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Published in:
IEEE Communications Magazine

DOI:
10.1109/MCOM.2018.1800078

Published: 01/10/2018

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Hellaoui, H., Bekkouche, O., Bagaa, M., & Taleb, T. (2018). Aerial Control System for Spectrum Efficiency in UAV-to-Cellular Communications. *IEEE Communications Magazine*, *56*(10), 108-113. Article 8493128. https://doi.org/10.1109/MCOM.2018.1800078

Aerial Control System for Spectrum Efficiency in UAV to Cellular Communications

Hamed Hellaoui, Oussama Bekkouche, Miloud Bagaa, and Tarik Taleb

Abstract— **The next generation of mobile systems, 5G, will be the communication standard that accommodates the proliferation of the Internet of Things (IoT). Unmanned Aerial Vehicles (UAVs) are envisioned to support many applications in providing 5G connectivity to the IoT, by extending high speed connectivity from the sky to objects on the ground, or even by carrying on board some IoT devices. However, given their critical nature, the management of UAVs induces high exchange of control messages with the Ground Control Station (GCS), resulting in a crowded spectrum used by the cellular networks. The authors raise the problem of degrading the network spectrum with UAVs' management messages, and discuss the need for an efficient orchestration system. In this paper, they propose a novel scheme, dubbed Aerial Control System (ACS), which is based on separating the data plane from the control plane of UAVs, and pushing the latter to be performed in the air by UAVs. The solution provides an orchestration logic that takes advantage of the autonomous nature of UAVs to organize UAVs in one or several clusters. UAV-to-UAV communication (U2U) enables spectrum reuse and avoids crowding the network with management messages, while dedicating more 5G spectrum for ensuring more bandwidth to the IoT through UAV-to-Infrastructure communication (U2I).**

I. INTRODUCTION

Amongst most technologies affecting human beings in the 21^{st} century, the Internet of Things (IoT) would be the most important one. Smart grids, smart cities, and environment monitoring are some noticeable IoT applications, just to name a few. The IoT evolution is expected to be even greater in the near future, with more than 20 billion connected devices by 2020. In this context, as the current communication networks are about reaching their limits, the upcoming generation of mobile systems, 5G, will be the de-facto communication standard to support a large number of diverse connectable devices. It goes beyond the capabilities of the current Long Term Evolution (LTE), providing higher data rates, zero delay, and high throughput. Spectrum efficiency is an important feature and requirement of 5G. The usage of millimeter waves, whose frequency spectrum is from 30 to 300 GHz, has been proposed for data transmission. This would enable the extra-capacity foreseen by 5G and accommodate the proliferation of the IoT.

The usage of Unmanned Aerial Vehicles (UAVs, alternatively known as drones) for providing high-speed wireless communications is expected to play a very important role in 5G [1]. When equipped with the dedicated radio access technologies, UAVs can be used to extend network connectivity from the sky to ground devices. Their ability to move to different locations allows redirecting the drones to support a desired area, such as those crowded with IoT devices. UAVs can be also equipped with IoT devices (e.g., sensors and cameras) and deliver IoT services from height. In addition, the usage of UAVs allows unlocking 5G spectrum potentials, by facilitating short-range line-of-sight communications. These factors make UAVs an important enabler for providing 5G connectivity to IoT devices. Compared to terrestrial communications, UAVs would allow rapid deployment, high mobility, and low operating-cost in many situations. This has been translated into several academic and industrial projects that are boosting the development of this approach. Big companies such as Facebook and Google have initiated projects (i.e., Aquila and Skybender, respectively) for providing high speed connectivity using drones.

However, beside UAVs' potential in providing 5G connectivity to IoT infrastructures, their usage presents challenges that affect the spectrum efficiency and impact the network performance. Indeed, the control and the management of UAVs are performed by a terrestrial entity, called Ground Control Station (GCS). The latter aims to ensure the efficient management of the drones as expected by the relevant applications (e.g., tracking and updating the followed paths, forming a swarm of drones, avoiding obstacles and collisions). The critical nature of UAVs necessitates the delivery of control messages at a high frequency. 3rd Generation Partnership Project (3GPP) specifies that an efficient management of a UAV would require 60-100 kbps for control messages [2]. As a consequence, the spectrum benefit, which is supposed to cope with the increasing number of devices, will be shared and utilized for the UAVs' management messages. Considering the important number of UAVs that are expected to be deployed supporting a wide plethora of drone applications, this issue would constitute a major concern that may downgrade the 5G network performance. The communication of UAVs from height will accordingly affect the spectrum of multiple small cells in the ground.

To tackle this issue, this article advocates the need for an efficient orchestration of UAVs in order to enhance the spectrum usage. It proposes separating the data plane from the control plane of UAVs, and pushing the latter to be performed in the air by UAVs. The introduced framework leverages the autonomous nature of drones and self-organized network (SON) to organize them in one or several clusters. A part of the management logic is moved from the GCS to be performed in air by the UAVs, enabling thereby the concept of Aerial Control System (ACS). The UAV-to-

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UAV communication (U2U) avoids crowding the network with management messages and enables spectrum reuse. This allows dedicating more network spectrum for IoT data through UAV-to-Infrastructure communications (U2I).

The remainder of this article is organized in the following fashion. We present the potential of UAVs in providing 5G connectivity to IoT devices in Section II. The problem of decreasing the spectrum efficiency is then discussed along with the proposed ACS concept in Section III. Section IV provides evaluations of the proposed solution. The paper highlights some future research directions and concludes in Sections V and VI, respectively.

II. UAVS' POTENTIAL IN PROVIDING 5G COMMUNICATIONS TO SUPPORT IOT

UAVs have received much attention from both scientific and industrial communities. They have become an integral part of several critical applications, such as disaster management, first aid, and traffic monitoring. More recently, UAVs have demonstrated their potential in providing wireless connectivity to IoT. Indeed, the concept of drone-aided wireless communications has enabled many opportunities in providing wireless connectivity and expanding network coverage [3]. As shown in Figure 1.a, when equipped with the required radio access technologies, UAVs can operate as mobile (flying) base stations (BSs) and provide network connection to the ground devices from height. These vehicles are easy and fast to deploy, more flexible to configure, and offer better communication channels due to the use of short-range line-of-sight links [4]. In addition, the ability to maneuver them provides new opportunities to enhance the network performance by directing UAVs to specific targets. This makes UAVs a very important enabler in providing 5G connectivity. Such applications are particularly interesting to extend network coverage to rural areas or to establish temporary coverage in zones where ground network infrastructure might fail [5]. This has been translated into several projects by different organizations. For instance, Facebook started working on its Aquila drone which is intended to provide Internet access to rural areas. The drone can circle with others in the sky over a specific region to deliver broadband connectivity. The ABSOLUTE project also envisions the implementation of low-altitude aerial networks consisting of LTE-Advanced (LTE-A) base stations on-board of balloons (Helikite platform) to serve ground users [6].

On the other hand, UAVs enable the integration of IoT and 5G in a unique way. As shown in Figure 1.b, drones can also carry on-board some IoT devices. Equipping UAVs with remotely-controllable IoT objects (e.g., sensors and cameras) would allow them to provide IoT services while they are carrying out their original tasks [7], [8]. Consequently, the IoT devices can be triggered to take measurements from the sky on-demand, or when the drone reaches a specific location, at a specific time, or when a specific event occurs. In addition, the ability to fly to different locations can be exploited to redirect the drones to the desired area specified by the users [9]. This enables opportunistic and fast establishment of IoT services over rural areas or in areas where IoT devices are not deployed. This also reinforces the collaboration of providing IoT services, by intelligently orchestrating UAVs and their on-board IoT devices. For instance, UAVs can share the task of measuring humidity and temperature in a big forest (for fire prediction), so imminent incidents can be anticipated and tackled before their occurrence. 5G will be the communication network to assist UAV-based integrative IoT platforms and will provide the required services. Its high data rates will preserve the requested quality of services, such as providing high-resolution videos from drones, while ensuring at the same time the communication of UAVs' contextual information (e.g., state information, geographical location, and energy budget). In addition, the ability of 5G to accommodate a large number of nodes will support the deployments of large swarms of drones. All the above-mentioned points make UAVs an important player for providing wireless connectivity to IoT and enabling diverse IoT services to be provisioned from height.

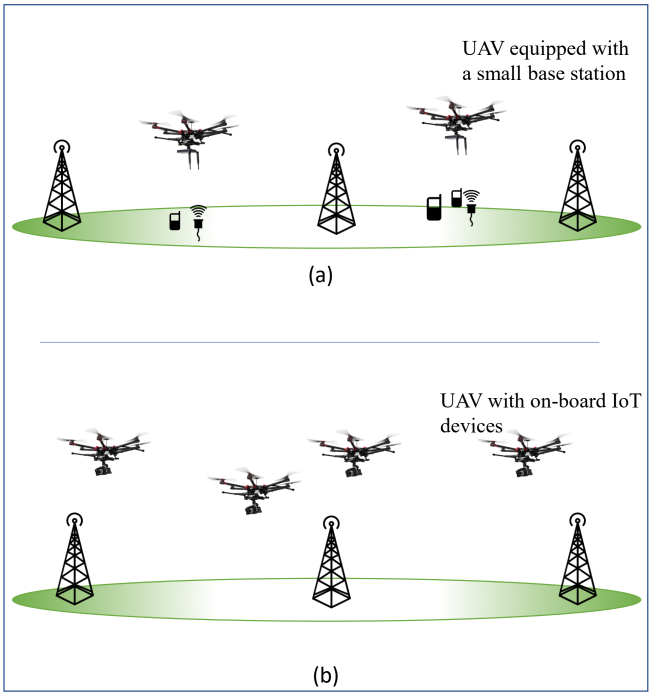


Figure 1: Two typical use cases of UAVs in providing 5G connectivity to support IoT: a) UAV-aided network communications; b) UAV-based integrative IoT.

III. UAV ORCHESTRATION FRAMEWORK

Even though UAVs demonstrate many potentials in providing 5G connectivity to support IoT services, their use raises many challenges that affect the network spectrum. Indeed, the control and the management of UAVs imply constant exchange of control messages with the GCS, so the latter can monitor and direct the drones to meet the expectations of the underlying applications. This includes indicating and updating the path to be followed by each UAV, organizing the drones in swarms, disseminating information among the UAVs to avoid obstacles, etc. The critical nature of UAVs makes such control messages very required and must be sent at a high frequency. As presented in Figure 3.a, each drone communicates with the GCS through UAV-to-Infrastructure (U2I) communication. Consequently, the spectrum may be congested with management messages, leaving therefore less bandwidth for actual data from IoT devices and other user equipments (UEs) on the ground. Real field evaluations performed by 3GPP [2] showed that UAV-based communication through a cellular network decreases considerably the throughput of the connected devices, including UEs on the ground. This is mainly due to the close to free-space propagation that characterizes UAV-BS communication. Compared to terrestrial UEs, drones cause more interferences on non-serving BSs, as shown in Figure 2. Considering the fact that UAVs used in such applications could be deployed in a massive number, this issue constitutes a major concern.

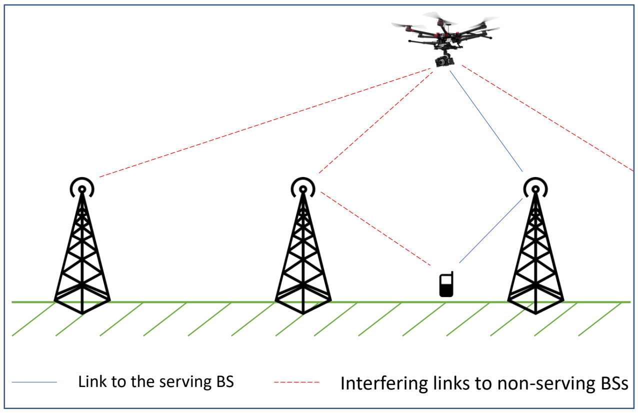


Figure 2: The close to free-space propagation conditions between the UAV and the BSs increases the interference to non-serving BSs.

As the GCS and its management logic are far from the controlled UAVs, making this logic closer to the drones may reduce the overhead. This can be achieved thanks to the use of Multi-Access Edge Computing (MEC) [10]. Indeed, MEC is deemed as a key enabling technology of 5G. It allows overcoming cloud limitations associated with latency and enables applications that require response times in the range of milliseconds. MEC is based on reforming the cloud hierarchy and performing the computation processes nearby end-users. Consequently, the response time is shorter compared to the case of centralized cloud. The MEC principle can be considered for UAV applications by pushing the control and the management logics to the edge servers nearest to the base stations drones are connected to. This would allow the management logic to be closer to UAVs. In addition, the advances in MEC would maintain the expected quality of service (QoS) throughout the drone mobility. Dynamic creation and migration of services can ensure that the computation resources follow the object mobility by being always performed in the nearest edge server. As presented in Figure 3.b, such approach can be seen as Mobile Control System (MCS) whereby the management logic follows the drones' mobility (similar in spirit to the Follow-Me-Cloud or Follow-Me-Edge concepts [11]–[13]). This would reduce the response time for managing the UAVs and decrease crowding the core network with management messages (between the cellular base stations and the GCS).

While moving the orchestration and control logics to the vicinity of UAVs, leveraging MEC, would allow reducing the response time, the issue of degrading the network spectrum remains the same. Even by being closer to UAVs at the edge level, the management of UAVs still requires intense communication with the base stations. It is clear that this approach alleviates the congestion that may occur between the core network and the GCS, but the congestion issue at cellular BSs remains unsolved. To overcome this issue, this paper proposes moving partially or fully the control and the management logics further and performing it in the air by a selective set of UAVs. Indeed, UAVs can be organized in clusters, in a flying ad-hoc networking (FANET) manner. Depending on different factors, such as energy budget or on-board equipments, a UAV can be elected as a cluster head (CH) and that is similar in spirit to diverse research work [14], [15]. The head of the cluster can hold the management logic of its cluster leading therefore to the concept of Aerial Control System (ACS). The management and the control that used to pass through U2I communication can therefore be directed to the CH through UAV-to-UAV (U2U) communication (Figure 3.c). This would save more network spectrum that can be actually used by IoT devices or other user equipments on the ground for data delivery.

The concept of ACS leverages the autonomous nature of UAVs and self-organized network (SON) to enable performing the orchestration by the drones in the air. Indeed, many drones can nowadays operate, partially or completely, in the autopilot mode. This allows UAVs to follow a pre-programmed mission rather than being controlled in real-time from the GCS. The mission specifies all the navigation parameters regarding the flight such as the paths, the altitude, and the velocity. Even if the missions are pre-planned, they can be adjusted during the flights to react to changes related to the application (arrow 1a in Figure 4). This introduced a revolution in UAVs which alleviated heavy tasks for humans. It is clear that without this principle, each flying drone would require total follow-up and command by humans that are standing behind the GCS. The ACS concept takes advantage of the autonomous nature of the drones and moves the management logic to be performed in the air by selective UAVs. Consequently, the CH will be responsible for ensuring the proper application of UAVs' missions established on the ground by the GCS, or even adjusting and re-planning the missions.

A key aspect of the ACS framework is the cluster formation and management. Indeed, the UAVs can be organized in a FANET manner and interconnected through U2U links. The CH can be elected (and re-elected periodically) so

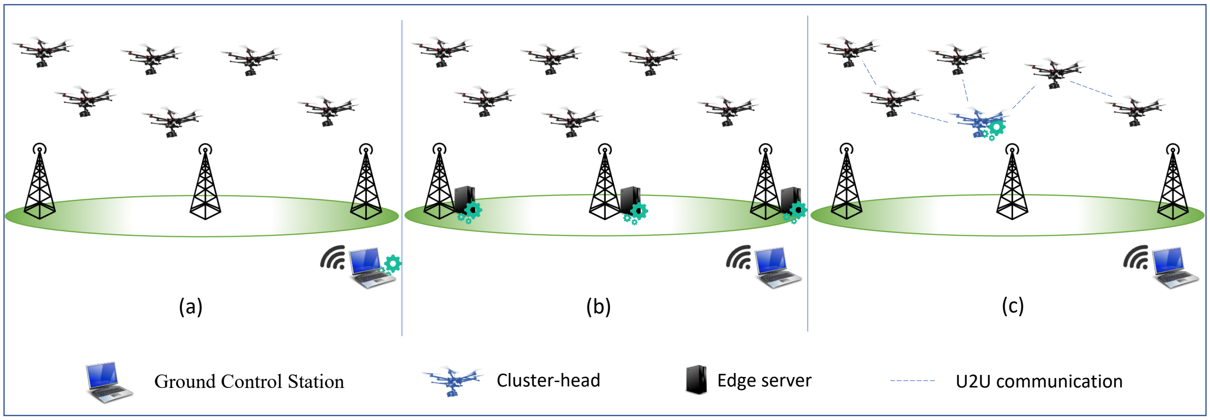


Figure 3: Different levels to perform UAV management; a) at the GCS level; b) at edge level; c) at the UAV level.

to maintain efficient management of the cluster in varying situations. Different criteria could be considered for this purpose, such as optimizing nodes' resources, the number of hops management messages need to pass through, etc. Once the group is formed and the CH is elected, the latter receives the necessary information from the GCS about the members' missions so it can ensure an efficient control, as depicted in Figure 4 through arrows 1b and 2, respectively. The GCS monitors the UAVs only through the CH, reducing therefore crowding the mobile network with control messages of the entire group.

Enabling U2U communication would also allow adding new dimension in providing connectivity to IoT services. Indeed, in addition to communicating IoT data through U2I links, U2U communication can also be used for this purpose. The cluster of UAVs can be seen as a network where each node participates in relaying data to a given destination, that can pursue the transmission through U2I. This would allow responding to different QoS required by the IoT applications. The services offered by the IoT devices (carried or served by the UAV-BS, and depicted by arrow 3 in Figure 4) can differ in terms of the required QoS (e.g., bandwidth and time). By intelligently steering data communication between U2U and U2I, such framework can meet the QoS expected by each application. In addition, this would also enhance the availability of IoT service by relying on many paths for data transport.

IV. PERFORMANCE EVALUATION

In the present section, we show the benefit of the ACS concept in reducing the overhead on the spectrum, comparing it to the baseline approaches that use GCS. Moreover, using the NS3 simulator, we evaluate the impact of the number of UAVs on the control packet rate and the packet loss, which are important parameters for ensuring the proper functionality of UAVs. The performance evaluation is carried using 3D topology and free space propagation model. U2U communication is based on the IEEE 802.11n standard with RTS/CTS disabled.

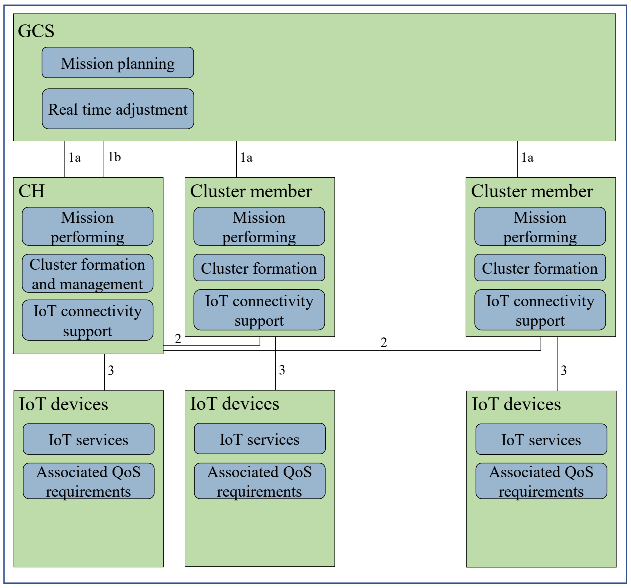
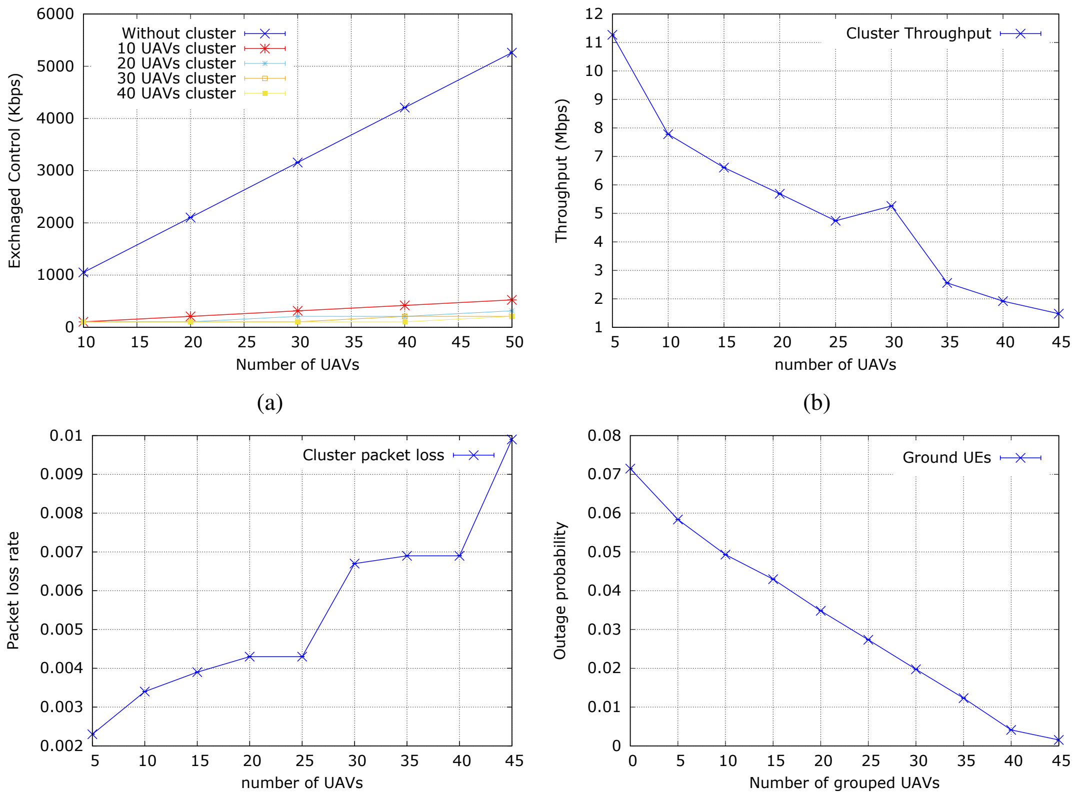


Figure 4: ACS framework architecture.

As shown in Figure 5.a, moving the orchestration logic towards the UAVs reduces considerably the number of control messages exchanged via the cellular network, which has a positive impact on the spectrum frequency. This difference is very important when the number of UAVs is high, which is the case in many applications. In addition, the more UAVs are organized in a cluster, the more the number of control messages that pass through the cellular base station are reduced. This directly affects the spectrum efficiency of the network and enhances the throughput for both IoT devices and UEs on the ground. It is worth noting that the messaging was based on the MAVLink protocol with 50 Hz rate update and 263 Byte packet size.

An evaluation of the impact of the number of UAVs on



(a) (b)

(c) (d)

Figure 5: Performance evaluation of the proposed approach: a) number of exchanged control packets; b) cluster throughput; c) cluster packet loss; d) outage probability for ground UEs.

the packet throughput is conducted in Figure 5.b. As shown in the figure, the packet throughput decreases along with the number of UAVs inside the cluster. Indeed, the more UAVs are grouped in a cluster, the more U2U spectrum is congested. However, the obtained results show that the packet throughput in the proposed approach is within the requirements defined by 3GPP for aerial vehicles connectivity. As mentioned in Table 1, efficient operations would require data rates in the range of 60-100 Kbps. Even in case of a cluster of large size (i.e., 45 UAVs), the proposed approach ensures largely the required throughput (i.e., more than 1 Mbps).

Figure 5.c depicts the impact of the number of UAVs on the packet loss. The first observation that we can draw from the figure is that the number of UAVs in the cluster has a negative impact on packet loss. This is mainly due to the interference that increases along with the number of UAVs and their mobility. From Table 1, an efficient management of UAVs requires a network reliability in the order of 10^{-3} packet loss rate. However, from Figure 5.c, we observe that the packet loss rate exceeds 10^{-3}, which can affect the management of UAVs. It is worth noting that we considered in this evaluation a scenario where each node sends at a high rate (100 Mbps). Reducing the transmission rate would decrease the packet loss to acceptable levels.

Metric	Value
Latency	50ms (one way from eNB to UAV)
Data rate	60-100 kbps
Reliability	Up to 10^{-3} Packet Error Loss Rate

Table 1: C&C requirements for aerial vehicles connectivity [2].

To evaluate the U2I communication, a communication model is implemented considering interferences, path loss and fast fading. The implemented model is based on the path loss proposed by 3GPP [2], while the fast fading follows a Nakagami-2 distribution for line-of-sight links and a Rayleigh distribution for non line-of-sight links. Figure 5.d shows the outage probability for ground UEs, which defines the probability that a UE fails in sending its packets because of the channel capacity. As we can see, grouping UAVs and performing their management in the air lead to decreased outage probability for ground user equipments. This proves that pushing the management logic to the cluster head and reducing the control messages in the U2I links ensure also good communication links for terrestrial UEs in the ground.

V. FUTURE RESEARCH DIRECTIONS

Separating UAVs' data plane from the control plane and pushing the latter to be performed by the UAVs proves to have its benefit on the spectrum usage. The recovered spectrum can be dedicated to IoT communication and enhance providing their services. Many research challenges are associated to the ACS concept. This starts with the organization of the clusters and the election of the associated CHs. Indeed, the more UAVs are grouped in a single cluster, the less control messages are sent through U2I links. However, this may increase the overhead associated to these messages inside the group. Efficient grouping techniques are required to establish a trade-off between U2U and U2I communication overheads associated to control messages. The grouping should also take into account the IoT devices (on-board or served by UAV-BSs), in a way to meet the application requirements (e.g., grouping UAVs with the same on-board IoT devices as their management could be linked). In addition, the CH selection plays a key role in optimizing the network performance and providing efficient IoT services. Different criteria could be considered. As the management of UAVs may require more resources, the CH could be elected to be always the most powerful node in the cluster. This should include the residual level of energy, the UAV processing power, and the UAV storage space. In addition, as the CH constitutes a central point in managing the cluster, its position would affect the number of hops management messages need to pass through. The CH could therefore be elected so to optimize the number of hops and the delay for control messages (e.g., in the middle of the cluster). It is also possible to consider the CH mobility to alleviate U2U communication, such as being near to UAVs requiring more management and exchange of control messages. It could be also elected to be the UAV that ensures direct and stable communication to the cellular base stations. The availability of U2U and U2I links can also be used to steer the communication in a way to meet the QoS required by the applications.

VI. CONCLUSION

UAVs would enable potential new applications in the sphere of IoT. They can be used to extend the communication to IoT devices from the sky, or even carry some IoT objects on-board. In this context, this paper discussed the issue of spectrum degradation due to frequent UAV control and management messages and highlighted the requirements for efficient UAV orchestration. As a remedy, a new concept, dubbed Aerial Control System (ACS), was introduced. It is based on separating the data plane from the control plane of UAVs, and shifting the latter from the ground to the air. UAVs are grouped in clusters; each governed by a cluster head. Management messages are redirected to the cluster head through U2U communication, leaving therefore more wireless resources for the delivery of actual data from IoT devices and other user equipments on the ground.

The performance of the proposed approach was evaluated and interesting results were obtained. It is clear that the cluster formation and the election of adequate CHs are of great importance in providing the expected quality of service. As future work, we plan to study other wireless communication for supporting the UAVs management from sky. Furthermore, we plan to propose efficient mechanisms for UAV clustering and for the election of cluster heads taking into account energy efficiency and U2U link stability, aiming for further spectrum efficiency and QoS guarantee.

ACKNOWLEDGEMENT

This research work was partially funded by the ”AALTO – 5G Meet Industrial Internet” project and by the European Unions Horizon 2020 research and innovation programme under the EU/KR PRIMO-5G project with grant agreement No 815191.

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