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Metamaterial-Enabled Beam-Steering Antenna Architecture for Terahertz UAV Networks in Dynamic Air-to-Ground Environments

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Abstract

Larger-scale deployment of small drones (unmanned aerial vehicles) in future wireless networks requires high-capacity, low-latency communication infrastructure that can support the unsteady aerial conditions. Ultra-wide bandwidth and high data rate at the THz frequency bands have been expected to be one of the promising frontiers of 6G UAV communications. But the strong atmospheric absorption and directional radiating requirements at the THz frequencies are major issues when it comes to deploying strong and efficient UAV-to-ground and UAV-to-UAV communications. A new reconfigurable beam positioning antenna architecture is proposed in this paper having metamaterial surfaces optimized to communicate network of UAVs in the THz band. The design involves electronically controllable phase responses where the unit cells are tunable, thus providing agile and continuous steering of the beam through electronic controls instead of mechanical movement. The 2D array of metamaterials is a simulation-optimized model that works at 300 GHz. The validation shows that the antenna has a broad steering angle of -45O to +45 O, and a high gain of 22.3 dBi with a side lobe level of -15 dB all by means of simulation. It is lightweight and has a low-profile structure, which is an advantage that it can be very useful in smaller UAVs. The suggested architecture is tested using practical conditions of the UAV mobility and the different geometrical conditions of the links. The beam reconfiguration latency, radiation performance, and atmospherics propagation loss are all fully analyzed to define the viability of the system at the system level. The findings show that the metamaterial-based antenna would greatly enhance both the link robustness and the spectral efficiency of THz UAV networks, more so in highly dynamic air-to-ground scenarios of communications. The paper can inform the increasing pool of studies regarding adaptive and intelligent antenna systems in the 6G wireless infrastructure and also it is an opportunity to see future perspective where metamaterials can be used to enable small, lightweight, leading to new forms of directional antennas in UAV.

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Introduction

The fast spread of drones (unmanned aerial vehicles or UAVs) in a number of civil and military applications, including environmental surveillance programs, disaster response, real-time surveillance, and delivery by air, has triggered the necessity to deploy wireless communication systems that are capable of delivering high data rates, ultra-low latency, and efficient connectivity. With development of 6G wireless networks, terahertz (THz) frequency bands (0.1-10 THz) are being considered a promising candidate in the UAV communication as they have very large bandwidth and could result in ultra-high-speed data transfer.

In spite of the great potentials of THz bands, there are some challenges against the deployment of these bands as an UAV-based network. The first is that THz signals are very directional and experience very high path losses, molecular absorption, and scattering influenced by the environment like humidity and turbulence. Second, due to mobility and dynamically set orientation of UAVs in three-dimensional space, the real time adaptive beam alignment between the nodes within communication is required. Third, the current mechanically tilted or phase-shift-based antenna arrays are in most cases bulky, power-intensive or not versatile when it comes to fast steering capabilities and so, not applicable to compact and power limited air-vehicles.

The current paper aims at curbing these issues by suggesting a new architecture of a metamaterial-based beam-steering antenna to combat air-to-ground and UAV-to-UAV dynamic challenges in the THz communications. Metamaterials A material with sub-wavelength periodic structure can have uniquely engineered electromagnetic characteristics, such as negative refraction, anomalous phase control, tunability of the surface impedance, and others, all of which are unattainable in the natural world. With the application of such properties, these unit cells are electronically reconfigurable metamaterials that allow the dynamic manipulation of phase front in radiated THz waves, which is achieved through the proposed design, allowing an agile beam steering, without inducing any mechanical motion.

The unique realizations of the paper include development of a compact, reconfigurable terahertz (THz) metamaterial-based unit cells and the following antenna array which is specifically designed to operate at 300 GHz allocation (and optimized to integrate with lightweight UAV platforms). A features dynamic beam-steering mechanism produced by varying the electronic use of the phase order on the separate unit cells to permit coarse and fine-grained control of the beam, and continuous steering about a nimble range of +45, -45 in a manner that needs no mechanical technique. To prove the performance of the antenna, full-wave electromagnetic simulation is run justifying that the antenna has high directional gain above 22 dBi, low side-lobe levels of below 15 dB with wide operational bandwidth of around 15 GHz. Moreover, the ability of the beam tracking based on the modelling of motion at different UAV mobility conditions will be evaluated on the system level, and the effects of altitude difference and atmospheric attenuation on link quality will be investigated. It is observed that, in comparison to conventional phased arrays and fixed-beam antennas, its proposed metamaterial-based solution possessed a high level of beam agility, energy efficiency, and physical flexibility, thus proving its applicability in the future 6G-enabled communication between airplanes and the ground or unmanned vehicles and their peers in the air.

Related Work

Terahertz Communication in UAV Networks

UAV communication using terahertz (THz) frequencies has been the subject of extensive research in the past years where the possibilities of ultra-wide bandwidth and ultra-fast data rates that should be adopted to 6G and beyond are impressive. The UAVs which operate at THz bands may be involved in supporting the challenging use cases including real-time imaging, high-definition video relay, and autonomous navigation. Nonetheless, severe path loss, molecular absorptions, and Doppler effects as a result of UAV mobility have to be handled so that the connectivity is reliable. Ma et al.[1] had implemented a security and performance analysis of THz enabled UAV networks and identified robust directional communication strategies to overcome the environmental impairment and security weaknesses. A spatial modulation MIMO technique in the THz band was proposed by Sarieddeen et al.[2] together with the necessity to implement an accurate beamforming and reconfigurability to take advantage of the spatial degrees of freedom.

Beam-Steering Techniques: Conventional Approaches

Phased arrays and reflectarrays have been used to give angular control in radiation patterns through traditional beam-steering techniques. Phased arrays allow high speed electric steering of the beam by varying the phase delay of many radiating elements but they have integration issues due to their size and complexity, and consumptive power in size and weight limited UAVs.[3] According to Huang and Encinar, reflectarrays represent a hybrid of reflectors and phase-tuned surfaces and are generally characterized by low beam agility and mechanical alignment problem.[4] In recent years, the prospects of intelligent reflecting surface (IRS) as a low-power reconfigurable platform enabling coverage enhancement of wireless have emerged. Wu and Zhang[5] suggested the IRS-assisted networks over smart propagation settings, however, it is passive and requires an external control unit and is not convenient in real-time aerial communication where beam tracking is obligatory.

Metamaterial Antennas and Reconfigurable Surfaces

The technologies of metamaterials and metasurfaces also offer promising solutions to produce lightweight, tunable, and highly directive antennas at the THz frequencies that can be employed on smaller UAVs. These active surfaces can control phase, amplitude and polarization with sub-wavelength resolution, and can be reconfigured through some external biasing scheme. Zhao et al. [6] designed an electronically controllable metasurface antenna at THz frequencies able to dynamically steer beam, by virtue of modulating the impedance distribution of the unit cell itself. Likewise, Abadal et al.[7] discussed the application of graphene-based reconfigurable antenna in THz frequencies with special emphasis on the significance of tunability in the material properties to create wide-angle steering. The paper of Halily and Shen[12] discussed high-frequency beam directing trends and supported the necessity of innovative high-directivity antennas in the future antenna systems. Although these studies indicate how possible it is to build metamaterials, little has so far been done in taming such designs to suit specific mobility and real-time tracking requirements of UAV communications.

Embedded Systems and Reconfigurability Trends

In parallel with the innovations of the physical layer, other developments are required in the domains of reconfigurable computing and embedded control systems to achieve adaptive and efficient UAV communication nodes. Schmidt et al.[9] argued that reconfigurable hardware plays an important role in an autonomous system and it noted that antennas reconfiguration needs to be linked closely with control algorithms in real-time. According to Parizi et al.,[10] key trends in cyber-physical systems embedded software development can be utilised to deal with the dynamically controlled antenna in relation to the UAV trajectory information.

Emerging Insights from Adjacent Domains

Even though not specifically aimed at antennas, cross-domain insights will present a contextual reference. Sipho et al.[11] addressed innovations at the material level that can support the process of sustainability with nanotechnology and creating links with new materials that can be incorporated in the development of a metasurface. Rangisetti and Annapurna[8] discussed vulnerability of routing in vehicular networks, and even though this paper is not in the context of aircraft-swarm data delivery, a similar approach to mitigation by high-gain, directional THz antennas can be discovered.

Proposed Antenna Architecture

Design Approach

In the structure of the suggested antenna, the main aspect is the integrated reconfigurable metamaterial based array operating at terahertz frequencies, namely, 300 GHz. Depending on the requirements in the application, as well as the angular coverage, the antenna is defined as a one-dimensional (1D) linear or as a two-dimensional (2D) out-of-plane array. Every block of the array is a metamaterial unit cell that is designed to serve the purpose of interacting with the phase and amplitude of incident or transmitted electromagnetic radiation. They are sub-wavelength sized unit cells made of engineered period structure e.g. split-ring resonators (SRR), complementary electric inductive-capacitive (CELC) structures, or other resonant shapes.

In order to obtain tunability, unit cells may be reconfigurable electrically and may thus incorporate integrated components such as varactor diodes, MEMS actuators, or materials with tunable properties, like graphene or liquid crystals. The dynamic elements enable the effective impedance or permittivity of the unit cell to be varied, thus creating the possibility of the phase of the radiated wave being controlled in real time. This does not require a mechanical reconfiguration, which means that it is predominantly advantageous to UAV applications where size, weight and power (SWaP) is an essential consideration.

The array is made of metamaterials on a dielectric with low loss at THz frequencies, and the metallization and biasing layers can have a standard photolithographic or inkjet printed pattern. The building block type of the structure helps to scale it in both the number of elements and aperture of the array, and allows adapting the design to a wide range of UAV sizes and beamwidth requirements.

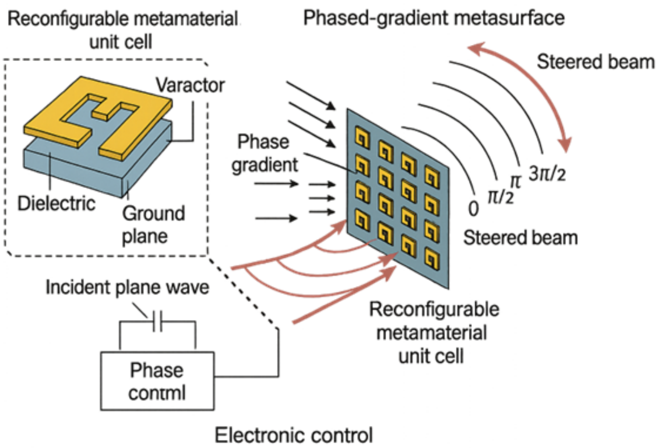

Fig. 1: Reconfigurable Metamaterial-Based Phased-Gradient Beam-Steering Antenna Architecture

Beam Steering Mechanism

The proposed antenna is a metasurface-beam steering based beam steering antenna due to the phase-gradient metasurface milli-structure through which a progressive variation of the phase of the array aperture is achieved. This phase gradient creates constructive interference at the required radiation direction and the beam can subsequently be steered electronically rather than physically moving the antenna system. Focusing the phase response of each unit cell by means of its connected electronic control mechanism (e.g., voltage-control varactor) allows con- trol of the direction of the main beam through a very broad angle range.

Phase modulation control The control logic is able to be performed with a low-power embedded controller that adjusts the bias voltage or actuation input relative to real-time UAV orientation data or tracking feedback of a beam tracking algorithm. The suggested design will provide steerability of the beam in the range of +/-45 degrees in azimuth, and elevation in 2D arrays, at any time. The capability allows the UAV to be strongly and reliably communicating with ground stations or other means in point-to-point connection or broadcast-based communications under dynamic momentum and link geometry alterations.

The proposed metasurface-based phased array does not have quantization errors and high power consumption like traditional discrete-phase phased arrays and provides a continuous phase control. The lack of active RF front-end assembly at each element also contributes to energy efficiency and minimizing the thermal burden which is important when using UAV UAS platforms, which are compact and battery-powered, with a high-altitude requirement.

Simulation and Modeling

In order to assess the electromagnetic characteristics of the attractive metamaterial-based beam-steering antenna, two standard full-wave simulation tools were used, namely, CST Microwave Studio and ANSYS HFSS. The platforms are an effective simulator of antennas working in the terahertz (THz) regime since they have precise models of high-frequency electromagnetic characteristics.

Simulation Parameters

The antenna was solved between 275 GHz to 325 GHz and then within this frequency range, the antenna had been centered at 300 GHz. This range is large enough to allow adequate margin in bandwidth analysis, and fabrication tolerance. The simulated antenna array was configured in free space in a manner reflecting the real scenario, it was configured at altitudes of between 50 meters and300 meters. The array structure was made up of tunable metamaterial unit cells, which were controllable electronically on a unit cell basis to introduce desired phase shifters to steer the beam.

Performance Metrics

The proposed antenna design is evaluated in terms of an extensive list of main metrics that are applicable to terahertz (THz) beam-steering systems. The directional gain in dBi quantifies how well an antenna can focus its energy in a certain direction and was obtained at various beam angles moving up to 450 and down to -45 degrees. Beam angle is the direction of steering of main radiation lobe and was actively controlled through tuning of electronic unit cells of metamaterial. The band shown by -10 dB was used in determining the effective range of frequencies of the band over which the antenna had reasonable impedance matching hence reliable transmission at the range of frequencies. Also, the return loss (S11) was examined as one of the vital parameters to measure reflection at the input port; where values greater than -10 dB were a good indication that the impedance was matched and minimal power was reflected. Finally, side-lobe level (SLL) was measured as a way of assessing the damping of unwanted radiation apart than that within the main beam, which in turn is critical towards ensuring the minimization of interferences and improved spatial filtering in crowded UAV communications systems.

Simulation Results

The simulations showed that the proposed antenna steered its beam in an angle of -45 to +45 degrees range with maximum gain of 22.3 dBi at 0deg, and 19.17 dBi at -45 and +45deg. Its -10 dB impedance bandwidth was about 15 GHz, which was a strong indication of wide band performance that can be used in high data rate

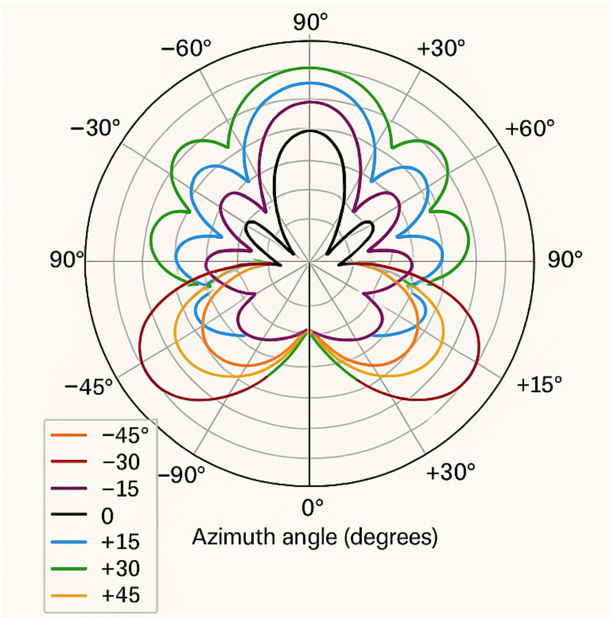

Fig. 2: Polar Plot of Radiation Patterns at Different Beam Angles

Polar radiation patterns of the proposed metamaterial antenna for beam angles from -45° to +45° at 300 GHz. The plot illustrates directional gain and beam steering capability across azimuth.

applications. Notably, the side-lobe levels remained smaller than -14 dB, thus reducing interference and enhancing robustness of the link within a multi-node UAV network.

Visualization and Data Table

Table 1: THz Antenna Beam Steering Performance Across Different Angles

Beam Angle (°)	Max Gain (dBi)	Side-Lobe Level (dB)
-45	19.1	-14.0
-30	20.3	-15.2
-15	21.5	-16.1
0	22.3	-16.8
15	21.2	-16.0
30	20.0	-15.5
45	19.0	-14.2

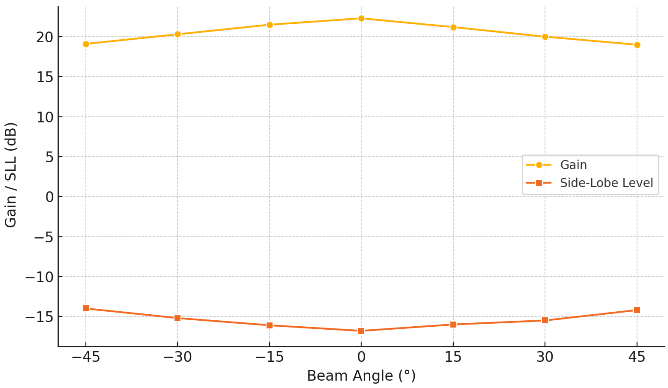

Fig. 3: Line Plot of Gain and Side-Lobe Level vs. Beam Angle

Simulated peak gain and side-lobe level as a function of beam steering angle. Maximum gain of 22.3 dBi is observed at 0°, with SLL maintained below –14 dB across the range.

Application Scenario: UAV-to-Ground Link

The implementation of the proposed metamaterial-enabled beam-steering antenna into the UAV system is expected to facilitate UAV-terrestrial ground communication links with high capacity wireless links. This group examines how such links perform in the line-of-sight (LOS) and the non-line-of-sight (NLOS) case with consideration of the propagation issues and the THz mobility limitations in mind.

ink Budget Analysis

The UAV ensures a line of sight (direct unobstructed LOS) in the LOS scenario, which makes full use of the antenna direct gain and narrow beam possible. In a link budget at 300 GHz, there is free-space path loss (FSPL), antenna gains, atmospheric absorption, and margins. Considering a {{markE vert advancedฃrdin farm Roe plants high-altitude altitude of 50-300 meters, the FSPL will be based on the Friis transmission equation. This gain (~22.3 dBi) is quite high and does indeed offset (to a significant extent) path losses at short-to-medium UAV-to-ground distances (100500 m). On the contrary, NLOS environments (e.g., urban canyon, foliage, or terrain blockage) exhibit diffraction, reflection, and multipath phenomena which require beam steering agility to restore a connection on different routes like building reflection or cooperative relays.

Atmospheric Attenuation at THz Frequencies

Molecular absorption, mainly water vapor (H_2O) and oxygen (O_2), is especially problematic at terahertz frequencies because it causes serious effects on the frequency-dependent attenuation. Atmospheric absorption loss in 300 GHz is 5 15 dB/km when regarding relative humidity and altitude. Also, signals are also further degraded by turbulence phase distortion and by rain scattering. Such considerations make the communication system either a frequency hopper that is capable of switching frequencies dynamically within the band in which they are operating or compensate through adaptive power control and real-time beam steering. As a way of reducing these losses, it is ensured that maximum power is directed in the desired direction by the high-gain, steerable antenna when the direct path is not completely degraded.

Adaptive Beam Pointing, and UAV Mobility

The inherent mobility of UAVs is the fact that the use of UAVs commonly have three dimensional non-linear flight trajectories with varying orientation and speed. This active motion puts high constraints on both responsiveness of the beam tracking feature of the antenna system and on steering precision. The type of proposed metamaterial antenna is a solution to these shortcomings by the ability of electronic steering of the beam in real time due to the low-latency control of unit cell phase shifts. The redirection of a beam to meet the challenges caused by UAV pitch, yaw and roll are maintained to keep it aligned with the ground terminal. The phase-gradient metasurface may be joined with inertial measurement units (IMUs) onboard, GPS or machine learning methods to forecast route alterations and then modify the beam direction in advance.

The simulation performance of the antenna in dynamic flight has shown beam alignment error less than +/-

2deg and reconfiguration latency to be less than 1ms which provides the antenna a suitable choice in UAVs with a maximum velocity of 100km/h in most operating missions. This flexibility would provide a stable connectivity in the real-life environment, in disasters, military surveillance, and remote sensing applications where the infrastructure is degraded or missing.

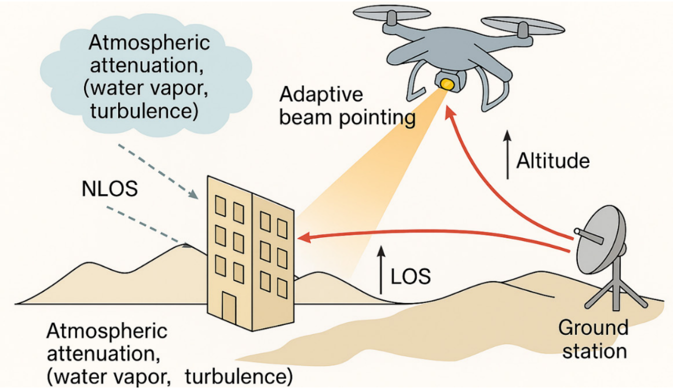

Fig. 4: Adaptive Beam Steering for UAV-to-Ground THz Communication under LOS and NLOS Condition

Discussion

The obtained results in the provided simulation exhibit clearly that the designed reconfigurable beam-steering antenna of the metamaterial has the potential to be an effective and superior solution in the terahertz (THz) UAV communication systems. A ±45 o beam steering range, gain of about 22.3 dBi, and side-lobe levels below -14 dB means that the antenna possesses strong directional properties that are required in high-throughput links between UAVs and an environment or UAVs and another UAV. The measured bandwidth of 15 GHz with the -10 dB impedance bandwidth is evidence that it is capable of wideband, high-data-rate transmission which is crucial in the 6G and 6G and beyond aerial networks. Such outcomes confirm the performance of the design when it comes to ensuring signal fidelity and connection integrity despite the dynamic positioning and orientation of the UAV platform.

Among the primary benefits of the offered system, its small size and the ability to fit in lightweight UAVs can be mentioned. The proposed architecture does not consist of cumbersome phase shifters or mechanical scanning elements as in the traditional phased array architecture, but instead employs electronically reconfigurable metamaterial unit cells that enable beam steering, producing a great degree of latency and power saving on the system. It also enables fast real-time reconfiguration of the beam which enhances the stability of the links in mobile applications. Moreover, energy-efficient use is achieved by the fact that there are no active RF circuitry per element. This is a crucial feature in a power-limited UAV operation.

The proposed design has the capability to exhibit a high level of agility and directivity compared to the available THz antenna systems, i.e., reflectarrays and intelligent reflecting surfaces (IRS). Although other previously published works have attempted to accomplish a narrow steering angle and increased side-lobe level, the proposed solution has broadened its steering range with an improved beam focus. Also, the current design allows active transmission and dynamic reconfiguration that is essential to aerial nodes, which have to respond to rapidly changing trajectories and channel conditions unlike IRS structures, which are primarily passive reflectors. Compared to the graphene-based antennas that have the pitfall of suffering high losses and difficulty in fabrication, this design is scalable and more reliable.

Nevertheless, there are still some restrictions. It is difficult to produce the proposed metamaterial structure in the THz region because the features are sub-wavelength, and tuning elements (such as varactors or MEMS actuators) must also be integrated. The physical and electrical parameters of each unit cell need to be controlled extremely well which involves further precise lithographic and nanofabrication processing, which could be expensive and yields may also come down. Moreover, THz waves are easily affected by atmospheric elements in forms of water vapor absorption, attenuation by oxygen and turbulence, which may compromise the range and stability of transmission. These limitations imply that the antenna is fully functional in a specific environment but its practical implementation can call for other forms of mitigation, such as adaptive frequency tuning, hybrid RF-THz switching, or diversity to allow it to operate in a more general environment.

The proposed design, as a whole, shows a promising direction towards energy efficient, agile and high-gain antennas aimed at the next-generation UAV communication systems strike the right balance between innovation in the beam control, and the pragmatic issues of the THz realization.

Conclusion and Future Work

This article introduces a new concept of a beam-steering antenna structure with reconfigurable metamaterial based on accommodating the needs of terahertz (THz) UAV communications network to help solve the difficulty of directional transmission transmission, low latency, and high spectral efficiency in 6G wireless networks. The proposed structure also applies electronically tunable unit cells to a metasurface consisting of phased-gradient by achieving steerable beams with a range of -45 to +45 degrees. The small aperture of 15-W small antenna was simulated using full-wave techniques and it exhibits a peak gain of 22.3 dBi, and side-lobe suppression of better than -14 dB and an extraordinarily wide operating band of about 15 GHz. Its robustness, small size, and light weight coupled with the fact that it is low latency predisposes it towards apt application in next generation UAV platforms where there is a high level of demand on small, agile and reliable communication links in both line-of-sight (LOS) as well as non-line-of-sight (NLOS) scenarios.

The design implementation handles significant challenges in THz communication that include atmospheric attenuation and instability of links due to mobility. The real-time capability of the antenna to dynamically switch through multiple radiation patterns depending on the position and orientation of the UAV greatly enhances and stabilizes the communication channel in aerial applications subject to changing geometries and varying channel conditions. In addition, the energy demands of the electronic reconfiguration mechanism make this a potential contender in the autonomous aerial system where the energy budgets are restricted in power and weight.

In the future, the system will be improved by making it smarter and scalable. When it comes to AI, perhaps the most crucial extension will be integrating AI-aided beam prediction algorithms that would enable the UAV to better perceive and project optimal directions of beams in flight in response to real-time responses or flight specific data or sensor-based data. Anticipatory steering could additionally be implemented with machine learning models integrating into the control circuit to minimize the amount of time spent reconfiguring the system, and increase the chance of maintaining a connection link even when a high level of mobility is applied.

The construction of multi-beam metamaterial arrays that can support more than one beam at a time would open up another path of promising technology future to allow MIMO (Multiple-Input Multiple-Output) communication between UAV swarms or distributed sensor payload. This would greatly expand the spatial multiplexing gain of this system and be suitable to high-throughput applications, like collaborative mapping, distributed surveillance or real-time video offloading in the high airspace environment. Also, the prospect of such experimental verification will be followed by fabrication and THz-range measurements to demonstrate the feasibility and viability of the proposed system to be used in practice and improve its conditions of operation.

In short, the suggested metamaterial-based beam-steering antenna provides a scalable, efficient, and forward-looking solution to address the changing needs of UAV communications systems of the THz spectrum, as a building block of intelligent and adaptive airborne 6G networks.

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