Nullforming Strategy Based on User Distribution for Spectrum Sharing Between High-Altitude Platforms and Terrestrial Networks

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***Abstract*—High-Altitude Platform Stations (HAPSs) enable wide-area coverage in 6G networks but introduce interference when sharing spectrum with terrestrial networks (TNs). Nullforming is a technique to mitigate this interference by directing low-power beams (nulls) toward terrestrial users. Traditional nullforming methods, such as Null-Sweeping, rely on changing null directions across the resource blocks (RB) to improve the impact of nullforming. Yet these null directions are predefined for uniform user distributions and may not fully account for non-uniform deployments. We propose a user-aware nullforming approach that leverages K-means clustering to adapt null positions to dense user regions in the terrestrial cells, while time-frequency resources are allocated proportionally to user density. Simulations show that our method reduces HAPS interference for terrestrial users and improves fairness in interference distribution.**

***Keywords*—HAPS, Nullforming, Interference Reduction.**

I. Introduction

High-Altitude Platform Stations (HAPSs) are gaining attention for providing wide-area coverage in 6G networks, particularly for user equipment (UE) outside terrestrial networks (TNs) or in disaster-affected areas. Operating below 2.7 GHz under IMT standards [1], HAPSs share spectrum with TNs, leading to interference concerns. While [2] suggests maintaining a 120 km separation from terrestrial base stations (TBSs), HAPSs' 100 km coverage radius makes overlap with TNs inevitable, necessitating interference management.

Advanced Multi-user Multiple-Input-Multiple-Output (MU-MIMO) techniques, such as beamforming, improve spectrum efficiency and mitigate interference by leveraging the spatial domain. Some approaches shape HAPS beams to direct power toward specific areas outside TNs [3], while CSI-based methods optimize received signal quality per user [4]. The precoding approach in [4] introduces nullforming, where HAPS signal cancellation is directed toward locations called null points. By choosing TBSs as null points, experimental studies [5] confirm its effectiveness in reducing interference within TBS cells.

Due to the Line-of-Sight (LoS) nature of HAPS links, null-point placement directly impacts interference protection. Using the TBS location as a null-point exposes cell-edge UEs to strong interference from both HAPS and neighboring BSs, degrading SINR. To address this, the Null-Sweeping scheme introduced in [6] dynamically alternates between multiple null directions across time-frequency resources. By aligning UE scheduling with the sweeping pattern, it expands the spatial coverage of nulls without increasing nullforming complexity. However, its manually pre-designed null directions, optimized for uniform UE distributions, can be less effective when it comes to real-world non-uniform UE distributions.

In this paper, we investigate how UE distribution knowledge can improve nullforming for HAPS-TN spectrum sharing. Assuming UE distribution is known through the backhaul network —consistently with [4], [6]—we propose a user-aware nullforming approach using K-means clustering to dynamically position nulls and allocate time-frequency resources.

The remainder of this paper is structured as follows: Section II formalizes the system model and defines the objective of this work. Section III presents the proposed method, while Section IV details the simulation setup and results. Finally, conclusions are provided in Section V.

Notations: In this paper, $\mathbb{R}$ and $\mathbb{C}$ denote the set of real and complex numbers, respectively. The imaginary unit is denoted by $j = \sqrt{-1}$; $\|\cdot\|$ is the L_2-norm for vectors and matrices; $\odot$ denotes the Hadamard product; $(\cdot)^T$, $(\cdot)^H$ and $(\cdot)^{-1}$ denote the transpose, the Hermitian conjugate and the inverse, respectively. $\mathbf{I}_m$ is the $m \times m$ identity matrix; and $\mathbf{0}_{m,n}$ is the $m \times n$ zero matrix. $\min(a, b)$ returns the smaller of two real numbers a and b.

II. System Model

A. Scenario and Channel Model

We consider a scenario inspired by [6], where a single HAPS at altitude A serves users distributed as $\mathcal{K}_0 \sim p(\mathcal{K}_0)$ within a circular coverage area of radius R_{HAPS} on the ground. This area overlaps with N_{BS} terrestrial BSs, each serving users $\mathcal{K}_b \sim p(\mathcal{K}_b)$ within a cell of radius R_{BS}. Users are drawn independently from their respective distributions, and their locations are assumed to be known to both the HAPS and BSs, though the method can extend to cases where only statistical information is available.

The HAPS uses a fully digital downward-pointing square antenna array with N_t elements, while BSs and users are equipped with single isotropic antennas as in [6]. Radio transmissions are structured into frames, each containing N_{RB} time-frequency resource blocks. In each block r, the HAPS serves a set $\mathcal{U}_r$ of N_u users from $\mathcal{K}_0$, while each BS serves one user $g_{br} \in \mathcal{K}_b$. For simplicity, each BS allocates all time-frequency resources within a frame, i.e., $|\mathcal{K}_b| = N_{\text{RB}}$. Frame durations are assumed short enough for HAPS and user positions to remain constant.

Let $\mathbf{h}_{0k}$ and h_{bk} denote the channels between the HAPS or BS $b \in \{1, \ldots, N_{\text{BS}}\}$ and a user $k \in \bigcup_{b=0}^{N_{\text{BS}}} \mathcal{K}_b$, respectively. The received signal $y_k \in \mathbb{C}$ at user k is given by:

$$y_k = \sqrt{p_0} \sum_{u \in \mathcal{U}_r} \mathbf{h}_{0k}^H \mathbf{W}_r \mathbf{s}_{0r} + \sum_{b=1}^{N_{\text{BS}}} \sqrt{p_b} h_{bk} s_{bg_{br}} + n_k, \quad (1)$$

where $\mathbf{s}_{0r}$ and $s_{bg_{br}}$ are unit-variance signals from the HAPS and BSs, respectively, p_0 and p_b are their transmit powers, $\mathbf{W}_r$ is the spatial precoder at the HAPS, and $n_k \overset{i.i.d.}{\sim} \mathcal{CN}(0, \Gamma)$ is an independent and identically distributed (i.i.d.) complex additive white Gaussian noise. The corresponding instantaneous SINR experienced by a HAPS user $u \in \mathcal{U}_r$ can be written as

$$\gamma_{0u} = \frac{p_0 |\mathbf{h}_{0u}^H \mathbf{w}_{0u}|^2}{\sum\limits_{\substack{u' \in \mathcal{U}_r \\ u' \neq u}} p_0 |\mathbf{h}_{0u}^H \mathbf{w}_{0u'}|^2 + \sum\limits_{b'=1,\ldots,N_{\text{BS}}} p_b |h_{b'u}|^2 + \Gamma}, \quad (2)$$

where $\mathbf{w}_{0u} \in \mathbb{C}^{N_u}$ is the column of $\mathbf{W}_r$ corresponding to the signal intended to user u. Similarly, a user $g \in \mathcal{K}_b$ served by BS b experiences SINR

$$\gamma_{bg} = \frac{p_b |h_{bg}|^2}{\sum\limits_{u \in \mathcal{U}_r} p_0 |\mathbf{h}_{0g}^H \mathbf{w}_{0u}|^2 + \sum\limits_{\substack{b'=1,\ldots,N_{\text{BS}} \\ b' \neq b}} p_{b'} |h_{b'g}|^2 + \Gamma}. \quad (3)$$

The HAPS is located at high altitude and the HAPS users are considered to be outdoor users, so that the signal propagation from the HAPS to the users is dominated by LoS propagation. Then for a user k the channel vector $\mathbf{h}_{0k}$ can be decomposed as

$$\mathbf{h}_{0k} = \mathbf{p}_k \odot \mathbf{d}_k \odot \mathbf{g}_k, \quad (4)$$

$$\mathbf{p}_k = \left[\left(\frac{4\pi}{\lambda} D_{k,1} \right)^{-1}, \ldots, \left(\frac{4\pi}{\lambda} D_{k,N_t} \right)^{-1} \right]^T, \quad (5)$$

$$\mathbf{d}_k = \left[\exp\left(j \frac{2\pi}{\lambda} D_{k,1} \right), \ldots, \exp\left(j \frac{2\pi}{\lambda} D_{k,N_t} \right) \right]^T, \quad (6)$$

$$\mathbf{g}_k = \left[g(\theta_{k,1}, \phi_{k,1}), \ldots, g(\theta_{k,N_t}, \phi_{k,N_t})) \right]^T. \quad (7)$$

Here, $\mathbf{p}_k \in \mathbb{R}^{N_t}$ and $\mathbf{d}_k \in \mathbb{C}^{N_t}$ are the free-space path loss and phase offset between user k and each HAPS antenna element, respectively, which depend on the distance $D_{k,n}$. $\mathbf{g}_k \in \mathbb{C}^{N_t}$ is the antenna gain, which is given by the radiation patterns of the antenna elements $g(\theta_{k,n}, \phi_{k,n})$, where $\theta_{k,n} \in [-90°, +90°]$ and $\phi_{k,n} \in [-180°, +180°]$ are the elevation and azimuth angles between antenna element n and user k, respectively. We assume that the HAPS has perfect knowledge of the channels to its users (e.g., obtained through channel estimation or using the user location).

Contrary to the HAPS, the communications links to the TBSs experience non-line-of-sight (NLoS) propagation, and are modeled according to the Hata model for suburban areas [7]. As for the HAPS, the channels are assumed to be known to the serving BS.

B. Precoding and Nullforming Design

1) Precoding Design: To reduce interference between the HAPS and the ground cell users, we assume that the HAPS performs nulling towards predefined *null-points* in each cell. Specifically, in line with [4] we assume that the HAPS assigns one null-point to each BS in each time-frequency resource, so the total number of null-points within a time-frequency resource equals N_{BS}.

The HAPS precoding matrix $\mathbf{W}_r$ can be factorized into a nullforming matrix $\mathbf{W}_r^{\text{NF}} \in \mathbb{C}^{N_t \times M}$ and a beamforming matrix $\mathbf{W}_r^{\text{BF}} \in \mathbb{C}^{M \times N_u}$ as

$$\mathbf{W}_r = \mathbf{W}_r^{\text{NF}} \mathbf{W}_r^{\text{BF}}, \quad (8)$$

where $M = N_t - N_{\text{BS}}$ is the number of degrees of freedom available for user-specific beams. For a set of N_{BS} null-points $\mathcal{N}_r$ in time-frequency resource r, the nullforming matrix $\mathbf{W}_r^{\text{NF}}$ is constructed to satisfy

$$\mathbf{H}(\mathcal{N}_r) \mathbf{W}_r^{\text{NF}} = \mathbf{0}_{N_{\text{BS}},M}, \quad (9)$$

where $\mathbf{H}(\mathcal{N}_r) \in \mathbb{C}^{N_{\text{BS}} \times N_t}$ is the matrix whose rows are the channel vectors between the HAPS and the null points $\mathcal{N}_r$, and $\mathbf{0}_{N_{\text{BS}},M}$ is the $M \times N_{\text{BS}}$ matrix of all zeros. $\mathbf{W}_r^{\text{NF}}$ can be computed using Singular Value Decomposition (SVD) by selecting M vectors from the null space of $\mathbf{H}(\mathcal{N}_r)$.

Let $\mathbf{H}(\mathcal{U}_r) = \left[\mathbf{h}_{01}^H, \ldots, \mathbf{h}_{0N_u}^H \right] \in \mathbb{C}^{N_u \times N_t}$ denote the channel matrix between the HAPS and the N_u users served by the HAPS in resource block r (we assume $N_u \leq M$). Following the construction of $\mathbf{W}_r^{\text{NF}}$, the beamforming matrix $\mathbf{W}_r^{\text{BF}}$ can be calculated by applying a conventional precoding scheme, such as zero-forcing (ZF) or minimum mean square error (MMSE) precoding, to the effective channel matrix $\tilde{\mathbf{H}}(\mathcal{U}_r) = \mathbf{H}(\mathcal{U}_r) \mathbf{W}_r^{\text{NF}}$. In the remainder of the paper, we will apply ZF precoding so that the beamforming matrix is computed as

$$\mathbf{W}_r^{\text{BF}} = \tilde{\mathbf{H}}(\mathcal{U}_r)^H (\tilde{\mathbf{H}}(\mathcal{U}_r) \tilde{\mathbf{H}}(\mathcal{U}_r)^H)^{-1}. \quad (10)$$

2) Nullpoint Assignment: As in [6], we assume the HAPS sweeps over a set of null directions across time-frequency resources. Each BS b has a predefined set of N_n candidate null points, denoted $\mathcal{N}_b = \{n_{b1}, \ldots, n_{bN_n}\}$. At each resource r, the HAPS assigns one null per BS, so that the set of null points in resource r is given as $\mathcal{N}_r = \bigcup_{b=1}^{N_{\text{BS}}} \{n_{b\pi_b(r)}\}$, where π_b maps resources to nulls. Note that null points may be reused across several time-frequency resources.

C. Objective

Our aim is to design for each terrestrial BS b the locations of the N_n null points in the set $\mathcal{N}_b$ and the null mapping function π_b such that the expected SINR degradation caused by the HAPS on the terrestrial BS users is minimized. More formally, we define the SINR degradation of a user $g \in \mathcal{K}_b$ served by BS b as

$$\Delta_{\text{SINR},bg} = \frac{\gamma_{bg}^{(\text{HAPS TX-off})}}{\gamma_{bg}}, \tag{11}$$

where

$$\gamma_{bg}^{(\text{HAPS TX-off})} = \frac{p_b |h_{bg}|^2}{\sum\limits_{\substack{b'=1,\dots,N_{\text{BS}} \\ b' \neq b}} p_{b'} |h_{b'g}|^2 + \Gamma} \tag{12}$$

is the SINR without the HAPS transmission—corresponding to the ideal case for interference reduction. Utilizing this, we define our overall objective as

$$\underset{(\mathcal{N}_b, \pi_b)_{b \in \{1,\dots,N_{\text{BS}}\}}}{\text{minimize}} \quad \mathbb{E}\left[\frac{1}{N_{\text{BS}}} \sum_{b=1}^{N_{\text{BS}}} \frac{1}{|\mathcal{K}_b|} \sum_{g \in \mathcal{K}_b} \Delta_{\text{SINR},bg}\right], \tag{13}$$

where the expectation is taken over the user distribution $p(\mathcal{K}_0, \mathcal{K}_1, \dots, \mathcal{K}_{N_{\text{BS}}})$.

III. User Distribution Aware Nullforming

To maximize the impact of null-point allocation on served users, we propose a method that leverages the spatial user distribution within each cell. In practice, the user distribution can be obtained through historical observations or domain knowledge, or using techniques such as channel charting [8]. However, for simplicity, in this paper we will assume that the locations of the users are perfectly known to the HAPS.

A. K-Means Nullforming

1) Clustering: K-means is an unsupervised clustering algorithm that partitions a dataset into K clusters while minimizing intra-cluster variance [9]. It iteratively assigns data points to the nearest centroid and updates centroids based on the mean position of assigned points. This results in compact, convex-shaped clusters, making it effective for spatial user grouping and optimizing null-point placement in terrestrial networks.

Each terrestrial BS b serves a set of users $\mathcal{K}_b$, with known angle coordinates relative to the HAPS (θ_g, ϕ_g) for $g \in \mathcal{K}_b$. The angular distance between two users g_1 and g_2 is given by:

$$d(g_1, g_2) = \sqrt{(\theta_{g_1} - \theta_{g_2})^2 + \min((\phi_{g_1} - \phi_{g_2})^2, (\phi'_{g_1} - \phi'_{g_2})^2)} \tag{14}$$

where $\phi'_g = \phi_g - 180° \pmod{360°}$ ensures continuity across the azimuth boundary.

The K-means algorithm is applied within the cell of each terrestrial BS b to cluster the dataset of UE positions $(\theta_g, \phi_g)_{g \in \mathcal{K}_b}$, where K is corresponding to the designated number of null-points N_n. As a result, we obtain the partition $(G_{bm})_{m \in \{1,\dots,N_n\}}$ of $\mathcal{K}_b$.

2) Null Directions Design: The clusters $(G_{bm})_{m \in \{1,\dots,N_n\}}$ formed in the previous step are utilized to determine the set of candidate null points $\mathcal{N}_b$ for each BS b. $\mathcal{N}_b$ is made of the centroids of each of the N_n clusters. Since each BS allocates one time-frequency resource per user, the HAPS assigns each null to a number of resources proportional to the number of UEs in the corresponding cluster, ensuring each UE has a

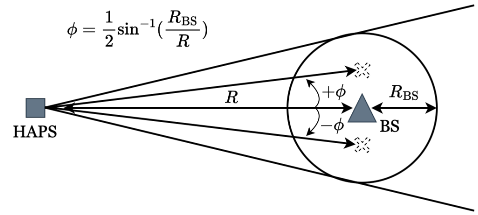


Fig. 1: Null directions for $N_n = 2$ in [6].

resource where the nearest null-point is assigned. Meaning that the mapping function π_b takes the value m as many times as there are users in G_{bm}, this can be written as

$$\pi_b(r) = m \quad \text{where} \quad \sum_{i=1}^{m-1} |G_{bi}| < r \leq \sum_{i=1}^{m} |G_{bi}|.^1 \tag{15}$$

B. Null-Sweeping

In the null-sweeping scheme [6], once the set of null directions $\mathcal{N}_r$ and the set of HAPS users $\mathcal{U}_r$ are designed, the precoding matrix W_r is computed and transmitted concurrently as the user-specific transmit power parameters to each terrestrial BS via the backhaul network. Each terrestrial BS schedules the UEs in its cell independently, by following a greedy algorithm for interference reduction. This algorithm optimizes user scheduling for the set of ground cell users $\mathcal{K}_b$ by initially computing the channel vectors $\mathbf{h}_{0g}$ between the HAPS and each ground user g using eq. (2). The residual interference power on a resource r is calculated as $I(r, g) = p_0 \|\mathbf{h}_{0g}^H \mathbf{W}_r\|^2$, and the resource is allocated to the user that minimizes this interference. Once a user is scheduled, it is removed from the set $\mathcal{K}_b$, and this process is repeated iteratively for all available resources.

C. Computational Complexity and Practical Considerations

The proposed method increases computational and transmission costs. Clustering terrestrial users requires $\mathcal{O}(nKdi)$ computational complexity per period T, where $n = N_{\text{RB}}$ is the number of ground users to schedule, $K = N_n$ is the cluster count, $d = 2$ is the coordinate dimension, and i (up to 100) is the number of Lloyd's algorithm iterations. Null-point updates at each period T create varying transmission costs depending on the null-sweeping scheme. The traditional approach transmits precoding matrix W_r to the terrestrial network with no additional overhead, while the limited control parameters scheme [10] requires transmitting null-points' positions to calculate approximated residual interference, adding transmission costs.

IV. Numerical Results

A. Null-Sweeping Baseline

The original Null-Sweeping scheme [6] is used here as a baseline for our method. In this method, the set of candidate

[1] This mapping remains a naive approach, and a more refined method would account for the set of HAPS UEs scheduled at each time-frequency resource r, while considering higher computational cost.

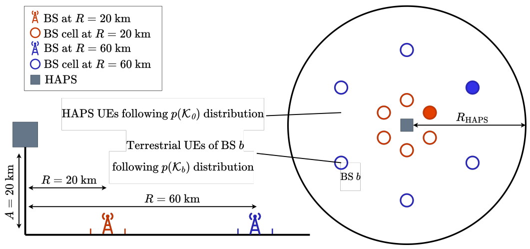


Fig. 2: Configuration of terrestrial BSs.

TABLE I: Simulation Parameters

	Parameter	Value
Common	Bandwidth B, Carrier frequency f	18 MHz, 2 GHz
HAPS	Number of HAPSs	1
	Altitude A	20 km
	Service area radius R_{HAPS}	100 km
	User-specific transmit power p_0	10 W
	Antenna configuration	Square
	Number of elements N_t	196
	Radiation pattern of an element	3GPP TR38.901 [11]
	Maximum gain	8 dBi
	Number of multiplexed users N_u	12
	Number of candidate nulls N_n	2 (each TBS)
Ground BSs	Number of BSs N_{BS}	6 (Altitude: 50 m)
	Cell radius R_{BS}	3 km
	Transmit power	20 W
	Number of antennas, Gain	1 (isotropic), 10 dBi
Users	Number of antennas, Gain	1 (isotropic), -3 dBi
	Noise power density, Noise figure	-174 dBm/Hz, 5 dB

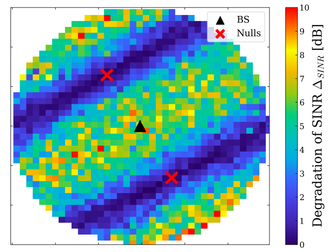
null directions $\mathcal{N}_b$ is manually pre-designed with nulls located at regularly spaced azimuth angles, and at same elevation angle as the TBS, as shown in Fig 1 for $N_n = 2$. The HAPS alternatively uses the designed nulls in the terrestrial cells, meaning that the null mapping function can be given as

$$\pi_b(r) = ((r-1) \mod N_n) + 1, \quad \text{for } r \in \{1, \dots, N_{\text{RB}}\}. \tag{16}$$

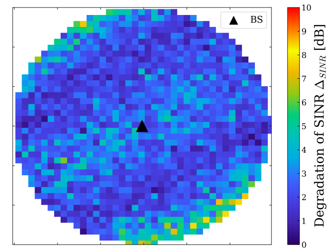
B. Simulation Setup

The proposed scheme is evaluated through numerical simulations in a spectrum-sharing scenario between a HAPS and TBSs. To ensure a fair comparison, the simulation model follows the framework established in [6], with a HAPS positioned at an altitude of 20 km, covering a service area with a 100 km radius. Within this area, six terrestrial BSs are arranged in a circular configuration at a distance R from the center, as shown in Fig. 2.

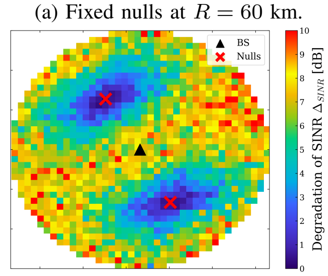
In abscence of real-world data, a UE distribution model is developed considering the HAPS UEs to be generated outside the terrestrial cells (TCs) within the HAPS service area following a uniform distribution. And the terrestrial UEs are distributed in the TCs, following a Gaussian Mixture Model (GMM) characterized by the following parameters: the number of components (N_c), the means (μ_n) of each component, and the covariance matrix being diagonal and the same for each component ($\Sigma_n = \sigma^2 I_2$)—the weights of the components being equal. In order to account for a wide variety of scenarios, the simulation procedure involves uniformly generating $N_c \in \{2, 3, 4, 5\}$ and the means $(\mu_n)_{n \in \{1,\dots,N_c\}}$ in



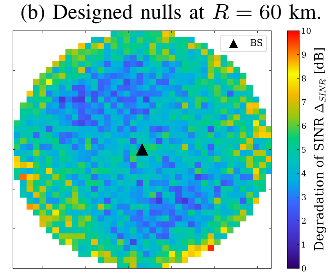
(a) Fixed nulls at $R = 60$ km.



(b) Designed nulls at $R = 60$ km.



(c) Fixed nulls at $R = 20$ km.



(d) Designed nulls at $R = 20$ km.

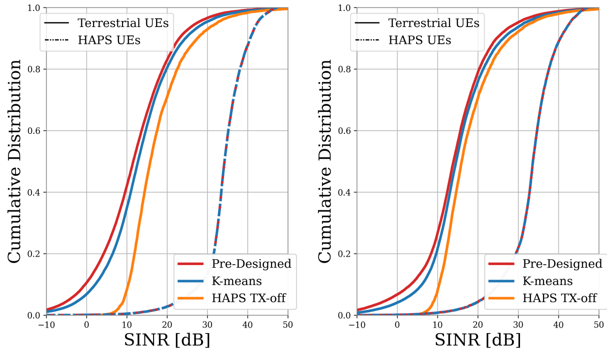
Fig. 3: SINR Degradation map within a terrestrial cell with $\sigma^2 = 0.5$ km^2.

the cell, and computing the probability distribution to generate the terrestrial users, leaving only σ^2 as a tunable parameter. As the TC represents bounded areas, increasing the variance σ^2 leads the distribution to approach uniformity.

The simulation parameters are listed in Table I. The HAPS utilizes a square array antenna of 196 antenna elements spaced on both axis at intervals of 0.5 wavelengths. The total HAPS transmit power is equal to $p_0 \times N_u = 120$ W. As in [6], we conducted 10,000 downlink communication trials using the following procedure. First, we randomly group 12 HAPS users from a generated set of 120,000 HAPS users following $p(\mathcal{K}_0)$ distribution. In each trial, the conventional method and the proposed method provide the set of null points $\mathcal{N}_r$ considered by the HAPS while communicating with 12 users. In each TC, we consider designing $N_n = 2$ null candidates. Terrestrial BSs schedule users in frames of $N_{\text{RB}} = 100$, following the algorithm described in III-B. The whole process is simulated for 100 frames, resulting in a total of 10,000 users per ground cell.

C. Results

The main contribution of our method—compared to the original method [6]—is its ability to adapt the interference reduction to any UE distribution in the terrestrial cells. The Fig. 3 shows the average SINR degradation Δ_{SINR} results for the 100 simulated frames. Within each resource frame, N_{RB} users are generated by a Gaussian Mixture distribution with $\sigma^2 = 0.5$ km^2 and are then scheduled by the greedy algorithm described in III-B. The position of the ground cell in these figures is depicted by a filled circle in Fig. 2. Blue users represent users having low Δ_{SINR}, indicating weaker HAPS interference and performance closer to the HAPS TX-off SINR. The proposed method reduces HAPS interference in ground cells through two key mechanisms. First, null directions are positioned to minimize the angular distance in



(a) $R = 20$ km.

(b) $R = 60$ km.

Fig. 4: Cumulative Distribution of the SINR for terrestrial users for $\sigma^2 = 0.5$ km^2 and HAPS users.

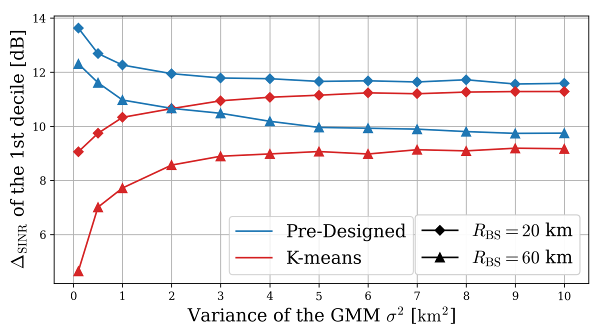


Fig. 5: SINR degradation of the first decile $\Delta_{\mathrm{SINR},10\%}$ as a function of σ^2 for both methods.

(14) between null-points and users. Second, the number of time-frequency resources allocated to each null is proportional to the number of users to whom that null is the closest. While the approach of [6] is effective for uniform UE distributions, it becomes less relevant when users are clustered away from the predefined nulls. Our proposed method addresses this issue and improves fairness among users by leveraging UE distribution. Besides, the stronger HAPS interference at $R = 20$ km vs. $R = 60$ km is due to closer proximity to the HAPS and the square antenna array, which amplifies received power for nearby users.

Figs. 4(a) and 4(b) show the cumulative distribution of SINRs for terrestrial cell users generated with $\sigma^2 = 0.5$ km^2 and HAPS users. Our nullforming method outperforms the original manual nullforming method of the null-sweeping scheme especially for the worst terrestrial users with improvements of 2.6 dB and 3.3 dB at the 1st decile, where six ground BSs were deployed at $R = 20$ km and 60 km, respectively, without degrading the HAPS users performance in the HAPS service area.

The performance of both methods clearly depends on the distribution of terrestrial UEs. Fig. 5 shows the SINR degradation of the first decile, $\Delta_{\mathrm{SINR},10\%}$, as a function of the GMM dispersion parameter σ^2 for terrestrial cells with $R_{\mathrm{BS}} = 3$ km. The proposed method consistently mitigates SINR degradation across all σ^2 values, with a notable advantage in highly clustered distributions (low σ^2). As the distribution becomes uniform (high σ^2), both methods converge in performance. This improvement stems from our method's ability to detect clusters and adjust nullforming accordingly. For uniform distributions, it partitions the terrestrial cell into N_n regions, placing null points at their centers to minimize intra-cluster variance, leading to a design similar to [6] (Fig. 1).

V. Conclusion

We introduced a user-aware nullforming method that integrates K-means clustering to dynamically adapt null directions based on the spatial distribution of terrestrial users. Unlike traditional approaches, such as Null-Sweeping, relying on predefined null positions, our method optimizes null placement to better align with real-world, non-uniform user distributions. Simulation results demonstrate that our approach enhances Null-Sweeping, particularly in concentrated user distributions, by reducing interference more effectively and improving fairness in resource distribution. As user distributions become more uniform, our method naturally converges to Null-Sweeping, confirming its adaptability across different deployment conditions. These findings emphasize the importance of incorporating user distribution into interference mitigation for more adaptive nullforming strategies.

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