2022 IEEE 95th Vehicular Technology Conference (VTC2022-Spring) | 978-1-6654-8243-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/VTC2022-Spring54318.2022.9860546

Interference Coordination Method for Integrated HAPS-Terrestrial Networks

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***Abstract*—Non-terrestrial network (NTN) is an important technique to provide extreme coverage towards 5G advanced and 6G. High-altitude-platform-station (HAPS), as one key factor in NTN, is attracting a lot of attentions. To achieve better resource utilization and performance, a unified design for integrated HAPS-Terrestrial networks is necessary, where the interference among these two systems may be important. Current methods usually consider fixed resource allocation among the two systems without considering the distribution of traffic load and hence have low resource utilization. In practice, the traffic load may change dynamically or semi-statically due to the wide coverage in HAPS, which should be considered in the design of integrated HAPS-terrestrial systems. In this paper, we proposed an interference coordination method based on the distribution of traffic load as well as the deployment of HAPS and terrestrial networks. The evaluation results show that the proposed method achieves higher throughput than existing fixed resource allocation method.**

***Index Terms*—High altitude platform station (HAPS), integration, interference, terrestrial**

I. Introduction

With the commercialization of Fifth Generation (5G) wireless communication systems, the study of Sixth Generation (6G) has attracted recent research focuses from all around the world. Realizing extreme and full coverage is one of the important visions of 6G. One representative technique targeting for this vision is integrated terrestrial and non-terrestrial networks (NTN) [1]–[3]. For NTN, the platform includes Low-Earth-Orbit (LEO)/Medium-Earth-Orbit (MEO)/Geostationary-Earth-Orbit (GEO) satellites as well as high-altitude-platform-station (HAPS), etc. Due to its advantages of easy deployment, rapid applicability and broad coverage [4] [5], HAPS deployed in the stratosphere has been treated as one important part towards 6G in Japan.

Due to the broad coverage of HAPS, e.g., 100 km coverage radius, multi-beam transmission is usually considered to increase the transmission efficiency. The inter-beam interference is one of the bottlenecks for HAPS performance enhancement. To overcome the inter-beam interference, two types of methods are widely discussed. First type of method is to reduce inter-beam interference by static or dynamic beamforming design. For example, considering the user distributions on the ground, beam-centers can be determined based on user clustering dynamically [4]. Considering the high complexity of user clustering algorithms, static beamforming methods are also proposed [5], where the number of beam layers, number of beams per layer as well as the static beam-centers are carefully designed. However, due to the limited payload at HAPS, the antenna capabilities could not fully solve the problem of inter-beam interference. Therefore, traditional inter-cell-interference cancellation (ICIC) methods are also widely considered for interference coordination in HAPS or NTN, e.g., fractional frequency reuse [6], where orthogonal frequency resources are allocated to adjacent beams or cells.

Most of the studies on HAPS focus on the stand-alone HAPS systems. With the development of integrated terrestrial and non-terrestrial systems towards 6G, the coexistence of HAPS and terrestrial systems is also a promising scenario. After world radio conference (WRC)'19, some bands allocated to HAPS are overlapped with some bands allocated to terrestrial cellular systems, e.g., around 2 GHz band and milimeter wave band, which will cause inter-system interference. To evaluate the impacts of inter-system interference, International Telecommunication Union (ITU) firstly studied it and concluded that HAPS can operate in the same bands as other services, without causing harmful interference, if used within certain parameters [7] [8]. These predefined constraints on HAPS deployment, e.g., on power, network planning and protection distance between HAPS and terrestrial base stations (BSs), can limit the interference in a simple way at the cost of restricting the flexible resource allocation and deployment of HAPS. For a better flexibility, similar interference coordination methods in standalone-HAPS systems are also studied for integrated HAPS-terrestrial systems. For example, dynamic beamforming design for HAPS based on the user distribution as well as the deployment of terrestrial systems was proposed in [9] with the cost of high computation complexity of user clustering algorithms. ICIC method with static frequency resource allocation was proposed in [10] based on the deployment scenarios. For example, orthogonal frequency bands should be allocated for HAPS and cell-edge terrestrial users in rural area, while same frequency bands can be used for HAPS and terrestrial users in other scenarios, e.g, cell-center terrestrial users in rural area and all users in urban area, without causing harmful interference.

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In a word, existing coordination methods for inter-beam and inter-system interference either consider dynamic traffic (user distribution) at the cost of high computation complexity, or design fixed resource allocation without considering dynamic traffic. How to design an interference coordination method based on dynamic traffic in a simple way still needs further study. In addition, the joint design for HAPS and terrestrial systems are not widely studied based on our survey. In this paper, we give a solution by flexible and semi-static or dynamic coordination between HAPS and terrestrial BS in spatial-time-frequency domain jointly. Evaluation results show the advantages of proposed methods on throughput performance. Furthermore, by turning part of the HAPS beams and terrestrial BSs into idle mode based on the traffic load, energy saving can be achieved.

The rest of this paper is organized as follows. Section II describes the system model of HAPS and terrestrial systems. In Section III, the interference between two systems is evaluated and summarized. In Section IV, the proposed method for interference coordination is introduced. Section V gives the evaluation results and section VI concludes this paper.

II. System Model

In this section, the system model for HAPS and terrestrial networks are explained.

A. System model for HAPS

Consider a HAPS system with a platform at altitude h_0 covering an area of radius R with multi-beam transmission. Two typical cases are considered as shown in Fig. 1. In case 1, HAPS provides services for customer premise equipments (CPEs) or terrestrial BSs on the ground and CPEs/BSs provides mobile services for user equipments (UEs). In case 2, HAPS directly provides mobile services for UEs on the ground. Considering the minor difference between case 1 and case 2 during the analysis of HAPS, the terminals served by HAPS, i.e., CPEs/BSs and UEs, are named as H-UE in the sequel for simplicity.

For downlink transmission, the receive power at the user side, P_{rx}, can be calculated as

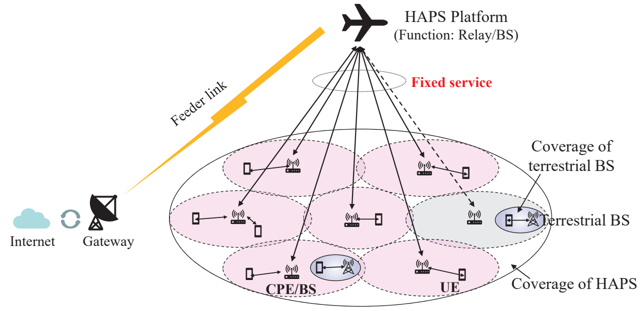
$$P_{\text{rx}} = P_{\text{tx}} + G_{\text{tx}} - PL + G_{\text{rx}}, \tag{1}$$

where P_{tx} is the transmit power, G_{tx} and G_{rx} denote the antenna gain at the transmitter and receiver, respectively, and PL denotes the path loss.

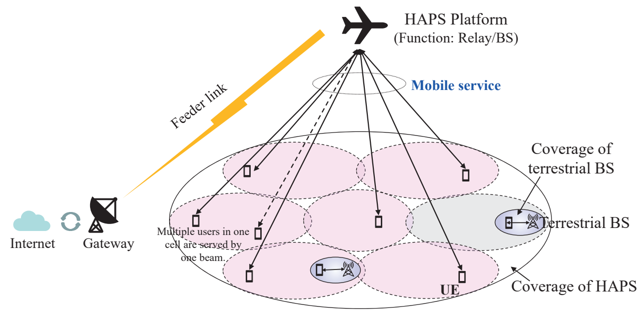
Based on [11], the path loss between HAPS and H-UE PL is composed of four parts, i.e., the basic path loss, the attenuation due to atmospheric gasses, the attenuation due to either ionospheric or tropospheric scintillation, and building entry loss. In this paper, only the basic path loss is considered without loss of generality, i.e.,

$$PL(h_0, \alpha, f_c) = FSPL(h_0, \alpha, f_c) + SF + CL(\alpha, f_c), \tag{2}$$

which further includes the free-space path loss $FSPL$, shadow fading SF and clutter loss CL affected by the height of HAPS platform h_0, the carrier frequency f_c, the elevation



(a) Case 1: HAPS provides fixed services for CPEs/BSs.



(b) Case 2: HAPS provides mobile services for UEs.

Fig. 1. Illustration of HAPS system model.

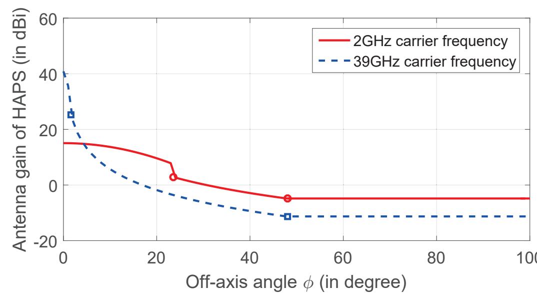


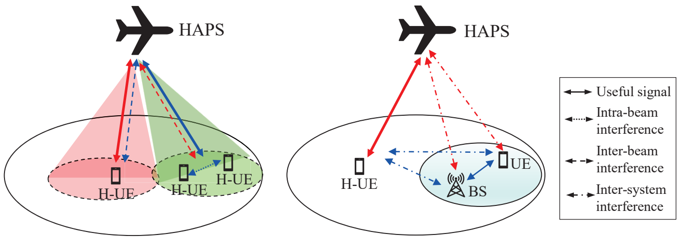
Fig. 2. Antenna gain of HAPS versus off-axis angle ϕ.

angle α between HAPS and H-UE. In addition, the deployment scenario (e.g., urban, suburban or rural scenario, etc.) also affects the values of clutter loss and distributions of shadow fading in (2) as shown in Table 6.6.2-1/2/3 in [11].

The antenna gain of HAPS in dBi can be modeled as [12],

$$G_{\text{tx}}(\phi) = \begin{cases} G_{\max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda}\phi\right), & 0^\circ < \phi < \phi_m, \\ 39 - 5\log\left(\frac{D}{\lambda}\right) - 25\log\phi, & \phi_m \le \phi < 48^\circ, \\ -3 - 5\log\left(\frac{D}{\lambda}\right), & 48^\circ \le \phi \le 180^\circ, \end{cases} \tag{3}$$

where ϕ denotes the off-axis angle in degrees, $G_{\max} \approx 20\log_{10}\left(\frac{D}{\lambda}\right) + 7.7$ is the maximum antenna gain in dBi, D and λ denote respectively the antenna diameter and wavelength, and $\phi_m = \frac{20\lambda}{D}\sqrt{G_{\max} - 15\log_{10}\left(\frac{D}{\lambda}\right) - 2}$ in degrees. The antenna patterns in different carrier frequencies are shown in Fig. 2. With the development and study of HAPS, other antenna patterns can be also considered.



(a) Traditional interference in standalone HAPS system
(b) New interference in integrated HAPS-terrestrial system

Fig. 3. Illustration of different types of interference.

The antenna gain at the receiver side G_{rx} is related to the terminal type. For CPEs in case 1, the same antenna gain model with HAPS in (3) can be used as discussed in [12]. For UEs in case 2, the omni-directional antennas with fixed antenna gain G_{rx} can be assumed.

B. System model of terrestrial networks

In integrated HAPS-terrestrial systems, the terrestrial BSs are randomly distributed in the coverage of HAPS as shown in Fig. 1. The path loss model in terrestrial networks can be obtained from [13], which is composed by propagation path loss and shadow fading. The detailed equations and parameters of path loss are mainly related to the scenario configuration (e.g., urban, suburban or rural, etc.) and are not introduced here due to limited space.

Different from HAPS with fixed antenna pattern due to limited payloads, fully dynamic beamforming and precoding schemes can be used at the terrestrial BSs for better performance, which will affect its antenna gain G_{tx}. Considering that the beamforming design in terrestrial networks is not the focus of this paper, we do not describe the details of antenna gain here.

Targeting to the unified terrestrial and non-terrestrial system design in 6G, users can be served by either HAPS system or terrestrial BSs in a transparent way as shown in Fig. 1. For example, if the received power or signal-to-interference plus noise ratio (SINR) from HAPS is higher than that from terrestrial BSs, the user can be served by HAPS system. Otherwise, it can be served by terrestrial BSs.

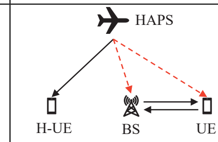
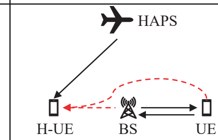
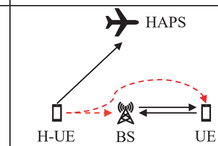
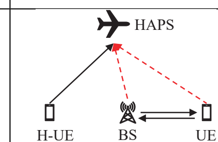
III. Interference Analysis in Integrated HAPS-Terrestrial Systems

Similar with the legacy terrestrial systems, there are various interference in integrated HAPS-terrestrial systems.

Firstly, as shown in Fig. 3(a), multi-beam transmission in HAPS would cause inter-beam interference. This is especially true considering the limited payload at HAPS and extreme large coverage of one beam. Users served by one beam could not be distinguished in spatial domain, which would cause intra-beam interference. In this paper, orthogonal time or frequency resource allocation is used for multiple users in one beam as usually done in the literature.

In addition, as shown in Fig. 1, there are some overlapping areas covered by both terrestrial BSs and HAPS. If both systems are deployed with same or adjacent frequency bands, inter-system interference would exist as shown in Fig. 3(b). Furthermore, the inter-system interference can be further divided into four types as listed in Table I.

TABLE I
Analysis for Inter-System Interference

Interference type	Illustration	Feature
HAPS downlink to terrestrial receiver		Dominant interference due to the wide coverage of HAPS and omni-directional antennas at the UE side.
Terrestrial transmitter to HAPS downlink		Little interference due to the large elevation angle for receiving at H-UE side.
HAPS uplink to terrestrial receiver		Little interference due to the large elevation angle for transmitting at H-UE side.
Terrestrial transmitter to HAPS uplink		Little interference due to the small elevation angle for transmitting at terrestrial BSs/UEs.

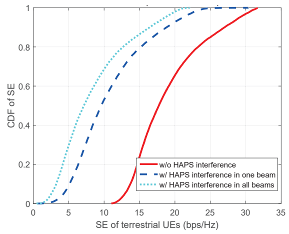
Based on the analysis in Table I, interference from HAPS downlink to terrestrial downlink (especially to UE) is the dominant type of inter-system interference, which is the focus in the sequel. The downlink data rate of k-th UE in integrated HAPS-terrestrial networks, R_k, can be calculated as

$$R_k = B_k \log_2 \left(1 + \frac{S_k}{I_{k,\text{H}} + I_{k,\text{T}} + N} \right), \tag{4}$$

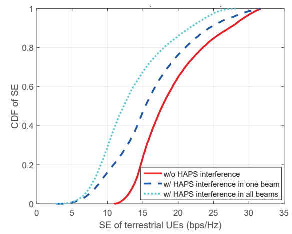
where B_k denotes the allocated bandwidth for user k, S_k denotes the received power of user k from either HAPS or terrestrial BS, $I_{k,\text{H}}$ and $I_{k,\text{T}}$ denote the total interference from HAPS system and terrestrial networks, respectively, and N is the noise variance.

To evaluate the affects of interference from HAPS to terrestrial UEs, some evaluations on the spectral efficiency (SE) of UEs in terrestrial network (TN) are carried out under various configurations in Fig. 4, including various carrier frequencies (2 GHz or 39 GHz), coverage radius of one HAPS (50 km or 100 km), number of HAPS beams (7 beams or 30 beams), and locations of terrestrial BSs (TN below or far away from HAPS). The observations are summarized below.

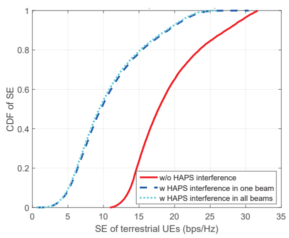
- For systems with low frequency band (e.g., 2 GHz) as shown in Fig. 4(a)-4(d), inter-system interference cannot be ignored and interference coordination method is necessary for performance enhancement.



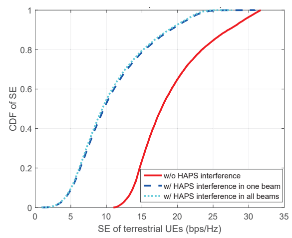
(a) 2GHz, 50km, 30 beams, TN @ Below HAPS



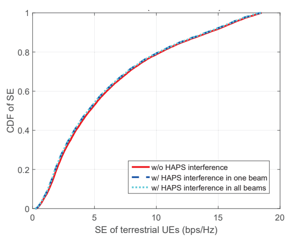
(b) 2GHz, 50km, 30 beams, TN @ Far-away from HAPS



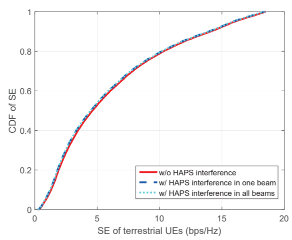
(c) 2GHz, 50km, 7 beams, TN @ Below HAPS



(d) 2GHz, 100km, 7 beams, TN @ Below HAPS



(e) 39GHz, 50km, 30 beams, TN @ Below HAPS



(f) 39GHz, 100km, 7 beams, TN @ Below HAPS

Fig. 4. Downlink SE performance in terrestrial network (TN) with or without the interference from HAPS downlink.

- For systems with low frequency band (e.g., 2 GHz), inter-beam interference cannot be ignored for large number of HAPS beams or small coverage area of one beam as shown in Fig 4(a)-4(b). This is because the overlapping among adjacent beams would cause severe interference. However, for large coverage area of one beam as shown in Fig. 4(c)-4(d), due to less overlapping among adjacent beams, inter-beam interference can be ignored.
- For systems with high frequency band (e.g., 39 GHz) as shown in Fig. 4(e) and Fig. 4(f), both of the inter-beam and inter-system interference can be ignored. The main reasons are the high path loss and narrow beamwidth for high frequency band as shown in Fig. 2.

There are already various solutions to solve inter-beam interference in standalone-HAPS systems, which can also be used in integrated HAPS-terrestrial systems. In this paper, we only focus on the inter-system interference and the inter-beam interference can be reduced by considering fractional frequency reuse.

IV. Proposed Interference Coordination Method

In this section, we will introduce a coordination method for inter-system interference, which is designed considering the

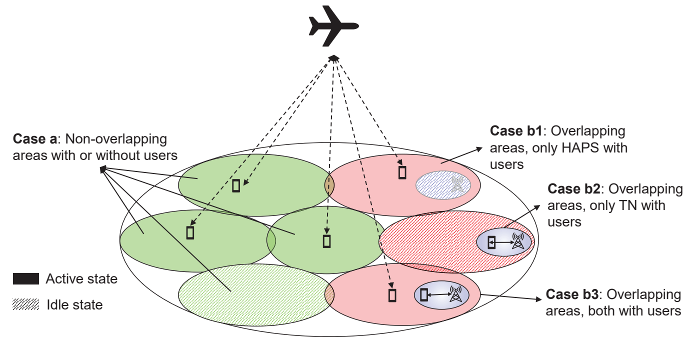


Fig. 5. Different cases based on the traffic distribution and the deployment of integrated system.

dynamic or semi-static traffic distribution and the deployment of terrestrial systems in the coverage of HAPS.

The traffic load usually varies in time (e.g., in hours) and in space (e.g., in rural or urban). For example, in TN which typically deployed in the dense user scenarios, the traffic load already changes dynamically in days and nights. In NTN, due to the large coverage area and the emerging of IoT services, the dynamic and unbalanced traffic load in time and space would be more severe.

A. Cases analysis for different traffic load and deployment

Based on the deployment of TN and the traffic distribution, the integrated HAPS and terrestrial systems can be divided into several cases as shown in Fig. 5,

- **Case a**: *Non-overlapping areas*, where only HAPS coverage is provided.
- **Case b**: *Overlapping areas between HAPS and terrestrial coverage*. Depending on the traffic distribution in HAPS and terrestrial networks, **Case b** is further divided into three cases.
  - **Case b1**: Traffic only in HAPS system.
  - **Case b2**: Traffic only in TN.
  - **Case b3**: Traffic in both HAPS and TN.

For non-overlapping areas in **Case a**, users are all served by HAPS, where inter-system interference does not exist. In this case, the traditional methods in standalone HAPS systems, e.g., fractional frequency reuse, can be used. Furthermore, considering the traffic load, HAPS beams or cells without traffic can be turned into idle mode for energy saving and inter-beam interference reduction.

For overlapping areas in **Case b1**, due to no traffic in terrestrial systems, the terrestrial BSs can be turned into idle state for energy saving and inter-system interference reduction. In this case, inter-system interference can be ignored, because of the long distance between active terrestrial BSs and HAPS users.

For overlapping areas in **Case b2**, due to no traffic in HAPS coverage, the HAPS beam or CPE for this cell can be turned off. In this case, the interference from HAPS to TN in this overlapping area does not exist. However, inter-system interference from other HAPS beams or cells can not be ignored in some scenarios as shown in Fig. 4(a) and Fig. 4(b), which may be reduced by fractional frequency reuse.

For overlapping areas in **Case b3**, users in both systems would suffer from not only the inter-beam interference from other HAPS cells but also the inter-system interference in this overlapping area. Then, it would be important to carefully design the interference coordination method between HAPS and terrestrial systems in Case b3, which are further analyzed below.

B. Interference coordination method for Case b3

For **Case b3**, the system can be further divided into four patterns:

- *Pattern 1*: HAPS and TN are both active and serve the users in their coverage with same time-frequency resources, i.e., no coordination.
- *Pattern 2*: HAPS and TN are both active and serve the users in their coverage with orthogonal time-frequency resources, i.e., ICIC method with orthogonal resources.
- *Pattern 3*: HAPS cell is turned into idle mode. All users in the overlapping cells are served by terrestrial BS.
- *Pattern 4*: Terrestrial BSs is turned into idle mode. All users in the overlapping cells are served by HAPS.

Then, the optimal serving pattern can be selected from the four patterns. The optimization problem maximizing the throughput subject to the minimum data rate requirement of users can be formulated as,

$$\begin{aligned} \max_{i, i \in \{1,2,3,4\}} \sum_{k \in \text{Users in Case b3}} & R_{k,i} \\ \text{s.t. } R_{k,i} \geq L_k, & \forall k \end{aligned} \tag{5}$$

where $R_{k,i}$ is the ergodic data rate of user k in Case b3 with pattern i, and L_k is the minimum data rate requirement of user k. Based on the definition of patterns, the data rate can be calculated as:

$R_{k,1} = B \log_2 \left(1 + \frac{S_k}{I_{k,H} + I_{k,T} + N}\right)$ for Pattern 1,

$R_{k,2} = B_k \log 2 \left(1 + \frac{S_k}{I_k + N}\right)$ for Pattern 2,

$R_{k,3} = B \log_2 \left(1 + \frac{S_{k,T}}{N}\right)$ for Pattern 3,

$R_{k,4} = B \log_2 \left(1 + \frac{S_{k,H}}{N}\right)$ for Pattern 4,

where B is the total bandwidth for HAPS and terrestrial systems, $B_k < B$ is the allocated bandwidth for user k in ICIC, and $S_{k,T}$ and $S_{k,H}$ are the signal power from the terrestrial BS and HAPS to user k, respectively.

By ergodic searching on all potential patterns, the optimal pattern can be obtained. Considering that the selected pattern is only related to the traffic load and the deployment of HAPS and terrestrial systems, the complexity of solving the optimization problem (5) can be acceptable.

V. Evaluation Results

In this section, the evaluation results are provided to show the performance gain of proposed method. Two baselines are considered for comparison. In baseline 1, the HAPS system and terrestrial network always use the same time-frequency resources no matter the traffic load and deployment. In baseline 2, orthogonal time-frequency resources are always considered for HAPS and terrestrial networks, where 15 MHz are allocated for HAPS and 5 MHz are allocated to terrestrial networks. In addition, in order to show the impact of inter-beam interference in HAPS, fractional frequency reuse is also considered in the evaluations. The locations of users and terrestrial BSs are randomly distributed in the coverage of HAPS. The users can be served by HAPS or terrestrial BS with maximum signal power. The detailed evaluation parameters are summarized in Table II.

TABLE II
Evaluation assumptions.

Parameters	Values or assumptions
Carrier frequency	2 GHz
Total bandwidth	20 MHz
Number of HAPS cells	30 cells
Layer number of HAPS cells and layout (Note: Cells with same distance from the center are defined in one layer.)	4 layers with, 1 cell for layer-1, 8 cells for layer-2, 9 cells for layer-3, 12 cells for layer-4
Radius of HAPS coverage	50 km
Number of users	Uniformly distributed in [0,30000]
Number of terrestrial BSs per HAPS cell	Uniformly distributed in [0,6]

In Fig. 6, the average throughput per cell in various layer index of HAPS is provided. The results show that for users below HAPS (i.e., layer-1), baseline 2 with orthogonal time-frequency resources achieves higher throughput than baseline 1 with same time-frequency resources. This is consistent with the evaluation results in Fig. 4(a), where the inter-system interference matters. For users and terrestrial networks far away from HAPS (i.e., layer-4), baseline 1 can achieve higher throughput than baseline 2, which indicates that the inter-system interference can be ignored and the full resource utilization is more important.

Furthermore, the results in Fig. 6 show that the proposed method always achieves the highest throughput than existing methods. The throughput gain is especially larger for users and TNs located in layer-2 and layer-3, i.e., not just below HAPS and not very far away from HAPS. The gain comes from the dynamic resource allocation between HAPS and terrestrial networks.

To validate the affects of inter-beam interference in HAPS, the throughput performance under 5-color frequency reuse in HAPS is provided in Fig. 7. Similar observations with the full frequency reuse in Fig. 6 can be obtained. In addition, we can find that baseline 1 achieves nearly identical performance with proposed method in layer-4. This indicates that with fractional frequency reuse, the interference from HAPS is reduced and can be totally ignored for users far away from HAPS.

Based on above analysis, we can obtain some hints for resource allocation method between HAPS and terrestrial systems. For example, for terrestrial networks close to HAPS, orthogonal resource allocation is preferred for interference

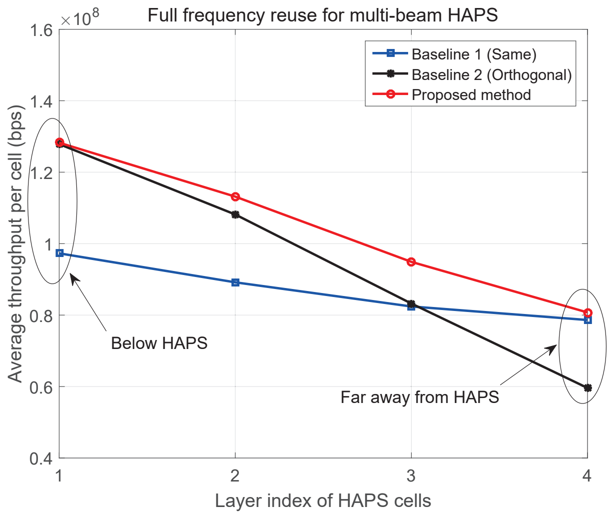


Fig. 6. Average throughput per cell versus different layer index of HAPS cells with full frequency reuse in HAPS.

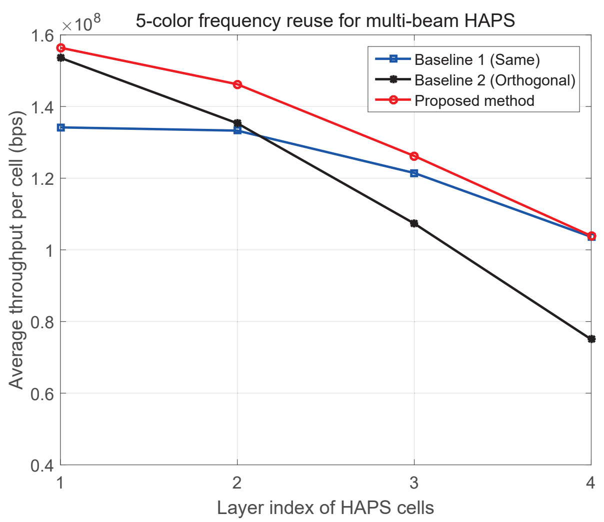


Fig. 7. Average throughput per cell versus different layer index of HAPS cells with 5-color frequency reuse in HAPS.

avoidance. For terrestrial networks far away from HAPS, same resource allocation is preferred for more resources. Otherwise, the resource allocation method as well as the serving systems (e.g., HAPS or terrestrial BSs) for users on ground should be designed based on the distribution of traffic load.

VI. Conclusion

In this paper, we analyzed the interference types for integrated HAPS and terrestrial systems and showed that inter-system interference matters in some cases through evaluations. Then, the interference coordination method is proposed considering the traffic load distribution and the deployment of HAPS-terrestrial network. The non-overlapping areas of HAPS and terrestrial systems are served by the two systems separately to ensure the coverage. For the cells without traffic load, the corresponding beams or BSs can be turned into idle mode for energy saving. The overlapping areas of HAPS and terrestrial systems are served by one or two systems, which can be determined based on some predefined patterns and maximizing the throughput. The evaluation results show that the proposed method can achieve higher throughput than existing methods with fixed resource allocation.

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