IEICE Communications Express, Vol.13, No.6, 185–189

ComEX

Special Cluster in Antennas and Propagation Technologies 2023

LETTER

Spectrum sharing in integrated HAPS and terrestrial systems using an interference canceler and coordination

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Abstract High-altitude platform stations (HAPSs) have the potential to expand the coverage of sixth-generation mobile communication systems, and several international mobile telecommunications (IMT) bands below 2.7 GHz have already been identified for HAPS service links. Because of the limited frequency resources, spectrum sharing techniques are needed to ensure that HAPSs can coexist with terrestrial base stations (BSs), but this means that a HAPS may interfere with the connection of terrestrial BS users within its line of sight. This letter proposes a scheme that combines an interference canceler and enhanced inter-cell interference coordination to reduce interference in an integrated HAPS–terrestrial system. Numerical simulations demonstrated that the integrated system greatly improved the signal-to-interference-plus-noise ratio of terrestrial BSs and improved the system capacity by 26% compared to a conventional system with no interference reduction.

Keywords: HAPS, spectrum sharing, interference canceler, eICIC
Classification: Wireless communication technologies

1. Introduction

High-altitude platform stations (HAPSs) are a promising solution for expanding the coverage of sixth-generation mobile communication systems [1, 2]. HAPS can provide service over a wide area from high altitudes, which offers new possibilities for network design. Several international mobile telecommunications (IMT) bands below 2.7 GHz have already been identified for HAPS service links [3]. Spectrum sharing with terrestrial systems is essential because of the limited frequency resources available, but this means that a HAPS may interfere with the connection of users of terrestrial base stations (BSs). Therefore, the development of key technologies for interference reduction is crucial to facilitate the coexistence of HAPSs and terrestrial BSs.

Various coordination methods have been proposed to address inter-cell interference between multiple terrestrial BSs. For instance, Hoshino et al. [4] proposed an interference canceler that treats multiple BSs as a coordinated multiuser multiple-input multiple-output (MU-MIMO) system, and they built a prototype for an experimental evaluation. This method allows the same wireless resources to be used across multiple BSs, but the interference reduction is minimal when the interference is exceedingly high. In terrestrial heterogeneous network (HetNet) configurations, approaches such as enhanced inter-cell interference coordination (eICIC) avoid interference with small cells by designating protected resources where the macro cell ceases transmission [5]. However, this approach reduces the wireless resources available for the macro cell, which decreases spectral efficiency.

In this letter, we combine the above interference canceler and eICIC to reduce interference in an integrated HAPS–terrestrial system, as shown in Fig. 1. Our study makes the following contributions:

- An interference reduction scheme for an integrated system is proposed, combining an interference canceler and eICIC to complement each other. The effectiveness of this scheme is evaluated through numerical simulations.
- An interference canceler is introduced that improves the signal-to-interference-plus-noise ratio (SINR) of terrestrial BSs. The performance limitations of the interference canceler are also described.
- A scheduling algorithm is proposed for applying eICIC to terrestrial BS users for whom the interference canceler is less effective.

Notations: The sets of real and complex numbers are denoted by $\mathbb{R}$ and $\mathbb{C}$, respectively. An imaginary unit is denoted by j and $(\cdot)^*$ is complex conjugate. For vectors and matrices, $\|\cdot\|$ is the L2 norm; $\odot$ denotes the element-wise product; $(\cdot)^T$ denotes the transpose. $E[\cdot]$ denotes the expectation value. δ represents the Kronecker delta.

2. System model

In the integrated HAPS-terrestrial system, a HAPS equipped with an N_t-element antenna provides N_c cells within its service area and coexists with N_b terrestrial BSs. Both the HAPS and terrestrial BSs share the same time–frequency resources. In this study, given the high traffic demand, we focused on downlink communications with single polarization. Interference from terrestrial BSs was ignored.

For terrestrial BS users, the interference from the HAPS should be considered. The signal from the terrestrial BS b is denoted by x_b, and the additive white Gaussian noise (AWGN) is denoted by n_b. The transmitted power of the BS is p_b while the isotropic antenna gain of the user equipment (UE) is G. If the channel between the BS and user is denoted as h_b, then the received signal of a user connected to the terrestrial BS b is given by

$$y_b = \sqrt{Gp_b}\,h_b x_b + \sqrt{G}\,\mathbf{h}_b^{(I)}\mathbf{W}\mathbf{P}'\mathbf{x}' + n_b, \tag{1}$$

where the second term represents interference from the

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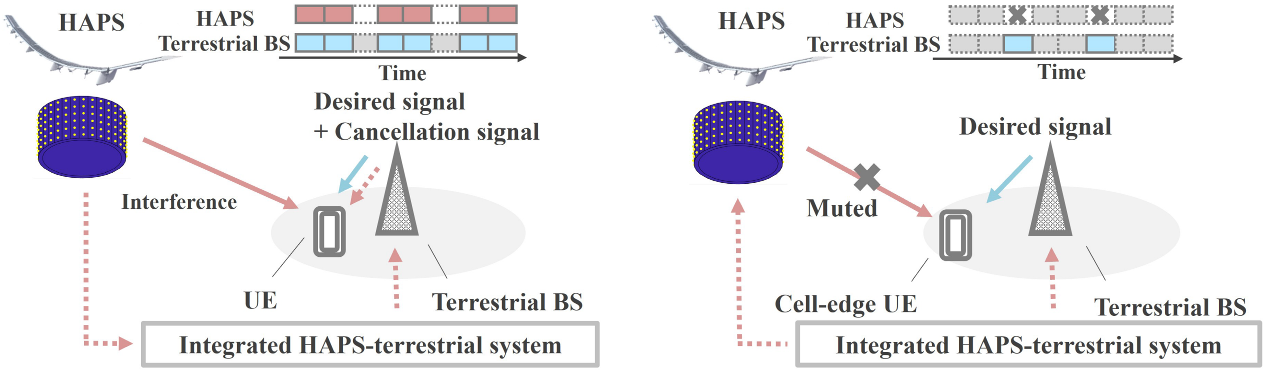
DOI: 10.23919/comex.2024SPL0019
Received January 26, 2024
Accepted February 21, 2024
Publicized March 12, 2024
Copyedited June 1, 2024



(a) Interference canceler.

(b) eICIC.

Fig. 1 Schematic pictures of the integrated system.

HAPS. Here, $\mathbf{h}_b^{(I)} \in \mathbb{C}^{1\times N_t}$ is the channel vector between the HAPS and user, $\mathbf{W} \in \mathbb{C}^{N_t\times N_c}$ is the beamforming weight matrix applied to the HAPS, $\mathbf{P}' \in \mathbb{R}^{N_c\times N_c}$ is the transmission power matrix of the HAPS, and $\mathbf{x}' \in \mathbb{C}^{N_c\times 1}$ is the transmitted signal vector. We assumed a normalization of $E[|x_b|^2] = 1$, noise power of $P_n = E[|n_c|^2]$, and orthogonality of $E[x_b^* n_b] = E[x_b^* x'_c] = 0$. Hence, the SINR of the terrestrial BS user can be expressed as

$$\gamma_b = \frac{p_b|h_b|^2}{\|\mathbf{h}_b^{(I)}\mathbf{W}\mathbf{P}'\|^2 + P_n/G}. \tag{2}$$

In this study, our aim is to reduce the first term in the denominator.

Because the HAPS remains in the stratosphere at an altitude of approximately 20 km, the direct path along its line of sight (LOS) is dominant. Therefore, we can simply model the channel vector between the HAPS and the user associated with terrestrial BS b as follows [6, 7]:

$$\mathbf{h}_b^{(I)} = \mathbf{l}_b \odot \mathbf{d}_b \odot \mathbf{g}_b, \tag{3}$$

$$\mathbf{l}_b = \left[\left(\frac{4\pi}{\lambda}D_{b,1}\right)^{-1}, \cdots, \left(\frac{4\pi}{\lambda}D_{b,N_t}\right)^{-1}\right], \tag{4}$$

$$\mathbf{d}_b = \left[\exp\left(j\frac{2\pi}{\lambda}D_{b,1}\right), \cdots, \exp\left(j\frac{2\pi}{\lambda}D_{b,N_t}\right)\right], \tag{5}$$

$$\mathbf{g}_b = \left[g(\theta_{b,1}, \phi_{b,1}), \cdots, g(\theta_{b,N_t}, \phi_{b,N_t})\right]. \tag{6}$$

where λ is the wavelength. The terms $D_{b,t}$, $\theta_{b,t}$, and $\phi_{b,t}$ represent the distance, elevation angle, and azimuth angle, respectively, between the user and antenna element t. The vectors $\mathbf{l}_b$, $\mathbf{d}_b$, and $\mathbf{g}_b$ correspond to the free-space path loss, phase rotation, and gain of the antenna elements, respectively. This model is also applicable to HAPS users.

The channel matrix between the HAPS and its users is denoted by $\mathbf{H}' \in \mathbb{C}^{N_c\times N_t}$. The received signal vector $\mathbf{y}'$ is given by

$$\mathbf{y}' = \sqrt{G}\mathbf{H}'\mathbf{W}\mathbf{P}'\mathbf{x}' + \mathbf{n}', \tag{7}$$

where $\mathbf{n}'$ is the AWGN vector. In addition, the matrices $\mathbf{H}'$, $\mathbf{W}$, and $\mathbf{P}'$ are divided into N_c parts corresponding to each cell, which are represented as $\mathbf{H}' = [\mathbf{h}_1'^T, \cdots, \mathbf{h}_{N_c}'^T]^T$, $\mathbf{W} = [\mathbf{w}_1, \cdots, \mathbf{w}_{N_c}]$ and $\mathbf{P}' = \mathrm{diag}(\sqrt{p'_1}, \cdots, \sqrt{p'_{N_c}})$. Similar to the terrestrial BS user, the SINR of the HAPS user in cell c is obtained as follows:

$$\gamma'_c = \frac{p'_c|\mathbf{h}'_c\mathbf{w}_c|^2}{\sum_{\substack{c'=1\\ c'\neq c}}^{N_c} p'_{c'}|\mathbf{h}'_{c'}\mathbf{w}_{c'}|^2 + P'_n/G}, \tag{8}$$

where we assume that the components of the vectors $\mathbf{x}'$ and $\mathbf{n}'$ satisfy $E[x_c^* x_{c'}] = \delta_{cc'}$, $E[x_c^* n'_{c'}] = 0$, and $P'_n = E[|n'_c|^2]$.

We assumed that users communicate with either the HAPS or a terrestrial BS during a single subframe. The system capacity is determined by summing up the capacities of N_c HAPS cells and N_b terrestrial BSs averaged over an almost blank subframe (ABS) pattern in eICIC [8], which in turn comprises N_{sf} subframes. The capacity can then be expressed as follows:

$$C = \frac{B}{N_{\mathrm{sf}}}\sum_{b,i_{\mathrm{sf}}}\log_2\left(1+\gamma_{b,i_{\mathrm{sf}}}\right) + \frac{B}{N_{\mathrm{sf}}}\sum_{c,i_{\mathrm{sf}}}\log_2\left(1+\gamma'_{c,i_{\mathrm{sf}}}\right), \tag{9}$$

where B represents the bandwidth and i_{sf} represents the index of the subframe. The first and second terms in Eq. (9) correspond to the capacities of the terrestrial BSs and HAPS, respectively.

3. Spectrum sharing in integrated systems

In this section, we propose the interference canceler and eICIC for reducing the interference of the integrated HAPS–terrestrial system. We also present a user-scheduling algorithm that selects terrestrial BS users for eICIC application based on the signal-to-interference ratio (SIR).

3.1 Interference canceler and eICIC

Terrestrial BSs can use antiphase signals to cancel the interference from the HAPS. If we replace the transmitted signal in Eq. (1) with $x_b \to x_b - \mathbf{h}_b^{(I)}\mathbf{W}\mathbf{P}'\mathbf{x}'/(\sqrt{p_b}h_b)$, the interference will be canceled perfectly. However, the signal power from terrestrial BSs must be normalized because simply adding the cancellation signal results in an increase in transmission power. Therefore, we introduce the following normalization coefficient:

$$\hat{x}_b = \alpha\left(x_b - \frac{\mathbf{h}_b^{(I)}\mathbf{W}\mathbf{P}'\mathbf{x}'}{\sqrt{p_b}h_b}\right). \tag{10}$$

The normalization condition, $E[|\hat{x}_b|^2] = 1$, is satisfied when

$$\alpha = \sqrt{\frac{p_b|h_b|^2}{p_b|h_b|^2 + \|\mathbf{h}_b^{(I)}\mathbf{W}\mathbf{P}'\|^2}}. \tag{11}$$

The coefficient is bounded by $0 \leq \alpha \leq 1$. Replacing x with $\hat{x}$ in Eq. (1) reduces interference from the HAPS signal,

$$\hat{y}_b = \alpha\sqrt{Gp_b}h_b x_b + (1-\alpha)\sqrt{G}\mathbf{h}_b^{(I)}\mathbf{W}\mathbf{P}'\mathbf{x}' + n_b. \tag{12}$$

Consequently, the received SINR can be improved,

$$\hat{\gamma}_b = \frac{\alpha^2 p_b|h_b|^2}{(1-\alpha)^2\|\mathbf{h}_b^{(I)}\mathbf{W}\mathbf{P}'\|^2 + P_n/G}. \tag{13}$$

The SINR is not always enhanced by the interference canceler because the interference is reduced at the cost of losing the desired signal power. For simplicity, we can define the SIR and signal-to-noise ratio (SNR) before cancellation as $\gamma_I = p_b|h_b|^2/\|\mathbf{h}_b^{(I)}\mathbf{W}\mathbf{P}'\|^2$ and $\gamma_N = Gp_b|h_b|^2/P_n$, respectively. Then, the equation $\hat{\gamma}_b = \gamma_b$ can be solved for γ_I. Here, $\gamma_I^{-1} = 0$ is trivial because no interference from the HAPS exists. The nontrivial solution is given by

$$\gamma_I = \left(1 - \gamma_N^{-1} + 2\sqrt{1-\gamma_N^{-1}}\right)^{-1}. \tag{14}$$

If the SIR is less than Eq. (14), the interference canceler degrades the SINR.

On the other hand, eICIC establishes protected time resources during which the data and related control-channel transmission of the HAPS is muted, allowing terrestrial BS users to communicate without interference. Here, we assumed that N_p subframes per ABS pattern (consisting of N_{sf} subframes) are protected resources. eICIC causes a tradeoff between the communication quality of terrestrial BSs and the capacity of HAPS cells. eICIC allows N_p terrestrial BS users to communicate without interference but reduces the capacity of the HAPS cells by N_p/N_{sf}. The rate of protected subframes should be set to strike a balance between the HAPS cells and terrestrial BSs.

3.2 Proposed scheme

The proposed interference reduction scheme compensates for the performance degradation of the interference canceler and capacity reduction due to eICIC. We apply the interference canceler to the majority of users in order to increase capacity. For users with a low SIR, who are typically at the edge of the cell, their interference can be reduced by using eICIC instead. The scheme enables to achieve a balance between communication quality of the terrestrial BSs and total capacity in the integrated HAPS–terrestrial system.

Because the interference canceler is less effective for low-SIR users, our scheme uses eICIC to allocate the protected N_p subframes to such users. Let $\mathcal{U}$ be the set of users associated with the terrestrial BS b. We add the index $u \in \mathcal{U}$ to distinguish each user, which is expressed as $h_{b,u}$ and $\mathbf{h}_{b,u}^{(I)}$. We then propose the following greedy algorithm:

1. Initialization: $i_{\mathrm{sf}} \leftarrow 1$
2. For all $u \in \mathcal{U}$, the SIR is evaluated as $\gamma_I(u) = p_b|h_{b,u}|^2/\|\mathbf{h}_{b,u}^{(I)}\mathbf{W}\mathbf{P}'\|^2$. The user with the minimal SIR is allocated to the subframe,

$$u_{i_{\mathrm{sf}}} \leftarrow \arg\min_{u\in\mathcal{U}} \gamma_I(u). \tag{15}$$

3. The selected user is removed from the user set because we allocate each user only one subframe,

$$\mathcal{U} \leftarrow \mathcal{U} \setminus \{u_{i_{\mathrm{sf}}}\}, \tag{16}$$

$$i_{\mathrm{sf}} \leftarrow i_{\mathrm{sf}} + 1. \tag{17}$$

4. Steps 2 and 3 are repeated if $i_{\mathrm{sf}} < N_p$.

This user allocation is applied to all terrestrial BSs. The remaining users are randomly allocated.

4. Simulation setup

Numerical simulations were performed to evaluate the performance of the integrated HAPS-terrestrial system with the proposed scheme. A HAPS was equipped with a cylindrical array antenna, and six HAPS cells were uniformly provided within a 100 km radius. Six terrestrial BSs were deployed at the boundaries of the HAPS cells, located 40 km away from the center. We assumed LOS propagation for HAPS and non-LOS (NLOS) propagation for the terrestrial BSs. We used the extended Hata model with suburban corrections for NLOS propagation [9, 10, 11].

Table I [12] presents the simulation parameters. Both the HAPS and terrestrial BSs used the same bandwidth and carrier frequency. The HAPS was equipped with a cylindrical array antenna as shown in Fig. 1 to cover a wide area. The beamforming weight for the HAPS was obtained from a pseudoinverse matrix [13] that satisfied the tilt angle and 3 dBi-beamwidth in the table. In the integrated system, the HAPS was muted for four subframes per ABS pattern, which reduced the capacity of the HAPS cells by 10%.

Table I Simulation parameters

	HAPS	Terrestrial BSs
Bandwidth, B	18 MHz	
Carrier frequency	2 GHz	
Number of ABS patterns	500 ($N_{\mathrm{sf}} = 40$ [8], $N_p = 4$)	
Number of HAPSs / BSs	1	$N_b = 6$
Altitude	20 km	50 m
Area radius	100 km	3 km
Transmit power	60 W (10 W/cell)	$p_b = 20$ W
Antenna configuration	Cylindrical	-
Number of antenna elements	186	1
Radiation pattern of an element	3GPP TR38.901 [12]	Isotropic
Maximum gain	8 dBi	10 dBi

	HAPS cells
Number of cells	$N_c = 6$
Tilt angle	16°
3 dBi-beamwidth	Horizontal: 32° Vertical: 30°
	UE
Altitude	1 m
Number of antenna elements	1
Radiation pattern of an element	Isotropic
Gain, G	−3 dBi
Noise power density	−174 dBm/Hz
Noise figure	5 dB

We simulated 20,000 downlink communications, which corresponded to 500 ABS patterns. The received SINRs of the integrated system were evaluated for each subframe. User sets for both the HAPS and terrestrial BSs were generated with uniform distributions. The protected subframes were allocated to terrestrial BS users according to the algorithm in subsection 3.2. The system capacity was evaluated for each ABS pattern. To evaluate the performance of the integrated system, it was compared to a conventional system with no interference reduction and terrestrial BSs only.

5. Simulation results

Figure 2 shows area maps of a terrestrial BS within a radius of 3 km comparing the SINRs of the integrated and conventional systems. The maps are divided into squares of 150 m by 150 m each, and the average SINR of users within each square is presented. Compared with the conventional system (Fig. 2(a)), the interference canceler (Fig. 2(b)) increased the size of the high-SINR area at the center. Meanwhile, eICIC (Fig. 2(c)) increased the SINR near the edge. Using both the interference canceler and eICIC (Fig. 2(d)) greatly enhanced the SINR across the entire area.

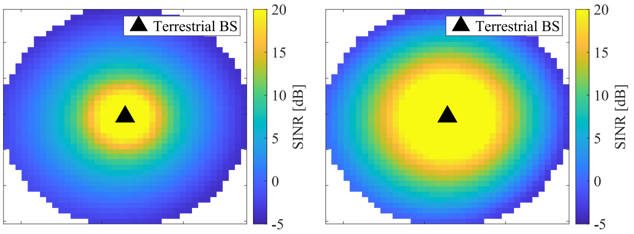
The median and 5th-percentile SINRs of the terrestrial BS users with different systems were as follows:

- Conventional system: 1.87 dB (−3.25 dB)
- Integrated system: 8.30 dB (0.45 dB)
- Terrestrial BSs only: 11.54 dB (6.85 dB)

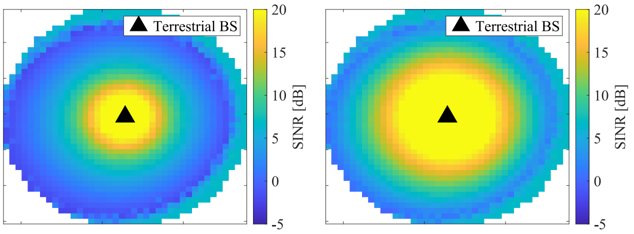
As shown in Fig. 2, the integrated system enhanced both the median and 5th-percentile SINRs. Finally, the median capacities of the systems as defined in Eq. (9) were as follows:

- Conventional system: 613 Mbps
- Integrated system: 772 Mbps
- Terrestrial BSs only: 507 Mbps

The capacity of the integrated system was 26% higher than that of the conventional system. Thus, the integrated HAPS–terrestrial system can enhance the SINR of the terrestrial BSs and improve the efficiency of spectrum sharing.



(a) Conventional system (no interference reduction). (b) With the interference canceler only.



(c) With eICIC only. (d) Integrated system with the canceler and eICIC.

Fig. 2 SINR area maps of a terrestrial BS with the conventional and integrated systems.

6. Conclusion

We propose a scheme that utilizes both an interference canceler and eICIC to reduce the interference in an integrated HAPS–terrestrial system. We performed numerical simulations that demonstrated that the interference reduction scheme improved the median SINR of terrestrial BSs by 6.4 dB compared to a conventional system with no interference reduction and improved the system capacity by 26%.

Acknowledgments

This study was supported in part by the Ministry of Internal Affairs and Communications of Japan through the “R&D on efficient spectrum use technologies for wireless communications systems using high-altitude platform stations” under Grant JPJ000254.

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