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UAV Assisted Heterogeneous Wireless Networks: Potentials and Challenges

LI Tongxin, SHENG Min, LYU Ruiling, LIU Junyu, and LI Jiandong
(State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an, Shanxi 710071, China)

Abstract

By fully exploiting the spatial resources, unmanned aerial vehicles (UAVs) are expected to serve as an efficient complementary to terrestrial wireless communication system to provide enhanced coverage and reliable connectivity to ground users. With the growing deployment of units such as small cell base stations (BSs), however, the incurred severe interference may hinder the potential benefits of the integration of UAVs. In this paper, we first discuss the intrinsic features and potential benefits of UAVs and introduce the architecture of multi-layer heterogeneous wireless network (MHetNet), in which traditional wireless network is assisted by UAVs. Then, an explicit discussion on the factors that limit the performance of MHetNet is presented, including the UAV topology, UAV density, and spectrum sharing of UAV and terrestrial networks. We use simulation results to investigate the performance of MHetNet in terms of spatial throughput (ST). It is shown that, together with the densities of UAV and terrestrial networks, the altitude of UAV is a limiting factor that should be optimized to improve the ST of MHetNet.

Keywords

unmanned aerial vehicles; heterogeneous network; ultra-dense network

1 Introduction

Providing massive device connectivity, enormous network capacity and mega user experienced data rates is one of the aggressive targets of the fifth generation (5G) wireless communications systems. In particular, it is forecasted that the requirement of global mobile data traffic in 2030 will show a 20,000 fold increase compared to that in 2020, and device connections will reach 100 billion [1]. Among the appealing approaches to achieve the ambitious goals, network densification with the deployment of heterogeneous infrastructures has been shown to be the one with the greatest potential [2]. Especially, a growing number of small cells, such as picocells and femtocells, have been deployed to provide high-speed service and boost network capacity. In consequence, spectrum resources could be more effectively exploited and network capacity be significantly enhanced.

While it is reported that network densification with heterogeneous deployments could lead to tremendous network capacity gain [3], [4], an ultra-dense deployment of small cells is not a cost-effective strategy due to capital expense (CAPEX) and operating expense (OPEX) issues. In particular, the quality of service (QoS) can hardly be met with insufficient deployment of small cells. At the same time, recent developments in unmanned aerial vehicles (UAVs) bring forward the idea of using UAVs for coverage extension and capacity enhancements [5]. Due to high mobility and low cost, it could serve as an efficient and flexible complementary to terrestrial heterogeneous wireless networks (HetNet), especially when users' behavior, density, and requirements keep rapidly changing in time and space [6]. The formed new architecture, termed multi-layer heterogeneous wireless network (MHetNet), is promising to provide better terrestrial coverage, enhanced network capacity, and scalable network architecture. For instance, UAVs are capable of providing wireless connectivity to users when the existing terrestrial networks fail to operate or satisfy the demand of wireless connections [7].

However, constantly increasing the density of terrestrial base stations (BSs) or UAVs would not always improve network capacity. Consensus has been recently reached in academia that over-deployment of small cell BSs would incur unexpected and overwhelming interference as well, which conversely results in high transmission outage and degraded user experience [8], [9]. Worse still, it is shown that network capacity would degenerate to be zero with the growing deployment of small cell BSs in ultra-dense networks [10], [11]. Therefore, overwhelming interference caused by deploying UAVs into ultra-dense heterogeneous networks would hinder the application of UAVs, which might conceal the merits and further worsen the performance of current terrestrial heterogeneous networks. Therefore, the integration of UAVs into terrestrial network should consider such factors as the density of BSs and the altitude of UAVs.

In this article, we discuss the characteristics of MHetNet by presenting a comparison of traditional terrestrial HetNet and MHetNet in Section 2, aiming to highlight the potential benefits of MHetNet. Afterward, the challenges posed by integrating UAVs into HetNet are elaborated in Section 3, followed by simulation results, which are presented to demonstrate the pros and cons of MHetNet in Section 4. Finally, a conclusion is drawn in Section 5.

2 Multi-Layer Heterogeneous Wireless Networks

In this section, we introduce the architecture of MHetNet by comparing the inherent features of MHetNet with traditional terrestrial wireless networks. Following that, the potential benefits of MHetNet are highlighted.

It can be seen from **Fig. 1** that, with the aid of UAVs, terrestrial HetNet could offload traffic to UAVs especially when user density is large (e.g., the left part in Fig. 1). In consequence, the users who fail to get service from terrestrial HetNet would be alternatively served through connecting to UAVs. The right part of Fig. 1 shows that the UAV network can provide additional coverage for ground users who are severely blocked by buildings. Therefore, the QoS of the ground users could be enhanced with the integration of UAVs in MHetNet. Due to the inherent features of MHetNets, there exist a number of differences between MHetNet and the traditional HetNet, the details of which are discussed in the following.

2.1 Dominant Features of MHetNet

MHetNet has good mobility. For traditional terrestrial wireless networks, in which access points such as BSs are basically deployed in a fixed manner, the mobility of access points is not supported. This means that limited users could be served by each access point even when techniques like cell splitting and merging are applied. In MHetNet, however, UAVs could move randomly or be organized as a swarm. Therefore, compared to traditional HetNet, MHetNet is capable of attaining rapidly-changing user demand [12].

Topology in traditional terrestrial wireless network is basically determined. Even considering the high-mobility vehicle-to-vehicle (V2V) scenarios, the network topology in successive time instants is almost identical. In contrast, topology variation is more straightforward and easier in MHetNet. If serving as access points, UAVs could adaptively adjust positions according to user demand. On the other hand, due to power limitation and malfunction, the UAV positions would be changed frequently and UAV links would form and vanish repeatedly. The topology change of UAV network would significantly influence the performance of terrestrial network. For instance, assuming that UAV access points move rapidly, the terrestrial users would be handed over to other terrestrial BSs or UAV access points, which may lead to substantial overhead. In addition, if no UAV access points serve as the backups and all the traffic is transferred to terrestrial BSs, traffic congestion and overload would be incurred.

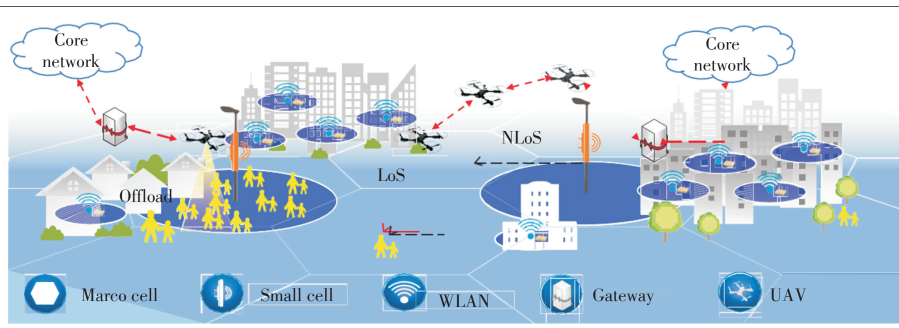
Since low-altitude UAVs could operate over a few hundred of meters, the air-to-ground channel is significantly different from the terrestrial channel. For instance, there are basically less obstructions between a UAV and a ground terminal. In consequence, line-of-sight (LoS) paths are more likely to exist for a UAV-terminal or UAV-BS link. Besides, directional antennas instead of omni-directional antennas are basically equipped on UAVs. In this case, 3D channel modeling would be more suitable for UAV network.

2.2 Potential Benefits of MHetNet

Based on the aforementioned features, we elaborate the potential benefits of MHetNet in detail as follows.

The MHetNet provides more LoS connections. Thanks to the mobility nature of UAVs, LoS paths are more likely to appear in the air-to-ground links, which would lead to smaller path-loss.In consequence, data transmission over the LoS paths could be accomplished with lower transmit power and failure, thereby improving the spectrum and energy efficiency. As well, it is worth noting that the existence of LoS paths is dependent on a number of factors, for instance, the altitude of UAVs.

The MHetNet can offload the traffic of terrestrial access network. The traffic in terrestrial HetNet significantly limits the increase of spectral efficiency especially when the number of users within one small cell is large. In consequence, a proportion of users would be temporarily blocked due to the high traffic load, processing capabilities and backhaul on small cell BSs. Moreover, dense deployment of



LoS: line-of-sight NLoS: non-line-of-sight UAV: unmanned aerial vehicles WLAN: wireless local area network

▲Figure 1. The integration of a multi-layer heterogeneous wireless network.

small cells may not be favorable, since it is indicated that over-densification of small cells would lead to a notable degradation of network capacity [13], [14]. In this case, UAVs can serve as an alternative to assist terrestrial access networks. The blocked users could connect to UAVs, which are capable of providing more LoS paths to ground users and better coverage. As a consequence, the terrestrial traffic could be better balanced and more users could be served.

The CAPEX and OPEX could be significantly reduced. Albeit it is cost-efficient to deploy small cells, the expenditures due to maintenance, operation and backhaul are 10–20 folds greater. Therefore, the tradeoff between the deployment of small cells and the resulting CAPEX and OPEX has been under long consideration in both academia and industry. Especially, considering a flash demand scenario, e.g., concert or open gathering, small cell BSs could only be active for a relative short period, whereas the cost for deployment and cooling would be considerable. Instead, it is more cost-efficient to deploy UAVs in such scenarios, since UAVs could be feasibly deployed to serve as access points only when there is requirement.

The MHetNet has a quick response to rapidly changing user demand. Since user demand may be rapidly changed and greatly differ in different geographic regions, the traffic of terrestrial HetNet is not balanced. Under this circumstance, the UAVs, which could be quickly deployed, can be used as mobile relays in moving overloaded scenarios (e.g., a parade) [15]. With the aid of UAVs, the blocked users could take advantage of unused resources in neighboring cells in priority.

Real-time optimization is feasible for UAVs. Due to fixed deployment, it is difficult for terrestrial wireless networks to deliver reliable service for users in severe shadowing or interference scenarios. However, UAVs are capable of optimizing the topology, altitude and connectivity to the ground users in real time, which has recently received extensive attention from academia [16], [17]. In [16], authors investigate the optimization of UAV altitude so as to maximize the coverage for users. Especially, it is shown that the optimal altitude is critically dependent on the statistical parameters of the underlying environment and pathloss. In addition, the impact of spectrum sharing between UAV and terrestrial network is studied and optimized in [17].

3 Fundamental Challenges of UAV-Assisted MHetNet

While the integration of UAVs into terrestrial wireless network may bring a number of potential benefits, critical issues and challenges remain to be settled before these potential benefits could be readily harvested. As earlier noted, the mobility nature of UAVs would render the topology of UAV network highly time-varying, which results in great difficulty in optimization. In addition, the integration of UAVs may result in additional interference due to the limitation of available spectrum resources. If not properly handled, the incurred interference would degrade the performance of MHetNet as well. In the following, we discuss several key challenges in detail.

3.1 Deployment of UAV Access Points

When UAVs are integrated into terrestrial network, the density of terrestrial BSs plays an important role in influencing the performance of the MHetNet. When the terrestrial BSs are insufficiently deployed, the integration of UAVs could enhance coverage and provide services to more users. Accordingly, the traffic of terrestrial network could be effectively offloaded to the UAV network. In contrast, when the terrestrial network is fully densified, few UAVs should be deployed. The reason is that, for users that are connected to small cell BSs, cross-tier interference from UAVs would become more severe. Hence, the demerits caused by the cross- tier interference overwhelms the benefits of spectrum reuse gain and offloading gain. The detail will be discussed later in Section 4.

3.2 Optimization of UAV Access Points

When UAVs serve as access points, the optimization of UAV access points is dependent on the terrestrial network, such as the topology and transmit power. Furthermore, the factors such as altitude, topology and power optimization. should be considered for the optimization of UAV. For instance, the increase of UAV altitude is likely to lead to an increasing number of LOS paths. Accordingly, the number of users that are served by UAVs would be significantly increased. Nevertheless, the cross-layer interference suffered by terrestrial terminals would be increased as well. Therefore, there exists an optimal altitude for UAVs, under which system performance in MHetNet could be optimized.

The topology of UAV network rapidly changes with the number of UAVs and the relative positions of the UAVs. As a consequence, traditional routing protocols are not always efficient, which may result in user session interruption. A slight move of a single UAV may result in substantive change of the whole network, especially when UAVs are densely deployed. Moreover, when one UAV is disconnected, another UAV should be properly selected as a substitute to minimize the overhead due to topological changes.

Onboard energy optimization is also a critical issue to be settled. For instance, the movement of UAVs should be care- fully controlled by taking into account the energy consumption associated with every maneuver. Moreover, ascending of UAVs is basically energy - intensive. Therefore, excessive frequent changes of UAV altitude should be avoided.

3.3 Spectrum Sharing of Terrestrial and UAV Networks

Spectrum sharing of terrestrial and UAV networks can be generally classified into two categories, namely, reuse mode and dedicated mode. In reuse mode, spectrum resources are identically allocated to terrestrial terminals and UAVs, thereby improving the reuse of available spectrum resources. However, cross-layer interference would exist between terrestrial terminals and UAVs. If not properly controlled, the induced interference may ruin the potential of the integration of UAVs. Therefore, how to mitigate the cross-layer interference, e.g., via tuning the UAV altitude, topology and transmit power, etc., is challenging in the reuse mode.

To avoid the cross-layer interference, the dedicated mode serves as an alternative especially when considering dense network deployment scenarios. In particular, non-overlapped spectrum resources are allocated to terrestrial terminals and UAVs, respectively. Apparently, the allocation of spectrum resources is a critical issue, which is to be well considered in this mode. Specifically, spectrum allocation is dependent on the parameters such as the densities of terrestrial and UAV networks, the demand of users, which connect to terrestrial BSs and UAVs, the deployment of terrestrial network, and the topology of UAV network. Moreover, it should be noted that reuse and dedicated modes should be dynamically configured to further optimize the performance of MHetNet.

3.4 Backhaul of UAV Network

Backhaul is one of the dominant factors that limit the performance of MHetNet when UAVs are applied as access points. Different from errestrial networks, in which wired backhaul is available, wireless backhaul is the only choice for UAV network. Accordingly, UAVs could connect to ground gateways through multiple hops or the backhaul link could be directly established via the connection to satellites. For either approach, however, delay would be the major concern, which impacts the performance of UAV network, since the delay would be basically increased with the number of relays if connecting ground gateway and real-time service could hardly be provided if connecting to satellites. For the above reasons, the design of backhaul should be fully taken into account when devising the architecture of MHetNet.

4 Simulation Results

In this section, we present simulation results to further investigate the impact of parameters, including densities of small cell BSs, UAVs and users, UAV altitude and LoS transmissions, on the performance of MHetNets. In particular, we adopt spatial throughput (ST) as the performance metric, which is defined by

$$ST = \mu \mathbb{P}(SINR > \tau) \log_2(1+\tau), [bits/(s \cdot Hz \cdot m^2)], \tag{1}$$

where μ denotes the density of active links, τ denotes the signal-to-noise-and-interference ratio (SINR) threshold and $\mathbb{P}(SINR > \tau)$ denotes the success probability of data transmissions. By definition, ST could capture the number of bits that are successfully conveyed over unit time, spectrum and area. Therefore, ST is an important indicator to network capacity.

Simulations are conducted using Matlab and the results are generated over 1 million Monte Carlo trials. In each trial, small cell BSs, UAVs and users are distributed in a 3-dimension space, the 2-dimension coordinates of which follow three independent homogeneous Poisson Point Processes (PPPs) with densities λ_{BS}, λ_{UAV} and λ_U, respectively. Unless otherwise stated, the altitudes of small cell BSs, UAVs, and users are set as $h_{BS} = 3$ m, $h_{UAV} = 11.5$ m and $h_U = 1.5$ m, respectively. In consequence, the antenna height difference (AHD) between BSs and users and the AHD between UAVs and users are $\Delta h_{BS} = 1.5$ m and $\Delta h_{UAV} = 10$ m, respectively.

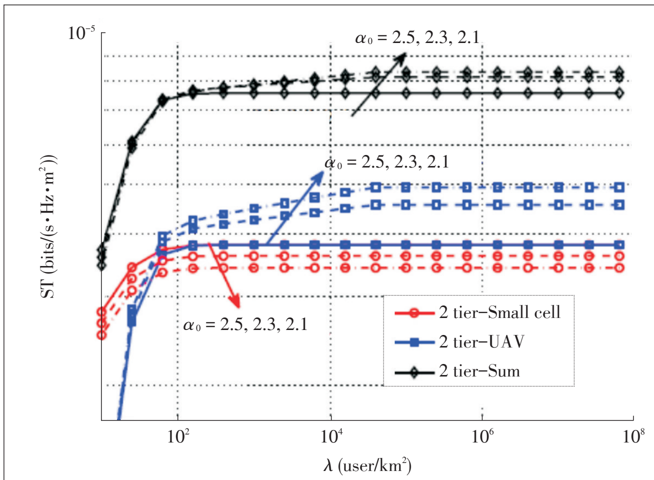
Serving as access points, UAVs reuse the available spectrum resources with terrestrial small cells to serve users with unlimited-capacity backhaul. Full spectrum reuse is considered for small cell BSs and UAVs such that each small cell BS or UAV could serve one user at one time. For user association, each user is first connected to the geometrically closest small cell BS. If the intended BS is connected by more than one user, it would randomly select one user to serve in each time slot and offload the other users to UAVs.

Dual-slope pathloss model (DSPM) is applied to comprehensively characterize the variation of pathloss with transmission distance. In particular, DSPM is defined by

$$l_2\left(\{\alpha_n\}_{n=0}^{1}; x\right) = K_n x^{-\alpha_n}, R_n \leqslant x < R_{n+1}, \tag{2}$$

where $K_0 = 1$, $K_1 = R_1^{\alpha_1 - \alpha_0}$, $R_0 = 0$ and $R_2 = \infty$. In simulations, we set $\alpha_0 = 2.5$, $\alpha_1 = 4$ and $R_1 = 20$ m for DSPM. In addition, transmit power of each small cell BS is set to be 23 dBm and transmit power of UAV is 30 dBm.

We first investigate the impact of LoS transmission on the performance of two-layer network. In **Fig. 2**, we plot ST as a



ST: spatial throughput UAV: unmanned aerial vehicle

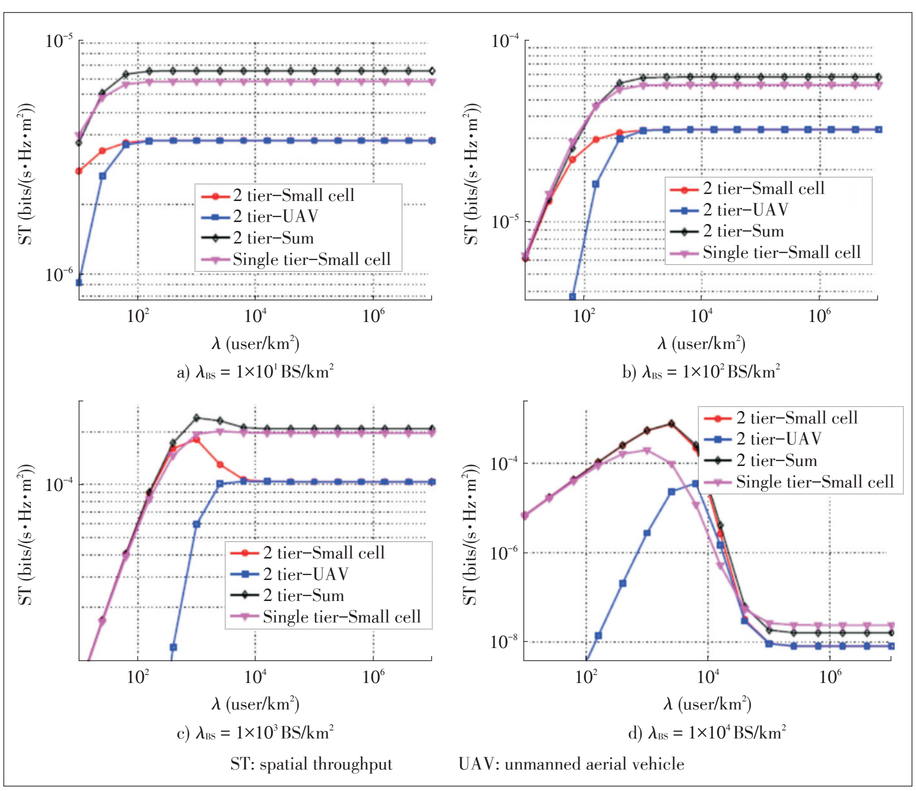
▲Figure 2. ST varying with under different pathloss exponent α_0. For the system settings, we set $\lambda_{BS} = 10$ BS/km^2 and $\lambda_{UAV} = 5$ BS/km^2.

function of user density under different pathloss exponents α_0 in the two-layer network. It is worth noting that a smaller α_0 means that the power loss over LoS paths is smaller and vice versa. It is observed from Fig. 2 that the ST of small cell network monotonously decreases with α_0, while the STs of UAV network and two-layer network would increase with α_0. The reason is that the channel gain over LOS paths inversely increase with α_0 and consequently the desired signal power of UAV-to-user pairs would be enhanced as α_0 grows. Meanwhile, for users that are connected to terrestrial small cell BSs, cross-tier interference from UAVs would become more severe. In consequence, the ST of small cell networks would decrease accordingly.

We then evaluate the performance of multi-layer networks under different BS and UAV densities. In particular, we plot ST as a function of user density under different BS and UAV densities in **Fig. 3**. To validate the benefit of integrating UAVs into terrestrial networks, we evaluate the ST in single-layer small cell networks for comparison as well. It is shown from Figs. 3a and 3b that, although the integration of UAVs would potentially degrade the ST of terrestrial small cell networks due to the generated cross-layer interference, the ST of the two-layer network is greater than that of the single-layer network. The reason is that the traffic of terrestrial network could be effectively offloaded to the UAV network.

However, as the densities of small cell BSs and UAVs grow, the benefits start to diminish. It can be seen from Fig. 3c that the ST of the two-layer network is almost identical to that of single-layer network. Worse still, if the densities of small cell BSs and UAVs further increase, the performance of two-layer network is significantly degraded especially when user density is large (Fig. 3d). The performance degradation is primarily due to the cross-tier interference in the two-layer network. Specifically, when small cell BSs and UAVs are densely deployed, the demerits caused by the cross-tier interference overwhelms the benefits of spectrum reuse gain and offloading gain.

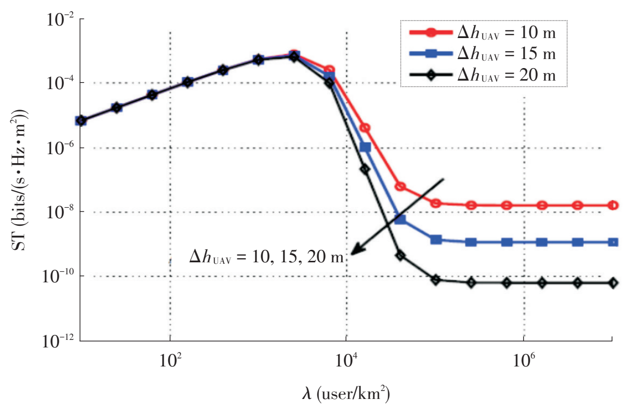
Afterward, we evaluate the impact of UAV altitude on network ST considering dense deployment of network infrastructures, i.e., small cell BSs and UAVs. In particular, **Fig. 4** shows the ST of two-layer network as a function of user density under different Δh_{UAV}. It can be seen that, the network STs under different Δh_{UAV} almost overlap when user density is small. In this case, terrestrial small cell BSs are sufficient to serve all ground users such that a small number of users are offloaded to UAV network. When user density further increases, it is obvious that network ST would decrease with Δh_{UAV}. The reason is that the increase of UAV altitude may result in a higher probability of LoS paths between UAVs and ground users. Although the desired signal power would be accordingly enhanced, the introduced cross-layer interference may be more severe. For this reason, there exists a critical UAV altitude in two-layer network, under which network ST could be maximized. Especially, we obtain the critical altitude of UAVs under different densities of BSs and UAVs in **Table 1**. It can be seen that the critical altitude inversely increases with the BS density. If the altitude of UAVs is greater than the critical altitude, the ST of two-layer network would be degraded. In other words, the critical altitude could serve as a upper bound, under which the integration of UAVs is beneficial to network ST in two-layer network.



▲**Figure 3. ST varying with user density under different BS and UAV densities. In simulations, the UAV density is set as $\lambda_{UAV} = 0.5\lambda_{BS}$.**

5 Conclusion

In this article, we have introduced the architecture of MHetNet, in which UAVs are applied to assist the traditional terrestrial wireless networks to provide better user experience and system performance. After discussing the potential bene- fits of MHetNet, an overview of the key issues and challenges brought by the integration of UAVs has been provided. Aided by simulation results, we have shown that the optimal UAV altitude should be decreased with the density of terrestrial small cell BSs so as to improve the MHet-



ST: spatial throughput   UAV: unmanned aerial vehicle

▲**Figure 4. ST as a function of user density under different Δh_{UAV}. (For system settings, we set $\lambda_{BS}=1\times10^4$BS/km^2 and $\lambda_{UAV}=5\times10^3$BS/km^2.)**

▼**Table 1. Critical altitude with BS density**

BS density (/km^2)	Critical altitude (m)
1×10^2	45.2
1×10^3	22.3
1×10^4	10.2
1×10^5	3.9

BS: base station

Net performance. In summary, although UAVs could serve as a promising complementary to existing terrestrial wireless network, it is imperative to investigate and fully exploit the characteristics of UAVs, thereby meeting the ambitious goals of massive connectivity and enormous capacity in the future wireless networks.

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Biographies

LI Tongxin (txli@stu.xidian.edu.cn) received the B.Eng. degree in communication and information systems from Xidian University, China in 2016. She is currently pursuing the M.A.Sc. degree with the State Key Laboratory of Integrated Service Networks, Institute of Information and Science, Xidian University. Her research interests include performance evaluation for UAV assisted cellular network and small cell caching in ultra-dense wireless networks.

SHENG Min (msheng@mail.xidian.edu.cn) received the M.S. and Ph.D. degrees in communication and information systems from Xidian University, China in 1997 and 2000, respectively. She is currently a full professor with the State Key Laboratory of Integrated Service Networks, Institute of Information Science, Xidian University. Her general research interests include mobile ad hoc networks, 5G mobile communication systems, and satellite communications networks. She was awarded as Changjiang Scholar by Ministry of Education, China.

LYU Ruiling (rllv@stu.xidian.edu.cn) received the B.Eng. degree from Inner Mongolia University, China in 2017. She is currently pursuing the M.A.Sc. degree with the State Key Laboratory of Integrated Service Networks, Institute of Information and Science, Xidian University. Her research interests include interference management and performance evaluation for UAV assisted cellular network, as well as ultra-dense wireless networks.

LIU Junyu (junyuliu@xidian.edu.cn) received the B.Eng. and Ph.D. degrees in communication and information systems from Xidian University, China in 2007 and 2016, respectively. He is currently a lecturer/postdoc with the State Key Laboratory of Integrated Service Networks, Institute of Information and Science, Xidian University. His research interests include interference management and performance evaluation of wireless heterogeneous networks and ultra-dense wireless networks.

LI Jiandong (jdli@mail.xidian.edu.cn) received the B.E., M.S. and Ph.D. degrees in communications engineering from Xidian University, China in 1982, 1985 and 1991, respectively. He has been a faculty member of the School of Telecommunications Engineering, Xidian University since 1985, and now serves as the Vice President of Xidian University. He was awarded as Distinguished Young Researcher from NSFC and Changjiang Scholar by Ministry of Education, China. His major research interests include wireless communication theory, cognitive radio and signal processing.