

EMF Compliance Boundary Assessment Based on Near-Field Power Density for Airy Beam Antennas

Shoki Enomoto and Kun Li

Advanced Wireless and Communication Research Center (AWCC)

The University of Electro-Communications

1-5-1 Chofugaoka, Chofu-shi, Tokyo, 182-8585, Japan

Email: enomoto@awcc.uec.ac.jp, li.kun@awcc.uec.ac.jp

Abstract—This study investigates the electromagnetic field (EMF) compliance boundary assessment for self-accelerating Airy beams generated by a 128-element linear array at 28 GHz. Airy beams self-accelerate along a caustic trajectory in the near-field region and are promising for obstacle-avoidance communications. Across six beam configurations designed for obstacle avoidance, we compare four compliance boundary methods: far-field circles based on (1) the uniform-excitation and (2) the Airy-excitation maximum gain, (3) a direction-dependent far-field method using $G(\theta)$, and (4) direct near-field power density computation. Method (1) is conservative but overestimates the compliance distance by a factor of about 3.3, while methods (2) and (3) are non-conservative, producing overflow rates of 15–49%. We then propose a near-field envelope-based compliance boundary that accurately captures the spatial power density structure of the Airy beam.

Index Terms—Airy beam, EMF compliance boundary, near-field power density, antenna array, millimeter wave.

I. INTRODUCTION

The deployment of millimeter-wave 5G, particularly in the 28 GHz Frequency Range 2 (FR2), has driven large-scale antenna arrays and beamforming [1], [2], where abrupt link degradation from human blockage is a serious challenge [3]. As arrays grow and beam steering advances, accurate compliance boundary assessment for electromagnetic field (EMF) exposure at millimeter-wave and terahertz bands has become important.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) specifies an incident power density of $S_{MPE} = 10 \text{ W/m}^2$ as the maximum permissible exposure for the general public above 2 GHz [4]. The boundary enclosing the region where this reference level is exceeded is called the compliance boundary, which has conventionally been determined from the far-field formula $S = P_{in}G/(4\pi R^2)$ [5], [6], [7]. In the millimeter-wave and terahertz bands, however, the large electrical aperture pushes the far-field distance far beyond the practical service range, and thus the users are typically located in the near-field region. Beam design for near-field communication at these frequency bands has therefore attracted attention for blockage-robust links [8], [9], where the self-accelerating beams provide an additional degree of freedom by curving the propagation path around obstacles. The near-field power density for 5G base stations has been studied in cases that consider conventional beamforming schemes designed for far-field communications [10], [11].

First proposed in quantum mechanics [12] and demonstrated in optics [13], the Airy beam features self-acceleration along a parabolic trajectory, quasi-diffraction-free propagation, and self-healing. Chremmos *et al.* [14] showed that accelerating beams can be generated in the Fresnel region of antenna arrays; Yang *et al.* realized this with a patch array at 5.8 GHz [15] and extended its range using directive elements [16], and an obstacle-avoidance link was recently demonstrated at millimeter-wave and terahertz bands [17]. Despite this promise for blockage mitigation, the compliance boundary of such beams has not been investigated, and since their trajectory lies in the near-field region, the conventional far-field formula is invalid.

In this study, we compare four compliance boundary assessment methods for a 128-element linear array at 28 GHz, quantitatively demonstrate the limitations of the far-field methods, and propose a method combining direct near-field power density computation with the beamforming envelope concept.

II. ANALYTICAL MODEL

A. Airy Beam Antenna Array

We consider an $N = 128$ element linear array with element spacing $d (= \lambda/2)$ at 28 GHz (wavelength $\lambda = 10.71 \text{ mm}$). The position of the n -th element is given by $x_n = (n - (N + 1)/2) \cdot d$. The (complex) excitation weight w_n of each element is set based on a truncated Airy function [14]:

$$w_n = |Ai(s_n)| \exp(\alpha s_n) \exp(j\varphi_n) \exp(-jkx_n \sin \theta_{\text{tilt}}). \quad (1)$$

Here, $s_n = x_n/x_0$ is the normalized coordinate, x_0 is the scale parameter controlling the bending strength, $\alpha = 0.02$ is the truncation coefficient, φ_n is the phase term (π when $Ai(s_n) < 0$, else 0), and θ_{tilt} is the beam tilt angle (a design variable). Power normalization $\sum |w_n|^2 = 1$ is applied, and the element gain is $G_{\text{elem}} = 6 \text{ dBi}$, typical of a microstrip patch element.

The generated beam self-accelerates along a caustic trajectory [14]:

$$x_c(z) = \frac{\kappa^3 z^2}{4k^2}, \quad (2)$$

$$\kappa = \frac{1}{x_0}, \quad (3)$$

where $k = 2\pi/\lambda$ is the wavenumber and a smaller x_0 gives larger caustic curvature. In a finite array, however, truncation of higher-order sidelobes reduces the deflection below the theoretical value of (2), and thus we use an effective caustic obtained by numerically tracking the main-lobe peak.

B. Power Density Computation

The electric field at an observation point (x, z) is computed as the superposition of spherical waves from each element:

$$E(x, z) = \sum_{n=1}^N w_n f(\theta_n) \frac{\exp(-jkR_n)}{R_n}, \quad (4)$$

$$R_n = \sqrt{(x - x_n)^2 + z^2}. \quad (5)$$

Here, R_n is the distance from the n -th element to the observation point, $f(\theta_n) = (\cos \theta_n)^{q/2}$ is the electric-field pattern of each element, and $\cos \theta_n = z/R_n$ is the angle from broadside ($+z$). The exponent q is set to $q = 1$ so that the element directivity $D = 2(q+1)$ matches $G_{\text{elem}} = 6$ dBi, keeping the element model consistent between the far-field gain and the near-field computation. The incident power density is given by

$$S(x, z) = \frac{|E(x, z)|^2}{2\eta_0} \cdot P_{\text{in}} \cdot C_{\text{scale}}, \quad (6)$$

where $\eta_0 = 377\Omega$ is the free-space impedance and P_{in} is the total input power. The calibration coefficient C_{scale} is fixed by matching the point-source output for uniform excitation to the far-field formula $S = P_{\text{in}} \cdot G_{\text{max}}^{\text{uni}} / (4\pi z_{\text{cal}}^2)$ (with $G_{\text{max}}^{\text{uni}} = G_{\text{elem}} \cdot N$) at a far reference $z_{\text{cal}} = 1000$ m, which is chosen to be sufficiently larger than the far-field distance z_R so that the far-field formula is valid. Since P_{in} cancels, C_{scale} is power-independent, and (6) yields the exact absolute power density (W/m^2) for any w_n and input power.

C. Analytical Scenario

Fig. 1 and Table I show the analytical scenario and parameters, respectively. The array at the origin radiates toward $+z$. A cylindrical obstacle of radius $r_{\text{obs}} = 0.15$ m sits at $(0.50, 2.5)$ m, and the Rx is at $z_{\text{rx}} = 5.0$ m, $x_{\text{rx}} = 0.5$ – 1.0 m (six points, 0.1 m spacing). Exploiting self-acceleration, we design beams passing below the obstacle to each Rx. For the aperture $D = (N - 1)d \approx 680$ mm the far-field distance is $z_R = 2D^2/\lambda \approx 86.4$ m. Therefore, the region of interest (0 – 5 m) lies well within it; the compliance region ($z < 2.0$ m) is even inside the radiating near-field lower bound $0.62\sqrt{D^3/\lambda} \approx 3.4$ m, where the far-field formula does not apply.

Note that $S_{\text{MPE}} = 10 \text{ W}/\text{m}^2$ [4] is the reference level for whole-body time-averaged exposure above 2 GHz to prevent excessive temperature elevation of humans [18]; here, no spatial averaging is applied and the peak value at each point is compared, giving a conservative condition.

All evaluations are in the xz plane at $y = 0$, which, since the x -directed linear array has no y -directivity, is the worst-case (maximum power density) plane.

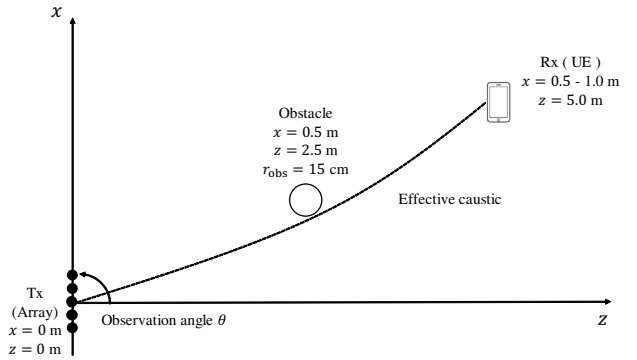


Fig. 1. Conceptual diagram of the analysis scenario. The Airy beam from the transmitting antenna (at the origin) reaches each Rx position while avoiding the obstacle from below.

TABLE I
ANALYTICAL PARAMETERS

Parameter	Value
Frequency f	28 GHz
Wavelength λ	10.71 mm
Number of elements N	128
Element spacing d	$\lambda/2$ (5.36 mm)
Aperture length D	680 mm (63.5 λ)
Far-field distance z_R	86.4 m
Input power P_{in}	10 W
Reference power density S_{MPE}	10 W/m ²
Element gain G_{elem}	6 dBi
Scale parameter x_0	2.0–2.2 λ (design variable)
Truncation coefficient α	0.02
Rx distance z_{rx}	5.0 m
Rx lateral position x_{rx}	0.5, 0.6, 0.7, 0.8, 0.9, 1.0 m
Obstacle position $(x_{\text{obs}}, z_{\text{obs}})$	(0.50, 2.5) m
Obstacle radius r_{obs}	0.15 m

D. Four Compliance Boundary Methods

We evaluate and compare the compliance boundary using the following four methods. The compliance boundary is defined as the contour enclosing the spatial region where the incident power density exceeds S_{MPE} ; the region outside this contour is considered safe from an EMF safety point of view.

1) *Method (1): Uniform-Excitation Far-Field Circle:* This is the most conservative method, using the uniform-excitation maximum gain $G_{\text{max}}^{\text{uni}} = G_{\text{elem}} \times N$ [5], and is independent of the beam design:

$$R_c^{\text{uni}} = \sqrt{\frac{P_{\text{in}} \cdot G_{\text{max}}^{\text{uni}}}{4\pi \cdot S_{\text{MPE}}}}. \quad (7)$$

2) *Method (2): Airy-Excitation Far-Field Circle:* This method uses the Airy-excitation maximum gain $G_{\text{max}}^{\text{airy}}$:

$$R_c^{\text{airy}} = \sqrt{\frac{P_{\text{in}} \cdot G_{\text{max}}^{\text{airy}}}{4\pi \cdot S_{\text{MPE}}}}. \quad (8)$$

Because the Airy amplitude distribution concentrates power on a portion of the array aperture, the effective aperture shrinks, which means that $G_{\text{max}}^{\text{airy}} < G_{\text{max}}^{\text{uni}}$. The compliance

distance decreases compared with method (1), but it is still evaluated as an isotropic circle.

3) *Method (3): Direction-Dependent Far Field Boundary* $R_c(\theta)$: This method uses the far-field gain pattern $G(\theta)$ [5]:

$$R_c(\theta) = \sqrt{\frac{P_{\text{in}} \cdot G(\theta)}{4\pi \cdot S_{\text{MPE}}}}. \quad (9)$$

Here, θ is the observation angle from the z -axis, $G(\theta) = G_{\text{elem}} |AF(\theta)|^2 / \sum |w_n|^2$, and $AF(\theta) = \sum_n w_n \exp(jkx_n \sin \theta)$ is the array factor. The compliance boundary becomes a non-circular curve that depends on the beam pattern, and R_c decreases in directions where the beam is not pointing.

4) *Method (4): Direct Near-Field Power Density Computation*: Using (4)–(6), $S(x, z)$ is computed at each grid point in the xz plane, and the $S = S_{\text{MPE}}$ contour defines the boundary [10]. Using no far-field approximation, it accurately captures the distance-dependent near-field structure of the beam.

E. Definition of the Overflow Rate

To quantify the discrepancy between the far-field methods (1)–(3) and the near-field method (4), we define the overflow rate O . For each cell with $S(x, z) \geq S_{\text{MPE}}$ in method (4), the distance R and angle $\theta = \arctan(x/z)$ from the origin are compared with the far-field $R_c(\theta)$:

$$O = \frac{N_{\text{overflow}}}{N_{\text{total}}} \times 100 \quad (\%), \quad (10)$$

where N_{total} counts cells with $S \geq S_{\text{MPE}}$ and N_{overflow} those with $R > R_c(\theta)$. Thus $O = 0\%$ means the far-field boundary fully encloses the near-field region (conservative), and $O > 0\%$ indicates overflow (non-conservative).

III. BEAM DESIGN AND COMPARISON OF THE FOUR METHODS

A. Beam Design Optimization

For each Rx, with θ_{tilt} as a design variable, we seek a beam satisfying two conditions: (a) the main-lobe peak x at $z = z_{\text{rx}}$ is within 100 mm of x_{rx} (Rx-reach), and (b) the peak at $z = z_{\text{obs}}$ is at most $x_{\text{obs}} - r_{\text{obs}} = 0.35$ m (obstacle-avoidance). Searching x_0 over 2.0 – 2.2λ , we adopt for each Rx the configuration minimizing the reach error among those satisfying (b), preferring larger x_0 (a more stable beam) when errors are comparable.

Table II shows the results: $x_0 = 2.00$ – 2.02λ for all the Rx positions, with larger downward θ_{tilt} at lower Rx to counter the natural $+x$ bending. The five configurations at $x_{\text{rx}} = 0.50$ – 0.90 m meet both conditions to within 1–2 mm. At $x_{\text{rx}} = 1.00$ m, even at the full margin (pk@obs = 0.348 m) the peak reaches only $x = 0.942$ m (58 mm error), and reducing x_0 further eventually removes feasible solutions, which corresponds to the physical reach limit of this scenario. Since x_0 is optimized per Rx, $G_{\text{max}}^{\text{airy}}$ ranges over 12.0–12.2 dBi.

TABLE II
BEAM DESIGN RESULTS (x_0 OPTIMIZED OVER 2.0 – 2.2λ)

x_{rx} (m)	x_0 (λ)	θ_{tilt} ($^\circ$)	pk@obs (m)	pk@rx (m)	Error (mm)	Result
1.00	2.00	−1.0	+0.348	+0.942	58	PASS
0.90	2.00	−1.5	+0.328	+0.902	2	PASS
0.80	2.00	−2.5	+0.278	+0.802	2	PASS
0.70	2.00	−3.6	+0.228	+0.701	1	PASS
0.60	2.00	−4.7	+0.178	+0.601	1	PASS
0.50	2.02	−5.6	+0.131	+0.501	1	PASS

pk@obs: main-lobe peak x position at $z = z_{\text{obs}}$;

pk@rx: main-lobe peak x position at $z = z_{\text{rx}}$.

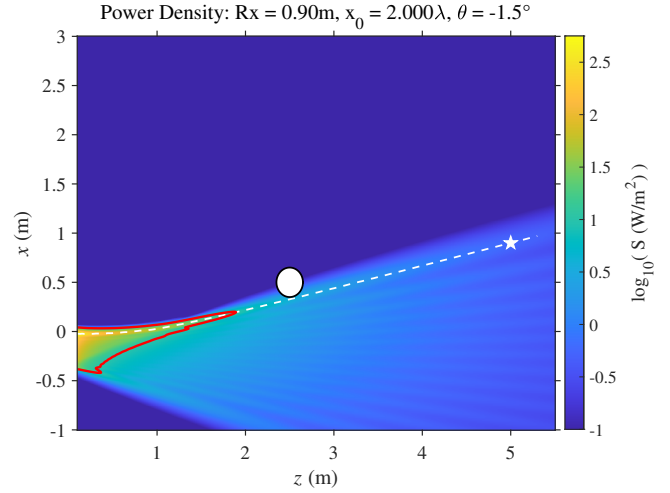


Fig. 2. Power density distribution of the Airy beam at $x_{\text{rx}} = 0.90$ m. The solid red line is the $S = S_{\text{MPE}}$ contour, and the white dashed line is the effective caustic.

B. Power Density Distribution of a Representative Beam

Fig. 2 shows the power density for $x_{\text{rx}} = 0.90$ m. The main lobe curves in $+x$ along the effective caustic (white dashed), passing below the obstacle (white circle) to the Rx (white star). The $S = S_{\text{MPE}}$ boundary (red) forms a closed asymmetric region near the antenna ($z < 2.0$ m), slightly extended in $+x$. Because caustic power concentration partially offsets the far-field $1/R^2$ decay, it differs fundamentally from a far-field circle.

C. Comparison of Compliance Distances

Table III compares the compliance distances. The uniform-excitation gain $G_{\text{max}}^{\text{uni}} = G_{\text{elem}} \cdot N \approx 27.1$ dBi exceeds $G_{\text{max}}^{\text{airy}} \approx 12.0$ – 12.2 dBi by about 15 dB, because the Airy distribution concentrates power on the tail region of the aperture, reducing the effective aperture. The resulting distances are $R_c^{\text{uni}} = 6.37$ m and $R_c^{\text{airy}} = 1.13$ – 1.15 m. Method (3)'s $R_c(\theta)$ peaks at the method-(2) value but drops sharply off the main lobe. Since the near-field envelope reach ($z_c \approx 1.95$ m, discussed later) is about $1/3.3$ of R_c^{uni} , method (1) substantially overestimates;

TABLE III
COMPARISON OF COMPLIANCE DISTANCES

Method	$G_{\max}$ (dBi)	R_c (m)	R_c/R_c^{uni}
(1) Uni circle	27.1	6.37	1.00
(2) Airy circle	12.0–12.2	1.13–1.15	0.18
(3) $R_c(\theta)$	12.0–12.2	0–1.15*	0–0.18
(4) Near field z_c	—	1.88–1.95	0.30–0.31

*Direction-dependent; the maximum coincides with method (2) in the $G_{\max}^{\text{airy}}$ direction.

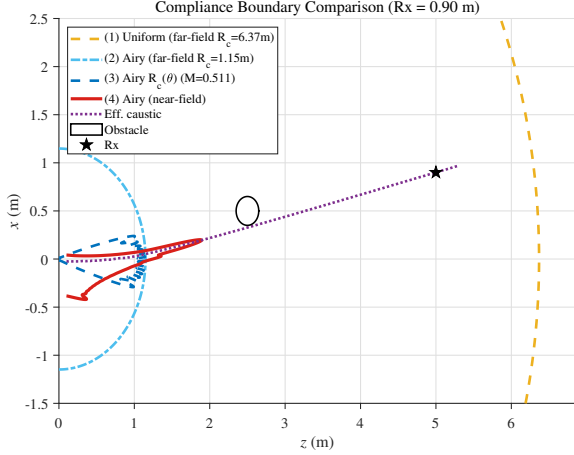


Fig. 3. Comparison of the four compliance boundaries at $x_{\text{rx}} = 0.90$ m ($P_{\text{in}} = 10$ W).

Airy excitation cuts the distance by about 82%, yet near-field overflow still occurs, as shown below.

D. Comparison among the Four Methods

Fig. 3 overlays the four compliance boundaries for $x_{\text{rx}} = 0.90$ m. Method (1)'s circle ($R_c^{\text{uni}} = 6.37$ m) encloses the near-field region but greatly overestimates it; method (2)'s Airy circle ($R_c^{\text{airy}} \approx 1.15$ m) is reduced but overflows in the caustic direction; and method (3)'s boundary extends along the beam, overflowing elsewhere.

Table IV lists the overflow rates. Method (1) yields $O = 0\%$ (complete enclosure) at all Rx, but methods (2) and (3) reach $O \approx 15\%$ and 48% , respectively. Method (3) being substantially worse than method (2) indicates that refining the far-field method does not improve the compliance boundary for the Airy beam.

E. Limitations of the Far-Field Methods

Counterintuitively, method (3) ($O_{(3)} \approx 48\%$) is far worse than the isotropic method (2) ($O_{(2)} \approx 16\%$). Because the Airy excitation concentrates gain in the main lobe, $R_c(\theta)$ extends along that direction but shrinks sharply elsewhere, leaving the “wide” near-field $S \geq S_{\text{MPE}}$ region (which spreads in $\pm x$ at $z < 2.0$ m) uncovered, whereas the uniform circle of method (2) retains coverage in all directions. Thus the far-field methods face a dilemma: method (1) is conservative but $R_c^{\text{uni}} = 6.37$ m is about 3.3 times the near-field reach

TABLE IV
OVERFLOW RATE O (%) (EACH FAR-FIELD METHOD VS. METHOD (4) NEAR FIELD)

x_{rx} (m)	$O_{(1)}$ (%)	$O_{(2)}$ (%)	$O_{(3)}$ (%)
1.00	0.0	14.7	48.8
0.90	0.0	14.7	48.9
0.80	0.0	14.9	48.7
0.70	0.0	15.0	48.6
0.60	0.0	15.1	48.4
0.50	0.0	16.2	48.1

$z_c \approx 1.95$ m, while methods (2) and (3) shorten the distance at the cost of overflow.

The fundamental cause is that the caustic trajectory is a near-field-specific phenomenon not reflected in the distance-independent pattern $G(\theta)$. Since $R_c(\theta) \propto \sqrt{G(\theta)}$ is always fan-shaped about the antenna, it cannot represent the parabolic power concentration along the caustic. We note that the overflow concentrates in the caustic ($+x$) direction close to the z -axis. This direction is near the peak of the $\cos \theta$ element pattern, where the attenuation is negligible. Therefore, the overflow rate and the non-conservative conclusion are insensitive to the element model.

IV. PROPOSED METHOD: NEAR-FIELD ENVELOPE COMPLIANCE BOUNDARY

A. Definition of the Envelope

Since the beam design changes dynamically with the receiver position, a compliance boundary covering all beam configurations is required. Extending the far-field traffic-beam envelope $G_{\text{env}}(\theta) = \max_i G_i(\theta)$ [5], [19] to the near field, we define a near-field envelope as the maximum power density over all configurations at each point:

$$S_{\text{env}}(x, z) = \max_i S_i(x, z). \quad (11)$$

The compliance boundary is the $S_{\text{env}} = S_{\text{MPE}}$ contour. Each S_i is computed in free space (LOS); ignoring obstacle shadowing is conservative, although local enhancement from obstacle reflections on the antenna side is not captured. Unlike the far-field envelope [19], the distance-dependent beam structure is preserved.

B. Results of the Envelope Compliance Boundary

Fig. 4 shows the near-field compliance boundaries of the six configurations and their envelope. Since each has a different θ_{tilt} , the regions differ in shape; the envelope spans $[-0.44, 0.21]$ m in x with a z -reach of 1.95 m.

Near $z \approx 1.5$ – 2.0 m, the contour shows finger-like structures from the spatial overlay of configurations with different side-lobe positions and θ_{tilt} , biased toward $-x$ by the downward-tilted configurations ($x_{\text{rx}} = 0.5$ – 0.6 m).

The proposed method remains conservative for all six configurations while avoiding method (1)'s overestimation: against $R_c^{\text{uni}} = 6.37$ m, the envelope z -reach of 1.95 m reduces the z -direction compliance distance by about 69% ($1 - 1.95/6.37 \approx 0.69$).

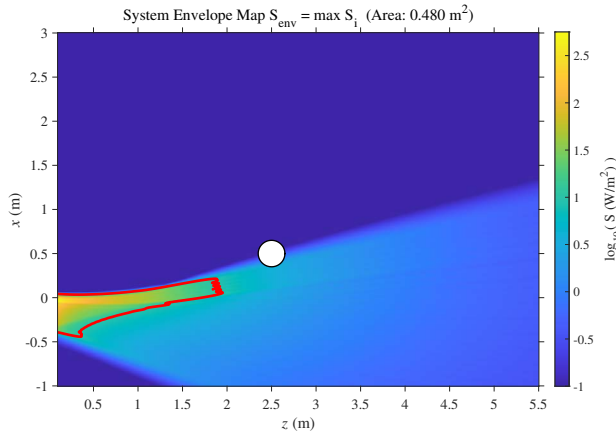


Fig. 4. Envelope power density S_{env} and compliance boundary (red line). The z -direction reach is 1.95 m.

V. CONCLUSION

In this study, we compared four methods for determining the compliance boundary of the Airy beam generated from a 128-element linear array at 28 GHz. Method (1) is conservative but overestimates the compliance distance by a factor of about 3.3, whereas methods (2) and (3) produce overflow rates of about 15% and 48%, respectively. None of the far-field methods can adequately evaluate the near-field region, and the result that method (3) is worse than method (2) shows that refining the far-field formula is not necessarily effective.

We therefore proposed a near-field envelope compliance boundary combining direct near-field computation with the beamforming envelope concept, reducing the compliance distance by about 69% relative to method (1) while remaining conservative for all configurations. The present evaluation is limited to the two-dimensional xz plane, in which the Airy beam forms a sheet rather than a pencil beam. Since the compliance boundary is essentially a three-dimensional quantity described by $r(\theta, \phi)$, a full three-dimensional evaluation is required in future work. In addition, the time-averaged exposure depends on the beam-steering pattern and the duty cycle of the Airy beam, which should be incorporated together with the actual communication requirements to obtain a realistic compliance boundary.

REFERENCES

- [1] T. S. Rappaport *et al.*, "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, May 2013.
- [2] A. Ghosh *et al.*, "Millimeter-wave enhanced local area systems: A high-data-rate approach for future wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1152–1163, Jun. 2014.
- [3] K. Li, H. Xu, X. Wang, and K. Ishibashi, "Human blockage analysis at 5G millimeter wave frequencies using a high-resolution voxel model," in *Proc. IEEE AP-WCS*, 2025.
- [4] ICNIRP, "Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)," *Health Phys.*, vol. 118, no. 5, pp. 483–524, 2020.
- [5] IEC 62232:2022, "Determination of RF field strength, power density and SAR in the vicinity of radiocommunication base stations for the purpose of evaluating human exposure."

- [6] B. Xu, I. Mrissa, I. Bahceci, C. Di Paola, K. Huisman, A. El-Keyi, and C. Törnevik, "Directional power control of 5G radio base stations for EMF compliance—Part I: Design principles and feature validation," *IEEE Trans. Antennas Propag.*, 2024, doi: 10.1109/TAP.2024.3430496.
- [7] B. Xu, I. Mrissa, I. Bahceci, C. Di Paola, K. Huisman, A. El-Keyi, and C. Törnevik, "Directional power control of 5G radio base stations for EMF compliance—Part II: Comparisons with cell-wide power control in a live network in Germany," *IEEE Trans. Antennas Propag.*, 2024.
- [8] S. Uchimura, J. M. Jornet, and K. Ishibashi, "Optimization and characterization of near-field beams with uniform linear arrays," *arXiv preprint arXiv:2503.13890*, 2025.
- [9] S. Uchimura, J. M. Jornet, and K. Ishibashi, "Optimal wavefronts for maximum ratio transmissions under path blockage effects," *IEEE Trans. Wireless Commun.*, vol. 25, no. 15, pp. 11051–11067, 2026.
- [10] D. Pinchera, M. D. Migliore, F. Schettino, and G. Panariello, "A simple and efficient procedure to evaluate the radiated power density near massive MIMO base stations," *IEEE Access*, vol. 8, pp. 222032–222041, 2020.
- [11] B. Xu *et al.*, "A Monte Carlo analysis of actual maximum exposure from a 5G millimeter-wave base station antenna for EMF compliance assessments," *Frontiers in Public Health*, vol. 9, Art. no. 777759, 2022.
- [12] M. V. Berry and N. L. Balazs, "Nonspreading wave packets," *Am. J. Phys.*, vol. 47, no. 3, pp. 264–267, 1979.
- [13] G. A. Siviloglou, J. Broky, A. Dogariu, and D. N. Christodoulides, "Observation of accelerating Airy beams," *Phys. Rev. Lett.*, vol. 99, no. 21, p. 213901, 2007.
- [14] I. D. Chremmos, G. Fikioris, and N. K. Efremidis, "Accelerating and abruptly-autofocusing beam waves in the Fresnel zone of antenna arrays," *IEEE Trans. Antennas Propag.*, vol. 61, no. 10, pp. 5048–5056, Oct. 2013.
- [15] Z. Yang, G. Wen, W. Hu, D. Inserra, Y. Huang, and J. Li, "Microwave Airy beam generation with microstrip patch antenna array," *IEEE Trans. Antennas Propag.*, vol. 69, no. 4, pp. 2290–2301, Apr. 2021.
- [16] Z. Yang, G. Wen, D. Inserra, and Y. Huang, "Propagation range enhancement of truncated Airy beam with antenna array at microwave frequencies," in *Proc. IEEE APCAP*, 2018, pp. 1–2.
- [17] H. Guerboukha, B. Zhao, Z. Fang, E. Knightly, and D. M. Mittleman, "Curving THz wireless data links around obstacles," *Commun. Eng.*, vol. 3, Art. no. 63, 2024.
- [18] K. Li, K. Sasaki, S. Watanabe, and H. Shirai, "Relationship between power density and surface temperature elevation for human skin exposure to electromagnetic waves with oblique incidence angle from 6 GHz to 1 THz," *Phys. Med. Biol.*, vol. 64, no. 6, art. no. 065016, 2019.
- [19] B. Xu, D. Colombi, and C. Törnevik, "EMF exposure assessment of massive MIMO radio base stations based on traffic beam pattern envelopes," in *Proc. 14th European Conference on Antennas and Propagation (EuCAP)*, Copenhagen, Denmark, 2020, pp. 1–5.