

Special Topic: Terahertz Communications for 6G and Beyond: How Far Are We?

Frequency-switching array based null-steering beamforming for physical-layer security in terahertz bands

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The terahertz (THz) band is envisioned as a key technique to meet the demand for terabit-per-second (Tbit/s) data rates in future sixth-generation (6G) mobile communication systems [1]. Although antenna arrays operating at (sub-)THz band can integrate a large number of elements to form highly directional narrow beams for preventing information leakage by using the low-complexity maximum ratio transmission (MRT) beamformer, confidential eavesdropping becomes inevitable when the eavesdropper (Eve) is located close to the legitimate user (Bob). Therefore, designing null-enabled physical-layer security (PLS) is a critical issue for future (sub-)THz communications.

In the following, we first present the channel and signal models, and the limitations of movable antennas (MAs) and frequency diverse arrays (FDAs) in achieving null steering are provided. Then, we show that the proposed frequency-switching array (FSA) is capable of flexibly generating null steering beams over the entire spatial domain.

Channel and signal models. In this study, we consider a PLS system, where Alice transmits confidential information to Bob in the presence of one Eve to intercept the confidential information. Specifically, Alice is assumed to be equipped with the proposed FSA comprising N antennas, where the carrier frequency can be flexibly adjusted and small frequency increments can be imposed on each antenna. Mathematically, the frequency at the n -th antenna is $f_n = f_c + \Delta f_n$ ($n \in \mathcal{N} \triangleq \{1, 2, \dots, N\}$), where f_c represents the adjustable carrier frequency and $0 \leq \Delta f_n \ll f_0$ denotes the small frequency increment imposed on the n -th antenna. To reduce hardware and computational complexity, we consider a well-adopted uniform frequency offsets across the antennas, i.e., $\Delta f_n = n\Delta f$. Moreover, accounting for the hardware constraint, the variable carrier frequency should satisfy $f_0 \leq f_c \leq f_H$, where f_0 and f_H denote the minimal and maximal value of the carrier frequency.

For the channel model, we assume that Bob and Eve are located at (θ_B, r_B) and (θ_E, r_E) , respectively. As such, the far-field channel from Alice to Bob is given by

$$\mathbf{h}_B^H(f_c, \Delta f, t) = \sqrt{N\epsilon_c\beta_B}\mathbf{a}^H(f_c, \Delta f, \theta_B, r_B), \quad (1)$$

where $\beta_B = \frac{\sqrt{\beta_0}}{r_B} e^{j\frac{2\pi f_c r_0}{c}}$ denotes the path gain in terms of the basic frequency f_0 with β_0 representing the reference channel power gain at a distance of 1 m. In addition, $\epsilon_c = \frac{f_0}{f_c}$ is the attenuation factor suffered by the adjusted carrier frequency f_c . Moreover, $\mathbf{a}^H(f_c, \Delta f, \theta_B, r_B)$ represents the array response vector, which can be modelled as follows [2]:

$$[\mathbf{a}(f_c, \Delta f, \theta, r)]_n = 1/\sqrt{N} e^{j2\pi\left(\frac{f_c \delta_n d_0 \sin \theta}{c} - \frac{n\Delta f}{c} r + n\Delta f t\right)}, \quad (2)$$

where $\delta_n = \frac{2n-N-1}{2}$, $\forall n \in \mathcal{N}$ denotes the coordinate of the n -th antenna. Additionally, the channel from Alice to Eve ($\mathbf{h}_E^H(f_c, \Delta f, t)$) can be modelled similarly to that in (1).

Based on the above, the received signal at Bob can be modelled by $y_B(t) = \sqrt{P_t}\mathbf{h}_B^H(f_c, \Delta f, t)\mathbf{w}_B(t)x_B + n_B$, where x_B denotes the signal transmitted from the Alice to Bob satisfying Gaussian distribution, i.e., $x_B \sim \mathcal{CN}(0, 1)$. Herein, we normalize the signal power. In addition, $n_B \sim \mathcal{CN}(0, \sigma_B^2)$ is the additive white Gaussian noise (AWGN) with power σ_B^2 . In addition, $\mathbf{w}_B(t) \in \mathbb{C}^{N \times 1}$ is the beamformer at the Alice and P_t is the transmit power at the Alice. Then, the achievable rate at Bob can be obtained as $R_B(t) = \log_2(1 + P_t|\mathbf{h}_B^H(f_c, \Delta f, t)\mathbf{w}_B(t)|^2/\sigma_B^2)$. Similarly, the eavesdropping rate of Eve for wiretapping x is given by $R_E(t) = \log_2(1 + P_t|\mathbf{h}_E^H(f_c, \Delta f, t)\mathbf{w}_B(t)|^2/\sigma_E^2)$, where σ_E^2 denotes the received noise power at Eve.

In this study, we design an efficient beam pattern with FSA to achieve two goals simultaneously: (1) maximizing the received signal power at Bob based on the MRT criterion, and (2) enabling null-steering beamforming over Eve.

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As such, the PLS is guaranteed at Bob and the achievable rate at Bob is obtained as $R_B = \log_2(1 + \frac{N|\beta_B|^2 f_0^2}{\sigma_B^2 f_c^2})$, which is monotonically decreasing with f_c . In the following, to shed useful insights, we show how to achieve null-steering beamforming with minimal carrier frequency with FSA, while the detailed optimization method for the secrecy rate of Bob without imposing strict null-steering beamforming is provided in the Supporting information. Next, we first analyze the limitations of MAs and FDAs and then show that with sufficiently large frequency offsets or tunable carrier frequency ranges, the proposed FSA can achieve null steering over Eve, regardless of its location.

Limitations of MAs and FDAs. For MAs, the antenna locations $\delta_n d_0$ can be adjusted, which can flexibly generate null-steering beams towards Eve in the angular domain if the moving regions are sufficiently large [3]. However, when Eve and Bob are located at the same angle, MAs cannot achieve null steering over Eve, since the channel between Eve and Bob is highly correlated.

Alternatively, FDAs can handle this issue by selecting specific frequency increment Δf . Specifically, the array response vector for the FDA is given by [2]

$$[\mathbf{a}(\Delta f, \theta, r)]_n = \frac{1}{\sqrt{N}} e^{j2\pi(\frac{\delta_n \sin \theta}{2} - \frac{n \Delta f}{c} r + n \Delta f t)}, \quad \forall n \in \mathcal{N}. \quad (3)$$

Lemma 1. Given a frequency increment Δf , the null-steering locations of the FDA satisfy

$$\Delta \theta = \frac{2k}{N} + \frac{2\Delta r \Delta f}{c}, \quad (4)$$

where $\Delta \theta = \theta - \theta_B$ and $\Delta r = r_B - r$. In addition, k should satisfy $k \in \{\mathbb{Z} \setminus \{0, \pm N, \pm 2N, \dots\}\}$.

Proof. Please refer to Appendix A.

Based on (4), it is observed that when Bob and Eve are located at the same angle (i.e., $\Delta \theta = 0$), we can set $\Delta f = \frac{c}{N \Delta r}$ to achieve null steering over Eve, where $\Delta r = |r_B - r_E|$. However, when Eve and Bob are located on a circle (i.e., $r_B = r_E$), we have $\Delta r = 0$. As such, Eq. (4) reduces to $\Delta \theta = \theta_E - \theta_B = \frac{2k}{N}$, for which null steering over Eve can only be achieved when the spatial angle difference between Eve and Bob is $\frac{2}{N}$. In other words, adjusting the frequency offset becomes ineffective for creating null steering toward Eve. To overcome this issue, we propose to utilize an FSA in the next section to flexibly achieve null steering over Eve.

Null steering using the proposed FSA. In this section, we show that, when the frequency offset or the tunable carrier frequency range is sufficiently large, the proposed FSA can achieve null steering toward Eve regardless of Eve's location.

Lemma 2. For the proposed FSA, the null-steering locations of $\mathbf{w}_B$ should satisfy

$$\frac{f_c}{f_0} \Delta \theta = \frac{2k}{N} + \frac{2\Delta r \Delta f}{c}. \quad (5)$$

Proof. The proof is similar to Lemma 1 and we omit it.

Lemma 3. Given any spatial locations of Bob and Eve, if the frequency offset Δf or maximum carrier frequency f_H is large enough, Eq. (5) always admits a solution with respect to f_c and Δf . In addition, the optimal solution to (P1) is

$$\begin{cases} f_c = f_0, \Delta f = \frac{c(\Delta \theta - \frac{2k}{N})}{2\Delta r}, & \text{if } \Delta r \neq 0, \\ f_c = \frac{2f_0}{N|\Delta \theta|}, \Delta f = 0, & \text{if } \Delta r = 0. \end{cases} \quad (6)$$

Proof. Please refer to Appendix B.

Based on Lemma 3, it is revealed that the proposed FSA can achieve null steering over Eve given any of the locations of Bob and Eve.

Remark 1. The movable FDA proposed in [4] faces several practical challenges, particularly in (sub-)THz bands. First, the mechanical control required for antenna movement in MAs incurs high hardware and energy costs and leads to increased device size [5]. Second, in ultra-high-speed (sub-)THz transmissions, M-FDAs are subject to more stringent response latency requirements, which further degrade the performance.

Numerical results. In this section, we plot the beam patterns of the proposed FSA under two special cases: (i) Bob and Eve share the same angle, and (ii) Bob and Eve are located at the same distance. The relevant parameters are provided in Appendix D. As shown in Figure 1, the proposed FSA can achieve null steering over Eve in both cases, thereby overcoming the limitations of FDAs and MAs.

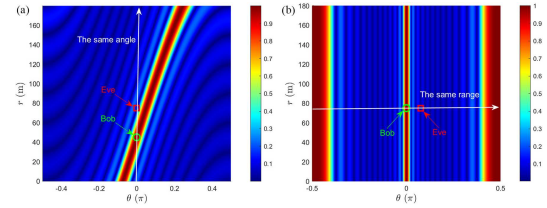


Figure 1 (Color online) Null steering achieved by the proposed FSA. (a) The same angle; (b) the same range.

Conclusion. In this study, we proposed an FSA to prevent information leakage in THz bands, which can flexibly adjust carrier frequency and impose a small frequency offset on antennas. We first analyzed the limitations of MAs and FDAs, that is, MAs fail to achieve null steering when Bob and Eve are located at the same angle, and FDAs are unable to create null-steering beams over Eve when Bob and Eve share the same range. Then, we obtained the null-steering locations of the FSA that, given any locations of Bob and Eve, FSAs can achieve null steering over Eve, which is verified via simulations.

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Supporting information Appendixes A–D. 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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