5G New Radio Techniques for 3D Networks in Connection-critical Scenarios

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Abstract—**The recent natural disasters, such as the Earthquake in Morocco in September 2023, have demonstrated one more time the necessity of immediately restoring lost connectivity to rescue victims living in rural villages that are far from urban areas. In such a framework, three-dimensional (3D) Non-Terrestrial Networks (NTNs) are expected to provide continuous wireless coverage at low Average Revenue Per User (ARPU), in disaster-hit and hotspot areas with the help of 5G New Radio (NR). This paper investigates the use of Unmanned Aerial Vehicles (UAV) as transparent aerial networks that perform signal amplification and frequency conversion between a satellite-based 5G network and a User Equipment (UE) using five different frequency bands (i.e., S-band, C-band, X-band, Ku-band, and Ka-band) supporting the satellite communication. The applications of the proposed technology concern connection-critical scenarios like emergency rescue and digital divide mitigation. Results show that 180Mbps to 4.85Gbps throughput can be achieved on the satellite-to-UAV link. Simulated transmission delay and average session time are also evaluated considering a delay budget of 2ms. The related results discussion confirms the viability and effectiveness of the proposed approach in the concerned case of study.**

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1. INTRODUCTION

5G technology standard for broadband cellular networks started its worldwide deployment in 2019 [1]. It supports new services based on three major scenarios: (i) enhanced mobile broadband (eMBB); (ii) massive machine-type communications (mMTC); and (iii) ultra-reliable low-latency communications (URLLC) [2]. However, there are still some areas and scenarios that experience cellular connectivity issues. People living in rural areas of Low- and Middle-Income Countries (LMIC) are 37% less likely to use mobile internet compared to those living in urban areas, with the largest rural-urban gap reported in Sub-Saharan Africa [3]. Another concern is the lack of Internet access during post-disaster recovery: communication towers usually get damaged depending on the intensity of the disaster, while Internet connectivity is very important for residents in disaster-hit areas to communicate their situation and needs [4].

With the evolution of beyond 5G, Non-terrestrial Networks (NTNs) using stand-alone satellite communications are meant to improve the limited performance of 5G terrestrial networks specifically in unserved/underserved areas, disaster-hit regions, or in hotspot areas [5]. Different types of frequency bands are used in satellite communication, such as S-band, C-band, X-band, Ku-band, and Ka-band [6]. 3GPP Release 16 [7] is already exploring the use of S- and Ka-band with the 5G New Radio (5G NR) to support NTN. However, frequency bands that are used by mobile service providers are on the Sub-6 GHz (e.g., in Germany the 3.6 GHz range is used in major cities and the 2.1 GHz range in other areas) [8], which is not compatible with satellite networks operating in either X-band ($\approx$ 7.5 GHz), Ku-band ($\approx$ 11.3 GHz), or Ka-band ($\approx$ 20 GHz). Also, higher carrier frequencies like the Ka-band for satellite communication suffer from high attenuation, which must be compensated with a larger antenna gain by employing a Very Small Aperture Antenna (VSAT) [9]. In this case, satellite communication with higher frequencies is not directly compatible with handheld/IoT terminals that use omni- or semi-directional antennas. Another concern with stand-alone satellite communications is that they experience extreme path loss and longer latency due to the high altitude from the ground station. Thus, an effective solution is to exploit an aerial relay between a satellite and end users equipped with transponders to convert X-, Ku-, and Ka-band to sub-6 GHz frequency. In such a way, we propose a 3D NTN network configuration to provide enhanced connectivity. As stated in a very recent white paper published by Keysight Technologies [10], NTNs now appear poised to bridge the digital divide by providing ubiquitous communication services to remote and rural areas and play also a crucial role in disaster response and emergency communications in these remote regions, enabling communication restoration in times of crisis.

3D networks, composed of High Altitude Platforms (HAPs), Low Altitude Platforms (LAPs), and satellite platforms, such as differently sized CubeSats, are currently being explored to improve the transmission data rate between the satellite and ground station [11]. Recently, the use of LAPs such as Unmanned Aerial Vehicles (UAVs) to provide broadband wireless connectivity in rural areas, during disasters or temporary events, and to relay services for terrestrial mobile nodes has been gaining increasing attention since they can be deployed on demand, making them more energy- and cost-efficient compared to always-on fixed terrestrial infrastructures [12].

To address the concerns raised on stand-alone satellite communications, this paper investigates the use of 5G NR and UAV as a transparent aerial network that performs signal amplification and frequency conversion. By using UAV as an aerial node, higher frequency bands can be converted to sub-6 GHz to be directly connected to handheld/IoT terminals with an improvement in terms of data rate. This research will focus particularly on a CubeSat-UAV aerial infrastructure where the performance is evaluated in terms of allowed transmission delay and achievable session time with respect to the satellite altitude and the elevation angle. Simulation results, in terms of link throughput with reference to the chosen carrier frequency and Quality-of-Service (QoS), will also be assessed for the considered 3D network-based scenario.

The paper is structured as follows: Section 2 will show an overview of the state-of-the-art UAV-assisted 3D networks, section 3 will provide a description of the proposed 3D NTN architecture, and section 4 will present the analysis of the selected performance parameters. The simulation results will be discussed in Section 5, while the paper's conclusion will be drawn in Section 6.

2. UAV-ASSISTED 3D NETWORKS

Satellite networks can be categorized according to their orbit characteristics and altitude [12]. Geostationary Earth Orbit (GEO) satellites operate at high altitudes ($35800km$), causing a huge signal propagation delay and attenuation. However, their orbit makes them continuously visible in a fixed position in the sky from terrestrial and aerial terminals. On the other hand, Medium Earth Orbit (MEO) and Low Earth Orbit (LEO) satellites have a lower altitude ($7000km$ to $25000km$, and $150km$ to $1200km$, respectively), which guarantees a lower signal propagation delay and better signal strength compared to GEO satellites. However, they have to operate in a constellation to provide continuity of service since they are non-stationary relative to the Earth's surface [13]. As far as LEO constellations of small satellites are concerned, one of the potential breakthroughs of 5G and beyond might be represented by CubeSats [14]. CubeSats are very small satellites organized in multiple payload units. The fundamental unit (1U) is a cube of 10x10x10 cm. The state-of-the-art shows CubeSats are made of 2U, 3U, and even 6U. Their orbit altitudes are generally lower than ordinary LEO ones and range up to 750 Km (Very Low Earth Orbits, V-LEOs.)

Since applications for satellite technology are developing fast, different frequency bands are in use for satellite communications [6]:

- S-band (2.17-2.2 GHz) - This frequency band is used by Eutelsat and Astra to serve markets for Mobile Satellite Services (MSS) [6].
- C-band (3.4-3.7 GHz) - This band is used in areas that commonly experience tropical rainfall since they can penetrate through many kilometers of precipitation with less loss compared to higher frequencies [15].
- X-band (7.25-7.75 GHz) - primarily used in military and government applications for weather monitoring, air traffic control, maritime vessel traffic control, defense tracking, and vehicle speed detection for law enforcement. [16]
- Ku-band (10.7-12.75 GHz) - This frequency is used in Europe for direct broadcast satellite services [6].
- Ka-band ($\approx$ 20 GHz) - This frequency band offers more available bandwidth resulting in a higher traffic throughput; however, it also experiences larger rain attenuation compared to lower frequency bands [17].
- EHF bands (above 30 GHz) [18] are currently in the phase of testing for future applications to multi-gigabit broadband satellite communications. So far, the Q/V band ($37-50$ GHz) is experimented in orbit by the ESA-Alphasat "Aldo Paraboni" geostationary payload [19]. These spectrum portions are characterized by wide bandwidth availability and low interference levels (as they are scarcely used), but the impact of atmospheric impairments on link availability may be huge. Site diversity techniques [20] would allow for exploiting the full potential of EHFs.

3D networks are realized by integrating aerospace heterogeneous networks with terrestrial stations and are characterized by a hierarchical structure [21]. Multi-layered hierarchical networks have been proposed in [22] to improve the performance of stand-alone satellite communications and provide better coverage, flexibility, and resilience. A recent study in [23] also shows that GEO-HAP-Earth 3D network configuration can best bridge satellite signals to the ground with $6\times$ higher capacity than a point-to-point GEO transmission.

An interesting research field concerning advanced NTNs is represented by the use of splitting and Network Function Virtualization (NFV) techniques in extreme environment applications. When no terrestrial network infrastructure is available on-site, a viable and effective solution is to use UAVs as flying base stations enabling mobile connectivity on-ground. Unfortunately, UAVs have serious issues in terms of energy consumption, as their batteries must supply not only the communication payload but, mostly, the hovering system. For this reason, the literature considers solutions where the computational burden is moved from the UAV to the node placed at a higher altitude, namely the satellite. In [24], a CubeSat-based 3D NTN is analyzed in the framework of border monitoring applications in remote areas. The CubeSat embarks some virtualized LTE network functions characterized by heavy computational load (i.e.: iterative turbo decoding), unloading them from the energy-hungry UAV. The use of CubeSat, orbiting at very low altitudes, instead of regular LEO satellites looks almost mandatory to cope with the latency requirements of LTE [24]. Similar concepts have been also considered to bring 5G mobile connectivity to the Mars surface [25], [26]. Again, the combination of CubeSat and UAV has been considered in a Martian 3D NTN architecture. The stringent latency requirements imposed by 5G imposed to lower the altitude of the CubeSat to about 75 Km. This would be impossible on Earth, but it is feasible on Mars due to the rarefied atmosphere of the Red Planet [25]. The analysis of the end-to-end performance of the 3D Martian network architecture [26], whose feasibility has been first assessed in [25], shows a satisfactory behavior of network delay and packet loss also when the theoretical latency constraints are relaxed.

3. System description

Fig. 1 shows the proposed 3D mission-critical network scenario. An NTN gateway, using the NG Satellite Radio Interface (SRI), links the 5G core network deployed at the ground station side to a CubeSat. The CubeSat becomes the gNodeB of the ad-hoc network, replacing non-existent (in the case of Digital Divide mitigation) or no longer operative (in the case of emergency communications) base stations. The choice of the CubeSat at a very low orbit (i.e., 150-500 km) is motivated by the necessity of minimizing the latency to ensure real-time network operation. The CubeSat performs the gNodeB functions and is connected to the UAV using any of the frequency bands currently used in the satcom practice (e.g., S-band, C-band, X-band, Ku-band, and Ka-band.). In addition, it is also assumed that the CubeSat hosts latency-sensitive 5G services (e.g., remote control of terrestrial rovers for emergency scenarios) by exploiting edge computing resources connected to a local intermediate UPF. The UAV, hovering at a height of 100 m, is used to convert the frequency to Sub-6 GHz by means of an amplify-and-forward (AF) relay strategy.

Different frequency down-conversion links have been proposed and investigated for 5G repeaters. In [27], a 39 GHz to 28 GHz down-conversion link was proposed as a part of a comprehensive 5G repeater featuring an ultra-efficient power adjustment technique. The authors were able to achieve a signal power conversion gain of $32dB$, a tuning range of $7dB$, and an input-referred $1dB$ compression point of $-22dBm$. In [28] a linearized mixer was also implemented, that covers operating frequencies from 16 to 35 GHz with an active balloon in $65nm$ CMOS technology for 5G applications.

To the best of our knowledge, our approach that considers multi-frequency AF UAV relaying in a 3D NTN is novel for the 5G framework. We think that the proposed arrangement

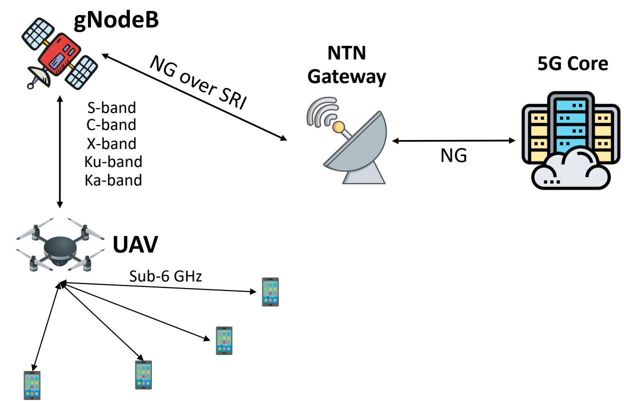

Figure 1. UAV-assisted 3D network implementation.

fully copes with the requirements of low cost, immediate deployment, and resilience that connection-critical scenarios impose. The theoretically more efficient Decode-and-forward (DF) relaying would have required a more complex UAV payload characterized by higher costs, increased weight, and additional energy consumption. To sum up, our solution reduces the computational and energy burden in the most critical node of the chain, i.e., the UAV, enabling the implementation of the architecture by using smaller, lighter, and cheaper drones.

4. Performance Parameters

The section describes different parameters chosen to evaluate the QoS of the satellite-to-UAV link on a 3D network. In particular, the performance of the proposed implementation will be assessed in terms of transmission delay, session time, and throughput.

Transmission Delay

The transmission delay is the time required to transmit data from the UAV to the satellite. In order to measure the transmission delay, an acceptable fixed delay budget ϕ is considered to satisfy the end-to-end (E2E) latency and avoid packet loss [26], considering a scenario where latency-sensitive services are deployed at the egde (i.e., in the satellite) co-located with the gNB. ϕ is the time needed to transfer and process that data from the UE to the gNodeB, or vice-versa, which can be computed by using the formula [29]:

$$\phi = t_{tx} + t_{bp} + t_q + t_{other}, \tag{1}$$

where t_{tx} is the transmission delay, t_{bp} is the baseband processing time, t_q is the queuing latency introduced by each node involved in the communication, and t_{other} is the time to perform other functions like inverse/fast Fourier transform (IFFT/FFT), thus the allowed transmission budget t_{tx} can be expressed as follows:

$$t_{tx} = \phi - t_q - t_{other} - t_{bp}, \tag{2}$$

We assume t_{bp} as the time taken by Low-density parity-check (LDPC) decoding; such a quantity can be expressed as follows [29]:

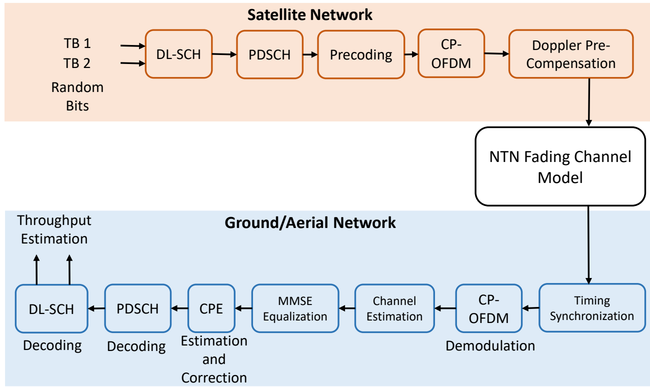

Figure 2. Throughput simulation using MATLAB Satellite Communication Toolbox.

Table 1. Carrier frequency and channel bandwidth of different frequency bands for satellite communication.

Frequency Band	Carrier Frequency	Channel Bandwidth
S-band	2 GHz	30 MHz
C-band	3.6 GHz	100 MHz
X-band	7.5 GHz	100 MHz
Ku-band	11.3 GHz	200 MHz
Ka-band	20 GHz	400 MHz

$$t_{bp} = \frac{LFk}{pO}, \tag{3}$$

where LFk/pO is the LDPC decoding time with k the number of decoding iterations, L the code block size in bit, F the decoder complexity in $operations/bit$, p the processing unit's (PU) clock rate in Hz and O the processor efficiency in $operations/cycle$ [29]. t_{tx} can also be expressed in terms of the slant range d, i.e., the length of the path connecting the UAV and the CubeSat, which depends on the elevation angle ϵ and the CubeSat altitude h [30]. In that case, $t_{tx} = d/c$, which can also be formulated as follows [25]:

$$t_{tx} = \frac{\left[\sqrt{\frac{(R_{Earth}+h)^2}{(R_{Earth}+a)^2} - cos^2(\epsilon)} - sin(\epsilon)\right] \cdot (R_{Earth} + a)}{c} \tag{4}$$

where R_{Earth} is the Earth's radius, a is the UAV's altitude and c is the light speed. In the next sub-section, we will show how the combination of Eq. (2) and Eq. (4) will be useful for estimating the session time t_s.

Session Time

The session time is the time within which data can be forwarded and received from the UE to the CubeSat through the UAV. Satellites orbit with speed v around the globe [31]. If we consider a UAV hovering over the UE, the CubeSat in V-LEO will have a session time t_s to communicate with the UE through the UAV, which receives, amplifies, and forwards the signal. The minimum elevation angle ϵ^{min} is retrieved by fixing the maximum number of LDPC decoding iterations k^{max} in Eq. (2), which leads to the maximum allowed transmission delay t_{tx}^{max}. For our purposes, maximizing t_s is preferable, thus a slow handover strategy could be utilized [32]. The UAV re-establishes a link to the CubeSat as soon as t_{tx}^{max} is exceeded. The session time t_s can be computed as follows:

$$t_s = \frac{\theta^{max} \cdot (R_{Earth} + h)}{v}, \tag{5}$$

where θ^{max} is the maximum Earth's central angle, defined as:

$$\theta^{max} = arcsin\left(\frac{d_{max} \cdot cos(\epsilon^{min})}{R_{Earth} + h}\right), \tag{6}$$

with $d_{max} = c \cdot t_{tx}^{max}$. To conclude, with the elevation angle ranging between $\epsilon = [\epsilon^{min}, \pi/2]$, t_s is a lower bound where we consider a CubeSat at the maximum distance d^{max} and another one approaching the Zenith, thus at $d^{min} = h$. The upper bound of t_s considers a CubeSat at $d^{max}(\epsilon^{min})$ and another one at $d^{max}(\pi - \epsilon^{min})$, thus roughly doubling the session time.

Throughput

The throughput is the amount of information that the link between the satellite and UAV can process. To simulate the physical downlink shared channel (PDSCH), the satellite communication toolbox of MATLAB is employed [33]. Using this toolbox, the PDSCH throughput of a 5G NR link in an NTN channel, as defined by the 3GPP NR standard in [7] [34], is measured for different SNR values. Fig. 2 shows the implemented processing chain, which features DL-SCH transport channel coding with up to 2 codewords and 8 layers, PDSCH precoding using singular value decomposition (SVD), Cyclic-prefixed Orthogonal Frequency Division Multiplexing (CP-OFDM) waveform, practical synchronization and channel estimation, and, finally, a single bandwidth part across the whole carrier. Using this simulation tool, the maximum achievable throughput and the minimum SNR required to achieve 100% throughput will be assessed for each frequency band listed in Table 1. The throughput is also simulated for a total of 10 frames ($100ms$) of data using 256-QAM modulation constellation with 1-2 layers.

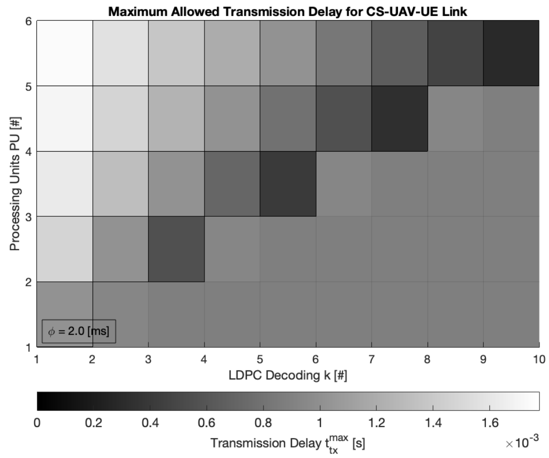

Figure 3. Maximum transmission delay t_{tx}^{max} vs. the number of processing units PU and k decoding iterations for the CubeSat-UAV link with a delay budget $\phi = 2.0$ms

The link throughput is particularly relevant, mostly depending on the signal-to-noise ratio (SNR) at destination. On the other hand, maximizing the throughput, which takes into account both goodput and redundancy to improve the robustness of the communication, means increasing the received signal strength (RSS), which leads to a better SNR. To this aim, PL attenuation should be lowered by reducing the UAV-CubeSat distance, i.e., the slant range. This reduces the transmission delay t_{tx} and saves time for baseband processing, which positively impacts the reachable QoS. However, by doing that, we pay a price in terms of reduced session time t_s.

5. Simulation results

This section discusses the obtained results related to the available transmission budget, and thus the allowed session time and achievable throughput. Their correlated behavior will be highlighted to show their tight interdependence.

Transmission Delay and Session Time

First, we are supposed to mount on board the CubeSat Leopard Digital Processing Units to support data processing operations [35]. One PU fits into a 1U-sized CubeSat. Thus, at each added PU, the CubeSat will enlarge by 1U. This PU has a clock frequency up to $p = 1.5\ GHz$. Assuming $O = 1\ operations/cycle$, $L = 8448\ bit$, which is the code block size of 5G NR, $F = 162\ operations/bit$ [36], $k = 1$ decoding iteration, a buffering delay $t_q = 40\mu$s per node, $t_{other} = 33.34\mu$s mostly for FFT processing [37] and a delay budget $\phi = 0.5\ ms$, a 6U CubeSat equipped with 6 PU guarantees a transmission delay budget $t_{tx} = 0.27\ ms$, which leads to a UAV-CubeSat distance $d \approx 81\ km$. However, the considered distance cannot be sustained as stated in [38]. With $\phi = 2.0\ ms$, which is the near-ideal maximum transmission delay [39], the allowed transmission delay sensibly improves, as shown in Fig. 3, which shows the transmission delay depending on the number of LDPC decoding iterations k and PU. As expected, a larger number of PUs is required to keep t_{tx}^{max} limited for increasing k: about 2 additional PUs are needed for a unitary increment of k.

Fig. 4 analyzes t_{tx} and t_s, where Fig. 4(a) shows the simulated transmission delay for the CubeSat-UAV link for an elevation angle $\epsilon = [0, \frac{\pi}{2}]$, a satellite altitude $h_{CS} = [150, 500]\ km$ and a UAV height $h_{UAV} = 100\ m$, while Fig. 4(b) shows the estimated session time t_s for the CubeSat-UAV link with the same parameterization concerning elevation angle, altitude and UAV height. The red "dotted" lines stand for the minimum allowed elevation angle ϵ^{min} with respect to 1U, 2U, 3U, and 6U-sized CubeSat and focusing only on $k = 1$ LDPC decoding iteration. Starting from the transmission delay budget in Fig. 3, we are able to understand the minimum elevation angle ϵ^{min}, which is the one providing the slant range at most equaling d^{max}. As ϵ^{min} is lowered, the session time t_s increases (i.e., lighter gray area). This is a great benefit for conveying a substantially increased amount of data with a reduced number of satellites needed in the constellation. In such a way, the system costs required for deployment and maintenance decrease as well. On the other hand, E2E packet loss and delay will represent the most relevant system degradation [26]. Moreover, a higher t_{tx} implies a higher PL and a lower SNR at the destination, which negatively impacts the link throughput. Fig. 4 also shows the effect of the satellite altitude to the transmission delay and session time. As the satellite altitude increases, the session time also increases with the advantage of increased transfer time between the satellite and the UAV. However, this also results in a higher transmission delay.

Throughput

The maximum achievable throughput of different frequency bands with 1 and 2 layers is reported in Fig. 5. The figure shows that the throughput increases as carrier frequency increases. This is because high-frequency spectrum can allocate more available bandwidths, as shown in Table 1, and the maximum throughput is somewhat proportional to the channel bandwidth.

Using 5G NR on multi-layered NTN, cellular connectivity can be provided for rural areas, post-disaster recovery, and hotspot areas with throughput from $180Mbps$ to $4.85Gbps$ depending on the frequency band, channel bandwidth, and number of layers used.

To determine the required SNR to achieve the maximum throughput reported in Fig. 5, Fig. 6 shows the throughput of each frequency band for varying SNR and a number of layers and antenna ports. In particular, the maximum throughput can be achieved even at a low SNR provided that a sufficient number of transmit and receive antennas are exploited. Also, the throughput doubles when doubling the number of layers. However, more antennas are needed to achieve the maximum throughput. With two layers, four antennas at the Tx and Rx sides are needed to achieve the maximum throughput, while just 1 Tx and Rx antenna (with higher SNR) is required on a single-layer implementation.

6. Conclusions and Future Works

In this work, the deployment of a 3D NTN multi-frequency network for connection-critical scenarios has been proposed and discussed. The network configuration considers a CubeSat employed as the gNodeB of the ad-hoc network and the use of UAV to convert the frequencies supported by satellite communication (S-, C-, X-, Ku- and Ka-band) to sub-6 GHz with an amplify-and-forward relay strategy. Such a solution would allow for reducing the weight, cost, and energy consumption of the UAV, which is the most critical

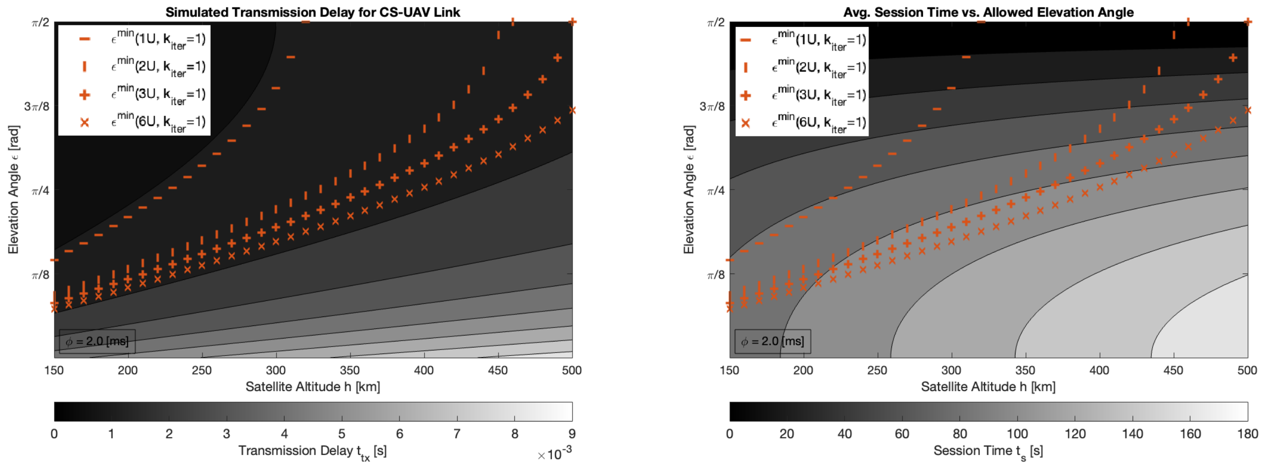

Figure 4. (a) Transmission delay for CubeSat-UAV link; (b) Session time for CubeSat-UAV link

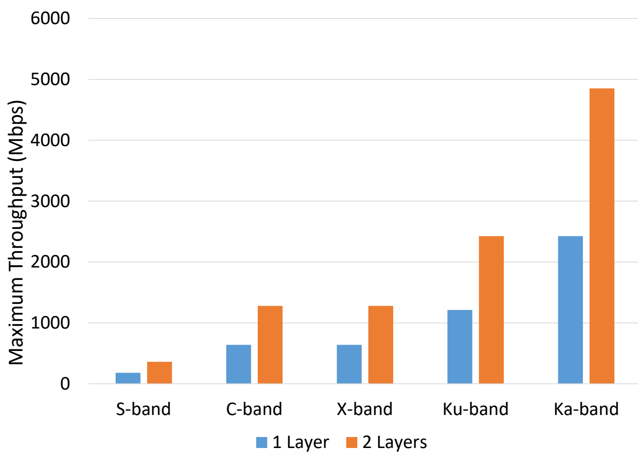

Figure 5. Maximum achievable throughput of frequency bands for satellite communication.

node of the network in terms of stability and lifetime.

Considering a delay budget $\phi = 2.0\ ms$, we evaluated the maximum transmission delay in terms of the number of processing units and decoding iterations. The effect of the minimum elevation angle (depending on the number of processing units) on the simulated transmission delay and session time has been also assessed. Results show that a throughput from $180 Mbps$ to $4.85 Gbps$ can be achieved on the satellite-to-UAV link depending on the frequency band, channel bandwidth, and number of layers used.

Since this paper only focuses on the amplify-and-forward relay strategy, future works may include the comparison with a decode-and-forward relay strategy and with the direct connection between the CubeSat and the UE. The comparison will be done not only in terms of delay and throughput but also in terms of cost, weight, and energy consumption of the different network nodes.

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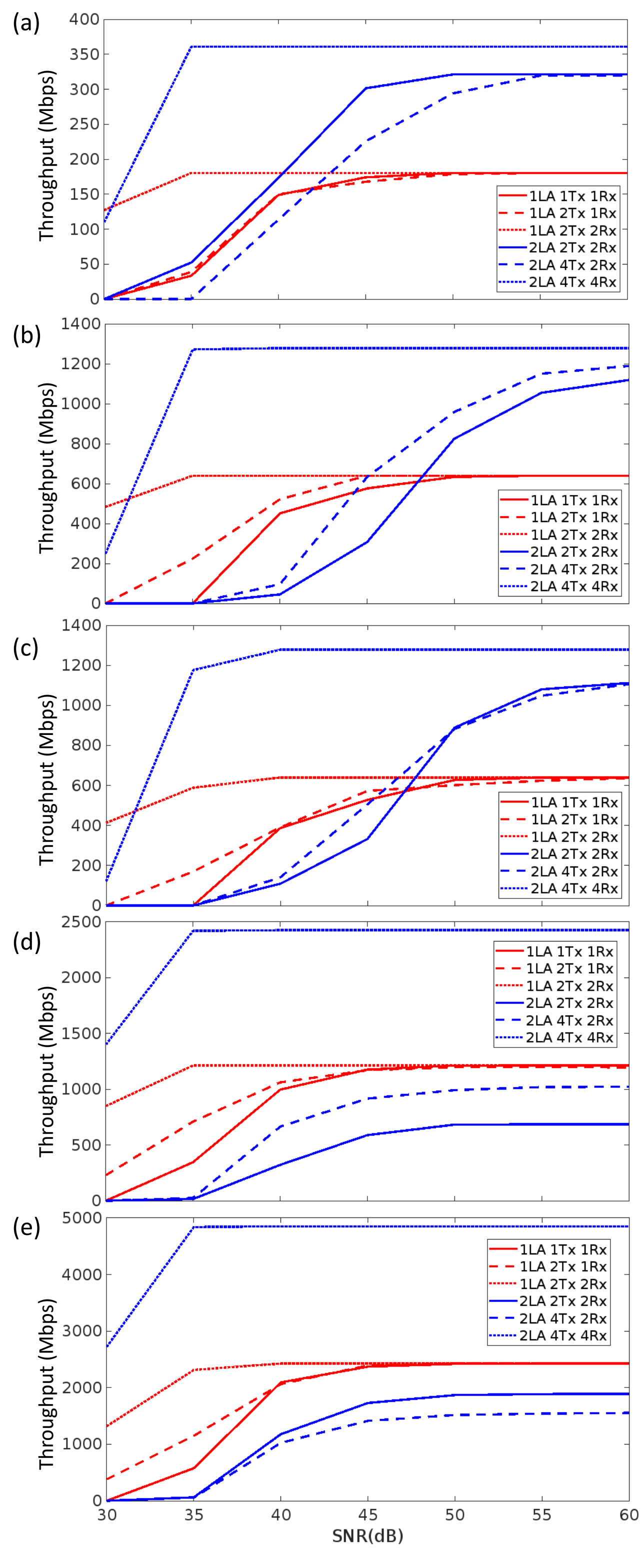

Figure 6. SNR vs Throughput of different frequency bands for satellite communication: (a) S-band; (b) C-band; (c) X-band; (d) Ku-band; (e) Ka-band.

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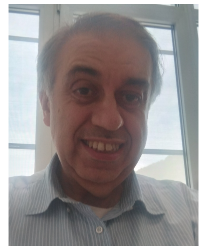

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