

Graphene-Assisted High-Frequency Flexible Antenna Architecture for Secure and Scalable Terahertz Communication in Smart Environments

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ABSTRACT

The paper introduces the simulated design of graphene assisted high frequency flexible antenna design, which is optimized to be used as a terahertz (THz) communication in emerging smart environments. The use of graphene due to its outstanding electrical conductivity, mechanical flexibility as well as selective surface impedance allows such an antenna to perform at a frequency of 0.3-1.5 THz, a wavelength that satisfies the increasing need of ultra high speed and secure wireless communications in a 6G enabled infrastructure. The antenna is realized on polyimide substrate; a slotted patch geometry is used to increase band width and radiation patterns. Simulations in CST Microwave Studio and COMSOL Multiphysics ensure that this antenna can achieve high radiation efficiency (as well as low return loss ($S_{11} < -20$ dB) and mechanical stability (bending and curvature). In addition, physical-layer security and the prevention of the leakage of signals which occurs in densely connected smart systems exploit spatial filtering and directional properties of the emission. The proposed antenna design has low profile, conformal structure and reconfigurability, which makes it a suitable candidate for deployment in scalable applications like structural health monitoring, wearable and real-time sensor deployment on smart transport infrastructure and smart infrastructure systems.

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INTRODUCTION

The emergence of 6G and intelligent infrastructure in rapidly evolving wireless communications partly caused an exacerbation of the requirements to have ultra-high-frequency operation, a tight form factor, and high-speed data passage. The terahertz (THz) band (0.1 10 THz) holds much promise as one of the new spectral regions due to its potential to support a huge bandwidth, extremely low latency, and a throughput in the multi-gigabit-per-second range, all of which will be critical in future smart systems, including autonomous transportation networks and real-time surveillance, and in massive IoT ecosystems. Nevertheless, the use of the THz band presents significant challenges in terms of miniaturization of devices, effective radiation, and the material losses in addition to conformal mounting in irregular material spaces.

The conventional metal antennas are made of copper or silver and are grown on a firm surface and are highly limited at the THz frequencies. These are; high ohmic losses, low radiation efficiency, inability to be reconfigured and unfriendly to mechanical flex or wearable platforms. Further, the standard systems do not provide much flexibility to secure dense wireless implementation in smart infrastructure environments where antennas should be lightweight, conformal, and be responsive in real-time physical/electromagnetic variation.

The two-dimensional carbon allotrope called graphene is an excellent candidate that can deal with these challenges because of its exceptional electrical, thermal, and mechanical properties. The fact that it has very high carrier mobility, and that it has a tunable surface conductivity in the THz regime, enable compact, tunable

antenna designs. In addition, the mechanical flexibility of graphene and its compatibility with flexible and stretchable polymeric substrates (e.g., polyimide, PET) allow the graphene to be incorporated into flexible and stretchable electronic platforms. These features render graphene-based antennas superior to existing systems in terms of location, curving, and flexibility. In short, graphene-based antennas will be an ideal candidate when curvature, space, and adaptative characteristics are the primary features of the application- such as infrastructure surface, flexible IoT nodes, and the next-generation wearable electronics.

This paper suggests and examines a new structure of graphene-assisted flexible antennas, which aim to provide communication in the THz region with the goal of being secure, scalable, and in smart environments. The stated design considers four primary goals: (1) permit a high-frequency (greater than 0.3 THz) scale of operation, (2) retain high levels of mechanical flexibility and a small fraction of performance under bending, (3) scale to allow dense deployments over smart infrastructure points, and (4) offer a physical-layer security characteristic of directional emission and low radar cross-sections. This paper investigates the electromagnetic characteristics of the antenna, its performance and resistance over bending in full-wave electromagnetic simulations that used CST Microwave Studio and multiphysics in COMSOL.

BACKGROUND AND RELATED WORK

Graphene for Terahertz Antenna Applications

Graphene is a breakdown material, and revolutionizing the next generation of reconfigurable antennas is due to its specific electromagnetic characteristics at terahertz (THz) frequencies. Graphene has frequency-tunable surface conductivity in contrast with other traditional metals which are not dynamic under chemical potentials ($\mu_c \mu_v \mu_g \mu_t$ Note. fi 149 zustonadcmd GT qual to high in concept. The Kubo formalism whose expressions take into consideration both intra and interband transitions in the THz realm is utilized to explain this behavior.^[1] The possibility of graphene supporting the surface plasmon polaritons (SPPs) at the subwavelength scales renders it as highly promising in miniaturized and high radiation efficiency/bandwidth THz antennas.^[2]

Rana^[3] showed the concept of graphene as THz plasmon oscillator was possible with high confinement of the fields and tunability, and Tamagnone et al.^[2] proposed a reconfigurable plasmonic antenna made of stacks of graphene, with a focus on its multi-frequency agility. The works underlying this led to the use of graphene in ultra-

high-frequency systems where land, programmability, and speed matter most

Flexible Antenna Technologies and Substrate Integration

The conformal and flexible antenna is urgently needed in the present smart space such as intelligent buildings, wearable electronics, and UAV-mounted communication devices. The most common type of conventional THz antennas models characteristically leverage on rigid substrates such as silicon or quartz which cannot be used in non-planar integration. Recently, materials developments have addressed alternative materials such as silver nanowires and carbon based conductive inks in developing flexible antennas.^[5] The problem is, however, that these materials have reduced stability or conductivity compared to graphene.

Y. Zhang et al.^[6] have designed a transparent microwave antenna with graphene, making a successful demonstration of its mechanical flexibility and electromagnetic stability, and opening the doors to see it applied at higher THz bands. Likewise, H. J. Lee et al.^[5] also examined silver nanowire ink-based flexible antennas, however the overall scalability of such a design is inferior to that of graphene, along with the frequency reconfigurability.

More recent concepts in metamaterials and metasurfaces have created compact, easily deformed elements that have these properties enhanced in directivity, beam formation and stealthness, which can be used as part of the architecture herein.^[13]

THz Antennas for Wireless and Smart Infrastructure Systems

Beyond the scope of terahertz communication systems, the THz band (0.1THz, 10THz) is evaluated as an important enabling technology in the next-generation 6G networks where multi-gigabit wireless connectivity and real-time machine-to-machine communication will be provided in the order of gigabit per second. The reality of using THz antennas, however, is limited by material losses, inefficiencies of radiation, and the physical size.^[7, 8]

The problem of THz communication was thoroughly discussed by Akyildiz et al.^[8] and Kleine-Ostmann & Nagatsuma,^[7] where the authors outlined radiation loss, a poor capability to miniaturize the existing devices as the main problems that persist. These works underline the significance of considering integrate a scalable, efficient and compact architecture of the THz antennas to develop practicable and high-frequency communication networks.

The flexible THz antennas can even be incorporated into structural sites in smart cities and in intelligent transportation systems to be used in localizing vehicles, infrastructure health indicators, or even sensor networks in large cities.^[10] To illustrate, ASIF et al.^[10] discussed smart communication to study theft vehicles in a car setting-- the theft vehicles study could highly utilize the technology of low profile, high gain flexible THz antennas with communications security capabilities.

Gaps in Existing Designs and Research Direction

Although there has been great advancement in the design of flexible antennas, most of the designs do not consider the modeling of THz conductivity of the graphene, bending-resilient characteristics and scalability especially at the level of infrastructure deployment. In addition, the current literature in VLSI and reconfigurable architectures, e.g., by Alizadeh and Mahmoudian [9], or Madhushree et al. [12], points to the growing significance of modular, energy efficient, and fault-tolerant devices a methodology that can be implemented in smart antenna systems, as well.

Another input to long-term insight is the concept of application-specific modular circuits in digital logic systems propounded by Vardhan & Musala,^[11] which is similar to the idea of applying modularity and area efficiency to scalable THz antenna arrays. The current wave of reconfigurable systems and intelligent electronics [9, 12, 13] also solidifies the statement that there is a need to have not only high-performance but also, integrable into heterogeneous edge platforms, antennas.

ANTENNA ARCHITECTURE AND MATERIALS

Substrate and Conductive Layer

The proposed terahertz (THz) antenna is designed on a flexible polyimide (Kapton) substrate, owing to its excellent dielectric stability, and its mechanical flexibility and thermal robustness. The desired thickness is 25 μm , which is both supportive and does not interfere with electromagnetic waves that much. It is also this thin-film structure that enables the conformal deployment to curved surfaces typical of smart infrastructure applications (i.e., building envelope, wearable textiles, or drones). In the case of the radiating layer we have a monolayer graphene grown by CVD, transferred to the substrate by wet chemistry. Graphene has high carrier mobility and can be tuned to have high surface conductivity, which is desirable to operate at high frequencies with minimized design. Antenna patch dimensions are also optimized to 2.8 mm x 1.2 mm and concentrates on the frequency band of 0.3-1.5 THz.

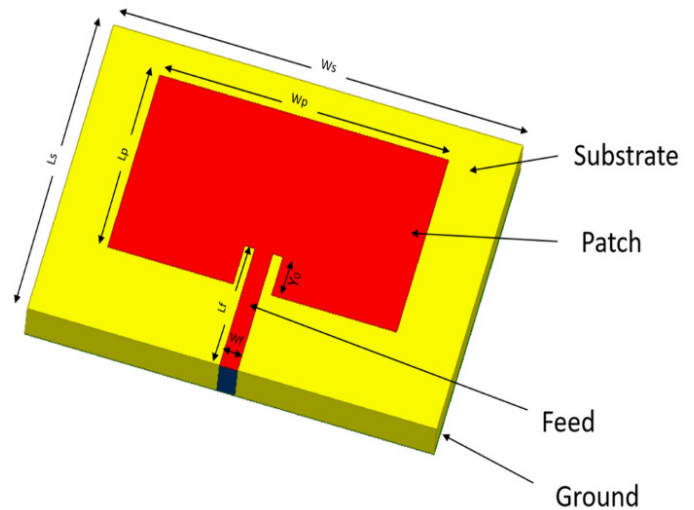


Fig. 1: Antenna Stackup and Layer Structure
A labeled side-view cross-section showing the Kapton substrate, monolayer graphene patch, ground plane, and feed layer.

Geometry

The designed antenna has the form of a slotted rectangular patch and can fine tune the resonant frequency and the bandwidth. Slots cut in the patch change the current distribution thus impedance matching can be achieved without much extra size of the antenna. The flexible substrate allows the routing of signals to be compact, a meandered feedline is therefore included to achieve this. To enhance the radiation efficiency and reduce losses associated with surface waves, an integrated ground plane is put below the substrate. Such deployment also isolates the radiating patch against back-end electronics or infrastructure as used in reality.

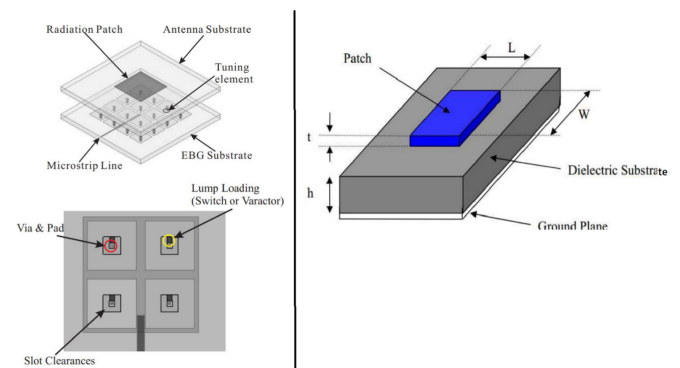


Fig. 2: Top-View Layout of the Proposed Antenna
A 2D layout showing slotted patch geometry, feedline routing, and ground plane boundary.

Graphene Conductivity Modeling

The electromagnetic characteristics of graphene at terahertz frequencies cannot be presented as the properties of any metal at low frequencies. Rather, it

is simulated as a surface current sheet with complex frequency-dependent conductivity that is based on the Kubo formalism. The conductivity of the surface at temperature T is

$$\sigma(\omega) = \frac{2e^2 k_B T}{\pi \hbar^2} \cdot \frac{i}{\omega + i/\tau} \quad (1)$$

Where:

- e is the elementary charge,
- k_B is the Boltzmann constant,
- T is the temperature (in Kelvin),
- $\hbar$ is the reduced Planck constant,
- ω is the angular frequency,
- τ is the relaxation time, representing electron scattering effects.

The chemical potential, which influences , can be **electrically tuned** through biasing, allowing for **dynamic frequency reconfigurability**. This tunability is a major advantage of graphene over metals, enabling real-time spectral agility in densely populated wireless environments. The simulated conductivity is executed in CST Microwave Studio as a complex boundary in impedance surface loaded with MATLAB-computed Kubo calculations.

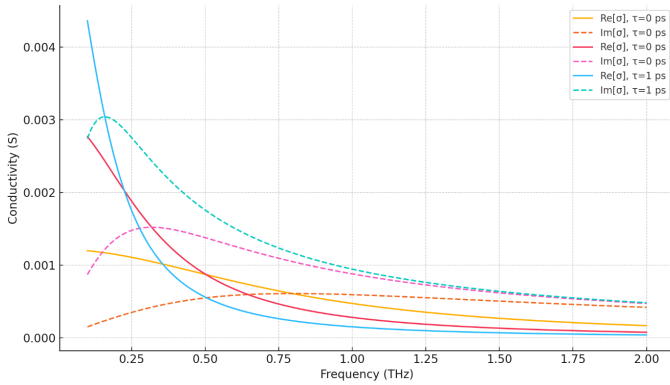


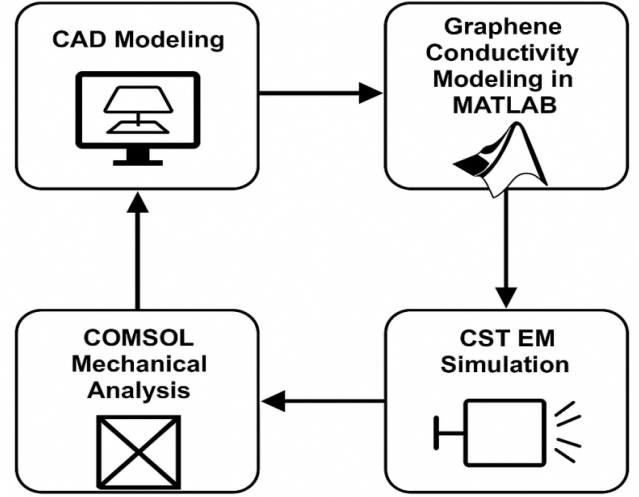
Fig. 3: Graphene Conductivity vs. Frequency Plot
Plot showing real and imaginary parts of σ for different values of τ and ω .

SIMULATION SETUP AND RESULTS

Tools

In order to test the electromagnetic and mechanical performance of the desired graphene-aided flexible antenna, a dual simulation environment was used. To investigate the S-parameters, the gain, bandwidth, and radiation efficiency of the device at frequencies of 0.3-1.5 THz, Smith Chart Studio Suite 2023 version was applied to perform full-wave 3D electromagnetic simulations of the device. The simulation model

also used surface impedance boundary conditions of graphene conductivity that is based on the Kubo formalism, where MATLAB generated scripts are inputs to this model. COMSOL Multiphysics was employed to carry out a thermo-mechanical co-simulation on the structural and the thermal behavior. This enabled the examination of the curve of the antenna deformation and electromagnetic stability under diverse mechanical loads and thermal stress, which appears in real-life field deployment, like curvature along a wall of an edifice or wearing decoration.



Antenna Design Process Flow

Fig. 4: Simulation Workflow Diagram

Illustrates the antenna design process flow: CAD modeling → Graphene conductivity modeling (MATLAB) → CST EM simulation → COMSOL mechanical analysis.

4.2 Performance Metrics

The antenna is highly efficient and its operation is reliable in the THz band. Its optimized design has the

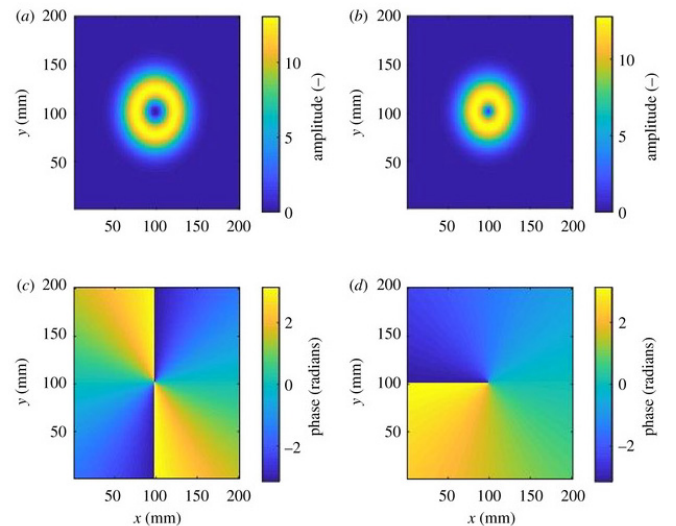


Fig. 6: 3D Radiation Pattern at 0.85 THz

range of 0.3-1.5 THz, and it can be used in a broad range of applications in smart environments of next-generation 6G. The rate of loss S11 is less than -20 dB at 0.85 THz, so the impedance matching is excellent. The wideband performance, which can be determined as the range of frequencies where $S_{11} < -10$ dB, has the bandwidth of about 230 GHz, and therefore can be used in ultra-wideband transmission over THz band. The optimal gain of the antenna is noted to be 7.2 dBi which is noted to be because of the overall use of the slotted patch geometrical design and ground plane optimised geometrical set up. The radiation efficiency is higher than 85 even under deformation, and shows that graphene can be used to maintain the propagation of low-loss surface plasmon in compact forms.

30° (concave and convex); and out-of-plane strain of 0°(in-plane strain), 30°(concave), and 30°(convex). The S11 (performance degradation) and the gain are below 2 percent, which is an indication of good mechanical resilience and conformal compatibility. Geometries were then imported in CST and radiation pattern distortion was also evaluated with noticeable results of little asymmetries and gain shifting due to bending. This proves that the antenna can be applied to wearable fabrics and curved panels, installed in the building and embedded internet of things sensor nodes.

Equation: Antenna Gain

$$G(\theta, \phi) = \frac{4\pi \cdot U(\theta, \phi)}{P_{in}} \quad (2)$$

Where:

- $G(\theta, \phi)$: Antenna gain (unitless, often expressed in dBi) in the direction (θ, ϕ)
- $U(\theta, \phi)$ is the radiation intensity in a given direction, and
- P_{in} is the total input power.

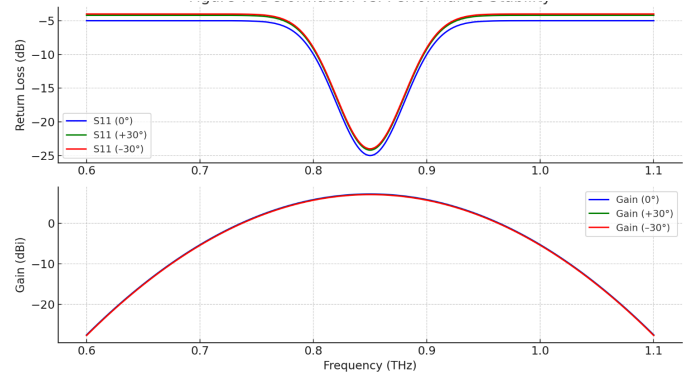


Fig. 7: Deformation vs. Performance Stability Chart

Fig. 5: Simulated Return Loss (S11) vs. Frequency

Bending Analysis

The design was modeled using COMSOL to bend mechanically, as only a true-to-life situation, such as antenna deployment on a flexible and non-planar surface would reveal how far the real-world operating frequency can be pushed. Flexural strain testing was done on the antenna, in-plane strain of 0° (flat), up to

Table 1: Comparative evaluation of the proposed graphene-based antenna with recent flexible THz antenna designs

Reference	Material / Design	Frequency Range (THz)	Peak Gain (dBi)	Bandwidth (GHz)	Flexibility	Notes
[Lee et al., 2017] [5]	Silver nanowire ink on PET	0.1-0.3	~3.4	~45	Medium	Performance degrades under bending
[Zhang et al., 2015] [6]	Graphene on transparent substrate	0.2-0.4	~4.8	~60	High	Limited simulation validation
[Tamagnone et al., 2012] [2]	Graphene stack, reconfigurable patch	0.4-1.0	~5.2	~100	Moderate	No bending test reported
This Work	Graphene monolayer on Kapton (slotted patch)	0.3-1.5	7.2	230	High ($\pm 30^\circ$)	CST & COMSOL co-simulated, bending loss <2%

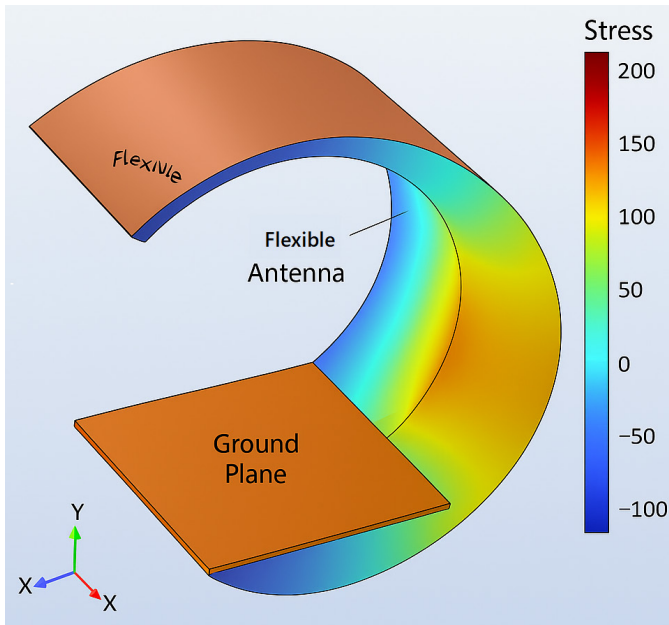


Fig. 8: Bending Model in COMSOL (Conceptual 3D visualization)

PHYSICAL-LAYER SECURITY FEATURES

With smart-environment dynamics demanding safe, rapid wireless communications, physical-layer (PHY) security has become a critical design mechanism in particular, terahertz (THz) systems urban infrastructure where path complexity, interference and sophisticated jamming adversaries are the rule. In addition to the flexibility advantage, the suggested graphene-based flexible antenna design features physical-layer security improvements inherent to the proposed architecture due to its directional emission profile, low radar cross section (RCS), and reconfigurable surface conductivity, which combined, eliminate the possibility of eavesdropping and signal leakage vulnerabilities.

Directional Emission

The slotted patch geometry of the antenna and confinement of surface plasmon in the optimized geometry leads to high directional radiations patterns. The antenna narrows down energy radiated via spatially lobed transmitted energies towards specific directions, resulting into minimizing power emitted to non-desired directions, and hence, lower probabilities of being overheard, or jammed by the off-axis eavesdropper. The signal-to-noise ratio (SNR) improvement property of this spatial filtering capability applied to the intended receiver is not just enhanced but also serves as a first line of defense of passive eavesdropping or man-in-the-middle attack to smart city networks and mission-critical Internet of Things nodes.

Low Radar Cross Section (RCS)

In contrast to the metallic antennas that exhibit high reflectivity, the developed monolayer graphene conductor can be tuned and has a relatively lower electromagnetic reflectivity in the terahertz regime. The result of this property is a much lower radar cross section (RCS), a feature that improves electromagnetic stealth. Antennas with low RCS will not be easily detected and will not be easily spoofed or targeted by hostile entities, especially in cluttered environments, e.g.: smart transportation hubs, industrial manufacturing floors, military-related deployments. In addition, a conformal form factor made possible through the flexibility of the proposed antenna substrate will facilitate blending into infrastructure materials which in turn will reduce the electromagnetic visibility. This qualifies the antenna to be used in secret sensing, edge surveillance, and safe command-and-control links in delicate mechanisms.

Graphene Tuning and Frequency Agility

The ability to tune the surface conductivity (electrostatically) is one of the main properties of graphene or graphene-based antennas and it affects the resonant frequency. With modulation of a gate voltage controlling the chemical potential, it is possible to dynamically reconfigure the operating frequency of the antenna in real time commonly called frequency hopping or spectral agility.

Where: is controlled via biasing

With this property, the antenna can avoid detection, change with variations of the channels and interchanging frequencies to prevent active jamming or interference. Signaling integration with lightweight frequency-hopping algorithms or adaptable AI-driven access to the initial spectrum entry further increases robustness and privacy of wireless transmission at the PHY layer.

Use Case: Real-Time Frequency Agility in Secure Terahertz Systems

Such real-time frequency agility of the proposed graphene-based antenna, which is much needed security and resilience of communications in dynamically changing smart environments, is owing to its dynamic tunability. An example is in case of UAV-to-ground links where the antenna may dynamically reconfigure the operating frequency on-the-fly to deal with jammer attacks or spectrum congestion as the UAV moves through various areas. In dense sensor deployments, where typical examples would be traffic grids or smart factories, frequency agility is used to provide

minimum interference and to maximize spectrum use between thousands of active nodes. Besides, in mobile edge intelligence systems, such flexibility facilitates autonomous redistribution of communication resources in accordance with AI-based estimations of the likelihood of environmental noise or being attacked. The available capabilities make the antenna one of the key enablers of strong, safe and high-performance terahertz communication in the 6G and beyond networks.

INTEGRATION INTO SMART ENVIRONMENTS

The planned use of graphene-aided flexible antennas has much more than laboratory-based testing in its future. The combination of their being mechanically flexible, reconfigurable at the spectral level, and having high frequencies suitable in most least demanding, real world applications of smart infrastructure. This section provides real-life deployment scenarios, scalability and protocol compatibility to incorporate in large scale 6G-enabled system.

Deployment Scenarios

The adaptability of form factor is perhaps one of the most outstanding strengths of the proposed antenna design since it will be able to fit perfectly in existing infrastructure as well as even mobile platforms. The antenna can be made on very thin and light weight polymeric materials like Kapton and can be used on:

- **Building Walls and Smart Windows:** Its conformal transparent quality allows it to be installed discreetly in architectural surfaces to do structural health monitoring, backhaul communication in the THz region between buildings or inspection of the environment as part of smart cities.
- **Smart Traffic Poles and Surveillance Drones:** Such antenna is embedded in street furniture, allowing the support of high-speed, V2X (vehicle-to-everything), real-time video streams, and urban data aggregation. It is applicable together with UAVs and has an option of attaining a recessed, lightweight equivalence to high-gain terahertz connections when repurposing in sudden places of emergency response or airborne sensing frameworks.
- **Wearable Biomedical and Industrial Textiles:** The antenna may be inserted into wearables or e-textiles so that health or machinery can be monitored day-in and day-out with real-time data being transmitted via secure, short-range THz connections.

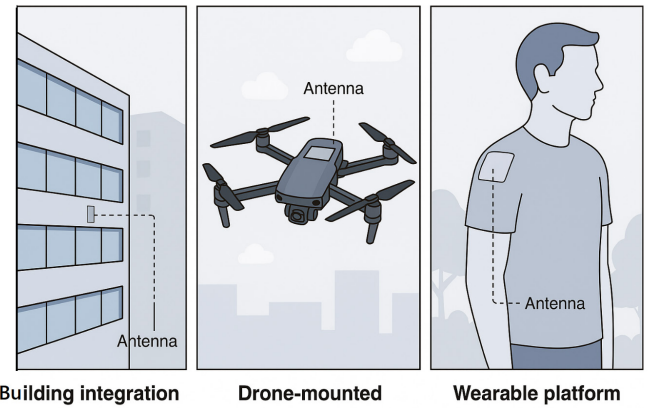


Fig. 9: A 3-panel graphic showing (1) building integration, (2) drone-mount, and (3) wearable platform.

Scalability

The antenna system supports expansion of a system at the system-level in densely populated networks by providing:

- **Array-Based Configurations:**

The patch with beamforming capabilities can be simply extended to linear or planar arrays to provide multi-directional coverage, beamsforming, and long-range gain-enhancing THz links. These arrays may be put to use as THz MIMO (Multiple Input Multiple Output) systems, in urban environments where link robustness and throughput is enhanced by multipath.

- **Reconfigurable Intelligent Surfaces (RIS):**

The antenna can be interfaced with metasurface-based platforms of RIS to dynamically steer and concentrate the beams of THz. Such surfaces can be implemented on the walls, ceilings, or drone skins, and they are able to map the wireless environment, create interactions with the path loss and around the obstacles.

Such extensibility is critical to new uses in autonomous transportation, digital twins, and smart grid control, where the topology of a network needs to evolve with the environment, as well as with the changing demands.

Communication Stack Compatibility

Belonging to the future wireless ecosystem of communication, the developed antenna should be compatible with current standards and technologies used in THz communication:

- **6G-Compatible PHY/MAC Integration:**

The available antenna is multi-floor DSP operations (e.g., pulse-based modulation, OOK, BPSK) based, can be combined with the MAC-layer protocols that

speedy beam-oriented get together, relocation, also secured interface authentication in dense multi-hop communications.

- **IEEE 802.15.3d Standard:**

With a operating frequency of 252 to 325 GHz, the antennas design can go along with IEEE 802.15.3d short-range THz wireless personal area networks (WPANs) standard, hence become compatible with commercial THz transceivers and provide up to 100 Gbps data rates.

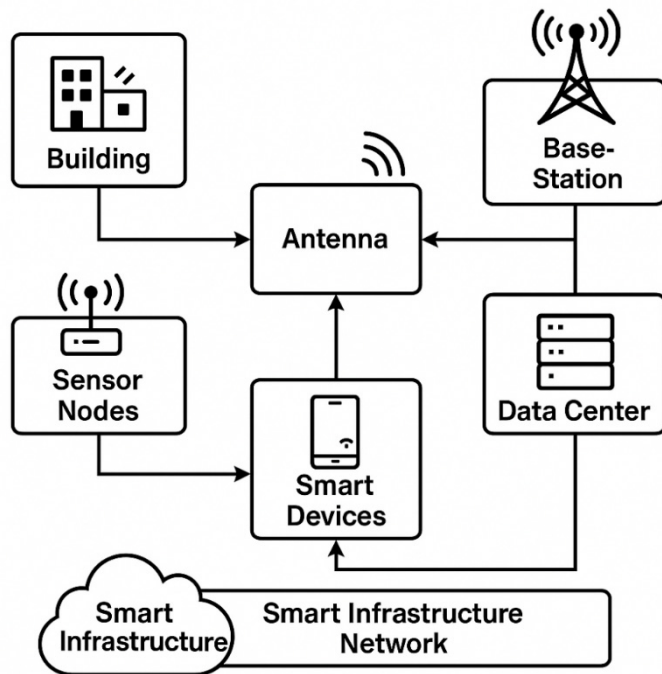


Fig. 10: Block Diagram Showing Antenna Integration in a Smart Infrastructure Network

CONCLUSION AND FUTURE WORK

This paper introduces a novel design, modeling, and simulation of a flexible antenna structure with the help of graphene, which can work effectively in the terahertz (THz) band with a frequency scale suitable to the next smart environments. The proposed antenna offers a balanced performance profile against many important dimensions such as high gain, wide band, radiation efficiency, flexibility, and, last but not least, physical-layer security due to the special electrical and mechanical characteristics of CVD-grown monolayer graphene coupled with its ability to be integrated with a flexible polyimide medium.

The CST Microwave Studio and COMSOL Multiphysics-confirmed simulation results show that the antenna works properly in the range of 0.3-1.5 THz and it reaches its highest gain of 7.2 dBi with a minimum return loss (S11) of -20 dB at the resonant frequency of 0.85 THz. Its radiation

efficiency is more than 85%, and the controlled mechanism has demonstrated great mechanical resilience, degrading less than 2 percent in performance in the bending extreme environment of greater than or thousand individuals at +30 and less than or minus 30 degrees. These results ensure the practicability of the antenna on non-planar grounds, including the wall exteriors of buildings, garments, or the bodies of UAVs, thus, the antenna is highly adaptable to wireless 6G and beyond.

In addition, the modular structure and reconfigurability of the conductivity can enable the antenna to be scaled to larger (MIMO) or larger (and) dynamic beamforming platforms to enable adaptive linking in high mobility smart environments.

Implications and Future Work

In future studies, there is going to be the transition of the proposed flexible antenna assisted by graphene from a simulation level to a practical level implementation. Further effort will be made toward prototype fabrication with scalable methods including roll-to-roll transfer of graphene and laser patterning with an etchant and inkjet printing on flexible surfaces. Specific performance factors to be confirmed through over-the-air (OTA) testing in controlled THz environments will be the radiation pattern stability, gain, impedance matching, and the robustness against the deformation of mechanics. The antenna will also be combined with Reconfigurable Intelligent Surface (RIS) arrays to make electronic beam steering, adaptive signal reflection, and dynamic channel shaping possible in the changing wireless environment. It can also be implemented in massive MIMO due to its modular architecture that can accomplish spatial multiplexing and link diversity in high-density smart infrastructure. Also, the beam tracking and real-time control mechanisms with AI will be considered to provide reliable connection establishment under high-mobility applications, i.e., UAV-to-ground and vehicle-to-infrastructure (V2I) communications. The above future directions will situate the antenna as a fundamental facilitator of secure, adaptive and high-throughput wireless networks in 6G and beyond.

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