Aalborg Universitet

Enabling Cellular Communication for Aerial Vehicles

Providing Reliability for Future Applications

Amorim, Rafhael Medeiros de; Wigard, Jeroen; Kovács, Istvan; Sørensen, Troels Bundgaard; E. Mogensen, Preben

Published in:
I E E E Vehicular Technology Magazine

DOI (link to publication from Publisher):
10.1109/MVT.2020.2980438

Publication date:
2020

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

Citation for published version (APA):
Amorim, R. M. D., Wigard, J., Kovács, I., Sørensen, T. B., & E. Mogensen, P. (2020). Enabling Cellular Communication for Aerial Vehicles: Providing Reliability for Future Applications. *I E E E Vehicular Technology Magazine*, *15*(2), 129-135. Article 9069873. Advance online publication. https://doi.org/10.1109/MVT.2020.2980438

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy
If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from vbn.aau.dk on: April 20, 2024

ENABLING CELLULAR COMMUNICATION FOR AERIAL VEHICLES

Providing Reliability for Future Applications

Rafhael M. de Amorim, Jeroen Wigard, István Zsolt Kovács, Troels B. Sørensen, and Preben E. Mogensen

xxxxx

Due to safety concerns, a reliable radio communication link is a key component in the future application of unmanned aerial vehicles (UAVs), as it will enable beyond visual line-of-sight (BVLOS) operations. In terms of cost and deployment time, radio communication for aerial vehicles will greatly benefit from the ready-to-market infrastructure and ubiquitous coverage of cellular networks. However, these are optimized for terrestrial users, and the different propagation environment experienced by aerial vehicles poses some interference challenges. In this article, field measurements and system-level simulations are used to assess interference-mitigation solutions that can improve aerial-link reliability. We then discuss how 5G New Radio (NR) favors the integration of UAVs into cellular networks, as its flexible air interface and beamforming-suited frequencies facilitate the deployment of interference-management solutions.

Background

In recent years, the popularity of UAVs (also known as *drones*) has experienced rapid growth as technological improvements have significantly reduced their cost and size. UAVs present great potential to reduce the risk, cost, and deployment time of many commercial and civil applications such as surveillance and monitoring, agriculture inspection, and disaster relief, among others [1]. Such potential is currently limited by early regulations, as public authorities need to ensure UAV's safe integration into the manned airspace.

Flight ranges are limited to VLOS in most countries, while technical solutions to enable safe BVLOS flight ranges are being developed. Common to these solutions is the requirement for a highly reliable command and control (C2) link between the UAV and its controller [2]. This article focuses on C2 for UAVs flying at heights up to 120 m. Since the C2 connection must be retained in all phases of the flight, the coverage must be continuous not only at cruise heights but also at ground level, to cover both takeoff and landing procedures.

There are several possibilities to provide the C2 link for UAVs. These include the option to use satellite systems that can provide coverage everywhere in the sky, including over oceans and in remote areas. They likely

Digital Object Identifier 10.1109/MVT.2020.2980438
Date of current version: 16 April 2020

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on April 24,2020 at 06:30:36 UTC from IEEE Xplore. Restrictions apply.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

present latency challenges and limited capacity and have high operation costs. In urban deployments, they may suffer from limited coverage between buildings.

A second option is to use a terrestrial network with a dedicated spectrum. However, UAVs need coverage everywhere, and installing and maintaining a dedicated communication network for the current density of UAVs, which is much lower than that of smartphones in cellular networks, may not be economically attractive.

A third option is to use cellular networks: they are widespread and ready to market, and operation costs are shared with the many cellular network users. Additionally, they have the capacity to provide the payload link for UAV applications such as video streaming and surveillance, and they can provide quality-of-service management combined with secure communications and user equipment (UE) identification. Cellular networks are, however, optimized to provide optimal coverage for terrestrial users, which poses technical challenges in terms of ensuring reliable C2 communications for UAVs (aerial users) [3]–[6]. Given the importance of the topic, the 3rd Generation Partnership Project (3GPP) has conducted a work item regarding enhanced support for UAVs in LTE [5]. Among these enhancements, 3GPP has approved the possibility of UAV-specific power-control (PC) settings and enhancements on mobility-measurement reporting and handover (handoff) mechanisms, as well as improved identification of aerial UE.

The cellular case is exemplified experimentally in this article. Measurements were collected with a 4G LTE modem onboard a UAV connecting to a commercial LTE network. Furthermore, simulation results are used to show the biggest challenges for serving UAVs in cellular networks, as well as the performance improvements offered by some potential solutions, based on the results presented in [4]. Finally, technical enhancements provided by the 5G NR technology are discussed, regarding how that technology supports more reliable communication for UAVs.

Traffic and Requirements

The data traffic related to UAVs can be split into two parts, with different requirements: C2 communication and application payload.

- *C2 link*: This low-data-rate, mission-critical link exchanges flight-related information between the UAV and its controller or operator. It must ensure the controller receives status and flight-related information (telemetry), while also conveying navigation commands and equipment control originating from the controller to control the drone in all phases of the flight. The 3GPP has set the C2 reliability requirements to 99.9%, fulfilling a maximum delay of 50 ms for a 1,250-B packet transmitted every 100 ms [5].
- *Application payload*: The use case specific with requirements is dependent on the UAV service. For example, it can be video streamed for surveillance or inspection [1]. The application payload does not differ from the general mobile broadband data traffic originating from cellular subscribers and is therefore served as a "best-effort" service by network operators.

UAV Radio Connectivity Over Cellular Networks

The radio-propagation conditions are very different for terrestrial and aerial users: aerial users are subject to less radio propagation obstruction from buildings, vegetation, terrain clutter, and others [5]. Therefore, they are more likely to experience radio LOS propagation and lower attenuation toward the base stations (BSs) in the network [7]. Additionally, the higher the UAV flies, the farther the radio link can extend without being blocked by buildings, trees, and the Earth's curvature.

Previous studies have indicated that radio interference is a problem for UAV coverage [5], [7]. Cellular networks are typically optimized for the best terrestrial coverage, which means that the BS antennas are tilted down, pointing toward the ground. Also, the (intersite) distance between BSs is planned to minimize the interference at ground level. The radio path clearance experienced by aerial users, combined with the high density of BSs in cellular networks, creates significant interference at the UAV side. Similarly, the aerial user transmissions will impact a large number of BSs [3].

Live LTE Measurements

To demonstrate the radio-interference challenges that result from connecting UAVs to cellular networks, radio measurement samples collected in a live LTE-operating network were analyzed. The tests provide an illustrative example of the signal quality experienced by a UAV. The data were collected in the urban area of Aalborg, Denmark, and in a nearby area representative of a Danish rural neighborhood in terms of network density and terrain. All data were recorded at night, between 2 and 5 a.m., to minimize the impact that a network can have on the results.

A test UE on the UAV was set to upload a large file via FTP in the reverse link (RL) from the UAV to the network. In the opposite direction [the forward link (FL)], the traffic is generated by the FTP handshake. The UE transmissions were performed at heights (H_{ue}) of 1.5 (ground level) and 100 m. At each height, the transmissions continued for 45 min, emulating video streaming. Different frequency bands were used: the 800-MHz band in the rural area and the 1,800-MHz band in the urban area.

The test UE is capable of recording LTE-related radio access information during the transmissions, including FL reference symbol (RS) received power (RSRP), RL transmit power, FL and RL data throughput, and physical resource block (PRB) usage [11]. Additionally, in RL, the interference-over-thermal noise (IoTN) results were collected from LTE radio cells (typically three on each BS).

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on April 24,2020 at 06:30:36 UTC from IEEE Xplore. Restrictions apply.

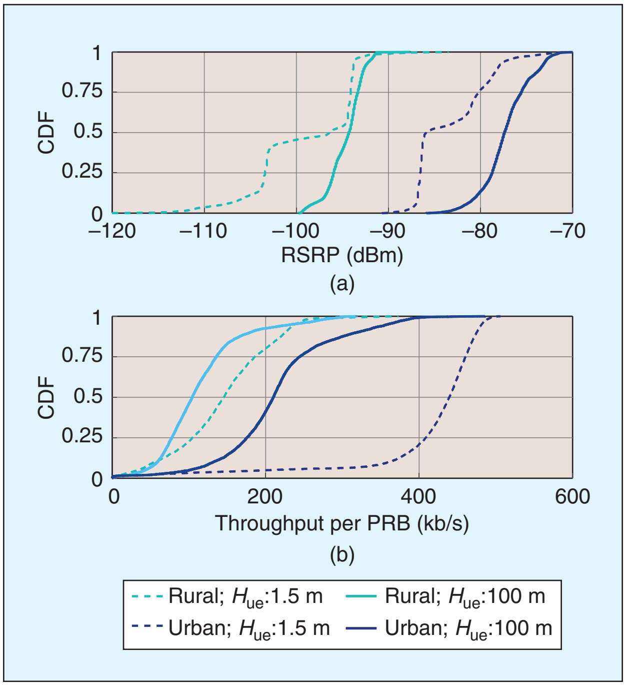

FIGURE 1 The downlink measurements in the urban and rural scenarios: (a) RSRP and (b) throughput per PRB. CDF: cumulative distribution function.

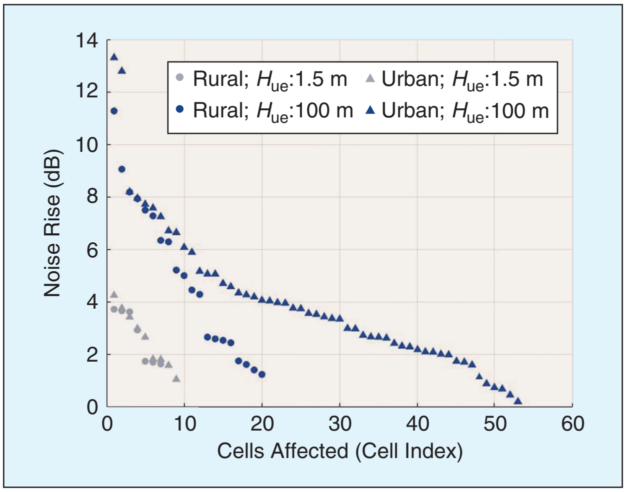

FIGURE 2 The RL noise rise, IoTN, per cell. Cell indices are ranked by the most impacted cell for each case.

In the area covering the measurement locations, each interference-over-thermal sample value corresponds to the median value over a 15-min time interval. The noise rise data were available for all cells in a radius of 15 (rural) and 30 (urban) km from the respective measurement locations.

FL Challenges

Figure 1 shows the FL results from the live LTE measurements. In both scenarios, the signal power, RSRP, was higher for the aerial transmissions due to improved radio clearance in the propagation and despite the downward tilt of the BS antennas. Differences between urban and rural values for RSRP are related to the distance between the serving cell and the measurement locations. Despite the better RSRP, the throughput per PRB was degraded for the aerial transmissions because of the lower signal-to-interference-plus-noise ratio (SINR). In the urban case, which has a higher BS density and hence more interference, the degradation was higher. Therefore, in both cases, transmission is less spectrally efficient, i.e., less data conveyed per radio resource (PRB).

Moreover, the performance degradation may be partially attributed to what is known as *pilot pollution*. Although the average traffic load in the network is expected to be low in the night hours of the test, RSs are transmitted constantly across the system bandwidth in LTE: for two-antenna port transmissions, 9.5% of PRB resources are used for RS. When a UE can detect reference symbols from multiple sources, as aerial UEs are likely to do because of the radio clearance, the RS SINR degrades, and the link performance is impacted.

Our main observation is that, in denser networks or in high-load traffic conditions, this degradation can mean more resources will be required to serve the aerial UE, which will otherwise occupy the cell capacity available for terrestrial UEs (TUEs).

RL Challenges

Due to path loss reciprocity, the signal strength received from the aerial UE is also high at the serving and other BSs, causing more harmful interference than that from terrestrial users. To illustrate this, the IoTN measured when emulating a full buffer transmission is compared to a baseline extracted from seven days of data over the same time frame.

Figure 2 shows the noise increase for the most impacted cells in each measurement, ranked by the amount of impact. It is observed that the aerial UE transmissions cause significantly more interference than the ground-level transmissions: nine and seven cells were affected at ground level compared to 48 and 20 at 100 m, for the urban and rural scenarios, respectively. A cell is defined as affected if the median noise rise during a given test is above the 99th percentile of the baseline level.

Techniques to Improve UAV Connectivity

The measurements presented in the "UAV Radio Connectivity Over Cellular Networks" section show that the interference, either caused by or toward the UAVs, is one of the key challenges to address when operating UAVs in cellular networks. To this end, this section presents several interference-mitigation solutions for UAVs.

Interference Cancellation

The typical solution to address the FL intrusion problem is implementing advanced interference-mitigation

Authorized licensed use limited to: Aalborg Universitetsbiblioteket. Downloaded on April 24,2020 at 06:30:36 UTC from IEEE Xplore. Restrictions apply.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

capabilities at the UE side. For example, earlier versions of LTE supported interference-rejection-combining (IRC) techniques that perform interference suppression by means of linear operations.

Later, LTE introduced interference cancellation (IC) in the form of more advanced and nonlinear techniques for network-assisted IC and suppression [8]. These IC techniques try to reconstruct the interfering signal and successively remove it from the received signal. However, the number of sources that can be suppressed is limited by the number of antennas available at the UE side, and the efficiency is limited by the dominant-to-others interference ratio (DIR), i.e., how much stronger the strongest interferer is compared to the total interference.

Intercell Interference Coordination

Intercell interference coordination (ICIC) is a network-based solution for the FL interference that blanks certain time and frequency resources, and hence transmissions, in the neighbor cells to protect the signal transmitted by a given BS. In other words, the resources that carry the C2 data can be protected from transmission in neighbor cells.

The LTE physical downlink control channel (PDCCH) conveys all of the radio control signaling for maintaining the radio connection. If the PDCCH is incorrectly decoded, the user cannot receive/decode or transmit the application data. In the first LTE release, the PDCCH always occupies the same position, at the beginning of each subframe, over the full bandwidth. Therefore, to protect the PDCCH of a given cell in a subframe, all neighbor cells must be prevented from transmitting data in that subframe, a solution known as the *almost blank subframe*. The drawback is reduced spectral efficiency as a result of the blanked subframes. In later releases, enhanced PDCCH (ePDCCH) is introduced; here, some data resources are converted into user-specific PDCCH resources for one or more users [9]. Using ePDCCH, it is possible to perform ICIC by blanking only part of neighbor cells' subframes, reducing the overall spectral efficiency loss.

Beam Switching at the UE side

The UEs are typically mobile devices whose orientation varies constantly, so they transmit and receive omnidirectionally. Compared to TUEs, UAVs cannot rely on physical obstructions to attenuate the undesired signals and therefore are likely to receive and, conversely, cause high interference to and from all directions.

By switching among a set of directive beams, the UAV can potentially mitigate the interference impact in both FL and RL. Since UAVs are not limited to a small form factor, they can support multiple-antenna deployments to increase the desired signal level and decrease interference.

Power Control

In the RL, the PCs, either open loop (OLPC) or closed loop (CLPC), adjust the UE transmit power in response to the wireless channel conditions, increasing the power when the losses increase. The interference caused by aerial UEs can be further reduced by applying stricter OLPC settings. For C2, with a low data rate, a lower transmit power may be compensated for with additional resources and more robust coding and modulation.

Performance Evaluation

In [4], extensive system-level simulations are used to evaluate interference-mitigation techniques to enhance UAV connectivity in a rural scenario. The simulations are performed in a framework used to investigate user mobility in LTE, as detailed in [4] and [10]. These UAV simulation results showed that the performance of the different interference-mitigation techniques vary with the scenario conditions, such as UAV height and network load.

Using the same simulation framework, this section presents the performance of several interference-mitigation solutions for UAVs, described in the "Techniques to Improve UAV Connectivity" section, when evaluated under the more challenging conditions of an urban scenario. To obtain a realistic large-scale evaluation, an actual LTE 800-MHz network configuration, deployed in the city of Aalborg, is imported into the simulator. The main parameters used for the simulations are listed in Table 1. The UAV users, corresponding to 1% or 10% of the total number of users, are deployed at a height of 120 m, which is compatible with the regulatory limit enforced in most countries. The TUEs use a finite buffer traffic model, while the UAVs have only a C2 link in the FL. In the RL, both UAVs and TUEs use a finite buffer traffic model. All UEs (TUEs as well as UAVs) are assumed to be moving at a constant speed of 30 km/h.

An LTE link adaptation is used, which means that, when the channel SINR conditions degrade, a more robust modulation and coding scheme can be adopted, at the expense of more radio resources used to maintain the same data throughput. In our simulations, the radio-link SINR is monitored and compared to two thresholds: Q_{out}, which defines the minimum level required to detect the most robust PDCCH multicircuit substation, and Q_{in}, which is the SINR required for recover the PDCCH. Outage is defined based on the ability to detect the PDCCH.

Figure 3 shows the outage results for the different studied interference-mitigation schemes when 1% of the users are UAVs. For IC, perfect cancellation of the three strongest interferers is assumed. A perfect cancellation provides an upper bound to the performance enhancement offered by IRC and IC techniques. In both load cases, there is no significant reliability gain from IC, defined as the reduction of time spent in outage. To increase this gain, more interfering cells must be cancelled, increasing the receiver complexity. Due to the high LOS probability and high cell density, the DIR tends to be low, which can compromise the efficiency of such techniques in practical implementations.

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on April 24,2020 at 06:30:36 UTC from IEEE Xplore. Restrictions apply.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE 1 The simulation parameters.

Parameter	Value
Number of cells	300
Intersite distance	470–7,600 m (average: 1,900)
Channel model	3GPP UMa model [5]
FL transmit power	49 dBm
System bandwidth	20 MHz
Carrier frequency	800 MHz
MIMO configuration	FL: two transmit, two receive RL: one transmit, two receive
2D shadowing correlation distance	25 m
Shadowing correlation between cells	0.5 (sites), 1 (cell)
Total number of UEs (TUE and UAVs combined)	3,000
User velocity	30 km/h
TUE FL traffic type	Finite buffer, 20 Mb/s
TUE FL packet interarrival time for medium and high loads	40 s (medium load) and 10 s (high load)
UAV FL C2 traffic type	Constant bit rate, 100 kb/s
TUE and UAV RL traffic	Finite buffer
SINR threshold Q_{out} and Q_{in}	–8 dB and –6 dB
Maximum RL transmit power	23 dBm
Open loop power control	P0 = –98 dBm per PRB, $\alpha = 0.8$
Delta P0 for UAVs	0, –3 dB, –6 dB
Duration of each simulation	200 s

MIMO: multiple-input, multiple-output.

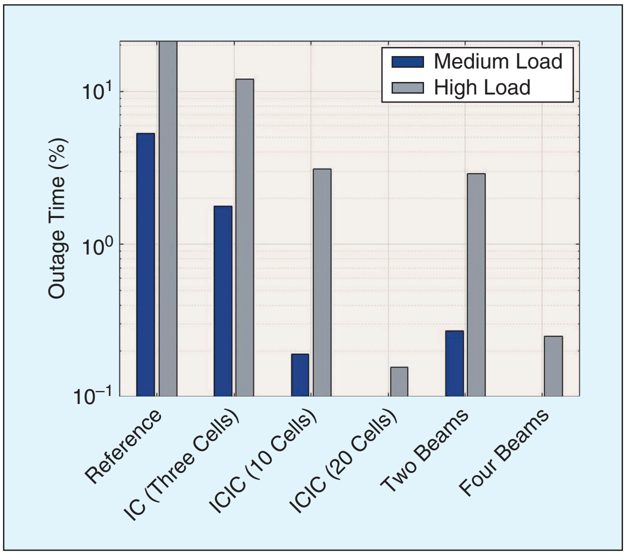

FIGURE 3 The outage time of UAVs for the reference case and different interference-mitigation solutions at medium and high load. UAVs are 1% of the number of users in simulations.

Figure 3 also includes ICIC simulation results considering the transmission blanking from the first 10 and 20 cells, which are selected as the most interfering. It is possible to infer that, in high load conditions when network resources are needed more, a high number of blanked cells is required to substantially improve the outage of an UAV. Moreover, coordinating such a large number of cells may be very complex in real deployments, especially when several UAVs are being served from different BSs in the same geographical area.

The terminal beam-steering results in Figure 3 indicate that the overall outage improves significantly with this UE antenna system, for both two and four beams. A setup similar to the one proposed in [4] is used, with two and four fixed-orientation directive antennas at the UE, having a 90° beamwidth, 6.6-dBi gain, and 13-dB front-to-sidelobe attenuation [4]. The active beam is chosen for both signal reception and transmission and is the one that maximizes the reference symbol received quality, akin to the reference symbol SINR. A comparison of the results for two and four beams suggests that deploying more beams can improve the reliability of the system even further.

Figure 4 focuses on the RL and shows the throughput improvement achieved by UAV-specific power control setting and beam steering for different drone densities at a medium system load. It leads to the conclusion that directive antenna elements can significantly increase UAV throughput compared to the omnidirectional antenna. The TUEs' throughput also benefits from UAV beam steering, due to less radiated interference, especially for the higher density of UAVs in the system.

For the power-control settings, the α value is the compensation factor for the path loss, while user-specific parameter P0 is the target receive power level at the BS for each aerial UE, which was reduced with 3 and 6 dB. Results show that this aerial UE-specific PC reduces the overall RL interference in the network and the TUE throughput increases compared to the reference case. This increase is more significant with a higher density of UAVs in the system, e.g., 1% versus 10% of UAVs. These gains, however, come at the expense of decreased UAV RL throughput. In the scenario with 10% of UAVs, the UAV RL throughput is reduced 14% when the P0 is reduced by 3 dB (from 3.54 to 3.05 Mb/s) and 20% for a 6-dB reduction (2.86 Mb/s)

Moving Forward with 5G NR

The 3GPP has recently finalized release 15, a new technological standard that is the first to include 5G NR. These technologies bring solutions that can significantly contribute to UAVs' integration into cellular networks.

User-Specific PDCCH

In LTE, user-specific PDCCH was not foreseen in the first releases. Hence, the ePDCCH is not a natively designed

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on April 24,2020 at 06:30:36 UTC from IEEE Xplore. Restrictions apply.

solution and therefore presents some inefficiencies. First, the ePDCCH is set up through reconfiguration signaling messages that require decoding of the legacy PDCCH channel. Also, the ePDCCH require a predetermined set of resources [9]. In 5G NR, the PDCCH is set in user-specific positions in the frame [11], which open many beamforming possibilities and facilitate more efficient ICIC solutions compared to LTE.

User-Specific Reference Symbols

In the "UAV Radio Connectivity Over Cellular Networks" section, pilot pollution was mentioned as one important cause of interference in LTE, even for low-traffic-load scenarios. In 5G NR, reference symbols are user specific [11] and not transmitted if the resources are unallocated to any user. Hence, especially in very dense networks and interference-limited scenarios, 5G NR radio performance is improved.

Higher Frequencies and Beamforming

Recent network deployments have adopted beamforming, a technique that linearly combines the signal from multiple antenna elements to generate high antenna directivity. The higher the number of antennas, the more directive are the generated beams. The different 3GPP LTE releases offer different options that can be used for beamforming at the cell side. However, it can be difficult to estimate the angular directivity in scenarios with severe multipath. UAVs are suited for beamforming techniques because they are likely to experience LOS and hence can increase the (coherent) antenna gain in the direction of the serving cell.

There are ongoing discussions in 5G to implement beamforming at the UE side, which can significantly improve UAV performance. 5G NR proposes different bandwidths and carrier frequencies compared to LTE: for example, carrier frequencies above the 6-GHz band and in the millimeter-wave (mm-wave) spectrum (between 30 and 300 GHz). These frequencies are usually assumed for small-cell coverage, as they are subjected to higher path losses. However, the antenna elements get smaller at higher frequencies, and with this it becomes feasible to assemble more elements into the same physical spaces, enhancing beamforming performance. In [12], Geraci et al. show that the use of beamforming can significantly improve the performance of UAV users. An elaborate discussion of mm-wave suitability for the UAV use case is given in [13].

On-Demand Power Boost

5G NR will likely introduce more advanced techniques for interference coordination than LTE [14]. Among those, it will allow dynamic, on-demand power boost (and muting) of specific signals. This solution offers increased degrees of freedom for interference coordination by allowing boosting of most interfered signals in the FL, such as the UAV C2.

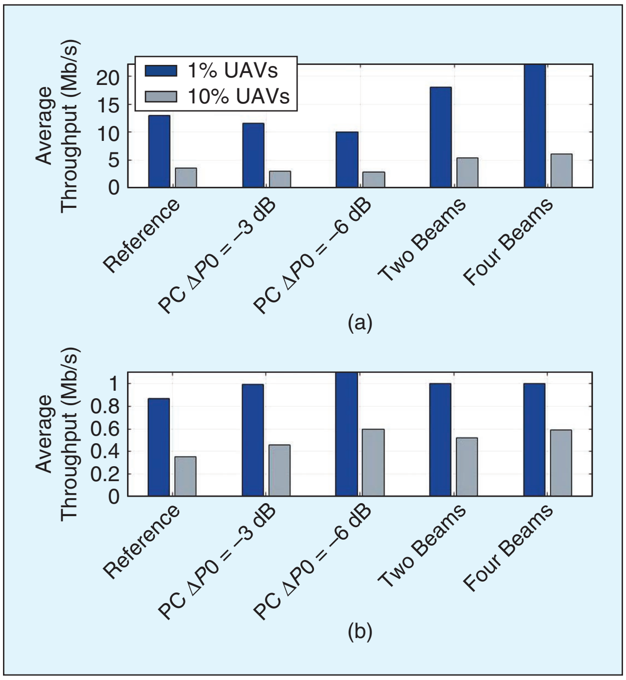

FIGURE 4 The average uplink throughputs for (a) UAVs and (b) terrestrial users in medium-load simulations for the reference case and different interference-mitigation solutions and UAV densities.

Dedicated Spectrum

5G NR solutions also open up possibilities for smart management of the spectrum. In other words, such solutions make it possible to reserve time-frequency resources on the cellular band specifically for UAVs using an on-demand basis. However, there still are some challenges involved in identifying the demand and the UAVs connected to the system to perform this resource allocation [15]. Another challenge is to estimate the area in which the resources should be blocked for terrestrial users: too large areas mean an inefficient use of spectrum, while too short areas may not be enough to mitigate the interference.

Conclusions

Existing cellular networks are a natural choice for providing the C2 link of future drone-based operations. For example, their ubiquitous coverage allows for drone applications in many areas of interest, and the economy of scale associated with current cellular technology will make the integration of drone services with manned aviation economically feasible. However, there are technical challenges to overcome.

Measurements presented in this article show that cellular networks face interference challenges in terms of integrating UAVs, making the required C2 link to the UAV unreliable. Based on simulations, it was shown that a number of interference-mitigation techniques can be used to enhance the reliability of the UAV C2 link, as well as preserve the connection quality of existing terrestrial users. However, there are also limitations and

Authorized licensed use limited to: Aalborg Universitetsbiblioteket. Downloaded on April 24,2020 at 06:30:36 UTC from IEEE Xplore. Restrictions apply.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

inefficiencies for these solutions in current LTE networks. The 5G NR air interface, operating at higher frequency bands and with improved flexibility compared to LTE, addresses some of these inefficiencies and puts cellular networks in an even better position for integrating UAV-based services alongside mobile broadband and other services.

Acknowledgments

This research received funding from the SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant 763601. The research is conducted as part of the DroC2om project.

Author Information

Rafhael M. de Amorim (rafhael.medeiros_de_amorim@nokia.com) is with Nokia Bell Labs Denmark, Aalborg. His main interests are performance enhancements on the physical layer transceiver and media access control layers in 3rd Generation Partnership Project technologies, especially regarding unmanned aerial vehicle connectivity and the deployment of nonterrestrial networks (satellites).

Jeroen Wigard (jeroen.wigard@nokia.com) is with Nokia Bell Labs Denmark, Aalborg. He is involved in studies and 5G standardization related to unmanned aerial vehicles and nonterrestrial networks.

István Zsolt Kovács (istvan.kovacs@nokia.com) is a senior research engineer with Nokia Bell Labs Denmark, Aalborg. where he conducts research on machine learning-driven radio resource management and radio connectivity evolution for nonterrestrial and aerial vehicle communications in LTE and 5G networks.

Troels B. Sørensen (tbs@es.aau.dk) is an associate professor with the Section for Wireless Communication Networks, Aalborg University, Denmark. His research and teaching activities include cellular network performance and evolution, radio resource management, propagation characterization, and related experimental activities.

Preben E. Mogensen (pm@es.aau.dk) is a principal scientist in the Standardization Research Lab, Nokia Bell Labs Denmark, Aalborg, and a full professor with the Department of Electric Systems, Aalborg University, Denmark. His research interest includes industrial use cases for 5G, 5G evolution, and 6G.

References

[1] M. Mazur et al., "Clarity from above: PwC global report on the commercial applications of drone technology," PwC, Warsaw, Poland, Tech. Rep., May 2016. [Online]. Available: https://www.pwc.pl/pl/pdf/clarity-from-above-pwc.pdf

[2] "European drones outlook study: Unlocking the value for Europe," SESAR Joint Undertaking, Brussels, Belgium, SESAR Tech. Rep., Nov. 2016. https://www.sesarju.eu/sites/default/files/documents/reports/European_Drones_Outlook_Study_2016.pdf

[3] B. V. D. Bergh, A. Chiumento, and S. Pollin, "LTE in the sky: Trading off propagation benefits with interference costs for aerial nodes," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 44–50, May 2016. doi: 10.1109/MCOM.2016.7470934.

[4] H. C. Nguyen, R. Amorim, J. Wigard, I. Z. KováCs, T. B. Sørensen, and P. E. Mogensen, "How to ensure reliable connectivity for aerial vehicles over cellular networks," *IEEE Access*, vol. 6, pp. 12,304–12,317, Feb. 2018. doi: 10.1109/ACCESS.2018.2808998.

[5] "Enhanced LTE support for aerial vehicles version," 3GPP, Tech. Rep. 36.777 v 15.0.0, Jan. 2018.

[6] "Evolving cellular technologies for safer drone operation," Qualcomm 5G White Paper and Presentations, Qualcomm, San Diego, CA, Tech. Rep., Oct. 2016. [Online]. Available: https://www.qualcomm.com/media/documents/files/leading-the-world-to-5g-evolving-cellular-technologies-for-safer-drone-operation.pdf

[7] R. Amorim, H. Nguyen, P. Mogensen, I. Z. Kovács, J. Wigard, and T. B. Sørensen, "Radio channel modeling for UAV communication over cellular networks," *IEEE Wireless Commun. Lett.*, vol. 6, no. 4, pp. 514–517, Aug. 2017. doi: 10.1109/LWC.2017.2710045.

[8] V. Fernandez-Lopez, K. I. Pedersen, J. Steiner, B. Soret, and P. Mogensen, "Interference management with successive cancellation for dense small cell networks," in *Proc. 2016 IEEE 83rd Vehicular Technology Conf. (VTC Spring)*, pp. 1–5. doi: 10.1109/VTCSpring.2016.7504295.

[9] S. Ye, S. H. Wong, and C. Worrall, "Enhanced physical downlink control channel in LTE advanced Release 11," *IEEE Commun. Mag.*, vol. 51, no. 2, pp. 82–89, Feb. 2013. doi: 10.1109/MCOM.2013.6461190.

[10] I. Viering, M. Dottling, and A. Lobinger, "A mathematical perspective of self-optimizing wireless networks," in *Proc. 2009 IEEE Int. Conf. Communications*, Dresden, Germany, pp. 1–6. doi: 10.1109/ICC.2009.5198628.

[11] "NR; Physical channels and modulation," 3GPP, Tech. Rep. 38.211 v 15.0.0, Jan. 2018.

[12] G. Geraci, A. Garcia-Rodriguez, L. G. Giordano, D. Lopez-Perez, and E. Bjoernson, "Supporting UAV cellular communications through massive MIMO," in *Proc. 2018 IEEE Int. Conf. Communications Workshops (ICC Workshops)*, Kansas City, MO, pp. 1–6. doi: 10.1109/ICCW.2018.8403630.

[13] Z. Xiao, P. Xia, and X.-g. Xia, "Enabling UAV cellular with millimeter-wave communication: Potentials and approaches," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 66–73, May 2016. doi: 10.1109/MCOM.2016.7470937.

[14] B. Soret et al., "Interference coordination for 5G new radio," *IEEE Wireless Commun.*, vol. 25, no. 3, pp. 131–137, Nov. 2017. doi: 10.1109/MWC.2017.1600441.

[15] R. Amorim, J. Wigard, I. Kovács, T. Sørensen, and P. Mogensen, "Forecasting spectrum demand for UAVs served by dedicated allocation in cellular networks," in *Proc. IEEE Wireless Communications and Networking Conf. (WCNC)*, Marrakech, Morocco, 2019, pp. 1–6. doi: 10.1109/WCNCW.2019.8902713.

VT

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on April 24,2020 at 06:30:36 UTC from IEEE Xplore. Restrictions apply.