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5G Connectivity for Aerial Scenarios: a New Spatial and Temporal Perspective for Wireless Networks

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***Abstract*—The incorporation of unmanned aerial vehicles (UAVs) or drones to the fifth generation of mobile communications systems (5G) is addressed in this paper, remarking challenges and mutual benefits for both technologies. Two configurations of these vehicles are described, on the one hand, operating as on-the-fly base stations, and otherwise, simply as user equipment. As explained, in any case the altitude of these devices provides certain advantages over ground stations, like better propagation conditions, and the difference lies in the capabilities that each configuration has. In contrast, the interference caused by these better propagation conditions and its impact on the system performance is pointed out. We also postulate that the combination of aerial-terrestrial infrastructures forms a new perspective both in time and space, which is derived from the drones' dynamics. Thus, diverse variables are identified through the paper, which are related to the operation of UAV-5G networks. Basically, these variables are latency, interference, effects of altitude, energy consumption, and channel modeling. Among these, a sensitive parameter is the latency, for which some approaches are exposed including the well-known mobile edge computing concept as an alternative to process information in a local manner. Key points are finally highlighted for future implementations.**

Keywords—5G, unmanned aerial vehicles, connectivity

I. Introduction

The ever-increasing proliferation of *unmanned aerial vehicles* (UAVs) or commonly referred as *drones*, around the world, both by the quantity and by the spatial distribution, requires taking into account that these vehicles need to be aware each other (at least in its own peripheral) in real time to use safely the aerial space. Hence, it is evident that these aerial vehicles need a widely deployed communication infrastructure. In this context, it is said that the *Fifth Generation* (5G) is a communications technology well-matched for the drones industry. Alternatively, UAVs can provide a fast and easy option to the traditional terrestrial mobile networks to deploy infrastructure of access. Thus, it is clear that UAVs and terrestrial mobile networks can operate with mutual benefits as is depicted in Fig. 1.

The objective of this paper is to outline those key elements involved in the integration of UAVs to 5G communication mobile networks and how these networks can support drone-based missions. Many topics covered in this paper are taken to illustrate use cases in the context of wireless connectivity. In this concern, it is important to point out that the integration of both technologies generates a new space-time approach to the system, which is derived from the UAV's dynamics. This observation represents our main contribution, so considerations related to spatial or temporal variations introduced by UAVs are underlined through this paper.

Thus, this paper is organized as follows: Section II outlines the service categories of 5G. The incorporation of UAVs into wireless networks is addressed in Section III. Section IV presents different aspects related to the altitude of UAVs. The latency as a function of vertical positioning of UAVs is exposed in Section V. Works on aerial communication channels are summarized in Section VI. Some points regarding the energy consumption of UAVs are pointed out in Section VII. Conclusions are highlighted in Section VIII.

II. 5G Service Categories

There are three service categories that form the essence of 5G as is described by the International Telecommunication Union (ITU) for the term *International Mobile Telecommunications-2020* (IMT-2020) and whose minimum requirements are specified in [1]. These categories are:

- Enhanced Mobile Broadband (eMBB) to achieve both extreme high peak data rate and extreme wide-area coverage.

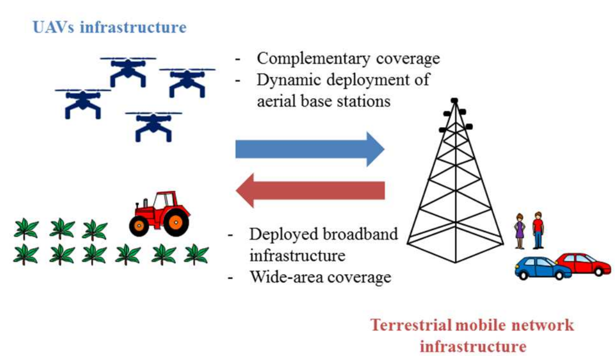

Fig. 1. Mutual benefits between UAVs and terrestrial mobile systems.

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- Massive Machine Type Communications (mMTC) to support a massive number of devices, mainly, oriented to IoT.
- Ultra-Reliable Low-Latency Communications (URLLC) to simultaneously support low-latency and very high reliability transmissions.

From these services, it is worth highlighting that the URLLC is an important requirement for a safe operation of multiple aerial autonomous vehicles using a common space.

III. Incorporation of UAVs to Wireless Networks

The use of UAVs has been considered recently to be integrated to mobile 5G communications [2], which is easier to deploy in a dynamic manner (i.e. where and when it is necessary) and can increase the performance of a heterogeneous network in terms of its coverage and data rate [3-5]. These devices can work in two modalities from which use cases can be considered. On the one hand, as part of the network infrastructure in such a way that they operate as on-the-fly base stations or aerial base stations (BSs). On the other hand, these vehicles can be another mobile device or aerial user equipment (UE) accessing to the 5G mobile network and its new capabilities. The 5G new radio (NR) specifications provide alternatives to facilitate the integration of UAVs into mobile cellular infrastructure [5]. 5G NR considers techniques to manage on-demand radio resources specifically for UAVS. In This concern, there are trade-offs that must be taken into account and are associated to the proportion of aerial and terrestrial UEs deployed in a common service area and its relationship with the potential interface between them.

A. On-the-Fly Base Stations

In essence, several UAVs can be integrated to the 5G mobile network as part of its infrastructure, either as relays or base stations. This option usually provides good propagation conditions because it is more probably that terrestrial users find paths without obstructions. Thus, the 5G range is extended in a vertical scope wider than that of traditional terrestrial base stations (remember that typical configuration of terrestrial base stations, antennas are downward tilt, see Fig. 2). Please note that this peculiar feature could introduce non-connectivity conditions to some aerial devices; hence, considerations on the antenna radiation pattern and positioning of UAVs in a tridimensional space become essential factors to take into account.

In addition, on-the-fly base stations should have certain backhaul capabilities to provide high-capacity links to send information from multiple users to the network core or terrestrial BS. In this framework, the Non-Orthogonal Multiple Access (NOMA) technique has been considered, which also solve the power differences given by the diversity of UAVs altitudes and the variety of massive UEs at ground with different bandwidth requirements [2].

The on-the-fly base stations can operate under two approaches. Firstly, when a single UAV attend a specific cluster of users or different clusters of users as depicted in Fig. 3. Secondly, for a denser quantity of users, multiple UAVs (a swarm of drones) can be required to provide cooperatively a particular service [2]. An example of the above is shown in Fig. 4 for a monitored zone with a high density of devices and where an event occurs (e.g. a car crash).

Two main points to have in mind are the data rate that aerial infrastructure can provide and the latency. Extended service areas will imply larger latency, so, it will be necessary to roll out a larger number of UAVs. This situation has been studied by Lin *et al*. [6] for the Fourth Generation (4G) Long Term Evolution (LTE) mobile technology, who conclude that for a huge UAVs deployment, 5G networks can provide better flexibility and connectivity capabilities.

B. Access Mode

In this modality, UAVs operate as UEs and therefore they access to the mobile infrastructure to send and receive information through terrestrial base stations. The information carried by these aerial UEs naturally varies depending on the type of application for which they are used. Thus, different resources can be required for each UAV.

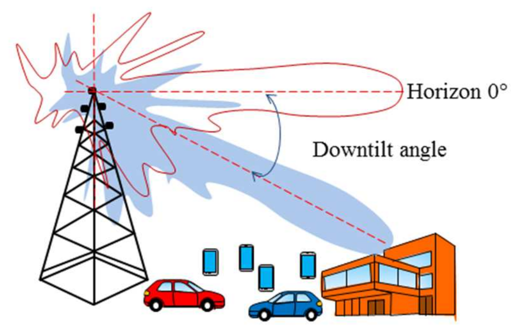

Fig. 2. Traditional vertical coverage provided by terrestrial base stations where antennas are downward tilt with the aim to attend ground UEs.

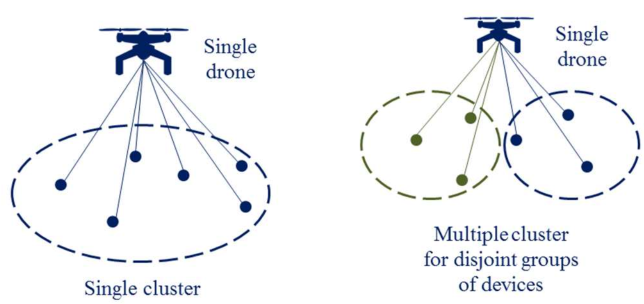

Fig. 3. Single UAV attending a specific cluster of users or attending different clusters of users.

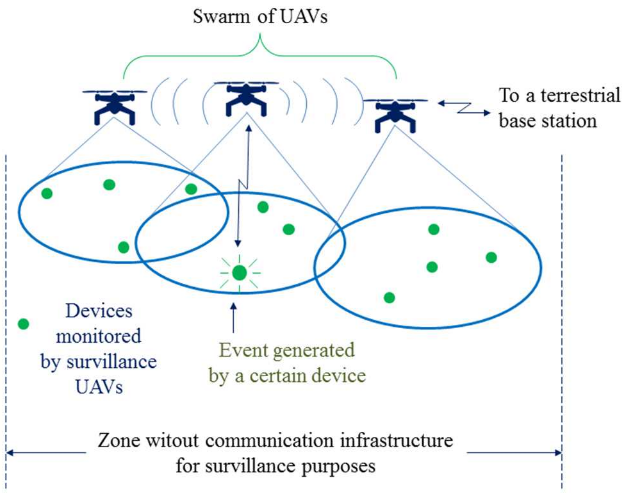

Fig. 4. Example of a swarm of drones providing cooperatively service to a high congregation of devices.

C. Interference

An important concern of the integration of UAVs into mobile cellular networks is the interference that these devices could potentially generate to the system (including that interference coming from ground-oriented devices occasionally attached to UAVs) or how they would be affected by interference coming from terrestrial devices. In essence, the increase of the interference levels is associated to better propagation conditions by higher altitudes where the aerial UEs operate.

This topic has been studied by Amorim *et al*. in [5] for an urban scenario with a high density of devices (3,000 UEs from which 1 and 10% were UAVs flying at 120 m) operating at the 800 MHz band. Different interference mitigation techniques are explained and evaluated by simulation: interference cancellation (IC), intercell interference coordination (ICIC), and beam switching at the UEs. According to their results, an improvement is achieved for the throughput and outage metrics, mainly for the beam switching techniques. Additionally, cognitive radio (CR) techniques represent a good alternative to share spectrum between aerial and terrestrial devices [2]. Moreover, machine learning techniques have been applied to identify UAVs in a heterogeneous aerial-terrestrial network [7].

D. Adaptive Coverage

As we have exposed, different types of devices will be operating in a 5G network. These devices will have different requirements not only by their own nature, but also due to their environment where they are located in a particular moment (residential zones, stadiums, crop fields, etc.). Under this optic, drones working as on-the-fly base stations can easily move towards those positions where devices require more resources (e.g. at the cell edge) as long as possible [8]. It is worth mentioning that the coverage of aerial BSs can be affected by random perturbations introduced by the airflow or body vibration of drones. This was studied by Zhu *et al.* [9] who model the behavior of the pitch, roll and yaw angles of a UAV through probability density functions of elevation and azimuth angles. On the other hand, when drones operate as aerial UEs, the coverage that mobile networks offer them is an important issue. In this concern, 5G capabilities will provide efficient algorithms for trajectory tracking, making an efficient planning and connectivity management [7], which in turn impacts on the cell coverage. From all the above, we can highlight that the use of UAVs in any modality stimulate having an adaptive coverage.

IV. Altitude

A. Wireless Networks Extended to a 3D Space

The height at which UAVs fly is one of their characteristics that distinguished them. Both high and low altitude UAVs have been considered to be connected to current mobile networks, but particularly the performance for low altitude UAVs is still under research in terms of interference and mobility for deployments in 5G [6]. In any case, depending on the UAVs height, natural or artificial obstructions will play an important role. This situation will impact on the received power levels and the interference amount as is analyzed by Lin *et al*. [6]. Also, shadowing and multipath fading phenomena, presented later, will be affected by the UAVs altitudes (see for example [10] and references therein). In this sense, practical considerations are analyzed in [11] for implementations in real environments. According to their results, the best system performance if for an altitude of UAV is 100 m with an external antenna pointing downwards.

From this tridimensional (3D) perspective, it is straightforward to consider a combination of drones flying at different altitudes as is depicted in Fig. 5. Moreover, the jointly capabilities of the UAVs can be extended using high altitude platforms and space satellite infrastructure as can be seen in this figure.

Fig. 5. Drones flying at different altitudes in combination with high altitude platforms and satellite platforms providing distinct services to terrestrial devices.

This architecture named *space-air-ground integrated networks* by Li *et al*. [2] can exploit the strengths of each segment (spatial, aerial or terrestrial) to the required service and where each is more efficient. Then, note that depending on the altitude, different performances are achieved to the end-to-end link, subject to constraints on size, weight and power (SWAP) of the UAV [2,3] and [12]. In other words, the SWAP conditions will limit the UAVs operational height.

In the context of joint operation of distinct devices sending and receiving information from different altitudes, it is clear that network layer aspects must be taken into account (e.g. protocols, technologies, etc.). Therefore, interface controllers, for instance, are essential for each segment of this type of heterogeneous network operating with distinct technologies, and it is necessary to determine the required communication protocols between them.

B. Unexpected Events

There are different applications of low altitude UAVs supported on mobile infrastructure such as search and rescue, emergency cases, early warning, and so on, which imply that drones have to fly in difficult access zones (see Fig. 6) or in certain moments that the communication infrastructure has been damaged. In the example of Fig. 6 the UAVs height allows to avoid obstructions and therefore provides more possibilities to reach directly or through relay UAV the nearest 5G infrastructure (see [13] where an algorithm to verify the communication conditions is exposed for UAVs based emergency services).

In this sense, it is important to highlight how the deployment of UAVs under these extraordinary circumstances introduces a temporal behavior to a mobile cellular network. That is, the system has to adapt to the new aerial infrastructure incorporated to the whole mobile network in an unexpected moment. This implies that the UAV-5G system must have fast and robust algorithms to schedule resources, make handoffs, etc.

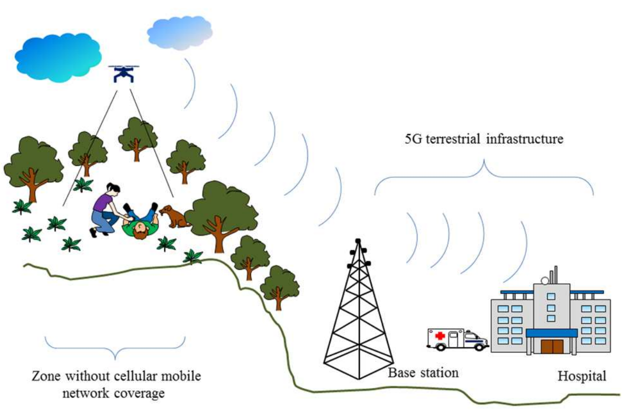

Fig. 6. Search and rescue supported by UAV-cellular infrastructure in difficult access zones.

C. Saturated Zones

The integration of UAVs in 5G can also be found in overloaded service areas [3]. From this perspective these aerial base stations complement the terrestrial mobile networks. This application is of great interest for the smart city concept as is addressed in [14].

For example, a swarm of drones flying at an optimal altitude can be used for surveillance purposes, where a certain event is monitored and its information is transmitted through the combined aerial-terrestrial infrastructure (see Fig. 4). In this circumstance, Ullah [4] points out that several facilities of 5G can resolve some requirements for real-time monitoring like bandwidth for 4K and 8K video, relatively low latency, etc. This can be useful for a high congregation of devices in a stadium uploading and downloading huge volumes of information.

D. New Spectral Option: mmWave Band

The coming 5G services exposed early of this paper will demand wider and wider bandwidths, so, the extremely high frequency band from 30 to 300 GHz, also known as millimeter wave (*mmWave*) band has been considered in the 5G NR (see [15] for a survey of the wwWave band in UAV 5G communications). This frequency band introduces severe atmospheric attenuation by rain and oxygen absorption, particularly at the higher segments of this band. Despite the above, reduced size devices can be designed and manufactured at these frequencies. This is particularly important for beamforming antenna array technology, since it is possible to design and built structures with a larger number of elements, providing more directive antennas with higher gains. This implies more efficient beamforming mechanisms and therefore lower interference levels. Hence, it allows to impulse the massive multiple input multiple output (MIMO) concept, increasing not only the antenna gain (and so making up the path losses), but also the devices range and the whole system capacity. All the above and other topics are well outlined by Li *et al*. [2], who provides key references.

Another important aspect of the mmWave band is how the 3D movement of UAVs is related to the communication links. This topic has been addressed in [13] where the beamforming technology is implemented to overcome variations into the communication links introduced by the UAV dynamics. According to their results, stable communication qualities are achieved with this technology.

E. Network Slicing

The wide range of applications implemented today on UAVs, like surveillance, search and rescue, precision agriculture, communications, health, entertainment, product delivery, among others, impacts on the diversity of traffic loads that the mobile network has to carry and process. To deal with this matter, 5G provides new alternatives [7]. One of them is the *network slicing* technique to create separated logical networks over which particular service capabilities are implemented and so, isolate services and resources of aerial and terrestrial devices.

V. LATENCY

As is well-known the latency refers to the total contribution of delays involved in a certain information transmission from end-to-end (round trip time). Of course, the end-to-end latency can include different delays depending on the particular purpose. Table 1 shows the delays involved for some applications and their required values [7].

In this concern, different studies for UAVs can be found in the open literature (see [7,16-18] for instance). it is worth underlying that the vertical positioning of UAVs introduces a new variable in the end-to-end latency. In fact, a study was conducted in [7] for different UAV heights operating with LTE infrastructure. Their results for control data transmission indicate end-to-end latency values of 200-300 ms at heights of 50 and 100 m, and 400-500 ms at 300 m high. While it is true that UAVs are limited to fly up to 120 m high, the corresponding latency values for 50 and 100 m are above of 100 ms required for a proper operation (see Table 1), which would impact on the UAV-mobile network system performance.

As an alternative to reduce the latency, Zhan and Ansari [16] proposed to implement UAVs as computer and relay nodes when these devices operate as on-the-fly base stations. Basically, the idea is to adopt the well-known 5G *mobile edge computing* (MEC) component [19] to the UAVs capabilities, in such a way that some computing services of the UEs are processed in a local manner instead of using network core resources [16] as is illustrated in Fig. 7. From this idea, a reduced latency can be achieved, which is particularly interesting to users at the edge of cells. In fact, a reduction up to 30% is reported in the average UE latency with three MEC-UAVs flying 100 m height, over a zone of 1 km^2 and using an algorithm designed for that aim [16].

The latency is highly related to the propagation channel, and data processing. From these, there can be different propagation conditions due to the diverse scenarios where aerial devices are deployed. Thus, it is important to study the characteristics that define the channel in order to derive theoretical models that provide tools to evaluate and predict the behavior of latency in different environments where UAVs are integrated to 5G mobile networks.

TABLE I. EXAMPLES OF END-TO-END LATENCY REQUIREMENTS

Application	Delays involved	Required latency
Image/video	Coding, air interface, core network, processing, transmission, decoding, display	< 400 ms
Remote real time control	Air interface, core network, processing, transmission	< 100 ms

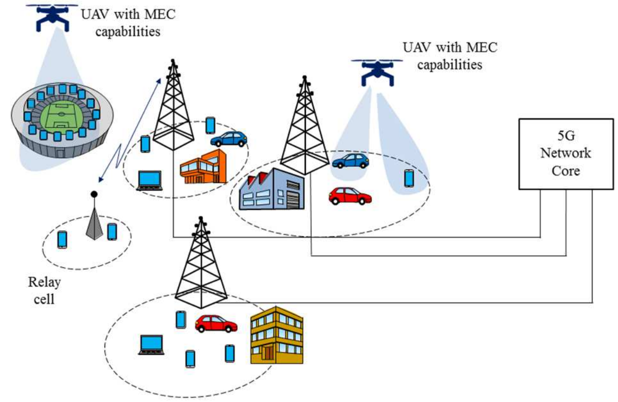

Fig. 7. Use of MEC at UAVs.

VI. COMMUNICATION CHANNELS

As just mentioned, another important element to take into consideration in the UAV-5G integration is the communication channel modeling. There is a vast quantity of references related to measurement campaigns, settings (technologies, frequencies, type and configuration of antennas, flight altitudes, environments, and so on), and simulations of UAV communication channels, which are well summarized in [2,10]. In what follows, the main points related to these channels are highlighted.

A. Types of Aerial Channels

The incorporation of UAVs into terrestrial mobile cellular networks presents a different perspective for the communication channels. In essence, it should be emphasized that the dynamics of UAVs causes a spatial and temporal behavior of the communication channel different to that of terrestrial mobile networks. Particularly this dynamics makes necessary to model the UAV channel in a 3D base, in contrast to terrestrial channels, where it is usually considered grazing propagation and so most components of signal can be assumed to be confined in a two dimensional (2D) space. From this perspective and depending on the devices to be connected, it is clear there are two types of aerial communication channels [2,10]:

- *Air-to-ground (AG) channel*: This channel is formed when a UAV is transmitting/receiving information to/from terrestrial devices (IoT nodes, handheld devices, laptops, base stations, vehicles, etc.). This channel has a higher probability of presenting larger attenuation in the propagation path than the air-to-air channel. The path loss is associated to possible obstructions that block, scatter or even absorb the signal in the transmitter-receiver path depending on the operation frequency. In addition to factors included in a conventional terrestrial channel, it is necessary to take into account variables that are related to the UAVs altitude and their elevation angle. Moreover, an analysis must be carried out about all those terrestrial factors that can be neglected.

- *Air-to-air (AA) channel*: It stands for the communication channel between aerial devices like UAVs, high altitude platforms, satellites, etc. The air-to-air channel exhibits mainly Line-of-Sight (LOS) propagation conditions, although some reflections could be also present depending on the altitude and flight dynamics. Thus, comparatively, an AA channel has better propagation conditions (e.g. reduced path loss) than an AG channel. It is worth mentioning that although most of works on AA channel modeling are focused on a 2D approach [10], one would expect the above generalities are hold for future 3D experimental research works.

B. Small Scale Fading and Shadowing

Given the UAVs altitude, it is not uncommon that several researches present measurement results where LOS conditions dominate in the propagation channel, and consequently it is modeled following a Rice or Nakagami-m distributions in terms of the small-scale multipath fading. The survey published in [10] provides a summary of researches about empirical models to characterize the propagation channel for both AA and AG links, some of them including cases of mobile UAV or for UAV operating in hover mode. Authors also presented a set of tables with different analytical channel models classified from deterministic and stochastic perspectives, some of them considering the UAV altitude, among other variables. From references cited there, it is worth mentioning the work of Ye *et al.* [20], where the channel modeling is based on a machine learning approach to determine which parameter in an AG scenario is most sensitive to the UAV height. According to authors, from the parameters considered (variation in the path loss, distribution of the multipath fading, Rician factor, delay spread, etc.), the Rician factor showed the greatest dependence on the UAV altitude.

On the subject of large-scale fading also known as shadowing, in these aerial channels it is not only attributed to large obstructions in the propagation paths, but also it is considered the fuselage, wings or even engine of the UAVs [10]. Some comments about the effects that the UAV height has on the shadowing variation derived from a measurement campaign conducted in rural areas at 800 MHz are presented in [21]. Essentially, authors observed that the higher altitude, the lower shadowing variation.

C. Temporal Variations

Drones operating both as on-the-fly base stations or aerial UEs can be flying in hover mode, but occasionally can also be in movement. This last situation implies a non-stationary channel behavior, which requires special considerations for the channel modeling like wideband characterization. In addition, different Doppler shifts are generated depending on the relative movement of aerial and terrestrial stations, in contrast to fixed base stations. The differences between Doppler shifts can be exploited in benefit of tracking and localization techniques, as is explained in [22]. This situation can be particularly useful for applications where swarms of drones are deployed. For a revision on models of aerial channels in the time and delay domains, we recommend [10] and references therein.

D. Considerations on Antennas

The radiation characteristics of antennas play an important role in the propagation channel. For example, as mentioned before, in order to make an efficient use of the antennas installed at terrestrial base stations, they are usually downward tilt (see Figure 2), providing better gain values to ground UEs. Nevertheless, for a 3D space, this antenna configuration could introduce some nulls towards flying UAVs, reducing their received power levels, which affects several system parameters like quality of service, throughput, SINR, and so on. On the other hand, the type, location and orientation of the antennas mounted on drones are important factors to consider in order to obtain a better system performance. This last sentence is related to the beamforming technology as is mentioned in Section IV.D in the context of the mmWave band, where some practical considerations are commented.

E. 3D Characterization

All the above factors associated to the UAV communication channel can be included by simulations in a 3D context for UAVs applications through the so-called *geometric-based stochastic models* [10]. In this approach, it is possible to assume a certain geometric space (e.g. a cylinder) within which different UAVs configurations, scenarios, etc. are evaluated. However, field campaigns are necessary to calibrate these approaches and have more reliable models.

VII. Energy

An essential aspect of UAV-based technologies is their energy consumption. In general terms, those platforms of high altitude have better energy conditions than simple, cheaper, lower altitude aerial platforms [2]. In any case, different mechanisms to extend the battery duration for a normal operation of drones are evolving day by day. A classic example is the well-known energy harvesting technique, which has been under research during several years. In this context, the solar energy is a direct alternative as power supply for UAVs.

In addition, optimization of the UAVs trajectories is essential to make an efficient use of the consumed power. In [12], for example, a study was conducted in which UAVs assist a terrestrial wireless network where ground users require a response within a certain time window (i.e. with latency constraints). The proposal explained there is based on the classical traveling salesman problem (TSP) but using dynamic programming to account the time window restriction. According to authors, this approach not only provides the shortest path, but also reduces the consumed energy. Thus, their results show a low complexity solution, where UAVs use a minimal quantity of energy, and it is achieved a performance near to that of the exhaustive optimal algorithm.

VIII. Conclusions and Future Considerations

Through this paper, different aspects involved in the integration of aerial devices, specifically unmanned aerial vehicles (UAVs), into the fifth generation of mobile networks (5G) have been addressed. These aspects include two functioning modalities of the drones (either as base stations or as user equipment), origins of interference, impact of altitude, latency, communications channels, energy considerations, etc. As main contribution of this paper, we also postulated that the UAVs dynamics opens a new perspective in a spatial and temporal base, which is particularly important for the channel modeling, and in general for the UAV-5G operation. In this context, the relationship of some parameters with the time or the space is emphasized in different points of the paper. Another element highlighted here is the incorporation of mobile edge computing capabilities to aerial user equipment which permit reducing the latency. This computing/communication strategy allows not only be a first approach to initiate and implement the operation of an aerial-terrestrial mobile infrastructure, but also provides computing capabilities to IoT devices using 5G facilities. Finally, it is worth pointing out that the expansion of drones in the deployment of future mobile networks implies new challenges for aerial vehicles and their interaction with terrestrial communications infrastructure and other aerial devices and satellite platforms. New approaches must be proposed specifically in terms of latency, energy and interference. Fortunately, the current experience and research efforts in the field of UAV-5G integration will impulse a variety of technological options for future mobile networks like the sixth generation mobile network projected for 2030.

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