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Multi-interface network framework for UAV management and data communications

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***Abstract*—Recent efforts to manage Unmanned Aerial Vehicle (UAV) operations in European civilian environments have resulted in the development of U-space, the European Union's UAS Traffic Management (UTM) concept of operations. This paper presents the primary purposes of the H2020 Labyrinth project (mainly focusing on the communications architecture), which has as its main challenge to create and validate UAV applications through the research and development of path-planning algorithms and new UTM services. In addition, this article performs a preliminary validation of a communications prototype (including three communication alternatives) with real equipment of the National Institute of Aerospace Technology (INTA) of the Spanish Ministry of Defense. The presented results show the functionality of the prototypes and serve as a starting point to develop the requirements defined in the communications architecture.**

***Index Terms*—UAV, UTM, U-space, GCS, Communications framework.**

I. Introduction

The same way we can find rules, normative, and agreements on procedures around the world to manage different aspects of ground or aerial traffic, several efforts during the last years have been addressed to organize and regulate the civil usage of Unmanned Aerial Vehicles (UAV) at a Very Low Level (VLL) airspace (below 500ft above ground level) [1].

One of these efforts recently resulted into U-space [2], the concept of operations (CONOPS) to harmonize the Unmanned Traffic Management (UTM) [3] in Europe by SESAR (Single European Sky ATM Research) [4]. This first high-level concept [5] will be progressively complemented with the ongoing and future definitions of requirements to make UAV flights safe, avoiding the adverse side effects these could have on citizens and the environment.

To test the U-space design and identify gaps and needs, the European Union, with its Horizon 2020 research and innovation program, has endorsed research projects that implement different aspects of the U-space system. One of those projects is Labyrinth [6], in which a U-space UTM system is being built to investigate and experiment with aspects such as route optimization, timely monitoring and separation of the traffic, security, or capacity of the communications [7]. This last area focuses on the performance of the different communications alternatives used in a UTM system, such as WiFi, Radio, 4G/LTE, 5G, or satellite communications (Satcom). Also, these links can coexist and coordinate when more than one is used to provide the UAV with a backup link or to provide the possibility to switch and choose the link with better quality of service (QoS).

This article presents some of the goals of the work package in Labyrinth dedicated to communications. The following section describes the information exchanges expected in a UTM system and how these will be implemented in the Labyrinth prototype to overview their role in the system. Section III presents the communication framework. Section IV presents a preliminary experimentation of the proposed communication prototype. Section V depicts some future research lines. Finally, section VI concludes the article.

II. Labyrinth details and requirements

In conventional aviation, each center where Air Traffic Controllers (ATC) perform their assignments is called an Air Traffic Services Unit (ATSU). Similarly, the UTM server will act as an automated ATSU for the UAVs. Like in an ATSU, the UTM server tries to keep a global picture of the traffic in the area (present and future). It will also perform relevant tasks such as: *(i)* assist the operators to design a feasible and optimized trajectory, free of collisions; *(ii)* monitor the traffic and send instructions during the flight to the pilots to guarantee the distance between the UAVs; *(iii)* rearrange the traffic to give way to priority specific flights; *(iv)* apply measures and warn pilots in case there is a problem with a UAV out of control; and *(v)* broadcast information of interest for the pilots.

In manned aviation, ATCs provide that help using tools or sources of information either on-site or from external locations. Also, in our case, what in the U-space jargon are called services, will be sources of information or applications that support the UTM server to perform its tasks. Those

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services can be inside the UTM server or another external server provided by a different entity or company. In particular, in Labyrinth, the path planner responsible for calculating the optimal path from origin to destination is provided as an external service [7].

U-space defines different types of airspace volumes, based on the risk of the operations. Those volume types determine the requirements so as to be allowed to fly in each of them. In the case of Labyrinth, where we are testing the UTM with different use cases (road transport, air transport, emergency, and waterbone transport), the type of volume for these use cases require the UAVs to constantly report their position to the UTM server. This report must be either done by the Ground Control Station (GCS), forwarding the reported position by the UAV, and by the UAV itself directly sending the position to the UTM server. To complete the reports from the UAV, it is essential to have a cellular or satellite connection. Ideally, the cellular connection will be the main alternative chosen to make these reports; however, the satellite connection provides a backup link that can complement the lack of cellular coverage.

In manned aviation, when ATCs need to change the trajectory of a certain flight, they send a text message with the instruction to the pilots or directly speak it to them using the radio. Therefore, ATCs issue the instruction but it is the pilot, after replying with a WILCO (message confirming that the pilot has received the instruction and will comply with it), who finally introduces the command and executes the instruction. In U-space, UAV pilots will receive the instructions from the UTM server and they must accept and load the command in the UAV, also during the flight. For the instructions, warnings or information, to reach to the UAV pilot, the GCS must be constantly connected to the UTM server and, of course, the UAV with the GCS, to be able to load and apply the commands.

To communicate with the UTM server we defined an Application Programming Interface (API), a protocol that describes how to send requests or reports to the UTM and the format of the replies that will be received. For the pilots to easily communicate with the UTM, they need some dialogues in a graphic user interface. These can be embedded in the GCS software, using the API to make those calls. But unfortunately, that is not always possible, since there may not be room left in the display for the dialogues, or the code of the GCS may not be modified for security reasons, or it might imply a considerable cost for the flight operator. To ease things in this sense, we are working on a web application to contain those dialogues and properly display the received information and warnings.

As previously said, the UTM sends instructions to the UAV pilots. Some of them can be simple, like a change of altitude or speed, with only one numerical value implied. But others could imply a long list of hundreds of complex values defining a new trajectory and in this case, we cannot expect the pilot to manually introduce them in the GCS. The problem is that, even if we had the web app running in a browser in the same computer as the GCS, for security reasons, is not possible to

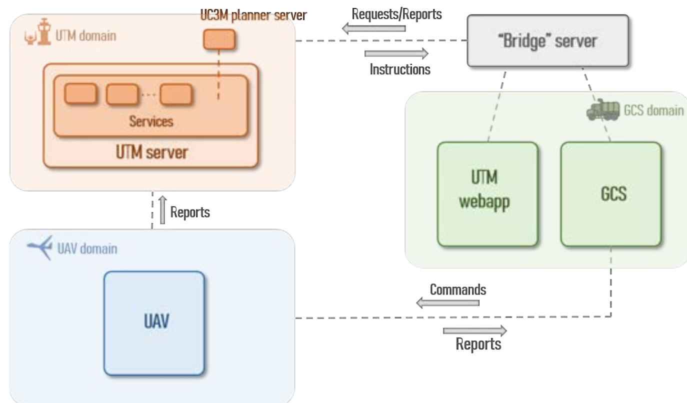


Fig. 1: Elements and communication links in the Labyrinth U-space UTM system.

get from a browser the level of interaction with the operative system that we would need for the web app to interact with the GCS (otherwise, it would be very easy to harm our computers while visiting malicious or infected webs). The solution here has been to use another server as a bridge to communicate the web app and the GCS. This server will also forward the position reports from the GCS to the UTM, and the requests of the pilot from the web app to the UTM. In the opposite sense, the bridge can also deliver the UTM messages to the web app, and the instructions to the GCS to be converted into commands and loaded in the UAV once accepted by the pilot.

The last type of message exchange, this one without the UTM or the GCS involved, appears in the case of swarms of UAVs. Inside the swarm, the UAVs can share between them their position or intentions to keep themselves separated. They can also use this UAV-to-UAV communication to coordinate their tasks during the mission.

A summary of these messages and the operation of the UTM can be seen in Figure 1.

III. Labyrinth network framework

As discussed in the previous section, the principal actors in a mission are within three main domains: the UAV domain, the GCS domain, and the UTM domain. The communication between these domains has to be reliable and remain stable during the mission for proper operation.

A. Inter-domain communication alternatives

Communication between UAV and GCS domains can be implemented using different alternatives, from the traditional approach through a direct link using a radio modem to novel paradigms such as the use of the public cellular network, which would allow a GCS-UAV communication beyond the line of sight as long as the two domains have Internet connectivity. In particular, in the Labyrinth project communication architecture (see Figure 2), four types of communications are considered: *(i)* a radio modem link; *(ii)* satellite, which is limited by a small bandwidth and a higher delay (this point to be checked in the project), but with available coverage in

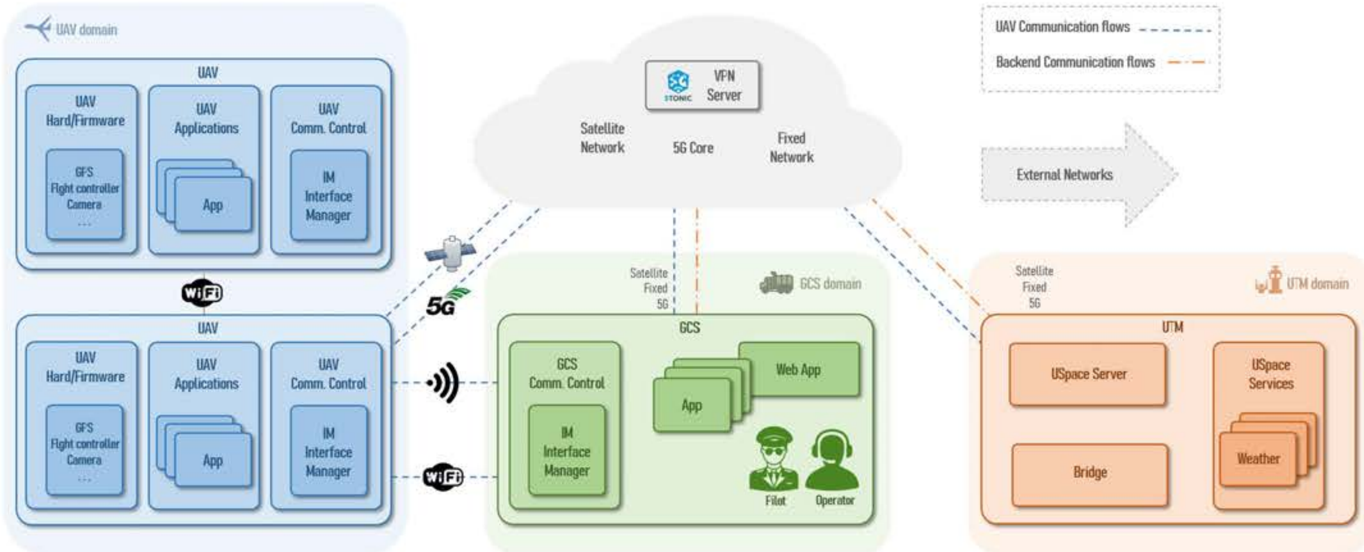


Fig. 2: Labyrinth communications framework.

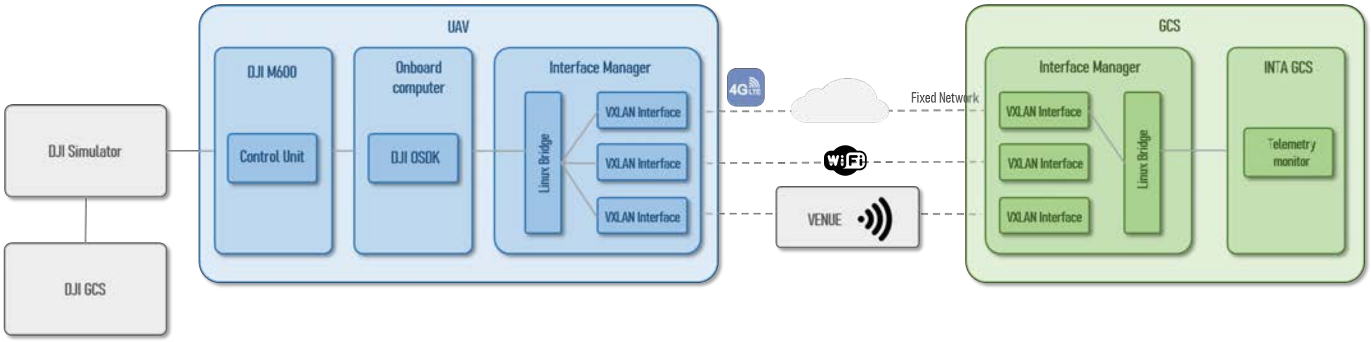
open environments; *(iii)* WiFi, not only to communicate UAV and GCS domains but also to enable the previously mentioned UAV-to-UAV communications if they are flying close together. Another representative use due to the small range of WiFi, is when the UAV is on the ground, the UAV operator has to access the equipment onboard the UAV if any configuration or adjust is needed; *(iv)* public cellular network (5G/LTE/4G), which enables the UAV not only to communicate with the GCS but also to report directly its position to the UTM server. It should be noted that the GCS can be connected to the public network (which enables connectivity with the UAV) using the fixed network or the cellular network interchangeably as long as one of them is available. The radio modem link is the most common in UAVs, especially in residential and recreational environments. In this project, and in particular, in this article, the focus is on cellular communication for several reasons: *(i)* It enables direct reporting of specific parameters directly from the UAV to the UTM; *(ii)* It does not limit the coverage range to connect UAV and GCS as both domains will be connected as long as both have connectivity to the public network, thus enabling the possibility of performing missions Beyond visual Line of Sight (BvLoS); *(iii)* With the imminent arrival of commercial 5G deployments, the cellular network performance will improve exponentially regarding the delay and available bandwidth, enabling innovative applications that require those values.

For security reasons and as a general rule, when user equipment connects the public network (Internet), it does not do so with a public IP address, but it accesses the network through a Network Address Translator (NAT) provided by the router (in the case of the fixed network) or the network operator (in the case of the cellular network). Therefore, the mentioned device is not reachable from externals networks and direct communication is not achievable. Although it is possible to connect to the Internet using public IP addresses, it has been decided to enable connectivity between the different devices using a Virtual Private Network (VPN) to make this framework solution more generic and approachable to the potential users but also more secure. The VPN server, which is located at 5G Telefonica Open Network Innovation Centre (5TONIC) [8] (a leading research laboratory focusing on 5G technologies based in Madrid), will relay the information/packets between all the devices connected to the VPN, thus facilitating communication. In our previous work [9], we have examined the performance impact of using a VPN service with cellular-enabled UAVs, proving that it does not penalize communication performance to a great extent and provides more benefits than disadvantages.

In order to connect the GCS and UTM domains, it is just required that the GCS is connected to the public network either using the fixed network, the cellular network, or even the satellite. In this case, it is unnecessary to use a VPN service since the interaction between the GCS and the UTM domains is performed through a web application, as explained in the previous section and shown in Figure 1.

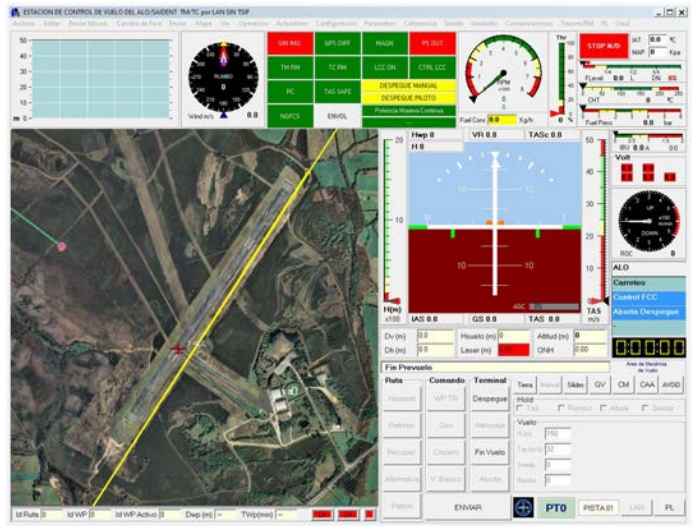
B. Interface Manager

As detailed above, there are several alternatives for inter-domain communication. It is mandatory to maintain stable communication over time in such an environment, but specific requirements regarding the network performance must be met to carry out the mission under the established parameters. For this reason, it is necessary to have an application in each of the connected devices (UAVs and GCS) that is responsible for selecting the best communication alternative depending on the needs of the moment. This application corresponds to the *Interface Manager* shown in Figure 2.



(a) Validation scenario.

(b) DJI Matrice 600.



(c) INTA Ground Control Station display.

Fig. 3: Validation scenario and components.

The *Interface Manager* should automatically select among the different alternatives based on different network parameters such as delay, bandwidth, or packet losses. For this purpose, it is necessary to constantly monitor the status of each of the available links. At the same time, this information about the state of the links must be available in the GCS at the operator's disposal, who can manually select the preferred alternative or let the *Interface manager* to automatically choose.

This application must assume that the selected links to be used may eventually be asymmetric, i.e., the UAV may use one certain link to communicate with the GCS and the GCS may use another different link instead to communicate back with the UAV. In the same way, it would also be interesting if different types of traffic could use a different link. Thus, it would be possible to isolate the types of traffic by channel, physically separating the most critical information such as command and control (tele-measurement and tele-comand) from other less critical information such as video.

Finally, it should be noted that all UAVs have the ability to include different payloads to carry out the application aspired by the user. In particular, UAVs will incorporate virtualization enabled equipment since virtualization technologies have positively shown many advantages enabling the deployment of communication services over aerial networks [9]

IV. Preliminary Validation

In order to perform a preliminary validation of the Labyrinth communications framework (final trials have been scheduled by the end of year 2022), we have conducted some experiments in a laboratory environment. These experiments have been carried out at the Instituto Nacional de Técnica Aeroespacial (INTA) [10], a research organization associated with the Spanish Ministry of Defense that participates in the Labyrinth project.

A. Validation details

As represented in Figure 3a, the validation involves a UAV and a GCS. The selected UAV is the DJI Matrice 600 (see Figure 3b). The aircraft carries as payload an onboard computer, responsible for collecting relevant data from the UAV (e.g., velocity, position, altitude) and sending it to the GCS. This data is represented at the GCS (see Figure 3c).

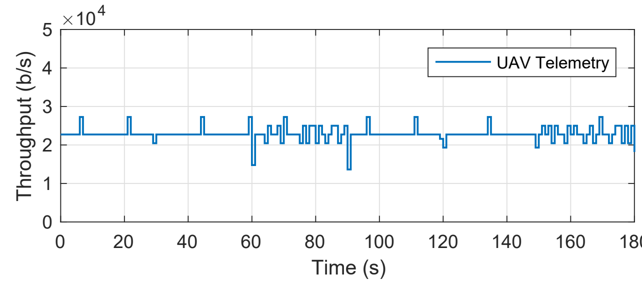
Both the GCS and the UAV use a communication prototype (that runs the *Interface manager*) with the basic features of the presented architecture. Two Raspberry Pi 4 B have been selected to implement the communication prototypes. The selection of these devices has been motivated by the large community of users and the support generated. In addition, these devices have the possibility of being powered by small batteries, and the prototype can be onboarded on the UAV for preliminary validation. This equipment has been previously used in real flight tests demonstrating its ability to onboarded as the UAV payload [9].

Among this equipment, three alternatives are considered, as depicted in Figure 3a: *(i)* public network (Cellular network in the case of the UAV, and fixed network in the case of the GCS), *(ii)* WiFi, and *(iii)* radio modem. However, due to the limitations of radiating in a laboratory environment and the current state of Labyrinth user developments, the radio modem link is emulated using the VENUE emulator [11], a UAV-oriented emulation platform. A 4G/LTE HAT is used to connect the UAV RPi to the public cellular network. As explained in the previous section, if devices connect to the Internet using private IP addresses, it is necessary to use a VPN service. This service has been deployed in the 5TONIC laboratory [8]. The VPN credentials (required to create the VPN tunnel) generated for the devices connecting to the VPN are unique and always assign the same IP addresses so that the configurations made on both devices are persistent. On the other hand, the WiFi link between the two devices is a 2.4 GHz ad-hoc link.

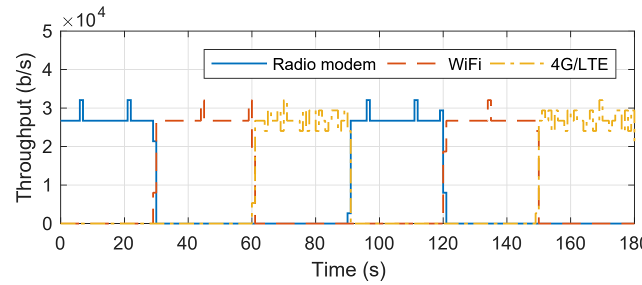
One Virtual eXtensible Local Area Network (VXLAN) [12] has been created for each of the communication links. A VXLAN is a network overlay protocol designed to transport data link layer traffic over the network layer. The essential operation of a VXLAN is that it encapsulates traffic from one Local Area Network (LAN) and transports it over an IP network to a different physical LAN. This way, it is possible for devices on both networks to communicate with each other in the same way as if they were on the same LAN.

VXLANs, on the one hand, enable UAV and GCS equipment (Onboard computer and Telemetry monitor in Figure 3a) to act as if they were on the same LAN regardless of which link they are using to communicate. Therefore, changes made in the IP network (the one that transports packets to the other end of the VXLAN) are transparent for UAV and GCS computers. In addition, the fact that the UAV and GCS equipment work as if they were on the same LAN simplifies the development process for Labyrinth users, who do not have to worry about IP addressing and routing. As a result, we obtain a programmable device that allows implementation, flexibly, any policy to select links, both upstream and downstream, independently.

Each of the VXLANs that have been created (one per link) are attached to a Linux Bridge (see Figure 3a). On the other hand, this Linux Bridge is attached to the Ethernet interface of the RPi, which will provide connectivity to the UAV equipment. The procedure is similar in the GCS; however, only one VXLAN is attached (one per link) to the Linux Bridge to select the link to enable communications. For example, a UAV operator can switch from the public network to the WiFi at a given moment, and this procedure is done by detaching the VXLAN corresponding to the public network and attaching the VXLAN corresponding to the WiFi to the Linux Bridge. More details about VXLAN configuration can be found in our previous work [13].



(a) Traffic received at Telemetry Monitor.



(b) Traffic received in the Interface Manager.

Fig. 4: Telemetry data sent from the onboard computer (UAV) to the Telemetry Monitor (GCS).

B. Experiments

The UAV, using DJI's flight simulator, performs a virtual flight mission (the DJI simulator sends the flying parameters to the UAV as if it were flying) at Rozas airfield, Lugo, Spain. The Rozas Airborne Research Center (CIAR) [14] is located at this aerodrome, where real flight campaigns will be carried out once the developments are in the validation stage (end 2022).

The onboard computer collects interest data from the main computer (Control Unit in Figure 3a) of the UAV via serial link and sends them to the INTA control station in order to monitor the UAV status, such as GPS, Inertial Measurement Unit (IMU), and battery load; it packages them in the corresponding format, and transmits them to the station. These packets are sent with a frequency of 10 Hz and have a predefined size of 241 bytes.

As a first approach and proof of concept, this information will be transmitted by the communication prototype. During this process, an operator at the GCS will be in charge of manually changing the links.

The traffic transmitted from the onboard computer (UAV) to the station and received at the Telemetry Monitor (GCS) can be seen in Figure 4a. The traffic frames are captured in the GCS communications equipment. In Figure 4b, the same traffic can be seen but captured on each one of the available interfaces. The graph shows that although the selected link has been changing during the mission (approximately every 30 seconds), the data flow has remained stable, and these changes have been transparent to the Telemetry monitor. The graph also shows that the traffic received on the interfaces is bigger than the traffic received in the station application. This is due to the overhead introduced by the use of VXLANs. This effect is more noticeable since the packets sent are quite small (only 241 bytes), and the header introduced by the VXLAN (20 bytes) although very small in general, here accounts for a significant percentage of the total size (8.2%). Finally, it can be appreciated that the telemetry flow is less stable when using the public network (4G/LTE) due to external factors.

V. Future work

This work serves as a starting point for developing the Labyrinth project communications architecture. Likewise, it opens several working and research lines that will be discussed in this section.

First, integration with the UTM server has to be carried out, both from the UAV and the GCS. It is necessary to define different details such as the report message format or the required transmitting frequency. In the same way, the messages/instructions received from the UTM server must be translated into the GCS to incorporate them into the UAV.

Other representative working line would be to integrate new communication solutions into the proposed communications prototype, such as a Radio modem or Satellite. Once we have all the available alternatives configured, it is necessary to characterize each link taking into account not only network parameters such as the available bandwidth or delay, but also other parameters such as the maximum coverage range or the energy consumption. All this information is required as input to decide which link to use in each specific case. In addition, this information must be available and constantly monitored in the GCS at the disposal of the UAV operator, who will be able to make decisions based on these parameters.

On the other hand, it would be of great interest to perform an asymmetric link selection. This means that the UAV and the GCS can use different links to communicate each other (i.e., the UAV may use the radio link while the GCS may use the public network). Likewise, different types of traffic should go through different links (at the same time), which will allow to physically isolate data that is highly critical (e.g., telemetry, commands) from traffic that is not critical for the security mission (e.g., video, payload data).

The Interface Manager can migrate towards a Software-Defined Networking (SDN) paradigm [15], where the selection of links will be decided automatically from an SDN Controller (that can be located in the GCS, the UAV, or an external domain). Similarly, this SDN controller should monitor the current state of each link and decide which alternative to use. However, each UAV should have some autonomy for decision-making to avoid accidents in case of loss of connectivity.

Finally, all these developments must be tested in real flight campaigns tests to demonstrate their feasibility and functionality before carrying out the use cases proposed in the Labyrinth project.

VI. Conclusions

This article presents some of the main objectives of the European Labyrinth project focusing on the communication architecture. This paper introduces the different domains required to carry out a UAV mission under the parameters established by the U-space UTM. In addition, it presents the communication architecture details.

With all these considerations in mind, initial validation is performed in a laboratory environment at the Instituto Nacional de Técnica Aeroespacial (INTA), where a proposed communication prototype connects the UAV with the GCS using different links (e.g., public network, WiFi, and radio) sending real telemetry data. The results prove that the proposed prototype operates correctly and serves as a starting point to reach the final development where all the architecture requirements will be accomplished.

References

[1] V. Alarcón, M. García, F. Alarcón, A. Viguria, Á. Martínez, D. Janisch, J. J. Acevedo, I. Maza, and A. Ollero, "Procedures for the integration of drones into the airspace based on u-space services," *Aerospace*, vol. 7, no. 9, p. 128, 2020.

[2] C. Barrado, M. Boyero, L. Brucculeri, G. Ferrara, A. Hately, P. Hullah, D. Martin-Marrero, E. Pastor, A. P. Rushton, and A. Volkert, "U-space concept of operations: A key enabler for opening airspace to emerging low-altitude operations," *Aerospace*, vol. 7, no. 3, p. 24, 2020.

[3] P. Kopardekar, J. Rios, T. Prevot, M. Johnson, J. Jung, and J. E. Robinson, "Unmanned aircraft system traffic management (utm) concept of operations," in *16th AIAA Aviation Technology, Integration, and Operations Conference*. AIAA, 2016, pp. 1–16.

[4] T. Bolić and P. Ravenhill, "Sesar: The past, present, and future of european air traffic management research," *Engineering*, vol. 7, no. 4, pp. 448–451, 2021.

[5] M. Huttunen, "The u-space concept," *Air and Space Law*, vol. 44, no. 1, 2019.

[6] "Ensuring drone traffic control and safety." [Online]. Available: http://labyrinth2020.eu/

[7] B. López, J. Muñoz, F. Quevedo, C. A. Monje, S. Garrido, and L. E. Moreno, "Path planning and collision risk management strategy for multi-uav systems in 3d environments," *Sensors*, vol. 21, no. 13, p. 4414, 2021.

[8] "5tonic: An open research and innovation laboratory focusing on 5g technologies." [Online]. Available: https://www.5tonic.org/

[9] V. Sanchez-Aguero, L. F. Gonzalez, F. Valera, I. Vidal, and R. A. López da Silva, "Cellular and virtualization technologies for uavs: An experimental perspective," *Sensors*, vol. 21, no. 9, p. 3093, 2021.

[10] "Instituto nacional de técnica aeroespacial." [Online]. Available: https://www.inta.es/

[11] V. Sanchez-Aguero, F. Valera, B. Nogales, L. F. Gonzalez, and I. Vidal, "Venue: Virtualized environment for multi-uav network emulation," *IEEE Access*, vol. 7, pp. 154 659–154 671, 2019.

[12] M. Mahalingam, D. Dutt, K. Duda, P. Agarwal, L. Kreeger, T. Sridhar, M. Bursell, and C. Wright, "Virtual eXtensible Local Area Network (VXLAN): A Framework for Overlaying Virtualized Layer 2 Networks over Layer 3 Networks," RFC 7348, Aug. 2014. [Online]. Available: https://rfc-editor.org/rfc/rfc7348.txt

[13] B. Nogales, V. Sanchez-Aguero, I. Vidal, and F. Valera, "Adaptable and automated small uav deployments via virtualization," *Sensors*, vol. 18, no. 12, p. 4116, 2018.

[14] "Ciar: Centro de investigación aeroportada de rozas." [Online]. Available: https://www.inta.es/CIAR/es/

[15] E. Haleplidis, K. Pentikousis, S. Denazis, J. H. Salim, D. Meyer, and O. Koufopavlou, "Software-Defined Networking (SDN): Layers and Architecture Terminology," RFC 7426, Jan. 2015. [Online]. Available: https://rfc-editor.org/rfc/rfc7426.txt