, missions and requirements, incremental changes to the design for a continuous improvement of the system performance, short timescale, and reduced cost. Agile approaches and the exploitation of the latest off-the-shelf technologies represent the two main drivers of the New Space Age [4].

In the following, a brief overview of the main applications and services of the SmallSats is provided. Since some of the following acronyms may be unknown to the reader, a comprehensive list is provided in Table 1.

(1) Earth Observation and Remote Sensing. So far, the primary use for nano/microsatellites has been Earth observation (EO) and remote sensing. The implementation of large satellite constellations allows performing many simultaneous and distributed measurements or observations (Earth resources

Table 1: List of the acronyms.

Acronym	Definition	Acronym	Definition
ACM	Adaptive Coding and modulation	ADC	Analog to Digital Converter
BP	Bundle Protocol	CCSDS	Consultative Committee for Space Data Systems
COTS	Commercial Off the Shelf	DLR	German Aerospace Center
DSA	Dynamic Spectrum Access	DSP	Digital Signal Processor
DTN	Delay Tolerant Network	DVB-S2	Digital Video Broadcasting - Satellite 2nd generation
EDRS	European Data Relay System	ELaNa	Educational Launch of Nanosatellites
EO	Earth observation	ESA	European Space Agency
FEC	Forward Error Correction	FPGA	Field Programmable Gate Array
FSK	Frequency Shift Keying	GEO	Geostationary Orbit
GPP	General Purpose Processor	GRACE	Gravity Recovery and Climate Experiment
GSTP	General Support Technology Programme	HTS	High Throughput Satellite
HTTP	Hypertext Transfer Protocol	HW	Hardware
ICN	Information-centric networking	IOT	Internet of things
IP	Internet Protocol	ISS	International Space Station
IT	Information technology	JPL	Jet Propulsion Lab
LDPC	Low Density Parity Check	LEO	low Earth Orbit
LTP	Licklider Transmission Protocol	LUCE	LUnar Cubesats for Exploration
LUMIO	Lunar Meteoroid Impacts Observer	MAC	Mean Access Control
MarCO	Mars Cube One	MEC	Multi-Access Edge Computing
MEO	medium Earth Orbit	MMIC	Monolithic Microwave Integrated Circuit
M2M	Machine-to-Machine	NASA	National Aeronautics and Space Administration
NC	Network Coding	NEA Scout	Near-Earth Asteroid Scout
NFV	Network function Virtualization	OPALS	Optical Payload for Lasercomm Science
OSIRIS	Optical Space Infrared Downlink	PICASSO	Pico-Satellite for Atmospheric and Space Science Observations
PRETTY	Passive REflecTomeTrY	QARMAN	QubeSat for Aerothermodynamic Research and Measurements on Ablation
QKD	Quantum Key Distribution (QKD)	QoS	Quality of Service
QoE	Quality of Experience	SCAN	Space Communications and Navigation
SDN	Software Defined Networking	SDLS	Space Data Link Security
SDR	Software Defined Radio	SOTA	Small Optical Transponder
SW	Software	TBIRD	Terabyte Infrared Delivery
TCP	Transmission Control Protocol	TTL	Time-To-Live
UHF	Ultra High Frequency	USD	US Dollar
USLP	Unified Space Link Protocol	VHF	Very High Frequency
VLC	Visible Light Communications	VMMO	Volatile and Mineralogy Mapping Orbiter

monitoring, weather monitoring, and disaster monitoring) with an increased temporal resolution of collected data (i.e., shorter revisit times) [12].

A more extensive use of small satellites for EO and remote sensing calls for higher and higher data rate links to download the acquired information in a short time.

(2) Science and Technology Demonstration Missions. Micro- and nanosatellites enable a wider access to space and represent an affordable test for young engineers and scientists to prove prototype systems and experience the idea of a future satellite. To this aim, NASA created the NASA Educational Launch of Nanosatellites (ELaNa), an initiative oriented to students of several disciplines (science, technology, engineering, and mathematics). A number of ESA CubeSat missions have been funded under the In-Orbit Demonstration part of the General Support Technology Programme (GSTP): GOMX-3 and GOMX-4B for demonstrating new capabilities of nanosatellites, QARMAN (QubeSat for Aerothermodynamic Research and Measurements on Ablation) for demonstrating re-entry technologies, PICASSO (Pico-Satellite for Atmospheric and Space Science Observations) for the analysis of the ozone distribution in the stratosphere, the temperature profile up to the mesosphere and the electronic plasma characterization in the ionosphere, RadCube for real-time monitoring of the cosmic radiation and space weather environment, and PRETTY (Passive REflecTomeTrY), a nanosatellite to measure and register ice on the glaciers or on the poles and wave movements of the oceans.

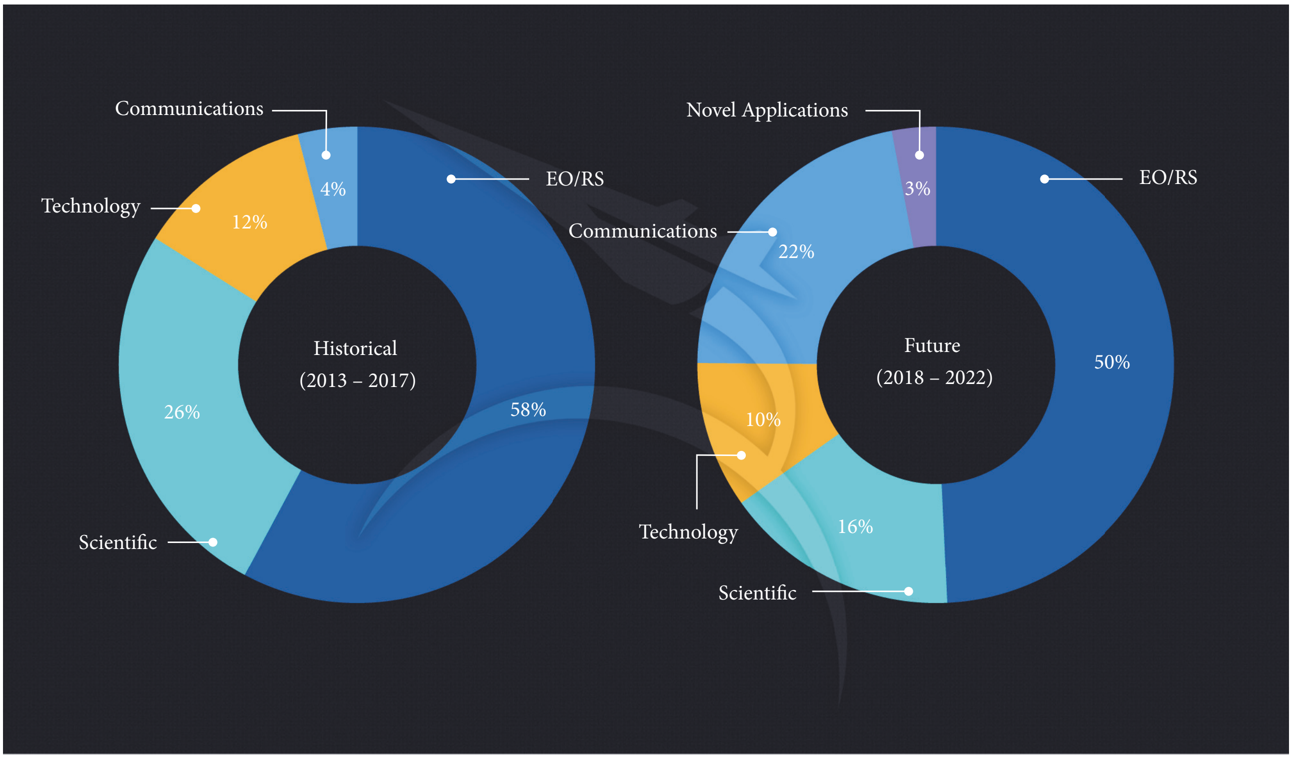

Figure 4: Nano/microsatellite market forecast, 8th edition, approved for public release, SpaceWorks Enterprises, Inc. (SEI), 2018.

(3) Interplanetary Exploration Missions. Small Satellite Platforms have led to a new era of space exploration especially thanks to new enabling technologies and new highly capable launch vehicles, which open many opportunities for future lunar and planetary exploration. National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) have adopted the Interplanetary CubeSat Model, supporting missions and studies, ranging from Mars and Lunar observation to the study of meteoroids and asteroids. Some of them are MarCO (Mars Cube One) [13], NEA Scout (Near-Earth Asteroid Scout) [14], LUCE (LUnar Cubesats for Exploration), LUMIO (Lunar Meteoroid Impacts Observer), VMMO (Volatile and Mineralogy Mapping Orbiter), Lunar Flashlight [15], and Arkyd series [16].

(4) Communications Services. Small micro- and nanosatellites organized in constellations can be used for providing data distribution (broadcasting applications) and data exchange (Internet of things and Machine-to-Machine paradigm) and also for extending the Internet access to the entire Earth [11]. According to Space Works Market outlook, in the next years, communication constellations of micro- and nanosatellites, which are now in the technology demonstration phase, will be used to serve and support the rapidly growing Internet of things (IOT) and Machine-to-Machine (M2M) market. Sky & Space Global, Kepler Communications, Hiber (Magnitude Space), Helios Wire, Astrocast, Blink Astro, Fleet Space, and Myriota are some of the main communications operators offering IOT/M2M and data relaying services.

An overview of the nano/microsatellite trends by application in the near term is provided in Figure 4 [1]. Although the analysis highlights that the primary use for nano/microsatellites will remain Earth observation and remote sensing, an increase of communications constellations is expected. SpaceWorks estimates that about 700 communications nano/microsatellites will require launch over the next 5 years.

(5) Commercial, Civil, and Military Applications. Transport, smart environments (including remote monitoring), quality of life, safety, and security represent the main application contexts of the adoption of small, micro-, and nanosatellites [17]. As examples of commercial constellation of nanosatellites, Aerial & Maritime and Sky & Space Global are two GomSpace commercial missions: the former is oriented to aircraft and vessel tracking for situational awareness, while the latter will provide a global communication infrastructure in space. Moreover, Astrocast has a project for offering global M2M services as remote monitoring, geolocalization, intelligent data collection, and predictive maintenance [18].

Figure 5 shows the SpaceWorks analysis on the Nano/Microsatellite Operator Trends: Military Operators (aiming to support national defense activities), Commercial Operators (whose purpose is profit revenue generating activities),

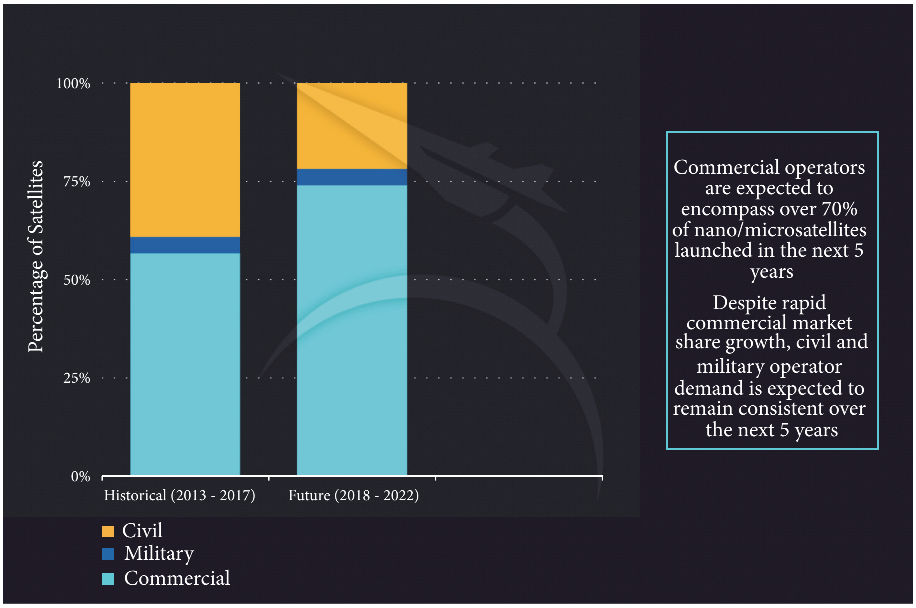

Figure 5: Nano/microsatellite market forecast, 8th edition, approved for public release, SpaceWorks Enterprises, Inc. (SEI), 2018.

and Civil Operators (nonmilitary or non-profit activities) are considered

4. Payload Evolution

In the early implementation of small satellites, mainly used as a platform for university and technology development projects [19], the payload was supposed to perform very simple operations such as transmission of a beacon, storing data or transmitting data collected by simple sensors at very low data rate (1 to 9.6kbps). Amateur frequencies at UHF were mainly used and operated via the standard AX.25 [20]. At such low frequencies, wire antennas (dipoles, monopoles, and helical) are especially common as the wavelength is long and achieving good radiation efficiency within a small volume is challenging. A considerable number of the CubeSats that are currently in space use wire antennas for their simplicity of implementation. Moreover, the omnidirectionality of dipoles makes them viable candidates for intersatellite communications. Emerging applications and the associate need for transmitting at higher data rate or performing more complex tasks, keeping low mass and weight, have raised the need for larger bandwidths and higher-frequency bands, an increasing request of digital implementation and SW control.

4.1. Evolution in the Frequency Bands and Antennas. In recent years, the use of higher frequencies than the common VHF/UHF bands such as S-Band (mainly for telemetry) and X-Band (for data transmission) has become more widely available thanks to the advent of commercially available Monolithic Microwave Integrated Circuits (MMICs). The shift towards higher-frequency bands implies other requirements on the spacecraft design, mainly on the power system and the antennas. For instance, already at frequencies higher than S-band, the efficiency of solid-state high-power amplifiers drops from 80% (at UHF) to 30%. At such frequencies, most common antennas are still wire antennas or planar antennas, such as patch and slot antennas. Patch antennas have gained special attention for CubeSats, as they are relatively easy to fabricate. A variety of patch antenna designs have been investigated at S bands. Downlinks on S-Band would be expected to be able to implement data rates from 100 kbps to 1 Mbps. Larger data rates require the use of higher-frequency bands such as Ku-, K-, and Ka-band, which are the state of the art for large spacecrafts, but they are still young technologies in the small satellite world. A Ka-band transmitter on a CubeSat began orbital operations in 2015 [21]. At such higher frequencies, it is possible to implement also high-gain reflector antennas which can meet the strict size and weight requirements of a small satellite. Reflectarray antennas are also very suitable, as they provide high gain and can be easily integrated with the CubeSat structure. Their structure consists of flat panels, which can be folded and stowed on the CubeSat [5]. In [22], the development of a reflectarray for the Mars Cube One (MarCO) is described. MarCO is the first CubeSat mission designed for Mars operation. The frequency of operation in this case was 8.425 GHz, with a measured gain of 29.2 dB.

As a matter of fact, small satellites also represent a viable and cost-effective way to test new frequency bands for satellite communications (both in terms of HW components and propagation channel), such as W-band [23]. The investigation of such high-frequency bands is mainly motivated by the need of bandwidths in High Throughput Satellites [24]. On the other hand, those frequencies could be an interesting option for intersatellite links of small sats [25]. At Q/V and W-band, horn antennas can be a viable option for small sats as they provide good gain and could be fabricated also for university experiments [26]. A potential horn design that could

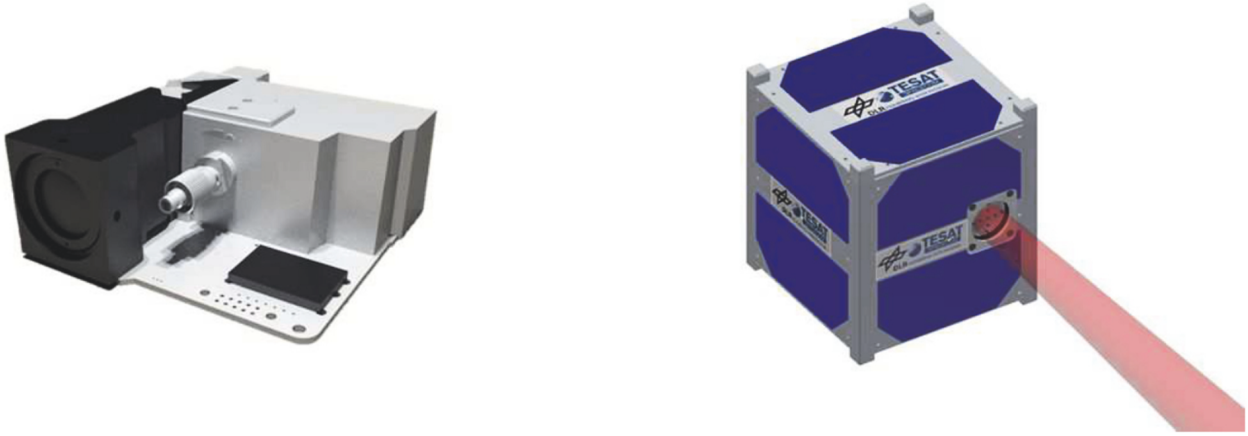

Figure 6: Left: CAD-model of OSIRIS4Cubesat terminal. Right: Artist's impression of terminal integration in 1U Cubesat [35].

be considered for future Ka-band CubeSat communication is discussed in [27, 28].

The need of higher data rates, low cost, and small size has also moved the attention towards FSO communications, especially for intersatellite links as presented in the next section.

4.2. Laser Communication Terminals for Small Satellites and CubeSats. In recent years, free-space optical communications have become a mature alternative to traditional RF communication systems. With the use of laser communication terminals in systems like the European Data Relay System (EDRS) [29] for intersatellite links, the technology has passed the barrier from research to the operational application. Concerning downlinks from satellite to Earth, a number of demonstrations have been performed in recent years, like the Small Optical Transponder (SOTA) experiment [30] of the National Institute of Information and Communications Technology, which used a dedicated satellite, or the Optical Payload for Lasercomm Science (OPALS) experiment [31] of the NASA's Jet Propulsion Lab (NASA-JPL), which demonstrated optical downlinks from the International Space Station (ISS). The Aerospace Corporation demonstrated an optical downlink from a 1.5U-CubeSat [32]. Even optical links from the Moon to Earth have been demonstrated [33].

A number of further demonstration missions are currently planned, such as NASA's Terabyte Infrared Delivery (TBIRD) mission, aiming at demonstrating a 100 Gbps link from a CubeSat to ground [34], or within the Optical Space Infrared Downlink (OSIRIS) programme of the German Aerospace Center (DLR), which aims at demonstrating optical downlinks from small satellites and CubeSats to Earth [35].

Practical implementations of current optical communication systems for small satellite applications may reach data rates of about 10 Gbps with a terminal weight in the order of 5 kg and a power consumption of about 50 W. For applications on CubeSats, Figure 6 shows OSIRIS4 CubeSat implementation as an example. The terminal weighs in the order of 300 g, consumes 8 W of electrical power, and requires only 0.3U of space within the CubeSat. It reaches a data rate of 100 Mbps. OSIRIS4CubeSat will be offered on the market by DLR's commercialization partner Tesat Spacecom under the market name *CubeL*.

An important challenge in optical satellite-to-ground communications is the limited availability due to clouds. This can be overcome by employing a world-wide network of optical ground stations. By using a sufficient buffer memory onboard the satellites, this enables overcoming the issues due to limited availability of the space-to-ground link [36]. Although most optical ground stations available to date have been developed mainly for research purposes, both new and established ground segment operators have expressed strong interest in building up the required infrastructure. Thus, it is only a matter of time until optical links can be used in an operational manner, even in small-satellite applications.

4.3. Towards SDR Payloads. Since the early development of small satellites, one trend in the payload design can be identified: privileging the use of low-cost COTS and in general HW components and moving towards a digital implementation. Thanks to the availability of modern high-speed and low-power digital signal processors and high speed memories, the trade-off between the HW/SW implementation is moving more and more towards the SW implementation and the concept of SDR. SDR is an evolution of flexible and reconfigurable payloads. An early adopter of reconfigurable technology for space applications was the Australian FedSat microsatellite communications payload launched in 2002. The FedSat communications payload utilized Field Programmable Gate Array (FPGA) components for baseband digital signal processing and included a code upload mode allowing it to be reprogrammed while in orbit [9]. The evolution from reconfigurable and reprogrammable devices to SDR has been driven by the demand for flexible and reconfigurable radio communications in support of military and public safety operations and it has been pushed by advances in the enabling technologies such as Analog to Digital Converters (ADCs), General Purpose Processors (GPPs), Digital Signal Processors (DSPs), and FPGAs. SDR payloads are considered as a needed technological step in traditional satellite systems for assuring a longer lifetime and a more efficient resource utilization [37], even if so far, few SDR payloads have flown on big satellites. For small satellites, which are designed with few years of lifetime in mind, the reason for moving towards SDR payloads is mainly related to the offered flexibility to adapt to new science opportunities and potentially reducing development cost and risk through reuse of common space platforms to meet specific mission requirements. SDR can be used to support multiple signals, increase data rates over reliable intersatellite and ground links to Earth, and also help in facing the shortage of available frequencies for communications in the more crowded bands. As a matter of fact, the use of an SDR approach also allows implementing Dynamic Spectrum Access (DSA) techniques and hence a more efficient spectrum utilization. To date, no satellite application of DSA is in use, although companies such as Tethers Unlimited (U.S.), with funding from NASA, are looking at upgrading SDR platforms with advanced cognitive radio.

The challenge of this more digital approach is related to one of the strong limitations of a small satellite: power consumption. For this reason, FPGA has been preferred so far, especially for higher data rates in the X- and Ka-band, as they allow performing compute intensive tasks in parallel and use more efficiently every clock cycle [38]. Additionally, modern FPGAs have embedded processing systems, such as ARM cores, integrated inside the FPGA. Few SDRs have already flown in small satellites and other are under development, e.g., AstroSDR, NanoDock SDR, GAMALINK, and STI-PRX-01. It is definitely a hot topic of research and development, and there is growing interest in developing and testing new solutions. Pinto et al. [39] exploited SDR in small satellite systems to design an intersatellite communication model which could be easily reconfigured to support any encoding/decoding, modulation, and other signal processing schemes. In [40], a novel SDR architecture on an embedded system is proposed, whose potential applications are the ground station for multisatellite communications, deployable mobile ground station network, and can be further extended to distributed satellite system.

A new generation of SDR technologies have been integrated in the SCAN Testbed (Space Communications and Navigation Testbed), which is an advanced integrated communications system and laboratory facility to be installed on the International Space Station (ISS), to develop, test, and demonstrate new communications, networking, and navigation capabilities in the space environment [41]. The SCAN Testbed consists of reconfigurable and reprogrammable SDR transceivers/transponders operating at S-band, Ka-band, and L-band, along with the required RF/antenna systems necessary for communications.

5. New Telecommunication Architectures

Small satellites are playing an increasingly important role in telecommunication architectures in two main ways:

(i) They are increasingly used to form application-focused segments of the infrastructure supporting existing communication architectures, notably the Internet.

(ii) They also form and/or utilize altogether new, distinct communication architectures.

5.1. As Supporting Infrastructure. The use of Earth-orbiting satellites to conduct Internet traffic is of course not new. From TELSTAR in 1962 through Iridium, Globalstar, ViaSat, and EchoStar, the market for relaying data via radio links to satellites has grown rapidly. But historically, those satellites have been large and expensive, whether operating in LEO or GEO orbits. What is new is the use of large numbers of small satellites for this purpose. The field has grown rapidly in recent years as new concepts are proposed; many of them highly ambitious:

(i) The OneWeb constellation is initially expected to comprise 882 small Internet service delivery satellites in LEO orbit, potentially growing to 2620 satellites [42].

(ii) Samsung has proposed a 4600-satellite constellation, projected to be able to carry one billion terabytes of Internet data per month [43].

(iii) The SpaceX corporation's Starlink constellation is envisioned to comprise up to 12,000 small satellites in LEO orbit, with the capacity to carry up to 10% of local Internet traffic in densely populated areas [44].

5.2. As Participants in New Architectures. In addition to supporting the propagation of traffic within the Internet, however, small satellites require new, increasingly capable telecommunication architectures to sustain their own operations. Coordination among satellites in LEO orbit relies on cross-links between satellites, relay services provided by ground stations (typically via the terrestrial Internet), or a combination of both. This capability is critical for constellations such as the GRACE (Gravity Recovery and Climate Experiment) mission and the QB-50 project.

Moving farther, the twin MARCO spacecrafts (each a 6U CubeSat) accompanying the InSight spacecraft on its mission to Mars will primarily serve to relay information from the InSight lander to its mission operations center on Earth, while the lander is engaged in entering the atmosphere of Mars, descending to the surface, and landing. As shown in Figure 7, the link from InSight to each MARCO orbiter will be in the UHF band, while the MARCO vehicles communication with Earth will be by X-band radio transmission. Each MARCO can use only one of these links at a time, so the communication architecture will be very different from the continuous end-to-end connectivity that characterizes Internet traffic.

Projecting that deviation from the Internet traffic model back to high-volume terrestrial communications, a satellite communications architecture that is designed to tolerate the associated delays in end-to-end communication on a large scale has been proposed. The "Ring Road" architecture [45]

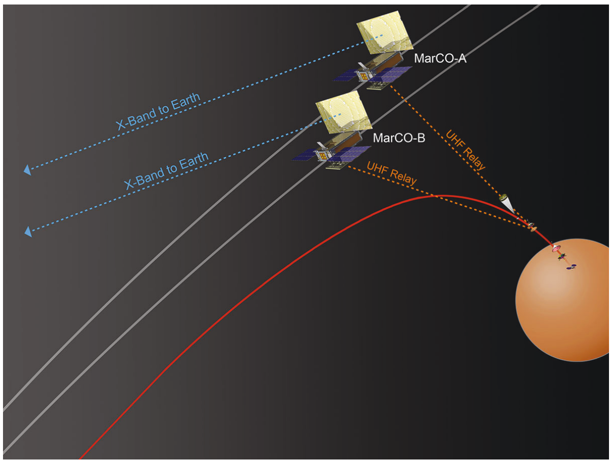

Figure 7: The MARCO communication architecture. Image credit: NASA/JPL-CalTech.

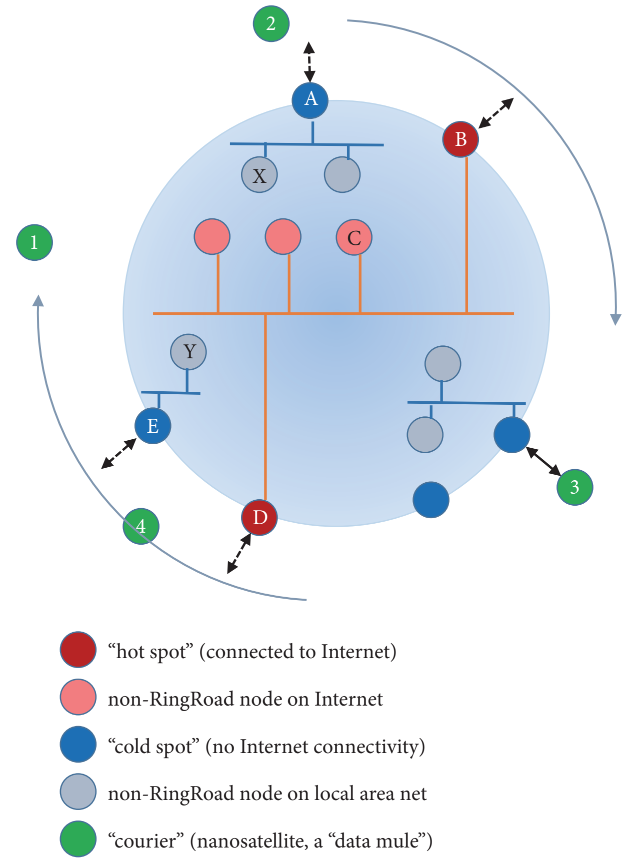

Figure 8: The Ring Road network architecture [45].

is based on the use of delay-tolerant networking (DTN) protocols [46], discussed later. The basic idea is to deploy, gradually, one satellite at a time, a constellation of DTN Bundle Protocol (BP) [47] routers in LEO orbit. As shown in Figure 8, the network encompasses three classes of DTN nodes:

(i) Router satellites, called "courier" nodes, in polar orbit

(ii) Nodes residing in computers that are attached to the Internet, called "hot spots"

(iii) Nodes residing in computers that are highly isolated, with no electronic connectivity, called "cold spots."

The constellation operates as follows:

(i) A user at a cold spot node issues data in a bundle (such as an email message or an HTTP proxy query). The node queues the bundle up for transmission to the next courier that flies overhead [48].

(ii) Eventually, a courier flies over the cold spot. The courier's orbit is well known, so the contact between the courier and the cold spot can be scheduled far in advance. The courier and cold spot begin communications using BP over LTP (Licklider Transmission Protocol [49]; see more details in the next section) over whatever radio frequencies are available. Bundles from elsewhere that are destined for this cold spot called "forward traffic" are transmitted from the courier to the cold spot node for forwarding within the local network, if any. Bundles issued from the cold spot called "return traffic" are transmitted to the courier and queued on-board for future transmission.

(iii) The courier computes a route for each bundle it receives from the cold spot. It knows about its own future scheduled contacts, so any bundle that is destined for some other cold spot that the courier will reach before the bundle's TTL (Time-To-Live) expires is queued for future transmission to that cold spot. All other bundles are queued for transmission to the next hot spot the courier will fly over.

(iv) When the courier flies over a hot spot, the queued bundles are transmitted to the hot spot and the courier receives bundles that the hot spot node has queued for transmission to that courier.

(v) When a hot spot node receives bundles from a courier, it computes a route for each bundle. If the bundle's destination endpoint is directly reachable via the Internet (e.g., a database server in Montreal), then the hot spot uses BP over TCP/IP to send the bundle immediately to that endpoint. Otherwise, the hot spot consults the contact schedule to determine which courier has the earliest scheduled contact with the destination cold spot and then reconsults the contact schedule to determine which hot spot has the earliest scheduled contact with that courier. If the first hot spot that will see that courier is the local hot spot itself, then the hot spot simply queues the bundle locally for future transmission to that courier; otherwise, it uses BP over TCP/IP to send the bundle immediately to that computed best-way-forward hot spot.

(vi) When a hot spot node receives bundles from some node in the Internet (possibly another hot spot), it computes a route for each bundle as above. When a courier flies overhead, it exchanges bundles with the courier. When the courier subsequently flies over a cold spot, it exchanges bundles with it in the same way, and so on.

The concept offers a number of advantages:

(i) Unlike a crosslink-based routing-fabric constellation, there is no need to orbit the whole constellation all at once in order to get data moving. The network could begin with one hot spot, one cold spot, and one courier. In that case, the round-trip time for the cold spot would be very long as there would be only one contact per N orbits of the satellite, where N is however many orbits would be needed to bring the cold spot back into the satellites ground track. Nonetheless, bidirectional data flow between the cold spot and any point on the Internet would be reliably supported, albeit at very low effective data rates. As more satellites are added, the frequency of coverage of any given cold spot increases and N drops, which increases the carrying capacity of the network as a whole (the aggregate storage capacity of all the couriers), so that the number of cold spots supported can increase. Adding more hot spots on the ground would also incrementally increase the carrying capacity of the network, by enabling earlier drainage of the return-traffic bundles in couriers' onboard storage and thereby making room for more bundles, which would further increase the number of supportable cold spots you could support.

(ii) While the routing is somewhat complex, it takes place in potentially powerful ground-based computers at hot spots, not in the courier satellites. This means that small, mass-produced satellites can be suitable as couriers.

(iii) All elements of the architecture are, therefore, relatively inexpensive.

As a conclusion, this SmallSat-based architecture could enable very widely available network data service at low cost, starting with a very modest initial investment.

5.3. Integration with Terrestrial Architectures. The potentials offered by Small- and CubeSats constellations from a service point of view have to be analysed from a wider angle in order to consider the data availability from different stakeholders. In the case of processing centres placed nearby control centres or in any case directly connected to them via dedicated terrestrial infrastructure, the architecture design may essentially consist in the extension of the exemplary one illustrated in the previous subsections. This can be achieved by terminating the proposed DTN architecture directly at the processing centres or by making use of *specialised* gateways capable of interfacing native DTN architectures with non-DTN aware counterpart (i.e., in the case of legacy networks building on *pure* TCP/IP protocol architectures).

On the other hand, the increasing interest towards the service provided by small satellite constellations may result in distributing data to enterprises, universities, schools, public authorities, and single users for different applications (e.g., space data exploitation, education purposes, surveillance and monitoring, etc.). In this context, data retrieval will likely happen over Internet terrestrial infrastructure, hence calling for proper integration strategies to be deployed between the ground segment of the small satellite system and the core terrestrial network. This integration task can be easily considered in the broader plan of converging satellite and 5G networks [50] (and papers included in that special issue), which has recently become a hot topic for the satellite industry. Without entering the details of the architecture proposals [51] elaborated to meet this goal, it is of pivotal importance to provide a flexible integrated architecture. Network flexibility is indeed recommended in order to ensure proper coexistence of existing Internet flows and small satellite data retrieval, which may be regarded in terms of different network slices, each characterised by diverse QoS/QoE characteristics. To this end, the implementation of proper SDN (Software Defined Networking) and NFV (Network Function Virtualization) solutions is desirable, so as to achieve also the "softwarisation" of the satellite network, whose understanding is however still not complete and will deserve additional studies for the case of small satellite constellations.

Still related to the objective of distributing small satellite data across the Internet is providing the network architecture with content-oriented functions in order to differentiate QoS management and routing functions applied to the data objects obtained from the small satellite systems. This may suggest the application of the existing Information Centric Networking architectures [52], whose baseline concept should be however adapted in order to meet the content characteristics of the data objects retrieved from the satellite systems and to interface with the network architecture (e.g., DTN-based) proposed for the satellite network (as illustrated in the previous subsection).

In more detail, ICN-based architectures build on publish-subscribe (*pub-sub*) paradigms, so that users subscribe to content distributions services and accordingly contents are distributed upon request reception. One of the main peculiarities of ICN networks is in that contents are explicitly mapped to *object names*, which enable more advanced content-aware routing and security schemes. Moreover, this approach helps implement a content-centric networking approach, hence superseding the typically employed host-centric approach (i.e., as implemented in IP-based systems), where locations and content descriptions are mapped into a unique identifier (e.g., IP address), hence posing some limitations on implementing content-based networking functions. Another intrinsic key advantage of ICN networks is to implement distributed caching functionalities throughout the entire network, hence possibly simplifying the integration of MEC (Multi-Access Edge Computing) and Cloud Computing functionalities, which are pivotal building blocks in the modern communication networks.

ICN functionalities are typically supported by specialised networking elements, i.e., ICN routers, which can be deployed not only in terrestrial networks, but also in the space counterpart, provided that satellites offer the necessary

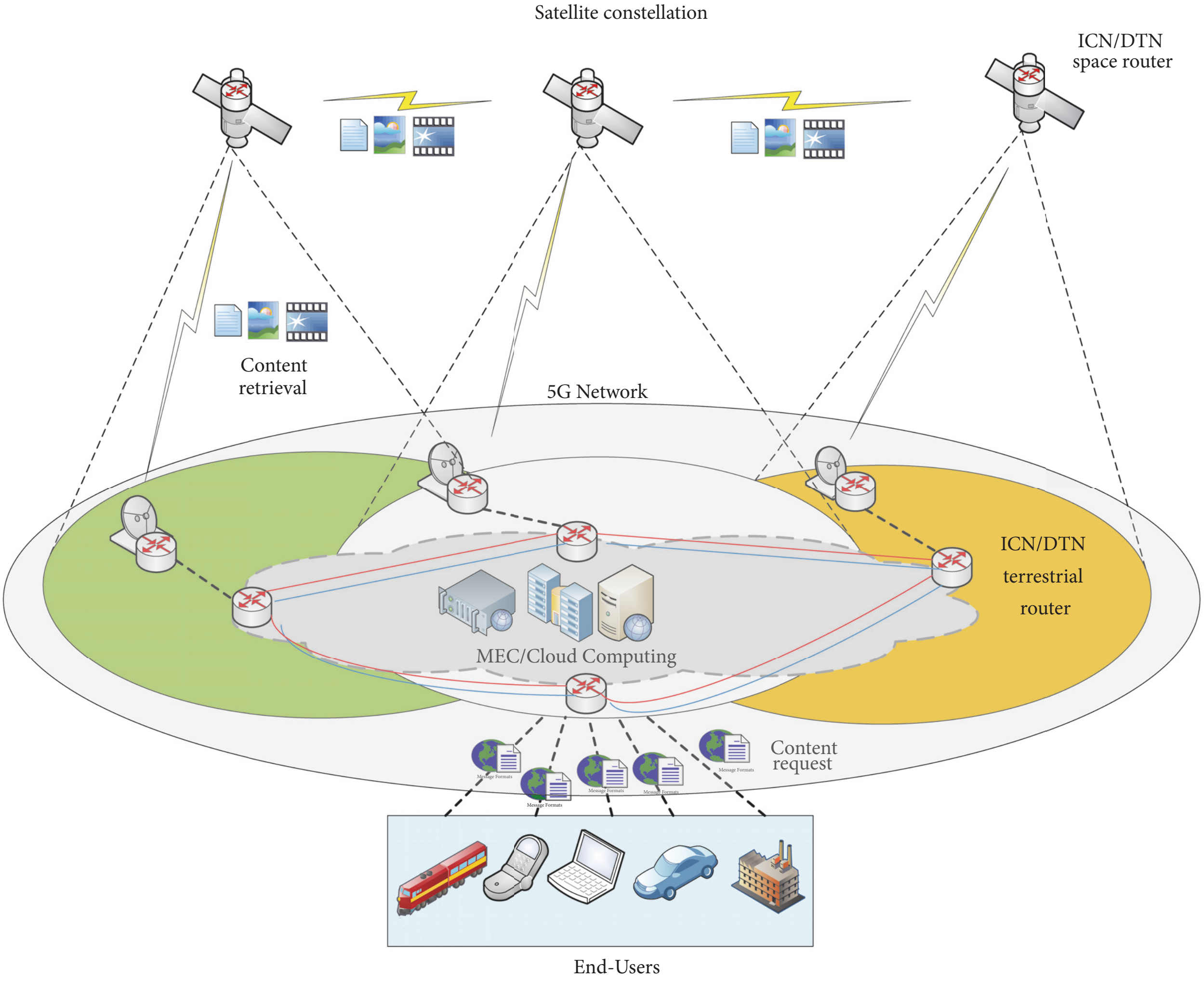

Figure 9: Integrated satellite-5G network based on ICN/DTN concepts for content delivery [52].

storage and computing capabilities. As a matter of fact, the coexistence of DTN- and ICN-based protocol architectures in the same network deployment is possible in order to exploit the main advantage offered by the two with respect to disruption resilience and caching, although specific adaptations of the protocol interfaces are necessary (not treated in this paper as beyond the scope).

In general, the overall network architecture encompassing 5G and satellite segments, building on ICN/DTN architectures, and interacting with MEC and cloud computing elements is exemplified in Figure 9, where the case of a satellite constellation complementing a 5G access network to boost the content delivery is sketched.

6. Advances in Communications and Network Protocols

New protocols for communication with and among small satellites have emerged rapidly in the past decade. The new capabilities are provided at multiple layers of the protocol stack.

6.1. Physical Layer. Originally, the only communication links supported for CubeSat satellites were UHF links operated via AX.25. Given the low requirements in terms of data rate of most of the original, mainly scientific, missions, simple modulation schemes have been used, such as binary-FSK [53, 54]. It is also worth outlining that the AX.25 protocol allows detecting errors but not correcting them. The emerging need for transmitting at higher data rate and keeping low mass and weight is pushing to use larger bandwidths and higher-frequency bands, as reported in Section 4, but also to use more efficiently the available bandwidths through more advanced modulations schemes. Moreover, the shift towards SDR payload and ground stations, made possible by the rapid evolution of digital electronics, opens the opportunity to implement more advanced communication protocols and modulation schemes, including error correction capabilities and dynamic adaptation of modulation parameters depending on the current link conditions [55]. This has motivated some theoretical studies on the choice of the most appropriate modulations [56, 57]. However, there are already some innovative transceiver designed for CubeSat and Small Satellites using higher-frequency bands such as X-band up to Ka-band, implementing Variable and Adaptive Coding and Modulation (VCM, ACM) capabilities [58, 59]. For instance, RADIOSAT is an innovative transceiver developed by ESA, working at a Ka-band and integrated with a DVB-S2 modem, overall characterized by low power consumption. On the design of intersatellite link, it is worth mentioning the recent studies on the use of Visible Light Communications (VLCs), which can provide higher data rates with smaller, lightweight nodes, while avoiding the usual interference problems associated with RF, as well as the apparent radio spectrum scarcity below the 6 GHz band. Furthermore, the electronics required for achieving precision pointing accuracy for laser communication systems will be avoided. With approximately 300 THz of free bandwidth available for VLC, high capacity data transmission rates could be provided over short distances using arrays of LEDs [60].

6.2. Link Layer. While operators of Earth-orbiting CubeSats initially had few options beyond AX.25, new and more capable protocols that are suited for space flight operations at Earth and beyond Earth orbit are becoming available. The new CCSDS Unified Space Link Protocol (USLP) [61] is designed to be adaptable to a very wide range of space data transmission conditions. It includes a "virtual channels" concept that enables a single physical link to be transparently shared among multiple data streams at higher layer, together with further multiplexing accommodation multiplexer access points that enable multiple data services to share a single virtual channel. It also provides mechanisms for aggregating small service data units and segmenting those aggregations, for extensive control over the sizes of protocol data units. CCSDS has also defined a security service at the link layer, called Space Data Link Security (SDLS). Security is rapidly becoming an urgent concern of space flight mission designers, as security breaches at ground stations and mission operations centers served by the Internet grow ever more troublesome. SDLS provides a security standard for simple space flight missions, where a single spacecraft is in contact with its control center through a ground station. It includes data origin authentication, connection and connectionless confidentiality, connection integrity with and without recovery, and connectionless integrity.

6.3. Network Layer. DTN concepts date back to the early days of the Interplanetary Networking Research Group of the Internet Research Task Force. DTN is a network architecture that is aimed at eking as much data communication as possible out of inhospitable networks—in particular, those where link interruptions (whether anticipated or not) are frequent and significant and/or where signal propagation latency is high. The effects of high delay and of disconnection are in fact similar in many ways, and the network architecture features developed for DTN serve to mitigate both. The central fact in both circumstances is the potential inability of each network node to request timely assistance from any other, for any purpose, and at any given moment. The unifying principle in the design of the features of DTN, then, is recognition of this fact. Nodes must be able to make their own operational decisions locally, on their own, with global information that may well be stale or incomplete, and the network must be able to continue to operate at some useful level even when these decisions are flawed. The core protocol of DTN is BP [47], a network-layer protocol that functions as the DTN analog to the Internet Protocol. BP is similar to IP in that a BP node receives data issued by an application entity, stores the data in some medium, and forwards the data through the network toward the node serving the application entity that is the destination of the data. It principally differs from IP in that a forwarding node does not immediately discard data items (called "bundles") for which no onward communication link is currently available; instead, it may store bundles for a lengthy period of time, waiting for a link to become available. The DTN analog to the Internet's TCP is the LTP [49]. An LTP "engine" divides an outbound bundle into small "segments" and transmits the segments to the LTP engine serving the BP node that BP has determined to be the best next proximate destination for the bundle the next step on the bundle's end-to-end path. Both LTP and TCP account for transmitted data, detecting data loss and automatically recovering from that loss by retransmitting segments as necessary. The principal difference between LTP and TCP is this:

(i) In TCP, the entity that discovers and reports data loss is the TCP instance serving the application entity that is the destination of the data, and the data loss is reported to the TCP instance that serves the application entity that was the source of the data. That is, retransmission is "end-to-end" and TCP is situated above IP in the Internet protocol stack.

(ii) In a space flight mission scenario, end-to-end retransmissions could result in extremely lengthy delays in data delivery because the source and destination of data might be on different planets separated by many light minutes of propagation latency. In LTP, data loss is instead reported to the LTP instance at the proximate source of the data (the immediately prior BP node on the end-to-end path), which retransmits the lost segments as early as possible. LTP retransmission is "point-to-point" within the network, and LTP is situated below BP in the DTN protocol stack.

Complementary to the use of DTN protocol solution is the exploitation of network coding (NC) [62] for improving the robustness of data transmission as well as optimised use of the available network resources (i.e., bandwidth). Taking as reference the case of Ring Road network model for small satellite constellations, network coding can be applied on all the network nodes (i.e., on the space and ground segments) [63]. In this case, network coding functionalities would actually consist in online (*on fly*) encoding and decoding functions. In more detail, each NC-enabled node will be in charge of collecting a given number of information packets and to encode them so as to generate a certain number of redundancy packets, where the overall network coding configuration plays an important role in what concerns both the specific number of input information and output redundancy packets as well as the adopted coding strategy [62]. In this respect, the use of random linear network coding has gained quite some popularity in the last two decades, so that it is nowadays considered on the most appealing approach to implement NC in real network deployments. In particular, the application on random linear network coding of data chunks to be dumped to ground stations would help increase the reliability of data exchange against sporadic fluctuations of the transmission channel quality. Moreover, the network coding can be also exploited to transmit a reduced number of data packets, hence improving the actual bandwidth utilisation. This advantage can be particularly relevant if multicast data communications are exploited [64, 65], so that the performance advantages recognised for network coding can be fully exploited.

On the other hand, in spite of the aforementioned advantages, it is also worth considering the complexity implications arising from the implementation of network coding on the space segment [66]. As a matter of fact, network coding implementation requires some dedicated computation capability for online coding functions as well as specific on-board storage to keep temporary copies of the data chunks being subject to encoding or decoding procedures. Moreover, some attention has to be also paid to the protocol layer wherein network coding is being applied, so that often either (i) layered or (ii) integrated approaches are considered [67]. In the former, NC is implemented as a dedicated shim layer placed in between existing protocol layers in order to have a limited increase in the overall system implementation. In the latter, instead, NC functionalities have to be incorporated in an existing protocol, hence increasing the overall implementation complexity. Another point relates to the actual position of NC functionalities in a protocol stack, for which no specific consensus has been reached yet. On the one hand, it would be desirable to keep NC implementation as much closer as possible to the lower layers of the protocol stack (i.e., datalink) in order to have a more efficient recovery of possible packet losses. On the other hand, implementing NC in the upper layers of the protocol stack would help matching more precisely the characteristics of data services and eventually also meet the corresponding QoS requirements. In this respect, a good compromise could be to implement NC functionalities directly within the bundle protocol or immediately beneath it as part of any of the convergence layers (i.e., UDP or LTP) considered for that specific mission design. As such, it is immediate to see that all these requirements have to be properly taken into account in the full system design, with respect to the capabilities offered by existing satellite payloads and the actual service requirements to be targeted by the considered system.

Another interesting point related to the use of network coding in the proposed network architecture is about their use in the form of [67] for mitigating packet losses. In this case, network coding is not implemented throughout the entire network, but only limited to the network legs exhibiting more challenges from a communication reliability point of view. As such, no re-encoding functionalities are necessary (as those made possible by random linear network coding) and on the contrary classical packet layer FEC solutions can be considered, i.e., based on LDPC or Reed-Solomon codes. In this respect, some proposals have been already worked out by CCSDS with reference to the case of erasure codes applied space downlinks [67], where the potential of LDPC-based erasure codes was exploited especially for the case of free-space optical link communications. Although in this case, network coding is implemented only on specific links, the node capability to implement encoding/decoding functionalities as well as to store data prior to processing functions is certainly an important requirement to be taken into account in the system design phase in the light of the typically resources-constrained implementations of nodes in space. Other activities looking into implementation of network coding for intersatellite links have been also considered, although the aforementioned constraints coming from the space segments were not completely taken into account, hence requiring additional study for a deeper understanding of all underlying implications and requirements.

7. Perspectives and Open Challenges

The paper has reviewed the state of the art of small satellite systems, highlighting the distinctive features enabling novel applications and focusing on telecommunication services.

The provision of advanced Internet services through mega-constellations of pico/nanosatellites is going to become reality in the near future. However, several challenges must be faced yet, which are summarized in the following.

(i) *Physical Layer.*

  (a) The use of frequency bands higher than Ka-band and the use of free space optical (FSO) communications for Earth-satellite links (i.e., not only for intersatellite links), as reported in Section 4, raise one important challenge: the propagation channel can be strongly attenuated. Both for high frequency RF transmission and for FSO, this issue could be overcome by providing a ground network with a high number of ground stations at highly diverse sites. The concept of site diversity has been extensively studied in the field of High Throughput Satellite (HTS), and recent works have highlighted the fact that SDN paradigm could provide the gateways implementing the concept of Smart Diversity, a high level of reconfigurability that could allow efficient resources allocation during traffic switching events [68].

  (b) Besides the few theoretical studies mentioned in Section 6.1, and some transceiver implementing ACM techniques, much more work is needed to design optimized modulation and coding schemes able to satisfy strict requirements in terms of mass, weight, size, and power consumption.

(ii) *MAC Layer.*

In view of emerging system constraints, the implementation in small satellites of the scheduled and random-access MAC protocols adopted in existing satellite networks needs further investigation.

(iii) *Upper Layers.*

Definition is needed for interoperable application-layer protocols to be employed on top of the lower layer satellite protocols, addressing a wide range of application scenarios and traffic data configurations.

(iv) *Routing over Time.*

Due to the frequent topology changes in a CubeSat network, successful data delivery will require ample long-term storage at intermediate nodes to deal with satellite link disruptions.

(v) *Security Issues in LEO Satellite Networks.*

Telemetry, command and control messages, and mission specific data are sent through radio links. Therefore, security concerns arise. CubeSats are susceptible to Denial of Service (DoS) attacks as well as eavesdropping and data can be accessed by unauthorized user. The attacker could send spurious commands causing excessive resources consumption, data loss, or mission failure. Security challenges are exasperated by the use of SDR payload which opens the possibility of placing new software on the SDR unit through unauthorized and potentially malicious software installed on the platform [69]. Another security concern that has been raised recently is related to the use of small satellites that have propulsion systems and they could be hacked and endangering other satellites [70]. As also reported in Section 6, communication protocols currently implemented for CubeSat have almost no security features. Security mechanisms developed for conventional terrestrial networks, characterized by lengthy handshake exchanges and substantial computational effort, can hardly be directly applied to networks of small satellites. Power, space, and weight constraints related to CubeSat pose challenges in implementing complicated encryption schemes and computational expensive mechanisms [3]. Scientists are already working on them [71, 72].

The challenge is still open. Interesting works are ongoing on the use of physical layer approaches to security in satellite communications [73, 74]. No specific work on application of physical layer security to CubeSat can be found; even this could open novel solutions to overcome the challenges of security in the small satellite framework.

Interesting research is ongoing on the use of quantum cryptography. Some missions have been designed and developed, using nanosatellites and CubeSats, which show the feasibility of ground-to-space quantum key distribution (QKD) [75–78]. QKD uses individual light quanta in quantum superposition states to guarantee unconditional communication security between distant parties. Satellite-based QKD promises to establish a global-scale quantum network by exploiting the negligible photon loss and decoherence in the empty outer space. No eavesdropping can take place as the distribution of entangled photons between the ground and the satellite is used to certify the quantum nature of the link. By placing the entangled photon source on the ground, the space segments contain "only" the less complex detection system, enabling its implementation in a compact enclosure, compatible with the 12U CubeSat standard [75]. In [76], a LEO satellite has been developed and launched to implement decoy-state QKD with over kHz key rate from the satellite to ground over a distance up to 1200 km, which is up to orders of magnitudes more efficient than that expected using an optical fiber (with 0.2 dB/km loss) of the same length. In [78], it was demonstrated that a 4 kg CubeSat can generate a quantum-secure key, which has so far only been shown by a much larger 600 kg satellite mission.

(vi) *Adoption of the SDN/NFV.*

It is clear that SDN/NFV paradigms will play a key role in the integration of satellite systems with 5G. However, the use of SDN/NFV in a network of small satellites has yet to be investigated; as discussed in Section 6, it could be important. Indeed, small satellite network deployments could accelerate the infusion of SDN concepts into satellite systems. For instance, on-board SDN-compatible routers could be developed and operated on small satellites as router functions migrate into software.

It is worth mentioning that 3GPP Service and system Aspects (SA) activities have identified satellite systems both as a possible solution for stand-alone infrastructure and as complements to terrestrial networks [79]. In this framework, HTS systems could play a key role in some of the 5G application scenarios once they will be able to provide extremely high data rate.

However, in many other 5G applications scenarios that focus on M2M communications or require extremely low latency, only small satellite constellations can really provide an effective complement to terrestrial systems. It is crucial to effectively face the challenges discussed above in order not to miss the opportunities offered by the 5G ecosystem.

8. Conclusions

An up-to-date review of the operational features of the small satellite has been provided in this paper, aiming at highlighting the reasons of their recent attention from the industries, universities, and stakeholders and describing the main trends of development. A special emphasis has been given to the telecommunication aspects such as the use of higher-frequency bands, optical communications, new protocols, and advanced architectures.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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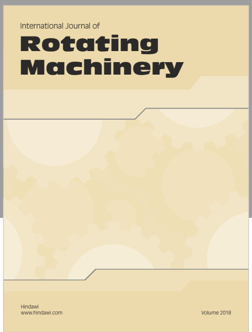
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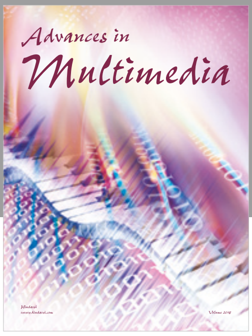
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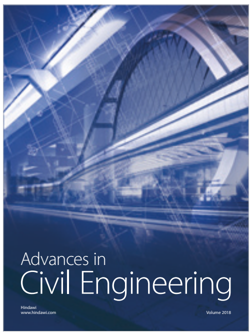
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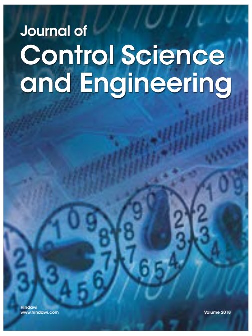
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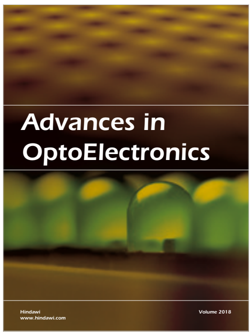
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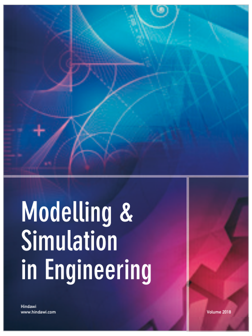
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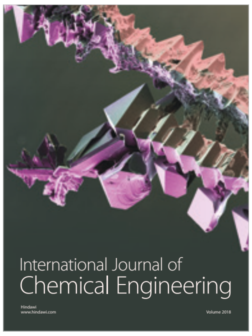
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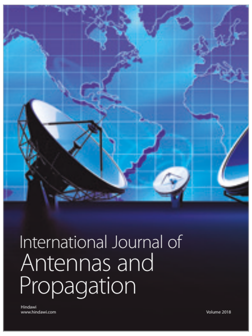
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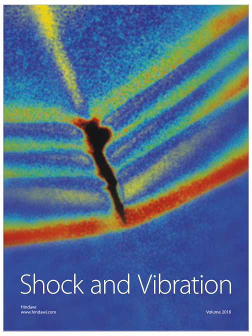
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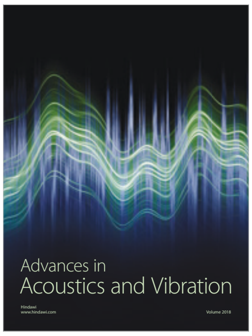
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