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ORIGINAL PAPER

On the usefulness of flying base stations in 5G and beyond scenarios

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Abstract

Considering that one of the goals of the future network generations is to provide ubiquitous communication in the most diverse scenarios to achieve high connection coverage, it is foreseen that the use of unmanned aerial vehicles as flying base stations (UAV-BSs) can potentially extend the network and communication range. UAVs as flying base station can bring the potential to assist user devices and vehicles by carrying communication resources that can accommodate clients that were not previously planned by the ground infrastructure design due to flash crowd events, sudden natural disasters, or any other event that let to an overloaded environment. Allocating UAVs as flying base station still poses significant challenges in their deployment and the effectiveness of information transmission through UAVs as flying base station in the context of wireless communication since it is necessary to deal with both wireless communication capability and interference in the presence of terrestrial infrastructures already present. Besides, it is essential to understand how communication resources affect network performance. This paper studies the feasibility of using UAVs as flying base station in the assistance of wireless communication in a scenario where there is a sudden demand for data transmission due to possible congestion of local infrastructure. We show how the number of communication resources provided by the UAV-BS, the interference caused by the presence of multiple next generation node Bs (gNBs), and the UAV as flying base station positioning affect the network performance. We also highlight the need for a better next generation node B (gNB) and UAVs placement criteria since the received signal power prevents the user equipments (UEs) from using most of the available resources.

Keywords Unmanned aerial vehicle · Heterogeneous network · Quality-of-service · Unmanned aerial vehicle as flying base station

1 Introduction

Unmanned aerial vehicle (UAV) assisted networks have been addressed since the fourth generation (4G) networks and are still being studied in the following network generations, including fifth generation (5G) and beyond fifth generation (B5G) for different applications ranging from communication assistance to disaster relief [21]. For instance, it is considered that data collection and dissemination, edge computing, data caching, and relay transmission can be highlighted as some of the primary services that UAV-assisted network can support soon [13]. In this way, these services consider the available UAVs as flying base station (UAV-BSs) to opportunistically provide network

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and communication assistance on the sky to ground users. Specifically, UAV-BSs are assembled with miniaturized and lightweight communication equipment and also carry computational resources for data processing [16]. Hence, UAV-BSs provide the required communication and computing resources for future network generation applications, which require short-time decision-making, automatic initialization, and a communication link to cloud radio access network (C-RAN) or existing multiple-access edge computing (MEC) entities, where the data is processed [13].

UAV-BSs are the key components to enable more ubiquitous mobile communication in hard-to-reach and computationally demanding scenarios [3]. In this scenario, a set of user equipments (UEs), *i.e.*, sensors or mobile devices, can take advantage of nearby communication resources, which can be ground units, such as ground base stations (BSs), and/or flying units, such as UAV-BSs. Hence, UAV-BSs can be swiftly deployed on-demand, and the inherited unrestricted 3D mobility can provide an enhanced line-of-sight (LoS) to the other ground devices [26]. However, the coexistence of different communication resource suppliers is not as simple as it seems, bringing challenges that must be addressed, such as interference, UE association, and resource allocation.

Resources management is vital for large-scale UAV-BS deployments or when resources are already scarce. Optimizing resource use makes improving the network's performance possible by increasing available capacity and minimizing interference or other signal-degrading factors. Additionally, optimizing resource use allows the network to quickly scale up or down as needed to meet changing demand. Strategies such as deploying drones only when necessary, using energy-efficient technologies, and implementing advanced algorithms and optimization techniques, can all aid in optimizing resource use and enhancing the efficiency and effectiveness of a drone-assisted network [4].

The success of UAV-assisted networks depends on the network characteristics and the user requirements. In fifth generation new radio (5G-NR) architecture, for example, it is important that the next generation node Bs (gNBs), which can be a BS or an UAV-BS, have enough resources to meet the UEs' demands. Therefore, an UAV-BS must meet the communication requirements mainly when the original network infrastructure is congested or presents some physical/structural damage.

Following this reasoning, many works aim to improve the network performance in the presence of a single or a set of UAV-BSs to enhance the communication aspects [2, 6, 7, 24]. Different proposals manage the number of UAV-BSs and/or their positions to improve the quality-of-service (QoS) experienced by the UEs. They usually consider gNBs with a limited throughput capacity, the co-channel interference among all the gNB types present in the scenario, and the UEs' positions as input. However, it is unclear which factors have the greatest impact when deploying UAV-BSs in assistance scenarios, where the pre-existence of ground gNBs is not sufficient to serve 100% of the UEs. Therefore, some primary challenges, such as the wireless network coverage, reliability, capacity, and energy efficiency, remain when employing UAV-BSs in the most diverse scenarios [15, 28]. Besides, few works still define the main parameters, their impacts, and how the communication aspects can be effectively improved in the presence of UAV-BSs.

This paper aims to evaluate the conditions in which the usage of UAV-BSs is cost-effective, considering that UAV-BSs are employed as a key complement for future network generations to provide connectivity and computational assistance. In the context of using UAV-BSs for network communication assistance, a cost-effective system achieves the maximum performance given the network scenario and condition. In our case, there is a trade-off when we add UAV-BSs to the solution that deals with the amount of resources available and the interference caused by the gNB node densification. Thus, the cost-effective solution reaches the best trade-off when reaching a specific number of UAV-BSs given the UE distribution over the area, meeting the highest QoS requirements of the poorly assisted UEs without affecting the others. The cost-effectiveness is defined in Sect. 4.2 as a relationship between the mean of the throughput rate and the delay experienced by the UEs.

We consider the type of resources and the amount required by an UAV-BS to provide connectivity to existing UE devices. Moreover, the UAV-BSs' interference and positioning aspects, the existence of a ground BS, and the UEs coexistence in the same scenario are also considered. We show that the amount of communication resources is the most important aspect that impacts the throughput performance of UE devices based on extensive simulations. The interference and UAV-BSs' positioning aspects impact equally since they mainly vary according to the distance among different nodes, both being important for positioning refinement.

The rest of the paper is described as follows. Section 2 shows the main related works. Section 3 explores the model and network architecture components used for evaluation, and it also introduces the results in terms of the amount of UAV-BSs' resources and interference, and Sect. 4 describes the impact of different UAV-BSs positioning. Finally, Sect. 5 presents the conclusion, open challenges, and future works.

2 Related works

Sun et al. [24] presented a joint optimization of a single e UAV-BS in a 3D plane together with UEs' association to maximize the overall throughput. The idea is to deploy a UAV-BS in a 3D environment able to provide connectivity in an assisted manner, connecting the most suitable UEs that are with communication issues. Fahim and Gadallah [6] studied the dynamic deployment of a single UAV-BS and provided an optimized coverage technique to improve the communication while it provides connectivity to groups of devices located out of reach of existent terrestrial gNBs. The proposal presents a joint optimal dynamic placement and uplink (UL) resource scheduling while considering the diverse QoS requirement from the existing UEs. However, the proposal does not consider 5G-NR interference management techniques.

Hayat et al. [9] presented a performance evaluation of an experimental 5G-NR to understand the impact of UAV altitude variation on the transmission rate and on the handover measurements. The experimental setup considers one UAV as an UE that flies through a predefined path and establishes a communication with the surrounding gNBs. The UAV was able to measure 5G-NR parameters as reference signal received power (RSRP), reference signal received quality (RSRQ), signal to interference plus noise ratio (SINR), UL, and downlink (DL) throughput while connecting to different gNBs in the scenario. Aydin et al. [2] explored the security aspects for a handover technique in the coexistence of terrestrial BS and UAV-BSs. The authors considered high-density areas where the UAV-BSs could be exploited to provide communication resources to the UEs. The proposal presents a more efficient approach in terms of time and energy by no data-sharing between the existing gNBs.

Fotouhi et al. [7] proposed a method to improve network performance through a game-theoretic mobility control algorithm. It considers a user association scheme based only on the received signal strength. In addition, Qiu et al. [18] introduced an optimization approach for UAVs' placement along with user association. It considers the interference impact of multiple gNBs and the bandwidth limitation of each one.

The development of heterogeneous networks (Het-Net)s has been crucial for devices equipped with different technologies to communicate and transmit the growing number of data from the most diverse applications. It is because Het-Net comprises different access points, signal power, data rate, communication capabilities, and energy capacity. It makes most of the UEs in a given scenario a good chance of experiencing interference, be it inter-cell or intra-cell. The use of UAVs further worsens this problem since being employed as an UAV-BS, it becomes a potential cause of interference, which can significantly worsen communication and applications dependent on it. However, many network resources are available through new access points. They must be efficiently allocated with a correct association between UAVs and UEs. Within this context, Ding et al. [5] proposed a deep-reinforced learning-based algorithm capable of enhancing the association of UEs in Het-Net as well as improving energy control. Likewise, Hassija et al. [8] proposed a block-chain based framework that coordinates dynamic bandwidth allocation for different UEs according to the UAV-BSs resources availability.

Although multiple access points intuitively allow better throughput, this is not enough for successful transmission, since each UE may suffer from inter-cell interference or signal fading. The search for the optimal combination can become complex as it considers the signal strength of the devices, the proximity among them, inter-cell interference, bandwidth capacity, and application requirements for each UE. Summakieh et al. [23] proposed a particle swarm optimization (PSO) based algorithm to increase throughput and a network balance index. The proposed algorithm can configure different throughput priority levels since it weights the factors following different priorities differently. Similarly, Javad-Kalbasi et al. [10] proposed a heuristic approach to address the user association problem, aiming to improve spectral energy and communication link efficiency.

The UE mobility prediction approaches can also present a significant impact on the UE association problem and the network performance once it foreseen where, when, and how much resources shall be needed [14]. Liu et al. [14] proposed a set of multi-agent q-learning (MAQL) based solutions for the optimal UE association and resource allocation in Het-Net. It assumes the implementation of virtual small cells (VSCs), which by default increases the system capacity and spectrum efficiency.

Zhang and Ansari [27] also argue that the use of UAV-BS has the potential to bring improvements to the network in terms of QoS, since thanks to a more favorable LoS and available features, such a device can offload the data generated by the UE. In this case, the authors predict the use of a link between a UAV-BS and a BS forming a dedicated backhaul employing free space optics (FSO), that allows no interference and no bandwidth reduction, since FSO and radio signals work at different frequencies. Within this scenario, the authors propose a way to determine the location of the existing UAV-BS, a new UEs association policy, and an optimal bandwidth allocation scheme for the network backhaul. Similarly, Siddiqui et al. [22] designed a reinforcement learning approach to maximize the number of served UEs through the UAV-UE association, and optimize the UAV-BS placement in an emergency scenario, where there is no deployed ground BS.

Fahim and Gadallah [6] studied the dynamic deployment of a single UAV-BS and provided an optimized coverage technique to improve the communication, while it provides connectivity to groups of devices located out of reach of existent terrestrial gNBs. The proposal presents a joint optimal dynamic placement and UL resource scheduling while considering the diverse QoS requirement from the existing UEs. However, the proposal does not consider 5G-NR interference management techniques.

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By analyzing the related works, we conclude that the feasibility of employing UAV-BSs in communication assistance must be deeply investigated. The studies, as mentioned earlier, show different ways in which UAV-BSs are employed to meet the most diverse scenarios and demands. In addition, the solutions optimize network coverage and/or UE association through UAV-BSs by considering dynamic scenarios or scenarios with multiple gNBs. However, few of them make an in-depth assessment of the factors that impact the performance of UAV-BSs in assistance scenarios where the present network infrastructure cannot effectively meet the UEs' communication requirements. Therefore, this work aims to present a quantitative and qualitative evaluation of the parameters that impact the network's performance and clarify the most important aspects to consider UAV-BSs for network assistance in 5G and B5G scenarios.

3 Network model and management

It is important to understand the following aspects to assess the feasibility of using UAV-BSs to improve communication. Specifically, it is important to analyze: i) the communication capacity of an UAV-BS in terms of network resources, ii) the behavior and impact of interference in different scenarios, and iii) how the different deployment arrangements impact the network performance, and whether a UE will make use of the new resources made available through the UAV-BSs.

In the context of UAV-BS for network assistance, communication, and connection coverage, 5G-NR has been chosen as the technology, as it presents some favorable aspects. The key advantages of 5G-NR are high bandwidth and low latency. It can also be employed on a large scale, providing higher data rates than the previous communication technology. Besides, it enables collaboration, cooperation, integrity, and confidentiality among nodes through the device-to-device (D2D), machine-to-machine (M2M), beam-forming, and network slicing capabilities [25].

In our assessment, we consider a scenario with a set of static UEs $U = \{u_1, u_2, \ldots, u_k\}$ with an individual identity ($k \in [1, o]$) and a set of gNBs $V = \{v_1, v_2, \ldots, v_i\}$ with an individual identity ($i \in [1, n]$) deployed in fixed known locations L_i, which is defined as a 3-tuple of geographical coordinates(x_i, y_i, z_i) in a 3D space, i.e., Cartesian coordinates, and altitude over the ground. In our case, every gNB v_i has a fixed transmission power P_{t_i}, being considered a BS or an UAV-BS depending on the P_{t_i} value. Every UE u_k connects to a single gNB v_{i_k} and receives a signal with a power $\mathrm{P}_{r_{k,i}}$. Each UE u_k also receives signal from the neighboring gNBs with a power $\mathrm{P}_{r_{k,i}}$. The gNBs V (BSs and/or UAV-BSs) are deployed to offload cellular traffic from the UEs U to a connected remote host. Each gNB v_i and user u_k are aware of their location within the space of interest positioning system, e.g., global positioning system (GPS) or Galileo.

3.1 Communication resources

In a 5G-NR network, each gNB has a limited amount of available communication resources. Therefore, we also study the amount of data that an gNB can handle regarding the chosen amount of resource blocks (RBs) configured. A RB is the smallest unit of resource that is allocated for a given user. Briefly, the RB is 1 slot long in time and 180 kHz wide in frequency. The RBs are allocated to each connected UE during the communication process.

The initial evaluation follows the parameters in Table 1, where we consider 1 UE, 1 gNB, and we have stressed the network by increasing the UE data rate until we find the maximum value that this single gNB can handle. The throughput rate is the chosen QoS metric since it represents the ratio of the amount of data transmitted by the UEs that reached the network over the total transmitted data. This evaluation is performed using the network simulator 3 (NS-3) [19] with the 5G-NR network using the 5G-Lena [12, 17] module, which is widely cited and used in the scientific community. In NS-3, the 5G-NR topology is composed of an 5G-NR module, which includes the radio protocols stack (MAC, PHY, radio resource control, packet data convergence protocol, radio link control) present in the UE and gNB devices, and the core of the 5G-NR network, which includes the main network interfaces, protocols, and other entities.

The given band is split in our simulation to improve the network's capacity and performance. The network operates

Table 1 Simulation parameters for single gNB capacity evaluation

Parameter	Value
Number of UEs	1
Number of UAV-BSs	1
UAV-BS altitude	10 m
UAV-BS-UE horizontal distance	100 m
Tx power UAV-BS	23 dBm
Resource Blocks UAV-BS	100
Application data rate UAV-BS	[20 - 200] Mbps

in time-division duplexing (TDD) in a given band, and the band is split into four equally-sized contiguous (CCs). The division of the band into multiple component carriers allows the network to manage interference between different types of traffic.

Figure 1 shows how much data a single gNB can effectively handle while one UE increases its configured data rate. In this case, the main impact comes from the amount of available RBs, where we have defined 50 RBs for both down-link and up-link connections. The throughput rate starts to drop significantly after 60Mbps of data rate in this simple scenario. In this case, the distance among the nodes and the number of RBs are fixed, where if the required data rate increases, the resultant throughput rate will start to decrease at a certain data rate threshold. Therefore, it is important to consider that every gNB, being it an BS or a UAV-BS, can attend a limited number of UEs.

Similarly, terrestrial infrastructure can be overloaded or damaged with reduced communication capabilities. Hereinafter, the deployment of UAV-BSs in these scenarios becomes a viable alternative since these devices carry communication resources and can quickly fly to the affected region. However, it is important to note that the UEs will be appropriately served only if the number of new resources is sufficient. Thus, it requires a reasonable estimation of how many UAV-BSs will attend the scenario. In the following sections, we will evaluate scenarios where a single BS is not enough to effectively attend all the UEs around it.

Efficient resource management is crucial for maximizing the benefits of using UAVs to improve network coverage and performance, especially in large-scale deployments or limited resources. By carefully managing resources and implementing strategies to optimize resource use, it is possible to enhance the efficiency and effectiveness of a drone-assisted network and achieve better performance in terms of various key performance indicators (KPIs), such as coverage, capacity, latency, and energy efficiency.

3.2 Coverage and Interference

The network coverage is one of the KPI foreseen by 5G that is not reached by existing terrestrial infrastructure, either due to the distance and deployment costs or some unavailability (overload, structural damage, etc.).

The RSRP is a parameter used in 5G-NR wireless communication systems to estimate the power of the DL reference signals from a cell. Most cell selection and handover algorithms take this RSRP as the main decision metric in the 5G-NR network. It is calculated based on the power of the pilot signals from the currently connected gNB. It does not depend on the channel width or considers spurious signals and interference. As a result, the RSRP always has a lower numerical value than the received signal strength indicator (RSSI), which measures the strength of the incoming signals. Besides, in Het-Net it does not represent the most effective selection criteria for a gNB selection, since it does not consider the available resources information, only the transmission power.

In its turn, the SINR enables a more precise assessment of the network coverage once it considers the interference. Specifically, higher SINR means a larger chance of transmission success once the metric considers the signal power received by the connected antenna and the noise caused by adjacent nodes. Typically, in 5G-NR networks, values greater than 20dB indicate a better transmission of

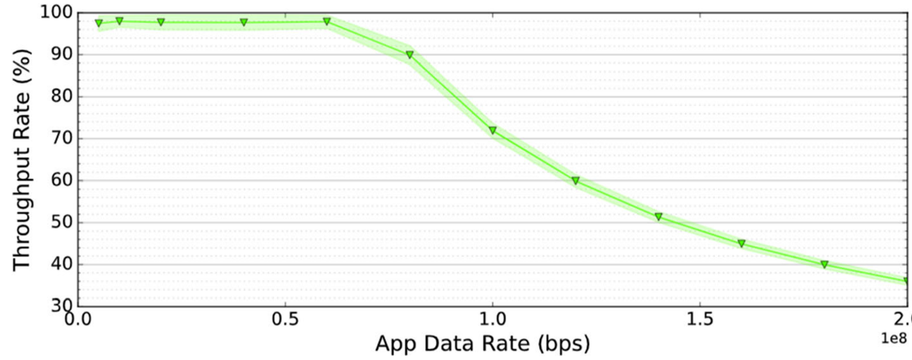

Fig. 1 Throughput rate while increasing the required UE data rate

information. On the other hand, values below 13dB compromise the communication performance between the transmitter and the receiver nodes [1].

Figure 2 shows the desired signal and the interference signal to an UE at the center. The impact of these signals depends on the distance between the UE and the existing gNBs. In this sense, the SINR depends on the signal received by the connected gNB and the neighboring gNBs. Hence, it is important to understand that, even with the presence of extra communication resources, the gNB deployment must be planned once the presence of interference signals affects the communication.

The SINR measures the quality of the received signal in a wireless communication system. The higher the SINR, the better the signal quality and the more reliable the connection. It is calculated based on the desired signal strength and the power of the interference and noise signals in the system. In a scenario with multiple gNBs causing interference, the SINR can be used to measure how well the UEs can communicate with its connected gNB. In this NS-3 simulation environment, the SINR calculation is based on the propagation loss model 1 and 2 defined in Table 7.4.1-1 of the 3rd generation partnership project (3GPP) TR 38.901 for urban macro (UMa) environment, which measures the received power at a distance from a transmitter considering the transmitted power, antenna gains, path loss, and noise power [29] as follows:

$$\mathrm{PL}_{LoS}(D,f_c) = 28.0 + 40\log_{10}(D(v_i,u_k)) + 20\log_{10}(f_c) - 9\log_{10}\left(\left(d'_{\mathrm{BP}}\right)^2 + \left(h_{\mathrm{gNB}} - h_{\mathrm{UE}}\right)^2\right) \tag{1}$$

$$\mathrm{PL}_{NLoS}(D,f_c) = 13.54 + 39.08\log_{10}(D(v_i,u_k)) + 20\log_{10}(f_c) - 0.6, \tag{2}$$

where $D(v_i, u_k)$ is the euclidean distance in meters between v_i and u_k, which represents the transmitter and the receiver, break-point distance $d_{\mathrm{BP}} = 4h_{\mathrm{gNB}} \times h_{\mathrm{UE}} \times f_c/c$, where f_c is the centre frequency in Hz, $c = 3.0 \times 10^8 m/s$ is the propagation velocity in free space, and h_{gNB} and h_{UE} are the effective antenna heights at the gNB and the UE, respectively.

The SINR_k for each pair gNB and UE is the ratio of the received power $\mathrm{P}_{r_{k,i}}$ from the connected v_i and the sum of the environmental noises ϱ and the power $\mathrm{P}_{r_{k,j}}$ received from the neighbors v_j, given by

$$\mathrm{SINR}_k = \frac{\mathrm{P}_{r_{k,i}}}{\varrho + \sum_{j=1, j\neq i}^{N} \mathrm{P}_{r_{k,j}}}. \tag{3}$$

It is essential to highlight that he SINR differs from the signal to noise ratio (SNR) because the first one also considers the interference signal from the neighbors gNBs.

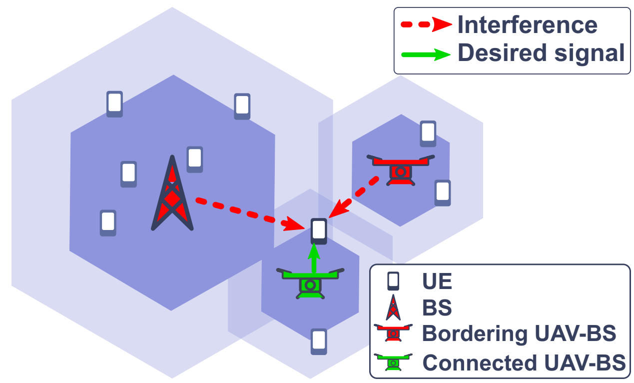

Fig. 2 Desired and interference signals illustration

Based on this modeling, we use the NS-3 to evaluate different scenarios and highlight the aspects that determine whether the use of UAV-BSs is effective and how this should be done. We start by evaluating a simple scenario, where a single BS is deployed at the center, and a set of 50 UEs are placed around it. Then, we demonstrate that multiple gNBs causes interference. Finally, in a more complex scenario, we deploy one BS, a set of 50 UEs, and different sets with a different number of UAV-BSs. Table 2 summarizes the parameters and the scenarios' configurations.

Figure 3 illustrates the positioning of a set of 50 UEs distributed around one single BS in the center to visually understand the SINR values over an area. The UE distribution follows different maximum distances from the BS and different densities, keeping the same number of UEs for the sake of simplicity. There is an unobstructed LoS between any UE and the ground BS.

In this case, the signal degradation increases with the distance to the existing ground BS, as defined in the SNR model. This happens because the transmission power decreases as $D(v_i, u_k)$ increases. Thus, the UEs at the edge experiences a larger signal fading, increasing the probability of data loss. This information is illustrated in Fig. 3, where the yellowish region of the map has a higher SNR value, while the darker region has a lower SNR value. It is also shown in 4 together with the throughput rate performance.

By analyzing Fig. 4, it is possible to see how much the distance between UEs and an existing gNB impacts the throughput rate and SINR. By comparing the results of Fig. 3a, b, when the maximum distance between an UE and the BS increases 10 times, the average SINR decreases approximately 80% and the throughput rate decreases almost 60%. This is because the SINR is directly affected by the distance between an UE and a gNB, since the larger this distance, the higher the PL which in turn depends on the same distance D and decreases the received power by the UE. The worst value of SINR and throughput rate is

Table 2 Simulation parameters for UAV-BS deployment evaluation

Parameter	Value
UAV-BS altitude	10 m
BS altitude	25 m
Tx power UAV-BS	23 dBm
Tx power BS	46 dBm
RBs RBs	50
Maximum application data rate (UL)	1 Mpbs
Simple scenario	[1, 50] UE
	0 BS
	[1, 3] UAV-BSs
Complex scenario	50 UE
	1 BS
	[1,5,10,25,30,35,40,45,50] UAV-BSs

reached in Fig. 3c, which decrease 61.63% and 3.81%, respectively, with a maximum UE-BS distance that increases 100 times comparing to Fig. 3a. Therefore, scenarios such as these, where the distance from the existing gNBs prevents part of the UEs from communicating effectively, pave the way to the UAV-BSs deployment. UAV-BSs can quickly fly to such areas and provide communication resources to the poorly attended UEs.

In this sense, it can be noted that it is not practical nor feasible to implement new ground BS infrastructure to meet the demands of scenarios that require quick assistance and a large number of communication resources during a short period, such as concerts, flash-crowd events, and even natural disasters. Therefore, deploying UAV-BSs in these scenarios becomes a potentially viable solution since they can quickly fly to the desired place, be equipped with communication resources, and more quickly serve hard-to-reach areas or areas with a temporary demand for communication resources. However, it is crucial to understand in which cases they represent an add-on and are not hampering the BS communication.

4 UAV-BS deployment evaluation

In this section, we evaluate different UAV-BSs configurations to assist the existing 5G-NR network in order to assess the feasibility of a UAV-BS network, where the communication support for UEs can be provided by either BS or UAV-BS. Again, the following evaluations were performed using the UAV-BS, such as introduced in Sect. 3. We first study a simple scenario by deploying only a tiny set of UAV-BSs and a single UE. Afterward, we consider a more complex scenario with different numbers and types of gNBs and also following different UAV-BSs positioning algorithms. The tests were performed with a 1Mbps constant bit rate (CBR) application for both download and upload. A set of 50 UEs were placed around one ground gNB (*i.e.*, BS), and a set of flying gNBs (*i.e.*, UAV-BSs) were placed following a circular or a clustering approach. Every gNB in the scenario has 50 RBs available for communication with the UEs. Table 2 summarizes the simulation parameters for UAV-BS deployment evaluation.

4.1 Communication performance

The objective of the first scenario is to predict the impact on UEs in terms of SINR by deploying UAV-BSs, as this metric is closely related to how good is the communication among the network entities; the interference signals come in the presence of two or more gNBs using the same communication channel. In this context, not only the number of UAV-BSs, but also their position may have a great impact on the management of the network coverage and interference. For instance, the shape of the coverage regions may not be completely circular in the presence of co-channel interference between multiple gNBs [11].

Figure 5a shows a single UAV-BS providing communication to a UE in the center of the scenario, while Fig. 5b shows 3 UAV-BSs, but only one providing communication to the UE in the center of the scenario as the UE is configured to choose only one gNB to connect with. The complementary scenarios enable to measure how the interference among the UAV-BSs impacts the communication performance of the network (see Fig. 5b), since the interference is not present in a scenario with a single gNB (see Fig. 5a). The results show that the increase of communication resources through the deployment of multiple UAV-BSs may not be as efficient for the communication between the UEs and the UAV-BSs, since there is also interference between the existing UAV-BSs. These aspects can be noted by comparing the shape and colors, which represent how good the SINR is around the UE. The whiter

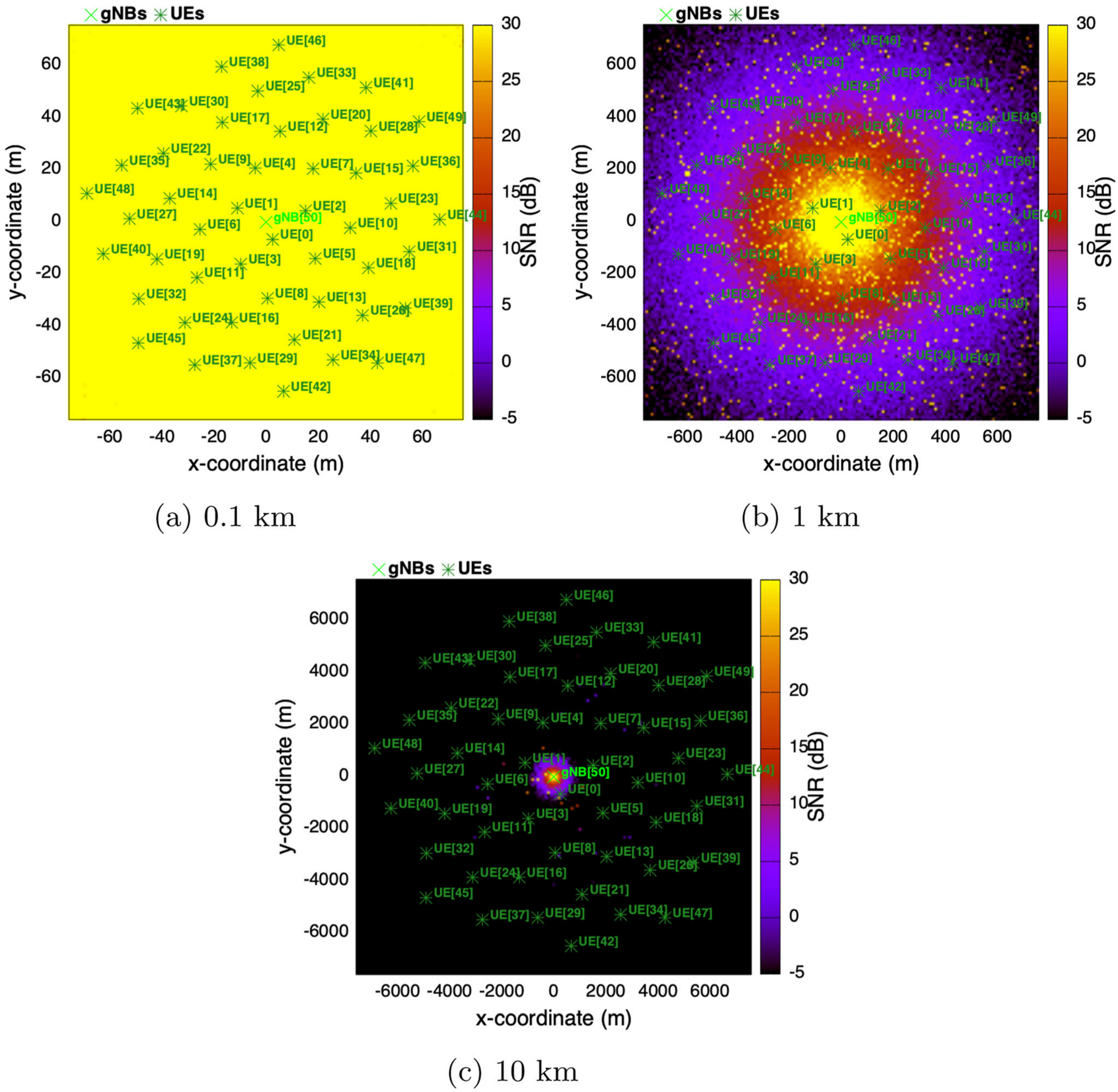

Fig. 3 SNR and throughput rate behaviour with the distribution of the UEs in different maximum distance from the central ground BS. The number of UEs is fixed in 50, and the distance from the center varies between 100 m, 1 km and 10 km

the region, the higher is the SINR, while the darker, the lower. In Fig. 5a, the shape of the signal strength coming from the UAV-BS is perfectly circular, showing that the signal propagates equally over the area, losing strength only with the distance. While in Fig. 5b, the UE has the same distance between all the 10 UAV-BSs, the signals coming from the UAV-BSs collide and attenuate faster due to the presence of more than one UAV-BS, affecting the UE' experienced SINR and throughput rate.

Figure 6 summarizes the values of SINR and throughput rate for scenarios with 1 and 3 UAV-BSs for the same scenarios of Fig. 5. By analyzing the results, it is possible to see that the presence of more than one UAV-BS can potentially decrease the throughput rate, since the higher the number of UAV-BSs in the same region, the higher the interference among them and experienced by the UE. In this case, the SINR experienced by the single UE decreases about 225%, while the throughput rate decreases 12% from the scenario illustrated in Fig. 5a to the scenario in Fig. 5b.

Figure 7 shows the SINR for the scenario with 50 UEs, 1 gNB, and different number of UAV-BSs. The UAV-BSs were placed following a clustering process of the UEs'

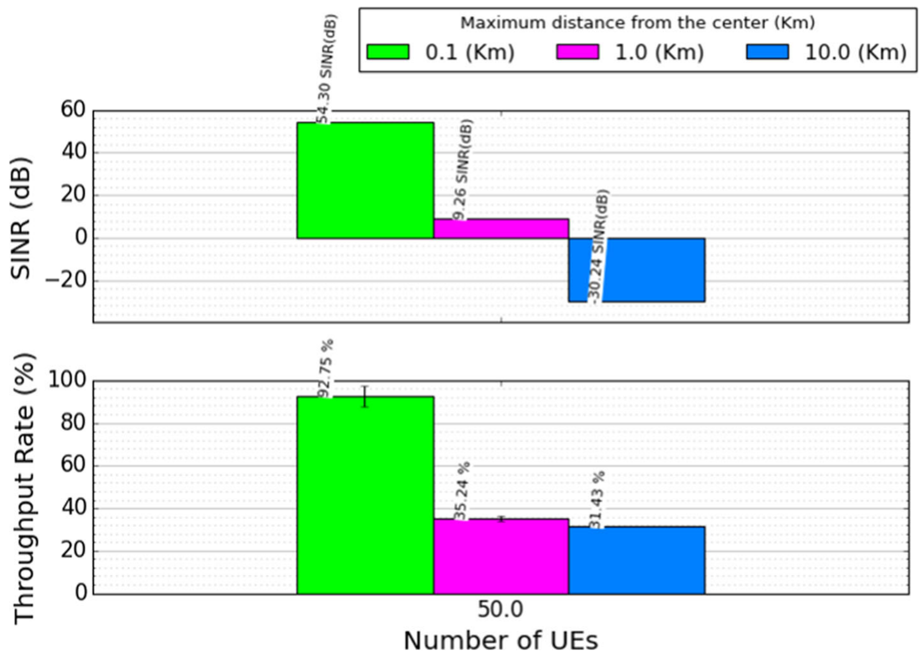

Fig. 4 SINR and throughput rate for 50 UE with different distance from the center (i.e., 0.1, 1, and 10 km), following the deployment of Fig. 3

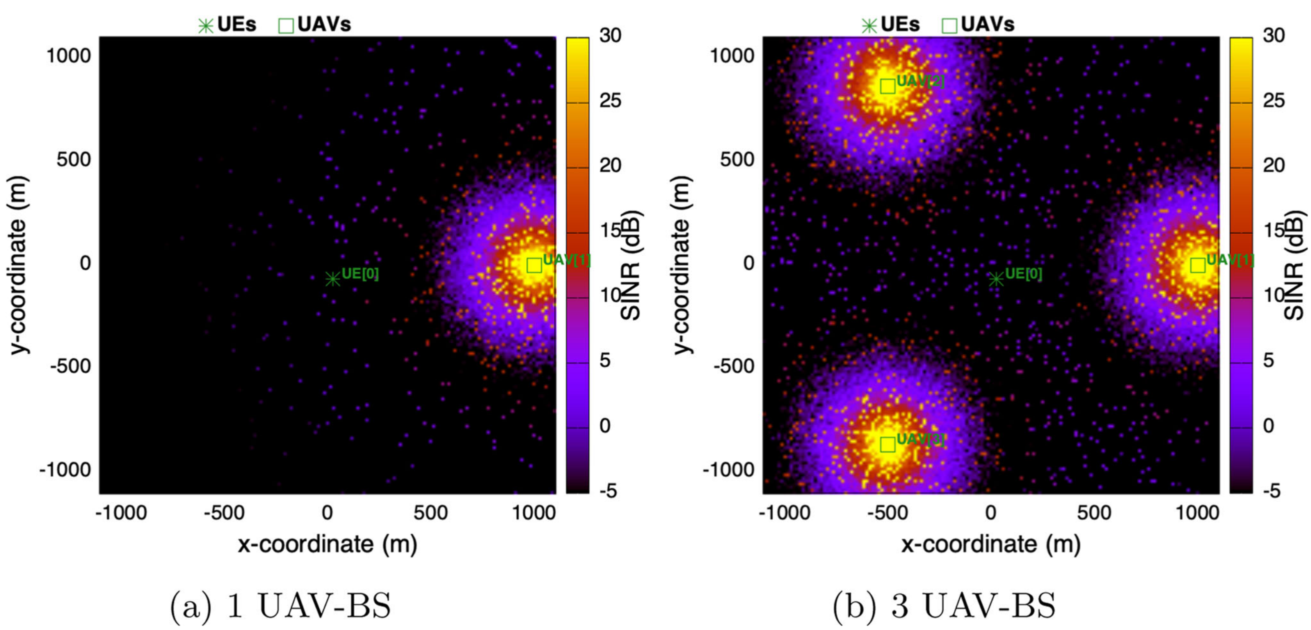

Fig. 5 The scenario with 1 UE and different numbers of UAV-BS

locations, where the clustering process takes into account the UEs' locations and the number of available UAV-BSs, and it returns a set of locations for the UAV-BSs that are usually evenly distributed over the region closer to the UEs. Figure 7 shows the SINR behavior when deploying multiple UAV-BSs since the higher power of an gNB leads to higher interference for either UAV-BSs. On the other hand, UEs farther away from the center experience weaker signal strength, and thus it is more difficult to obtain a reasonable SINR if they are not close enough to an UAV-BS. For instance, in Fig. 7a, UEs with 1 km of distance from the BS experience a SINR of approximately 12 dB, which is a value close to a quality threshold.

Figure 8 summarizes the values of SINR and throughput rate for the same scenarios of Fig. 7. It is possible to see that from 1 to 30 UAV-BSs, the performance increases with a more significant factor. This is because there is a greater demand for communication resources. From 30 UAV-BSs, this performance increase may no longer be as substantial, since the proximity between the gNBs causes

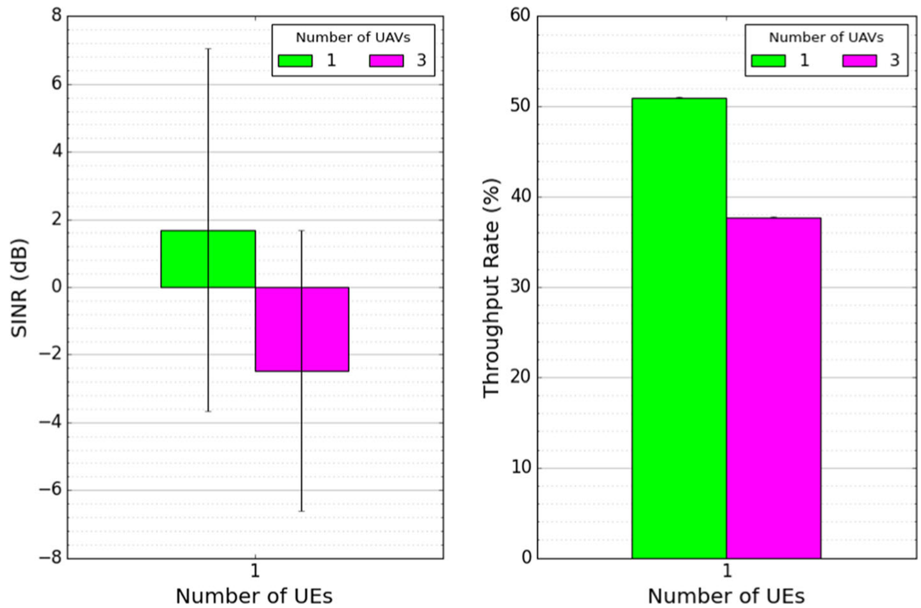

Fig. 6 Interference impact on the throughput rate by deploying different number of UAV-BSs

higher packet collision due to interference. It also shows that the throughput rate reaches 100% when the number of UAV-BSs is equal to the number of UEs (i.e., 50) and is located right over them, which is not realistic in practice, once the deployment of 1 UAV-BS for each UE can be very costly. In other words, it is possible to observe that a higher number of UAV-BSs leads to a greater chance of a UAV-BS to be deployed closer to the UEs using the clustering approach. Thus there is a higher chance of an UAV-BS to overcome the received signal strength from the existing BS. It can then be foreseen that when there is the same number of UEs and UAV-BSs, each UAV-BS will be located just above an UE – as following the clustering positioning method –, keeping the shortest possible distance between them. In this case, every UE experiences the highest possible SINR value.

The UAV-BS positioning has a different impact on the throughput rate by considering that the distances among the gNBs are the main factor that impacts the interference, i.e.SINR experienced by a UE. Taking this into account, we have tested two different deployment patterns to see how the UAV-BSs' locations affect the network performance. In addition to the clustering method, we have also added a circular method, which deploys the UAV-BSs around the ground BS forming a circle, both depicted in Fig. 9. The idea behind the latest approach is to attend to the edge of the area formed by the BS signal propagation, trying to avoid the potential interference caused by the deployed UAV-BSs and also trying to reach the UEs that experience a weaker signal strength from the BS.

Figure 10 shows the SINR and the throughput rate for the clustering and the circular UAV-BSs deployment methods. The circular method performs slightly better when the number of available UAV-BSs is small. On the other hand, the clustering method performs better once the number of UAV-BSs increases. It is because this method distributes the UAV-BSs over the area in a more efficient way, while in the circular method, the UAV-BSs get too close to each other, causing more interference among the UAV-BSs. Besides, we have seen that, with more gNBs in the scenario, the more communication resources are available to the UEs, which significantly increases the overall throughput rate of the UEs that choose a UAV-BS to connect. It reinforces that using UAV-BS for network assistance also defines a Het-Net scenario. Therefore, it is essential to evaluate which gNB a UE will connect to make use of all existing communication resources, whether it is an UAV-BS or a BS.

4.2 Cost-effectiveness

Depending on the application, the network requirements may follow different criteria, such as throughput or delay. To assess the cost-effectiveness of using UAV-BSs, we start by defining ξ, used to represent the trade-off of a wireless network, and it is based on two key performance indicators: the throughput and the delay. The throughput is the data delivery rate over the communication channel, measured in bits per second. The delay is the time it takes for a packet to travel from the source to its destination, measured in milliseconds. ξ is proportional to the average throughput and inversely proportional to the delay (4 and 5).

$$\xi \propto \text{Throughput} \tag{4}$$

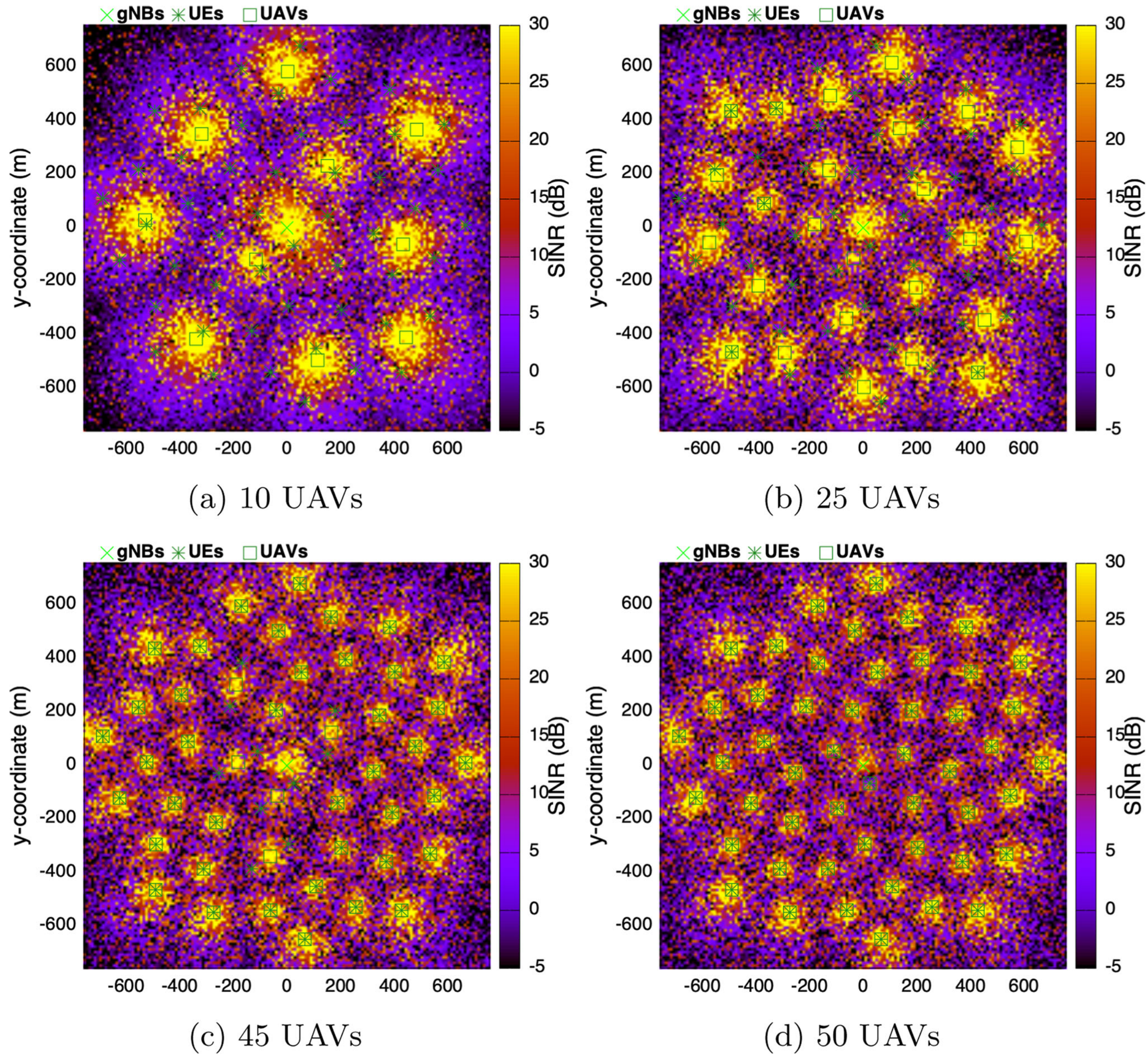

Fig. 7 The impact on the SINR over the UEs with the maximum distance of 1 km and the different number of UAV-BS in a clustered deployment

$$\xi \propto \frac{1}{\text{Delay}} \tag{5}$$

For cost-effectiveness evaluation, we consider a network system based on the clustering algorithm to deploy the UAV-BSs and attend 50 UEs. This clustering approach provides better overall network performance and node distribution than the circular method, as shown previously. The average throughput for all the UEs in each simulation round is stored in a 2D array. The rate varies from 0Mbps to 1Mbps. The average throughput from the UEs is kept in a 2D array T for each simulation round ($R_{u,v}$), where u represents the number of employed UAV-BSs and d is the radius of the UE distribution over the area. Similarly, the average delay is kept in L. We also assume that both throughput and delay have the same importance but opposite effects on the network performance: a higher throughput and a lower delay are preferable. Therefore, the average throughput values (T) and average delay values (L) of each end-user are normalized, and given by

$$\hat{T} = 2\left(\frac{T - \min(T)}{\max(T) - \min(T)}\right) - 1, \tag{6}$$

and

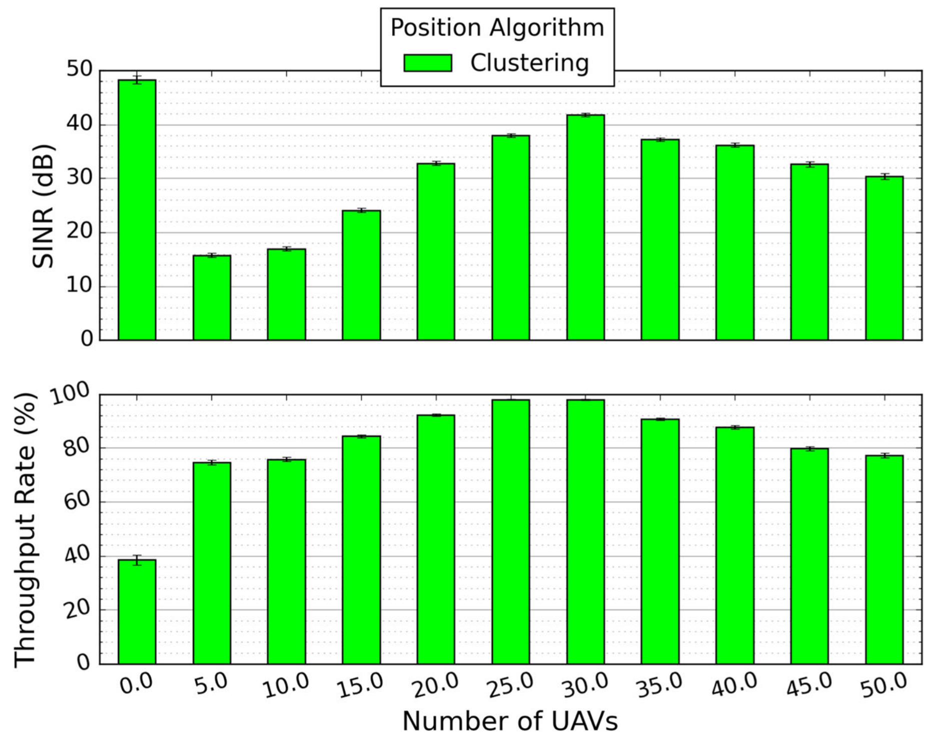

Fig. 8 Number of connected UEs to the UAVs, SINR, and throughput rate when varying the number of UAV-BSs in a scenario with a single ground BS at the center and 50 UEs in a range of 1 km

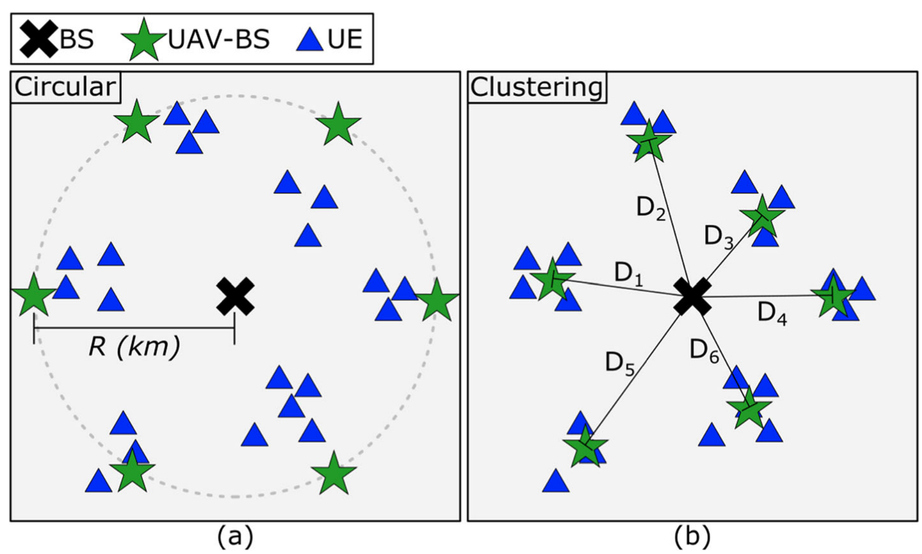

Fig. 9 Circular topology in (**a**), where all the UAV-BSs are placed with the same distance *R* from the BS. Clustering topology in (**b**), where the UAV-BSs are placed over the UEs according to the density of such nodes in the area, therefore keeping different distances from the BS

$$\hat{L} = 2\left(\frac{L - \min(L)}{\max(L) - \min(L)}\right) - 1. \quad (7)$$

ξ is the sum of the average throughput and the inverse of the average delay:

$$\xi = \hat{T} + \frac{1}{\hat{L}}. \quad (8)$$

Equation 8 measures ξ for the collected simulation data, where T is the average throughput 2D array, L is the average delay 2D array, $\hat{T}$ is the normalised T, and $\hat{L}$ is the normalised L.

To find the system's cost-effectiveness, we measured ξ by varying the number of UAV-BSs and the radius of the area where the UEs are distributed. Figure 11 shows how the trade-off changes when varying the number of UAV-BSs and the radius of the area. Thus, for a clustering deployment approach, ξ increases with the number of UAV-BSs as more network resources are provided to the UEs. ξ increases until it reaches a cost-effective region, where the number of UAV-BSs reaches the maximum ξ for the given area radius distance. After that, the trade-off

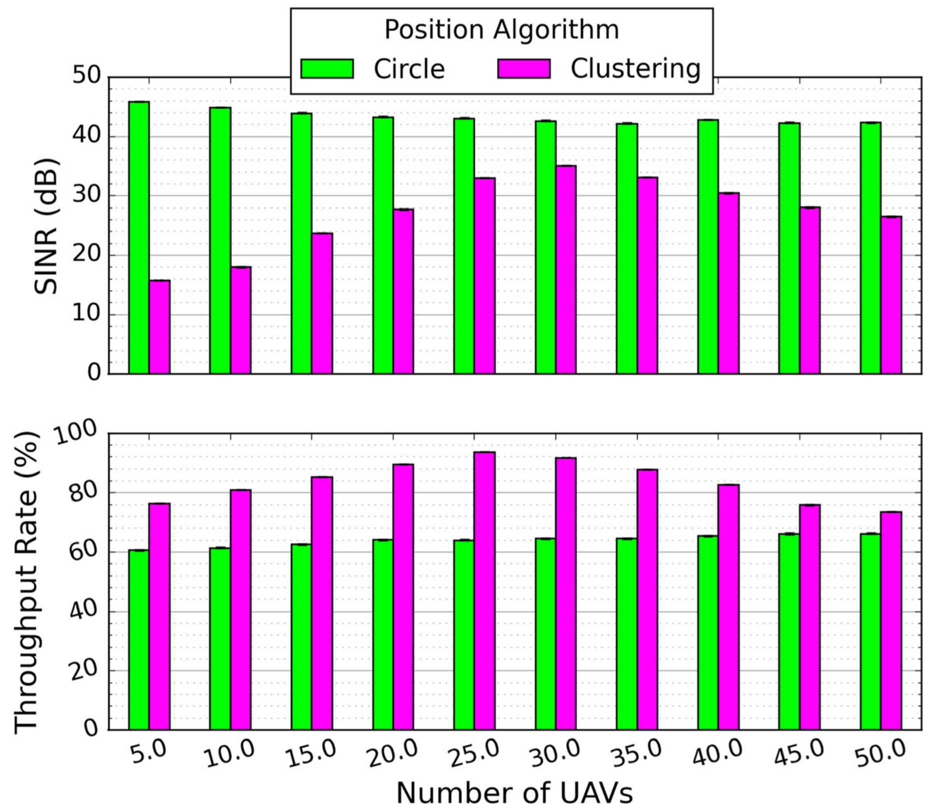

Fig. 10 Number of connected UEs to the UAVs, SINR and throughput rate while using different deployment patterns

decreases due to the interference caused by the UAV-BSs densification.

Further modeling is also possible. ξ can be estimated as a function of two variables: the number of UAV-BSs (u) and the radius of the area (d) where the 50 UEs are evenly distributed. Based on the simulation data shape and analysis, we assume this function has a quadratic form, as shown in 9. The coefficients of this function are obtained by performing a linear regression with polynomial features of degree 2 using the Statsmodels library [20].

$$\xi(u,d) = 27.12\times10^{-2} + 45.98\times10^{-3}u + 80.97\times10^{-5}d + 96.40\times10^{-5}u^2 + 7.76\times10^{-6}ud - 3.39\times10^{-7}d^2 \quad (9)$$

To summarize our findings, Table 3 depicts the main conditions to consider when deploying a set of UAV-BSs for network assistance and how the UAV-BSs' locations impact the network behavior. From this study, the main aspects raised were the number of available communication resources and the distance among all the involved devices, each aspect impacting the network in different ways and degrees. The trend is that the amount of communication resources available tends to impact more strongly when considering adding new UAV-BSs. However, it is also necessary to consider the impact generated by the proximity of the UEs with the different gNBs (BS or UAV-BS) to ensure that the available communication resources are appropriately used.

Independently on the resources available on the network (through the existing gNBs), a UE has a high chance of failing not using the idle resources because it considers only the highest signal strength as the criterion for choosing an gNB. This factor leads us to believe that, for a significant improvement in the network, the addition of more communication resources through the UAV-BSs should be associated with a smart management of these connections. This management can be done from the UE, since it is aware of which gNBs are close, and thus, it can choose the one that meets its needs.

5 Conclusion and future works

This paper studied the usage of UAVs as flying BSs and the quantitative and qualitative impact on the UEs' throughput rate. The UAV-BS performance is highly dependent on the number of devices to be deployed to assist the ground infrastructure, the distances among all the existing gNBs (BS or UAV-BS), and between the gNBs and its connected UEs.

We first showed that communication resources are fundamental for any data transmission. No matter how close an UE is to its selected gNB, the data will only be

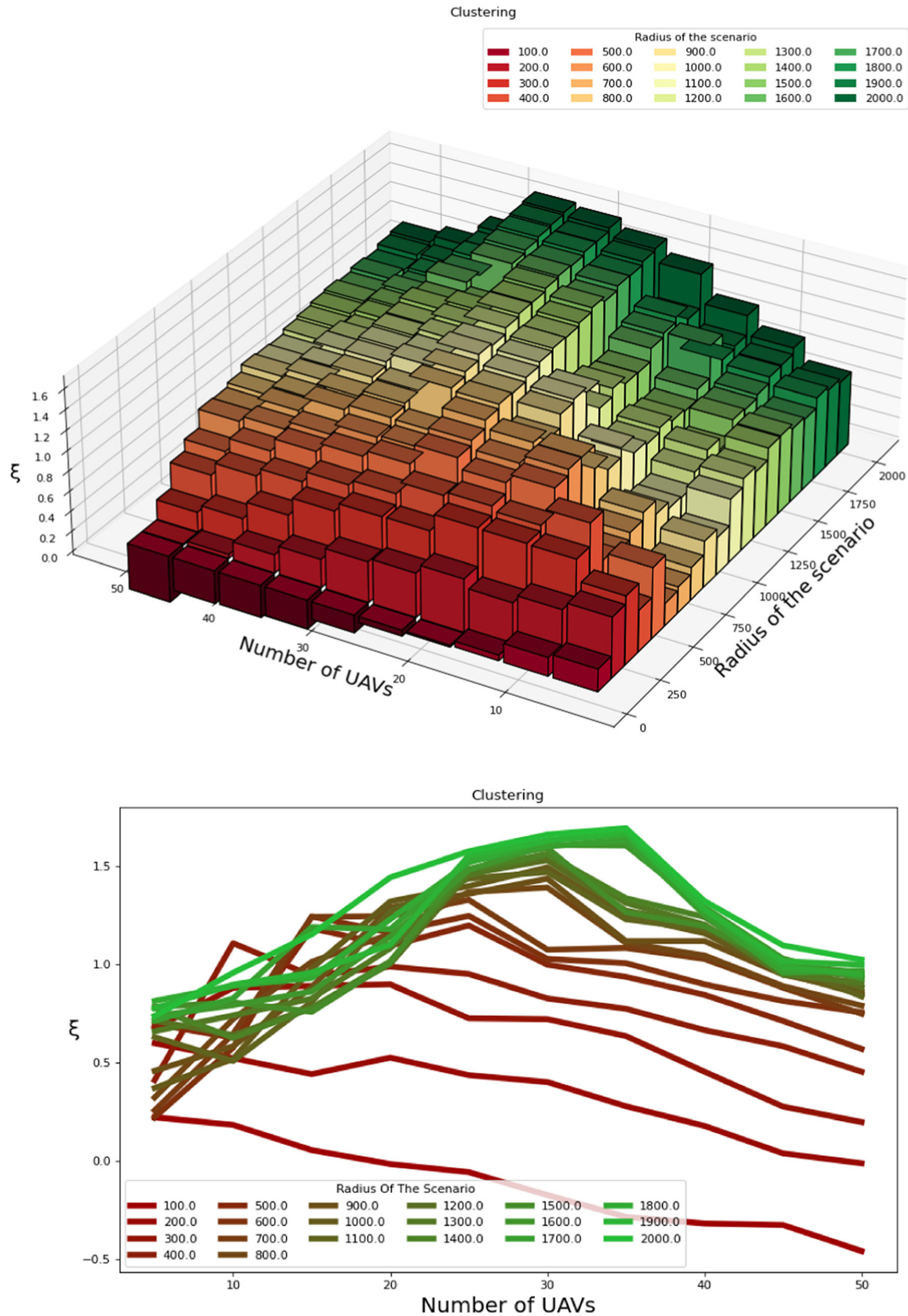

Fig. 11 The cost-effectiveness behaviour considering the clustering UAV-BS deployment in a scenario with 50 UEs

Table 3 UAV-BS deployment conditions and impact summary

Main aspects raised	Network impact	UAV-BSs' clustering positioning	UAV-BSs' circular positioning	Impact factor	Observation
Number of available UAV-BSs	Affects the number of available resource blocks	Depends on the ratio between the number of UAV-BSs and the number of UEs	Use all available UAV-BSs	High. Provides the main communication resource (resource block)	An optimized value can be estimated based on the UE's requirements and the UAV-BS capacity
Distance between UEs and UAV-BSs	Affects the choice of the best eNB: the shorter, the better	Tends to move the UAV-BSs towards dense regions of UEs	Benefits those on the edge	Reasonable. Varies the SINR accordingly	Highly dependent on the position of other network nodes. Hard to predict
Distance between the BS and UAV-BSs	Impacts on the interference: the larger, the better	Even UAV-BS distribution over the UEs	Poorly UAV-BS distribution over the UEs	High. Prevents the UE from "seeing" the available UAV-BSs and varies the SINR accordingly	Highly dependent on the position of other network nodes. Hard to predict
Distance between existing UAV-BSs	Impacts on the interference: the greater, the better	UAV-BSs' approximation depends on the UEs' arrangement in the scenario	Circular method is unaware of the UAV-BSs' approximation	Reasonable. Impacts on the number of packet loss due to interference	Highly dependent on the position of other network nodes. Hard to predict

effectively transmitted if a suitable amount of communication resources is available. Second, we showed the interference behavior among the nodes and how the presence of multiple gNBs in the same region causes this interference, influencing the throughput rate experienced by the UEs. Third, the placement of the UAV-BS is critical since the distances between the devices directly impact the received signal power and interference. Moreover, we showed that the default mechanism used by the network to define a connection between a gNB and an UE also significantly impact how much of the available resources are being effectively used. The current method is based on the gNB received signal strength, and it seems to not be efficient in the presence of heterogeneous gNBs; it prioritizes those gNBs with the highest signal strength but sometimes presents a limitation on the available resource blocks.

We have also calculated the cost-effectiveness of the UAV-BSs assisted network system. The expression we obtained shows the feasibility of deploying UAV-BSs and indicates that the optimal number of UAV-BSs needs to be carefully designed.

In future work, we aim to evaluate new positioning algorithms and study different UE-gNB association mechanisms to deal with a heterogeneous network.

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