Energy Efficiency of Heterogeneous Air-Ground Cellular Networks

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Abstract. With the development of aerial platforms, it becomes possible for aerial platform-based base stations to coordinate with terrestrial cellular networks and provide services for terrestrial users immediately and effectually. Hence, in the paper, a heterogeneous air-ground cellular network is proposed which can provide high data rate for local users while enhancing energy efficiency of the heterogeneous network. Different from regular topology of terrestrial cellular networks, performance of heterogeneous air-ground networks are analyzed with a random topology of aerial and terrestrial base stations using Poisson point process with different densities respectively. And the relationship between energy efficiency of heterogeneous networks and densities of aerial and terrestrial base stations is given in an explicit form. Simulations are carried out and show that energy efficiency of the heterogeneous network can be significantly improved with appropriate densities of terrestrial and aerial base stations.

Keywords: Aerial platforms · Heterogeneous air-ground cellular network · Poisson point process · Energy efficiency

1 Introduction

With aerial platforms developing quickly, a potential solution to satisfy the growing wireless business requirement lies in aerial platforms, which carry communications relay payloads [1, 2]. A payload can be a complete base station, or simply a transparent transponder [3]. Akin to the majority of satellites communications, line-of-sight propagation paths can be provided to most users, with a modest free-space path loss [4, 5], thus enabling services to take advantage of the best features of both terrestrial and aerial communications. A single aerial platform can replace a large number of terrestrial base stations, along with their associated costs, environmental impact and backhaul constraints.

Although aerial platforms provide a way to solve the communication business expansion, there are still some problems need to be overcome. On the one hand, aerial platforms cannot be deployed widely due to the high cost of installation and maintenance; on the other hand, energy efficiency has been the problem worthy of concern as green communication emerging. In paper [6], system energy efficiency was improved by reducing the number and size of active macro cells following traffic load conditions in both heterogeneous and homogeneous networks. And in paper [7], by analyzing the

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relationship between the optimal partial spectrum reuse factor and active probability ratio, energy consumption minimization in heterogeneous networks can be addressed. When set up aerial platforms, the density of base stations should not only be planned to reinforce the user throughput and system capacity, but also guarantee the improved energy efficiency (EE) with user's transmission rate constraint [8].

In this paper, we build a model of heterogeneous networks with terrestrial base stations and aerial platform-based base stations, where the distributions of aerial and terrestrial base stations are modeled as independent homogeneous Poisson point processes (PPPs) with different densities λ [9–11]. We further derive the more compact closed-form EE and find that with the respect of densities of terrestrial and aerial base stations changing into different values, the maximum EE of heterogeneous network will be obtained with exact values of λ. The theoretical framework is verified by simulations.

The rest of this paper is organized as follows. In Sect. 2, the hierarchy architecture and system model are described. Section 3 formulates and derives the EE model of the heterogeneous air-ground cellular networks. In Sect. 4, simulations are carried out to show and analyze numerical results. Finally, the conclusions are summarized in Sect. 5.

2 System Model

2.1 Hierarchy Architecture

We consider ground-ground and air-ground communications coexisting in the heterogeneous networks. A hierarchical architecture is proposed in Fig. 1, which includes both aerial and terrestrial base stations Poisson-point distributed in the heterogeneous air-ground networks. And user equipment (UE) makes connection with aerial or terrestrial base stations according to the channel state information (CSI). In general, the coverage of aerial base stations is much larger compared with terrestrial base stations.

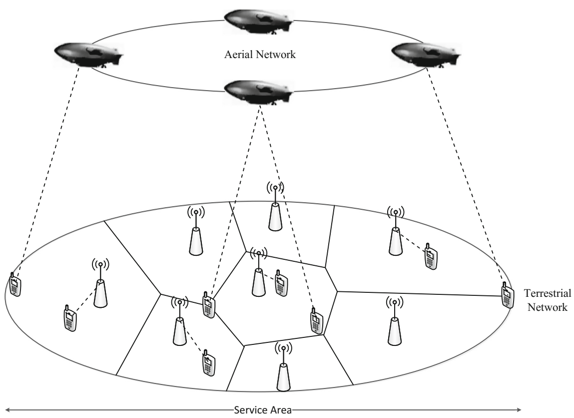

Fig. 1. Hierarchy architecture for air-ground heterogeneous networks

2.2 System Energy Efficiency

The cellular network model consists of terrestrial base stations arranged according to homogeneous Poisson point process (PPP) Ψ_b^m of intensity λ_m in the Euclidean plane. Consider an independent collection of aerial base station projections on the ground, located according to Poisson point process Ψ_b^s of intensity λ_s, and the attitudes of all the aerial base stations are assumed to be consistent in this paper. So the set of all base stations can be expressed as $\left\{ \cup_i \Psi_b^i : \ i \in m, s \right\}$. Use $b_j^{(i)} \in \Psi_b^i$ to denote the *jth* base station belong to $i \in \{m, s\}$ layer. Furthermore, the distributions of system users are also assumed to be independent Poisson point distributed with density of λ_u. Let α_1, α_2 denote the pass loss coefficient of ground-ground link and ground-air link, which satisfy to $\alpha_1 > \alpha_2 \geq 2$ as a condition through this model.

In an arbitrary cell, the whole users can be denoted as Ψ_b^u, where $\left|\Psi_b^u\right| = N \in N^+$. The total bandwidth of base station $b_j^{(i)}$ for downlink is BHZ, and it is equally divided into N sub-bands (i.e. each user belonging to base station $b_j^{(i)}$ has $B_0 = B/N$ HZ). In the kth sub-band, the associated user requires a specific service rate $R_{k,\min}$. We assume both terrestrial and aerial stations have the adaptive power control ability according to zero-delay channel state information. Therefore, the BS transmission power $P_{j,k}$ for $R_{j,k}$ on its sub-band is allocated to ensure the required service rate $R_{k,\min}$, and the total transmission power of base station $b_j^{(i)}$ can be obtained:

$$\begin{aligned} R_{j,k} &= B_0 \log_2\left(1 + \frac{P_{j,k} g_{j,k}}{I_{j,k} + \sigma^2}\right) \geq R_{k,\min}. \\ P_{total}^j &= \sum\nolimits_k P_{j,k} \quad s.t. P_{total}^j \leq P_M. \end{aligned} \tag{1}$$

where σ^2 denotes power spectral density of Gaussian noise. $I_{j,k}$ is inter-layer interference plus cross-layer interference, $g_{j,k}$ is the power channel gains between user and its associated base stations.

When calculating the maximum transmission rate, many literatures just consider the transmission power of network of sending data, ignoring the circuit power consumption of equipment which occupies large proportion especially for aerial base stations. To comprehensively analyse the energy efficiency of wireless communication, we adopt the formula as follows to measure the utility of energy efficiency.

$$\eta_{EE} = \frac{\log_2\left(1 + \frac{P_{j,k} g_{j,k}}{I_{j,k} + \sigma^2}\right)}{P_{total}^j + P_c}. \tag{2}$$

where P_c denotes circuit power loss, which is usually a fixed value and has no relationship with the transmission rate.

3 EE Analysis for Heterogeneous Networks

3.1 Interference Analysis and EE Formulation

For the users belonging to terrestrial base stations, unless otherwise noted, we assume that the tagged user and its associated base station experience only Rayleigh fading with mean 1. Employ a constant transmit power of $P_{j,k}^{(m)}$ and in this case, the received power of a typical user at distance $r_{j,k}$ from the home base station is $P_{j,k}^{(m)} h_{j,k}^{m} r_{j,k}^{-\alpha_1}$, where the random variable $h_{j,k}^{m}$ follows an exponential distribution with mean 1, denoted as $h_{j,k}^{(m)} \sim \exp(1)$. The transmission rate can be represented as follows:

$$R_{j,k}^{(m)} = B_0 \log_2\left(1 + \frac{P_{j,k}^{(m)} h_{j,k}^{m} r_{j,k}^{-\alpha_1}}{(I_{10} + I_{11}) + \sigma^2}\right). \tag{3}$$

where I_{10} and I_{11} are the interferences of inter-layer and cross-layer. Since the total interference at a user is greatly higher than the noise power, i.e. $\sigma^2 \ll I_{10} + I_{11}$, we will not consider the effects of noise in this paper. The corresponding transmission power needed by user $u_{j,k}^{(m)}$ is

$$P_{j,k}^{(m)} = \left(2^{R_{j,k}^{(m)}/B_0} - 1\right)(I_{10} + I_{11}) r_{j,k}^{\alpha_1}. \tag{4}$$

The interference power at the receiver is the sum of the received powers from all other base stations other than the home base station. For users connected with terrestrial base station $b_j^{(m)}$, the inter-layer interferences can be formulated as:

$$I_{10}^{\lambda_m} = \sum\nolimits_{n \neq j} P_n h_{n,k}^{(m)} \left\| u_{j,k}^{(m)} - b_j^{(m)} \right\|^{-\alpha_1}. \tag{5}$$

where P_n is transmission power of interferential base stations.

Hence, for the users that belong to terrestrial stations, the moment generation function of I_{10} can be calculated as:

$$F_{I_{10}} = \exp\left(2\pi\lambda_m \int_{r_{j,k}^{(m)}}^{+\infty} \left(1 - \exp\left(-t \frac{P_m}{N r^{\alpha_1}}\right)\right) r dr\right). \tag{6}$$

where P_m represents the maximum transmission power of terrestrial base stations.

According to the property of moment generation function, we have

$$I_{10} = E\left(I_{10}^{\lambda_m}\right) = -\frac{\partial}{\partial t} \ln F_{I_{10}}(t)|_{t=0} = \frac{2\pi\lambda_m P_m}{(\alpha_1 - 2)N} r_{j,k}^{(m)2-\alpha_1}. \tag{7}$$

In this paper, we assume that overages of aerial base stations do not overlap with each other, so the users connected with terrestrial base stations just receive interferences from their closest aerial base station, i.e.

$$I_{11} = E(I_{11}^{\lambda_s}) = \frac{P_s}{N}\left\{\sqrt{\left(E(r_{n,k}^{(s)}\right)^2 + h^2}\right\}^{-\alpha_2} = \frac{P_s}{N}\left\{\sqrt{\frac{\left[\Gamma\left(\frac{3}{2}\right)\right]^2}{\pi\lambda_s} + h^2}\right\}^{-\alpha_2}. \quad (8)$$

where P_s is the transmission power of aerial base station with attitude h, and $\Gamma(x) = \int_0^{+\infty} r^{x-1}e^{-r}dr$.

According to Eqs. (7) and (8), the average transmission power needed by $u_{j,k}^{(m)}$ can be obtained as follows:

$$E\left[P_{j,k}^{(m)}\right] = \int\limits_{r_{j,k}>0} \left(2^{R_{j,k}^{(m)}/B_0} - 1\right)(I_{10} + I_{11})r_{j,k}^{\alpha_1} \cdot 2\pi\lambda_m r_{j,k} e^{-\pi\lambda_m r_{j,k}^2} = \frac{\left(2^{NR_{j,k}^{(m)}/B} - 1\right)X_1}{N}. \quad (9)$$

$$X_1 = \frac{2P_m}{\alpha_1 - 2} + P_s\left[\sqrt{\frac{\left[\Gamma\left(\frac{3}{2}\right)\right]^2}{\pi\lambda_s} + h^2}\right]^{-\alpha_2} \frac{\Gamma\left(\frac{\alpha_1}{2}+1\right)}{(\pi\lambda_m)^{\frac{\alpha_1}{2}}}. \quad (10)$$

Assume that the coverage area of base station $b_j^{(m)}$ is S_m and all of terrestrial base stations have same transmission rate, i.e. $R_{j,k}^{(m)} = R_m$. With $\lambda_u S_m$ denoting the number of users belonging to $b_j^{(m)}$, total transmission power of terrestrial base station $b_j^{(m)}$ can be expressed as:

$$P_m^{S_m} = X_1\left[\left(2^{NR_m/B} - 1\right)\lambda_u S_m\right]. \quad (11)$$

Because the overages of aerial base stations do not overlap with others, for the users served by aerial base stations, they just suffer from interference of cross-layer. In a similar way, the average transmission power of an aerial station with coverage of S_s can be represented as:

$$P_s^{S_s} = X_2\left[\left(2^{NR_s/B} - 1\right)\lambda_u S_s\right]. \quad (12)$$

when assuming the following substitutions:

$$X_2 = \frac{2\pi\lambda_m P_m}{\alpha_1 - 2}\beta^{\frac{2-\alpha_1}{\alpha_1}} \frac{\Gamma\left(\frac{\alpha_2}{\alpha_1}+1, h\right)}{(\pi\lambda_s)^{\frac{\alpha_2}{\alpha_1}}}. \quad (13)$$

where $\beta = P_m/P_s$, and $\Gamma(x, y)$ is half-baked gamma function which can be expressed as:

$$\Gamma(x, y) = \int_y^{+\infty} r^{x-1} e^{-r} dr. \tag{14}$$

The energy efficiency formula of heterogeneous network can be obtained from the derivation above:

$$\eta_{EE} = \frac{\lambda_u (R_m + R_s)}{B\left[\lambda_m \left(P_m^{S_m} + P_{OM}^{(m)}\right) + \lambda_s \left(P_s^{S_s} + P_{OM}^{(s)}\right)\right]}. \tag{15}$$

In formula (16), $P_{OM}^{(m)}, P_{OM}^{(s)}$ separately represent the circuit power consumption of terrestrial and aerial base stations.

3.2 Proof of Existence of the Optimal Solution

It can be discovered that the energy efficiency formula contains of λ_m and λ_s, then it will be verified how λ_m and λ_s influence the energy efficiency in system.

$$\begin{aligned} \frac{\partial \eta_{EE}}{\partial \lambda_m} = & \frac{-\lambda_u (R_m + R_s)}{B^2\left[\lambda_m \left(P_m^{s_m} + P_{OM}^{(m)}\right) + \lambda_s \left(P_s^{s_s} + P_{OM}^{(s)}\right)\right]^2} \\ & \cdot \frac{\partial\left\{B\left[\lambda_m \left(P_m^{s_m} + P_{OM}^{(m)}\right) + \lambda_s \left(P_s^{s_s} + P_{OM}^{(s)}\right)\right]\right\}}{\partial \lambda_m}. \end{aligned} \tag{16}$$

$$\frac{\partial\left\{B\left[\lambda_m \left(P_m^{s_m} + P_{OM}^{(m)}\right) + \lambda_s \left(P_s^{s_s} + P_{OM}^{(s)}\right)\right]\right\}}{\partial \lambda_m} = B\left[P_{OM}^{(m)} + \frac{\partial\left(\lambda_m P_m^{s_m}\right)}{\partial \lambda_m}\right] + \theta. \tag{17}$$

where $\theta = \frac{2\pi P_m}{\alpha_1 - 2} \beta^{\frac{2-\alpha_1}{\alpha_1}} \frac{\Gamma\left(\frac{\alpha_2}{\alpha_1} + 1, h\right)}{(\pi \lambda_s)^{\frac{\alpha_2}{\alpha_1}}}$.

Let $P_s\left[\sqrt{\frac{\left[\Gamma\left(\frac{3}{2}\right)\right]^2}{\pi \lambda_s} + h^2}\right]^{-\alpha_2} \cdot \frac{\Gamma\left(\frac{\alpha_1}{2} + 1\right)}{\pi^{\frac{\alpha_1}{2}}} = C$, we have $\frac{\partial(\lambda_m P_m^{s_m})}{\partial \lambda_m} = \mu \cdot \left[\frac{P_m}{\alpha_1 - 2} + C\left(1 - \frac{\alpha_1}{2}\right) \frac{1}{\lambda_m^{\frac{\alpha_1}{2}}}\right]$, where $\mu = \left(2^{NR_m/B} - 1\right)\lambda_u S_m$, it is obvious that $\gamma = P_{OM}^{(m)} + \mu \cdot \frac{P_m}{\alpha_1 - 2} > 0$, hence

$$\frac{\partial \eta_{EE}}{\partial \lambda_m} = \frac{-\lambda_u (R_m + R_s)}{B^2\left[\lambda_m \left(P_m^{s_m} + P_{OM}^{(m)}\right) + \lambda_s \left(P_s^{s_s} + P_{OM}^{(s)}\right)\right]^2} \cdot \left\{B\left[\gamma + \mu C\left(1 - \frac{\alpha_1}{2}\right) \frac{1}{\lambda_m^{\frac{\alpha_1}{2}}}\right] + \theta\right\}. \tag{18}$$

In the formula above,

$$\frac{-\lambda_u(R_m + R_s)}{B^2\left[\lambda_m\left(P_m^{s_m} + P_{OM}^{(m)}\right) + \lambda_s\left(P_s^{s_s} + P_{OM}^{(s)}\right)\right]^2} < 0. \tag{19}$$

Because $\alpha_1 \geq 2$ and $C > 0$, by the extremity theory:

$$\lim_{\lambda_m \to 0} B\left[\gamma + \mu C\left(1 - \frac{\alpha_1}{2}\right)\frac{1}{\lambda_m^{\frac{\alpha_1}{2}}}\right] + \theta < 0,\ i.e. \frac{\partial \eta_{EE}}{\partial \lambda_m} > 0. \tag{20}$$

$$\lim_{\lambda_m \to +\infty} B\left[\gamma + \mu C\left(1 - \frac{\alpha_1}{2}\right)\frac{1}{\lambda_m^{\frac{\alpha_1}{2}}}\right] + \theta > 0,\ i.e. \frac{\partial \eta_{EE}}{\partial \lambda_m} < 0. \tag{21}$$

Due to the continuity of η_{EE}, there must be a constant λ_m^* making $\frac{\partial \eta_{EE}}{\partial \lambda_m} = 0$. Namely when given in the density of aerial base stations, the energy efficiency of heterogeneous network will achieve a maximum value with a suitable density of terrestrial base stations, and more detailed influences are shown in the following simulations.

By the same token, for the density of aerial stations we can draw the same conclusion, the proof in detail will not be given here.

4 Simulation Results

We consider an area of 10 km $\times$ 10 km on the ground serviced by terrestrial and aerial stations. The free path loss model is adopted for the air-ground radio link. Table 1. gives some of the main system-level simulation parameters.

Table 1. Simulation parameters

Parameter	Value
Radius of aerial and terrestrial cell	2000 m, 500 m
Maximum transmission power of aerial base stations	46 dBm
Maximum transmission power of terrestrial base stations	20 dBm
System bandwidth	20 MHz

We firstly simulate the relationship of energy efficiency and densities of terrestrial and aerial base stations to illustrate energy efficiency model conducted in the paper. Then we adjust the density of the users to observe the change in transmission power of terrestrial and aerial base stations. Finally, we simulate the change of system energy efficiency with varying densities of users.

Figure 2 shows that the variation of energy efficiency with varying densities of aerial base stations λ_s and terrestrial base stations λ_m under the condition of $R_s = R_m = 0.2\,\text{Mbit/s}$ and $\lambda_u = 1000/\text{km}^2$, we note that given in a certain λ_s, with λ_m increasing, energy efficiency of network is improved firstly and lowers then and there is

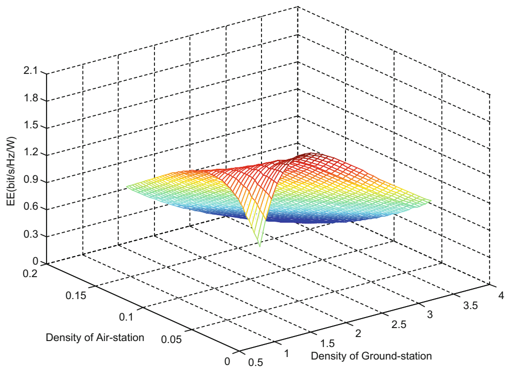

Fig. 2. Energy efficiency of integrated air-ground heterogeneous networks with different densities of terrestrial and aerial base stations

a certain value of λ_m which maximize the energy efficiency; and likewise when λ_m is given, there is an optimal value of λ_s. When terrestrial and aerial base stations are planned in small densities, throughput of the network is deficient and transmission power of terrestrial or aerial base stations need to be improved to satisfy the demand of users, which results in the reduction of energy efficiency. With increasing densities of terrestrial or aerial base stations, higher traffic rate can make the network throughput increase quickly, which leads to the improvement of energy efficiency.

In Fig. 3, we note that higher user density leads to the increase of transmission power of terrestrial and aerial base stations, and obviously higher rate needed by users means increasing transmission power, which results in the rise of power consumption. In addition, transmission power of aerial base stations is larger than which of terrestrial base stations with same density of users.

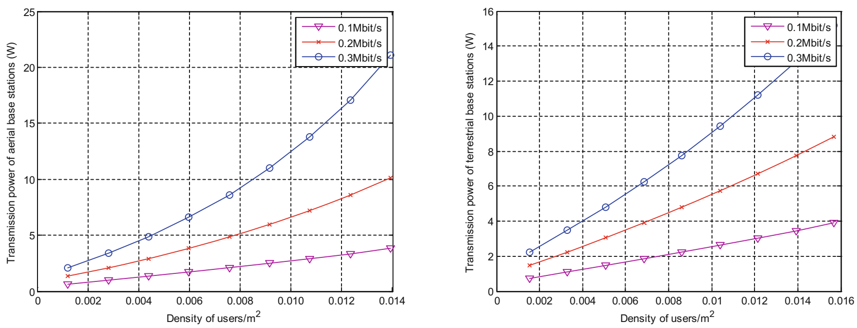

Fig. 3. Transmission power of aerial and terrestrial base stations with different densities of user

As illustrated in Fig. 4, the performance of energy efficiency over the heterogeneous network in varying $R_{k,\min}$ from 0.20, 0.25 to 0.30 Mbit/s is compared when λ_m and λ_s are given in a medium value. We note that with the density of network user increasing, energy efficiency of network is improved firstly and lowers then and there exists an optimal λ_u to maximize the energy efficiency. With small density of users, higher transmission rate needed by users leads to high energy efficiency. However, when the number of system user increases, power consumption increases rapidly to satisfy users' service request and leads to the increase of interferences, which restrict the increase of system throughput. As a result, although the higher traffic rate is needed with increasing users, high power consumption and serious interferences lead to lower energy efficiency.

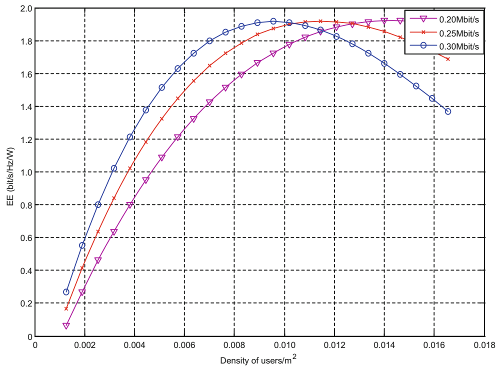

Fig. 4. Energy efficiency with various densities of users in different service rate ($\lambda_s = 0.14/\text{km}^2$; $\lambda_m = 3.54/\text{km}^2$; $B = 20\,\text{MHz}$)

5 Conclusion

In this paper, we take a deep analysis of energy efficiency heterogeneous air-ground cellular networks. After considering density of base stations, energy consumption and network deployment parameters, the tractable closed-form expression of energy efficiency is given. And it is proved that when the density of terrestrial or aerial base stations is given, there is an optimal energy efficiency of the heterogeneous networks. In our simulation, we evaluate energy efficiency with varying densities of base stations and users. Ultimately we conclude that energy efficiency of the heterogeneous networks can be improved effectively by deploying terrestrial and aerial base stations in reasonable densities.

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