An Analytical Study on Functional Split in Martian 3-D Networks

As space agencies are planning manned missions to reach Mars, researchers need to pave the way for supporting astronauts during their sojourn. This will also be achieved by providing broadband and low-latency connectivity through wireless network infrastructures. In such a framework, we propose a Martian deployment of a 3-D network acting as cloud radio access network (C-RAN). The scenario consists of unmanned aerial vehicles (UAVs) and small satellite platforms. Thanks to the thin Martian atmosphere, CubeSats can stably orbit at very-low-altitude. This allows to meet strict delay requirements to split baseband processing functions between drones and CubeSats. The detailed analytical study, presented in this article, confirmed the viability of the proposed 3-D architecture, under some constraints and tradeoff concerning the involved network infrastructures, that will be discussed in detail.

I. INTRODUCTION

The new horizon of space exploration is to land a human crew on Mars around 2026 by accepting a certain degree of risks [1]. Some other forecasts state that, in more or less a hundred years, we shall be able to set a base on the Martian surface to host up to 50 persons [2]. In such a perspective, researchers need to tackle multifaceted problems before being able to move people on Mars: from the design and development of the long-journey vehicle to the support of the astronauts during their sojourn. To this aim, it is of paramount importance to support human life and operations on Mars through the deployment of efficient connectivity infrastructures. This will allow the exchange of real-time information, emergency messages, postprocessing of data,
navigation and remote control of rovers, landers, and unmanned aerial vehicles (UAVs). Experiments conducted by NASA demonstrated that delays and limited bandwidth in extra-terrestrial missions would produce frustration and uncertainty in the crew [3]. On the other hand, the presence of efficient connectivity would improve sociality, the quality of life and, as consequence, increase the probability of success of the mission. In the recent literature, few works have been focused on the provision of efficient mobile connectivity on Mars. Some contributions are mainly devoted to measure the Martian radio propagation in the context of machine-to-machine communications [4], [5]. Other papers preliminarily analyzed the viability of porting terrestrial LTE (and LTE-A) services on Mars obtained by installing eNodeBs somewhere on the planet surface [6], [7]. Despite the interesting and useful results presented in these works, such approaches do not still provide reliable technical answers to the connection requirements of a future manned mission.

In the present work, we study the deployability of “Beyond 5G” wireless infrastructure in the framework of Martian communications, where heterogeneous devices, such as UAVs and nanosatellites, constitute the C-RAN, while higher orbit platforms will form the core network. Connectivity is, hence, provided by means of a 3-D network—one of the driving pillars for the upcoming terrestrial 6G [8]—deployed on Mars. The advantages taken by the availability of such an advanced network infrastructure are supported by various considerations: low end-to-end (E2E) latency, large bandwidth availability, and high energy efficiency, which is attested around 90% more than the 4 G one [9]. With respect to an on-ground fixed architecture, the advantages are in terms of increased coverage, on-demand anywhere-anytime connectivity, high degree of reconfigurability, and reduced outage, which, on the contrary, might be experimented with high probability by a conventional surface wireless connection due to the heavily rocky and craterized nature of Mars [10]. Moreover, in a futuristic perspective, by supposing to have many UAVs and CubeSats, respectively, flying and orbiting on Mars, we should be able to integrate them in the same space ecosystem and coordinate them with on-ground devices. In such a perspective, a space habitat might be interconnected with machines far away, while the human personnel might easily acquire data from them.

The problem to be solved is how to virtualize the necessary network functionalities into flying and orbiting nondedicated hardware present in the Martian environment, which will be conveniently equipped with transceivers, antennas, processing units, and other scientific payload. The way toward a viable solution to this problem may be represented by the work of Bassoli et al. [11], where the feasibility of advanced functional splitting and C-RAN solutions has been studied in a challenging terrestrial scenario, related to secure and efficient border monitoring. The authors of [11] and, especially [12], deeply analyzed and also simulated the so-called “Split D” between UAVs (hosting the LTE radio headend) and CubeSats. The results open up to the possibility of customizing and upgrading such an architecture, by meeting stricter requirements imposed by the 5G standard, to assure connectivity, whenever and wherever is needed. For the aforesaid motivations, we believe that 3-D network solutions may deserve study and consideration also in the Martian context. The present work will investigate in an analytical framework the main feasibility constraints related to a Martian C-RAN architecture for B5G 3-D network, based on UAVs and CubeSats. In detail, the splitting options characterized by the most stringent specification in terms of latency will be analyzed by computing the required CubeSat altitude with respect to the propulsion force needed to maintain the orbit. The next step will be the estimation of the elevation angle and the resulting session time available from CubeSat and the hovering UAV, while fixing the altitude. Consequently, we shall correlate drag force and session time to find the best CubeSat orbit altitude and provide the main architectural parameters. To conclude the analysis, few considerations will be made about the deployment of CubeSats into higher orbits in order to substantially increase their lifetime, so to ensure service continuity even without performing continuous orbit corrections. To the best of our knowledge, no other contribution published in the open literature tried to propose such a kind of analysis applied to a nonterrestrial context.

The rest of this article is organized as follows. Section II describes the Martian 5G scenario, Section III details the proposed methodology, Section IV presents selected simulation results. Finally, Section V concludes this article.

II. SCENARIO

A. Overall Architecture

The current picture of Martian wireless networking looks quite far from readily providing broadband and global connectivity to computing machines, humans, sensors, and any other UE that will operate on the Red Planet surface. Thus, we propose a solution based on an ad hoc network composed by the following four layers:

1) a surface layer, essentially made by the UEs;
2) an aerial layer, which will be devoted to perform remote radio unit (RU) functions of the base station (BS);
3) a very-low Mars orbit (VLMO) layer, in which constellations of CubeSats will take in charge to run the distributed units (DUs) and centralized units (CUs) network functions;
4) a low Mars orbit (LMO) layer, with larger orbiters such as the Mars Reconnaissance Orbiter (MRO), which will host the evolved packet core (EPC) of the B5G network and will provide backhaul links with aerostationary orbiters, communicating, in their turn, with earth to forward and receive data.

In this article, we concentrate our focus on the network setup concerning the aforesaid nodes and, especially, in the challenging UAV-to-CubeSat Martian link where the baseband processing is split. The analysis of the issues inherent to the integration of the deployed local infrastructure with
the long-haul interplanetary connection will be matter for future work.

The four network layers are vertically and horizontally interconnected, meaning that a communication happens by sending data through the uplink path from the UE to the UAV, i.e., the RU, from the UAV to the CubeSat, i.e., the DU and CU, and from the CubeSat to a higher orbiter, i.e., the EPC. On the other hand, UEs can download information, which are delivered by the EPC following the reverse route from orbit to surface. Moreover, the nodes within a layer could exchange data between themselves, for instance, to counteract against possible failures. Service continuity is enabled through the handover between serving satellites, i.e., CubeSats covering UA Vs and orbiters covering CubeSats. Among the various techniques detailed in the state-of-the-art, the slow handover described in [13] well cope with the requirements of the proposed application. A UA V associates to the satellite closest to the Zenith for the best conditions in terms of delay and pathloss. Once the satellite comes to the position of loss-of-signal, occurring when delay requirements are no longer met, the user relinks with the next satellite approaching the Zenith. The same happens for LMO orbiters, which are deployed in low circular orbits to reduce the contact distances between them and CubeSats. Although the fast handover could overall guarantee a better link budget [13], the slow handover offers, for the same number of satellites, a higher session duration $t_s$ that is more advisable for our scenario. We will see in the following a detailed evaluation of such a parameter.

Besides the antennas systems and the processing unit mounted to operate network functions and communicate with the on-ground UEs and with the CubeSat constellation, UAVs will be equipped with solar panels recharging lithium-ion batteries. However, due to their reduced size and weight and the thin Martian atmosphere ($\frac{1}{100}$ of the terrestrial atmospheric density [14]), most of the available power has to be used to make the UAV flying for a considerable range of time. Therefore, battery life is a crucial parameter to be optimized, and so, the processing unit should consume as less as possible, while operating for maintaining a continuous and reliable connection with the UEs. It should be remarked here that experiments related to Martian drones are in a very early stage and, so far, have been only devoted at demonstrating the possibility for small remotely controlled rotorcrafts to fly in the thin Martian atmosphere [15]. Such experiments will achieve further goals in the near future that may enable future Martian drones to embark light but vital payloads, i.e., to survive the cruise to Mars, to autonomously charging themselves with their solar panels, and to communicate to and from the helicopter via a subsystem called Mars helicopter base station [15].

However, virtualizing BBU (v-BBU) functions will remain a heavy processing task, even for advanced and efficient UAV systems. For this reason, we aim to move the most complex functions of the v-BBU on CubeSats (options 7.3-8 [16] shown in Fig. 1). Clearly, these CubeSats should be characterized by size greater than the typical cubic-shaped unit (1U) of $10 \times 10 \times 10$ cm in order to embark the scientific payload. The remaining available room on the CubeSat will be filled with computing and storage units. The energy resources should be harvested, thanks to solar arrays and lithium-ion batteries. The recent development of MarsCubeOne (MarCO) mission, targeted at sending swarms of CubeSats on Mars, is designing small satellites supplied by solar panels. Their size and weight look suitable to host advanced payloads. Indeed, MarCO’s design is a six-unit (6U) CubeSat. Each of the two platforms has a stowed size of $36.6$ cm by $24.3$ cm by $11.8$ cm [17] (see Fig. 2). So far, the results of the MarCO mission have been contrasting. MarCOs satellites, named EVE and WALL-E, served as communication relays during the InSight rover landing, beaming back data at each stage of its descent to the Martian surface in near-real-time [18]. WALL-E sent some remarkable images of Mars, while EVE performed some radio science experiments. The last contact with the MarCO pair was in early 2019. The NASA mission team investigated the reasons for why they have not been able to contact the pair. WALL-E should have experienced problems due to a leaky thruster along with some control issues.
Moreover, the brightness sensors that allow the CubeSats to stay pointed at the Sun and recharge their batteries could have been another failure point. However, as claimed in [18], the mission was always about pushing the limits of miniaturized technology and seeing just how far it could have taken. MarCO satellites demonstrated to be capable of orbiting and transmitting/receiving signals. Future versions are expected to go farther in advanced radio system experimentation, of course after solving the problems inherent to the platform and the control system that hindered the early phase of the mission. In such a perspective, the possibility of embarking a processing payload capable of supporting more advanced tasks, like those related to v-BBU processing, might become more realistic.

B. Splitting Options

The interest around the various splitting options is due to the possibility of enabling a complete virtualization of BBU tasks in nondedicated hardware, as it will be a reconfigurable processing unit installed on a CubeSat or UAV. The third generation partnership project (3GPP) identified eight possible functional split options, as shown in Fig. 1. Here, split option 1 (namely: opt.1) detaches the packet data convergence protocol (PDCP) from the network layer of radio resource control (RRC), while opt.2 performs the same operation between the radio link control (RLC) and the PDCP. Opt.3 is operated within the RLC and opt.4 divides the medium access control (MAC) from the RLC, while Opt.5 separates the lower MAC from the upper MAC. The last splitting operation within the datalink layer is opt.6, which is done before the forward error correction (FEC). From opt.7-8 we move to the physical (PHY) layer. Opt.7.3 is performed between the detection, equalization, modulation, precoding, and the FEC, while opt.7.2 goes deeper into the PHY-layer detaching the resource element (RE) mapping, or demapping, functions. The CP, insertion or removal, and fast Fourier transform (FFT), or inverse FFT (I-FFT), is implemented in RU if opt.7.1 is considered. Lastly, opt.8 is considered just after the analog-to-digital (AD) or digital-to-analog (DA) conversion. Note that bandwidth and latency requirements should be met when considering these splits as specified in 3GPP TR 38.801 [19].

The achievement of the fronthaul data rate needed to guarantee the fulfillment of the splitting functionalities depends on many factors, such as the number of antennas at RU side, the available sampling rate of the analog front end (AFE), and the selected split option [20]. A detailed study regarding such aspects has been carried out in [21], where the CubeSat-based fronthaul communication system coping with the requirements of different v-BBU splitting options has been thoroughly described and technical solutions for its practical implementation have been proposed. Here, we summarize the outcomes of this analysis for what concerns data rate and bandwidth occupation aspects. Assuming a single antenna at the UAV side and the typical 5G sampling frequency of 153.6 MHz, the data rate to be transferred through the UAV-to-CubeSat link for opt.8 approximately equals to 6.14 Gb/s, while it equals 2.6 Gb/s for option 7.1, 1.474 Mb/s for option 7.2, 396 Mb/s for option 7.3 and, finally, 104 Mb/s for option 6. [20]. Considering the use of commercial AFE components, a net spectral efficiency of 4.61[bit/symbol] can be achieved [21]. Assuming a roll-off factor of the pulse-shaping filter of 0.3, the occupied bandwidth would become equal to 1.73 GHz for option 8, 733.2 MHz for option 7.1, 126 MHz for option 7.2, 111.6 MHz for option 7.3, and 29.3 MHz for option 6, respectively. X-band, Ku-band, and Ka-band would offer spectrum portions large enough to allocate the radio resources required by the fronthaul link in all the considered splitting configurations. Such frequency bands are negligibly impaired by Martian atmospheric attenuation due to the combined effect of H2 and H2O (CO2 and N2 do not absorb electromagnetic energy in the microwave frequency range). Such an attenuation has been evaluated as less than 10^-4 dB/Km in the range 1–40 GHz [22].

The latency requirements to be met in order to split BBU functions are imposed by various standardization bodies upon specific criteria. For instance, the Small Cell Forum (SCF) defines the one-way maximum latency $\tau_{\text{ideal}} = 0.25$ ms as for the ideal case, $\tau_{\text{near-ideal}} = 2$ ms for the near-ideal case, $\tau_{\text{subideal}} = 6$ ms and $\tau_{\text{nonideal}} = 30$ ms, respectively, for the subideal and nonideal case [23]. For the 3GPP [19], the latency for splitting opt.6-8 should be less than 0.25 ms, while for opt.5, it should be of the order of hundreds of microseconds. Such a parameter should be approximately equal to 0.1 ms for opt.4, ranging from 1.5 to 10 ms for opt.2-3 and, finally, equal to 10 ms for opt.1. The authors of [16] state that, for opt. from 1 to 5, the requirements to be accounted for designing the network architecture and the communication links are more relaxed than those imposed for opt. 6 to 8. It seems, then, that the critical latency is $\tau_{\text{ideal}} = 0.25$ ms [20]. This last will be assumed as our reference value. Enabling splitting opt.8 means to ensure the possibility of meeting most of the requirements of the other splitting operations. For this reason, we find more interesting to deal with opt.7-8, at least for what concerns our application. As said before, our aim is to consider the RU supported by the UAVs, while most of the DU and the CU functions are implemented on the CubeSat.

Power consumption aspects may result critical in the fulfillment of such kind of advanced networking tasks. In this article, we shall provide some notes about the concerned issues, leaving for future work further detailed analysis.
Citing the literature, a dual-site virtualized RAN (vRAN) model has been described in [24], where remote and central sites are utilized to split the RAN functionalities. The RAN components at the central site are assumed to be virtualized. The authors of [24] reported detailed bandwidth, power consumption, and energy efficiency metrics as a function of functional split percentage deployed at the respective sites. Furthermore, the virtualization of RAN functions is expected to provide more advantages, such as energy consumption due to dynamic resource allocation and load balancing as described in [25]. In [26], the authors reported that a significant energy savings could be obtained by offloading RAN functions such as CP, FFT, and I-FFT to a field programmable gate array (FPGA). Note that changing the functional split option from opt.7.1 to opt.7.2x at the RU, provides a variable bit rate by further reducing fronthaul bitrate. Another issue that may deserve discussion is related to the impact of the high data rate of the fronthaul link on the effectiveness of the handover operation. In particular, during the handover execution, some sort of link redundancy, similar to that used by the terrestrial seamless handover [27], should be considered in order to avoid the huge data loss that would be involved by the hard switching between the links connecting the UAV with the two serving satellites (i.e., the current and the new one). Despite their intrinsic interest, these aspects require a detailed analysis in terms of resource management, control signaling, and algorithmic complexity that are outside the scope of this article and will be left for future work.

In the following section, the discussion will address the fulfillment of the requirements of ideal latency $\tau_{\text{ideal}}$ in the context of splitting operations, which will introduce some interesting considerations about the possibility of lowering CubeSat’s orbits due to the Martian intrinsic physics and atmosphere. Such considerations might constitute the basis for the future enabling of low-latency applications in forthcoming Martian missions.

III. PROPOSED METHODOLOGY

The feasibility of the splitting options 7-8 is assessed by meeting the latency requirement in terms of $\tau_{\text{ideal}} = 250 \mu s$ [19] that is our reference in the system design. This implies that the distance $d$ between the UAV and the CubeSat (CS), lately referred as slant range, can range up to $d_{\text{max}} \approx 75$ km, given $d = c \cdot \tau_{\text{ideal}}$, where $c$ is the speed of the light. By starting from this assumption, the proposed methodology can be summarized in the points listed as follows:

1) evaluating the Martian atmospheric density $\rho$ by sweeping the altitude value;
2) computing the approximate drag force $F_{\text{drag}}$ over 1, 6, 12U CubeSat, thus, evaluating the required propulsion force $F_{\text{prop}}$ to correct and maintain the orbit;
3) analyzing the acceptable elevation angle $\epsilon$, while computing the slant range $d$ between the hovering UAV and the orbiting CubeSat, to cope with the $\tau_{\text{ideal}}$ requirement;
4) obtaining the maximum session time $t_s$ between UAV and CubeSat.

First of all, we estimate the Martian atmospheric density $\rho(h_{\text{CS}})$ with reference to the model proposed in [28], i.e.,

$$\rho(h_{\text{CS}}) = \rho_0 \cdot e^{-h_{\text{CS}}/h_0}$$

where $H = 11.1$ km is the atmosphere scale height [29], $h_{\text{CS}}$ is the CubeSat altitude, and $\rho_0$ may assume two reference density values, a lower one $\rho_0 = 0.0001 \text{ kg/m}^3$, and a higher one $\rho_0 = 0.001 \text{ kg/m}^3$. Consequently, the drag force $F_{\text{drag}}$ can be expressed as follows [28]:

$$F_{\text{drag}}(h_{\text{CS}}) = \frac{1}{2} \left( \rho(h_{\text{CS}}) \cdot v_{\text{CS}}(h_{\text{CS}})^2 \cdot C_D \cdot A_{\text{CS}} \right)$$

and computed according to the different sizes of the CubeSats. Indeed, $v_{\text{CS}}$ stands for the circular velocity of the CubeSat, which is given by [30]

$$v_{\text{CS}}(h_{\text{CS}}) = \sqrt{\frac{G \cdot M_{\text{Mars}}}{h_{\text{CS}} + R_{\text{Mars}}}}$$

$G = 6.67 \times 10^{-11} \text{Nm}^2/\text{kg}^2$ being the gravitational constant, $M_{\text{Mars}} = 6.39 \times 10^{23}$ kg and $R_{\text{Mars}} = 3389.5 \times 10^3$ m, the planet mass and radius, respectively [29], while $C_D = 2.0$ is the drag coefficient, and, finally, $A_{\text{CS}}$ is the CubeSat cross-section obtained by the following formulation, valid for parallelepiped-shaped spacecraft [31]:

$$A_{\text{CS}} = \frac{1}{2} (S_1 + S_2 + S_3)$$

where $S_1$, $S_2$, $S_3$ represent the mean area of the visible CubeSat surfaces, which does not consider the area occupied by the possible presence of the solar array. The considered CubeSat dimensions are: $10 \times 10 \times 10$ cm for 1U, $20 \times 30 \times 10$ cm for 6U and $20 \times 30 \times 20$ cm for 12U.

Now, in order to evaluate the minimum orbital altitude of the CubeSat under which it would be impossible to counteract the drag force and maintain the orbit, it is necessary to evaluate the propulsion force $F_{\text{prop}}$, applied by the thrusters installed on the small satellite platform. $F_{\text{prop}}$ should be, at least, equal to $F_{\text{drag}}$ in order to allow at continuously correcting the satellite orbit. Later, we shall deal with some commercial and noncommercial thrusters, assessing their impact on the minimum allowed altitude. As briefly introduced above, the minimum altitude is the minimum acceptable distance $d_{\text{min}}$ between UAV and CubeSat. Indeed, while we consider for simplicity the UAV hovering on the Martian surface, the CubeSat is circularly orbiting in LMO or VLMO, around Mars at the velocity expressed in (3). Consequently, the CubeSat will approach the nearest point to the UAV only when the elevation angle, i.e., the angle between the line of sight (LOS) connecting CubeSat and UAV and the relative horizontal plane, is $\epsilon = \frac{\pi}{2}$. The LOS length $d$ (slant range) is formulated by starting from
between CubeSat with radius that is the circular arc traveled by the CubeSat, we can understand that the selected

$$h_{\theta} + \epsilon$$ is computed is defined in the range $8$ and center in the

$$F = \frac{44 \text{ kg}}{\pi \cos(h_{\theta} + \epsilon)}$$

over $1$, $6$, and $12$U CubeSats on VLMO with

$\cdot$ applied by off-the-shelf, Vacco’s MiPS, and JPL hybrid thrusters (HT).

The minimum allowed altitude angle

$$\epsilon_{\text{min}}$$ by the circular minor arc, representing the orbit within

the law of cosines [32]

$$(R_{\text{Mars}} + h_{\text{CS}})^2 = (R_{\text{Mars}} + h_{\text{UA}})^2 + d^2 - 2d(R_{\text{Mars}} + h_{\text{UA}})\cos(90 + \epsilon)$$

and, consequently, derived from (5) as follows:

$$d = \left[ \sqrt{(R_{\text{Mars}} + h_{\text{CS}})^2 - \cos^2(\epsilon) - \sin(\epsilon)} \right] \cdot (R_{\text{Mars}} + h_{\text{UA}})$$

where $h_{\text{UA}}$ is the drone height, as shown in Fig. 3, and the elevation angle $\epsilon$ is defined in the range $[0, \frac{\pi}{2}]$. The minimum allowed elevation angle $\epsilon_{\text{min}}$ is computed by searching, in the matrix representing the slant range, the maximum admissible LOS distance $d_{\text{max}} = c \cdot \tau_{\text{ideal}}$ between UAV and CubeSat for each $h_{\text{CS}}$ and $h_{\text{UA}}$. Now, thanks to trigonometric functions, the session time between UAV and CubeSat, i.e., the time elapsed during the elevation arc travel $\epsilon = [\frac{\pi}{2}, \pi - \epsilon_{\text{min}}]$, can be estimated. Such a range is inherent to the slow handover mode, as introduced in Section II, where a UAV reconnects to a new CubeSat close to the Zenith when the distance from the previous CubeSat exceeds $d_{\text{max}}$. First, the angle $\theta$ in (rad) subtended by the circular minor arc, representing the orbit within $\epsilon = [\epsilon_{\text{min}}, \frac{\pi}{2}]$ with radius $r = h_{\text{CS}} + R_{\text{Mars}}$ and center in the

Mars’ core, is computed in the following manner:

$$\theta_{\text{max}} = \arcsin\left(\frac{d_{\text{max}} \cdot \cos(\epsilon_{\text{min}})}{R_{\text{Mars}} + h_{\text{CS}}}\right).$$

Finally, the session time $t_s$, during which the UAV and the CubeSat can communicate together is given by the distance $d_{\text{arc}}$ that is the circular arc traveled by the CubeSat, divided by the orbital speed $v_{\text{CS}}$, i.e.,

$$t_s = \theta \cdot (R_{\text{Mars}} + h_{\text{CS}}) \over v_{\text{CS}}$$

with $\theta \leq \theta_{\text{max}}$. To conclude and further clarify, $t_s$ is the session time achievable if we suppose to establish a communication between a UAV at a certain altitude and a CubeSat exactly moving from Zenith to the loss-of-signal position, corresponding to $d = d_{\text{max}}$. By the way, this estimate accepts a certain degree of approximation, which, however, seems reasonable for the purpose of assessing the feasibility of the functional split in Martian 3-D networks.

IV. RESULTS

As previously mentioned in Section III, by comparing the drag force $F_{\text{drag}}$ and the propulsion force $F_{\text{prop}}$, we are able at estimating the minimum allowed altitude for the $1$, $6$, and $12$U CubeSats.

From the literature, we have found that the propulsion systems used by $1$U commercial CubeSats can roughly apply $F_{\text{prop}} = 1$N. For what concerns $6$U CubeSats, we take as reference the MarCO platform, whose size well fits with the $6$U model. MarCO satellites have been equipped with eight Vacco’s thrusters but only four of them have been used for trajectory correction. Thus, from the data sheet of [33] detailing the ‘‘Micro Propulsion System’’ (MiPS) adopted by MarCOs, we fixed $F_{\text{prop}} = 4 \times 10$N. However, in the perspective of Martian deep space missions, it would be useful to have more room to host advanced scientific payloads. In this context, $12$U CubeSat are the biggest available platforms. Without going too much into the details, the authors of [34] presented a $12$U CubeSat, weighing about $25$ kg, equipped with a single main hybrid rocket motor able at producing $F_{\text{prop}} = 44.4$ N, while occupying the $76\%$ of the total platform volume. This is more than three orders of magnitude above the previously mentioned $F_{\text{prop}}$ required by $6$U CubeSats. Fig. 4 shows, as first instance, that such a propulsion system, implemented with the current technologies, would be not suitable for terrestrial applications. Indeed, by parameterizing (1) with $H_{\text{Earth}} = 8.5$ km and $\rho_0 = 1.217$ kg/m$^3$ [14], we can understand that the selected thrusters for the $1$U, $6$U and $12$U CubeSat cannot provide enough propulsion force to correct trajectories and altitudes under $163.5$ km for $1$U, $143.0$ Km for $6$U, and $86.5$ Km for

![Fig. 3. Two-dimensional geometrical representation of the circular arc in which communication happens in session time $t_s$ between CubeSat and UAV.](image1)

![Fig. 4. Drag force $F_{\text{drag}}$ over $1$, $6$, and $12$U CubeSats on VLMO with respect to the low earth orbit (LEO). The dotted lines stands for the propulsion force $F_{\text{prop}}$ applied by off-the-shelf, Vacco’s MiPS, and JPL hybrid thrusters (HT).](image2)
12U, respectively. This is quite interesting but also expected, thanks to the Martian atmosphere that is much thinner than the terrestrial one. This suggests that the environment of the Red planet can be regarded as advantageous for the future in situ deployment of B5G networks. However, it is also evident from Fig. 4 that common commercial thrusters for 1U CubeSats and the Vacco’s MiPS for 6U CubeSat cannot be used to guarantee Martian orbits with altitudes under 134.5 km for 1U and 108.0 km for 6U, respectively, while our upper bound is $h_{max} \approx 75$ km. On the other hand, the JPL hybrid thruster can allow to decrease the minimum acceptable orbit well below $h_{max} \approx 75$ km, thus, meeting the fundamental latency requirement of the splitting options 7.3, 7.2, 7.1, and 8. 12U hybrid CubeSat can support a minimum altitude $h_{min} \approx 35$ km. Clearly, it is neither necessary nor convenient to place constellations of CubeSats at such a low altitude. First of all, it would be almost impossible to maintain the thrusters always active, as required, for sake of energy consumption reasons. Then, the coverage would be negatively affected by such a low orbit, thus, leading to the necessity of launching many more CubeSats to serve the same area. However, the outcomes of this analysis provide us some consistent indications about the fact that, in the near future, CubeSat Martian missions might be launched at extremely low altitudes.

The next step of our analysis aims at showing in Fig. 5 the minimum acceptable elevation angle $\epsilon_{min}$ for altitudes ranging from $h_{min} = 35$ km and $h_{max} = 75$ km. As we can see by following the red dotted line, the slant range is fixed at $d_{max} = 75$ km to cope with the latency constraint $T_{ideal} = 250 \mu s$. The lower elevation angle $\epsilon$ is found when $h_{min} \approx 35$ km, while for $h_{max} = 75$ km it would be possible to establish the connection only when $\epsilon = \frac{\pi}{2}$, meaning a session time $t_s \approx 0$.

The series of results of Fig. 6 depicts, for each altitude $h_{CS}$, the achievable session time related to the connection between UAV and CubeSat; this last moving at a speed $v_{CS} \approx 3.5 \frac{km}{s}$. If we lower the altitude of the CubeSat, we can noticeably increase the session time up to $t_s = 18$ s for really low altitudes. The price to be paid is in terms of resources consumed to correct the trajectory of the CubeSat and overall reduced coverage.

In Fig. 7, the drag force and the session time are directly correlated through a Pareto front. As we increase the CubeSat altitude $h_{CS}$, we decrease the drag force $F_{drag}$ but also the achievable session time $t_s$. On the contrary, a lower $h_{CS}$ implies higher $t_s$ but also higher $F_{drag}$ that must be counteracted by increasing $F_{prop}$. If we normalize the two terms, while giving them the same weight, we can compute the optimal altitude minimizing the following cost function:

$$h_{opt} = \min_{h} \left( abs(t_s(i + 1) - t_s(i)) + abs(F_{drag}(i + 1) - F_{drag}(i)) \right)$$  (9)

where $i$ is the index running the vectors. The computed optimal altitude is $h_{opt} = 67.1$ km with $F_{drag} = 2.34$ N (the 5.2% of the maximum $F_{prop}$ applied by the JPL hybrid CubeSat) and $t_s = 9.6$ s. However, the selection of the best altitude should be done by unevenly weighing the objectives with respect to precise scientific requirements.
TABLE I CubeSat Parameters

| Type               | Form Factor     | Mass (kg)     | Weight (kg)   | Nominal Thrust |
|--------------------|-----------------|---------------|---------------|----------------|
| Commercial CubeSat | 1U              | 10×10×15 cm   | 1.33 kg       | 1mN (40-60-deg) |
| Mars CubeSat       | 4U              | 20×20×10 cm   | 13.54 kg      | 10N (50-80-deg) |
| Hybrid CubeSat     | 12U             | 20×30×20 cm   | 25.08 kg      | 44.4 N (90 deg) |

Fig. 8. 1, 6, 12U CubeSat lifetime without thrusters, thus, no altitude correction over time.

Now, let us consider the option of avoiding the thruster usage. In such a case, CubeSats should be placed into higher LMOs as compared to those ones that fulfill the ideal latency requirements for the functional split. Their orbital lifetime can be iteratively estimated, starting from an initial chosen altitude \( h_{CS}(t_0) \), an initial time \( t_0 = 0 \), and the combination of the following equations.

1) The relation between the orbital period \( P \), at the iteration \( t_i \), and the semimajor axis (or radius \( r \)) of the circular orbit, defined in Section III, i.e., [35]

\[
P(t_i) = 2\pi \sqrt{\frac{(h_{CS}(t_i) + R_{Mars})^3}{G \cdot M_{Mars}}}.
\]

2) The period decrease \( dP \) caused by the atmospheric drag \( F_{drag} \) [35]

\[
dP(t_i) = -3\pi \rho (h_{CS}(t_i) + R_{Mars}) \left( \frac{A_{CS} \cdot C_D}{m_{CS}} \right) dt_i
\]

where \( m_{CS} \) is the CubeSat weight that is shown in Table I, \( A_{CS} \) and \( C_D \) have been already defined in Section III, \( \rho \) depends on \( h_{CS} \), as in (1) and, finally, \( dt_i \) is the discrete-time iteration step. At the iteration \( t_{i+1} \), the updated CubeSat altitude \( h_{CS}(t_{i+1}) \) is computed starting from the decreased orbital period \( P(t_{i+1}) = P(t_i) - dP(t_i) \) by using (10). The orbital lifetime is the time iteration \( t_{life} \), for which \( P(t_{life}) \rightarrow 0 \). As shown in Fig. 8, the ratio between effective area and weight of CubeSats with form factor 6 and 12U helps to gain orbital lifetime with respect to 1U CubeSats. Indeed, as we lower the term \( \frac{A_{CS} \cdot C_D}{m_{CS}} \), we also lower the differential \( dP(t_i) \), which is the main actor in the orbital period decrease. For \( h_{CS} = 75 \text{ km} \), without using thrusters, a 12U CubeSats would fall within a couple of minutes, while for \( h_{CS} = 150 \text{ km} \) it would take just few more than a terrestrial day. As we move to higher orbits, such as \( h_{CS} = 175 \text{ km} \), 1, 6, and 12U CubeSats would last, respectively, 4, 10, and 13 days. On the other hand, an altitude of \( h_{CS} = 250 \text{ km} \) would lead to a 12U CubeSat orbital lifetime of about 25 years.

Referring to the “Nanosats Database,” probably the largest database of information regarding nanosatellites missions, it is claimed that 12U CubeSats have approximately an operational life of at least a couple of years [36]. To guarantee two years of operational lifetime, we should guarantee at least two years of orbital lifetime, which can be achieved by selecting \( h_{CS} \approx 225 \text{ km} \). Supposing \( \epsilon = \frac{2}{3} \), thus, \( t_i \approx 0 \), the propagation delay will approximately be \( \tau = 0.75 \text{ ms} \). This noticeable latency increase would have, for sure, some measurable impact on the overall performance of the 3-D network. Future work will address this point by means of extensive network level emulations targeted at assessing QoS metrics, such as E2E delay, packet loss, throughput, and achievable goodput.

V. CONCLUSION

This article presented the deployment of a Martian C-RAN using a 3-D network architecture formed by CubeSats and UAVs. We assessed the possibility of performing splitting options 7-8 on non-dedicated hardware to divide the computational load of RU, DU, and CU functions. Results quantitatively demonstrate the feasibility of the proposed architecture on Mars, at least in terms of latency requirements, assuming that lifetime and stability issues noticed in the early experiments of UAV and CubeSat launches in the Martian environment will be properly solved. Future work will concern with the end-to-end performance assessment of the considered Martian 3-D networking system by using proper emulation tools. In such an analysis, the impact of relaxing latency and fronthaul data rate requirements on network performance will be discussed in detail. Further work should also consider an in-depth analysis of the energy consumption of the various splitting options and the related impact on the design and future implementation of the proposed Martian 3-D network architecture.

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REFERENCES

[1] I. Ahmed and L. Aubourg, “America has sent five rovers to Mars—when will humans follow?,” Accessed: Jul. 21, 2021. [Online]. Available: https://phys.org/news/2021-02-america-rovers-mars-when-humans.html

[2] R. Potter, S. Saikia, and J. Longuski, “Resilient architecture pathways to establish and operate a pioneering base on Mars,” in Proc. IEEE Aerosp. Conf., 2018, pp. 1–18.

[3] NASA, “NASA is laser-focused on deep space communication,” Accessed: Aug. 25, 2021. [Online]. Available: https://www.nasa.gov/mission_pages/station/research/news/comm_delay_assessment

[4] V. Chukkala, P. De Leon, S. Horan, and V. Velusamy, “Modeling the radio frequency environment of Mars for future wireless, networked rovers and sensor webs,” in Proc. IEEE Aerosp. Conf. Proc. (IEEE Cat. No.04TH8720), 2004, vol. 2, pp. 1329–1336.

[5] V. Chukkala and P. De Leon, “Simulation and analysis of the multipath environment of Mars,” in Proc. IEEE Aerosp. Conf., 2005, pp. 1678–1683.

[6] C. Sacchi and S., “From LTE-A to LTE-M: A futuristic convergence between terrestrial and Martian mobile communications,” in Proc. IEEE Int. Black Sea Conf. Commun. Netw., 2019, pp. 1–5.

[7] S. Bonafini and C. Sacchi, “Building cellular connectivity on Mars: A feasibility study,” in Proc. IEEE Aerosp. Conf., 2020, pp. 1–12.

[8] E. Calvanese Strinati et al., “6G in the sky: On-demand intelligence at the edge of 3D networks (Invited Paper),” ETRI J., vol. 42, no. 5, pp. 643–657, 2020. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.4218/etrij.2020-0205

[9] R. Cardone, “Achieving sustainability with energy efficiency in 5G networks,” Accessed: Aug. 26, 2021. [Online]. Available: https://wwwericssoncom/en/blog/3/2021/1/achieving-sustainability-with-energy-efficiency-in-5g-networks

[10] S. Bonafini and C. Sacchi, “3D ray-tracing analysis of radio propagation on Mars surface,” in Proc. IEEE Aerosp. Conf. (501001), 2021, pp. 1–10.

[11] R. Bassoli, F. Granelli, C. Sacchi, S. Bonafini, and F. H. P. Fitzek, “CubeSat-Based 5G cloud radio access networks: A novel paradigm for on-demand anytime/anywhere connectivity,” IEEE Veh. Technol. Mag., vol. 15, no. 1, pp. 39–47, Jun. 2020.

[12] S. Bonafini, R. Bassoli, F. Granelli, F. H. Fitzek, and C. Sacchi, “Virtual baseband unit splitting exploiting small satellite platforms,” in Proc. IEEE Aerosp. Conf., 2020, pp. 1–14.

[13] A. Al-Hourani, “Session duration between handovers in dense LEO satellite networks,” IEEE Wireless Commun. Lett., vol. 10, no. 12, pp. 2810–2814, Dec. 2021.

[14] NASA, “Earth fact sheet,” Accessed: Sep. 1, 2021. [Online]. Available: https://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html

[15] Jet Propulsion Laboratory, “Ingenuity Mars Helicopter: Landing press kit,” Accessed: Feb. 7, 2022. [Online]. Available: https://www.jpl.nasa.gov/news/press_kits/ingenuity/landing

[16] L. M. P. Larsen, A. Checko, and H. L. Christiansen, “A survey of the functional splits proposed for 5G mobile crosshaul networks,” IEEE Commun. Surv. Tut., vol. 21, no. 1, pp. 146–172, Jan.–Mar. 2019.

[17] “Mars cube one demo,” Accessed: Feb. 7, 2022. [Online]. Available: https://www.jpl.nasa.gov/news/press_kits/insight/launch/appendix/mars-cube-one/

[18] “In depth: MarCO (Mars cube one),” Accessed: Feb. 7, 2022. [Online]. Available: https://solarsystem.nasa.gov/missions/mars-cube-one/in-depth/

[19] 3GPP, “Study on new radio access technology: Radio access architecture and interfaces (Release 14),” Accessed: Jul. 23, 2021. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3056

[20] J. K. Chaudhary, “Analysis of bandwidth and latency constraints on a packetized cloud radio access network fronthaul,” Ph.D. dissertation, Fakultat Elektrotechnik und Informationstechnik, Dresden Univ. Technol., Dresden, Germany, 2020.

[21] S. Bonafini, C. Sacchi, R. Bassoli, K. Kondepu, F. Granelli, and F. H. P. Fitzek, “3D Cloud-RAN functional split to provide 6G connectivity on Mars,” in Proc. IEEE Aerosp. Conf., 2022, pp. 1–12.

[22] C. Ho, N. Golshan, and A. Kliore, “Radio wave propagation handbook for communication on and around Mars (JPL publication 02-5 series),” Jet Propulsion Lab., California Inst. Technol., Pasadena CA, USA, 2002.

[23] Small Cell Forum, “Small cell virtualization functional splits and use cases,” Document 159.07.02, Release 7.0, Jan. 2016. [Online]. Available: https://www.smallcellforum.org/

[24] T. Ismail and H. H. M. Mahmoud, “Optimum functional splits for optimizing energy consumption in V-RAN,” IEEE Access, vol. 8, pp. 194333–194341, 2020.

[25] ETSI GS NFV-IFA 001, “Network functions virtualization (NFV); acceleration technologies; report on acceleration technologies and used cases,” ETSI group specification, version V1.1.1, Sophia Antipolis, France, Dec. 2015.

[26] J. Borromeo, K. Kondepu, N. Andriolli, and L. Valcareghini, “Experimental evaluation of 5G vRAN function implementation in an accelerated edge cloud,” in Proc. Eur. Conf. Opt. Commun., 2021, pp. 1–3.

[27] S. Tabbane, Handbook of Mobile Radio Netw. (Artech House Mobile Commun. Library Ser.). Norwood, MA, USA: Artech House, 2000. [Online]. Available: https://books.google.it/books?id=SSRTAAAAMAAJ

[28] K. Wickhusen, J. Oberst, and F. Dannre, “A proposed mission to very low mars orbit - supported by an electric propulsion system,” in Proc. Eur. Planetary Sci. Congr., 2018, Paper no. EPSC2018-364.

[29] NASA, “Mars fact sheet,” Accessed: Aug. 30, 2021. [Online]. Available: https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html

[30] J. Lissauer and I. de Pater, Fundam. Planet. Sci.: Phys., Chem. and Habitability, Cambridge, U.K.: Cambridge Univ. Press, 2013. [Online]. Available: https://books.google.it/books?id=QiggAwAAQBAJ

[31] T. Coail-Fourrier, “Evaluation and correction of the orbital decay, deorbit calculation for a 3 U Cubesat in low earth orbit,” Institut Polytechniques des Sciences Avances de Paris, Paris, France, Tech. Rep., Sep. 2016, pp. 1–41.

[32] S. Cakaj, B. Kamo, A. Lala, and A. Rakipi, “The coverage analysis for low earth orbiting satellites at low elevation,” Int. J. Adv. Comput. Sci. Appl., vol. 5, no. 6, pp. 6–10, 2014. [Online]. Available: http://dx.doi.org/10.14569/IJACSA.2014.050602

[33] V. Industries, “Standard micro propulsion system,” Accessed: Aug. 30, 2021. [Online]. Available: https://www.vacco.com/images/uploads/pdfs/MIPS_standard_0714.pdf

[34] E. T. Jens, A. C. Karp, J. Rabionovich, A. Conte, B. Nakazono, and D. A. Vaughan, “Design of interplanetary hybrid CubeSat and SmallSat propulsion systems,” Jul. 2018. [Online]. Available: https://arc.aiia.org/doi/abs/10.2514/6.2018-4668

[35] J. Kennewell, “Satellite orbital decay calculations,” Accessed: Feb. 18, 2022. [Online]. Available: https://www.ssw.bom.gov.au/Category/Educational/Space%20Weather/Space%20Weather%20Effects/SatelliteOrbitalDecayCalculations.pdf

[36] Nanosats Database, “World’s largest database of nanosatellites, over 3300 nanosats and CubeSats,” Accessed: Feb. 18, 2022. [Online]. Available: https://www.nanosats.eu/