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Inflight Broadband Connectivity Using Cellular Networks

NAVID TADAYON, (Student Member, IEEE), GEORGES KADDOUM, (Member, IEEE), AND RITA NOUMEIR, (Member, IEEE)
École de Technologie Supérieure, Montreal, QC H3C 1K3, Canada

Corresponding author: N. Tadayon (tadayon@emt.inrs.ca)

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ABSTRACT After three decades from the public debut of cellular networks, there are hardly parts of populated lands where cellular coverage is absent. Day after day, mobile users have been provided with wider range of services at higher speed. Today, long terminal evolution (LTE) networks support broadband connectivity for users moving as fast as 350 km/h, and the support for speeds up to 500 km/h is under consideration. Unfortunately, none of these efforts were aimed at airborne travelers due to the lack of aerial coverage. Provided that 5G networks are meant to provide anywhere and anytime connectivity for anyone, many operators are providing the free onboard Wi-Fi through proprietary terrestrial networks or satellite links. Unfortunately, both of these solutions have serious drawbacks, where the latter provides very limited speed, and the former is expensive and unscalable. In this paper, we discuss the technical possibilities of enhancing the existing LTE infrastructure for air to ground communications. We identify the major challenges and obstacles in this path, such as uplink/downlink interferences, frequent roaming, large Doppler effect, and channel degradation. We also discuss appropriate solutions to counteract them using some of the emerging antenna, signal processing, beamforming, and multi-beaming ideas.

INDEX TERMS Air-ground, cellular networks, LTE, link-budget, Doppler effect, beam steering, MU-MIMO.

I. INTRODUCTION

The desire for connectivity is growing quickly. The coverage of cellular networks in-use today is not comparable with that of a decade ago. In fact, nowadays, there is barely a part of inhabited land that is not covered by the cellular networks. Statistical studies reveal more than seven billion mobile subscriptions by the end of 2014 [1]. The same report unveils a 30% increase (roughly 150 millions) in the number of mobile subscriptions on a year-by-year basis. By 2020, it is expected that more than 70% of the world population will use smartphones [1]. It is now a rule of thumb that if population and demand exist, cellular coverage will be provided. Sadly, this is not the case in the skies. More than thirty years past from the emergence of cellular communication and there is still no broadband coverage of any kind for airborne passengers. Statistics from international air transport association (IATA) [2] show that more than eight million passengers fly every day. For the most profitable industry in the history that has so far created beyond 2.2 trillion dollars in economic activities, it is mysterious why the inflight broadband connectivity is still deemed as such a daunting task.

In the continent of U.S., despite what is widely believed, the abandonment of using cell-phone onboard and during flight time was not a restraint solely imposed by federal aviation agency (FAA), but by the federal communication commission (FCC) as well. At the time, the alleged reason for placing such ban was a common belief that transmissions in uplink direction (from aircraft to the cellular network) might have triggered several BSs (see Section III-F) at the same time and brought down the network in special circumstances. The same fear spread across in other regulatory domains. Though this might have been a valid postulation for older generations of cellular networks, it is not a concern in today's modern cellular networks. Quite the opposite, 3GPP[1] has recently introduced a feature in Release-11 of LTE-Advanced (long terminal evolution), namely Coordinated Multi Point (CoMP), that exactly leverages multiple BS (a.k.a eNodeB in LTE terminology) activation as a mean to increase network capacity [3]. As such, FCC has recently

[1]3GPP is the international standardization body responsible for developing cellular standards.

realized that such restriction is no longer useful but rather restraining [4]. This reorientation is spurring industries to develop solutions for air-ground communication based on cellular networks.

From network operators' perspective, serving the airborne population can increase their customer base around the world by only 0.1%, at best. Yet, there are multitudes of other justifications that drive them to take air-ground communication more seriously; first of all, aerial passengers are willing to pay for onboard connectivity more than what they regularly pay on the land; secondly, airlines have recently felt the urge to offer inflight Wi-Fi connectivity as a value-added service. In this vein, United Airlines was the first to offer such service on international flights in 2012. By July 2015, eight airlines have been offering free Wi-Fi services and some 50 airlines offer Wi-Fi as premium service on their selected airplanes [5]. As more and more airlines join this cause, those who fall behind feel more compulsion to reconsider their choices because this will be less about bucks they collect from their passengers for the provisioned connectivity service and more a concern about losing their customer bases. In view of the competitive nature of the aviation market, this increased churn rate is an unbearable risk for airlines. Consequently, provided the rising demand and willingness of the passengers to pay for inflight high-speed internet connectivity, it is expected to have comprehensive connectivity service offered by all airlines in the foreseeable future.

II. AERONAUTICAL COMMUNICATIONS: EXISTING TECHNOLOGIES

A. VHF AIRBAND COMMUNICATION

The primary and classic way of communication between the aircraft and ground station happens over the very high frequency (VHF) spectrum, $118 - 137$MHz, commonly known as "airband". This 19MHz band is split into 760 sub-channels of 25kHz width each, used to transmit a single voice channel. At some European regions, these sub-channels are further shrunk down to 8.33kHz to gain better spectral efficiency. After almost a century since its invention, the analog amplitude modulation (AM) is still in-use for data transmission over these frequencies. Due to AM's spectral inefficiency, substantial increase in the number of concurrent flights, and existing strict radio-communication regulations that prohibit the use of airband for "non-air-traffic-controlling" purposes [6], it can hardly be imagined that airband will open up for public broadband access in the near future.

B. SATELLITE COMMUNICATION

Most of the existing inflight Wi-Fi networks are connected in the back-end to satellites. Satellite Communication (SatCom) has been used for voice communication for many decades but its intrinsic capacity limits, high round-trip delay, and lack of scalability make it unfitting for carrying multimedia and real-time traffic [7]. To clarify this point, it is enough to note that the end-to-end communication latency between two devices connected by a geosynchronous orbit (GEO) satellite can exceed 250ms. Incorporating into this number the latencies caused by queueing, processing and framing delay, the total delay can easily surpass 400ms. This hardly renders SatCom as an acceptable mean for voice-over-IP (VOIP) and other streaming traffic types whose latency shall be less than 300ms for human's ear to bypass it. On the other hand, since the frequency cannot be reused, only a limited capacity is effectively shared among many users in an extensive geographical region, providing each user with a very limited throughput that is just enough for voice communication. Given the large upfront capital expenditures and costy subscription fees, SatCom is not considered a viable broadband technology capable of pacing with future needs.

C. PROPRIETARY TERRESTRIAL COMMUNICATION

For the shortcomings of SatCom and VHF, an aero-communication service provider named Gogo has recently introduced its own proprietary terrestrial network for air-ground communication to provide high-speed inflight broadband connectivity [8]. Prior to that, on 2012, Qualcomm submitted a "petition for rule-making" to FCC on a new air-ground communication system operating in Ku band $14.0 - 14.5$GHz on a secondary basis. According to that proposal, 150 ground stations (GSs) were to be deployed in USA to track up to 600 airplanes at any moment. Using 500MHz available in this band, 300Gbit/s aggregate throughput can be achieved. By sharing this spectrum with fixed satellite service (FSS) such that half is opened up for air-ground communication (i.e. 250MHz), 150Gbit/s aggregate throughput can be guaranteed. Time division duplexing (TDD) was proposed to schedule uplink/downlink (UL/DL)[2] transmissions from/to an on-board unit that gives passengers broadband access using a Wi-Fi interface. The network was hexagonally tessellated where GSs were situated at every other vertices of hexagon cells. Antennas pointing toward the north with beamwidth (maximum azimuth angle) $\pm 60°$ and elevation angle less than $10°$ to avoid inflicting interference onto FSS antennas pointing toward the south. This results in an inter-GS spacing of 250km. GSs transmit with high power to be able to serve aircrafts flying in the $300 - 600$km range. In May 2013, FCC summarized this proposal and comments from opponents/proponents having decided to legalize air-ground communication [4].

Even though the idea of separating spectrum is important, the destructive impact of the Doppler spread was underestimated in Qualcomm's proposal. To give readers an idea, in 14.5GHz range, with an airplane travelling at 900km/h, one should expect almost 9kHz Doppler shift. In situations where the OFDMA interface is used, this is more than half of the carrier spacing (15kHz). In such a system, Doppler

[2]Despite the unique definition of UL that is the transmission from a user to GS, readers should be aware that the direction of propagation (w.r.t earth center) is downward in air-ground scenario, whereas is upward in terrestrial networks.

effect compensation needs much more painstaking attention that what was provisioned in that proposal.

D. CELLULAR COMMUNICATION

As more airlines offer inflight connectivity, further void in the market is felt and more diverse proprietary solutions emerge. These solutions may be based on different technologies developed by companies that are active in different countries and regions. The continuation of this trend leads to a predicament where intercontinental flights should either be equipped with multiple proprietary transceivers and provide an end-to-end flight-time connectivity or remain loyal to a single technology and offer partial connectivity. In the former case, there will be long-lasting connectivity disruptions when an airplane enters a new regulatory domain/region. Moreover, expense-wise, it is unjustifiable and unsustainable to have multiple transceivers mounted on an airplane. On the other hand, the latter solution is less attractive to passengers and lucrative for service providers as connectivity is only partially provided.

Spurred by these facts, few air-ground communication projects based on standardized cellular networks kicked off recently. In 2012, Deutsche Telekom, Alcatel-Lucent and Airbus announced the completion of a trialled LTE-based air-ground communication system [9]. The test was conducted over a state of Germany, carried out by Alcatel-Lucent, who supplied the end-to-end solution. The network comprised of two base stations (BSs) positioned 100km apart. On March 2013, the Chinese Telecom equipment provider, ZTE, [9] announced the outcomes of an air-ground communication pilot project where inflight connectivity lasted for 70 minutes out of a two hours flight at a nominal rate of 12Mbps. A bit earlier, ITU Radiocommunication study group published the properties and characteristics of air-ground communication networks capable of supporting public broadband communication [10]. Results were based on three different test cases conducted in Europe. The first system was built using off-the-shelf LTE equipment (LTE release 8+), where it was explicitly stated that mandatory modifications have been incorporated into the network including synchronization algorithm improvement (to cancel out the Doppler frequency shift), increasing the transmit-power of on-board unit (ONU) (37dBm compared to maximum 23dBm allowed for handheld devices in LTE), as well as up-tilting the transceiver antennas of the eNodeBs. The traffic can then be distributed among the passengers by the ONU through a second tier that uses WLAN,[3] GSM[4] onboard, or femto-size UMTS[5]/LTE. It was reported in [10] that, at $4-10$km altitude, where the cruising speed is $500-800$km/h, the radio connection established at a distance of 100km from a GS provided download and upload throughputs of 30Mbit/s and 17Mbit/s, respectively. Moreover, high quality video-conferencing was experienced with round trip time (RTT) as little as 50ms. In the second test case, steerable antenna arrays at the GSs and ONU were implemented obviating the need for power enhancement with the shortcoming of requiring precise airplane tracking. The third and final trial was based on 3GPP release-7, UMTS, equipment.

These observations unanimously corroborated that cellular networks can be used to provide widespread and high quality broadband connectivity for aerial passengers. In the face of its advantages, there are technical challenges associated with implementing a cellular-assisted air-ground system. These difficulties are discussed in the next section.

III. CELLULAR-ASSISTED AIR-GROUND SYSTEM: CHALLENGES

A. ANTENNA TILT

Commercial cellular networks cannot be directly used for air-ground communication without certain modifications. The reason is that antennas in such networks are deliberately tilted downwards not to receive unwanted radiations from sources located at higher elevation angles. This gives rise to a line-of-sight (LoS) channel where GS and ONU antennas do not see each other through their main lobes. Also, due to the lack of obstructions, the channel is a poor scattering environment. As a result, the signal transmitted by the ONU (in the UL) may only reach the closest GS after reflecting off the ground or by the side lobes. Given that an ONU and eNodeB's main lobes do not intercept, the primary reflection will likely be from Earth rather than other man-made structures (buildings etc.). This first reflected ray, which carries the most power among other reflections, has a small incidence angle θ (or zenith angle) resulting in a small reflection angle, accordingly. In this situation, there is a very high chance that this ray escapes the ground entirely and does not induce any charge on nearby GS antennas. On the other hand, rays that hit the ground at higher incidence angles θ, are more likely to be picked up by farther GSs. In such situation, if the minimum link budget requirement is met, it is very likely that an airplane gets connected to farther GSs than closer ones. This being the case, the experimental findings in [11] prove that 2 and 3-ray models are decent approximations for air-ground link with $\theta \gg 0$. This idea is portrayed in Fig. 2a.

B. CHANNEL IMPAIRMENTS

Airplanes fly in the tropospheric layer of the atmosphere which is way lower than the ionosphere and stratosphere layers in which "bounce" effect is the prevailing phenomenon. Even if an airplane was, hypothetically, flying in these layers, no such effect would have been experienced in frequencies above 30MHz [12].

In its most general form, the impulse response of the wireless channel, when small scale fading, large scale attenuation, as well as Doppler effect are in place, can be expressed as [13]–[15],

$$h(\tau; t) = \sum_{i=1}^{n(t)} \alpha_i(t)\, e^{j2\pi (f_i(t)(t-\tau_i(t)) - f_0 t)}\, \delta(t - \tau_i(t)), \qquad (1)$$

[3] Wireless Local Area Networks.

[4] Global System for Mobile Communications.

[5] Universal Mobile Telecommunications System.

where f_0 is the carrier frequency, $n(t)$ is the number of multi-path components, and $\alpha_i(t)$, $\tau_i(t)$ are ith component's attenuation and delay, respectively. As alluded before, in the case of air-ground communication channel, no reflection, refraction or shadowing happen due to the lack of obstructions in the propagation environment (not counting those on the land). Therefore, either no multi-path component exists, or if it does, it is extremely weak in strength. This claim was substantiated in [12] where the Rician factor $K_{\text{Rice}} \approx 2-20$ dB was reported. The lack of multi-path fading and shadowing renders the "free-space path loss" an acceptable model for air-ground communication channels where (1) has only a single component (i.e. $n(t) = 1$). Signals traversing through a path of length $d_i(t)$ experience a delay $\tau_i(t) = d_i(t)/c$, where c denotes the speed of light. Thus,

$$h(\tau; t) = \alpha(t)\, e^{j2\pi(f(t)(t-\tau(t))-f_0 t)}\delta(t-\tau(t)). \quad (2)$$

An important metric in assessing the performance of such system is the the total free space path loss (FSPL) $\mathcal{L}$ which (assuming the channel is a linear system) is given by,

$$\mathcal{L} = \frac{\mathcal{P}_t}{\mathcal{P}_r} = \frac{\int_{-\infty}^{\infty} S_{t,t}(f)\mathrm{d}f}{\int_{-\infty}^{\infty} \mathcal{F}\{h(\tau;t)\}^2 S_{t,t}(f)\mathrm{d}f}, \quad (3)$$

where $\mathcal{P}_r$, $\mathcal{P}_t$, $S_{t,t}(f)$ are the received power, transmit signal power, and its power spectral density, respectively, and $\mathcal{F}\{h(\tau;t)\}$ is the corresponding frequency response of the air-ground communication channel impulse response mentioned in (2).

C. DOPPLER EFFECT

Every frequency component of a signal propagating through space can be exposed to a shift, known as Doppler effect, whose severity depends on how fast channel characteristics vary. Such channel variation that is caused by relative motions of transmitter, receiver, and other objects in the environment and manifests itself as a time-varying impulse response (as noted from (1)), is more drastic when the motion is concentrated around the receiver. In the ultimate case where the receiver is moving, Doppler shift is quantified by,

$$f(t) = f_0\left(1 + \frac{v}{c}\cos(\theta(t))\right), \quad (4)$$

where v is the airplane speed, and $\theta(t)$ is the incidence angle that the line connecting transmitter and receiver makes with the speeding direction.

In DL direction, since the propagation environment in air-ground communication is not *rich*, the arriving rays are not isotropically distributed around the receiver and the ONU only receives signal from a specific direction. This claim was proven in [16] where it was shown that the beamwidth of the scattered rays are only in 3.5° deviation. Therefore, the Doppler power spectral density (PSD) of the air-ground link is only part of Clark's Doppler PSD introduced for uniform scattering environment [12]. This is clarified in Fig. 2b where the 2D as well as 3D Doppler PSDs are plotted. In particular, the red/yellow region within the 3D/2D plots illustrates the Doppler PSD for the possible range of shifts that an airplane may undergo. The maximum shifts $\Delta f_{\max}$ corresponds to maximum values that angles θ and ϕ may take.

When the airplane is en-route, the fading is truly fast, hence, the Doppler effect can be a much more severe culprit and cause harmful inter-carrier interference (ICI) [17] compared to what is experienced in terrestrial networks (e.g. cellular networks).[6] Particularly, in the case of multi-carrier modulation, such as OFDM, two side effects arise: First, the ICI induced due to Doppler effect can be more devastating due to closely spaced sub-carriers. Second, channel fading is fast and coherence time is way smaller than symbol length, thus, the channel estimation gains (obtained through transmitting reference signals and used in many algorithms) may change several times within a symbol. To illustrate the extent of this problem, when the GSs are spaced 100km apart, as was the case in [10], an airplane flying at 12km altitude and cruising with 800km/h can experience a Doppler shift as high as $\Delta f_{\max} = \pm 4$kHz. For typical OFDM settings with inter-carrier spacings of 15kHz, the negative effect of this unwanted shift can only be nullified by assigning around 30% of the spectrum in the form of guard-band between every two contiguous sub-carriers. For these reasons, our most advanced cellular network in the market today, i.e. LTE, is not able to maintain safe connectivity to devices speeding above 300km/h [18], let alone an airplane flying at three times this speed.

D. INTERFERENCE

Assuming the issue of aligning the transmitter/receiver antenna patterns is sorted out, the second matter is the interference from co-channel cells. To have a better idea, we consider LTE networks in which the same frequency is reused in every cell to improve the network-wide spectral efficiency. Though, such a small frequency reuse (FR) factor can potentially improve data rate of user equipment (UE) on the land, interference can easily become a serious problem for UEs[7] on the sky (in DL) as all cells other than the serving cell are considered interference sources. For that reason, Section IV-B is devoted to the analysis of interference for air-ground communication through cellular networks.

E. FREQUENT HANDOFF

Further to increased ICI, high airplane speed spawns another complication known as frequent handoff. The latter is the normal process of attaching to the closest eNodeB as a user enters

[6] Herein after, the term "terrestrial communication" is used to refer to air-ground communication through cellular networks as opposed to the more specific term "cellular communication" that only refers to communication on land.

[7] To remain compliant with LTE terminology, terms UE^{air} and eNodeB-E (to refer to enhanced eNodeB) may alternatively be used in this study to refer to ONU and GS, respectively.

a new cell while detaching from the old eNodeB as it leaves its zone. However, if done frequently, handoff can deteriorate the communication quality causing period service disruptions for the $\mathrm{UE}^{\mathrm{air}}$ as well as wasting the valuable resources on controlling tasks that may otherwise be used for serving other land UEs. To exemplify this point by numbers, at altitudes above 30000ft (9km) and assuming the nominal 5km macro-cell size, an airplane with a cruising speed 900km/h, on average, has as little as 20s to traverse through the coverage area of a particular cell before handoff mechanism initiates. LTE networks are able to handle frequent handoff swiftly and more efficiently [18]. However, this is not the case for GSM.

F. MULTI-CELL ACTIVATION

For it is possible that a transmission from an $\mathrm{UE}^{\mathrm{air}}$ is heard by multiple eNodeBs, it may activate them all at once causing coordination complications and confusion in the core of the former access network, such as GSM. Fueled by the recent advancements in making the architecture of cellular networks simpler, more agile, smarter, and better coordinated, mutli-eNodeB activation has lately been offered to improve connectivity experience of cell-edge UEs. There are good reasons to believe that mutli-eNodeB activation can also be leveraged in the future to facilitate the communication quality in air-ground communication systems. Yet, there are some required adaptations on the association and cell-search mechanisms of LTE [18] in order to make more efficient use of resources for the latter scenario. For instance, $\mathrm{UE}^{\mathrm{air}}$ may need to remain connected to an eNodeB-E beyond the borders of the associated cell in order to reduce the overhead imposed by handoff/cell search mechanisms.

IV. CELLULAR-ASSISTED AIR-GROUND SYSTEM: PROPOSED SOLUTIONS

Rising demand for broadband access has already reached the aviation industry. To cater these needs, airlines are seeking solutions that are expandable, sustainable and up to date. The existing terrestrial and satellite networks discussed in section II do not have these properties. For that reason, a standardized technology is needed to create a unified solution that remains operational beyond any border. The terrestrial cellular network seems like a fulfilling candidate provided its widespread coverage. Nonetheless, the cellular network in its existing form is unable to provide aeronautical connectivity. This is, chiefly, because eNodeB antennas on the ground are tilted downwards to keep the radiation within their own cells and to reduce interference to neighboring cells. Consequently, these antennas are unable to establish a true LoS path to airplanes flying overhead. If this was not the case, LoS communication would be possible and free-space path loss propagation model would provide valid predictions. Using Omni-directional antenna is certainly not a reasonable workaround as it equally radiates transmit-power in all directions causing severe interference to other cells. Therefore, we suggest the enhancement of the existing eNodeBs with separate top-mounted aerial modules (as opposed to terrestrial modules used for land users) having a set of laid-down sector/panel antennas that face the sky in order to have LoS link to $\mathrm{UE}^{\mathrm{air}}$. This is illustrated in the right-hand-side illustration of Fig. 5. The new BS is termed eNodeB-E (to stand for enhanced eNodeB), hereinafter. This being the case, the remainder of this section deals with investigating detailed aspects of the subject.

A. LINK BUDGET ANALYSIS

The cellular-assisted air-ground communication system proposed above is interference-limited, i.e. interference is the dominant performance degrading factor. To have an idea concerning the degree of interference that is tolerable, we resort to numerical calculations (as opposed to table-based experimental power-budget analysis) focusing on the DL direction, i.e. from the serving eNodeB-E to the $\mathrm{UE}^{\mathrm{air}}$.

In LTE networks, transmit-power of eNodeBs is $\mathcal{P}_t = 13$ to 18dB with an antenna gain of 18dB. This gain is obtainable by using directional sector antennas. Assuming a typical 2dB cable power loss and that $\mathrm{UE}^{\mathrm{air}}$ is equipped with omni-directional receive antenna, the isotropically radiated power (EIRP) 32dB is gained. For the minimum signal-to-interference-plus-noise-ratio (SINR) of -10dB, the following relationship must be satisfied for correct reception,

$$\mathrm{EIRP}^{\mathrm{dB}} - \mathcal{L}^{\mathrm{dB}} - 10\log_{10}\left(\mathcal{P}_{\mathcal{N}}^{\mathrm{Out}} + \mathcal{P}_I\right) > \mathrm{SINR}_{\mathrm{min}} = -10\mathrm{dB}. \tag{5}$$

Factor $\mathcal{P}_{\mathcal{N}}^{\mathrm{Out}}$ in (5) is the noise power at the output of receiver radio frequency (RF) frontend and is related to thermal noise at the input $\mathcal{P}_{\mathcal{N}}^{\mathrm{In}}$ through the noise factor $\mathrm{F}_{\mathcal{N}} > 1$ according to

$$\mathcal{P}_{\mathcal{N}}^{\mathrm{Out}} = \mathcal{P}_{\mathcal{N}}^{\mathrm{In}} \cdot \mathrm{F}_{\mathcal{N}} = k_{\mathrm{F}}\mathrm{TBF}_{\mathcal{N}}, \tag{6}$$

where B, k_{F}, and T are $\mathrm{UE}^{\mathrm{air}}$'s allocated bandwidth (BW) in the DL direction, Boltzmann constant, and system noise temperature, respectively. For typical LTE receiver circuitry, $\mathrm{F}_{\mathcal{N}} = 7$dB. Granted that N resource blocks (RB) of 180kHz is allocated to a $\mathrm{UE}^{\mathrm{air}}$,

$$\mathcal{P}_{\mathcal{N}}^{\mathrm{Out}} = 36.1N \cdot 10^{-16}. \tag{7}$$

Then, based on (7) and (5),

$$10\log_{10}\left(36.1N \cdot 10^{-16} + \mathcal{P}_I\right) < 42\mathrm{dB} - \mathcal{L}^{\mathrm{dB}}. \tag{8}$$

For an eNodeB-E operating at L-band over $f = 1800$MHz covering an area with radius $R = 5$km (as is the case for most commercially deployed LTE networks), and when the airplane is flying at $h = 10$km ($\cong$ 35000ft)

$$\mathcal{L}^{\mathrm{dB}} < 10\log_{10}\left(\frac{4\pi f\sqrt{h^2+R^2}}{c}\right)^2 = 111.5\mathrm{dB}, \tag{9}$$

where c is the wave propagation speed. According to (8) and (9), the total interference $\mathcal{P}_I$ collected at $\mathrm{UE}^{\mathrm{air}}$ receiver shall remain less than -69.5dB (0.1122μw).

B. INTERFERENCE ANALYSIS

It is the very existence of signal power falloff due to the path loss and shadowing in cellular networks that makes frequency reuse possible. These accumulative phenomena that are abstracted in the form of a path loss exponent (PLE) in the familiar *Ferris* free space path loss model can be as large as 5 in suburban areas and 3.5 in urban areas. Therefore, same frequencies can be reused in farther cells to enhance the capacity by making more spectrum available to each UE. In 2G/3G cellular networks, depending on how large each cell is and how much interference is tolerable, the number of neighboring cells that are using distinct frequencies is different (FR $>$ 1). Though this is fine when users are on the land, the lack of ''shadowing'' effect in air-ground communication results in a power falloff that is not as steep, with PLE that is approximately 2 or a little less. This assertion was experimentally affirmed by other studies [19]. The outcome would be a large amount of interference collected by eNodeB/UE$^{\text{air}}$ in either UL/DL directions due to co-channel frequency reuse. This is illustrated in Fig. 1a where an airplane associated with the central green cell receives strong interference from all co-channel red cells.[8] Given that the distance between a cell and its first layer co-channel cells [20] is[9]

$$\mathcal{D}(i,j) = \sqrt{i^2 + j^2 + ij}\sqrt{3}R, \tag{10}$$

where cell radius $R = 5$km, the total interference power an airplane receives from m layered co-channel cells would approximately be equal to

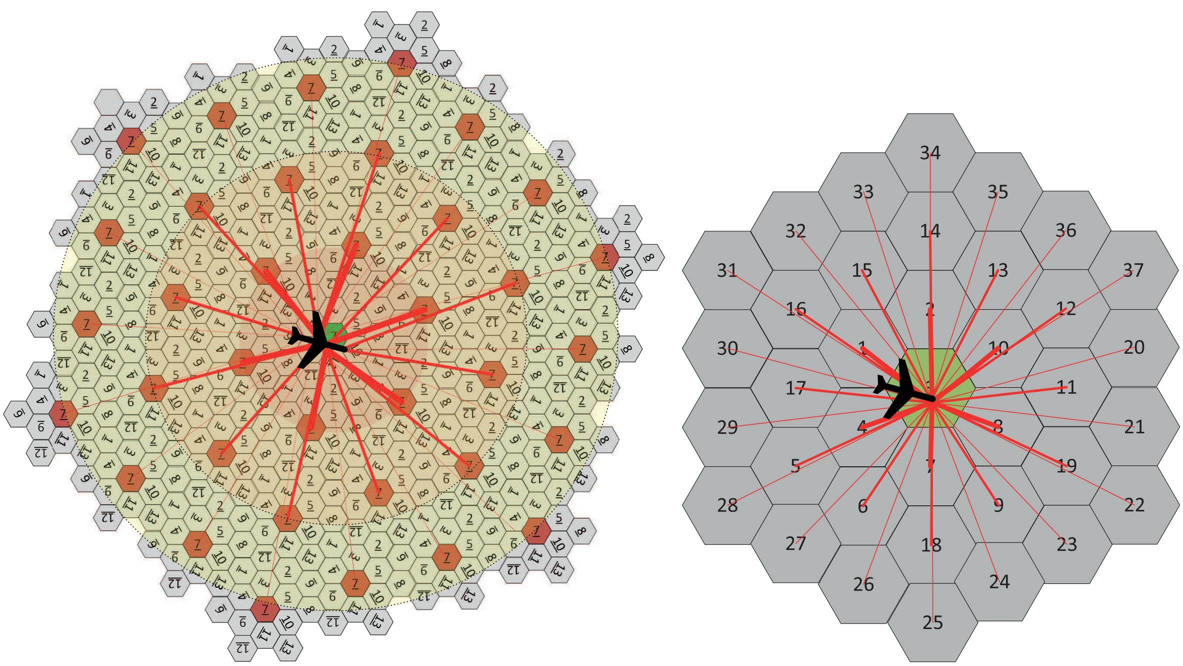
$$\mathcal{P}_I = \sum_{n=1}^{m}\sum_{k=0}^{n-1} \frac{\lambda^2 \mathcal{P}_t^n G_t^n 6}{\left(\mathcal{D}\left(ni + kj, -ki + (n-k)j\right) + h\right)^2}. \tag{11}$$

The outer summation in (11) is over co-channel layers (as illustrated in Fig. 1a with translucent circles of different colors), and the inner summation is over the co-channel cells within the same layer. The symbols $\mathcal{P}_t^n$, G_t^n are the transmit-power and antenna gain of an interfering cell at the nth layer, and h, λ are the aircraft's altitude and the transmit signal wavelength, respectively. For the fact that FR$^{\text{LTE}} \cong 1$ ($i = 1$, $j = 0$), interference is a more severe culprit in LTE networks. This is illustrated in the Fig.1b. The total interference received by a UE$^{\text{air}}$ from an LTE network can be alternatively stated as

$$\mathcal{P}_I = \sum_{n=1}^{m} \sum_{\substack{x,y \\ x,y \in \mathbb{N}\cup\{0\} \\ x+y=n-1}} \frac{6\lambda^2 \mathcal{P}_t^n G_t^n}{\left(\mathcal{D}(1+x,y) + h\right)^2}, \tag{12}$$

[8]Please remember the assumption here is that the airplane falls inside the main lobe of both the interfering and serving eNodeB-Es, either due to using isotropic or directional antennas, otherwise the discussion is invalid.

[9]The common way of laying out the cellular network is as follows: start from a cell, chose a direction perpendicular to an edge, move i cells in that direction, turn $\pi/3$ counter-clockwise in the new cell, and move another j cells along the new direction. The arrived cell is the first closest co-channel cell.



(a) (b)

FIGURE 1. Air-ground communication through cellular network. Interference from co-channel cells is shown with straight lines whose thicknesses indicate the interference intensity. (a) 2G/3G networks with $i = 1$ and $j = 3$ (frequency reuse (FR) > 1) with 3 layers of co-channel cells. (b) 4G (LTE) network (frequency reuse (FR) = 1).

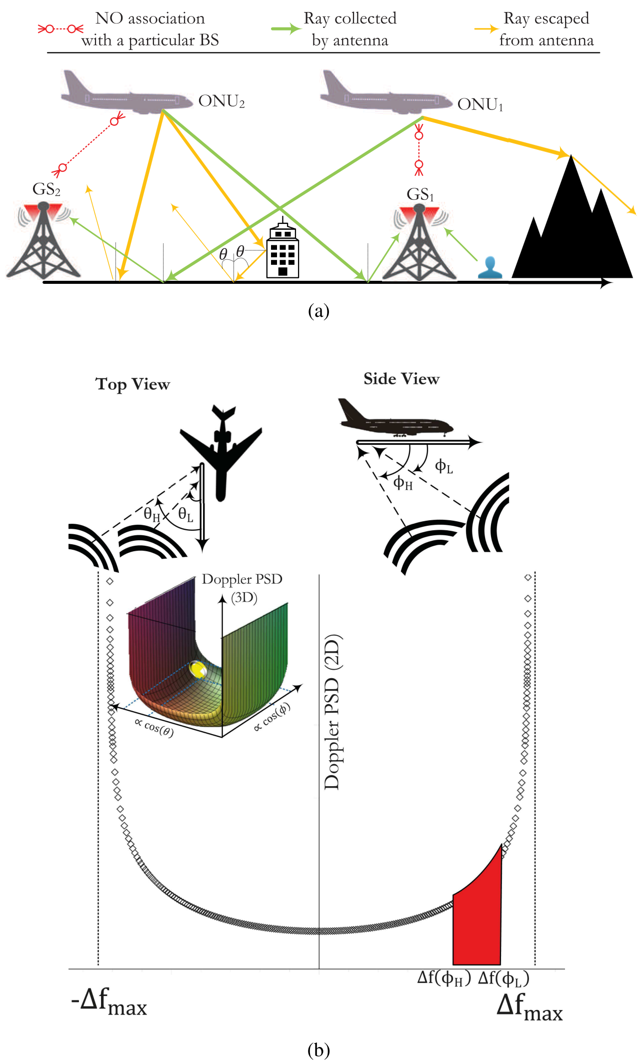


FIGURE 2. Propagation and Doppler effects in air-ground communication. (a) Propagation mechanisms in an air-ground communication scenario. ONU_1/ONU_2 associates with farther GS_2/GS_1. (b) 2D and 3D representation of the Doppler PSD. Zenith/azimuth angles vary within $\theta_L < \theta < \theta_H$ and $\phi_L < \phi < \phi_H$.

where $\mathcal{D}(\cdot, \cdot)$ is given by (10). In the simplistic case where all antennas are isotropic, transmit-powers are equal, and the interfering eNode-Bs in the same layer have exact similar distances from the serving eNode-B. Therefore, (12) can be approximated by

$$\mathcal{P}_I = \frac{\lambda^2 \mathcal{P}_t}{R^2} \big(\Psi\,(m+1-\beta) + \Psi\,(m+1+\beta) - \Psi\,(1-\beta) + \Psi\,(1+\beta) \big), \tag{13}$$

where the imaginary number $\beta = jh/\sqrt{3}R$ and $\Psi\,(\cdot)$ is the *Digamma* function. It is obvious from (13) that in an infinite size network (i.e. when $m \to \infty$), the total interference received by the UE^{air} grows boundlessly, $\mathcal{P}_I \to \infty$. In reality, no network is of infinite size though, thereby, the interference sum remains limited but highly unpredictable due to its large variations. Fig. 3a shows the simulation results for the total interference collected from the neighboring cells in the scenario of Fig. 1b. As it is seen in this plot, the interference cap −69.5dB that is derived in previous section is not satisfied even when there is only one layer of interfering cells (i.e. $m = 1$). Another important implication from this plot is that the interference inflicted by closer cells is larger than the cumulative interference collected by the farther ones. Therefore, these are the immediate neighboring LTE cells whose influence should be eliminated as much as possible. All this implies that air-ground communication through the cellular network where interference pattern is isotropic is infeasible, at least on the paper.

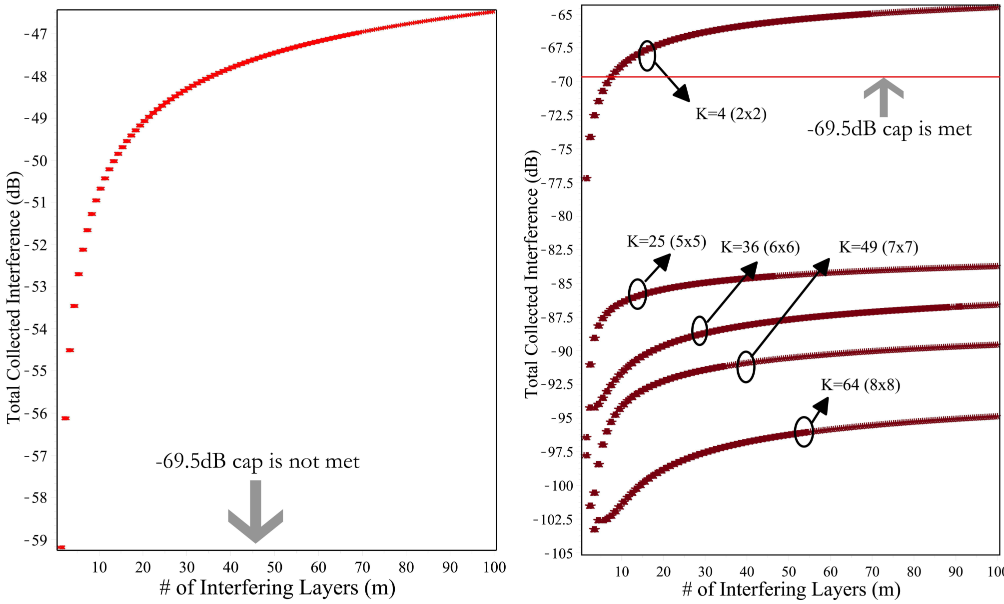
C. BEAMFORMING

A classic digital signal processing technique, called beamforming, is a remedy to the aforementioned problem. Beamforming concentrates the radiating power of transmitter towards a specific direction in space. In practice, this is possible by feeding a number of closely-spaced antenna elements collocated in an array format with the same signal but precoding with different phases and amplitudes. If designed precisely, these phase differences can nullify radiation strength in undesirable directions and magnify it at its boresight (antenna axis), thus, improving the antenna gain. In its simplest form, beamforming is only a narrowing of antenna beamwidth along its axis. For a planar array laid in $X - Y$ plane with inter-element spacing $r = \lambda/2$, uniform weights, and equal phases, the $3D$ array factor (alternatively known as antenna gain) can be written as [21],

$$G\,(\theta, \phi) = \left| \frac{1}{\mathcal{K}_1} \frac{\sin\left(\mathcal{K}_1 \pi r \lambda^{-1} \sin\,(\theta) \cos(\phi)\right)}{\sin\left(\pi r \lambda^{-1} \sin\,(\theta) \cos(\phi)\right)} \right| \times \left| \frac{1}{\mathcal{K}_2} \frac{\sin\left(\mathcal{K}_2 \pi r \lambda^{-1} \sin\,(\theta) \sin(\phi)\right)}{\sin\left(\pi r \lambda^{-1} \sin\,(\theta) \sin(\phi)\right)} \right|, \tag{14}$$

where $\mathcal{K}_1$, $\mathcal{K}_2$ are the total number of cross-polarized dipole antenna elements along the two orthogonal axes (say X and Y) and λ is the wavelength of the radiating wave. Also, θ and ϕ are the respective zenith and azimuth angles in the corresponding polar coordinate. Our simulator corroborates that beamforming damps down the interference and makes the air-ground communication possible by meeting the −69.5dB interference cap. This is depicted in Fig. 3b for different values of $\mathcal{K} = \mathcal{K}_1 \mathcal{K}_2$.

But there is no such thing as a free meal: Narrowing down the beams to reduce interference creates hazard zones at cell boundaries. To be more specific, while using more directional antennas (tighter beamwidth) results in a better service quality within the cell, very large directionality can create zones not covered by any eNodeB-E. This fact is portrayed in Fig. 4. Quiet the opposite, it is the cell boundaries that are of paramount importance, since that is where the interference is stronger and desired signal strength is weaker. They are the bottlenecks of communication seamlessness in any cellular network, especially in air-ground communications where handoff is to be frequently executed. In order to meet both



(a) (b)

FIGURE 3. **Total interference $\mathcal{P}_I$ collected by an airplane from neighboring cells in an LTE network. (a) Isotropic transmit pattern. (b) Directional transmit pattern.**

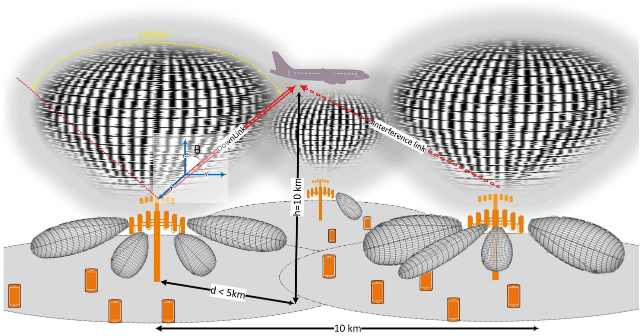


FIGURE 4. **Using directional array antenna for aerial module to reduce co-channel interference.**

coverage and service quality requirements, antenna's half-power beamwidth (HPBW) should satisfy the following two inequalities,

$$2 \arctan\left(\frac{R}{h}\right) < \text{HPBW} < \mathcal{P}_I^{-1}\left(-69.5\text{dB}\right), \qquad (15)$$

where the total interference is described as a function $\mathcal{P}_I(\cdot)$ (of antenna beamwidth) that can be inversed $\mathcal{P}_I^{-1}(\cdot)$ at -69.5dB to attain the boundary beamwidth.

D. BEAM STEERING

Cost-wise and performance-wise, there is a more effective way of utilizing antenna arrays in order to make air-ground communication possible. Known as beam steering, the idea is to track an airplane in the sky by continuously adjusting the array elements' amplitudes and phases in such a way that the airplane always falls within antenna's main lobe. Therefore, beam steering not only creates a directional pattern, but also constantly changes its axis of directionality, a.k.a antenna boresight. This is illustrated in Fig. 5.

Beam-steering is a much more attractive solution for air-ground communication compared to the communication on land. This is due to the fact that exact airplane trajectory is always known beforehand which is in contrast to unpredictable motion of a mobile user on the land. Moreover, it is the very existence of physical obstructions within a cell, especially in urban areas, that makes beam steering less precise. This is because almost all beam steering algorithms need to know precise locations of UEs or signals angles of arrival (AoA). Both of these are difficult to estimate in NLoS situations where due to signal reflection/refraction and diffraction from these obstructions, many versions of the same signal may arrive from different directions. Of course, this is not the case in air-ground scenarios by virtue of the fact that the link is almost always line-of-sight (LoS). Finally, the pointed antenna boresight that is aimed for a land UE, may cause severe interference to other UEs who can fall anywhere within the beamwidth of this antenna. This is, obviously, not the case in air-ground communication as it is unlikely that an airplane passes through the narrow beam of another one. In fact, even if this is a possibility, scheduling can resolve the issue quite easily.

Through steering the beam, several advantages are gained. First, the total interference $\mathcal{P}_I$ received from other co-channel cells are reduced by several magnitudes. Second, the communication range increases as the signal power becomes concentrated towards the desired direction. The latter hugely cuts down operators backbreaking capital expenditure (CAPEX)

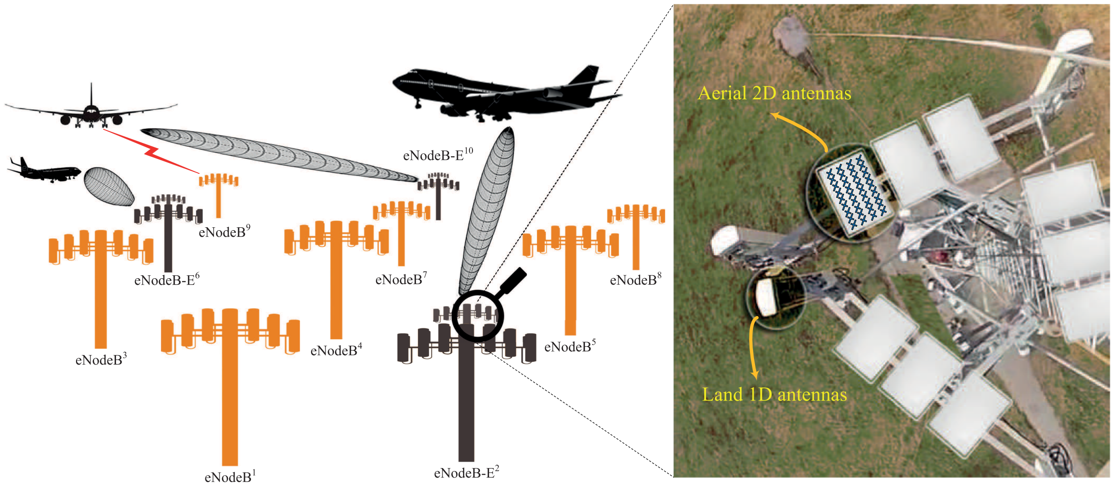


FIGURE 5. **Beam steering technique to reduce interference, CAPEX and OPEX in cellular-assisted air-ground communication. Interference coupling between the terrestrial/aerial LTE modules of two different eNodeBs is shown on the the top-left corner.**

and operational expenditures (OPEX) by requiring only a fraction of eNodeBs to be enhanced (eNodeB-E) to support air-ground communication. This is depicted in Fig. 5 with 3 out of 10 enode-Bs enhanced to support aerial users. Third, the handoff rate, which is one of the main quality of service (QoS) degrading factors in cellular networks, especially in cases where users are highly mobile, is substantially reduced. This is due to the fact that the handoff in LTE involves frequent cell-search operations followed by a series of negotiations between management and controlling entities in network's evolved packet core (EPC) such as mobility management entity (MME) and serving Gateway (S-GW). Alternatively, beam steering is a decision that can almost be made locally, thereby, is fast and reliable.

Having a directional antenna that has restricted beamwidths in both elevation and azimuth planes can be realized through 2D (planar) antenna arrays [21]. Technology-wise, these antennas are no different than linear (columned) cross-polarized antenna arrays (commercially known as sectorized antennas) that are in-use today for serving land UEs. The only difference is that planar antennas are comprised of cross-polarized antenna elements that are distributed in a rectangular lattice, whereas elements in sectorized antennas are distributed over several columns. Therefore, a separate set of planar antennas can be utilized to steer the beam and serve UE^{air}. These aerial antennas are to be laid flat facing the sky either in vertical, horizontal or circular placements, or as a combination of them [21]. This is illustrated in Fig. 5 showing the top-view of an LTE eNodeB-E.

There are situations that beam steering can bring a diminishing return into the system. This happens when the airplane is far away from the serving eNodeB-E (say on top of farther cells) at an elevation angle that is way too low. As showcased in Fig. 5, in the DL direction, UE^{air} attached to eNodeB-E^{10} may receive interference from the terrestrial module of the eNodeB^{9} that transmits over the same frequency. Similar situations can happen in the UL direction where a transmission from UE^{air} to the serving eNodeB-E^{10} may be collected by terrestrial modules of eNodeB^{9} and perhaps other neighboring eNodeBs. To avoid this problem, network-wide coordination among eNodeBs is required. Still, such coordination can be costly for two reasons: first, coordinating the allocation of resources among eNodeB-Es, which may be located tens of kilometers apart, is a difficult and expensive task. Second, it can reduce the spectral efficiency.

E. MULTI-BEAMING AND MU-MIMO

One solution to tackle the coupled interference problem between terrestrial/Aerial LTE modules and control the overhead between eNodeB-Es is to dedicate separate spectrum to these modules. Yet, for the latter method to be economically justifiable, the spectrum dedicated for aerial communication should be as small as possible and other means must be sought to improve its utilization. Multi beaming and multi-user multiple-input multiple-output (MU-MIMO) are among these techniques. Conceptually, both techniques are based on classic spatial division multiple access (SDMA) that takes advantage of the spatial diversity of airplanes in order to improve allocation efficiency as well as reduce the control overhead of the beam steering technique. This has the advantage of serving multiple airplanes from a single eNodeB-E over the same frequency and at the same time without worrying about having coupled interference between terrestrial/Aerial LTE modules or high inter-cellular coordination overhead. Fig. 6 portrays the receiver architecture for the proposed beam steering/MU-MIMO technique. Each eNodeB-E should frequently update the beam former precoding matrices using (a) channel reports that UE^{air}s sent in the preceding UL transmission, (b) UE^{air}s' precise locations, and (c) the AoA of the signals received in the preceding UL direction. It should be noted that the aforementioned reports are sent in response

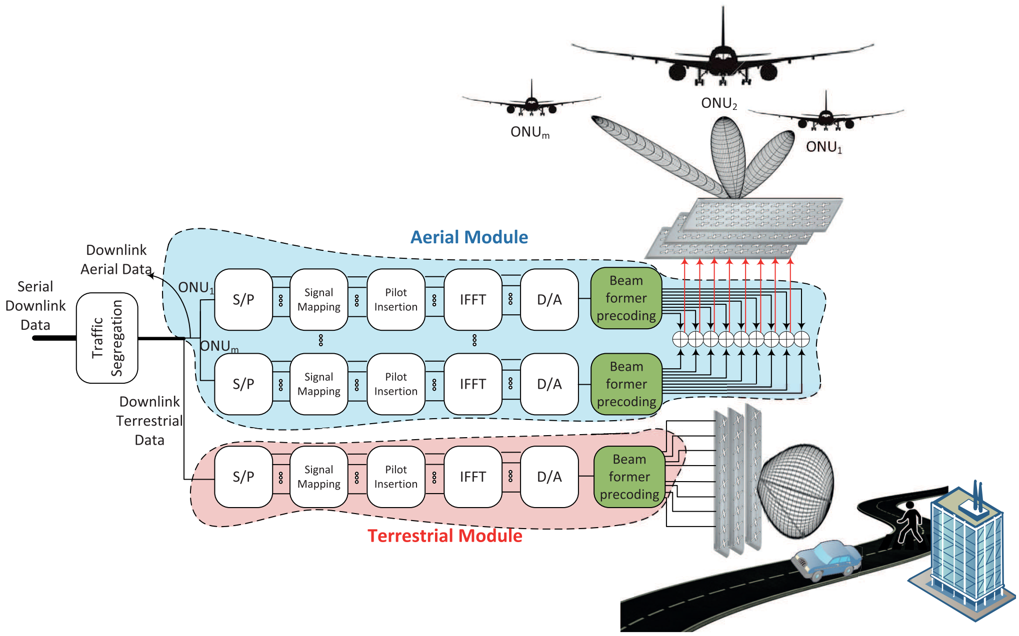


FIGURE 6. Receiver architecture of the eNodeB-E enabled with multi beaming/MU-MIMO technologies.

to reference signals (RSs) that UE^{air}s receive from eNodeB-E in the latest DL subframe.

V. AIR-AIR MULTI-HOP AD-HOC NETWORKING

While the cellular-assisted air-ground communication requires the permanent existence of an operating cellular network on the ground, airplanes may pass through zones where terrestrial coverage can not or do not simply exist. These blind zones can be desserts, lakes, oceans, mountainous regions or simply inhabitable districts whose extent can be thousands of square kilometers. In such situations, direct connectivity to terrestrial network is not possible and other means of communication are to be sought. Even though automatic fallback to SatCom is always the last resort, the aeronautical ad-hoc networking (AANET) appears as an appealing choice. In AANET, a proactive mobility-aware (e.g. [22]) and stable routing protocol is needed in order to establish a multi-hop aerial connection, through a number of ONUs, to the cellular network. Associativity-based routing protocol [23] whose emphasis is on connection durability can be a suitable candidate for deployment in AANET. Such stress on link durability guarantees smoother connection (less frequent aerial handoff event) as well as a smaller Doppler shift as it is the relative speed of two airplanes that influences both. To have a higher throughput and lower delay, authors believe that using AANET is almost always preferred over SatCom, particularly when the number of hops is small. The latter is almost the case, in a country like the U.S., China, India, and the entire European region because of the high population density and deep penetration of mobile networks. The question to be answered is whether AANET is possible given the density of airplanes in the sky.

In that vein, a report published by the national air traffic controllers association (NATCA) in 2015 [24] reveals that, roughly, 5000 planes are in the sky of the U.S. at any given moment. This is equivalent to traffic density $\Lambda = 5.1 \cdot 10^{-4}$ aircraft/km^2. In Europe, this number is more than 25000 planes per day. Assuming no constraint on transmit-power, two ONUs can communicate, if one is located within the visibility zone of the other one. This visibility zone is illustrated by a transparent spherical dome in Fig. 8. From geometry we know that the total area of this dome is equal to

$$\mathcal{S} = 2\pi\, (h + \mathfrak{R})^2\, (1 - \cos(2\theta))\,. \tag{16}$$

Knowing that $\cos(\theta) = \mathfrak{R}/(\mathfrak{R} + h)$ and $\cos(2\theta) = 2\cos^2(\theta) - 1$, the visibility area of an airplane would be equal to [25],

$$\mathcal{S} = 8\pi h\mathfrak{R}(1 + \frac{h}{2\mathfrak{R}})\text{km}^2, \tag{17}$$

where $\mathfrak{R} = 6378$km is the earth radius, and h is the airplane altitude.

When transmit-power is limited, an ONU transmitting with 23dBm (typical UE transmit-power) using 8dB air-air directive antennas is able to reliably communicate with pairs as far away as 500km, provided that the transmitting ONU air-air antenna is directive and can swiftly track (using the beam steering technology described before) the receiver with high precision. The latter prerequisite, also, ascertain that no interference from other sources transmitting over the same frequency is collected. Now, assuming the flight paths are distributed according to spatial *Poisson* distribution with

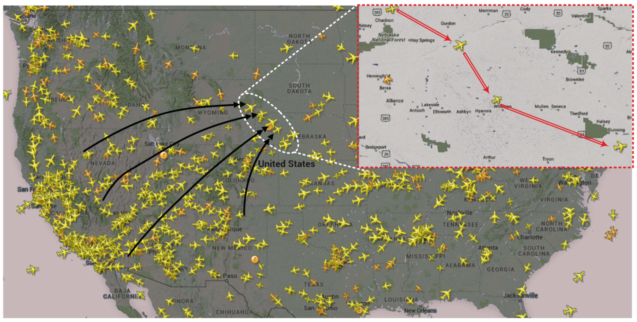


FIGURE 7. Multi-hop ad-hoc networking between airplanes flying in the same direction. Flight trajectories are represented by black splines with double arrow head and communication hops by red straight arrows [source: www.flightradar24.com].

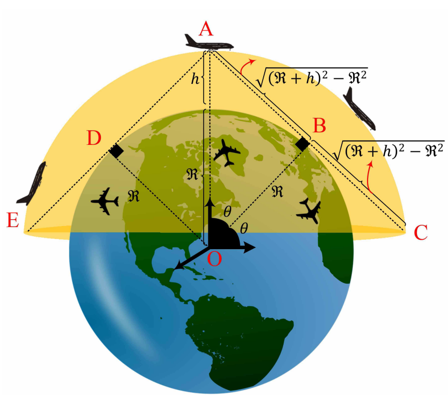


FIGURE 8. The visibility zone of an airplane.

probability mass function

$$\Pr\left(M^{\text{air}}=i\right)=\frac{(\Lambda\mathcal{S})^i}{i!}e^{-\Lambda\mathcal{S}}, \quad (18)$$

the probability of finding at least one communicating pair in both cases is very close to one. Knowing that the Poisson assumption is quite pessimistic and airplane trajectories are a-priori known and not instantaneously varying, in reality better coverage is expected. Hence, the beam tracking (steering) problem on the sky is merely a tuning/precision problem rather than an uncertain prediction/estimation problem. This is better illustrated in Fig. 7. The downside of using a very directive air-air receiver antenna is the connection loss caused by airplane body blockage. This effect, which may occur due to air turbulences or change of direction, can cause complete signal loss and is more severe when the air-air antenna is bottom mounted [26]. On the other hand, if omnidirectional antennas are deployed, a more uniform connectivity is attained at the expense of larger interference allowed into the receiver, and shorter communication ranges.

VI. CONCLUSIONS

Despite the ceaseless efforts to offer better service qualities for mobile users on the land, users on the sky are deprived from very basic services. Even though, the reason for such deprivation was once declared as the negative impacts that the aeronautical transmission could have on the cellular network, this is not a concern any longer with recent advancements in signal processing, antenna design and electronics. Satellite communication is bandwidth-limited and incapable of providing broadband access. On the other hand, preparatory air-ground communication solutions are unscalable, non-standard, and non-competitive. Inspired by the "ubiquitous connectivity to everyone at anytime" promise of 5G networks, this paper investigates the possibility of providing airborne broadband connectivity through existing cellular networks and discusses several possible solutions. It was argued that cellular networks in their current form can not be used for air-ground communications due to the high amount of interference, high Doppler effect, frequent handoff rate and channel impairments. It is explained that by using technologies such as beam-forming, beam steering, and multi-user MIMO, most of the above mentioned shortcomings can be alleviated and cellular networks can be enhanced to provide both terrestrial and aerial connectivity. Aside from the technological aspects, we also explore the economic and societal justifications for operators to step toward providing connectivity to airborne passengers.

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NAVID TADAYON (S'10) received the B.Sc. degree in electrical engineering and telecommunications from Ferdowsi University, Mashhad, Iran, in 2006, and the M.Sc. degree from the University of Massachusetts, Dartmouth, USA, in 2011. He is currently pursuing the Ph.D. degree with the Institut National de la Recherche Scientifique-Energy, Materials, and Telecommunications, University of Quebec, Montreal, QC, Canada. From 2008 to 2010, he was a Researcher with the Iran Telecommunication Research Center. He is currently an Associate Researcher with the École de Technologie Supérieure. His research interests include modeling and analysis of wireless networks as well as designing mechanisms and algorithms for the such networks, with a particular focus on 5G enabling technologies, such as cognitive radio networks, HetNets, and D2D.

He has been the holder of several prestigious Canadian awards, including the NSERC Post-Doctoral Fellowship and the FQRNT Ph.D. Merit Scholarship. The outcomes of his investigations have been a book and dozens of papers published in distinguished transaction journals and flagship conferences.

GEORGES KADDOUM (M'11) received the bachelor's degree in electrical engineering from the École Nationale Supérieure de Techniques Avancées, Brest, France, the M.S. degree in telecommunications and signal processing (circuits, systems, and signal processing) from the Université de Bretagne Occidentale and Telecom Bretagne, Brest, in 2005, and the Ph.D. (Hons.) degree in signal processing and telecommunications from the National Institute of Applied Sciences, University of Toulouse, Toulouse, France, in 2009. Since 2013, he has been an Assistant Professor of Electrical Engineering with the École de Technologie Supérieure (ETS), University of Quebec, Montreal, QC, Canada. In 2014, he was awarded the ETS Research Chair in physical-layer security for wireless networks. Since 2010, he has been a Scientific Consultant in the field of space and wireless telecommunications for several companies (Intelcan Techno-Systems, MDA Corporation, and Radio-IP companies). He has authored over 70 journal and conference papers and holds two pending patents. His recent research activities cover wireless communication systems, chaotic modulations, secure transmissions, and space communications and navigation. He received the best paper award at the 2014 IEEE International Conference on Wireless and Mobile Computing, Networking, and Communications, with three coauthors, and the 2015 IEEE Transactions on Communications Top Reviewer Award.

RITA NOUMEIR received the M.Sc. and Ph.D. degrees in biomedical engineering from Ecole Polytechnique, University of Montreal. She is currently a Professor with the Electrical Engineering Department, École de Technologie Supérieure (ETS), University of Quebec, Montreal, QC, Canada. She has been actively involved with IHE since its inception. As a member of the Radiology IHE Planning Committee, she has been involved in establishing the broad direction and scope for the IHE demonstrations and in planning IHE workshops and other activities. She presented IHE at various international conferences and workshops. As a member of the Radiology IHE Technical Committee, she has participated in developing the IHE integration profiles that are detailed in the actual IHE technical framework. She has written numerous articles in biomedical informatics. She has published and lectured extensively in software analysis and image processing and participated in launching the new software engineering program at ETS. She has provided consulting services, including architecture analysis, workflow analysis, technology assessment, and image processing for several software and medical companies.