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Movable antennas for THz multicasting: grating-lobe analysis and position optimization

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Recently, movable antenna (MA) technology has emerged as a promising solution for enhancing data rates in next-generation wireless communication systems [1–3], due to its capability to reconfigure wireless channels via antenna movement. Different from the antenna selection (AS) technique that selects a given number of antennas from a set of fixed-position antennas (FPAs), MA technology enables each antenna to continuously adjust its position within a specified region, which offers more spatial degrees of freedom (DoFs). In this study, we focus on the application of MAs in Terahertz (THz) communications. THz communication can offer vast bandwidth and ultra high data rate for future wireless systems [4]. However, it also drastically increases the hardware cost and energy consumption due to the need for an extremely large number of antennas to compensate for the severe path loss over the THz frequency band. An alternative approach is the use of sparse arrays, which tackles the above issue by reducing the number of antennas while maintaining the overall antenna aperture. Although sparse arrays typically suffer from undesired grating lobes, these lobes can be advantageous for THz multicasting by directing equally strong power to users in different directions simultaneously. However, due to their fixed antenna positions, sparse arrays offer limited flexibility in controlling grating lobes, which may result in suboptimal multicast performance, especially for arbitrarily located users.

Motivated by the above, we propose in this study an MA-enhanced THz multicast system, where a multi-MA BS sends a common message to multiple users, each equipped with a single FPA, simultaneously. We aim to jointly optimize the BS's transmit beamforming and the MAs' positions to maximize the minimum received SNR among all users, which turns out to be a non-convex optimization problem that is difficult to solve optimally. To drive essential insights, we first conduct theoretical analyses and reveal that under certain conditions, the maximum beamforming gain can be achieved for all users at the same time, leading to more customized grating lobes compared to conventional sparse arrays with FPAs. Next, we propose an alternating optimization (AO) algorithm to solve the MA position optimization problem. Numerical results corroborate our analytical results and demonstrate that MAs can significantly reduce the number of antennas required to achieve certain performance compared to the conventional FPAs.

System model and problem formulation. As shown in Figure 1, we consider an MA-enhanced multicast system that operates at the THz frequency band, where a BS sends a common message to $K \geqslant 1$ users each equipped with a single FPA at the same time[1)]. Let $\mathcal{K} = \{1, 2, \ldots, K\}$ denote the set of all users. We consider fully digital beamforming at the BS, which is equipped with N MAs each connected to a radio-frequency (RF) chain[2)]. The positions of these N MAs can be flexibly adjusted within a two-dimensional (2D) transmit region, which is assumed to be a square of size $A \times A$ and denoted as $\mathcal{C}_t$. Without loss of generality, we assume that $\mathcal{C}_t$ is parallel to the x-y plane, as shown in Figure 1. Denote by $\boldsymbol{t}_n = [x_n, y_n]^{\mathrm{T}}$, $n \in \mathcal{N} \triangleq \{1, 2, \ldots, N\}$, the coordinate of the n-th MA, given the reference point $\boldsymbol{t}_0 = [0, 0]^{\mathrm{T}}$. Let $\boldsymbol{T} = [\boldsymbol{t}_1, \boldsymbol{t}_2, \ldots, \boldsymbol{t}_N] \in \mathbb{R}^{N\times 2}$ denote the collection of the coordinates of the N MAs and $\boldsymbol{h}_k(\boldsymbol{T}) \in \mathbb{C}^{N\times 1}$, $k \in \mathcal{K}$, denote the channel from the BS to user k.

Due to the considerably limited scattering and reflection over the THz band, we assume line-of-sight (LoS) propagation over all BS-user channels. Let θ_k and ϕ_k denote the elevation and azimuth angles of departure (AoD) from the BS to user k, respectively. Then, the BS-user k channel is given by

$$\boldsymbol{h}_k(\boldsymbol{T}) = \sqrt{\beta d_k^{-2}} \left[\mathrm{e}^{\mathrm{j}\rho_k(\boldsymbol{t}_1)}, \mathrm{e}^{\mathrm{j}\rho_k(\boldsymbol{t}_2)}, \ldots, \mathrm{e}^{\mathrm{j}\rho_k(\boldsymbol{t}_N)} \right], \quad (1)$$

where d_k denotes the distance between the BS and user k

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1) Considering the lower computational and control capability of users compared to the BS, we only consider BS-side MAs in this study.

2) Note that due to the single-stream multicast transmisison, the number of users, K, can be larger than that of the antennas or RF chains, N.

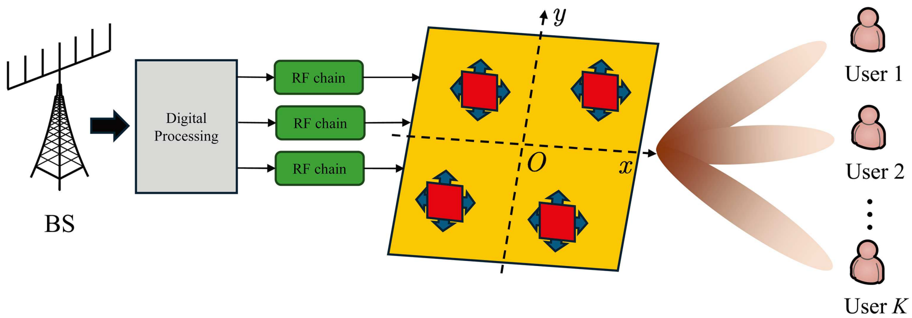

Figure 1 (Color online) MA-enhanced THz multicast system.

and $\rho_k(\boldsymbol{t}_n) = \frac{2\pi}{\lambda}(x_n \sin\theta_k \cos\phi_k + y_n \cos\theta_k)$ denotes the phase difference between the position of the n-th MA and $\boldsymbol{t}_0$; β is the path loss at the reference distance of 1 m; and λ is the wavelength[3)].

Let $\boldsymbol{w} \in \mathbb{C}^{N\times 1}$ denote the transmit beamforming vector of the BS, with $||\boldsymbol{w}||^2 \leqslant P_{\max}$ and $P_{\max}$ being its maximum transmit power. Then, the received signal-to-noise ratio (SNR) at user k is expressed as

$$\gamma_k(\boldsymbol{T}) = \frac{|\boldsymbol{h}_k^H(\boldsymbol{T})\boldsymbol{w}|^2}{\sigma_k^2}, \tag{2}$$

where σ_k^2 denotes the received noise power at user k[4)].

We aim to maximize the minimum SNR among all users by jointly optimizing the BS's transmit beamforming $\boldsymbol{w}$ and the antenna positions vector (APV) $\boldsymbol{T}$. Hence, the optimization problem can be formulated as

$$\text{(P1)} \quad \max_{\boldsymbol{w},\boldsymbol{T}} \min_{k\in\mathcal{K}} \quad \gamma_k(\boldsymbol{T})$$

$$\text{s.t.} \quad \boldsymbol{t}_n \in \mathcal{C}_t, n \in \mathcal{N}, \tag{3a}$$

$$||\boldsymbol{t}_i - \boldsymbol{t}_j||_2 \geqslant D_{\min}, \forall i,j \in \mathcal{N}, i \neq j, \tag{3b}$$

$$||\boldsymbol{w}||_2^2 \leqslant P_{\max}, \tag{3c}$$

where $D_{\min}$ denotes the minimum spacing between any two MAs to avoid mutual coupling. Here, we assume that all required channel state information (or all users' locations) is available by applying the existing channel estimation techniques dedicated to MAs. Furthermore, we consider a quasi-static scenario where all MAs can be moved to their optimized positions within the channel coherence time. To minimize movement delay, electronically driven schemes can be employed to achieve equivalent antenna movement [5], which also prevents potential inter-antenna collisions associated with physical movement.

However, (P1) is difficult to solve optimally due to the intricate coupling between the transmit beamforming $\boldsymbol{w}$ and the antenna positions $\boldsymbol{T}$. In addition, the constraints in (3b) are both non-convex. In the next section, we first conduct theoretical analyses to gain essential insights.

Grating-lobe analysis. In this section, theoretical analyses are presented to show the superiority of MAs to FPAs in enhancing the multicast performance by manipulating the positions and levels of grating lobes. Please check Appendix A for more details.

Proposed solution to (P1). To solve (P1) in the general case with a finite transmit region and an arbitrary number of MAs, we propose an AO algorithm to decompose (P1) into two subproblems and solve them alternately (See Appendix B for details.)

Numerical results. The numerical results are provided in Appendix C.

Conclusion. In this study, we investigated the joint transmit beamforming and antenna position optimization for an MA-enhanced THz multicast system. Our theoretical analyses unveiled the capability of MAs for controlling grating lobes, such that the maximum beamforming gain can be achieved at all users. An AO algorithm was proposed to solve the antenna position optimization problem, which is shown to be able to yield a high-quality sub-optimal solution. Our numerical results demonstrate that MAs play different roles depending on the size of the transmit region for THz multicasting. Additionally, it was shown that MAs can significantly reduce the number of antennas required compared to conventional FPAs, thereby opening up new possibilities for THz communications.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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3) For ease of exposition, we assume in this study that the molecular absorption over the THz band is negligible (e.g., in an indoor environment), while the results are also applicable to the scenario with molecular absorption by subsuming its effects into the path losses.

4) Note that in the LoS-dominated channel model considered, employing MAs at the user side may not provide any performance gain, as the channel power gain remains uniform within the receive region of each user.