# mmBAC: Location-aided mmWave Backhaul Management for UAV-based Aerial Cells

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## ABSTRACT

Mobile cells are seen as an enabler of more flexible and elastic services for next-generation wireless networks, making it possible to provide ad hoc coverage in failure scenarios and scale up the network capacity during peak traffic hours and temporary events. When mounted on Unmanned Aerial Vehicles (UAVs), mobile cells require a high-capacity, low-latency wireless backhaul. Although mmWaves can meet such data-rate demand, they suffer from high-latency link establishment, due to the need to transmit and receive with highly directional beams to compensate for the high isotropic path loss. In this paper, we review the benefits of side-information-aided beam management and present a GPS-aided beam tracking algorithm for UAV-based aerial cells. We prototype the proposed algorithm on a mmWave aerial link using a DJI M600 Pro and 60 GHz radios and prove its effectiveness in reducing the average link establishment latency by 66% with respect to state-of-the-art non-aided schemes.

## KEYWORDS

mmWave, UAV, Cellular Networks, Mobile Cells.

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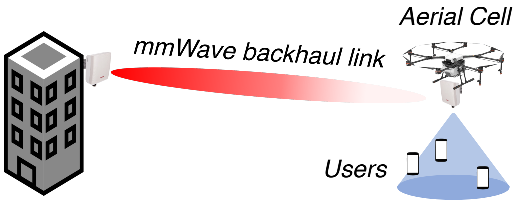

Figure 1: UAV-based aerial cell with mmWave backhaul.

## 1 INTRODUCTION

The 5th Generation (5G) of cellular networks is being designed to sustain the highly demanding communications requirements of the next decade. It will feature a number of cutting-edge technologies both in the radio access and in the core network, to deliver multi-gigabit-per-second throughput and ultra-low latency and pervasive connectivity [11]. 3GPP NR, the set of 5G specifications for cellular networks, allow the use of millimeter wave (mmWave) technologies in the Radio Access Network (RAN) to leverage the massive bandwidth availability that is accessible at such high frequencies and provide unprecedented data rates to end users [1, 21]. Moreover, innovations will be introduced throughout the whole protocol stack and network deployment, including the use of mobile base stations to address subscribers coverage and increasing capacity demands. These nomadic cells can be mounted, for instance, on Unmanned Aerial Vehicles (UAVs), and deployed in areas where the cellular network service is unavailable (e.g., because of natural calamities) [16], to offload ground infrastructure during peak demand hours, or to scale up the network capacity during temporary events (e.g., rallies and concerts), while helping mobile operators save on the deployment costs of additional ground infrastructure. Ultimately, nomadic-cell-based solutions will shift the cellular networking paradigm toward proactive, cost-effective, and elastic resource deployment strategies.

The deployment of nomadic cells, however, demands a high-bandwidth and low-latency wireless backhaul infrastructure, as the fiber optic cables typically employed at ground-based cells are not a feasible solution for UAV-based aerial cells. On the other hand, while mmWaves point-to-point

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or point-to-multipoint links have been proposed as a solution for high-capacity wireless backhaul in cellular networks [22, 23], they face unprecedented challenges when applied to nomadic cells. Specifically, the mmWaves promise of high data-rates comes at the cost of high directionality that is needed to overcome the high isotropic path loss typical of such high frequency bands [21]. It is thus crucial that the mmWave link endpoints set and maintain directional beam alignment throughout the whole mobile scenario deployment. This is normally done through an initial link setup phase aimed at establishing the first connection between two radios, and a beam tracking procedure following the endpoints movements [9]. Consequently, the key to mobile mmWave backhaul connectivity of UAV-based aerial cells is an efficient, low-overhead beam management. As discussed in [9], however, most of the beam management solutions for mmWave networks lead to significant initial access delays, which increases with the number of available beams and, consequently, directions to scan. These solutions are unfit for highly mobile cells, where UAV-based aerial cells frequently relocate to satisfy the users' service demands. In these scenarios, in fact, achieving a low-latency backhaul link establishment becomes paramount to avoid the overhead that could worsen the user experience and prevent timely communications. In conclusion, there is a need for a fast and efficient beam identification procedure toward rapid backhaul link establishment and management for UAV-based aerial cells.

In this article, we propose mmBAC, a low-overhead location-aided mmWave backhaul beam management scheme for UAV-based cellular networks. We envision a beam management strategy in which the relative positioning between the UAV and the ground mmWave backhaul endpoints is leveraged to perform an efficient beam scan aimed at identifying the strongest beam path. Specifically, by using a sub-6 GHz link dedicated to the control plane, the aerial cell coordinates with the ground backhaul endpoint, removing the need for a blind scan that would inherently increase the link establishment latency. We prototyped mmBAC mounting a 60 GHz mmWave radio on a UAV, which continuously relocates to emulate different user traffic demands. Our results show that the proposed beam management scheme reduces the average latency of the mmWave link establishment by 66% with respect to a state-of-the-art iterative scan, leading to up to a 10× spectral efficiency gain in highly mobile scenarios.

The remainder of this paper is organized as follows. In Section 2, we propose our location-aided beam management scheme. The mmBAC prototype is described in Section 3, while experimental results are discussed in Section 4. In Section 5, we review the existing literature approaches on mobile cells and mmWave beam management schemes. Finally, Section 6 concludes our work.

## 2 LOCATION-AIDED BEAM MANAGEMENT

Beam management solutions proposed for wireless cellular networks such as 3GPP NR [1] usually envision an exhaustive sequential scan of the available beam directions, searching for the optimal transmitter-receiver beam pair [9]. During this procedure, the transmitter sends known pilot symbols that are used at the receiver to evaluate channel quality metrics (e.g., Signal to Noise Ratio (SNR)) for each beam pair.

Other possible and more advanced solutions are based on a faster multi-tier scan. In this case, a small subset $S$ of all the available beam pairs $D_{tx} \times D_{rx}$ (with $D_i$ the directions available at endpoint $i$) is tested during a first initial phase, where each of these beam pairs $\mathbf{b} = [b_{tx}, b_{rx}]$ is ranked by its measured SNR $\Gamma_{\mathbf{b}}$. The best ranked beam pair $\tilde{\mathbf{b}} = \arg\max_{\mathbf{b} \in S}(\Gamma_{\mathbf{b}})$ is then used as a starting point for a more refined test involving $(2N+1)^2 - 1$ beam pairs around $\tilde{\mathbf{b}}$, with $N$ a tunable parameter.

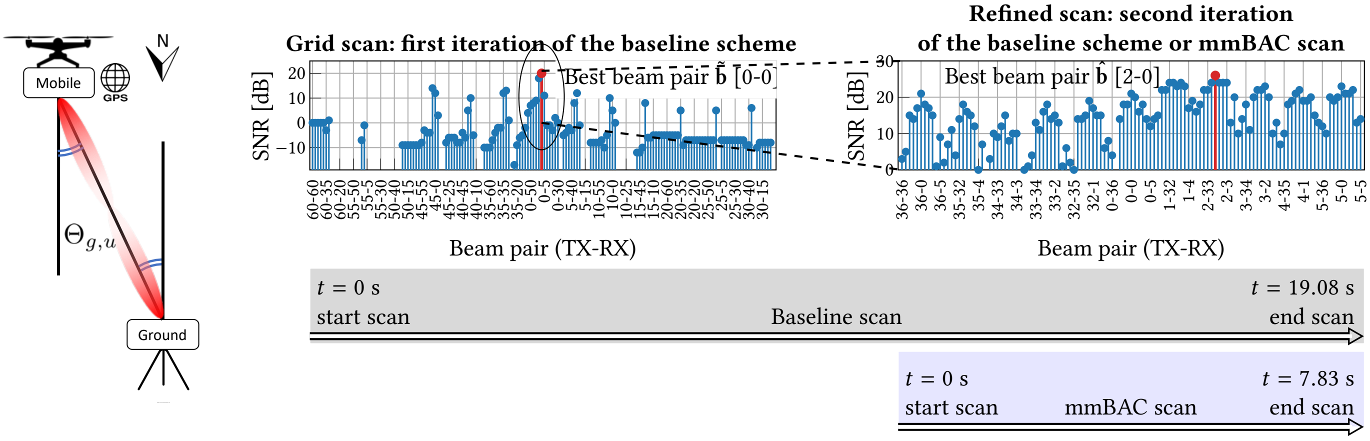
These schemes, however, lead to very high initial access delays and do not scale well to UAV-based aerial cell deployments. In such scenarios, in fact, beam management is challenged by faster and more erratic mobility than in traditional cellular networks, and the initial link establishment latency may prevent users from accessing the network for long periods of time. Other more refined techniques have been proposed for cellular networks, but they often require significant changes in the signal processing chain, and/or in the radio hardware implementation [6]. On the other hand, works such as [4, 5, 14] have shown the benefits of leveraging side information (e.g., the relative location of the two endpoints of the link) for beam tracking, toward a faster, more reliable beam management for mobile cellular networks.

In this work we (i) present a location-aided beam tracking algorithm by exploiting the GPS coordinates of a mobile cell, and (ii) experimentally evaluate the benefits of employing side information for beam management of UAV-based aerial cells with mmWave wireless backhaul.

**Aerial cellular networks.** The mmBAC link establishment procedure starts when the UAV reaches a target location to supply service to mobile users. In order to do so, it needs to quickly establish a high-data-rate backhaul link using a 60 GHz mmWave connection with the ground radio. Given the relative locations of the ground radio $(x_g, y_g)$ and of the UAV $(x_u, y_u)$, mmBAC computes the angle between the radio on the UAV and the one on the ground, relative to a North-South axis (Fig. 2a) as follows :

$$\Theta_{g,u} = \tan^{-1}\left(\frac{x_g - x_u}{y_g - y_u}\right). \tag{1}$$

We consider the antenna arrays of the UAV facing North, and those of the ground station facing South. This can be



**(a) Geometry.**

**(b) Example of beam scan patterns with baseline and mmBAC schemes.**

**Figure 2: mmBAC and baseline scan examples.**

generalized by adding an offset to $\Theta_{g,u}$ and extended to a scenario with multiple ground radios covering different sectors. mmBAC maps $\Theta_{g,u}$ to a beam index $b_{g,u}$, and defines a set of directions to be scanned at the two endpoints of the mmWave link as $D_{g,u} = \{b_{g,u} - N, \ldots, b_{g,u}, \ldots, b_{g,u} + N\}$. Considering that the computed angle $\Theta_{g,u}$ might not offer enough precision to identify the strongest beam path, the scan width $N$ can be tuned based on the GPS localization inaccuracy and the flying stability of the UAV.

This beam tracking logic is implemented at the UAV, which coordinates with the ground station about the set of beams to scan by leveraging multi-connectivity (i.e., through a sub-6 GHz control link). In this way, the ground station transmits over the beams in $D_{g,u}$ known pilot symbols which are, then, used at the UAV for channel quality evaluation as in 3GPP NR. The radio at the UAV side measures the channel quality (e.g., SNR) for every beam combination and selects the best beam pair to use. Specifically, given the set of beam pairs $D_{g,u} \times D_{g,u}$ and the monitored SNR $\Gamma_{\mathbf{b}}$, $\mathbf{b} \in D_{g,u}$, mmBAC selects as the optimal beam pair

$$\hat{\mathbf{b}} = \underset{\mathbf{b} \in D_{g,u} \times D_{g,u}}{\arg\max} \; \Gamma_{\mathbf{b}} \qquad (2)$$

Data transmission on the backhaul link follows the link establishment phase. The experimental evaluation of this paper focuses on the latter.

By employing relative positioning information to find an initial master beam pair, the proposed algorithm significantly reduces the initial scanning overhead towards a more efficient and lightweight beam management. A qualitative example of the difference between a state-of-the-art multi-tier blind scanning procedure (which we consider as baseline) and mmBAC is shown in Figure 2b. The multi-tier blind scheme starts with an initial fast scan, measuring the SNR of one out of every 25 beam pairs at regular angular intervals and identifies a master beam pair, which is used in a second phase as the starting point for a refined search. The left part of Figure 2b reports the results in terms of SNR and beam pairs for the initial scan, which identifies $\tilde{\mathbf{b}} = [0, 0]$ as the master beam pair. Then, as shown in the right part of Figure 2b, a second, more refined scan is performed around $\tilde{\mathbf{b}} = [0, 0]$ ($N = 5$), which terminates with the final selection of the best beam pair being $\hat{\mathbf{b}} = [2, 0]$. On the other hand, mmBAC avoids the initial time-demanding search by identifying at a glance the master beam pair, thanks to the knowledge of the approximate relative locations of the two mmWave link endpoints. This translates into a faster best beam pair search which is highlighted at the bottom of Fig. 2b.

## 3 mmBAC PROTOTYPE

We prototyped mmBAC on a DJI Matrice 600 (M600) Pro UAV [20] mounting a 60 GHz mmWave Facebook Terragraph radio [8] and an Intel NUC 7i7DNKE Mini PC. The mmBAC aerial mmWave endlink prototype is shown in Figure 3.

The DJI M600 Pro is a professional 6-motor UAV built for industrial applications. Its unfolded dimensions are 1.67 × 1.52 × 0.73 m including propellers, arms and landing gear, it weighs 9.5 kg (including batteries) and can reach a maximum speed of 18 m/s. This UAV model supports six 4500 mAh TB47S batteries that guarantee 16 minutes of hovering time at its full payload capacity of 6 kg. The DJI M600 Pro houses three Inertial Measurement Units (IMUs) sensors, employing a combination of accelerometer, gyroscope, and magnetometer; and three Global Navigation Satellite Systems (GNSS) units allowing centimeter scale localization precision. Both sensors and motors interface with the A3 Pro DJI flight controller that guarantees a stable and precise UAV navigation. The A3 unit exposes an API to an Onboard SDK that enables drone control by uploading flying missions with specific GPS waypoints, as well as the monitoring of telemetry readings such as the drone altitude and its GPS location.

**Figure 3: mmBAC prototype: hardware and components diagram.**

The mmBAC code runs on the Intel NUC Mini PC mounted on the M600 Pro. The Intel NUC is a commercial Mini PC, whose limited dimensions (101.60 × 101.60 × 25.69 mm), light weight (0.61 kg), and good computational capabilities (Intel Core i7 processor with 32 GB RAM) make it particularly suitable to be carried on board. The Intel NUC is powered by the UAV batteries through a DC-DC step-up power supply module and interfaces the DJI A3 flight controller through a JTAG-USB cable and the 60 GHz radio through a 1 Gbit/s Ethernet cable. The compute board runs Ubuntu 16.04 LTS and executes the Python 3.7 implementation of the mmBAC algorithm which (i) interacts with the DJI APIs through the Onboard SDK to read the UAV location, and (ii) performs the location-aided scanning procedure described in Section 2.

The mmWave transceiver carried by the UAV is a Facebook Terragraph mmWave radio. This radio is optimized for working in the 60 GHz frequency band and is equipped with TX and RX arrays of 36 × 8 antenna elements each. Each array covers an angular space of 90° with a total of 64 beam directions. Specifically, the beams from 0 to 31 and from 32 to 63 cover the angular spaces (0°, +45°) and (0°, −45°), respectively. Each beam is as fine as 2.8° and the radio has an EIRP of 45 dBm. A second Terragraph mmWave radio is located on an adjustable tripod placed on the ground. The UAV-mounted and the ground radios communicate through a mmWave aerial link. We employed a Dell Latitude 3550 laptop with Ubuntu 16.04 LTS to drive the ground radio through a 1 Gbit/s Ethernet interface. The two controllers exchange target beam information over an out-of-band Wi-Fi channel. The mmWave radios were provided with a limited closed-source firmware (i.e., they can only be used for channel sounding) and could not be used for data transmission, which we consider outside the scope of this work. Moreover, at the current state of the firmware, the time scale at which the Facebook Terragraph radios perform channel sounding (approximately 70 ms per beam pair) is not comparable to that of commercial solutions [1]. Thus, the duration of the beam search procedures reported in Section 4 is longer than that of a commercial deployment.

## 4 EXPERIMENTAL EVALUATION

**Experimental Setup.** We deployed one mmWave radio as fixed ground transmitter and let the UAV-mounted mmWave receiver operate in full line-of-sight conditions typical of aerial links. We operated the UAV-mounted mmWave receiver following a predefined flying mission with intermediate stopping points to mimic an aerial cell following time-varying user traffic demands. We performed two sets of experiments envisioning two different aerial trajectories, both starting from an initial waypoint located 5 m away from the ground station, mounted on an adjustable tripod. We set the tripod and the UAV hovering height to 3 m, the flying speed to 2 m/s, the hovering duration to 30 s over each waypoint, and operated in line-of-sight conditions. For each mission, we evaluated our *location-aided beam tracking algorithm* against the *fast multi-tier beam scan algorithm* described in Section 2 and accounted for three different metrics: (i) the total beam searching time $\Delta_s$ to find the best beam pair; (ii) the SNR $\Gamma_{\hat{b}}$ corresponding to the selected beam pair; and (iii) the spectral efficiency $S$ of the mmWave backhaul link. The latter is computed starting from the Shannon capacity equation and accounting for the overhead of the link establishment. Given the relocation interval $\Delta_h$, the spectral efficiency is

$$S = \frac{\Delta_h - \Delta_s}{\Delta_h} \log_2 \left(1 + \Gamma_{\hat{b}}\right) . \tag{3}$$

**Line mission.** The first set of experiments concerns a UAV-based aerial cell relocating across 5 waypoints forming a line trajectory and stopping for 30 s at every waypoint throughout the mission. The nomadic cell trajectory is shown in the top part of Figure 4. Upon each cell relocation, the mobile cell performs a beam tracking procedure following the two techniques described above. The average performance in terms of SNR and beam tracking overhead for the two algorithms are shown in Figure 4. While the multi-tier iterative beam scanning algorithm has an average beam search overhead of 64.1%, the proposed location-aided beam tracking algorithm operates with an average 23.6% overhead, achieving a 72.6% higher link efficiency with a minimal SNR drop.

**Trapezoid mission.** In the second set of experiments, the UAV-based aerial cell relocates across 6 waypoints drawing a trapezoid trajectory (top part of Figure 5) covering an

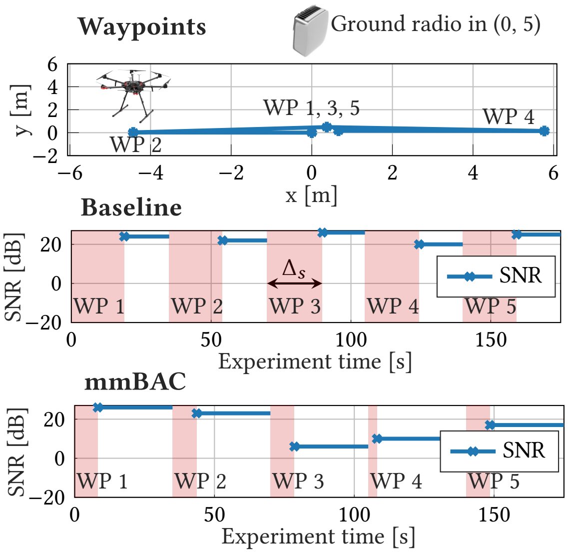


**Figure 4: Line experiment. The red boxes represent the overhead to find the best beam pair for different schemes.**

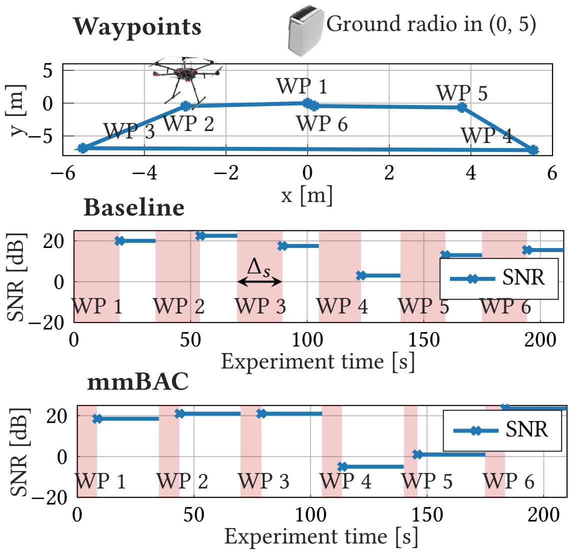


**Figure 5: Trapezoid experiment. The red boxes represent the overhead to find the best beam pair for different schemes.**

approximate area of 58 $m^2$. The cell stops for 30 s at each waypoint, as for the line experiment. The performance of the baseline and the location-aided beam tracking algorithm is shown in Figure 5. As for the previous case, the proposed algorithm ensures higher link spectral efficiency by reducing the beam search overhead by 2.34 times (8.1 s vs. 19.01 s) while maintaining approximately the same signal quality.

**Takeaways.** The beam management experiments conducted on mmBAC highlight the importance of a fast, lightweight beam tracking solution. The proposed GPS-aided beam tracking algorithm ensures a 66% overhead reduction in link establishment compared to a state-of-the-art blind beam management scheme, while guaranteeing minimal link quality loss, which results from the strong secondary paths at the minimal height of 3 m. Reducing mmWave communication link establishment overhead leads to a higher spectral efficiency which is particularly important in mobile mmWave networks. Figure 6 shows the spectral efficiency $S$ as a function of the mobile cell relocation interval $\Delta_h$. Smaller values of $\Delta_h$ represent a more dynamic network environment, where service demands rapidly change over time and call for frequent cell relocations, while large values of $\Delta_h$ represent a slowly varying service demand scenario characterized by longer relocation intervals. Figure 6 highlights how location-aided beam management schemes lead to significant performance gains for highly dynamic network scenarios. For instance, the proposed algorithm outperforms the baseline by 10.7 times for $\Delta_h = 20$ s and by 1.65 times for $\Delta_h = 30$ s. This article presents some real-world experimental results of dynamic beam-tracking algorithms, and envisions possible gains coming from side-information-aided beam management for future continuous-motion mmWave aerial links. A video demonstration of mmBAC can be found at [18].

## 5 RELATED WORK

During the last decade there has been great research interest in radio fronthaul and service provisioning solutions for UAV-based cellular networks [19, 26], with also mmWave links as a wireless backhaul. Extensive reviews of beam management and initial access solutions for mmWave links can be found in [9, 15]. In this domain, the usage of context information on the reciprocal position of the two endpoints of a mmWave link has been investigated in [2, 4, 5, 14, 24], also with analyses on the precision of the beam identification according to the error in the available context information. However, the proposed solutions are limited to traditional cellular network scenarios (i.e., fixed base station and users with low mobility), and have not been implemented in an experimental prototype as in this work.

The combined usage of mmWaves and UAVs has been investigated in a number of recent papers. Xiao et al. review the

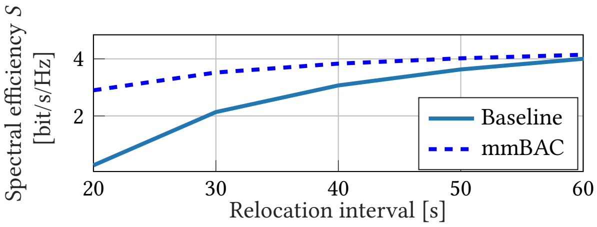


**Figure 6: Backhaul link spectral efficiency $S$ as a function of the relocation interval.**

main opportunities and challenges associated with mmWave-based UAV communications [25]. Cuvelier and Heath evaluate the capacity of the mmWave link in a UAV scenario [7]. Mezzavilla et al. discuss applications of mmWave links in UAV-enabled public safety scenarios [17], while Zhao et al. evaluate the performance of integrated flight control and channel tracking mechanism for mmWave aerial links [27]. The above-mentioned work presents simulation results, but an established channel model for mmWave aerial links has not been identified yet. Some preliminary results in this area have been presented by Khawaja et al. in [12], where a combination of an experimental setup with a UAV-mounted channel sounder and ray tracing software is used to characterize 28 GHz and 60 GHz spectrum bands. Results show that the behavior of the fading follows a two-ray model. This model is then extended by the same authors to account for the spatial and temporal evolution of the fading at 28 GHz, through ray tracing simulations [13]. The accurate modeling of the UAV mobility is also fundamental for a correct evaluation of the capacity of the mmWave aerial link, as discussed in [10]. Finally, [3] measures the performance of IEEE 802.11ad devices on a UAV.

## 6 CONCLUSIONS

In this work, we reviewed different mmWave backhaul link management schemes for UAV-based aerial cells and proposed mmBAC, a GPS-aided beam management algorithm for mmWave aerial links. We first prototyped a mmWave aerial link, employing a DJI M600 Pro UAV and Facebook Terragraph mmWave radios, and then evaluated mmBAC against a state-of-the-art iterative beam scanning algorithm over two sets of flying experiments, achieving an average 66% link establishment overhead reduction and up to 10× higher spectral efficiency for highly mobile scenarios. Future work will focus on side-information-aided beam management schemes for mmWave aerial links in non-line-of-sight conditions employing 3D-maps of the surroundings and aerial cell relocation strategies.

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