UAVs Traffic Control based on Multi-Access Edge Computing

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***Abstract*—Given the continuously increasing use of Unmanned Aerial Vehicles (UAVs) in different domains, their management in the uncontrolled airspace has become a necessity. This has given rise to new systems called UAVs Traffic Management (UTM) systems. Nevertheless, currently, there is a lack of communication infrastructures that can support the requirements of UTM systems. Luckily, the envisioned 5G mobile network has introduced the concept of Multi-access Edge Computing (MEC) in its architecture to support mission-critical applications by decreasing the end-to-end latency and the unreliability of communication. In this paper, we evaluate the impact of the network latency and reliability on the control of UAVs' flights. The obtained results show that a UAV can deviate from its intended path with more than $5m$ if the network latency exceeds $400ms$ and with more than $2m$ if the packet loss probability exceeds 0.2. To overcome these limitations, we have leveraged MEC to provide a new UTM framework that enables an efficient traffic management. Moreover, due to MEC resource-limited nature and in order to give an insight about the resource provisioning, we have evaluated the scalability of the proposed solution in terms of the number of UAVs that can be handled without affecting the efficiency of the proposed UTM framework.**

I. Introduction

Unmanned Aerial Vehicles (UAVs), commonly known as drones, are one of the emerging technologies that attract a lot of industrial and academic interests. The UAVs market has been valued at $18 billion in 2017 and is expected to reach $52 billion by 2025 [1] given their endless applications in numerous domains, such as military reconnaissance, inspection of infrastructures, smart agriculture, traffic management, border surveillance and cargo delivery [2], [3].

Despite the several benefits and practical applications of UAVs, several challenges are yet to be addressed before the final integration of these UAVs in our everyday lives. Indeed, today's commercialized Unmanned Aerial Systems (UASs) are qualified to be semi-autonomous as the intervention of a human pilot equipped with a Ground Control Station (GCS) within a Visual-Line-of-Sight (VLOS) to the UAVs is required for either programming a predefined mission or controlling the UAVs in a real-time fashion, which hinders the full exploitation of UAVs' potential.

From another side, human-controlled UAVs may cause several security and privacy issues. According to the Federal Aviation Administration (FAA) [4], more than 100 reports are received each month signaling the sighting of UAVs by pilots of commercial aircrafts. This is mainly due to the fact that each UAV is operated manually and individually without taking into consideration the state of air traffic and the geofences. Furthermore, keeping a UAV within a VLOS to the human-pilot, during missions in challenging environments, presents high risks in the context of safety. For these reasons, the introduction of a system that can ensure efficient, intelligent, secure and reliable control of UAVs Beyond the Visual Line-of-sight (BVLOS) is mandatory. In this context, the existing Air Traffic Management (ATM) systems rely on voice communication between air traffic controllers and pilots, and not designed to handle the expected high density of UAVs traffic [5]. This has given rise to new systems called UAV Traffic Management (UTM) systems. Several UTM projects are being developed [6], but the most advanced and mature one is the UTM system proposed by the National Aeronautics and Space Administration (NASA) in collaboration with the FAA [7].

The main functionalities that a standard UTM must offer are the identification, the localization and the steering of UAVs, which means that direct communication between the UTM and the UAVs is required. This communication is qualified to be an Ultra-Reliable and Low-Latency Communication (URLLC), as the loss or the lateness of a packet may cause several damages. Cellular mobile networks are well placed to support the communication between the UTM services and UAVs. Indeed, mobile networks can ensure a scalable, secure and ready-for-use connectivity to UAVs using a licensed spectrum. Moreover, cellular-connected UAVs are considered as an Aerial User Equipment (AUE) that can benefit from all services provided by the mobile operators to conventional User Equipment (UE), such as localization, identification, and secure communication. These services can be harnessed by the UTM.

In spite of the advantages that current mobile networks offer, their performances dramatically drop when used to serve AUE with URLLC. For instance, the work in [8] presents the challenges that face the integration of UAVs in the LTE mobile network. Fortunately, the envisioned 5G system had introduced a set of new paradigms that would be of benefit to cellular-connected UAVs.

Multi-access Edge Computing (MEC) is one of the most exciting paradigms in the era of 5G and Internet-of-Things (IoT). Leveraging MEC technology, cloud-like services are pushed to the network edges (e.g., base stations) [9], [10]. This will reduce the latency and increase the reliability of the communication between the applications running on the connected devices (e.g., UAVs and IoT devices) and the remote services hosted at the edge network. As a result, MEC is well placed to host the UTM services.

The primary contributions of this paper are two-fold. First, we investigate the effects of the latency and the reliability of the communication between the UTM services and the UAVs on the management of the air traffic. Second, we propose a high-level architecture for a MEC-based UTM inspired by the NASA's UTM architecture, followed by its evaluation using a real MEC server in order to give an insight about resources provisioning for such services.

The remainder of this paper is organized as follows. Section II discusses some related research work. Section III investigates the communication requirements in terms of latency and packet loss for an efficient UAVs' air traffic management. An overview of the proposed architecture, along with its main components, is presented in Section IV. Section V illustrates the experimental setup and discusses the obtained results. Finally, Section VI concludes the paper.

II. Related work

A lot of research work has been conducted to investigate how the current and the next generations of mobile networks can be harnessed to provide an efficient backend for the autonomous systems in general, and for UAVs in particular. Sasaki et al. [11] have proposed a vehicle control system coordinated between cloud and MEC. The presented work investigates the effect of the latency on the stability of the driving trajectory by applying two control methods. In the first method, the vehicle controller is hosted in the cloud far away from the vehicle, whereas in the second method the vehicle controller is hosted in a MEC node at the edge of the network. The obtained results show that the vehicle has higher stability when controlled from a MEC node.

The work presented in [12] discussed another layered vehicle control system, coordinated between multiple edge servers to overcome the limitations induced by the resource-restricted nature of MEC nodes. In [13], a cloud-based MEC offloading framework in vehicular networks is proposed to minimize the total cost of the offloading process. Aissioui et al. [14] discuss the use of the Follow Me edge-Cloud (FMeC) concept to enable the migration of vehicular services among the edge nodes, in a way that the services follow the mobile vehicles. The idea of offloading heavy computation from UAVs to a MEC node, discussed in [15], shows the benefits of MEC in terms of energy saving and response time improvement. Furthermore, a 5G-based framework for preventive maintenance of critical infrastructure using UAVs is proposed in [16]. This framework takes advantages of the envisioned 5G network architecture to introduce an extended version of MEC that can support the real-time control of UAVs, as well as the processing and the analysis of their collected data. The research work, presented in [17] and [18], addressed the optimization of UAVs' flight trajectory for an efficient computation offloading at the edge of multiple cells. Moreover, UAVs' control and tasks offloading require a reliable connection to the mobile network. For this matter, Motlagh et al. [19] propose an efficient connection steering mechanism between mobile networks for reliable UAV-based communication. Work in [20] discusses the mitigation of the interferences created by cellular connected UAVs by adjusting the transmission power. 3GPP in [8] presents an advanced study of the performance of Release-14 LTE networks when used to serve UAVs, and identify the possible performance-enhancing solutions.

III. UAV Traffic Management: Communication Perspective

The management of UAVs' traffic is mainly based on the dynamic definition of aerial geo-fences to specify the allowed and the restricted flight zones. For this matter, the UTM controls the flight plan of each UAV to ensure that it is flying inside an allowed geo-fence. However, the restriction of the airspace may influence the services provided by the UAV. e.g., a UAV that is charged to collect data from a specific region cannot perform its mission if this region is situated inside a restricted geo-fence. Therefore, the UTM must capitalize on the allowed airspace; so it must be able to efficiently control the UAVs even in the borders of the allowed geo-fence and without crossing the borders. In order to achieve such level of control, an acceptable Quality-of-Service (QoS) in terms of latency and packet loss is required for the communications between the UTM and the UAVs. In this section, we investigate the impact of the latency and the packet loss on the remote control of the UAVs' flights.

A. Methodology of experimentation

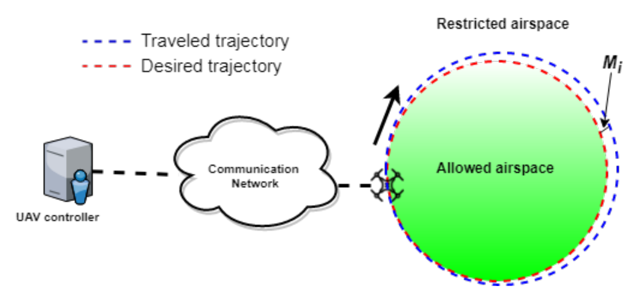


Fig. 1: Experimentation methodology.

In order to investigate the effect of latency and packet loss on the efficiency of UAVs' control, we consider the most challenging case of control. As illustrated in Fig. 1, a UAV must fly on the border of an allowed geo-fence, then the stability of the flight is evaluated by measuring two parameters:

- The deviation ratio D_r: This parameter represents the percentage of the distance traveled outside the allowed geo-fence, which can be calculated using the following equation:

$$D_r = \frac{O_D \times 100}{T_D}$$

where O_D is the distance traveled outside the allowed geo-fence and T_D is the total traveled distance.

- The average of crossing distances C_{avg}: This parameter represents the average of the distances by which the UAV has crossed the allowed geo-fence. To calculate this parameter, periodical measurements of the distance that separates the UAV from the borders of the allowed geo-fence are performed. Then C_{avg} is calculated using the following equation:

$$C_{avg} = \frac{\sum_{i=1}^{Nb_m} M_i}{Nb_m}$$

where M_i are the measured values and Nb_m is the number of the performed measurements.

B. Experimentation setup

To evaluate the previous parameters, we emulate the remote steering of UAVs using the Software-In-the-Loop (SITL) emulator that allows running the open-source UAVs' autopilot ArduCopter in a normal PC without any dedicated hardware and with the same behavior of a real UAV. The experimentation setup consists of a UAV Controller (UC) developed using the Python drone-kit API which is an implementation of the MAVLink protocol [21], used for the communication with drones, and a SITL-emulated UAV. The communication traffic between the UC and the emulated UAV pass through a network emulator to simulate the communication latency and packet loss. we have used three virtual machines (VMs) deployed on top of our cloud network that uses Openstack as virtual infrastructure manager (VIM). While the first VM is used as a UAV controller, the second VM plays the role of the network emulator, whereby we can enforce some rules to change the network delay and reliability. Meanwhile, the third VM runs SITL emulator for mimicking the UAV's behavior.

The UC defines a circular geo-fence with a radius of $200m$ and drives the simulated UAV through its borders at a speed of $10m/s$ during a period of $300s$. The developed UC functions with a frequency of $100Hz$, which means that it checks the state of the UAV (i.e., position and velocity) each $10ms$ and sends commands accordingly to correct any possible deviation.

The measurements required to calculate the C_{avg} parameter are performed by the UC itself, whereas the post-processing of the UAVs' data-flash logs, using the Mission Planner software, allows us to reproduce the flight trajectory of the UAV in order to compare it with the borders of the geo-fence and calculate the evaluation parameter D_r using Google Earth software.

C. Results discussion

1) Effect of latency: Fig. 2a illustrates the trajectory traveled by the UAV (the yellow circle) versus the desired trajectory (the red circle) in the presence of high latency. The first observation that can be drawn from the figure is that the latency has a negative impact on the control of the UAV flight. Indeed, the UAV has crossed the borders of the allowed geo-fence in almost all the flight trajectory. Fig. 2c shows that the deviation ratio D_r increases considerably from 50% to 89% when we vary the latency from $0ms$ to $400ms$. Moreover, as depicted in Fig. 2b, the average of crossing distances C_{avg} increases proportionally with the increase of the latency, which means that a high latency will cause the crossing of borders with higher distances.

2) Effect of packet loss: Fig. 3c and Fig. 3b, respectively, show that the deviation ratio D_r and the average of crossing distances C_{avg} increase gradually when we vary the packet loss percentage from 0% to 20%. It should be noted that it is not possible to establish any connection between the UC and the UAV when the packet loss ratio is higher than 20%. From the obtained results of Fig. 3, we have noticed that the impact of packet loss on the flight trajectory is less than the impact of the latency. This is due to the fact that the UC functions with a relatively high frequency (i.e., $100Hz$), so it is able to correct any deviation caused by the loss of a control packet within a time interval of $10ms$. Nevertheless, the UC is ineffective when facing consecutive losses of packet. As a result, peaks of deviation are observed on the flight trajectory of the UAV (points A and B in Fig. 3a).

In these experiments, we measured the exact averages of crossing distances and the deviation ratios for different values of network latency and packet loss. This would help to choose the placement of the remote UAV controller according to the tolerated deviation.

IV. MEC-BASED UAVS' TRAFFIC MANAGEMENT FRAMEWORK

Based on the aforementioned results, the latency and packet loss have a dramatical impact on the control of the UAVs' flights. For this reason, in this section, we propose a new framework that leverages MEC for ensuring that the UAVs stay within their defined geo-fences as much as possible. In fact, the use of MEC for the management of UAVs' traffic would alleviate the problems caused by the poor quality of communication. Indeed, many issues known in legacy networks, such as congestion and packet loss, are eliminated when the UAVs are controlled from edge-hosted services.

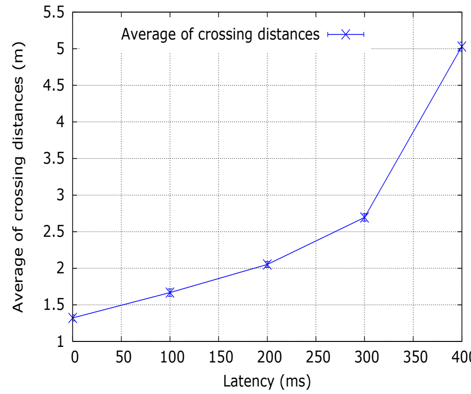
As shown in Fig. 4 the architecture of the proposed framework can be divided into three parts.

A. Cloud domain

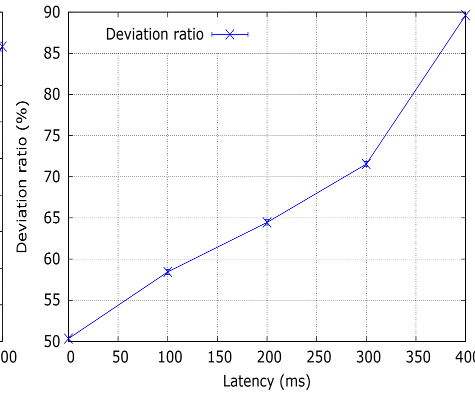
The cloud domain hosts all the management services. Here, three principal services can be identified:

- **UAVs Traffic Management Service (UTMS):** The UTMS has all the information regarding the air traffic, namely registered UAVs, UAVs' locations, UAVs' flight plan and airspace restrictions. Also, this service is responsible for defining static and dynamic geo-fences.
- **Supplementary Data Provider Service (SDPS):** This service provides additional information that may be useful for planning the UAVs' flights, such as weather forecasts and locations of interest (e.g., accidents and disasters locations, service requester' s location).

(a) Desired (red) vs Traveled (yellow) trajectory in presence of high latency.



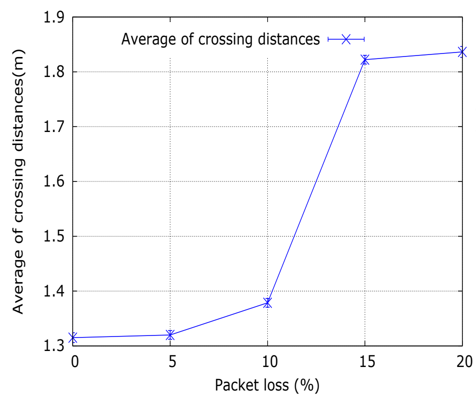
(b) Average of crossing distances.



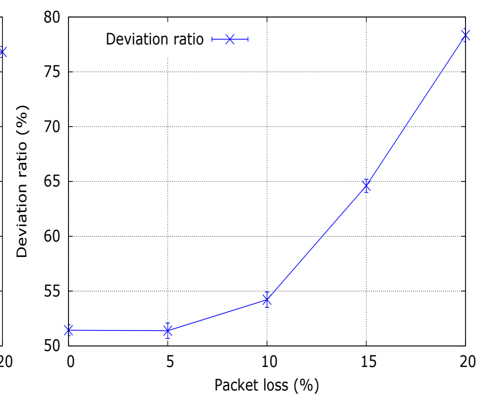
(c) Deviation ratio.

Fig. 2: Effect of latency.

(a) Desired (red) vs Traveled (yellow) trajectory in presence of Packet loss.



(b) Average of crossing distances.



(c) Deviation ratio.

Fig. 3: Effect of Packet loss.

- **Operator Command and Control Service (OCCS):** The OCCS provides an interface for the remote operators to monitor and interact with UAVs in real time when

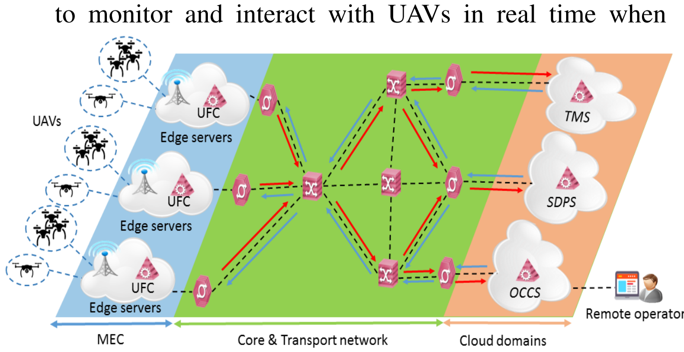


Fig. 4: Architecture of the proposed framework.

B. Core and transport network

The core and transport networks ensure the transmission of communication traffic between MEC-hosted services and the previous Cloud-hosted services. Given that this communication belongs to URLLC, the generated traffic must be treated with a high QoS. In this context, Software-defined Networking (SDN) is one of the emerging technologies introduced in the architecture of the next generation mobile networks [22] to ensure a flexible QoS provisioning [23], [24]. In our proposed framework, the core and transport networks are considered to be SDN-enabled networks.

C. Mobile Edge Computing

In our proposed framework, MEC nodes are used to host the UAVs Flight Controller service **(UFC)**. The UFC service is responsible for the monitoring and the control of the on-going flights of the set of UAVs connected to the access point associated with the MEC node. Indeed, the UFC collects information (i.e., geo-fences, weather forecasts, and locations of interest) and commands from cloud-hosted services, and accordingly adapts UAVs' flights. For example, when receiving a new geo-fence event from the UTMS, the UFC will enforce all the connected UAVs to respect this new geo-fence. Furthermore, the UFC service forwards the telemetry data streamed from the UAVs to the UTMS service. Thanks to the deployment of **UFC** at the edge of the network, the communication latency should be close to zero, which is the best possible case.

V. Evaluation

Despite the advantages of using MEC for the next generation of mobile applications, the resource-limited nature of the edge servers imposes several constraints. Indeed, it is not possible to install powerful servers and data-centers on all network edge. Therefore, an optimal resource provisioning is required before the final exploitation of the edge services. In this section, we investigate the computational and network resources required by the framework proposed in Section IV. For this matter, we have considered the same experimental setup and scenario discussed in Section III, and we improve the UAV controller to meet the specification of the UFC service, so it would be able to control multiple UAVs at the same time by the creation of multiple control agents (CAs). Furthermore, the UFC service is running in a real MEC server (i.e., Intel Fog Reference Design as depicted in Fig. 5) [1],

instead of running in a virtual server hosted in the cloud. Also, as this experiment mimics the real case of MEC-controlled UAV, the communication latency and the packet loss are considered to be nil. Table. I summarizes the different parameters of our experiment testbed.

Fig. 5: The Edge server used in our testbed.

TABLE I: Experimentation parameters.

Parameter	Description	Values
CPU cores	The number of physical CPU cores in the edge server.	4
RAM	Available RAM in the edge server.	32 GB
Throughput	Available throughput for the communication between the edge server and the UAVs.	100 Mbps
UAVs number	The number of UAVs connected to edge.	20, 40, 60, 80, 100
Speed	The speed of the UAVs	10 m/s
Duration	The duration of the flights and the simulations.	300 s
Radius	The radius of the allowed geo-fence.	200 m

[1] The Fog Reference Design is not a product sold by Intel, and is instead a reference design offered to select industry leaders to enable quick Edge product development.

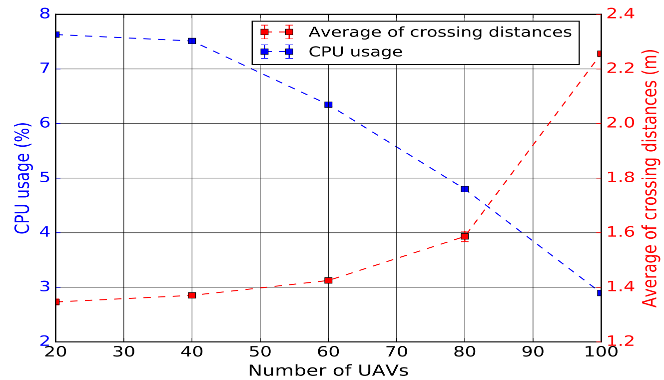


Fig. 6: CPU usage VS average of crossing distances.

Fig. 6 shows the CPU percentage allocated to a control agent (CA) versus the average of the C_{avg} values of the set of UAVs connected to the edge server. The first observation that can be drawn from this figure is that the allocated CPU percentage for each CA decreases from 7.7% to 2.9% when we vary the number of UAVs from 20 to 100. This is mainly due to the fact that the CPU time is fairly shared among the increased number of CAs. The decrease of CPU percentage allocated to the CAs is accompanied by an increase of the average of crossing distances from $1.36m$ to $2.24m$, which means that the flight stability is highly impacted by the computational resources allocated to the CA. It should be noted that a CA requires at most 8% of CPU usage. As a result, the resource provisioning at the edge must aim to keep this value constant regardless the number of connected UAVs.

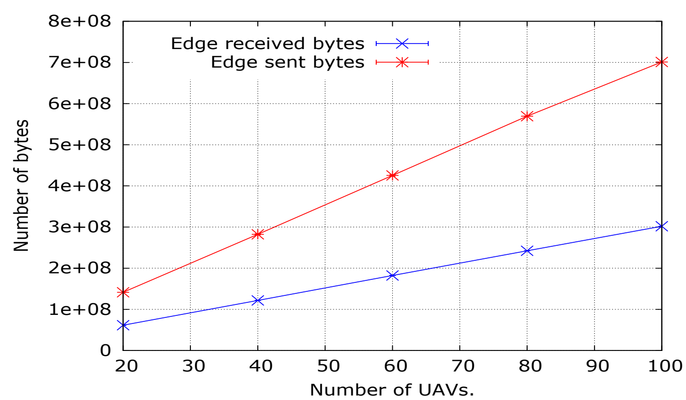


Fig. 7: Exchanged traffic.

Fig. 7 illustrates the evolution of the traffic exchanged between the edge server and the connected UAVs as a function of the number of UAVs. We notice that the amounts of received and sent bytes increase linearly along with the increase of the number of connected UAVs. The extracted slopes are $\alpha_r = 3028437$ and $\alpha_s = 7152453$ for received and sent bytes, respectively. As a result, each UAV has generated around $3028Kb$ of traffic during the experiment time ($300s$), which corresponds to a rate of $10Kbps$, and has received around

$7152Kb$ of traffic, which corresponds to a rate of $24Kbps$. In light of these results, the network provisioning must aim to ensure at least the previous communication throughputs in both the wireless and wired networks connecting to the MEC nodes.

VI. Conclusion

Along with the ever-increasing number of UAVs, the on-site control of UAVs, by pilots within VLoS, is becoming all but impossible. In this vein, UAVs Traffic Management (UTM) systems are gaining lots of momentum. However, UTM systems can be affected by different parameters, such as the network state and weather conditions. In this paper, we have studied the impact of the network parameters, in terms of communication latency and reliability, on the efficiency of the UTM systems. We have shown that the control of UAVs is negatively impacted by the increase of the latency and packet loss rate. To overcome these limitations, we have proposed a new UTM framework that enhances the existing approaches by leveraging MEC technology. In fact, in the proposed framework, the UAVs Flight Controller (UFC) service has been placed at the edge near to the UAVs to ensure highly reliable and low latency communication. Moreover, in this paper, we have evaluated the scalability of the proposed framework by varying the number of UAVs connected to the MEC and measuring the computational and network resources consumed during the management process. The obtained results give an insight about the required resource provisioning at the edge of the network in order to ensure an efficient UAVs' traffic management.

Whilst the performance evaluation was conducted using one single UAV and one single Edge node, as future research work, we intend using more realistic scenarios involving multiple UAVs flying over a wide region served by multiple edge nodes and that is leveraging our Mobile Service Usage Cartography tool. We also plan devising and evaluating different algorithms for the placement of UFC services across these edge nodes as per the mobility features of UAVs [25].

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References

[1] (2018, February) Unmanned aerial vehicle (uav) market by system uav platforms, uav payloads - 2025 - marketsandmarkets. Market and Market. [Online]. Available: https://www.marketsandmarkets.com/Market-Reports/unmanned-aerial-vehicles-uav-market-662.html

[2] N. H. Motlagh, T. Taleb, and O. Arouk, "Low-altitude unmanned aerial vehicles-based internet of things services: Comprehensive survey and future perspectives," *IEEE Internet of Things Journal*, vol. 3, no. 6, pp. 899–922, Dec 2016.

[3] S. Ouahouah, T. Taleb, J. Song, and C. Benzaid, "Efficient offloading mechanism for uavs-based value added services," in *2017 IEEE International Conference on Communications (ICC)*, May 2017, pp. 1–6.

[4] (2017, December) Uas sightings report. Federal Aviation Administration. [Online]. Available: https://www.faa.gov/uas/resources/uas_sightings_report/

[5] (2018, February) Mobile-enabled unmanned aircraft. GSMA. [Online]. Available: https://www.gsma.com/iot/mobile-enabled-unmanned-aircraft/

[6] H. Hellaoui, O. Bekkouche, M. Bagaa, and T. Taleb, "Aerial control system for spectrum efficiency in uav to cellular communications," *To appear in IEEE Communications Magazine*.

[7] (2018, April) Nasa utm :documents. National Aeronautics and Space Administration. [Online]. Available: https://utm.arc.nasa.gov/documents.shtml

[8] *Study on Enhanced LTE Support for Aerial Vehicles*, 3GPP TR 36.777 V1.0.0, 2017.

[9] T. Taleb, K. Samdanis, B. Mada, H. Flinck, S. Dutta, and D. Sabella, "On multi-access edge computing: A survey of the emerging 5g network edge cloud architecture and orchestration," *IEEE Communications Surveys Tutorials*, vol. 19, no. 3, pp. 1657–1681, thirdquarter 2017.

[10] P. Porambage, J. Okwuibe, M. Ylianttila, and T. Taleb, "Survey on multi-access edge computing for internet of things realization," *To appear in IEEE Communications Surveys Tutorials*.

[11] K. Sasaki, N. Suzuki, S. Makido, and A. Nakao, "Vehicle control system coordinated between cloud and mobile edge computing," in *2016 55th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE)*, Sept 2016, pp. 1122–1127.

[12] ——, "Layered vehicle control system coordinated between multiple edge servers," in *2017 IEEE Conference on Network Softwarization (NetSoft)*, July 2017, pp. 1–5.

[13] K. Zhang, Y. Mao, S. Leng, Y. He, and Y. ZHANG, "Mobile-edge computing for vehicular networks: A promising network paradigm with predictive off-loading," *IEEE Vehicular Technology Magazine*, vol. 12, no. 2, pp. 36–44, June 2017.

[14] A. Aissioui, A. Ksentini, A. Gueroui, and T. Taleb, "On enabling 5g automotive systems using follow me edge-cloud concept," *IEEE Transactions on Vehicular Technology*, vol. PP, no. 99, pp. 1–1, 2018.

[15] N. H. Motlagh, M. Bagaa, and T. Taleb, "Uav-based iot platform: A crowd surveillance use case," *IEEE Communications Magazine*, vol. 55, no. 2, pp. 128–134, February 2017.

[16] T. Zahariadis, A. Voulkidis, P. Karkazis, and P. Trakadas, "Preventive maintenance of critical infrastructures using 5g networks drones," in *2017 14th IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS)*, Aug 2017, pp. 1–4.

[17] X. Cao, J. Xu, and R. Zhang, "Mobile Edge Computing for Cellular-Connected UAV: Computation Offloading and Trajectory Optimization," *ArXiv e-prints*, Mar. 2018.

[18] F. Cheng, S. Zhang, Z. Li, Y. Chen, N. Zhao, R. Yu, and V. C. M. Leung, "Uav trajectory optimization for data offloading at the edge of multiple cells," *IEEE Transactions on Vehicular Technology*, vol. PP, no. 99, pp. 1–1, 2018.

[19] N. H. Motlagh, M. Bagaa, T. Taleb, and J. Song, "Connection steering mechanism between mobile networks for reliable uav's iot platform," in *2017 IEEE International Conference on Communications (ICC)*, May 2017, pp. 1–6.

[20] H. Hellaoui, A. Chelli, M. Bagaa, and T. Taleb, "Towards mitigating the impact of uavs on cellular communications," in *GLOBECOM 2018 - 2018 IEEE Global Communications Conference*, Dec 2018, pp. 1–6.

[21] (2018, March) Mavlink micro air vehicle communication protocol. Dronecode. [Online]. Available: https://mavlink.io/en/

[22] P. K. Agyapong, M. Iwamura, D. Staehle, W. Kiess, and A. Benjebbour, "Design considerations for a 5g network architecture," *IEEE Communications Magazine*, vol. 52, no. 11, pp. 65–75, Nov 2014.

[23] D. L. C. Dutra, M. Bagaa, T. Taleb, and K. Samdanis, "Ensuring end-to-end qos based on multi-paths routing using sdn technology," in *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, Dec 2017, pp. 1–6.

[24] I. Farris, T. Taleb, Y. Khettab, and J. S. Song, "A survey on emerging sdn and nfv security mechanisms for iot systems," *To appear in IEEE Communications Surveys and Tutorials*.

[25] A. Laghrissi, T. Taleb, M. Bagaa, and H. Flinck, "Towards edge slicing: Vnf placement algorithms for a dynamic and realistic edge cloud environment," in *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, Dec 2017, pp. 1–6.