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Small satellites and CubeSats: Survey of structures, architectures, and protocols

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Summary

The space environment is still challenging but is becoming more and more attractive for an increasing number of entities. In the second half of the 20th century, a huge amount of funds was required to build satellites and gain access to space. Nowadays, it is no longer so. The advancement of technologies allows producing very small hardware components able to survive the strict conditions of the outer space. Consequently, small satellites can be designed for a wide set of missions keeping low design times, production costs, and deployment costs. One widely used type of small satellite is the CubeSat, whose different aspects are surveyed in the following: mission goals, hardware subsystems and components, possible network topologies, channel models, and suitable communication protocols. We also show some future challenges related to the employment of CubeSat networks.

KEYWORDS

CubeSat, CubeSat architecture, CubeSat channel model, CubeSat communication protocols, CubeSat hardware components, CubeSat network

1 | INTRODUCTION

With the beginning of the new millennium, the number of satellite missions has been increasing year after year with a different set of goals, such as weather monitoring, disaster prevention, and space observation, in several fields such as astronomy, atmospheric science, biology, Earth observation, and telecommunications.[1] The main characters of this sort of "second golden age" for the aerospace industry have changed with respect to the past. They are no longer the huge geostationary orbit (GEO) or the classical big medium earth orbit (MEO) and low Earth orbit (LEO) satellites, but satellites whose size and weight are much smaller. They are called micro-, nano-, and pico-satellites. A comparison between some of the features of the different satellite categories is reported in Table 1 in order to better understand why small satellites are becoming so appealing.

Looking at Table 1, the main advantages of small LEO satellites lie in the much lower cost, low communication latency, low energy consumption, and high fault tolerance, if the employment of tens of small satellites at the same time is considered. These aspects make small satellites appealing for different application scenarios. For example, if hundreds or even thousands of small satellites should be employed to implement a worldwide satellite transport network to extend the Internet access to the entire Earth's population, as anyway envisioned by several companies such as Google, Facebook, and SpaceX, specific tasks already performed by LEO satellite systems could be performed by small satellites at a lower cost and a lower energy consumption, such as Earth monitoring, disaster recovery, remote surveillance, machine-to-machine (M2M), and Internet of Things (IoT) applications, especially if the devices are located in rural and remote areas.

Microelectronics (MEs) and microsystems technologies (MSTs) contribute to reducing the size of satellite hardware components,[2] both the primary ones, such as engine, attitude control, battery, antennas, and the payload ones, such as sensors. Microelectronics and MSTs allow also decreasing satellite mass, getting power savings, and increasing flexibility as well as robustness. Currently, all electronic systems can be embedded in objects whose weight is only few kilograms instead of few tons and whose size is in the order of centimetres instead of metres. A kind of currently employed small satellite is called CubeSat[3] (Figure 1).

TABLE 1 Most relevant features of different satellite categories

	GEO	MEO	Big LEO	Small LEO
Cost	Very high: estimated production and launch cost of $300 million	High: estimated production and launch cost of $150 to $200 million	High: estimated production and launch cost of $150 to $200 million	Low: estimated production and launch cost of $100,000 to $200,000
Communication latency	High: one-way propagation delay ranges from 120 to 140 ms due to the altitude of about 36 000 km over the Equator	Moderate: one-way propagation delay ranges from 20 to 120 ms due to the altitude ranges between 6000 and 35 000 km	Low: one-way propagation delay up to 15 ms due to the altitude ranges between 200 and 2000 km	Low: one-way propagation delay up to 15 ms due to the altitude ranges between 200 and 2000 km
Throughput	High: hundreds of Gbps	Moderate: few Gbps	Moderate: hundreds of Mbps	Low: from few kbps to few Mbps
coverage	High: one satellite is able to cover about one-third of the Earth surface (except for the polar zones)	Moderate: tens of satellites are required to cover the entire Earth surface (eg, the GPS system requires a minimum of 24 satellites with partially overlapped footprints)	Moderate: tens of satellites are required to cover the entire Earth surface (eg, the IRIDIUM system is composed of 66 satellites with footprint partially overlapped)	Very low: hundreds or maybe thousands of satellites will be required to cover the entire Earth surface
Fault tolerance	Low: since they are very expensive, usually each constellation is composed of only three satellites with no backup ones	Moderate: most constellations keep also few satellites in orbit as backup in case of faults or damages	Moderate: most constellations keep also few satellites in orbit as backup in case of faults or damages	Very high: since they are cheap and small, tens of satellites can be employed at the same time, making them interoperable
Available resources	High: they can be designed without any limitations in terms of hardware components size and weight	High: they can be designed without any limitations in terms of hardware components size and weight	High: they can be designed without any limitations in terms of hardware components size and weight	Low: severe limitations on on-board HW/SW components: size and weight, computational power, energy, and storage capacity
Energy consumption	High: a considerable amount of energy is required especially to transmit data to the Earth due to their high altitude	High: a considerable amount of energy is required especially to transmit data to the Earth due to their medium to high altitude and to the possible presence of intersatellite links	Moderate: a discrete amount of energy is required especially to transmit data to the Earth and to the possible presence of intersatellite links	Low: low energy is consumed for data transmission, both to the Earth and to other satellites

Abbreviations: GEO, geostationary orbit; LEO, low Earth orbit; MEO, medium Earth orbit.

FIGURE 1 CubeSat illustration [Colour figure can be viewed at wileyonlinelibrary.com]

The CubeSat program was started at Stanford University in early 1999 to meet the educational need to have a very low-cost/weight satellite that could be developed within 1 or 2 years.[4] California Polytechnic State University (Cal Poly) and Stanford University developed CubeSat specifications as an extension of pico-satellite ones used in Stanford OPAL spacecraft.[5] Their concern was also to allow everyone creating their own customizable satellite, but with standard shape and weight, in order to simplify launch and deployment operations.[6] A CubeSat has to be made by one (1U) or more (*n*U) $10 \times 10 \times 10$ cm cube units, with a mass of up to 1.33 kg per unit. The great attraction of this product is that it can be entirely built by using commercial off-the-shelf (COTS) hardware components that better fulfil the target mission keeping low construction cost.

This paper offers an overview of many aspects about CubeSat and of the possible future challenges of CubeSat-based networks. The remainder of the paper is organized as follows: In Section 2, there is an overview of the main already deployed and planned CubeSat missions focusing on their different goals. A description of the CubeSat subsystems and hardware components is reported in Section 3, followed by a classification of the possible network topologies in Section 4. Channel models for CubeSat/ground stations and CubeSat/CubeSat links are analysed in Section 5. The communication protocols suitable for small satellite and CubeSat networks are listed in Section 6. The communication challenges involving CubeSat networks are investigated in Section 7. Finally, in Section 8, the conclusions are drawn.

2 | RELATED WORK

Since 2000, more than 100 universities and several emerging nations have been planning to launch CubeSats into space for different purposes.[7]

Most missions are based on the deployment of a single CubeSat. The CubeSail mission[8] uses a 3U CubeSat launched to demonstrate the possible deployment of a 25-m^2 solar sail from this kind of satellites and its use for de-orbiting purpose using aerodynamic drag forces at the end-of-life. Delfi-C[9] CubeSat was developed at Delft University to offer students the opportunity to work on a real space mission. It acts as a test-bed for three different payloads: a thin film solar cell, an autonomous wireless Sun sensor, and a high efficiency transceiver. GeneSat-1 [10] is a 3U CubeSat that aims to validate the use of instrumentation for biological research and processing. In particular, it focuses on detecting the levels of green fluorescent protein expressed in living cultures. In Waydo et al,[11] two missions are reported whose common goal is to take distributed measurements within the ionosphere plasma to aid the understanding of ionospheric density structures and contribute to the creation of accurate models. To analyse the ionosphere phenomena is also the purpose of the dynamic ionosphere CubeSat experiment (DICE) mission.[12] It aims to investigate the physical processes responsible for the formation of the ionospheric storm-enhanced density (SED) bulge and the relationship between penetration electric fields and SED formation. To test the possibility to use CubeSats as data relays in order to increase the time available for satellite to ground station communications and the throughput capacity is the aim of CommCube 1 and CommCube 2 missions developed at the Massachusetts Institute of Technology.[13] The QuakeSat mission objective[14] is to detect, record, and send extremely low-frequency (ELF) magnetic signal data, which may lead to the prediction of earthquakes, to a ground station. One of the last deployed CubeSats is the LituanicaSAT-2,[15] which is a 3U in-orbit technology demonstration CubeSat whose science payload, called FIPEX, is able to measure the time-resolved behaviour of atomic and molecular oxygen of the lower thermosphere. It also carries a technology demonstration payload, aimed at testing the orbital manoeuvring and drag compensation capabilities of a CubeSat by using an integral green monopropellant microthruster. The 3U CubeSat belonging to the radiometer assessment using vertically aligned nanotubes (RAVAN) mission[16] was deployed in 2016 to measure the Earth's radiation imbalance in order to predict the course of climate change over the next century.

Some missions are based on the deployment of more CubeSats in order to perform complex tasks where the required number of sensors and the amount of data to be processed and sent to the Earth are more relevant. The orbiting low-frequency antennas for radio astronomy

(OLFAR)[17] is a distributed system composed of a swarm of 50 CubeSats orbiting around the Earth's Moon. Three are the major tasks depending on the satellite position[18]: (1) observation: each CubeSat samples the cosmic background radiation when it is located beyond the Moon; (2) data distribution and processing: once sampled, data are shared among all the members of the swarm and processed; (3) downlink: while facing Earth, satellites will send the processed data to a base station on the Earth. Such a system is highly scalable and highly tolerant to the failure or nonavailability of a fraction of its components. The QB50 mission is composed of a satellite constellation composed of 50 CubeSats.[19] They include 40 atmospheric 2U CubeSats for scientific exploration and 10 2U or 3U CubeSats for in-orbit technology demonstration.[20] Atmospheric CubeSats carry sets of standard sensors to conduct multipoint, in situ, long-duration measurements of key parameters and constituents in the largely unexplored lower thermosphere and ionosphere. All CubeSats are injected subsequently by a single launcher into a near-circular highly inclined orbit at an expected altitude of about 320 km.[21] The use of a single launch vehicle in order to deploy CubeSats into a formation is faster and cheaper, even though there is a greater risk of collision. They have no propulsion systems, so they will be able to explore the lower thermosphere for 6 months before the orbital decay due to atmospheric drag starts.

A lot of CubeSats missions have been planned to start in the near future, such as LunaH-Map and the CuSPED. The Lunar Hydrogen Mapper (LunaH-Map)[22] will be one of the 13 CubeSats to be launched in 2018 whose goal is to map the hydrogen content of the South pole of the Moon at high resolution. It is a 6U CubeSat that will orbit at low altitude above the Moon collecting high spatial resolution pictures of the hydrogen distribution in the lunar regolith for 60 days (141 passes). In the CubeSat for GNSS sounding of ionosphere-plasmasphere electron density (CuSPED)[23] mission, a 3U CubeSat will measure the plasma density in the ionosphere and lower magnetosphere by using a miniature plasma spectrometer. It will contribute in determining the dynamics of the Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.

3 | PHYSICAL STRUCTURE AND HARDWARE COMPONENTS

CubeSats can be built by combining more units of 10 ×10×10 cm each. This feature allows to arbitrarily set the maximum size and weight of the overall subsystems, both primary and payload ones, depending on the mission goal and, consequently, on the required instrumentation.

The subsystems that provide the primary functionalities are

- Structure[11]: It consists of three parts: rails, beams, and panels. The rails make up four parallel edges of the CubeSat. The beams are epoxied to the rails to create the other eight edges. Three side panels are epoxied to the beams and rails in a U-shape to form half of the external surface of the satellite. The final three sides are formed by a single U-shaped panel that can be set in place following the integration of internal components. Internal components are linked to the structure as a single package by using brackets and fasteners. There are different possible configurations obtained by increasing the number of used CubeSat units, which are driven in part by launch-vehicle integration-and-deployment hardware.
- Propulsion and de-orbit[24]: Due to the limited mass, volume, and available power, most CubeSats do not have any propulsion or de-orbit subsystem. The easiest way to implement a simple de-orbit mechanism is to increase the atmospheric or magnetic drag by increasing the surface area of the satellite once on orbit. Microthrusters can also be applied to ease CubeSats to keep their position in nano-satellite swarms. Other developed technologies provide minimal orbital manoeuvring by using vacuum arc and colloid thrusters, electrospray technology, and pulsed-plasma thrusters. Microthrusters can be cold gas thrusters, possibly in combination with resistojets, or monopropellant thrusters by using catalytic decomposition, eg, hydrogen peroxide or hydrazinium nitroformate (HNF)- or ammonium dinitramide (ADN)-based monopropellants.
- Attitude determination and control (ADC)[7]: The aim of this subsystem is to measure, maintain, and adjust the orientation of the CubeSat, depending on the mission requirements, power generation, and communications. Different sensors determine orientation, and different actuators maintain or change the attitude. Attitude determination and controls belong to two classes: passive and active. Passive systems utilize the space environment to naturally orientate the satellite. The most common approach for CubeSats is a combination of permanent magnets that orientate one face towards the Earth's magnetic pole (often used to point radio antennas) and magnetic hysteresis rods so to damp nutation or "wobble" in satellite motion, again by interacting with the geomagnetic field. Active systems utilize more sophisticated components that allow to set satellite orientation in a more precise way but require much more power. The trend in active systems is to use a two- or three-axis control to support more challenging mission requirements.
- Command and data handling (CDH)[9]: This subsystem collects mission and science data for transmission to the ground stations, controls the deployment of antennas and solar panels, provides the ability to execute commands that have been uploaded from the ground stations, and provides some measure of robustness in order to cope with failing subsystems. Popular used microprocessors are peripheral interface controllers (PICs) and mixed signal processors (MSPs). Advanced RISC machines (ARMs) from various suppliers are also popular due to their higher processing capabilities. The satellites that use a distributed CDH subsystem mostly adopt the I^2C data protocol for communication between the microcontrollers, also providing a simple serial interface to the payload.
- Electrical power supply (EPS)[1,3]: It is composed of a printed circuit board, solar panels, and batteries:

  - Solar panels: Most deployed CubeSats are equipped with solar cells installed on their faces. Gallium arsenide (GaAs) solar cells are the most widely used. They provide very high conversion efficiency up to 30% and are widely available. Silicon (Sil) solar cells are also used. Their cost is very low compared with the GaAs cells, although they have lower efficiency. Considering the limited size of the external structure, the area of the solar arrays is small, and consequently, the average available power ranges from less than 1 to 7 W. The conversion method of the raw available power from the solar cells to the power on the spacecraft bus is based on either direct energy transfer (DET) or peak power tracking (PPT). The DET method takes the power at a predetermined voltage point on the current-voltage (IV) characteristic of the solar cells and shunts the power in excess. The PPT method just follows the IV curve from the open-circuit voltage with DC-DC converters. Peak power tracking can lead to problems if there is a too large instantaneous current surge. Deployable solar arrays offer much greater power generation at the cost of increased complexity and risk of deployment failure. They potentially generate 20 to 60 W in full sunlight.

- Batteries[1,7]: Typical LEO orbits expose the spacecrafts to the Sun for about 66% of each 90 to 105 minutes orbit, so they require energy storage to keep functioning during eclipses. Lithium-ion battery technology is well suited to this task in terms of energy density and little "memory" effect: They do not have to be fully discharged before recharging, and they do have to be appropriately managed for charge/discharge cycles and thermal parameters. Depending on the orbital parameters, heaters may be needed to keep the batteries in their operating temperature range. Even when the satellite is in sunlight, batteries can help temporarily bridge high-power demand, such as when the radio is transmitting. Some of the early CubeSats had nonrechargeable batteries based on Mercury elements. Currently, most CubeSats have rechargeable batteries of lithium-ion (Li-ion) or lithium-polymer (Li-pol) type, although some use nickel-cadmium (Ni-Cd) or lithium-chloride (Li-Chl) batteries.

- Communication[25]: CubeSats receive operational commands from the ground and transmit collected data. Nearly all CubeSats have a transceiver and one or more deployable antennas, which use the amateur radio portion of the frequency spectrum for beacon purposes and often also for data uplink/downlink. For noncommercial publicly accessible use, the actions to get authorization for amateur radio allocation is considerably less complex than the process commercial satellite operators must follow to obtain frequency allocations through the International Telecommunication Union (ITU). The low cost of amateur radio equipment has led to its wide adoption in CubeSat projects for ground station communication. The very high frequency (VHF) band (0.03-0.3 GHz) is often used for the downlink, while the ultrahigh frequency (UHF) band (0.3-1 GHz) for the uplink. L-band (1-2 GHz) and S-band (2-4 GHz) are also widely used. The achievable transmission rate ranges from about 1 kpbs to few Mbps, even though it could increase up of 30 to 40 Mbps by using X-band (8-12 GHz), Ka-band (27-40 GHz), or V-band (40-75 GHz) transceivers.[26] The communication subsystem can consume 50% or more of the total available power when transmitting, which typically occurs for only a matter of minutes per day when the satellite is in the line of sight of the ground stations. A challenge for the communications with CubeSats is their high rate of motion with respect to ground stations. The quality of the link varies considerably during a pass, which may last only a few minutes, limiting the amount of data that can be transmitted on the downlink and uplink.

TABLE 2 CubeSat missions hardware components

Project name	Size	Solar panel	Battery	ADC	Propulsion	Power supply, W	Tx/Rx frequency bands
CubeSail[8]	3U	GaAs	Li-pol	Active 3-axis	No	0.32	UHF uplink, VHF downlink
Delfi-C[9]	3U	GaAs	No	Passive rotation rate damping	No	1	UHF uplink, VHF downlink
Genesat-1 [10]	3U	GaAs	Li-ion	Passive magnet/ hysteresis rod	No		S
DC/PIP[11]	1U	GaAs	Li-pol	Gravity gradient stabilization	No	1.3	VHF uplink, UHF downlink
GPS scintillation[11]	1U	GaAs	Li-pol	Gravity gradient boom	No	1.3	VHF uplink, UHF downlink
DICE[12]	1.5U	GaAs	Li-pol	Passive magnetic stabilization	No	1.7	UHF
CommCube 1 [13]	2U	GaAs	Li-ion	Passive magnet/ hysteresis rod	No	38.4	UHF, L, S
CommCube 2 [13]	3U	GaAs	Li-ion	Active 3-axis	No	28.8	S
QuakeSat[14]	3U	GaAs	Li-ion	Passive magnetic stabilization	No	7.9 ÷ 19	UHF
LituanicaSAT-2 [15]	3U	Sil	Li-ion	Semipassive aerodynamic stabilization	Monopropellant microthruster	4.5	UHF
OLFAR[17,18]	3U	GaAs	Li-ion	Active 3-axis	Electric micropropulsion	2	UHF uplink, VHF downlink

Abbreviations: ADC, attitude determination and control; DICE, dynamic ionosphere CubeSat experiment; GaAs, gallium arsenide; Li-ion, lithium-ion; Li-pol, lithium-polymer; OLFAR, orbiting low-frequency antennas for radio astronomy; Sil, silicon; UHF, ultrahigh frequency; VHF, very high frequency.

- Deployers[27-29]: All already launched CubeSats have been brought into space as a secondary payload of bigger LEO satellite launches. At the time the vector rocket reaches the CubeSat deployment position, a tool, called deployer, detaches the CubeSat from the rocket by throwing it into the outer space. The deployer aim is also to protect the CubeSat during the launch phase. Several entities have developed deployers. Cal Poly developed a CubeSat deployer called Poly-Picosatellite Orbital Deployer (P-POD). Poly-Picosatellite Orbital Deployer is an aluminium tube with a spring-assisted ejection, a door, and a nonexplosive release mechanism. It controls the deployment of the CubeSats opening the door in order to minimize the shock to the launch vehicle and of the satellite. It was developed to protect the primary payload, the launch vehicle, and the CubeSat from any mechanical, electrical, or electromagnetic interference, to safety group multiple CubeSats, to eject CubeSats for safe deployment, to increase the access to space for CubeSats, and to provide a standard interface to launch vehicles. Moreover, it reduces the risk of damage due to debris produced by structural damage or prematurely deployed antennas. Its mass is kept to a minimum, and it incorporates a modular design that allows more CubeSats to be carried and launched into space at the same time. During the deployment sequence, the CubeSats ride on rails built into the corners of the tube and a simple spring provides the force to push the CubeSats out of the deployer with a linear velocity of approximately 0.3 m/s. Other deployers are the one developed by the University of Tokyo, called Tokyo-POD (T-POD), which can hold only a single CubeSat unit, and the eXperimental-POD (X-POD), which is a custom, independent separation system designed and built at the University of Toronto's Institute for Aerospace Studies/Space Flight Laboratory. It may be tailored to satellites of different sizes, ranging from a single CubeSat to larger nano-satellites of arbitrary dimension. Reverse-compatible designs that permit larger nano-satellite secondary launches include the NASA Ames's nano-satellite launch adapter system (NLAS),[30] which can accommodate a total of 24U in single spacecraft increments as large as 6U.

Table 2 summarizes the used hardware components in some CubeSats.

4 | NETWORK TOPOLOGIES

As for any other satellite, the orbital plane and the position of a single CubeSat can be uniquely identified by a set of parameters called orbital parameters,[31] as shown in Figure 2:

- Eccentricity e: It defines the shape of the orbit ($e = 0$: circular, $0 < e < 1$: elliptic);
- Semimajor axis R: It defines the size of the orbit (in a circular orbit, R is the radius of the orbit);
- Inclination i: The angle of the orbital plane with respect to the Earth's equatorial plane;
- Right ascension of the ascending node (RAAN) Ω: The angle that defines the location of the ascending and descending orbital crossing points with respect to the fixed direction in space called vernal equinox, which is the direction of the line joining the Earth's centre and the Sun on the first day of spring;
- Argument of perigee ω: The angle that indicates the orientation of the orbit in its plane. It is measured positively in the direction of the satellite's movement from 0° to 360° between the ascending node and the orbit's perigee;
- True anomaly θ: The angle that indicates the actual position of the satellite in its orbital plane. It is measured positively in the direction of the satellite's movement from 0° to 360° between the perigee and the satellite. Another variable that describes the actual position of the satellite is the mean anomaly M, which is defined as the angular distance from the perigee that the satellite would have if it moved in a circular orbit with constant speed and with the same orbital period as the real orbit (true anomaly and mean anomaly are the same if the orbit is circular).

All these and other parameters that allow to uniquely identify each satellite and its initial position can be represented in a standard format called two-line orbital element (TLE) set.[32] An example of a CubeSat mission TLE is shown in Figure 3, while a database of CubeSat TLEs can be found with open access at the URL in reference.[33]

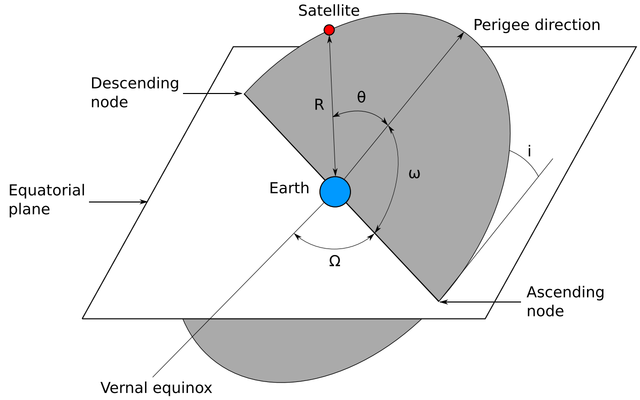


FIGURE 2 Space orbital parameters [Colour figure can be viewed at wileyonlinelibrary.com]

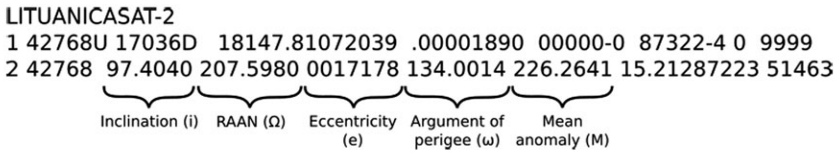


FIGURE 3 LithuanicaSAT-2 two-line orbital element

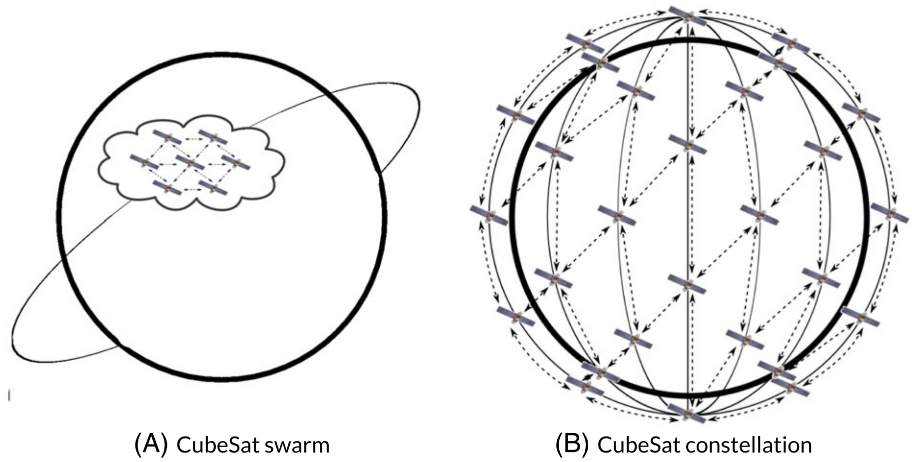


FIGURE 4 Schematic representations of CubeSat topologies [Colour figure can be viewed at wileyonlinelibrary.com]

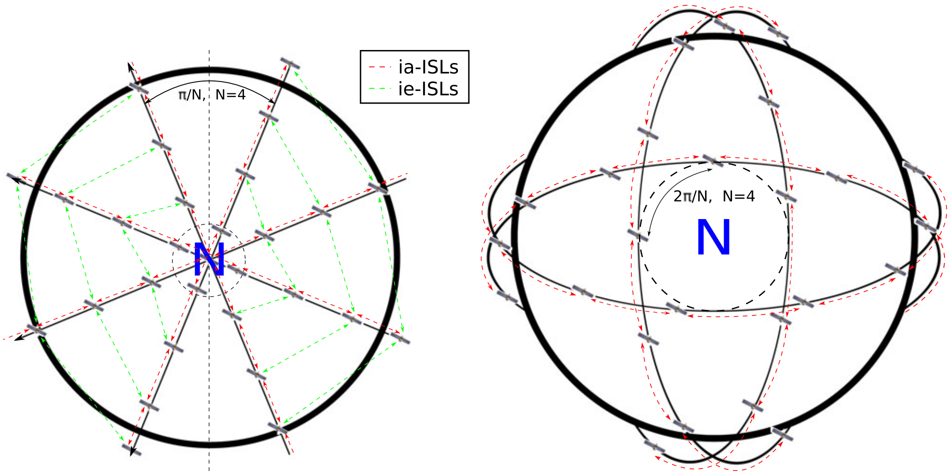
Some CubeSat missions are based on the employment of more than one satellite to better achieve the mission target. These CubeSats can be grouped in swarms or constellations, as depicted in Figure 4 and described in Bacco et al.[34] In this way, they can share their available resources in order to optimize their usage. This is a valuable advantage, especially when the satellites are small like the CubeSats and the available resources, eg, in terms of available energy and storage capacity, are very limited.

The choice between swarm and constellation depends on the deployment strategy. In a swarm (Figure 4A), satellites are rapidly deployed one after the other so to be located in the same orbital plane and to make the distances among them very small.[18] In a constellation (Figure 4B), the deployment of the satellites is sequential and highly synchronized, so they can be equally spaced among one or more orbital planes.[19] There are two main kinds of constellations[35,36]:

- π-constellation, also called Walker star or polar[37]: It is composed of a set of orbits of the same inclination, usually 90° or little less (in this case, the orbits are called near-polar), equally spaced with an angle of $\pi \backslash N$, where N is the number of orbital planes. It is called "star" because, if drawn on a polar map, the orbital planes intersect so to make a star, as shown in Figure 5A. The main advantages of this configuration are the high coverage especially in the polar zones and the fact that satellites are able to exchange data among them through intersatellite links (ISLs). In particular, ISLs are active among adjacent satellites located in the same orbital plane (intra-orbit ISLs [ia-ISLs]) and in adjacent orbital planes (interplane ISLs [ie-ISLs]), allowing each satellite to exploit up to four ISLs (two ia-ISLs and two ie-ISLs). Intersatellite links can be always active with two exceptions: (1) satellites belonging to adjacent planes always move in the same direction except for the two planes separated by the black dotted line and (2) in high latitude zones. In both these cases, adjacent satellite relative velocities are too high to guarantee communications through ie-ISLs due to the consequent problems of high Doppler effect and antenna alignment.
- 2π-constellation also called Walker Delta or rosette[38]: It is composed of a set of orbits of the same inclination equally spaced with an angle of $2 \cdot \pi \backslash N$. It is called "rosette" due to the shape of the orbit seen from above a pole. This configuration allows obtaining a better coverage at the mid-latitudes, increasing the number of simultaneously visible satellites. However, it does not provide coverage around the poles above the latitude identified by the inclination angle and does not guarantee ie-ISLs because satellites belonging to adjacent planes always move in opposite direction, as shown in Figure 5B.

An example of multiple nano-satellite mission is Rajan et al,[17] where tens of 3U CubeSats perform data gathering, processing, and transmission towards ground stations in a distributed way throughout the whole swarm. The presence of ISLs allows better exploit the limited resources, such as computational power and energy, by sharing them. The pros and cons of the three possible network topologies (single, swarm, and constellation) are well summarized in Bacco et al.[34, table 1.1]

A table containing information about orbit, mission type, mission objectives, and lifetime, for more than 2100 nano-satellite missions, can be found in previous study.[39]



(A) π-constellation (Walker Star) (B) 2π-constellation (Walker Delta)

FIGURE 5 Structure of CubeSat constellations [Colour figure can be viewed at wileyonlinelibrary.com]

5 | ANTENNAS AND PROPAGATION ISSUES

Antenna systems play a very critical role in the establishment of the communication link between the small satellite and the ground terminal.[40] There are many technical challenges for the design of antenna systems considering the antenna gain/pattern and the antenna size taking also into account the CubeSats standards. There is a trade-off between communication link quality (data rate, high availability) and the need to satisfy the guidelines for size and other multifunctional capabilities of CubeSats defined by standards.[41] As reported analytically in Rahmat-Samii et al,[40] and in the references therein, the categories of the antenna systems that are used for CubeSats are[40] (*a*) wire antennas (monopoles, dipoles, Yagi- Uda arrays, and helical antennas) operating at UHF/VHF bands, (*b*) reflector antennas operating from S-band to Ka-band,[42] (*c*) relectarrays operating at X-band and Ka-band, (*d*) membrane antennas, (*e*) planar antennas (patch and slotted), and (*f*) horn and guided wave antennas. In Rahmat-Samii et al,[40] there are numerous references that give the technical details of the antenna systems implementation for various missions.

Before proceeding to present some propagation issues for the CubeSat satellite links, it is worth clarifying that specific experimental campaigns are required in order to characterize the propagation channel properties of the CubeSat link, since there are no available measurements. The main models reported and used for land-mobile satellite (LMS) channels for satellite systems with time varying topology, which are also supported by measurements, are briefly described in this paper.

Propagation issues in LMS links are related to local environment effects and to the movement of the satellites.[43] Nano-satellites at LEOs are moving through the visibility area of the moving terminal. Therefore, the elevation angle of the communications link varies with time. At L- and S- bands, if the line-of-sight (LoS) is not always reassured, the received power of the signal is highly affected by the local environment, such as trees, bridges, buildings, and smaller elements like passing cars or pedestrians, small urban elements like lamp posts, and traffic signs.

Depending on the environment and the mobility of the users, the LMS channel can be characterized as narrow- or wide-band, slow- or fast varying[44] through physical and statistical models. For nongeostationary orbit (NGSO) satellite systems, the models that have been proposed in the literature are statistical ones. Depending on whether there is a direct, wanted signal and LoS conditions or not, various distributions have been proposed. They range from the Rayleigh distribution, in which it is always supposed that there is no high-power received signal or LoS conditions, to the Ricean distribution, in which the received signal is the superposition of a great number of reflected rays and a direct signal.

Moreover, for LMS systems, composite channel models have been developed and are mainly used. In particular, the Loo distribution[45] and Corazza-Vatalaro model[46] are two composite channel models, among others. In both models, it is assumed that the received signal is a superposition of (*a*) a direct signal that may or may not be the strong component, which experiences shadowing phenomena, eg, due to obstacles, and follows a log-normal distribution, and (*b*) the multipath component, which follows the Rayleigh distribution. Furthermore, the Corazza-Vatalaro model is especially proposed for Earth-NGSO satellite communications systems, and the parameters of the distribution are given as a function of the elevation angle.

For the Loo model, the distribution of the signal envelope is given by

$$f(r) = \frac{8.686r}{\sigma_L^2 \Sigma \sqrt{2\pi}} \int_0^{\infty} \frac{1}{\alpha} \exp\left(-\frac{r^2+\alpha^2}{2\sigma_L^2}\right) \exp\left[-\frac{(20\log\alpha - M)^2}{2\Sigma^2}\right] I_0\left(\frac{r\alpha}{\sigma_L^2}\right) d\alpha, \tag{1}$$

where α is the direct signal's amplitude and $\sqrt{\sigma_L^2}$ represents the amount of diffuse multipath from which the multipath component can be calculated in dB as $10log(2\sigma_L^2)$. Σ and M are the standard deviation and mean value of the associated normal distribution for the direct signal's amplitude, respectively. The function $I_0(.)$ is the zero-order modified Bessel function of the first kind.

In Kourogiorgas et al,[47] the Loo distribution is fitted to the four polarization components for various intervals of elevation angles, and the received power distribution for Earth to NGSO satellite links can be calculated based on the distribution of the elevation angles. Moreover, an airship which follows the actual paths of NGSO satellites, such as IRIDIUM and Galileo, is used to obtain the measurements. In Figures 6 and 7, the time series of elevation angles and received power for a Galileo orbit are shown, respectively,[47] for a ground station at Stromovka park in Prague, Czech Republic. An airship was used to emulate the path of the Galileo satellite over the city of Prague. The received power has been normalized for a constant height set to 20 km. It can be easily observed that, at lower elevation angles in the range 20° to 40°, the shadowing phenomena and multipath effects are more severe than at high elevations. From the processing of these measurements, the Loo distribution gives the best fit.[47] The inverse Gaussian distribution is tested for the modelling of shadowing effects in various intervals of elevation angles in Kourogiorgas et al.[48]

Considering the channel simulation for NGSO LMS systems, a small number of models have been developed. In Sung-Chan et al,[49] a first method is proposed for the generation of time series of received signal for LMS channels with NGSO satellites. For NGSO satellites, Doppler shift takes extremely high values (several tens of kHz[43,49]) due to movement of both ground terminals and NGSO satellites. Therefore, fading bandwidth can be approximated as equal to the maximum Doppler shift, and so filters are used for the incorporation of Doppler effects.

A general and widely used channel model for LMS channels has been presented in Fontan et al.[43] Markov chains are used in order to represent the various states of the channel. These states are classified as the LoS conditions, moderate shadowing, and deep shadowing events. Such classification is reasonable considering that the direct wanted signal can be received without meeting any obstacles or through light or heavy obstruction. Furthermore, the Loo distribution is used to model the received envelope at every state with different statistical parameters. Moreover, the Loo distribution parameters do not change only for every state but also for every elevation angle at a given state.[43] Therefore, for the NGSO satellite link, the triggering of the Markov chain can be enabled either due to the movement of the mobile ground terminal or in the case that the elevation angle takes values of different intervals. For the separation of elevation angle intervals, a 10° step is used. Considering the Doppler spectrum, in Fontan et al,[43] a geometrical statistical model is used through the positioning of scatterers, and the total Doppler shift is divided into the one due to the movement of the mobile terminal and the one due to the movement of the satellite.

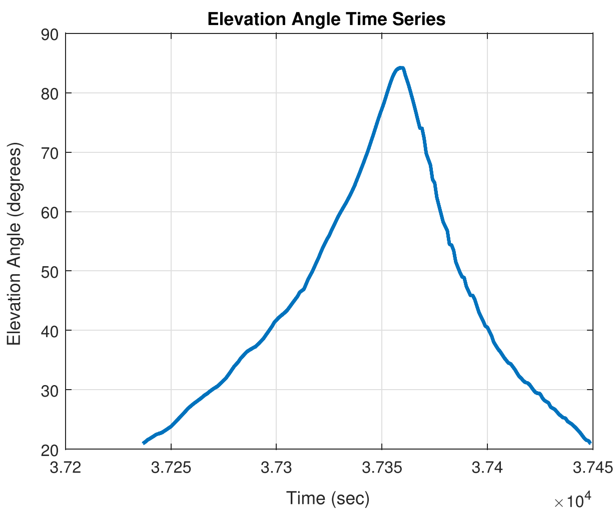


FIGURE 6 Time series of elevation angle of an orbit of Galileo [Colour figure can be viewed at wileyonlinelibrary.com]

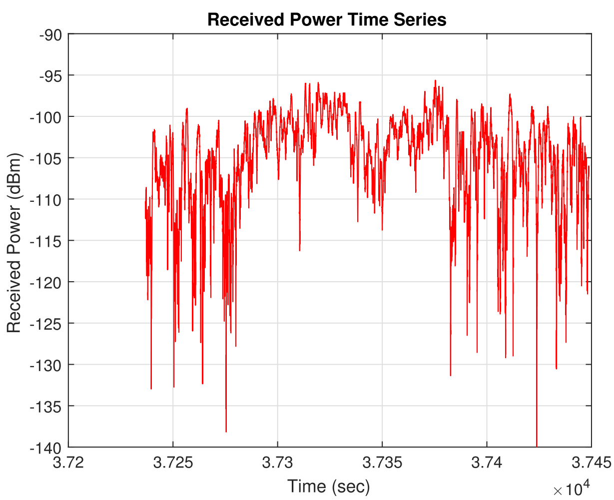


FIGURE 7 Time series of received power at a constant slant path of an orbit of Galileo [Colour figure can be viewed at wileyonlinelibrary.com]

The parameters of the above-described models can be easily configured considering the orbital characteristics of the CubeSat (eg, velocity).

6 | COMMUNICATION PROTOCOLS

Satellite networks differ from classical networks, such as the cabled Internet, in higher delays, higher error rates, and, in some cases, lower transmission rates. Moreover, a LEO satellite antenna is able to cover only a small area of the Earth's surface, which leads to possible temporary disconnections between satellites and ground stations. These aspects led experts to consider some protocols of the transmission control protocol (TCP)/Internet protocol (IP) suite inappropriate for communications through space. In particular, TCP is not efficient over satellites, owing mainly to the following problems (see, among others, the book,[50] chapter 12 and references therein, and Chotikapong et al[51] for the LEO environment):

- Variable satellite round-trip times (RTTs): Due to the satellite movement, the distances between satellites and ground stations change, and consequently, the RTTs may change from 40 to 400 milliseconds.
- Large and variable delay-bandwidth products (often created by long and variable RTTs) lead to a waste of bandwidth due to the TCP's acknowledgement mechanism, which may be very slow and affects the increase speed of the transmission window.
- Asymmetric links: Satellite links are highly asymmetric (uplink and downlink bandwidths are often different). This negatively affects TCP's flow control for similar motivations as explained just above.
- High bit error rates (BERs): Signal interferences, either natural like atmospheric or ionosphere effects or caused by artificial jamming, lead to high BERs and, consequently, high packet losses. The Transmission Control Protocol considers these losses as a sign of congestion and reacts by decreasing the transmission bitrate.

Specific communication protocols have been developed for satellite networks.[52] Some of them have been defined adapting protocols already developed for terrestrial networks, such as the ones that adapt TCP over satellite acting dynamically on the slow start, congestion avoidance, and fast retransmit/recovery algorithms.[50]

Due to their additional hardware and link budget constraints, small satellites have to employ lightweight protocols in order to keep the resource consumption as low as possible and better exploit limited available bandwidth. There are several papers in the literature that define ad hoc protocols for small satellites; some of them developed within each mission, others with a more general purpose:

- Data link layer protocols:
  - New satellite data link protocol (NSLP)[53]: Simple data link layer protocol suitable for small satellite IP networks. Its header size is small, and its functionalities limited to data frame encapsulation, transmission, and error detection performed by using a 2 byte CRC field.
  - Low-altitude multiple satellite data link control (LAMS-DLC)[54]: Data link protocol that attempts to integrate the advantages of ARQ protocols with those of FEC schemes. It provides a reliable service based on a negative acknowledgement ARQ (NAK) scheme to accomplish error recovery and a check-point mechanism to provide a zero-loss, zero-duplicate packet transmission without in-sequence delivery constraint. It has been designed to minimize the impact of idle time due to link initialization and link synchronization and re-synchronization, in order to maximize the throughput efficiency during the short time contact periods.
  - Nanolink[55]: Reliable, packet-oriented, connection-based data link layer protocol designed just for CubeSats or small satellites with limited hardware resources. It is designed to operate with high efficiency and high reliability over links with a small bandwidth-delay product and weak signal quality. Nanolink exploits both FEC and ARQ principles. It multiplexes several frame streams into one physical channel through virtual channels that can have different priorities, latency requirements, and can facilitate the implementation of traffic classes.
  - AX.25 [56]: It is a data link layer protocol that derives from the layer 2 of the X.25 protocol suite and is designed for use by amateur radio operators. It is mainly responsible for establishing connections and transferring data encapsulated in frames (possibly and most frequently used UI - Unnumbered Information - frames) between nodes and detecting errors introduced by the communications channel.
  - Proximity-1 [57]: Short haul (approximately between 1 and 100 000 km) delivery communication protocol developed by the consultative committee for space data systems (CCSDS) and designed to establish bidirectional communications (half duplex or full duplex), negotiate data rate and communication mode, and reliably deliver data. It is connection-oriented, point-to-point or point-to-multipoint, and suitable for modest to low-delay bandwidth product links with relatively (at least in terms of deep-space communications) short time delays, moderate (not weak) signals, and short independent sessions. It supports both synchronous and asynchronous modes of communication and comprises both data link and physical layers.[58,59]
  - Unified space data link protocol (USLP)[60]: Data link layer protocol defined to transfer data using variable-length protocol data units. It has been recently proposed by the CCSDS and includes some improvements compared with the previously defined CCSDS space data link protocols, such as a larger maximum transfer frame size and an increased capability of spacecraft identification. It also performs segmentation and aggregation of data units reducing and increasing their size, in order to reduce the data unit error probability and lower the header overhead size, respectively. Optional services have also been included to ensure reliable data unit transmission in sequence and without gaps or duplications.

- Network and transport layer protocols:
  - Space packet protocol (SPP)[61]: Network layer protocol that provides a unidirectional and asynchronous data transfer service from a single source user application to one or more destination user applications without confirmations, guaranteed quality of service (QoS), and retransmission mechanism.
  - Space communications protocol specification (SCPS)[62]: Set of protocols defined by the CCSDS that includes different layer protocols, from the network to the application layers, based on the Internet protocols with modifications and extensions designed to meet the specific needs of space missions. They have all been retired except for the transport layer protocol called SCPS—transport protocol (SCPS-TP).[63] It defines extensions to TCP and UDP aimed at supporting additional options and behaviours to compensate for the high packet losses and high latencies of space links.
  - Licklider transmission protocol (LTP)[64]: Retransmission-based protocol designed to run over unreliable transport protocols, such as UDP, or directly over data link layer protocols. Its features are: reliable data transport for important data (such as a file header); unreliable data transport for less important data (such as image pixels); no negotiation exchange due to potentially higher RTTs and to avoid link underutilization; energy efficiency, as it only sends data if a link is available and can distinguish between important and unimportant data; timers work together with communication schedules and can be suspended whenever a scheduled link outage occurs; unidirectional sessions.
  - CubeSat space protocol (CSP)[65]: Small network and transport layer delivery protocol expressly designed for CubeSats. Its header size is 4 bytes and its layering corresponds to the same layers as the TCP/IP model. It uses a simple short fragmentation protocol (SFP) to transmit packets bigger than the maximum transmission unit (MTU). It enables distributed embedded systems to deploy a service-oriented network topology. The implementation is compliant with CCSDS standard and supports a connection-oriented transport protocol, a network protocol, and several network interfaces. The physical layer includes several other technologies such as CAN, I2R, RS-232 using the KISS protocol, and CCSDS space link protocol.

- Application layer protocols:
  - Saratoga[66]: It is a lightweight file transfer and content delivery protocol based on the UDP. It was developed by Surrey Satellite Technology Ltd (SSTL) in cooperation with NASA Glenn Research Center for transfers of imaging data recorded on-board the IP-based disaster monitoring constellation (DMC) satellites. It is designed to cope with highly asymmetric links and implements a selective negative acknowledgement (SNACK) mechanism for loss recovery to ensure reliable data exchanges. It guarantees high-link utilization sending data at line rate to maximize throughput. It is useful in case of limited duration links such as LEO satellites to ground links.
  - CCSDS file delivery protocol (CFDP)[67]: It is a file transfer protocol that provides functionalities of both the application and the transport layers, guaranteeing complete, in-order, without duplicate data delivery. It has been designed to be efficient over simple, half-duplex, and full-duplex and highly asymmetric links, minimizing link traffic and resources required to operate, such as on-board memory requirements and employing automatic store-and-forward operations.

Other communication protocols can and have been employed in small satellite networks even if they have been defined for and are widely employed in terrestrial networks, such as IP and UDP, owning to their features that allow them to operate also in the satellite environment.

7 | FUTURE CHALLENGES

CubeSats have been chosen especially by universities and small/medium industries thanks to their simplicity, customizability, reduced capital expenditure (CAPEX) and operational expenditure (OPEX), and reduced design times. Mission targets of already deployed CubeSats missions are quite simple and require neither complex sensors nor stringent performance. However, CubeSats advantages are appealing also for industries that could decide to employ these satellites for more elaborate purposes, giving them additional functionalities. If we think about possible future satellite networks composed of hundreds or maybe thousands of CubeSats that collect, process, and transmit/receive different kinds of data to/from ground stations or among them, challenges that do not concern CubeSat missions so far could arise. For example, nowadays, most CubeSats act as hosts, collecting data from their on-board sensors and sending them to a ground station (or to a set of ground stations) as soon as the satellite link is available. In CubeSat networks, satellites could also or only act as relays, forwarding data received from other satellites or ground stations and destined to other nodes.

Some of the challenges related to the design and employment of small satellite networks are described in the following:

- Protocols: Different aspects and parameters have to be taken into account. They are extensively listed and described in Radhakrishnan et al.[68]
  - Physical layer: From the physical layer viewpoint, transceivers, antennas, and hardware components needed to keep the alignment between satellite antennas have to be chosen or designed in order to keep the overall mass and weight below a given threshold. Parameters such as frequency band, data rate, modulation, and coding schemes have to be set in order to increase the obtained performance. For example, multiple antennas lead to a higher energy consumption, higher required computational load due to additional functionalities such as routing algorithms, and higher storage capacity due to the increased amount of sent/received data, which could be stored also for a long time.

  - Data link layer: MAC protocols should be designed taking into account mission goals, satellites number, and network topology and should guarantee energy efficiency, scalability, adaptability, fairness, and given throughput. They have also to avoid collisions due to the access to the shared channel and provide error control, flow control, and synchronization.[69] There are two main families of MAC protocols for satellite networks: scheduled access, such as the combined free/demand assignment multiple access (CFDAMA),[70] based on resource reservation mechanisms and scheduled transmissions in order to avoid channel contention, and random access, such as contention resolution diversity slotted ALOHA (CRDSA),[71] which provides contention resolution mechanisms and, for some of them, interference cancellation techniques. Research efforts have been performed to increase their reliability and efficiency (eg, previous studies[72,73]), but their implementation in small satellites needs further evaluation to consider the system constraints.
  - Upper layers: Considering a CubeSat network as a multihop network where satellites are not always in contact with ground stations or among them, there could not be always persistent paths between data sources and destinations, because satellite links are not always up. In addition, in case all data generated by CubeSat sensors are processed and stored in a control station linked to the ground stations through wired cable, in the path between CubeSat and control station, there are different kinds of links (satellite and terrestrial), and the communication through each link could be based on different protocols. The DTN paradigm[74] is a possible solution to deal with this aspect, allowing intermediate nodes to store data until the next contact is available and allowing communications among heterogeneous links. Marchese et al[75] investigate the use of DTN in a nano-satellite constellation network proposing a possible network architecture. Both multiple access and DTN principles have been considered in the development of the DTN-based solution accomplished for the nano-satellite–based sensor networks in Bedon et al,[76] where a communication architecture composed of the bundle protocol, a multiple access mechanism based on extended unslotted ALOHA with gateway priority called ALOHAGP, and a properly defined convergence layer (ALOHAGP-CL) is proposed. At the application layer, most projects use specific application protocols defined ad hoc to fulfil mission requirements. A better solution should be to define interoperable application layer protocols for a wider set of application scenarios and traffic data configurations, which could be employed on top of already defined lower layer satellite protocols, also evaluating the chance to adapt protocols not explicitly designed for satellites. For example, Fanfani et al[77] describe a CubeSat mission called D-SAT where the CSP has been used to transmit alert messages between the satellite and an alert authority generated by the multiple alert message encapsulation over satellite (MAMES) application protocol.[78] Another example is the employment of small satellite constellations for IoT applications, where data may be generated by application protocols developed ad hoc for this kind of traffic, such as MQTT[79] and CoAP.[80] The employment of these protocols should be tested also in the satellite environment, as Bacco et al[81] started investigating.

- Routing: Even if implemented as protocols, the routing schemes have a strong algorithmic component and deserve specific attention. The routing problem may at first appear as the standard problem of dynamic routing with extended link failure times, but it is not so. For the standard dynamic routing problem, the topology is assumed to be connected, and the objective of the routing algorithm is to find the best currently available path to move traffic end-to-end. In a CubeSat network, the topology changes as a consequence of the satellite movement. Routing has to be performed over time to achieve information delivery by employing long-term storage at intermediate nodes to deal with satellite link disruptions (see DTN solutions mentioned before). In this kind of networks, the routing problem is a constrained optimization problem where links may be unavailable for extended periods of time and a storage constraint exists at each node. Data packets are to be moved across a network, which can be modelled as a directed multigraph, where each pair of nodes may be linked by more than one edge (link) that is generally time-varying.[82] Link capacity and propagation delay are time dependent. The time interval during which link capacity is greater than zero is called a contact, and it is the opportunity that a given pair of nodes has to exchange data. In the literature, there are a lot of different routing algorithms that differ in the information used to implement the forwarding decisions. This information concerns contact start and end times, which can be predictable considering that satellite movements are deterministic; contact capacity, ie, amount of data that can be exchanged between two nodes during each contact, which depends on the transmission rate and the contact duration; available storage capacity; and available energy. Routing algorithms can be structured into different classes by using different separation criteria,[82] such as proactive vs reactive, source vs per-hop, and forwarding vs flooding. One of the most used routing algorithms in networks with full information about future contacts is the contact graph routing (CGR).[83] Contact graph routing is designed for use in networks where changes in connectivity are planned and scheduled rather than predicted or discovered. There are papers in the state of the art whose purpose is to prove the reliability of CGR in LEO satellite networks, such as Caini and Firrincieli.[84] The analysis reported in Fraire et al[85] shows that the current version of CGR is not suitable to make an optimal utilization of communication resources, extremely valuable for CubeSats. Further efforts have to be performed on this topic. Marchese et al[75] represents an example.
- Security: To prevent unauthorized access to the network, which could lead to waste network resources and to introduce loss of data, the security aspect has to be taken into account. There are many security issues in LEO satellite networks.[86] Proposed solutions in the literature are based on security mechanisms developed for conventional terrestrial networks, such as the encapsulation security payload (ESP) of IPSec, the Internet key exchange (IKE) protocol, transport layer security/secure socket layer (TLS/SSL), and certification-based public key systems. Nevertheless, these mechanisms, not originally developed for satellite networks, can hardly be directly applied to satellites. For example, TLS requires public key transmission and verification between clients and servers, resulting in long handshake latency. Complicated encryption schemes are not suitable for satellites due to the high BER and long delay of satellite links. Moreover, most of these solutions require a computational effort that could be not affordable for small satellites such as the CubeSats. Scientists are already working on it,[87] but it is still an open problem.

8 | CONCLUSIONS

A strong interest in small satellites recently arose and is still increasing. The number of industries and universities that are working on this issue and have developed small satellite projects is increasing year after year. CubeSat is a kind of small satellite widely used especially thanks to its reduced costs and short design times. Severe design limitations are imposed in terms of maximum size and weight. However, the miniaturization of hardware components allows the implementation of compliant primary components, such as solar panels, battery, antennas, and payloads for a wide range of missions. Most CubeSat missions are based on the deployment of a single satellite equipped with all required instrumentation, even if more CubeSats could be deployed in swarms or constellations. In this way, more complex mission targets could be accomplished exploiting resource sharing and data exchange among satellites. Many challenges and open design problems are still to be solved. We have provided a short overview, addressing structural, architectural, and protocol issues.

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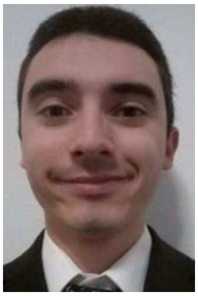

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