Pico Satellites for Cloud Radio Access Network

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***Abstract*—Among main targets of fifth generation and beyond networks, there are perceived availability of 99.999% and 'anytime anywhere' connectivity. That would allow future generation networks to fully support very sensitive governmental services such as military and emergency ones. However, verticals like complex border monitoring would require connectivity in places where there is no available access network. Thus, the deployment of mobile base stations and the design of a system, based on virtualisation (e.g. cloud radio access network) and satellite-based network function virtualisation, can promise to achieve the desired goals for the mentioned verticals. This paper investigates the possibility to implement cloud radio access network in a system based on mobile base stations and CubeSats (pico satellites), which host the virtual network functions and the baseband processing. In particular, the investigation takes into account baseband functional split to study the feasibility of satellite-based cloud radio access network.**

***Index Terms*—5G, network function virtualisation, cloud radio access network, pico satellite, CubeSat, space data centre.**

I. Introduction

The main objective of future fifth generation (5G) networks and beyond (B5G) is to provide an infrastructure to support concurrently different kinds of verticals such as broadband communications, Internet-of-Things (IoT), emergency, governmental and military services. In order to do that, current 4G/LTE network infrastructure requires significant modifications and the applications of new paradigms. One of these technologies is represented by network virtualisation.

The main enablers of network virtualisation are software-defined networking (SDN) and network function virtualisation (NFV). The former deals with the decoupling of control and data plane by allowing traffic, resource management and network slicing via deployment of SDN controllers and SDN switches, which communicate with each others via Openflow protocol. The latter translates classical hardware-based network functions into software-based ones, which can be run on general purpose hardware using software containers.

Among the major requirements of 5G and B5G networks [1], the fundamental ones to guarantee reliable networks for emergency, governmental and military applications are *perceived availability* of 99.999% (network should practically be always available) and *almost 100% coverage* for 'anytime anywhere' connectivity (ensuring complete coverage irrespective of users' locations). In fact, very sensitive verticals such as autonomous complex border monitoring require the realisation and deployment of network, where cellular coverage is not available or not reliable.

In this context, the research activities of the Dynamic Architecture based on UAVs Monitoring for border Security and Safety (DAVOSS) project aim at employing mobile base stations (BSs) based on autonomous unmanned aerial vehicles (UAVs), which act as network access points for on-ground peripherals. Then, the UAV-based BSs are connected via satellite backhaul in order to be connected to the internet. Especially, as expressed in [2], cloud radio access network (C-RAN) is fundamental paradigm to guarantee acceptable battery life and performance of UAV-based BSs. In fact, energy and weight limitations of drones imply that mobile BSs must rely on virtualisation of baseband units (BBUs). So called baseband units are equipment that performs baseband (PHY/MAC) processing. In LTE standard, this equipment is within each BS, close to the Remote Radio Head (RRH). However, virtualisation of processing tasks performed by current BBUs allows their remote implementation (e.g. into satellites) as virtual network functions (VNFs). Allocation of resources of BBUs at satellites promises to improve the effectiveness of UAV-based BSs where no network coverage is available.

In the context of C-RAN research, the idea of RAN functional split [3] has become a leading paradigm for some years. The main idea behind that is the effective and efficient split of BBU 'black box' into its logical sub-functions in order to guarantee flexible deployment and optimal performance of virtual BBUs (v-BBUs) between centralised network entity (e.g. data centre) and RRHs. Figure 1 depicts the functional architecture of radio and baseband unit (uplink/downlink). The split points are highlighted together with the backhaul requirements in terms of latency and throughput for RAN virtualisation.

This article studies the theoretical and technical implementation of C-RAN virtual sub-functions in pico satellites (CubeSats). The idea behind it is to understand how C-RAN can be realised using CubeSats and what are the characteristics and limitations of C-RAN functional split in a system composed by UAVs and pico satellites. To the best of authors' knowledge this is very original approach/study, which has not been undertaken yet.

The structure of this article consists of Subsection I-A, which introduces the context and the motivation of this research. Next, Section II describes the system model, characteristics and assumptions, which will be used in the study. Finally, Section III shows theoretical results/discussion and (under those insights) analyses/validates our testbed correctness and suitability.

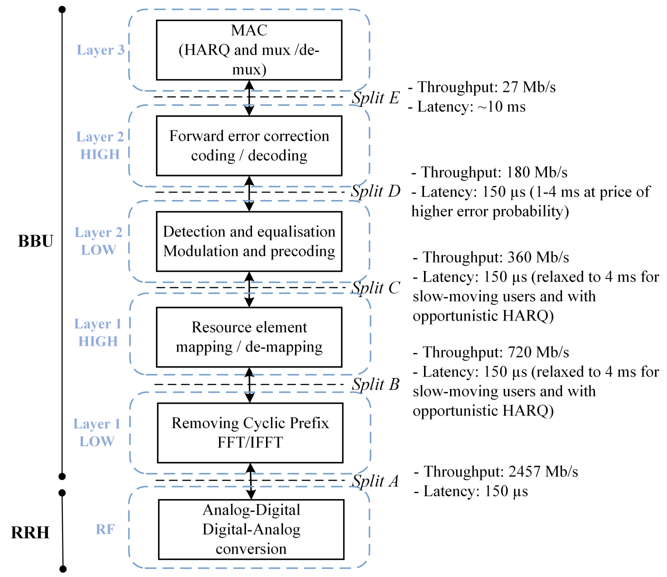


Fig. 1. Functional architecture of radio and baseband unit (uplink and downlink), considering the possible split points. On the right side, the backhaul requirements for C-RAN split options [4], [5].

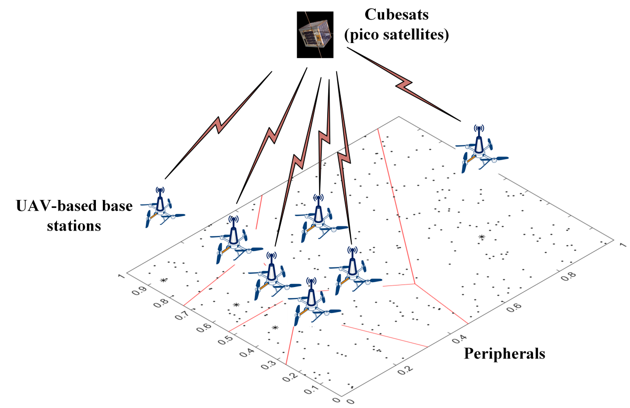


Fig. 2. Scenario of complex border monitoring, where no reliable cellular connectivity is available.

A. Related Works and Motivation

The research about integration between 5G terrestrial networks and satellite networks [6] has proposed architectures and solutions to merge terrestrial-based and satellite-based RAN into a unique infrastructure, where the main enabler is network virtualisation [7].

Investigation of C-RAN has involved significant amount of researchers. Regarding C-RAN functional split, paper [5] specifically surveys the latest achievements in the field, by considering backhaul perspectives. In particular, the challenges and requirements are summarised in Figure 1. Cloud RAN has been divided into six main sub-layers: analog-to-digital and digital-to-analog conversion (*Radio Frequency* at RRH), Removing cyclic prefix and FFT/IFFT (*Layer 1 Low*), resource element mapping/de-mapping (*Layer 1 High*), detection equalisation modulation precoding (*Layer 2 Low*), forward error correction (FEC) (*Layer 2 High*) and medium access control (MAC) with hybrid automatic repeat-request (HARQ) (*Layer 3*). Each one of the five possible split has its own minimum requirements in terms of latency and throughput in order to guarantee same behaviour/performance between BBU and v-BBU. In the same context, critical issues, modelling and dimensioning of C-RAN system were also studied in [8], [9], by taking into account the perspectives of C-RAN different sub-functions. Next, examples of studies of processing C-RAN functions in data centres can be found in [10], [11].

CubeSats [12] were born in 1999 as a collaborative effort between Jordi Puig-Suari, a professor at California Polytechnic State University (Cal Poly), and Bob Twiggs, a professor at Stanford University's Space Systems Development Laboratory. The original intent of the project was to provide affordable access to space for the university science community. While part of the research focused on using pico satellites for store-and-forward operations [13], more recently some investigation was devoted to analysing the capabilities of CubeSats for autonomous processing and classification of images [14].

As it is possible to see, the challenging problem of transforming the CubeSat into a pico data centre for C-RAN and virtual network functions like v-BBUs, has never been investigated. Thus, the motivation of this article is to set up a preliminary theoretical model and assumptions to start the analysis of CubeSat-based C-RAN, by taking into account the issues, limitations and capabilities. Then, the contribution of this work includes:

- Theoretical modelling of C-RAN system composed by on UAV-based BSs and CubeSat-based v-BBUs. The model focuses on baseband processing requirements and deploys stochastic-geometric model to have somehow accurate theoretical description of the traffic load.
- Evaluation of the system considering applicable C-RAN functional split. The study concentrates on latency, throughput, processing demand and physical limitations.
- Preliminary design and characterisation of a testbed based on pico cluster to model the virtual functions of C-RAN in the CubeSat.

To the best of authors' knowledge, this is the first work investigating C-RAN based on CubeSats, which are used as pico data centres.

II. System Model and Assumptions

Figure 2 represents the scenario where peripherals are distributed on the ground for border monitoring. Since the terrain under consideration has no reliable cellular coverage, the connection is provided via mobile base stations (i.e. UAVs). Next, the UAVs are connected to pico satellites, which provide computing resources (pico data centre) for RAN virtualisation, thus satellite link represents the backhaul.

Let's consider a geographical flat region, which can be mathematically represented as a two-dimensional Euclidean space $\mathbb{R}^2$. The end users are static peripherals of different kinds, which transmit at the same average data rate*. Since the peripherals cover homogeneously the border, without loss of generality, we can consider them distributed according to a two-dimensional homogeneous Poisson point process (PPP) Φ_s of intensity λ_s. Thus, the number of peripherals in a Voronoi cell, associated to a randomly chosen mobile BS, follows the probability mass function (pmf) of N_s [15]

$$P\left[N_s = n\right] = \frac{3.5^{3.5}\Gamma\left(n+3.5\right)\left(\lambda_s/\lambda_{BS}\right)^n}{\Gamma\left(3.5\right)n!\left(\lambda_s/\lambda_{BS}+3.5\right)^{n+3.5}} \tag{1}$$

where $\Gamma\left(x\right)$ represents the gamma function. The peripherals are considered like classical cellular end users, thus, the amount of baseband processing load they produce can be estimated as [16]

$$p_{UE} = \left(3A + A^2 + \frac{1}{3}MCL\right)\frac{R}{10} \tag{2}$$

where A is the number of antennas, M the modulation bits, C the code rate, L the number of spatial MIMO-layers and R the number of physical resource blocks (PRBs). The processing load p_{UE} is measured in Giga operations per second (GOPS).

Next, let's consider UAV-based BSs, which we can imagine following specific routes of flight: this assumption is enforced by the characteristics of current legal regulation, which forbids beyond line-of-sight remote piloting. Thus they will follow autonomous pre-defined routes using GPS navigation. Without loss of generality, we can consider mobile BSs in hover and active status to be distributed according to a two-dimensional PPP Φ_{bs} of intensity λ_{bs}. In particular, a mobile BS is a multirotor helicopter, which carries RRH and other limited computing hardware.

Finally, the mobile BSs are connected via backhaul/fronthaul satellite links to pico satellites (CubeSats). These satellites not only contain the communication hardware but also have storage and processing capacity to enable RAN virtualisation. These satellites are in an orbit of radius 450-650 km and are equipped with high data rate (HDR) radio [17]. In particular, this radio achieves a data rate expressed by

$$R = \frac{R_s}{s}M \tag{3}$$

where R_s is the symbol rate and s the number of samples per symbol.

III. Results and Discussions

The combination of expressions (1) and (2) permits the estimation of the total average baseband processing load, given the number of peripherals and mobile BSs on terrestrial network. Figure 3 depicts some curves to show the characteristics of this trend. Given fixed $A = 2$, $C = 3/4$ and $L = 2$, the variation of modulation bits M and the increase in transmission rate (i.e. PRBs assigned to users) affect the baseband processing per cell. Especially, while parameter M can slightly change

*The transmission rate is $\frac{PRB\cdot M\cdot R\cdot sub\cdot cp}{\tau_{slot}}$, where PRB is the number of PRBs, R is the coding rate, sub is the number of subcarriers, cp is the number of CP symbols and τ_{slot} is the duration of the slot (0.5 ms).

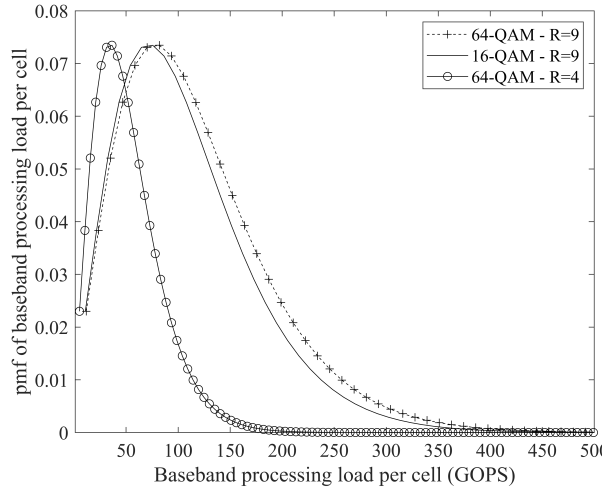


Fig. 3. Probability mass function of baseband processing load per cell.

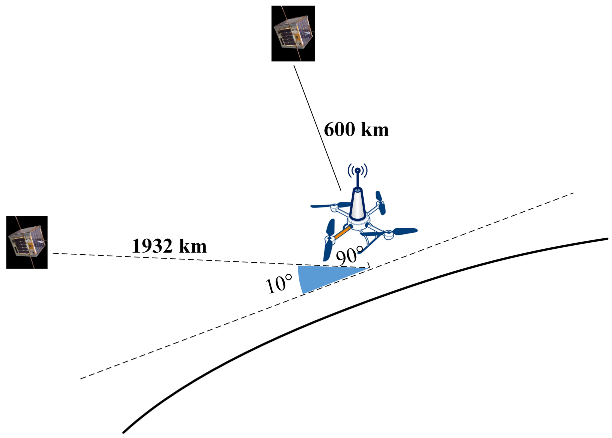
the baseband processing load, the principal parameter remains R. Then, the expected values obtained for baseband processing load per cell becomes 52 GOPS (64-QAM – R=4), 108 GOPS (16-QAM – R=9) and 117 GOPS (64-QAM – R=9).

Let's start the analysis of the proposed CubeSat-based C-RAN system by using Figure 4. As assumed in Section II, UAVs hover during time of communication with a CubeSat. When the amplitude of the angle between the drone and the satellite is 10°, the propagation delay τ_p is 6.44 ms (see Figure 4(a)). On the other hand, when the satellite is perpendicular to the drone, τ_p becomes 2 ms. According to the orbit and the speed, the time to cover that arc is ≈20 min, which is comparable to the hovering time of the UAVs.

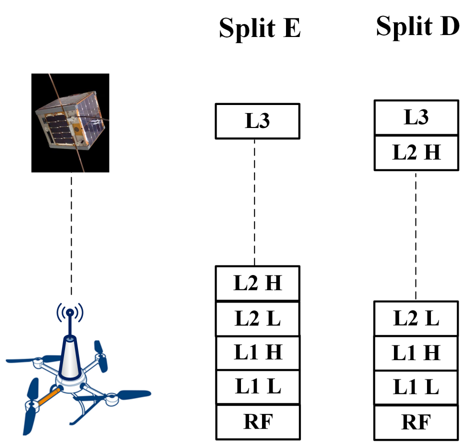
1) Case 1 (Split E): Given the requirements in Figure 1, Split E (see Figure 4(b)) case requires latency ≈10 ms and throughput of 27 Mb/s. The delay requirement of 10 ms is satisfied along all the orbit because of the range just mentioned above. Regarding data rate, equation (3) shows the threshold of 27 Mb/s is satisfied since $R = 60$ Mb/s can be achieved by setting $R_s = 45$ MS/s, $s = 3$ and $M = 4$ (i.e. 16-QAM).

2) Case 2 (Split D): On the other hand, the main technical issues for C-RAN implementation in CubeSats start from application of Split D (see Figure 4(b)).

- **Throughput.** Split D requires a throughput of 180 Mb/s. In the HDR of a CubeSat, that means playing with parameters of equation (3). First, the possibility to use QAM modulation schemes with greater constellations. The threshold would be achievable by using 256-QAM ($M = 8$) and $s = 2$. However, this is paid by an increased bit-error rate per signal-to-noise ratio. A better choice would be to augment the sample rate $R_s = 135$ MS/s via the usage of a more powerful Field Programmable Gate Array (FPGA) in the HDR than the one proposed in [17]. However, that would require an evaluation of heat dissipation since more powerful FPGA would increase probability of overheating the CubeSat.



(a)



(b)

Fig. 4. (a) Analysis of link variation between mobile BS and CubeSat according to specifications in [18]. It is important to underline the impact on the propagation delay due to the variation of distance between the satellite and the UAV (b) Two initial scenarios of BBU virtualisation for CubeSat-based C-RAN, which are reasonably realisable (Split E and D) according to their requirements. The layers are the ones described in detail in Figure 1.

- **Latency.** The suggested requirement of Split D is 150 μs, which is physically unachievable. In fact, Low Earth Orbit (LEO) varies in the range of 200-1000 km, while an orbit of 45 km would be needed to guarantee such delay τ_p.

What are the consequences of such a threshold on delay for CubeSat-based v-BBU? First, the relaxation of this strict upper bound to a larger range (between 1-4 ms), which unfortunately would imply greater bit-error rate (BER) at the BBU [5].

Let's consider the round-trip delay between BBU and RRH, calculated in [19]. The total delay τ_{tot} can be written as

$$\tau_{tot} = \tau_p + \tau_{proc} \tag{4}$$

where τ_{proc} is the processing delay due to FEC operations. Then, in more detail, the total delay can be expressed as

$$\tau_{tot} = \frac{d}{c} + \frac{kLF}{pO} \tag{5}$$

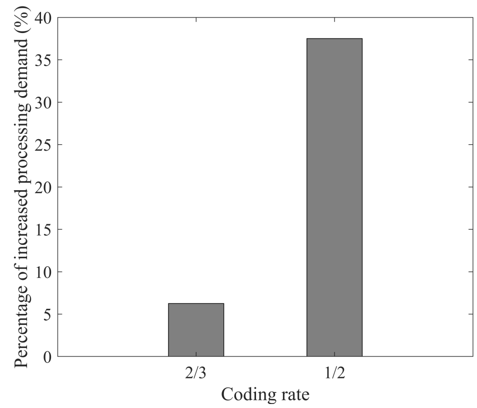


Fig. 5. Percentage of increased processing requirement by augmenting coding rate because of increasing BER (λ_{bs} = 10 and λ_s = 500).

where d is the distance between drone and CubeSat, c is the speed of light, k is the number of iterations of FEC decoder, L is the code block length (bits), F complexity of two identical combined decoders (operations per bit), p is the clock rate of processor (Hz) and O is the processor efficiency (operations per cycle). From expression (5), it is possible to extract the second term, which is a reasonable function to describe the time due to FEC. Thus, by experiencing greater BER, because of relaxed latency requirement, it is necessary to increase the redundancy of the error-correcting code (i.e. the code block length L) and the number of iterations k.

Equation (5) allows to estimate the processing capacity required at the CubeSat as a function of the distance (i.e. the propagation delay τ_p)

$$Op = \frac{kLF}{\bar{\tau} - \tau_p} \tag{6}$$

where $\bar{\tau}$ is the target total latency[†]. Let's set $\lambda bs = 10$, $\lambda s = 500$ and $\tau_p = 2$ ms, while number of iterations k and redundancy of error-correcting code increase because of augmenting BER. We can consider coding rate of 2/3 and 1/2 in respect of initial one of 3/4. Figure 5 clearly depicts the result per Voronoi cell, covered by a mobile BS: the necessary processing to FEC operations can increase till $\approx$ 38% per cell. Especially, that can have even greater impact when the difference $\bar{\tau} - \tau_p$ decreases: this would happen when the CubeSat is not perpendicular to mobile BSs and propagation latency τ_p becomes grater than 2 ms.

Equation (2) and equation (6) are very meaningful since, by analysing them together, it is possible to understand the specification requirements at the CubeSats according to the angle of the orbit, the communication load at the peripherals, the modulation scheme, the transmission rate and the decoding performance. In particular, the first term of equation (6) displays an inverse proportion between the clock rate of processor p and the processor efficiency O. That conveys the importance

[†]The value of $\bar{\tau}$ for LTE is $\approx$3 ms [19].

Fig. 6. Pictures of pico cluster containing five Raspberry pies 3.

of parallel processing, which could also contribute to reduce overheating issues, given lower clock rates.

A. Preliminary Testbed Analysis

Theoretical above considerations can help us to evaluate the suitability of our testbed to emulate C-RAN Split D at pico satellite. Figure 6 shows a picture of the testbed, a pico cluster, which consists in a cube. This pico data centre hosts five Raspberry Pie 3 in parallel of $p = 1.2$ GHz (2.441 GOPS). Moreover, the cube has enough free space to contain HDR hardware similar to the one in [17], which would allow communication with the UAV-based BSs.

According to these testbed setup, equation (6) can set $O = 5$. So, parallelisation allows to have less powerful processors to reduce the overheating because of processing hardware dissipation. In particular, given $\tau_p = 2$ ms and $O = 5$, p becomes 1.72 GHz (i.e. ≈ 3.49 GOPS).

IV. Conclusions

To the best of authors' knowledge, this article is the first publication exploring the possibilities and requirements of pico satellites to host C-RAN operations. The previous analysis has employed stochastic geometry to evaluate the total processing load per cell given a number of peripherals. Moreover, the paper has investigated the realisation of Split D at the CubeSat, underlining the limitations and the trade-offs. The required latency and throughput increase the BER, which increases the required processing and the processing latency at the pico satellite. Future investigation will focus on backhaul satellite channel characterisation considering different QAM schemes and their impact on FEC VNF.

Finally, we have presented the main characteristics of our testbed and its suitability to emulate a virtualisation of RAN at the CubeSat. Further research will include the presentation of real emulated results of C-RAN VNFs running at the pico cluster.

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