Hellaoui, Hamed; Chelli, Ali; Bagaa, Miloud; Taleb, Tarik

Towards Mitigating the Impact of UAVs on Cellular Communications

Published in:
2018 IEEE Global Communications Conference, GLOBECOM 2018

DOI:
10.1109/GLOCOM.2018.8648083

Published: 01/01/2018

Document Version
Peer reviewed version

Towards Mitigating the Impact of UAVs on Cellular Communications

Hamed Hellaoui[1], Ali Chelli[2], Miloud Bagaa[1], and Tarik Taleb[1]

[1]Communications and Networking Department, Aalto University, Finland. Email:firstname.lastname@aalto.fi
[2]Faculty of Engineering and Science, University of Agder, 4898 Grimstad, Norway. Email: ali.chelli@uia.no

***Abstract*— The next generation of Unmanned Aerial Vehicles (UAVs) will rely on mobile networks as a communication infrastructure. Several issues need to be addressed to enable the expected potentials from this communication. In particular, it was demonstrated that flying UAVs perceive a high number of base stations (BSs), consequently causing more interferences on non-serving BSs. This unfortunately results in decreased throughput for ground user equipments (UEs) already connected. Such a problem could be a limiting factor for mobile network-enabled UAVs, due to its consequences on the quality of experience (QoE) of served UEs. This underpins the focus of this article, wherein the effect of UAVs' communication on ground UEs in the *uplink scenario* is studied. First, given the fact that the nature of flying UAVs introduces particularities that make the underlying communication models different from traditional ones, this work proposes a model for mobile network-enabled UAVs (considering interferences, path loss, and fast fading). Moreover, we also tackle the QoE issue and propose an optimization solution based on adjusting the transmission power of UAVs. Simulations are conducted to evaluate the mobile network performance in the presence of flying UAVs. Our results reveal that as the number of added UAVs increases, a significant increase in the outage is observed. We demonstrate that our power optimization strategy guarantees the QoE for UEs, offers good communication links for UAVs, and reduces the overall interference in the network.**

I. Introduction

Estimated at 3 million units in 2017, the production of Unmanned Aerial Vehicles (UAVs also known as drones) is growing rapidly. This increase reflects the success that UAVs are achieving in both personal and commercial sectors. Indeed, UAVs have become an integral part of several critical applications, such as rescue management, first aid, and crowd surveillance. Their ability to move could be exploited to deliver packets, achieving therefore reduced cost and time compared to terrestrial vehicles. Companies such as Amazon and Finnish post are exploring the possibility of using drones to transport their packets. Recently, UAVs have demonstrated many potentials in providing services related to the Internet of Things (IoT). When equipped with the dedicated devices (e.g. sensors, cameras), they can be oriented to a specific area and perform the measurements requested by users [1]. As their use cases are countless, many regulation efforts are made to ease the spread of drones in the future.

Both scientific and industrial communities perceive an opportunity in using mobile networks as a communication infrastructure for UAVs. This will push the boundary of their applications and take them to a new stage. Indeed, as consequence of the limited range of their underlying communication technology (e.g. Telemetry radio, WiFi, etc.), the usage of drones is nowadays more restricted to visual line-of-sight scenarios. This goes against the potential applications expected from drones, where they are supposed to travel far from their control center (e.g. for cargo delivery or for providing IoT services). One of the most important benefits from considering mobile networks for UAVs is the achievement of beyond visual line-of-sight, in which communication between the drones and the controller goes via the cellular networks. The latter are today widely deployed, ensuring therefore the necessary coverage for UAVs and their related applications. In addition, drones will also benefit from the efficiency of mobile networks. Through the current Long Term Evolution (LTE) and the upcoming 5G networks, UAVs would achieve zero delay and higher throughput, which are very crucial given the critical nature of drone applications. The usage of mobile networks has become the future direction for Unmanned Aerial Vehicles.

Beside the potentials that could be achieved from mobile network-based UAVs, several issues need to be addressed. For instance, when communicating through cellular networks, flying UAVs perceive a high number of terrestrial base stations (BSs). This is mainly due to the line-of-sight propagation conditions to the UAVs, and thus more cells become detectable. For the uplink scenario (from the connected devices to BSs), a drone can experience better channel conditions compared to a UE on the ground (because of the close free-space signal propagation) [2]. However, it was also demonstrated that ground UEs could be affected negatively, in that way their throughput is degraded. Indeed, as result of the high number of detectable BSs, each UAV could cause interferences on the non-serving BSs. As the number of connected UAVs increases, the throughput for terrestrial UEs is degraded. This could be a key limiting factor for the development of mobile network-based UAVs, as it directly affects ground devices already connected.

In the literature, some works dealing with computation offloading and mobile edge computing in UAVs consider the case of cellular networks (e.g. [3]–[5]). However, the communication itself was not the focus of these works and its effect on the network was not studied. Other works such as [6], [7] consider mobile networks with drone-testbed communicating from the ground. Nevertheless, the communication model in the sky is different compared to that in the ground, which would lead to different effects and results. Beside the fact that the impact of UAVs on cellular communications can be reduced by shifting part of the communication from the ground to be performed in the air by the UAVs [8], many applications are based on the direct communication between the UAVs and the BSs. With this perspective, 3rd Generation Partnership Project (3GPP) has recently started performing real field tests, considering the inputs from several partners such as Ericsson and Nokia. The results provided in the Technical Report TR 36.777 [9] conclude that flying UAVs could cause considerable interferences on non-serving BSs, leading therefore to reduced throughput for terrestrial UEs.

To deal with the problem, this paper conducts a study on the effect of UAVs communication over mobile networks. Given the lack of works that consider the nature and the characteristics of drones, this study is a step forward towards cellular network-enabled UAVs. First, as the fading channel of mobile network-enabled UAVs is different compared to traditional ones, a communication model is proposed considering the characteristics of flying UAVs. While some recent works have focused on the use of UAVs as mobile BSs [10]–[12], mobile network-enabled UAVs are less studied and more challenging. The model we propose in this paper goes further than the prior works by considering interference, path loss, and fast fading in order to reflect more the reality. Moreover, we also tackle the issue of QoE and propose a solution based on adjusting the transmission power of the UAVs. A problem formulation and an optimization solution are provided to achieve the objective. This would enable the coexistence of ground UEs and flying UAVs, but also reduce the energy consumption of the drones.

The rest of this paper is organized as follows. We introduce our proposed communication model for mobile network-enabled UAVs in Section II. To enhance the QoE in such network, a problem formulation and an optimization solution are provided in Section III. Thereafter, Section IV describes the conducted simulations and illustrates the obtained results. Finally, Section V concludes the paper.

II. Communication model for mobile network enabled-UAVs

With the perspective of UAVs communicating over mobile networks, regulations are seeking towards establishing systems for managing the traffic. NASA has made much progress for this purpose with its UTM [13]. The management system is always aware of the different information about the UAVs, so it can efficiently orchestrate them. Our proposed framework can be set up on the top of this orchestration system for the purpose of achieving the expected QoE in the network.

We consider a set, $\mathbb{B}$, of terrestrial BSs deployed to serve devices. This include both UEs on the ground, as well as flying UAVs. The sets of UEs and UAVs are denoted, respectively, by $\mathbb{U}$ and $\mathbb{V}$. The **uplink scenario** is considered in which data is sent from the connected devices to the BSs. As in similar works [10]–[12], we consider that BSs use a Orthogonal Frequency Devision Multiple Access (OFDMA) technique to serve their users, resulting in no intracell

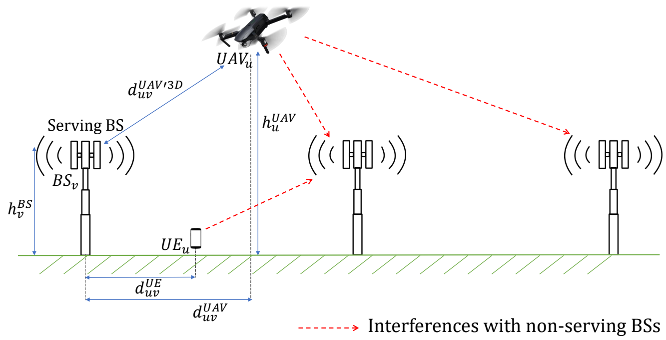

Fig. 1: Uplink system model: a UAV and a terrestrial UE creating interference to neighboring BSs.

interferences. However, intercell interferences are possible from devices connected to other BSs. The interference can be caused either by a UAV or a ground UE. Nevertheless, as a drone can have a line-of-sight (LoS) condition with several BSs, it causes significant interference (see Fig. 1). We use uv to denote the link from a device u to its serving BS v, while tv stands for the link from a device t interfering to the BS v. In (1), we express the received signal y_v at the BS v, which includes the contribution of both the signal of interest and interfering signal

$$y_v = \alpha_{uv}\sqrt{P_u}x_u + \sum_{t\in\mathbb{U}\cup\mathbb{V}}^{t\neq u} \alpha_{tv}\sqrt{P_t}x_t + n_v \tag{1}$$

where α_{uv} and α_{tv} refer respectively to the fading coefficients of the links uv and tv. P_u and P_v denote respectively the transmission powers of devices u and v, while x_u and x_t refer to the transmitted symbols by devices u and t, respectively. n_v is a zero-mean additive white Gaussian noise with variance N_0. Let γ_{uv} denote the instantaneous received signal-to-noise ratio for the link uv, which can be expressed as

$$\gamma_{uv} = P_u/N_0\alpha_{uv}^2. \tag{2}$$

As the transmitting device (u or t) can be a UE or a UAV, the corresponding fast fading and path loss are different accordingly. In the case where the signal is received from a UE, the fast fading follows a Rayleigh distribution and the mean value of γ_{uv} can be expressed as

$$\bar{\gamma}_{uv} = P_u^{UE}/N_0 \times 10^{-\frac{PL_{uv}^{UE}}{10}} \tag{3}$$

where PL_{uv}^{UE} is the path loss for the link uv. We consider for our work the path loss provided by 3GPP (for a carrier frequency of 2 GHz) [14]

$$PL_{uv}^{UE} = 15.3 + 37.6\log_{10}\left(d_{uv}^{UE}\right) \tag{4}$$

where d_{uv}^{UE} refers to the distance between the UE u and the BS v, as shown in Fig. 1. If a UAV is the sender, the propagation channel is modeled considering LoS and non line-of-sight (NLoS) links. The LoS situation results in better channel conditions for the UAV. We adopt in our work the probabilistic model proposed by 3GPP to characterize the LoS condition between a UAV u and a BS v [9]

$$P_{uv}^{LoS} = \begin{cases} 1 & \text{if } h_u^{UAV} > 100 \\ 1 & \text{if } d_{uv}^{UAV} \le d_1 \\ \frac{d_1}{d_{uv}^{UAV}} + \exp\left(\frac{-d_{uv}^{UAV}}{p_1}\right)\left(1 - \frac{d_1}{d_{uv}^{UAV}}\right) & \text{if } d_{uv}^{UAV} > d_1 \end{cases} \quad (5)$$

with $p_1 = 4300 \log_{10}(h_u^{UAV}) - 3800$ and $d_1 = \max(460 \log_{10}(h_u^{UAV}) - 700, 18)$. As shown in Fig. 1, h_u^{UAV} is the altitude of the vehicle u and d_{uv}^{UAV} is the 2D distance to the serving BS v. We can see from the above that increasing the height or reducing the distance would lead to increased LoS probability. Note that *NLoS* probability, P_{uv}^{NLoS}, can be obtained as $P_{uv}^{NLoS} = 1 - P_{uv}^{LoS}$. The path loss depends indeed on this condition [9]

$$PL_{uv}^{UAV} = \begin{cases} 28.0 + 22 \log_{10}(d_{uv}^{UAV'3D}) + 20 \log_{10}(f_c) \\ \quad \text{for LoS link} \\ \\ -17.5 + (46 - 7 \log_{10}(h_u^{UAV})) \log_{10}(d_{uv}^{UAV'3D}) + 20 \log_{10}(\frac{40\pi f_c}{3}) \\ \quad \text{for NLoS link} \end{cases} \quad (6)$$

where f_c is the carrier frequency and $d_{uv}^{UAV'3D}$ is the direct distance between the UAV u and the BS v, as shown in Fig. 1. The effect of fast fading is taken into account in the proposed communication model. The fast fading follows a Nakagami-m distribution for LoS links, and a Rayleigh distribution for NLoS links. We define two parameters A_{uv} and B_{uv} for the link uv as follows

$$\begin{cases} A_{uv} &= P_{uv}^{LoS} \times P_u^{UAV} / N_0 \times 10^{-\frac{PL_{uv}^{UAV}}{10}} \\ B_{uv} &= P_{uv}^{NLoS} \times P_u^{UAV} / N_0 \times 10^{-\frac{PL_{uv}^{UAV}}{10}}. \end{cases} \quad (7)$$

For the uplink, the instantaneous received signal to interference plus noise ratio (SINR) for the link between a device u and the BS v can be defined as

$$SINR_{uv} = \frac{\gamma_{uv}}{1 + \sum\limits_{t \in \mathbb{U} \cup \mathbb{V}}^{t \neq u} \gamma_{tv}}. \quad (8)$$

***Theorem** 1: A UE u connected to a BS v fails in transmitting its packets on the uplink iff $SINR_{uv}$ falls below a threshold γ_{th}. This event, called outage, occurs with a probability $P_{out,uv}^{UE}$ that can be expressed as*

$$P_{out,uv}^{UE}(\gamma_{th}) = 1 + \exp\left(-\frac{\gamma_{th}}{\bar{\gamma}_{uv}}\right)\left(\sum_{t=1}^{N_1} \frac{\alpha_t}{\frac{\gamma_{th}}{\bar{\gamma}_{uv}} + \frac{1}{\bar{\gamma}_{tv}}} + \sum_{t=N_1+1}^{N} \frac{\alpha_t'}{\frac{\gamma_{th}}{\bar{\gamma}_{uv}} + \frac{1}{B_{tv}}} - \sum_{t=N_1+1}^{N} \sum_{j=1}^{m} \frac{\alpha_{t,j}}{\left(\frac{\gamma_{th}}{\bar{\gamma}_{uv}} + \frac{m}{A_{tv}}\right)^j} \frac{(-1)^j}{(j-1)!} \Gamma(j)\right) \quad (9)$$

where $\Gamma(j)$ is the gamma function. $[1, \ldots, N_1]$ and $[N_1 + 1, \ldots, N]$ refer to the list of interferer UEs and UAVs, respectively. α_t, α_t' and $\alpha_{t,j}$ are unique values satisfying the following equality (fractional decomposition)

$$\prod_{t=1}^{N_1} (1 - x\bar{\gamma}_{tv})^{-1} \prod_{t=N_1+1}^{N} (1 - xB_{tv})^{-1} \left(1 - \frac{xA_{tv}}{m}\right)^{-m} = \sum_{t=1}^{N_1} \frac{\alpha_t}{x - \frac{1}{\bar{\gamma}_{tv}}} + \sum_{t=N_1+1}^{N} \frac{\alpha_t'}{x - \frac{1}{B_{tv}}} + \sum_{t=N_1+1}^{N} \sum_{j=1}^{m} \frac{\alpha_{t,j}}{(x - \frac{m}{A_{tv}})^j}. \quad (10)$$

Proof: See Appendix I. ■

From (9), it can be concluded that the outage probability increases proportionally with the threshold γ_{th}. For large values of the sensitivity threshold γ_{th}, the outage probability $P_{out,uv}^{UE} \longrightarrow 1$. In addition, the outage event can also occur for the link between a flying UAV connected to a terrestrial BS.

***Theorem** 2: The probability of outage on the uplink for a UAV u communicating with a BS v is expressed as*

$$\begin{aligned} P_{out,uv}^{UAV}(\gamma_{th}) = \sum_{j=1}^{m} \Bigg(\beta_{1j} \frac{(-1)^j}{(j-1)!} \left(\frac{m}{A_{uv}}\right)^{-j} \Bigg(\Gamma(j) + \sum_{t=1}^{N_1} \alpha_t f_{j,1}(\bar{\gamma}_{tv}) \\ + \sum_{t=N_1+1}^{N} \alpha_t' f_{j,1}(B_{tv}) - \sum_{t=N_1+1}^{N} \sum_{j'=1}^{m} \alpha_{t,j'} \frac{(-1)^{j'}}{(j'-1)!} f_{j,j'}(A_{tv}/m) \Bigg) \Bigg) \\ - \beta_{21} B_{uv} \Bigg[1 + \exp\left(-\frac{\gamma_{th}}{B_{uv}}\right) \Bigg(\sum_{t=1}^{N_1} \frac{\alpha_t}{\frac{\gamma_{th}}{B_{uv}} + \frac{1}{\bar{\gamma}_{tv}}} + \sum_{t=N_1+1}^{N} \frac{\alpha_t'}{\frac{\gamma_{th}}{B_{uv}} + \frac{1}{B_{tv}}} \\ - \sum_{t=N_1+1}^{N} \sum_{j=1}^{m} \frac{\alpha_{t,j}}{\left(\frac{\gamma_{th}}{B_{uv}} + \frac{m}{A_{tv}}\right)^j} \frac{(-1)^j}{(j-1)!} \Gamma(j) \Bigg) \Bigg] \end{aligned} \quad (11)$$

with β_{1j} and β_{21} are unique values satisfying the following formula

$$\left(1 - x\frac{A_{uv}}{m}\right)^{-m} (1 - xB_{uv})^{-1} = \sum_{j=1}^{m} \frac{\beta_{1j}}{(x - \frac{m}{A_{uv}})^j} + \frac{\beta_{21}}{(x - \frac{1}{B_{uv}})}. \quad (12)$$

The function $f_{j,j'}(S)$ is provided as

$$f_{j,j'}(S) = \sum_{p=1}^{n} S^{j'} (\theta_p)^{j'-1} \lambda_p \Gamma\left(j, \frac{m\gamma_{th}(\theta_p S + 1)}{A_{uv}}\right) \quad (13)$$

where λ_p and θ_p denote respectively the weight and the zero factors of the n-th order Laguerre polynomials [15]. $\Gamma(a,z)$ is the upper incomplete gamma function defined as $\Gamma(a,z) = \int_z^{\infty} t^{a-1} e^{-t} dt$.

Proof: See Appendix I. ■

The outage probability (in (11)) has indeed two parts. The first one is related to the LoS condition (where the underlaying fast fading follows nakagami-m distribution), while the second part is related to the NLoS condition.

III. Problem formulation and proposed optimization

The aim is to enable UAVs communication over mobile networks without adversely affecting the QoE of connected UEs. This paper proposes adjusting the transmission power of the drones in a way to achieve this objective. Indeed, the LoS condition enabled the UAVs to reach and interfere with non-serving BSs, and adjusting their power could reduce this effect.

From Theorem 2, it can be deduced that the impact of the interferers on the outage is reflected in the terms A_{tv} and B_{tv}. Decreasing the value of these terms would increase the probability of outage for the concerned UAVs. We formulate therefore the optimization problem in the following manner

$$\min_{P^{UAV}}\text{-}\max \; P^{UAV}_{out,uv} \qquad \forall u \in \mathbb{V} \tag{14}$$

$$\text{subject to: } P^{UE}_{out,uv} \leq P_{th} \qquad \forall u \in \mathbb{U} \tag{15}$$

$$0 < P^{UAV}_{u} \leq P_{\max}. \tag{16}$$

The objective function in the above equation is to minimize the outage probability for flying UAVs, while maintaining that of the already connected terrestrial UEs below a given threshold P_{th} that guarantees the required QoE for them. These outage probabilities are provided in Theorems 1 and 2. Note that this should be for each device u connected to its serving BS v ($v \in \mathbb{B}$). This problem is non linear which is complex to solve, especially for a large network.

For this reason we propose the optimization provided in Algorithm 1. To determine the suitable transmission power for the UAVs, we consider initially the maximum value $P_{\max}$. Then, if a terrestrial UE would have an outage probability greater than the threshold P_{th}, some actions are performed to maintain $P^{UE}_{out,uv} \leq P_{th}, \forall u \in \mathbb{U}$. This is done by finding the interfering UAVs with that UE (function interferer_UAV(u) in Algorithm 1) and reducing the power for those operating with highest level. Line 6 in the Algorithm returns the UAV using the highest power among the interferers. The stp parameter is used as a step for reducing the power.

Algorithm 1 Power optimization Algorithm

```
1: procedure UAV POWER OPTIMIZATION
   Input: P_th, P_max
   Output: P^UAV
   Initialization: P_a^UAV = P_max, ∀a ∈ 𝕍
2:     for u ∈ 𝕌 do
3:         if P^UE_out,uv > P_th then
4:             𝕊 = interferer_UAV(u)
5:             repeat
6:                 a = high_pwr_UAV(𝕊)
7:                 P_a^UAV -= stp
8:             until P^UE_out,uv ≤ P_th
```

Managing and operating the UAVs require generally an orchestration center that monitors and controls these vehicles. This center is aware of the different information about the drones, such as their locations, the used transmission power, and their energy budget. The optimization solution is performed by the orchestration center and uses the different information about the UAVs. This reduces considerably the resource consumption for the drones compared to performing the optimization by these vehicles.

IV. Performance Evaluation

To evaluate the proposed communication model and the optimization solution, a simulator is developed using python programing language. The deployment area is of size (1Km x 1Km) with the different devices and BSs being randomly deployed. 12 BSs are considered in total while the number of devices is varied depending on the underlying scenario. The altitude of the UAVs is randomly attributed between 22.5 and 300 m, which is the applicability range for the used path loss model [9]. The communication model is implemented considering $m = 2$ for the Nakagami fading, 2GHz for f_c, and N_0 in the order of $-130dBm$ (10^{-16} [16]). Note that as stated in [9], f_c in equation (6) is considered in GHz, while the international system of units is used elsewhere. The maximum transmit power for both UEs and UAVs is $0.2W$.

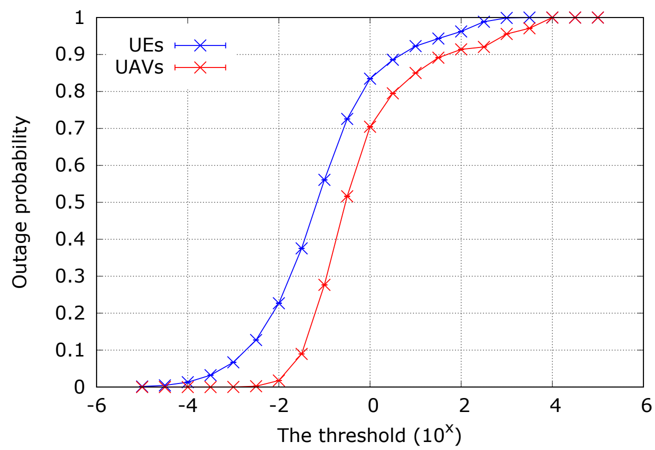

Fig. 2: Effect of the threshold γ_{th}.

The sensitivity threshold γ_{th} indicates the threshold that the SINR should exceed so the packet is received successfully. As the sensitivity threshold of the receiver increases, its ability to detect weak signals decreases. As shown in [17], γ_{th} can have great effect on the network performance. Thus, we evaluate the effect of the threshold γ_{th} on the perceived outage. The results are shown in Fig. 2 and are obtained considering average outage for 50 UEs and 50 UAVs. We can see that decreasing the threshold leads to decreased outage probability. The value of γ_{th} needs to be adequately chosen. In addition, with the same threshold, the average outage probability for UAVs is better than that for UEs on the ground. This is mainly due to LoS condition characterizing the UAVs communication and leading to smaller outage probability compared to ground UEs. From this evaluation, we use in the following 10^{-3} as a value for the threshold γ_{th}.

To evaluate the effect that UAVs can cause through the communication via mobile networks, the following scenario is investigated. We start with 70 deployed UEs (and no-deployed UAVs) and we increase the number of UAVs. As shown in Fig. 3, this directly leads to increased outage probability for UEs already deployed. Moreover, this degradation is very high compared to the case when the added devices were UEs (blue line in Fig. 3). The UAVs ability to perceive and reach more BSs is unfortunately translated into

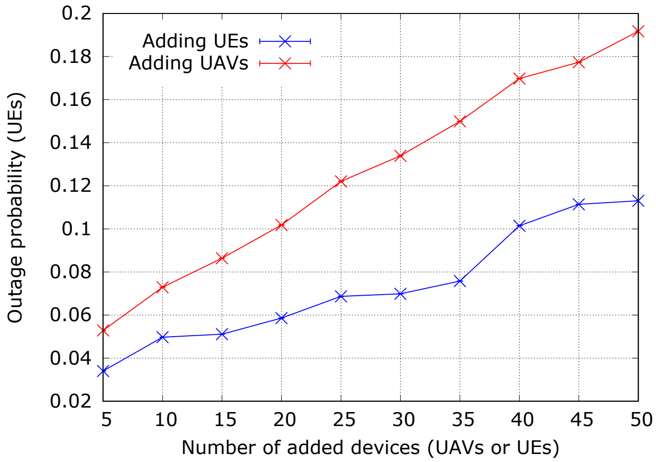

Fig. 3: Effect of increasing the number of UAVs, or UEs, on already deployed network of 70 UEs.

more interferences on non-serving BSs, causing therefore increased outage compared to that caused by ground UEs.

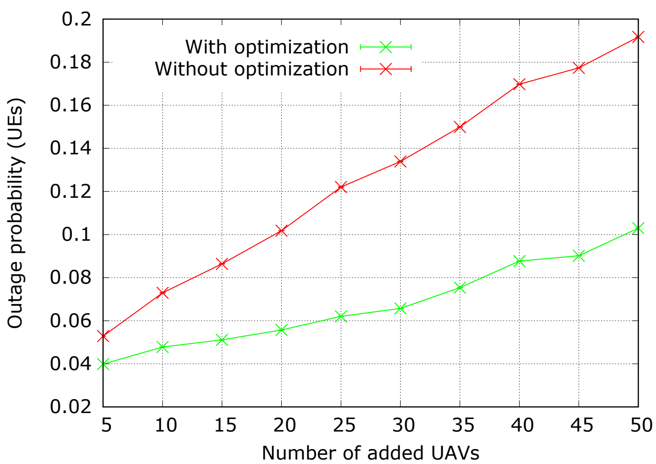

Fig. 4: Evaluation of the power adjustment method (adding UAVs to already deployed network of 70 UEs).

We also evaluated the proposed power optimization to enhance the QoE of the deployed UEs in the presence of flying UAVs. Four possible values for the transmit power of each UAVs are considered (0.2W, 0.15W, 0.1W and 0.15W). The obtained results considering $P_{th} = 0.1$ are shown in Fig. 4. The scenario is similar to the previous one (adding UAVs to an already deployed network of 70 UEs). The results show great enhancement in the mean outage probability of UEs, even before achieving P_{th}. Adjusting the transmit power for one UAV has a positive impact on all interfered devices connected to the other BSs. This is translated into enhancements in the overall network QoE, proving therefore the effectiveness of the proposed scheme. In addition, the obtained results also show that the average outage probability for UAVs is under 0.02, preserving therefore efficient communication for them even after power adjustment.

V. Conclusion

While the consideration of mobile networks as a communication infrastructure for UAVs would enable new applications and push heir boundaries further, real field trials showed that many challenges need to be addressed. The present paper study the communication in a cellular network in presence of drones. As the communication model for flying UAVs is different from traditional ones on the ground, a new model is introduced in this paper. The model is designed to reflect the reality by considering the characteristics that reign the communication (e.g. interferences, fast fading). The conducted evaluations show that the UAVs' communication over a cellular network negatively affect the QoE of connected UEs. Moreover, they show that this degradation is very considerable when increasing the number of deployed UAVs. In addition, this paper also proposes an optimization solution to enhance the QoE. As the LoS condition enables the UAVs to perceive and reach a big number of BSs, the solution is based on adjusting their transmission power so to reduce their negative impact. The effectiveness of the proposed solution is demonstrated through simulations.

Acknowledgment

This work was supported in part by the Academy of Finland Project CSN under Grant No. 311654, and in part by the Aalto 5G meets Industrial Internet (5G@II) project.

References

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

[2] X. Lin, R. Wiren, S. Euler, A. Sadam, H.-L. Maattanen, S. D. Muruganathan, S. Gao, Y.-P. E. Wang, J. Kauppi, Z. Zou *et al.*, "Mobile networks connected drones: Field trials, simulations, and design insights," *arXiv preprint arXiv:1801.10508*, 2018.

[3] M. A. Messous, H. Sedjelmaci, N. Houari, and S. M. Senouci, "Computation offloading game for an UAV network in mobile edge computing," in *2017 IEEE International Conference on Communications (ICC)*, May 2017, pp. 1–6.

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

[5] O. Bekkouche, T. Taleb, and M. Bagaa, "UAVs traffic control based on multi-access edge computing," in *GLOBECOM 2018 - 2018 IEEE Global Communications Conference*, Dec 2018.

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

[7] N. H. Motlagh, M. Bagaa, and T. Taleb, "UAV-Based IoT Platform: A Crowd Surveillance Use Case," *IEEE Communications Magazine*, vol. 55, no. 2, pp. 128–134, February 2017.

[8] H. Hellaoui, O. Bekkouche, M. Bagaa, and T. Taleb, "Aerial control system for spectrum efficiency in UAV to cellular communications," *IEEE Communications Magazine*, to appear 2018.

[9] 3GPP, "Study on enhanced LTE support for aerial vehicles," *Technical Report,3GPP TR 36.777*, 2017.

[10] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Efficient deployment of multiple unmanned aerial vehicles for optimal wireless coverage," *IEEE Communications Letters*, vol. 20, no. 8, pp. 1647–1650, Aug 2016.

[11] ——, "Optimal transport theory for cell association in UAV-enabled cellular networks," *IEEE Communications Letters*, vol. 21, no. 9, pp. 2053–2056, Sept 2017.

[12] ——, “Mobile unmanned aerial vehicles (UAVs) for energy-efficient Internet of things communications,” *IEEE Transactions on Wireless Communications*, vol. 16, no. 11, pp. 7574–7589, Nov 2017.
[13] N. UTM, “Unmanned aircraft system (UAS) traffic management (UTM),” https://utm.arc.nasa.gov/, 2017.
[14] 3GPP, “RF system scenarios,” *Technical Report, (TSG) RAN WG4*, 2000.
[15] M. Abramowitz and I. A. Stegun, *Handbook of mathematical functions: with formulas, graphs, and mathematical tables*. Courier Corporation, 1964, vol. 55.
[16] A. F. Molisch, *Wireless Communications*. Chichester: John Wiley & Sons, 2005.
[17] M. Bagaa, A. Chelli, D. Djenouri, T. Taleb, I. Balasingham, and K. Kansanen, “Optimal placement of relay nodes over limited positions in wireless sensor networks,” *IEEE Transactions on Wireless Communications*, vol. 16, no. 4, pp. 2205–2219, 2017.
[18] M. K. Simon and M.-S. Alouini, *Digital communication over fading channels*. John Wiley & Sons, 2005, vol. 95.
[19] X. Cui, Q. Zhang, and Z. Feng, “Outage performance for maximal ratio combiner in the presence of unequal-power co-channel interferers,” *IEEE Communications Letters*, vol. 8, no. 5, pp. 289–291, may 2004.
[20] A. Papoulis and S. U. Pillai, *Probability, random variables, and stochastic processes*. Tata McGraw-Hill Education, 2002.

APPENDIX I
APPENDIX: PROOF OF THEOREMS 1 AND 2

This appendix derives the proofs of Theorems 1 and 2. Theorem 1 (Theorem 2) provides the expression of the outage probability for the uplink channel between the BS v and a UE (a UAV) u. An outage event occurs if the $SINR_{uv}$ falls below a threshold γ_{th}. To determine the outage probability, we must compute the CDF (Cumulative Distribution Function) of $SINR_{uv}$ [18]. The $SINR_{uv}$ is expressed as

$$SINR_{uv} = \frac{\gamma_{uv}}{1 + \sum\limits_{t \in \mathbb{U} \cup \mathbb{V}}^{t \neq u} \gamma_{tv}} \tag{I.1}$$

where γ_{uv} is the instantaneous SNR of the desired signal and γ_{tv} is the interference signal from node t. Note that u and t can be either a UE or a UAV. In our model, we take into account the impact of pathloss and fast fading. We assume that the fast fading follows a Rayleigh distribution for the case of UE and UAV with NLoS link to the BS. However, for UAV with LoS link to the BS, we assume a Nakagami distribution for the fast fading. We denote by $\bar{\gamma}_{uv}$ and $\bar{\gamma}_{tv}$ the mean values of γ_{uv} and γ_{tv}, respectively. For the UE, the Moment Generating Function (MGF) and the Probability Density Function (PDF) can be expressed as

$$M^{UE}_{\gamma_{uv}}(s) = (1 - s\bar{\gamma}_{uv})^{-1} \tag{I.2}$$

$$P^{UE}_{\gamma_{uv}}(x) = \frac{1}{\bar{\gamma}_{uv}} \exp\left(-\frac{x}{\bar{\gamma}_{uv}}\right). \tag{I.3}$$

For a UAV, it can have a LoS link to the BS with a probability P^{LoS}_{uv} and NLoS link with a probability P^{NLoS}_{uv}. Therefore, the MGF in the case of UAV can be computed as

$$M^{UAV}_{\gamma_{uv}}(s) = \left(1 - s\frac{A_{uv}}{m}\right)^{-m} (1 - sB_{uv})^{-1} = \sum_{j=1}^{m} \frac{\beta_{1j}}{(s - \frac{m}{A_{uv}})^j} + \frac{\beta_{21}}{(s - \frac{1}{B_{uv}})} \tag{I.4}$$

where the expressions of A_{uv} and B_{uv} are provided in (7). The left hand side of (I.4) is obtained using fractional decomposition [19, Eq. (11)]. Note that β_{1j} and β_{21} are the same in Theorem 2 satisfying equation (12). From the MGF of γ_{uv}, we can obtain the PDF using the Inverse Laplace transform as

$$\begin{aligned} P^{UAV}_{\gamma_{uv}}(x) &= \sum_{j=1}^{m} \left(\beta_{1j}\mathcal{L}^{-1}\left[\frac{1}{(s - \frac{m}{A_{uv}})^j}\right]\right) + \beta_{21}\mathcal{L}^{-1}\left[\frac{1}{(s - \frac{1}{B_{uv}})}\right] \\ &= \sum_{j=1}^{m} \left(\beta_{1j}x^{j-1}\exp(-\frac{mx}{A_{uv}})\frac{(-1)^j}{(j-1)!}\right) - \beta_{21}\exp(-\frac{x}{B_{uv}}). \end{aligned} \tag{I.5}$$

With $I = \sum_{t \in \mathbb{U} \cup \mathbb{V}}^{t \neq u} \gamma_{tv}$ and $I' = 1 + I$, we can redefine the SINR as

$$SINR_{uv} = \frac{\gamma_{uv}}{1 + I} = \frac{\gamma_{uv}}{I'}. \tag{I.6}$$

I includes both UE and UAV interferers. In the same manner, the MGF of I is obtained as

$$\begin{aligned} M_I(s) &= \prod M_{\gamma_{tv}}(s) = \prod_{t=1}^{N_1}(1 - s\bar{\gamma}_{tv})^{-1} \prod_{t=N_1+1}^{N}(1 - sB_{tv})^{-1}(1 - \frac{sA_{tv}}{m})^{-m} \\ &= \sum_{t=1}^{N_1} \frac{\alpha_t}{s - \frac{1}{\bar{\gamma}_{tv}}} + \sum_{t=N_1+1}^{N} \frac{\alpha'_t}{s - \frac{1}{B_{tv}}} + \sum_{t=N_1+1}^{N}\sum_{j=1}^{m} \frac{\alpha_{t,j}}{(s - \frac{m}{A_{tv}})^j} \end{aligned} \tag{I.7}$$

where $[1, \ldots, N_1]$ and $[N_1 + 1, \ldots, N]$ refer respectively to the list of UEs and UAVs interferers. Note that the last line of the above equations is the result of the fractional decomposition. α_t, α'_t and $\alpha_{t,j}$ (which are the same parameters in Theorems 1 and 2) can be computed using multinomial Theorem. The PDF of I can be obtained as

$$P_I(x) = \mathcal{L}^{-1}[M_I] = \mathcal{L}^{-1}\left[\sum_{t=1}^{N_1} \frac{\alpha_t}{s - \frac{1}{\bar{\gamma}_{tv}}} + \sum_{t=N_1+1}^{N} \frac{\alpha'_t}{s - \frac{1}{B_{tv}}} + \sum_{t=N_1+1}^{N}\sum_{j=1}^{m} \frac{\alpha_{t,j}}{(s - \frac{m}{A_{tv}})^j}\right] \tag{I.8}$$

$$\begin{aligned} &= \sum_{t=1}^{N_1} \alpha_t(-1)\exp\left(-\frac{x}{\bar{\gamma}_{tv}}\right) + \sum_{t=N_1+1}^{N} \alpha'_t(-1)\exp\left(-\frac{x}{B_{tv}}\right) \\ &\quad + \sum_{t=N_1+1}^{N}\sum_{j=1}^{m} \alpha_{t,j}\frac{(-1)^j}{(j-1)!}\exp\left(-\frac{mx}{A_{tv}}\right)x^{j-1}. \end{aligned} \tag{I.9}$$

Now, we can determine the outage probability as

$$\begin{aligned} P_{out}(\gamma_{th}) &= P(SINR \leq \gamma_{th}) = P\left(\frac{\gamma_{uv}}{I'} \leq \gamma_{th}\right) \\ &= E_{I'}[P(\gamma_{uv} \leq \gamma_{th}y | I' = y)] = \int_1^\infty F_{\gamma_{uv}}(\gamma_{th}y)P_{I'}(y)dy \end{aligned} \tag{I.10}$$

where $F_{\gamma_{uv}}(x)$ is the CDF of γ_{uv} which is defined as $F_{\gamma_{uv}}(x) = \int_0^x P_{\gamma_{uv}}(y)dy$. If γ_{uv} is associated with a UE, the corresponding CDF is

$$F^{UE}_{\gamma_{uv}}(x) = \int_0^x P^{UE}_{\gamma_{uv}}(y)dy = 1 - \exp(-\frac{x}{\bar{\gamma}_{uv}}). \tag{I.11}$$

If γ_{uv} is associated with a UAV, $F_{\gamma_{uv}}$ is given by

$$F^{UAV}_{\gamma_{uv}}(x) = \int_0^x P^{UAV}_{\gamma_{uv}}(y)dy$$
$$= \sum_{j=1}^{m}\left(\beta_{1j}\frac{(-1)^j}{(j-1)!}\underbrace{\int_0^x y^{j-1}exp(-\frac{my}{A_{uv}})dy}_{K_1}\right) - \beta_{21}\underbrace{\int_0^x \exp(-\frac{y}{B_{uv}})dy}_{K_2} \tag{I.12}$$

with

$$K_1 = \left(\frac{m}{A_{uv}}\right)^{-j}\left(\Gamma(j) - \Gamma\left(j, \frac{mx}{A_{uv}}\right)\right) \tag{I.13}$$
$$K_2 = B_{uv}\left(1 - \exp\left(-\frac{x}{B_{uv}}\right)\right) \tag{I.14}$$

where $\Gamma(j)$ being the gamma function and $\Gamma(j, \frac{mx}{A_{uv}})$ is the upper incomplete gamma function defined as $\Gamma(a,z) = \int_z^{\infty} t^{a-1}\exp(-t)dt$. As for the PDF $P_{I'}(y)$, it is determined using equation (I.9) and the fundamental Theorem for the transformation of random variables [20] as

$$P_{I'}(y) = \sum_{t=1}^{N_1}\alpha_t(-1)\exp\left(-\frac{y-1}{\bar{\gamma}_{tv}}\right) + \sum_{t=N_1+1}^{N}\alpha'_t(-1)\exp\left(-\frac{y-1}{B_{tv}}\right)$$
$$+ \sum_{t=N_1+1}^{N}\sum_{j=1}^{m}\alpha_{t,j}\frac{(-1)^j}{(j-1)!}\exp\left(-\frac{m(y-1)}{A_{tv}}\right)(y-1)^{j-1}. \tag{I.15}$$

Finally, the outage probability if u is a UE can be expressed as

$$P^{UE}_{out}(\gamma_{th}) = \int_1^{\infty} F_{\gamma_{uv}}(\gamma_{th}y)P_{I'}(y)dy = 1 - \int_1^{\infty}\exp\left(-\frac{\gamma_{th}y}{\bar{\gamma}_{uv}}\right)P_{I'}(y)dy$$
$$= 1 + \exp\left(-\frac{\gamma_{th}}{\bar{\gamma}_{uv}}\right)\left(\sum_{t=1}^{N_1}\frac{\alpha_t}{\frac{\gamma_{th}}{\bar{\gamma}_{uv}} + \frac{1}{\bar{\gamma}_{tv}}} + \sum_{t=N_1+1}^{N}\frac{\alpha'_t}{\frac{\gamma_{th}}{\bar{\gamma}_{uv}} + \frac{1}{B_{tv}}}\right.$$
$$\left. - \sum_{t=N_1+1}^{N}\sum_{j=1}^{m}\frac{\alpha_{t,j}}{\left(\frac{\gamma_{th}}{\bar{\gamma}_{uv}} + \frac{m}{A_{tv}}\right)^j}\frac{(-1)^j}{(j-1)!}\Gamma(j)\right) \quad \blacksquare \tag{I.16}$$

which is the result presented in Theorem 1.

In the case that u is a UAV, the corresponding outage probability will be

$$P^{UAV}_{out}(\gamma_{th}) = \int_1^{\infty} F_{\gamma_{uv}}(\gamma_{th}y)P_{I'}(y)dy$$
$$= \sum_{j=1}^{m}\left(\beta_{1j}\frac{(-1)^j}{(j-1)!}\left(\frac{m}{A_{uv}}\right)^{-j}\left(\Gamma(j) - \int_1^{\infty}\Gamma(j, \frac{m\gamma_{th}y}{A_{uv}})P_{I'}(y)dy\right)\right)$$
$$- \beta_{21}B_{uv}\left(1 - \int_1^{\infty}\exp(-\frac{\gamma_{th}y}{B_{uv}})P_{I'}(y)dy\right) \tag{I.17}$$
$$= \sum_{j=1}^{m}\left(\beta_{1j}\frac{(-1)^j}{(j-1)!}(\frac{m}{A_{uv}})^{-j}\left(\Gamma(j) + \sum_{t=1}^{N_1}\alpha_t\Big(\sum_{p=1}^{n}\bar{\gamma}_{tv}\lambda_p\right.\right.$$
$$\Gamma\left(j, \frac{m\gamma_{th}(\theta_p\bar{\gamma}_{tv}+1)}{A_{uv}}\right)\Big) + \sum_{t=N_1+1}^{N}\alpha'_t\Big(\sum_{p=1}^{n}B_{tv}\lambda_p$$
$$\Gamma\left(j, \frac{m\gamma_{th}(\theta_pB_{tv}+1)}{A_{uv}}\right)\Big) - \sum_{t=N_1+1}^{N}\sum_{j'=1}^{m}\alpha_{t,j'}\frac{(-1)^{j'}}{(j'-1)!}(\sum_{p=1}^{n}(A_{tv}/m)^{j'}$$
$$\left.\left.\lambda_p\theta_p^{j'-1}\Gamma\left(j, \frac{m\gamma_{th}(\theta_p(A_{tv}/m)+1)}{A_{uv}}\right))\right)\right)$$
$$- \beta_{21}B_{uv}\Big(1 - \int_1^{\infty}\exp(-\frac{\gamma_{th}y}{B_{uv}})P_{I'}(y)dy\Big) \tag{I.18}$$

$$= \sum_{j=1}^{m}\left(\beta_{1j}\frac{(-1)^j}{(j-1)!}(\frac{m}{A_{uv}})^{-j}\left(\Gamma(j) + \sum_{t=1}^{N_1}\alpha_t\Big(\sum_{p=1}^{n}\bar{\gamma}_{tv}\lambda_p\right.\right.$$
$$\Gamma\left(j, \frac{m\gamma_{th}(\theta_p\bar{\gamma}_{tv}+1)}{A_{uv}}\right)\Big) + \sum_{t=N_1+1}^{N}\alpha'_t\Big(\sum_{p=1}^{n}B_{tv}\lambda_p$$
$$\Gamma\left(j, \frac{m\gamma_{th}(\theta_pB_{tv}+1)}{A_{uv}}\right)\Big) - \sum_{t=N_1+1}^{N}\sum_{j'=1}^{m}\alpha_{t,j'}\frac{(-1)^{j'}}{(j'-1)!}(\sum_{p=1}^{n}(A_{tv}/m)^{j'}$$
$$\left.\left.\lambda_p\theta_p^{j'-1}\Gamma\left(j, \frac{m\gamma_{th}(\theta_p(A_{tv}/m)+1)}{A_{uv}}\right))\right)\right)$$
$$- \beta_{21}B_{uv}\left(1 + \sum_{t=1}^{N}\alpha_t\frac{\exp(-\frac{\gamma_{th}}{B_{uv}})}{\frac{\gamma_{th}}{B_{uv}} + \frac{1}{\bar{\gamma}_{tv}}} + \sum_{t=N_1+1}^{N}\alpha'_t\frac{\exp(-\frac{\gamma_{th}}{B_{uv}})}{\frac{\gamma_{th}}{B_{uv}} + \frac{1}{B_{tv}}}\right.$$
$$\left. - \sum_{t=N_1+1}^{N}\sum_{j=1}^{m}\alpha_{t,j}\frac{(-1)^j}{(j-1)!}\left(\frac{\gamma_{th}}{B_{uv}} + \frac{m}{A_{tv}}\right)^{-j}\exp\left(-\frac{\gamma_{th}}{B_{uv}}\right)\Gamma(j)\right) \tag{I.19}$$
$$= \sum_{j=1}^{m}\left(\beta_{1j}\frac{(-1)^j}{(j-1)!}\left(\frac{m}{A_{uv}}\right)^{-j}\left(\Gamma(j) + \sum_{t=1}^{N_1}\alpha_t f_{j,1}(\bar{\gamma}_{tv})\right.\right.$$
$$\left.\left. + \sum_{t=N_1+1}^{N}\alpha'_t f_{j,1}(B_{tv}) - \sum_{t=N_1+1}^{N}\sum_{j'=1}^{m}\alpha_{t,j'}\frac{(-1)^{j'}}{(j'-1)!}f_{j,j'}(A_{tv}/m)\right)\right)$$
$$- \beta_{21}B_{uv}\left[1 + \exp\left(-\frac{\gamma_{th}}{B_{uv}}\right)\left(\sum_{t=1}^{N_1}\frac{\alpha_t}{\frac{\gamma_{th}}{B_{uv}} + \frac{1}{\bar{\gamma}_{tv}}} + \sum_{t=N_1+1}^{N}\frac{\alpha'_t}{\frac{\gamma_{th}}{B_{uv}} + \frac{1}{B_{tv}}}\right.\right.$$
$$\left.\left. - \sum_{t=N_1+1}^{N}\sum_{j=1}^{m}\frac{\alpha_{t,j}}{\left(\frac{\gamma_{th}}{B_{uv}} + \frac{m}{A_{tv}}\right)^j}\frac{(-1)^j}{(j-1)!}\Gamma(j)\right)\right]. \quad \blacksquare \tag{I.20}$$

The integrals in equation (I.17) involve Gamma function with exponential function. We use Laguerre polynomial, defined as $\int_0^{\infty} e^{-x}f(x)dx = \sum_{p=1}^{n}\lambda_p f(\theta_p)$, to perform numerical evaluation, with λ_p and θ_p being respectively the weight and the zero factors of the n-th order Laguerre polynomials. The result can be seen in equation (I.18) with the mean of variable change. The expression of $f_{j,j'}(S)$ is provided in equation (13). Note that the result in (I.20) is the same as the outage probability expression presented in Theorem 2.