CubeSat-based 5G Cloud Radio Access Network

A novel paradigm for on-demand anytime-anywhere connectivity

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5G networks are planned to become main infrastructure for security verticals such as disaster relief, humanitarian aid, governmental and defence communications. Especially, in case of defence services, there are complex areas, where coverage and connectivity are not reliable or completely absent. Thus, the deployment of drones as mobile base stations also needs the design of a system for reliable backhaul, based on satellites. However, baseband unit (devoted to baseband signal processing at radio access network) on drones is not a flexible solution, which may require great power supply and processing capabilities, a drone can hardly host.

This work studies and designs a cloud radio access network system based on mobile base stations and CubeSats, where baseband units are virtualised on low-cost satellites. In particular, the work takes advantage of split of virtual baseband unit in order to virtualise upper layers on CubeSats while guaranteeing the satisfaction of technical requirements.

1. Introduction

The main aim of future fifth generation (5G) and beyond (B5G) networks is to create an ecosystem, which will be able to concurrently support heterogeneous services with different requirements. Apart of 'civilian services' such as media distribution, smart transportation, smart cities and smart industry, 5G and B5G networks are also expected to host services related to governmental and defence activities, emergency and safety, disaster relief and humanitarian aid. Inside this context, border monitoring and security represent activities, which will be included in such future networks ecosystem.

Nevertheless, hosting such critical verticals requires the warranty of 100% coverage and network availability in order to ensure so called *anytime anywhere connectivity* [1]. That implies the effective and efficient provisioning of network resources for reliable communications not only in urban and populated areas but also in rural ones and in so called *complex areas*, i.e. where existing terrestrial networks are absent or cannot properly work. For example, a specific use-case can be the one of *complex borders*, where monitoring technologies cannot rely on or connect to legacy terrestrial wireless networks. In such contexts, current solutions suggest the deployment of either direct satellite connection to terrestrial end-users or mobile base stations (drones).

Recently, the deployment of unmanned aerial vehicles (UAVs) has become an efficient solution to provide on-demand network coverage and additional security, by deploying drones as monitoring aerial peripherals and/or as mobile base stations (BSs) for connectivity provisioning. However, a significant challenge can arise such as whether to run baseband processing when UAVs are used in areas without reliable (or with absent) connectivity (i.e. complex borders).

When providing cellular-like coverage in areas such as complex borders via UAVs, the legacy solution has been to implement full base station but an issue can arise since baseband processing is the most complex part of the radio access network (RAN). The entity, which is responsible to perform baseband processing, is called baseband unit (BBU). Both that and the remote radio head (RRH) constitute the cellular base station (BS). Adding a BBU to each drone does not represent an efficient solution. Side by side, the UAVs should also support satellite backhaul connections to allow communications between mobile BSs and satellite-based core network. Nevertheless, when mobile BSs are deployed, it can be useful to virtualise BBUs in order to move processing and load to centralised entities, which have higher capabilities and do not have battery constraints as drones.

Given above considerations, the solution of virtualising BBU on satellites may come out. Nevertheless, baseband processing has very strict and stringent requirements thus its implementation on satellite-based virtual BBUs does not become straightforward.

A preliminary structure of the proposed system was firstly presented in [2]. However, that work considers drones equipped with LoRaWAN gateways, without providing detailed system-level description and evaluations. In fact, the scope of [2] is the estimation of an upper bound on power gain that virtualisation of BBUs can provide. Moreover, the analysis in [2] neglected the problem of virtual BBU split with respective requirements in terms of latency and throughput.

On the other hand, this article proposes and presents a detailed system-level analyses of novel satellite-based approach to C-RAN. This paper describes the characteristics of UAV-Cubesats architecture in order to design and to perform lower-layer baseband functions at the drones, while moving upper-layer baseband functions to satellites. The proposed design allows CubeSats and UAVs providing effective connectivity to terrestrial end-users or peripherals, guaranteeing the satisfaction of requirements of C-RAN on fronthaul/backhaul in terms of latency and throughput. In particular, this work deals with characterisation of link between UAV and CubeSat in order to support specification, needed by virtualisation of BBU.

The article is organised as follows. Section 2 provides some preliminaries to introduce the reader into the context of this work. Section 3 describes the system architecture and characteristics in detail. Finally, Section 4 presents simulations, evaluations and preliminary considerations to justify the feasibility of the system, its effectiveness and its main design guidelines (from CubeSat and satellite link perspectives).

2. System Preliminaries

The proposed C-RAN system is mainly composed of three layers. A terrestrial layer, an aerial layer and a satellite-based layer. The satellite-based layer includes small satellites providing computing resources to allow virtualization of RAN functions. The choice of using CubeSats at the third layer comes from the fact that these satellites have recently become very popular because of their low deployment cost and high flexibility.

A CubeSat [3], is a kind of standardised satellite, which belongs to the family of small satellites (i.e. satellites that weight less than 300 kg). A small satellite has to satisfy specific requirements in terms of shape, size and weight. A single-unit CubeSat is a satellite of cubic shape of size 10 cm × 10 cm × 11 cm, with mass approximately 1-1.33 kg. Then, from that basic unit, bigger standard CubeSats have been proposed such as ones of size 1.5U, 2U, 3U and 6U. Examples are represented on the right side of Figure 1.

As mentioned above, in current fourth generation (4G) cellular networks, the BBU is the core processing entity of the RAN. Figure 1(a) displays the composition of 4G RAN and legacy BBU. The RRH is located on the radio site, consisting of transmitting/receiving antennas, while the BBU contains lower-layer processing and hybrid automatic repeat request (HARQ). The two components RRH and BBU are connected to each other via a cable (normally fibre) supporting the so called Common Public Radio Interface (CPRI) standard. This standard imposes to guarantee a bit error rate (BER) for data and control plane less than 10^{-12} and it employs forward error correction (FEC) based on Reed-Solomon (RS) codes [4].

In such a context, C-RAN was proposed in order to centralise baseband processing while avoiding the presence of a physical BBU at each radio site. In this way, virtual BBUs could have run on general purpose servers at datacentres in the operators' core network. That would have also implied the optimisation of assignment of resources, scalability and energy efficiency. Furthermore, in the last decade, virtual BBU splitting [5], [6] arose significant interest. The concept of BBU split starts from the idea that BBU function can be divided into logic sub-functions, which can be run as separate entities. However, inter-function communications have specific and very stringent requirements in terms of latency and throughput, according to the specific split that is chosen.

Figure 1(a) shows the legacy solution for logic split of BBU functionalities [6], [7]. The ground layer consists of radio frequency processing (RF), for Analog-Digital and Digital-Analog conversion of received signals. Above that, there are five layers, each of which has its own specific requirements to guarantee seamless communications. *Layer 1 Low* (L1 Low) is responsible for cyclic redundancy check (CRC), fast Fourier transform (FFT) and inverse FFT (IFFT). The separation of these layers is called *Split A*. Its required latency is strict 150 µs, with throughput equal to 2457 Mb/s [6]. *Layer 1 High* (L1 High) is devoted to mapping/de-mapping of resource elements. Split B is called the division between L1 Low and L1 High, which requires throughput equal to 720 Mb/s and latency of 150 µs (with a possible relaxation in case of slow-moving users and opportunistic HARQ, at a price of degraded performance). Next, *Layer 2 Low* (L2 Low) performs modulation/demodulation and equalisation of signals while *Layer 2 High* (L2 High) is responsible for FEC procedures. The split between L1 High and L2 Low is called Split C, which needs throughput equal to 360 Mb/s and latency equal to 150 µs (with a possible relaxation in cases already mentioned above). On the other hand, Split D separates L2 Low and L2 High. Finally, *Layer 3* (L3) manages HARQ with transmission/reception of ACKs/NACKs. Split E divides L2 High and L3. The requirements of Split D and Split E are represented in Figure 1(b).

Side by side, for completeness and clarity, Figure 1(a) also includes the notation of the various level of split, which were proposed by Ethernet-based Next Generation Fronthaul Interface (NGFI), small cell forum (SCF), Next Generation

Mobile Network (NGMN) alliance and 3rd Generation Partnership Project (3GPP) [8].

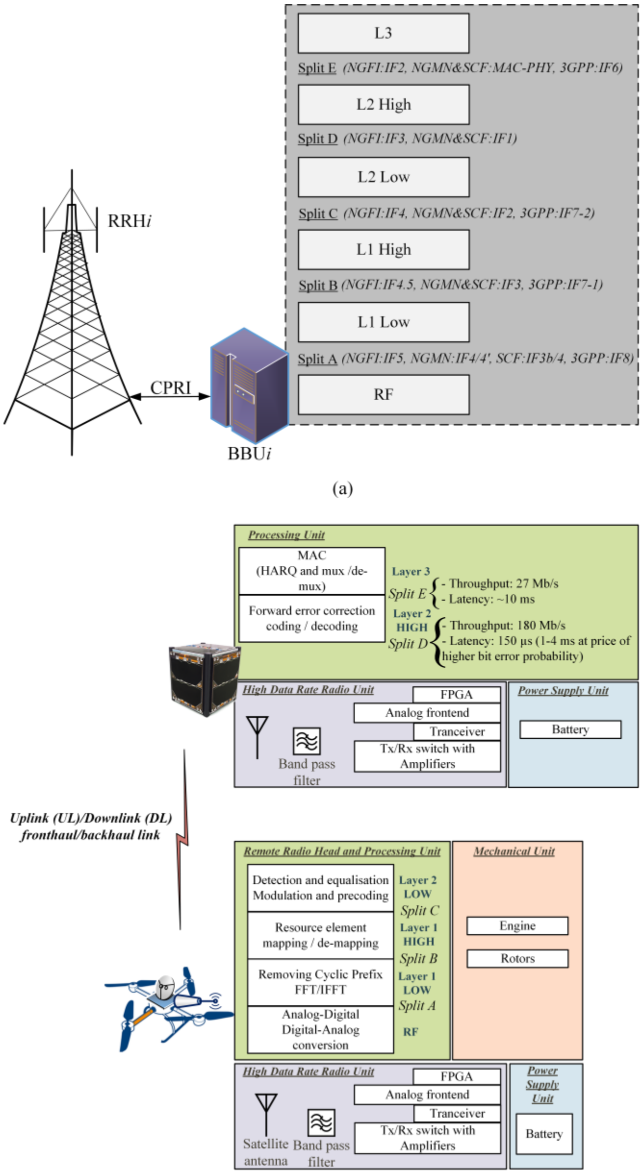
Whole baseband processing of legacy 4G network requires a general threshold of 3 ms to be completed (may be extended to 4 ms but at an eventual higher price in terms of errors) [6], [7]. Moreover, HARQ employs acknowledgements with FEC using concatenated convolutional codes of variable rate (normally between 1/3 and 1/2) with turbo decoding: especially, Layer 3 should target a BER less than 10^{-5}. A possible alternative is to use HARQ with pure FEC coding, without retransmissions. Such a solution can be of interest for long-range C-RAN settings as it avoids delay due to ACK/NACK transmissions (as previously demonstrated by [9] in the context of vertical handovers). In such a case, robust FEC coding with low rate (1/3 or 1/2) should be adopted in order to guarantee powerful error correction capabilities and the avoidance of ARQ techniques.

Regarding communication between UAVs and CubeSats, it is important to notice that both devices move, one in respect of the other one. That implies the presence of a Doppler effect, which affects the frequency of the signal and that should be taken into account during system design. Figure 2 shows the main elements required in the calculation of Doppler effect (for simplicity we consider the drone hovering) [10]. In particular, the Doppler shift considering communications with low Earth orbit (LEO) satellites becomes the product among frequency of transmission (f), the module of velocity $\vec{V}$ and the cosine of θ angle, all divided by speed of light (c).

The *High Data Rate Radio Unit* block in Figure 1 identifies the hardware involved in physical layer satellite communications for fronthaul/backhaul. The achievable data rate R [11] can be calculated as

$$R = rs^{-1}M \tag{1}$$

where r is the symbol rate, s the number of samples per symbol and M the modulation bits. Thus modulation with greater constellations can increase the data rate but at a price of higher BER. In such case, Reed-Solomon FEC coding, forecasted by CPRI standard, should be adequately designed. In order to have reliable analogic front-end operations (e.g. A/D and D/A conversion), s is normally set to 3 [11]. On the other hand, r is generally imposed by specific hardware constraints [11].



(a)

(b)

Figure 1 *(a) Structure of legacy 4G radio access network, with representation of logic split of BBU. Different notations are included for completeness (b) Diagram representing the detailed architecture of proposed C-RAN system and its main characteristics.*

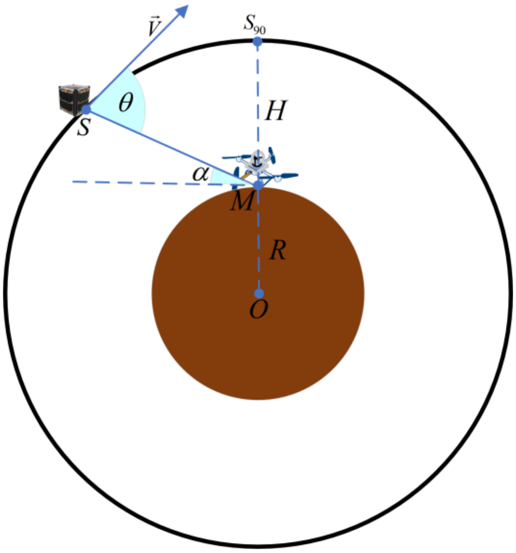


Figure 2 *Simplified scheme of CubeSat's relative movement in respect of hovering UAV. The brown circle is the earth with centre O and radius R. Point M is the position of the drone while S is the position of the satellite (which changes in time). Point* S_{90} *is the position of satellite, perpendicular to M.*

3. CubeSats for Virtualisation of Radio Access Network

As previously mentioned, the proposed C-RAN system for network access provisioning in complex areas is composed of three main layers. The *terrestrial layer* includes all end users consisting of *things* (e.g. cameras, sensors of different kinds, 3D optical scanners, monitoring buoys, etc.) or smart mobile devices (for human-to-human communications). All these devices are connected via wireless cellular links to second layer. The *aerial layer* consists of mobile BSs, that are realised with the deployment of UAVs (i.e. multirotors or multicopters). These devices are equipped with two antennas, one for terrestrial RAN and the other one for satellite backhaul, and a processing unit to perform Layer 1-Layer 2 Low procedures. The coloured blocks of Figure 1 depict the logic parts of virtualised baseband processing and 4G link, the ones referred to satellite link, and the ones devoted to power supply and mechanics. In this work, we focus on the virtualisation of BBU Split D thus automatically implying the support of Split E. Regarding UAVs, mechanical parts and power supply equipment affect not only the movement but also the performance and characteristics of communications. That happens because engine and rotors consume battery, while battery life is a key metrics to guarantee reliable and acceptable transmissions. Finally, a *satellite layer* is composed by CubeSats. These satellites contain the radio antenna for backhaul communications and processing units hosting virtual functions of Layer 2 High and Layer 3.

The fronthaul/backhaul link can suitably use 2400 - 2483.5 MHz free frequency space in the S-band band 2300 - 2450 MHz, which can be assigned to satellite applications (including CubeSats). In particular, International Telecommunication Union (ITU) recommendation is to avoid interference with terrestrial WiFi and ISM (Industrial, Scientific and Medical) services [12]. However, this concern is not affecting the proposed system since it is focused on complex border monitoring, thus areas without connectivity.

Next, the Doppler shift changes with time due to the variation of the radial satellite velocity inherent to the variation of the elevation angle during the orbit travel. For this reason, the satellite receiver should be able to estimate and compensate the Doppler variation, time after time, in order to guarantee the correct carrier synchronization.

4. System-level Evaluation

In Figure 2, the importance of the angle θ has been represented, from Doppler perspective As far as latency is concerned, given the characteristics of CubeSat's orbit, the distance between drone and satellite – and, therefore, the propagation delay – changes until reaching the minimum when the elevation angle α is 90 degrees. Thus, the maximum delay is achieved when α is zero. In order to simulate CubeSat's orbit and the characteristics of its trajectory we have taken into account a circular orbit. The orbit simulation has been done with Matlab. Especially, Figure 3 shows the simulation of various satellites' orbits across complex areas in Europe, where the proposed system would be applicable to host a vertical devoted to border monitoring operations. Then, we consider three terrestrial points in three areas, which have to connect to the CubeSat. Furthermore, three curves were considered in order to guarantee a communication's delay between 1.5 ms and 3 ms. That to satisfy the mandatory requirement of latency less than 4 ms for Split D.

Finally, given the defined ranges for CubeSats's altitude, we reasonably consider average distance of CubeSat from Earth between 250 km and 600 km.

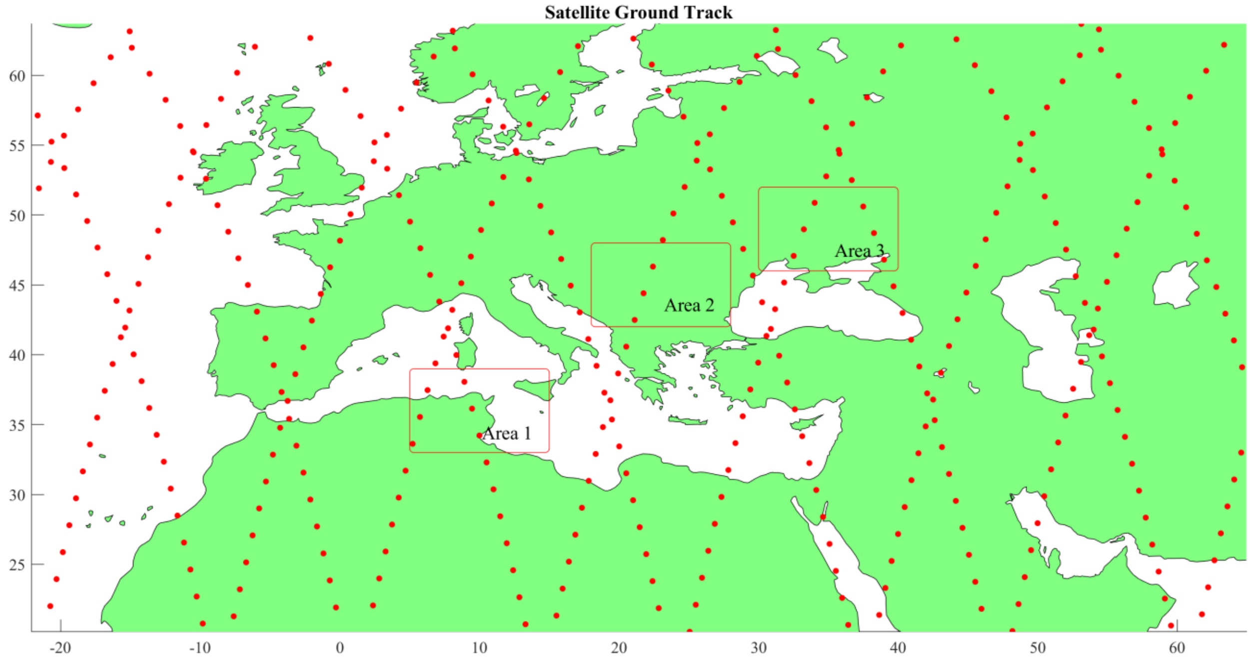


Figure 3 *Scenario of simulation. The orbit of CubeSat crosses three main areas (Area 1, Area 2 and Area 3) where there are complex European borders to be monitored.*

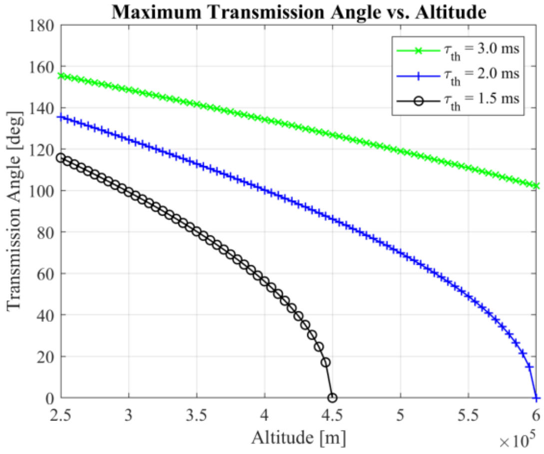


Figure 4 *Evaluation of maximum transmission angle between UAV and CubeSat according to the altitude of orbit of satellite. The curves are calculated for the thresholds $\tau=1.5$ ms, $\tau=2$ ms and $\tau=3$ ms.*

Figure 4 shows the variation of the maximum transmission angle according to satellite's altitude (i.e. segment MS_{90}). Transmission angle is calculated as $2(90-\alpha)$, where α is the elevation angle, thus the angle between the two maximum acceptable distances to start and to end the transmission because of propagation delay. It is possible to see that this angle almost linearly decreases if we allow a delay of 3 ms while it reduces more rapidly if we need to guarantee a lower threshold. Clearly, the usage of lower orbits significantly increases the transmission angle. Indeed, given a fixed requirement on the maximum propagation delay (in order to allow the BBU to perform the virtualized task), the maximum acceptable distance from the drone to the CubeSat, namely the slant range, will also be fixed. This implies that, lowering the CubeSat altitude, the elevation angle α must be reduced in order to obtain the required slant range. Thus, the transmission angle increases with the flight time, accordingly.

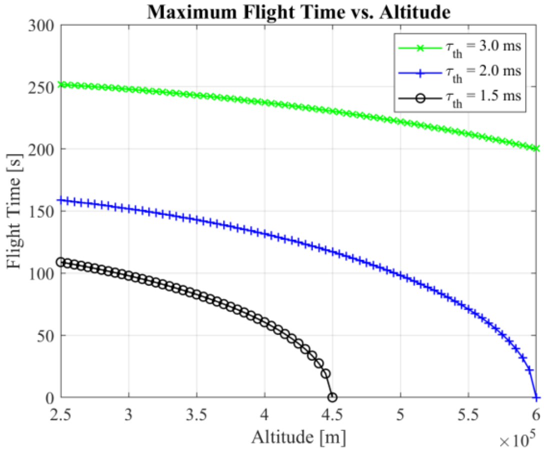


Figure 5 *Evaluation of maximum flight time of the CubeSat according to the altitude of orbit of satellite. The curves are calculated for the thresholds $\tau=1{,}5$ ms, $\tau=2$ ms and $\tau=3$ ms.*

In parallel, it is also important to look at the curves in Figure 5. By considering a reasonable average satellite speed of 7.5 m/s [10], the time for backhaul/fronthaul transmission diminishes from 230 s to 180 s approximately (for $\tau_{th}=3$ ms) while it falls approximately from 150 s to 10-20 s (for τ_{th}=2 ms) and from 100 s. to 5-10 s (for τ_{th}=1.5 ms).

Next, Figure 6 focuses on evaluation of Doppler shift for τ_{th}=3 ms, τ_{th}=2 ms and τ_{th}=1.5 ms. As expected, the Doppler shift inversely increases with the altitude and is in line with what estimated before in [10].

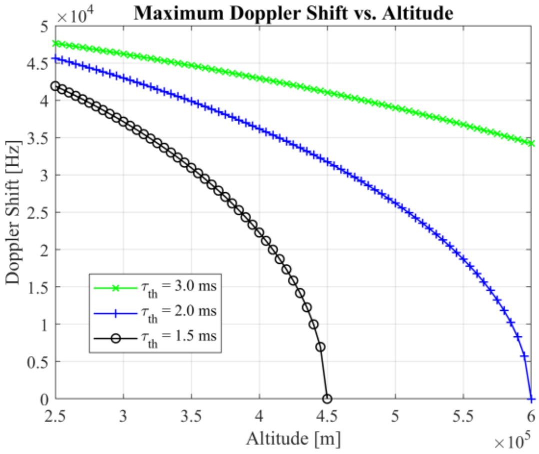


Figure 6 *Evaluation of the maximum Doppler shift because of CubeSat relative movement in respect to UAV, according to the altitude of orbit of satellite. The curves are calculated for the thresholds τ=1.5 ms τ=2 ms and τ=3 ms.*

Finally, it is fundamental to analyse the impact of the latency on C-RAN performance from perspective of LTE turbo decoding operation performed by Layer 2 High at the satellite. An initial study was presented in [13] for terrestrial fibre-based virtual BBU-RRH connections. Turbo decoding is iterative and BER performance of the decoder essentially depends on the number of iterations that the remote BBU can execute within a maximum delay (namely: delay budget [14]), imposed by LTE network temporisation constraints. For what concerns Layer 2 High, all the decoding operations must be completed within a mandatory delay budget of 4 ms [6]. In this paper, we consider the more reliable value of 3 ms, pointed out in [13]

In order to avoid the transmission/reception of ACKs/NACKs, our work considers pure FEC for reliable Layer 3 transmissions. Under this conditions, the number of turbo decoding iterations that the remote BBU can support is given as follows [13]:

$$k=\max\left\{0,\left\lceil \frac{pO\left(\Phi-J-D-T_{proc}\right)}{LF}\right\rceil\right\} \qquad (2)$$

where:

- p is the computational power of a single core processor in Giga operations per second (GOPS),
- O is number of core processors installed inside the BBU,
- Φ is the delay budget,
- J is the time required for processing other wireless functions (e.g. synchronisation);
- D is the RRH-BBU link delay;
- L is turbo-coded block length in bit,
- F is the number of elementary operations required per decoding iteration,
- T_{proc} is the processing time required by LTE turbo-coded block detection from RRH. It is given by $L/R_{C\text{-}RAN}$, being $R_{C\text{-}RAN}$ the bit-rate of the dedicated RRH-BBU connection.

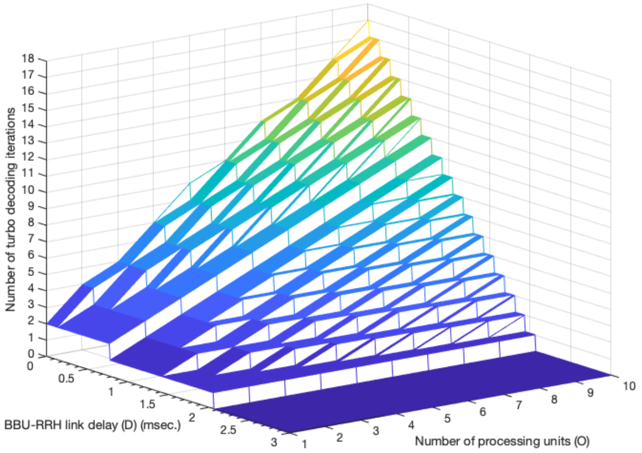


Figure 7 *Number of turbo decoding iterations allowed in case of Split D of virtual BBU.*

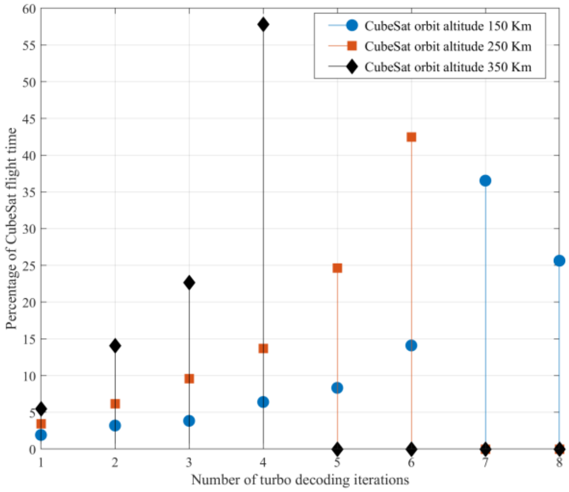


Figure 8 *Percentage of CubeSat flight time vs. number of turbo decoding iterations allowed in case of Split D of virtual BBU, with the constraint of at least one turbo decoding iteration executed on board of the CubeSat*

In Figure 7, the value of k is plotted according to O and D, assuming p=1.2 GOPS, Φ=3 ms, J=0.9 m [13], L=6144 bit (as per LTE standard [13]), F=200 [13], and $R_{C\text{-}RAN}$=181 Mb/s (the required bit-rate for efficient splitting of Layer 2 High functionalities is 180 Mb/s [6]). It is evident from Figure 7 that the execution of the iterative turbo decoding operation during the assigned time slot fails when D exceeds 2.1 ms. For lower D, k increases also as O increases. A satisfactory range of values should be k greater and equal to 3, as shown in [13]. Indeed, it can be easily verified that iterative turbo decoding generally converges to very low BERs after few iterations and for low signal-to-noise ratios, when robust turbo codes with low coding rates (1/3 or 1/2) are adopted [14]. Following such considerations, altitude of CubeSat's orbit, the transmission angle, and the BBU processing architecture should be carefully designed in order to cope with the PHY-layer performance requirements. In Figure 8, some preliminary results about the percentage of CubeSat flight time vs. k have been shown. For such series of results, the transmission angle has been computed in order to satisfy the constraint of having at least a single turbo decoding iteration during the CubeSat flight time. Moreover, the number of core processors O has been fixed equal to 6. In Figure 8, we can notice that for an orbit altitude of 350 km, the BBU can support k decoding iterations greater and equal to 3, for 80.6% of the CubeSat flight time. Decreasing the orbit altitude, the percentage of flight time for which the turbo decoding satisfactorily performs increases up to 90.4% for 250 km and to 94.9 % for 150 km, respectively. The theoretical convenience of lower CubeSat orbits is also confirmed by the results shown in Table I, related to the CubeSat flight time, subjected to the constraint of k_{min}=1. However, the decrease of orbit altitude is always paid in terms of reduced orbit stability and satellite lifetime.

TABLE 1: CUBESAT FLIGHT TIME FOR DIFFERENT ORBIT ALTITUDES. (IMPOSING K_{MIN}=1)

CUBESAT ORBIT ALTITUDE	FLIGHT TIME
350 km	128 s
250 km	146 s
150 km	156 s

Finally, one may ask how many CubeSats are necessary to guarantee the h-24 continuity of service. Table II can answer to this important question. In such a table, the number of daily visions for CubeSats with an altitude lower than 570 km and a sun-synchronous polar orbit have been obtained, at the latitude of the border areas considered in this paper, using the equation (1) of [15]. The number of required CubeSat is computed accordingly.

TABLE 2: CUBESAT DAILY VISIONS AND NUMBER OF SATELLITES NECESSARY TO GUARANTEE H-24 SERVICE CONTINUITY

BORDER AREA	DAILY VISIONS	CUBESAT NUMBER
Area 1	5	5
Area 2	6	4
Area 3	7	4

5. Conclusion

This article has studied and described the realisation of C-RAN in a system based on UAVs (mobile BSs) and CubeSats, when the scope is the realisation of reliable wireless networks in complex areas. In particular, the work has provided main design guidelines and results to realise Split D of virtual BBU, being able to perform FEC (and consequently HARQ) in a centralised manner on the satellites.

To the best of authors' knowledge this is the first work dealing with the design of C-RAN and virtual BBU split, using CubeSats. The importance of this work comes from the growing interest in deploying low-cost satellites and drones to provide connectivity in extremely rural and remote areas. Future work will concern with end-to-end performance evaluation in terms of bit-error-rate and achievable throughput of the system, keeping into account issues and constraints of the CubeSat's feeder link.

References

[1] M. Agiwal, A. Roy and N. Saxena, "Next Generation 5G Wireless Networks: A Comprehensive Survey," in *IEEE Communications Surveys & Tutorials*, vol. 18, no. 3, pp. 1617-1655, thirdquarter 2016.

[2] R. Bassoli, C. Sacchi, F. Granelli and I. Ashkenazi, "A Virtualized Border Control System based on UAVs: Design and Energy Efficiency Considerations," *2019 IEEE Aerospace Conference*, Big Sky, MT, USA, 2019, pp. 1-11.

[3] NASA CubeSat Launch Initiative (2017), "CubeSat101 – Basic Concepts and Processes for First-Time CubeSat Developers", [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/nasa_csli_cubesat_101_508.pdf.

[4] Ericsson AB, Huawei Technologies Co. Ltd, NEC Corporation, Alcatel Lucent and Nokia Networks (2015), "CPRI Specification V7.0 - Common Public Radio Interface (CPRI); Interface Specification", [Online]. Available: http://cpri.info/downloads/CPRI_v_7_0_2015-10-09.pdf.

[5] U. Dötsch, M. Doll, H. Mayer, F. Schaich, J. Segel, and P. Sehier, "Quantitative analysis of split base station processing and determination of advantageous architectures for LTE," *Bell Labs Technical Journal*, vol. 18, no. 1, pp. 105–128, Jun. 2013.

[6] M. Jaber, M. A. Imran, R. Tafazolli, and A. Tukmanov, "5G backhaul challenges and emerging research directions: A survey," *IEEE Access*, vol. 4, pp. 1743–1766, 2016.

[7] V. K. Q. Rodriguez, F. Guillemin. Towards the deployment of a fully centralized Cloud-RAN architecture. *2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC)*, 2017.

[8] C. Chang, N. Nikaein, R. Knopp, T. Spyropoulos and S. S. Kumar, "FlexCRAN: A flexible functional split framework over ethernet fronthaul in Cloud-RAN," *2017 IEEE International Conference on Communications (ICC)*, Paris, 2017, pp. 1-7.

[9] R. Bassoli, "Network Coding for Efficient Vertical Handovers", Ph.D. thesis, University of Surrey (UK), Sep. 2015, http available at: http://epubs.surrey.ac.uk/812743/1/thesis.pdf.

[10] 3rd Generation Partnership Project (3GPP) (2018), "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on New Radio (NR) to support non terrestrial networks (Release 15)", [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3234.

[11] B. Butters and R. Raad, "A 2.4 GHz high data rate radio for picosatellites," *in 2014 8th International Conference on Telecommunication Systems Services and Applications (TSSA)*, Oct. 2014, pp. 1–6.

[12] A. Matas, “De-mystifying articles of the RR related to small satellites,” in 2015 ITU Symposium and Workshop on small satellite regulation and communication systems, March 2015, http available at: https://www.itu.int/en/ITU-R/space/workshops/2015-prague-small-sat/Presentations/AM-PHA-ART5.pdf

[13] M. A. Marotta, H. Ahmadi, J. Rochol, L. Da Silva and C. B. Both, "Characterizing the Relation Between Processing Power and Distance Between BBU and RRH in a Cloud RAN," *IEEE Wireless Communications Letters*, vol. 7, no. 3, pp. 472-475, June 2018.

[14] M. F. Brejza et al., “20 years of turbo coding and energy-aware design guidelines for energy-constrained wireless applications,” *IEEE Communications Surveys & Tutorials*, vol. 18, no. 1, pp. 8–28, 1st Quart., 2016.

[15] A. Modiri, and L. Mohammady, "Mathematical Prediction of Sun-Synchronous Polar LEO Satellite Visions for Earth Stations," *2008 10th International Conference on Advanced Communication Technology*, Gangwon-Do, 2008, pp. 1559-1563.

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