A Virtualized Border Control System based on UAVs: Design and Energy Efficiency Considerations

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Abstract—**European borders are hard to be controlled in an effective and efficient way. The recent emergencies related to immigration revealed the substantial inefficiency of conventional means of border patrolling based on warships, coast guard speedboats and helicopters. A reliable technical answer to these emergency problems may come from the use of different kinds of unmanned aerial vehicles (UAVs). These flying vehicles may allow at improving border control. Nevertheless, such technologies require significant amount of personnel, energy and infrastructure to properly serve border protection. In order to be really effective, UAVs should autonomously cooperate in networked manner, collecting information from the on-ground and/or water-surface sensors, exchanging data among them and conveying the critical information to remote border control centres. This is the main objective of DAVOSS project (Dynamic Architectures based on UAVs Monitoring for border Security and Safety), funded by NATO in the framework of the Science for Peace and Security Programme. This paper aims at presenting the novel adaptive and virtualized aerospace network architecture proposed in DAVOSS. The leading concepts of DAVOSS are flexibility, dynamic reconfigurability, energy efficiency and broadband connection availability also in critical application scenarios. In order to improve robustness and resilience of the avionic network and to enable the efficient information backhaul also in absence of terrestrial links, advanced networking and communications technologies like Software-Defined Networking (SDN), network slicing and virtualization are introduced. System requirements, coming from potential end-users, along with real application scenarios will be carefully analyzed in order to drive the architectural design phase, whose preliminary outcomes will be shown in the paper. Preliminary results demonstrate the effectiveness of the adoption of virtualization techniques for the considered aerospace network architecture in terms of reduced power consumption at the drone side, with an observed tradeoff with latency.**

Table of Contents

978-1-5386-6854-2/19/$31.00

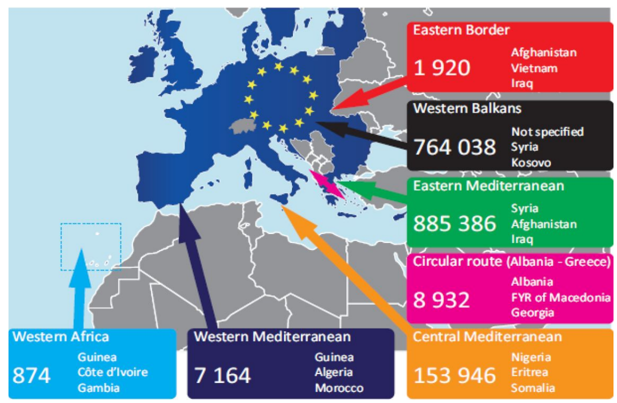


Figure 1. Routes and number of entries of illegal immigration in EU during 2015

1. Introduction

Border surveillance has started to play a major role in domestic and foreign policy issues, with the increasing number of terrorist attacks and the increasing mass illegal immigration. In Fig.1, the distribution of the illegal entries to EU in the 2015 is shown. The numbers look really impressive and fully justify a reasonable social alert. Indeed, the big international criminal trusts supporting the business of illegal immigration manage a global turnover estimated in terms of many billions of USD per year. Moreover, the daily chronicle often reports about the terrible destiny of thousands of people sadly drown in shipwrecks of overloaded rafts or dead for frostbite during mountain storms.

Military forces utilize advanced technologies for border monitoring. However, limitations are due to the number of people that can be deployed, to the governmental infrastructure, and to increasing costs. Conventional means of border patrolling like cost guard speedboats and helicopters, although well connected with the remote command and operational centers, demonstrated to be ineffective when the real-time intervention is required in case of sudden events occurring offshore. Thus, worldwide interest is growing to use advanced technologies, such as unmanned aerial vehicles, to improve coverage, efficiency and to reduce expenses. Despite the potential benefits of unmanned aerial vehicles in applications like disaster recovery [1], environmental monitoring [2], flood area detection [3], and aerial surveillance of public areas [4], there are still several open issues to be addressed. These are mainly related to effective data/information collection, communication and processing. Moreover, regulation about data access requires the efficient selection of authorized personnel to manage sensitive information. Finally, the network of unmanned vehicles needs to adapt to unpredictable events, attacks and network dangerous states to guarantee optimal quality of monitoring experience: eventually, the network should be capable not only to detect but also to prevent dangerous network situations.

In this context, the research activities of the Dynamic Architecture based on UAVs Monitoring for border Security and Safety (DAVOSS) project, funded by the NATO in the framework of the Science for Peace and Security Programme (funding period: 2018-2021), aim at advancing the current monitoring networks based on unmanned aerial vehicles to help to overcome some of their technological limitations. The project will study and design a virtualized cloud-based architecture to enhance capabilities of current border surveillance and counter-terrorist operational networks based on sensors, cameras and unmanned aerial vehicles. The DAVOSS solution will consider different kind of environments. Moreover, given its dynamic network structure and adaptability, it will provide higher security against physical attacks and natural catastrophes. The centralized structure of the architecture will allow for easier implementation of traffic measurement and anomaly detection processes, even in case of disaster forecast: its dynamic reconfiguration will optimize network performance, information management and processing, by ensuring optimal coverage to sensors and monitoring peripherals. Finally, the architecture will define and develop an appropriate wide-range connectivity functionality to provide the most suitable communication paradigm for connecting with the remote control center, via 4G/5G cellular backhaul, through the intervention of an Ultra Light aerial Vehicle (UVL), multi-hop wireless mesh networking or, in a possible future scenario, the usage of satellites. In particular, lightweight flying platforms such as ULV or small satellites will represent a viable alternative to terrestrial backhaul in terms of easy and low cost deployment and robustness against attack and environmental disruption. The proposed solution will also prevent information leakage, since no sensitive military/security data will be processed at unsecure network entities. It will also possible to easily monitor the effectiveness and the efficiency of network updates since they will be performed in a centralised manner.

We believe that the DAVOSS approach really represents a step ahead with respect to the current state-of-the-art about the use of avionic networks for environmental and border monitoring. This claim is justified by the analysis of the related contributions published in the literature. In [5], a solution based on the integration of Ku-band radar systems installed on UAVs and GNSS localization is proposed for patrolling of sea borders in the Mediterranean area. In [6], the use of acquatic drones is considered for marine safety. In these works, the focus is on the optimal sensor deployment and on the best routing approach, with state-of-the-art technology deployed and standard network configuration. Other papers, like e.g. [7] and [8] consider the use of UAVs in combinations with ground sensors in order to foster and optimize the border monitoring and minimizing the false alarms. However, such approaches are not based on an effective integration of the different network infrastructures involved and still require human operators' intervention to work. In [9], Kim, Mokdad and Ben-Othman analyze the design of UAV-based surveillance networks in two different scenarios: the smart city and the extensive ocean. Differentiated UAV typologies and network configurations are proposed in [9] for the two scenarios, evidencing a substantial weakness of UAV-based monitoring in terms of lack of adaptivity to potential modifications of the test field. The flexibility and reconfigurability introduced by DAVOSS network architecture in terms virtualization and softwarization should effectively cope with dynamic changes of the application scenario.

1.1 Article's Motivation, Objectives and Structure

Most of the works about mobile base stations (BS) consider the deployment of drones as relays, additional BSs or as BS for network recovery after disasters [10]. That is focused on enhancing Quality-of-Service (QoS) and end-users' experience or on supplying the loss of a number of BSs. Nevertheless, monitoring networks for border protection and control are mainly deployed in areas where cellular networks are not available or where BSs cannot guarantee reliable coverage. In this context, this article aims at proving how virtualization can be fundamental and beneficial in UAV-based cellular networks for complex border control. In fact, the realisation of cloud random access network (RAN) permits the effective and efficient use of drones for border control in the context of mobile BSs supported by satellite networks.

In fact, Base-band units (BBUs) are units that perform baseband (PHY/MAC) processing. In the LTE standard, this equipment is within each BS, close to the Remote Radio Head (RRH). However, the virtualisation of processing tasks performed by current BBUs allows their implementation in the satellite network as virtual network functions (v-BBUs). Thus, the allocation of resources of BBUs at satellites can improve the efficiency of the current UAV-based cellular monitoring networks. At the best of authors' knowledge no work has been published yet about benefits of RAN virtualisation in UAVs-satellite based systems.

In this paper, the DAVOSS network concept and architecture along with some possible design alternatives are presented (Section 2). Next, Section 3 provides the analysis of users' requirements and real application scenarios for DAVOSS project. Section 4 describes DAVOSS's theoretical system model and assumptions in order to evaluate the benefits of RAN virtualisation towards reduced energy consumption. In Section 5, the analysis of energy efficiency and latency, supported by some preliminary results, will be proposed and discussed. Finally, Conclusion will be drawn in Section 6 along with a summary of the future research activities of DAVOSS project.

2. DAVOSS Network Concept

2.1 Global Architectural Overview

Fig.2 depicts the proposed DAVOSS architecture. The system can be divided into four main layers:

- *Layer 1* consists of the ground-level sensors and peripherals, which are devoted to different kind of sensing procedures according to the application scenario and the environment.
- *Layer 2* represents the fleet of UAVs equipped with a camera and hardware for data transmission/reception. The UAVs provide network resources and furter monitoring functionalities both in case of disasters and border security/terrorist attacks.

Table 1. Sigfox and LoRa standard comparison

Sigfox	**LoRa**
Narrowband (or ultra-narrowband) technology	Wide band (125Khz or more) Spread-Spectrum technology
Uses a standard radio transmission method (BPSK)	Uses on frequency-modulated chirp Wide band (125Khz or more)
Requires an inexpensive End node radio, but expensive HW at the Gateway	Both the End node and the Gateway are relatively inexpensive
Uplink quality– good, Downlink quality - Limite	Looks at a wider amount of spectrum than SigFox – so can get more Interference. The larger receiver frequency bandwidth is mitigated by the coding gains
Technology and protocols from the end node to the server are not open.	Anyone can join the LoRa Alliance. LoRa Gateway spec is open. LoRaWAN which is the MAC protocol above LoRa is an open standard developed by committee. Network management spec is open.

• *Layer 3* provides network and resources virtualisation, and manages virtual network function assignment and slicing. This layer will implement a Software Defined Networking approach to control the connectivity and performance of the underlying mobile nodes (e.g. the UAVs), and well as Network Function Virtualization to assign or re-locate relevant processing and security functionalities.
• *Layer 4* (wide-area connectivity) is responsible to collect information from UAVs and to transmit it scurely to the cloud servers located at the remote control center. Different solutions for communication with cloud servers will be analyzed, tested and experimented, including direct usage or mesh-based solutions for efficient usage of the existing 4G/5G cellular infrastructure as backhaul, usage of a manned ULV to collect data by the virtualized network of UAVs and sensors in a delay-tolerant paradigm, usage of satellite communication (CubeSat scenario). This layer will be the key to guarantee coverage, security, availability and reliability, in case of both disasters and terrorists' threats. The project testbed will implement a subset of the solutions at Layer 4 considered to be the best ones, but will also investigate future extension of the architecture through CubeSat or other advanced solutions.

2.2 Sensor Network Deployment Solutions

The optimal Sensor Network Deployment solutions mainly based on Low Power Wide Area Network (LPWAN) wireless telecommunication technologies [11]. The basic characteristics of this technology are: (a) ability to inter-connect battery-powered end-devices over long ranges, (b) the end-devices must operate at low power, (c) downlink and uplink traffic is at low bit rate (0.3 kbit/s to 200 kbit/s) per frequency channel, (d) the frequencies used are licensed or unlicensed , (e) proprietary or open standard protocols are used. The following technologies are the most popular: Sigfox, LoRa, NB-IOT (Narrowband IOT) , LTE-M. We examined closely Sigfox and LoRaWAN and found the main characteristics as described in Tab. 1. Based on the above, we decided to focus on LoRa technology and to use LoRaWAN as the MAC protocol for the Network Deployment solution.
The technical specification of LoRa/LoRaWAN is:

• LoRa ISM Band : 868MHz - 900MHz (EU) , 902MHz - 928MHz (US);
• Ranges: 5 km (Urban) - 15 km (LoS);
• Security: Authentication and Encryption AES-128;
• Data Rates: 0.3Kbps – 50Kbps.

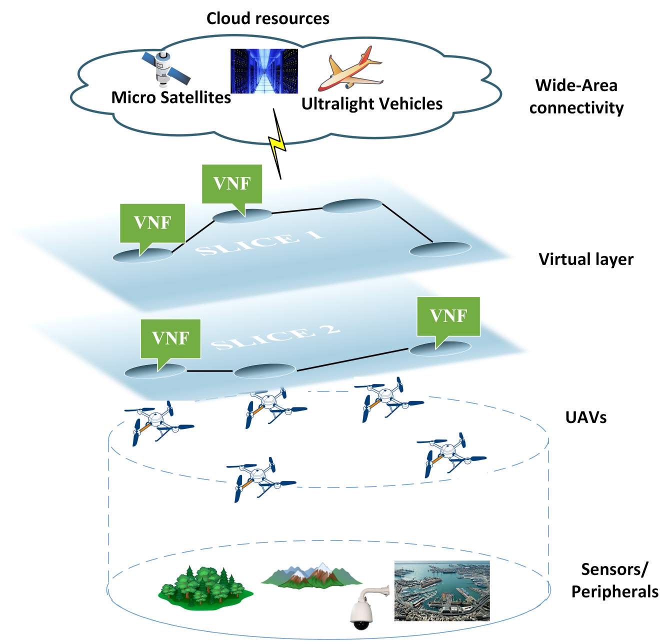


Figure 2. Structure of the DAVOSS proposed system.

The LoRaWAN specification version 1.1 defines 3 device classes:

• Class A devices have the lowest power consumption by opening two short receive windows after transmission (see Fig. 3).
• Class B devices extend Class A by adding slotted communication.
• Class C devices extend Class A by keeping the receive windows open unless they are transmitting.

For the deployment of the LoRaWAN LPWAN technology, we shall use the following components (see Figs. 4 and 5):

Sensor HW:

• STM Nucleo-L073RZ development board – with 32 MHz ARM core, USB, LCS controller , 192Kb of Flash memory

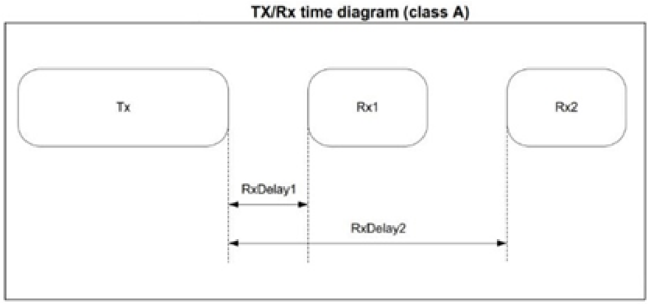


Figure 3. LoraWAN Class A Devices.

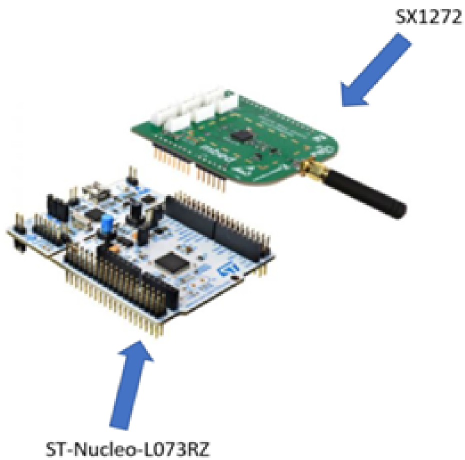


Figure 4. Hardware components of LoRa sensor communication section.

and 20Kb SRAM;
- SX1272MB2DAS LoRa RF expansion board (From Semtech™ Corporation) – with SX1272 low-power transceiver.

Gateway HW:

- Raspberry Pi-3;
- Semtech™ SX1272 LoRa transceiver.

Note that according to LoRaWAN protocol spec, gateways are built from a concentrator board, which listens to multiple channels (freq, tx power, data rate). Our SX1272 RF transceiver supports single channel, and so our gateway is a single-channel Gateway.

2.3 SDN and Virtualization

Layer 3 will maximise system automation and autonomy, centralised configuration, quick and secure access to information, and encapsulating information at different user's levels thanks to SDN and slicing procedures.
SDN represents an emerging paradigm which enables the separation of control functionalities from traditional Internet routers in order to transform them into dumb "Switches" controlled by a central entity (namely: the SDN controller) [12]. SDN demonstrated its effectiveness in improving the control and programmability of the current packet networks. Indeed, the SDN controller, having a central and global vision of the whole network, is capable of optimizing the performance,

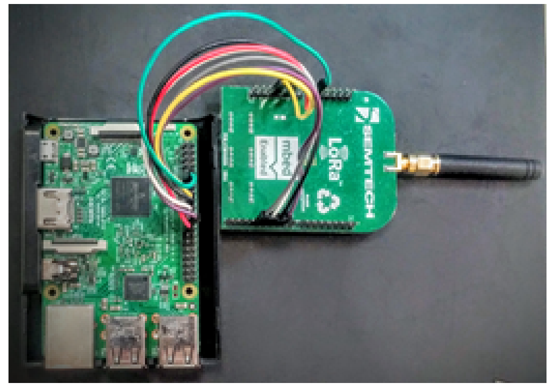


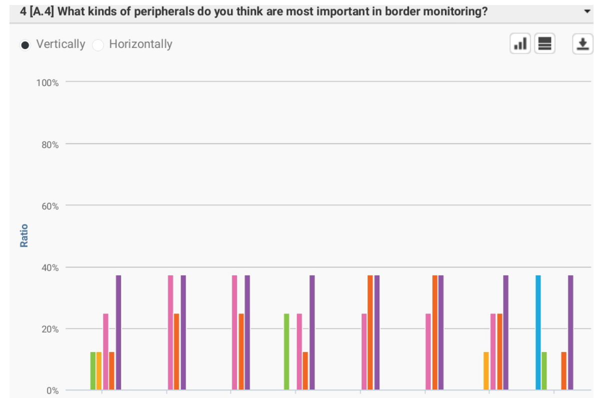
Figure 5. Hardware components of LoRa gateway.

managing in effective manner the various traffic flows and finally guaranteeing a satisfactory Quality of Service (QoS) to the users.
Virtualisation technologies will efficiently handle different kinds of traffic, with different priority. DAVOSS will provide the necessary centralised-cloud communications system. When available, other networks such as cellular networks or the Internet will also provide the required connectivity and infrastructure. Based on these communication technologies, DAVOSS also aims to exploit adaptive slicing. That will be used to bring rich computational and network resources to authorized UAVs. Authorized end users will have more information by increasing the number of information gathering nodes, real-time availability, and interoperability among systems: that is made possible by deploying dynamic slicing. With the amount and quality of information available in real-time, action will be immediately steered to the location of interest. A centralized analysis of network status, and of data about border surveillance will prevent network monitoring to fail because of attacks and lack of resources. Last, but not the least, UAVs, cameras and sensors with dynamic virtualisation and slicing will significantly reduce intensive human interaction and control.
We believe that the DAVOSS virtualization approach with adaptive slicing really represents a novelty with respect to the state-of-the-art. A very recent work [13] considered the use of SDN and virtualization in UAV networks. However, the SDN architecture of [13] is targeted at managing the multi-path routing only, by searching for the best available path. In DAVOSS approach, SDN and virtualization are regarded as a tool capable of dynamically and adaptively manage the overall link resources involved in the border patrolling tasks.

2.4 Satellite-based Long Distance Backhauling

The long distance backhaul plays a key role in the DAVOSS network architecture. Indeed, the information acquired by the ground sensors and processed by the drone layer should be forwarded in real time to remote control stations that may be considerably far from the border area. Moreover, the DAVOSS system considers scenarios where the terrestrial network connection is not available (e.g. desert areas or open sea). For this reason, a satellite solution to the task of long distance backhauling might be envisaged.
The use of satellite links for long-range data transmission in emergency recovery and public safety applications is regarded as a resilient solution, whose deployment costs are limited and convenient [14]. Geostationary (GEO) satellites present very favorable coverage and availability, but, as drawback, they are characterized by high latencies due to the very long distances from the Earth. Low-Earth-Orbit

(LEO) satellites placed at orbital heights of 500-700 Km offer reduced coverage with respect to the GEO counterparts, but also acceptable latencies.
In the framework of DAVOSS research, a novel solution for long-distance backhaul will be studied, based on the use of the CubeSat picosatellites. Nowadays, CubeSats are raising a lot of interest in the aerospace research community thanks to the reduced development and launch costs. Despite to their small amount of available volume, CubeSat missions have been proven to be very effective in high added-value applications like scientific data gathering, educational purposes and small-scale industrial equipment testing [15]. The on-board processing capabilities of CubeSats are not so limited as one can expect. Indeed, the use of dedicated processors, based e.g. on FPGA technology [16], allows to perform on-board image processing [15] [16] with fully-affordable power consumption. As far as communication aspects are considered, considerable research efforts have been done in order to overcome the bottleneck of low-rate standard radio interfaces, like e.g. AX-25 or similar variants [17], capable of providing small throughput of the order of 9.6 Kb/s. In [17], an X-band CubeSat communication system, compatible with the NASA Near Earth Network,offering a downlink data rate of 12.5 Mb/s has been implemented and tested. In [18], a prototype of 2.4 GHz High-Data Rate (HDR) radio for CubeSat has been implemented, able at supporting a topic data rate of 60 Mb/s. We believe that these last numbers and consideration can fully justify the CubeSat solution for DAVOSS long-range communication, thus solving the tradeoff between costs and coverage (the footprint diameter of a single CubeSat is well enough for DAVOSS purposes).



	0	1	2	3	4	NONE
A4.1 Seismic sensors	0	1	1	2	1	3
A4.2 Thermal sensors	0	0	0	3	2	3
A4.3 Noise sensors	0	0	0	3	2	3
A4.4 Light towers	0	2	0	2	1	3
A4.5 Night vision cameras	0	0	0	2	3	3
A4.6 Video surveillance systems with recognition	0	0	0	2	3	3
A4.7 Unmanned aerial vehicles (UAVs)	0	0	1	2	2	3
A4.8 Others (please specify it in the question below)	3	1	0	0	1	3

Figure 6. User requirement collection: the peripherals that are considered more important in networks for border monitoring.

3. Users' Requirements and Real Scenarios

3.1 User requirements

In order to understand the needs of players in the field of networks for monitoring and emergency response, a survey was publicly released online by the DAVOSS project: some of the answers are shown in Figs. 6, 7, 8, 9 and 10.

A high level analysis of these responses can show that having reliable and efficient data networks for border monitoring will be pivotal for future generations. Moreover, the complexity of different technologies and devices involved in border monitoring will require mandatory efficient and effective interoperability, which can only be achieved via virtualisation (at acceptable costs). Furthermore, it appeared important that terrestrial wireless networks and satellite networks become efficiently and effectively interoperable towards a single collaborative infrastructure: that will improve significantly the capabilities of virtualisation in networks for border monitoring and the effectiveness of response against attacks and illegal activities.

3.2 Potential application scenarios

The basic sensor network scenario we conceived in based on Single-Channel Gateways as described in Fig. 11. On this topology we shall be able to demonstrate the following use cases:

- End-node Over The Air Activation (OTAA);
- End-node Activate By Personalization (ABP);
- Cluster load balancing. This was done by instructing the End-node sensor with a standard LoRaWAN MAC command to change its channel (frequency) and associate it with a different less loaded Gateway;
- End-node sensor Duty-cycle –i.e wakeup every x seconds and send sensor information up to the server;
- Switch End-node from Duty-cycle mode to standard Asynchronous-mode (information is sent synchronously – once sensing event occurs);
- End-node sensor battery status – using standard DevStatus MAC command;
- Propriety MAC commands – for example: to blink a LED on the End-node.

Our plan for the next project phase is to construct a mobile LoRaWAN gateway utilized on a drone as described in Fig. 12, and implement advanced sensor network use cases – such as End-node sensor firmware update as well as sensor location estimate based on RX signals.

4. System Model of DAVOSS

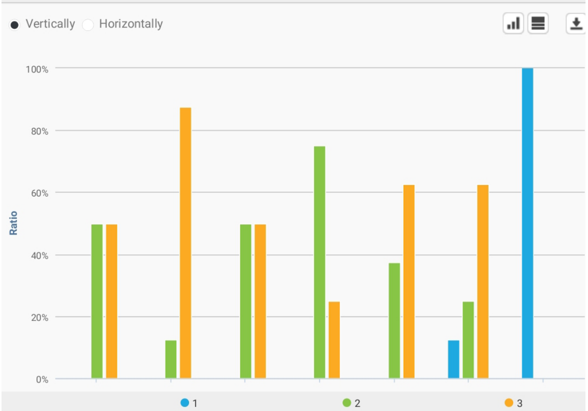
This article considers the monitoring activities of European north-eastern border (see Figure 13). That is mainly a flat region so it can be mathematically represented as a two-dimensional Euclidean space $\mathbb{R}^{\nvDash}$. In particular, we study a rectangular region of area $\mathcal{A}$ =1378 km^2, where 3G/4G network coverage is not guaranteed or completely absent. As depicted in Figure 2, the system consists of three layers. In the following, we list the mathematical/technical assumptions of the system. The following theoretical model uses stochastic geometry, which has been previously employed in UAV-

7 [B.1] How do you estimate the importance of interoperability of different peripherals (different types of sensors such as seismic sensors, thermal sensors and noise sensors, light towers, night vision cameras, video surveillance systems and UAVs) in public security/safety applications?

Answer Choices	Responses	Ratio
1 / 5	0	0 %
2 / 5	0	0 %
3 / 5	0	0 %
4 / 5	3	37.5 %
5 / 5	5	62.5 %

Figure 7. User requirement collection: the importance of interoperability among different kinds of peripherals in networks for border monitoring.

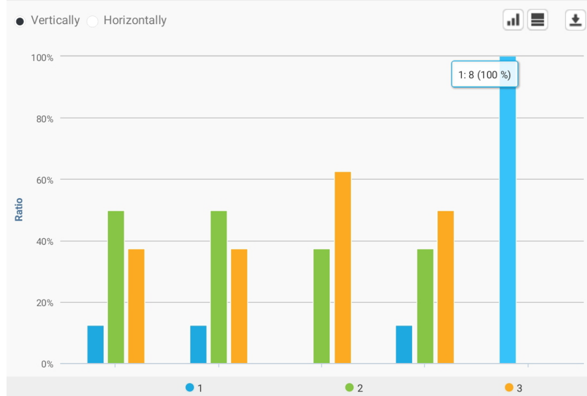
16 [B.9] Which services could be more important for the operators in emergency and border monitoring scenarios?



	1	2	3
B9.1 Voice service availability	0	4	4
B9.2 Data service availability	0	1	7
B9.3 Wireless sensor network deployment	0	4	4
B9.4 Broadband connectivity	0	6	2
B9.5 Availability of the absolute positioning information	0	3	5
B9.6 Availability of the relative positioning of each member of the rescue team	1	2	5
B9.7 Other (please indicate below):	8	0	0

Figure 8. User requirement collection: services that are more important for operators in networks for emergency and border monitoring.

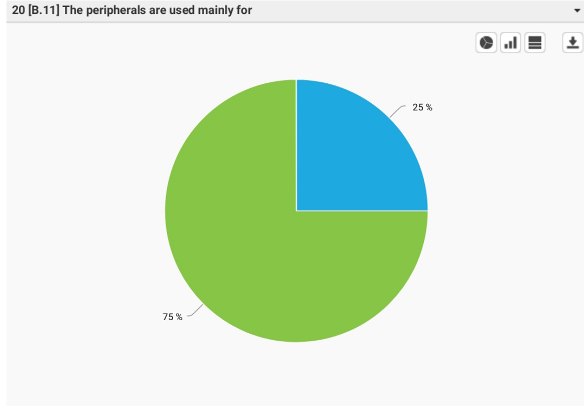
18 [B.10] Which level of interoperability would be pursued by tomorrow operations?



	1	2	3
B10.1 Integration between GPS and cellular networks	1	4	3
B10.2 Integration between TETRA and LTE	1	4	3
B10.3 Integration between satellite and wireless terrestrial communications	0	3	5
B10.4 Integration between wireless and wired networks	1	3	4
B10.5 Other (please indicate below):	8	0	0

Figure 9. User requirement collection: forecast of level of interoperability required in future networks for border monitoring.

20 [B.11] The peripherals are used mainly for



#	Risposta	Risposte	Rapporto
●	Voice	2	25 %
●	Data	6	75 %
●	Streaming	0	0 %

Figure 10. User requirement collection: the service that is more important in networks for border monitoring.

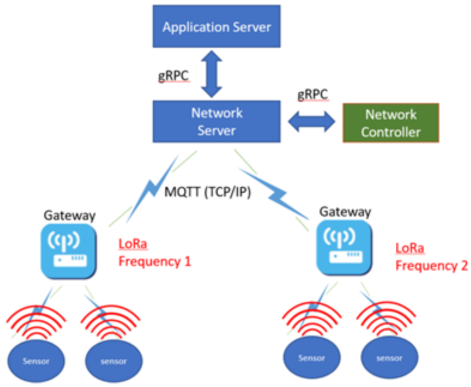


Figure 11. Basic sensor network scenario.

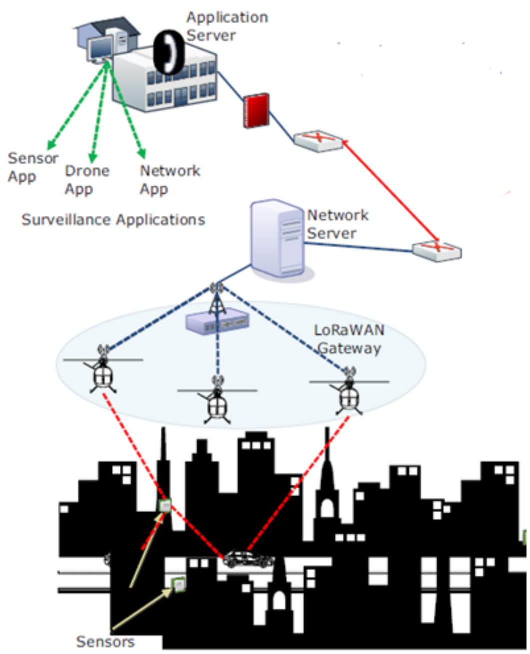


Figure 12. Scenario with LoraWAN Gateway mounted on a drone.

based network analysis by [10].

4.1 Assumptions of Layer 1

- The monitoring network includes static peripherals of different kinds, which transmit at the same constant 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.
- By considering the stochastic-geometric model studied in [19, 20], it is possible to derive the random variable N_s, which denotes the average number of peripherals in a Voronoi cell [21] associated to a randomly chosen BS. Hence, the probability mass function (pmf) of N_s is

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

where $\Gamma\left(x\right)$ represents the gamma function.

Figure 13. Partial snapshot of EU north-east border, using Google Maps.

- Since there is no standardised solution for sensors/peripherals network in 5G, and 5G networks are not yet implemented, we consider them connected and authenticated as 'fixed' mobile terminals.

4.2 Assumptions of Layer 2

- The layer includes UAVs, representing mobile base stations, which collect data from the peripherals and transmit them to the satellites.
- Without loss of generality, we can consider mobile BSs in hover and active status to be distributed according to a two-dimensional homogeneous Poisson point process (PPP) Φ_{bs} of intensity λ_{bs}.
- A mobile BS is a multirotor helicopter which carries either an RRH and a BBU or only an RRH.
- The flight time t_{fl} and the operational time t_{op} of a mobile BS is limited by its weight, its battery's capacity and its transmission power.
- The total average power p_{tot}, consumed by a mobile BS, considers the average power consumed during takeoff (p_{to}), flight (p_{fl}), hover (p_{ho}) and landing (p_{la}): especially, during hover, the average power consumption includes the average transmission p_{tr} and processing power p_{pr}. In general, the average power consumed during hover can represent an upper bound on the average power during flight [22]. Next, the average power consumed during takeoff and landing is approximately equivalent to the power consumed during hover [22]. Then, an upper bound on total average power, consumed by a mobile BS, can be expressed as

$$p_{tot} = 4p_{ho} + p_{tr} + p_{pr} \qquad (2)$$

- In the present dealing, we assume that the takeoff/landing stations of mobile BSs are not farther than 1 km from the hovering point, where the mobile BSs transmit/receive.
- The initial evaluation of this article ignores the impact of weather conditions on drone battery consumption. For example, flying against wind could significantly reduce the battery life and thus its operational time. That will be kept for future more detailed evaluations and measurements.
- Mobile BSs are assumed to be comparable to pico BSs in terms of power consumption and coverage. The reference

Table 2. Power consumption of different parts of BS [23].

Origin	Power consumption [W]
Power amplifier (P_{PA})	1.9
Radio frequency (P_{RF})	1
Baseband unit (P_{BBU})	3

values for pico BSs power consumption (considering both the contributions of RRH and BBU) can be found in [23].

• Since the number of peripherals is much larger than the one of mobile BSs ($\lambda_s >> \lambda_{bs}$), we assume all the mobile BSs to be active.

• The number of peripherals a BBU can support is approximately stated by the parameter η.

• The power consumption of a mobile BS can reasonably follow the model obtained in [23]. While power consumption is load-dependent for macro BSs, the load dependency is negligible for pico BSs [23]. Then the power p_{BS} becomes:

$$p_{BS} = P_{PA} + P_{RF} + P_{BBU} \tag{3}$$

where P_{PA} is the power due to power amplifier, P_{RF} is the one due to radio frequency transceiver and P_{BBU} is the one due to BBU.

4.3 Assumptions of Layer 3

• The layer includes virtualisation technologies and resources to realise Cloud RAN within DAVOSS system. Especially, the capability to virtualise BBU processing and moving it from the mobile BSs to the satellite, which hosts a micro/nano datacentre with v-BBU pool.

• Let t_c be the computing latency, i.e. the time to perform BBU computing tasks in the pico datacentre at the satellite.

• Let P_{comp} be the power spent by the CPU at the datacentre to compute BBU data.

4.4 Assumptions of Layer 4

• The layer includes satellites, which can either directly communicate with mobile BSs or via a ultralight vehicle.

• The paper consider two kinds of satellite to host the datacentre for BBU virtualisation: (i) geostationary satellites, which can have high computational capabilities but cause higher latency due to its higher orbit (ii) CubeSats, which can have lower computational capabilities but guarantees lower latency because of its altitude between 450-650 km. The downlink transmission rate of the geostationary satellite, according to the multi-spot Ka-Band beam performance of EUTELSAT [24] is assumed equal to 475 Mb/s. On the other hand, the downlink transmission rate of the CubeSats is assumed equal to 60 Mb/s, according to [18].

• According to [25], the chosen battery for the CubeSat is a lithium-iodine batter with a nominal voltage of 3.7 V (range from 3 to 4.2 V) and a capacity of 920 mAh (equal to about 3404 mWh). The battery weighs 26 g and the dimensions are 69 x 39 x 4.9 mm. The battery goes through 2 cycles every day, for a total of 730 cycles per year. After 730 cycles in one year, it will have a capacity of about 80 % equal to 736 mAh. A quantum of four batteries will be used to fulfill the capacity-need of the satellite giving a capacity of 13616 mWh.

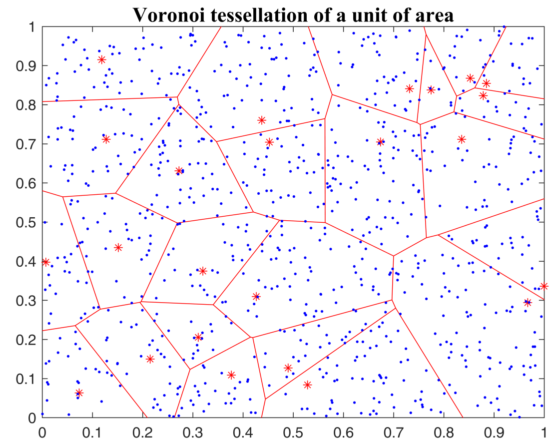


Figure 14. Voronoi tessellation, which provides a snapshot of the coverage of a unit of area. The red stars are the mobile BSs while the blue dots are the peripherals.

5. Energy and Latency Analysis and Discussion

This section uses the model described before, based on stochastic geometry, in order to calculate the variation of the average number of v-BBUs and the impact of virtualisation on the power consumption of the system.

In order to provide a realistic data of BBUs, the technical specifications of the Ericsson-Baseband-5212-5216 [26] are used. However, the generality of the model allows the correct use of any BBUs' data sheet. The average traffic provided constantly by peripherals is set to 500 kb/s.

The deployment of virtualisation allows the definition of a dynamic scenario, in which there are not physical BBUs always active at each mobile BS but only v-BBUs, which are activated according to network requirements. This does not happen in current monitoring networks based on 4G/LTE, where each active mobile base station must always host an active BBU. Given $\lambda_{bs} = 30$ AP/km^2 and $\lambda_s = 900$ peripherals/km^2, this means that 4G/LTE-based monitoring network keeps 30 BBUs/km^2 on. The energy consumption of a BBU can be estimated to be 3 W for pico cells mobile BSs [23].

Fig. 14 shows the Voronoi tessellation of a unit of area to depict the properties related to coverage. According to expression (1), Fig. 15 depicts the probability mass function (pmf) of the number of peripherals in a Voronoi cell (i.e. under the coverage of a randomly chosen mobile BS).

Given these premises, the value of peripherals that a mobile BS has to serve, with higher probability, is 22.

Given the power model, described in the previous section, and given the power values, assumed for mobile BSs as pico BSs, the relationship between weight of the drone (mobile BS) and the power consumption is depicted in Fig. 16. Especially, the gain is calculated in respect of mobile BSs, which carry BBU less than 4 kg.

Let's consider the geostationary satellite, which hosts the BBU. For the considered border area, it has to handle $\lambda_{bs} A_u$,

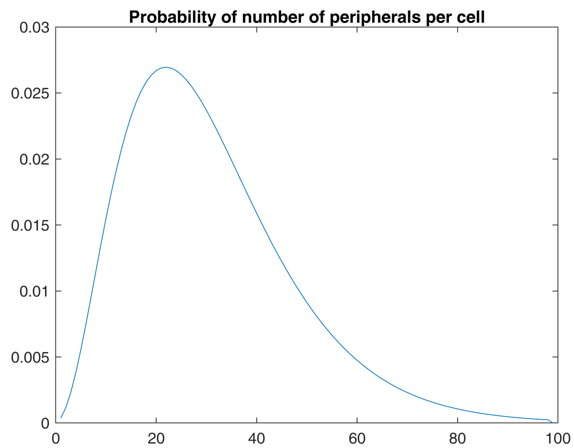


Figure 15. Probability mass function of the random variable referred to the number of peripherals in a Voronoi cell of a randomly chosen mobile BS.

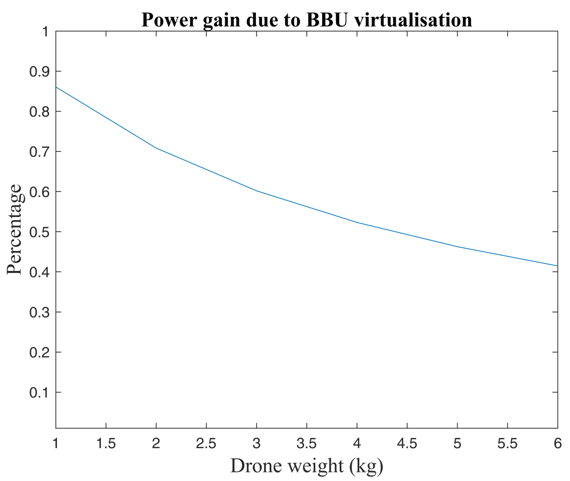


Figure 16. Power gain at the mobile BSs (drones) when BBU is virtualised. Obviously, by increasing the load of the drone, the impact of the weight of the BBU decreases.

where A_u is the unitary area. That means 41340 mobile BSs. Given the limited capacity of a v-BBU [26] at the geostationary and CubeSat satellites, the datacentre processors serve mobile BSs according to a queueing model. This analysis will be included in future works.

Regarding latency, the total delay of the two approaches can be modelled as

$$t_{totnoV} = t_{prop} + t_{BBUproc} + t_{RRH} \tag{4}$$

and

$$t_{totV} = t_{prop} + t_{Cloudproc} + t_{RRH} + t_{back} \tag{5}$$

where t_{totnoV} and t_{totV} are the total latency without virtualisation and with BBU virtualisation respectively. In particular, t_{prop} is the propagation delay, $t_{BBUproc}$ is the processing time of a physical BBU, $t_{Cloudproc}$ is the processing time in the cloud (i.e. the satellite) of v-BBUs, t_{RRH} [27] is the remote radio head (RRH) delay and t_{back} is the backhaul latency.

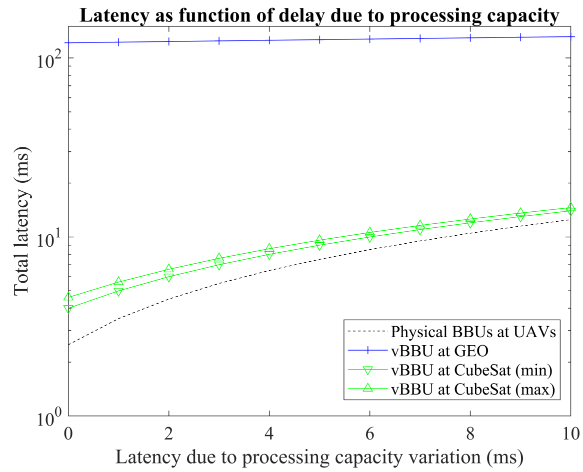


Figure 17. Behaviour of total latency functions depending on the increase in processing time at physical BBUs or vBBUs at satellites.

By considering the values of latency for Legacy long term evolution (LTE) uplink in [28], equation (4) and equation (5) becomes respectively $t_{totnoV} = x + 2.5$, $t_{totV} = x + 121.5$ (GEO satellite) and $x + 4 \leq t_{totV} \leq x + 4.66$ (CubeSat). The latencies of these formulas are measured in ms. As expressed before, we do not consider queuing time in calculation of t_{totV} to schedule requests from RRHs at mobile BSs. This aspect will be analysed in detail in future works.

As clearly appears by Fig. 17, the trade-off between reduction in energy consumption and latency becomes significant when satellites are involved in cloud RAN realisation. Furthermore, it also becomes clear that the choice of CubeSats is fundamental to have reasonable response time in case of data transmissions whose quality is hardly affected by latency. In that sense, a possible vision of DAVOSS to choose ultralight aerial vehicles as an alternative to satellites to host cloud computing, shows its importance.

On the other hand, the deployment of physical BBUs at the UAVs is an optimal choice in terms of latency but it increases a lot the energy cost at the drones. That means a fleet of UAVs which have very short flight time and require very frequent charging time and other UAVs to replace them. That is not a reliable and efficient solution in networks of long and complex border monitoring.

6. Conclusion

In this paper, some novel concepts for border monitoring has been presented, based on the seamless integration of on-ground wireless sensor networks, drone networks and long-distance satellite backhaul. Link virtualization and network slicing will enable the design and implementation of a novel monitoring architecture, characterized by reconfigurability and resilience also in critical application scenarios. The network architecture and the preliminary requirement analysis have been discussed and some preliminary results have been shown about power consumption and latency. In this framework, the use of CubeSats could be proposed as an easily deployable cost-effective solution for long-distance backhauling, taking into account the tradeoff in terms of payload efficiency and energy consumption of such small satellite infrastructures, together with latency requirements of data services.

Future work will go ahead with the planned research activities of DAVOSS project and will mainly concern with the optimization of the sensor network configuration, the feasibility study of the CubeSat backhaul link, the virtualization of the radio resources and, last but not the least, the deployment of a physical demonstrator, able at testing the proposed innovative technological approach.

ACKNOWLEDGMENTS

This work has been partially funded by NATO Science for Peace and Security (SPS) Programme, in the framework of the project SPS G5428 "Dynamic Architecture based on UAVs Monitoring for Border Security and Safety".

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BIOGRAPHY

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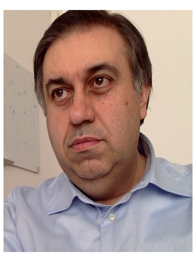

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