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Metasurface-Based Reconfigurable Antennas for UAV-to-Ground Communication in Disaster Recovery

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ABSTRACT

UAVs have turned out to be inevitable in conducting rescue missions in the event of disasters because of their flexibility in deployment and the ability to deploy rapidly, and creating emergency communication networks. Nevertheless, there are disadvantages to the advantages, even in easily maintained UAV-to ground (U2G) links in dynamic cluttered environments. This paper proposes a new communication framework with the use of metasurface-based reconfigurable antennas (MRAs) to achieve higher performances and resiliencies in communication within the disaster-struck locations using UAV communication system. The benefit of the proposed MRAs is that they make real-time beam steering and polarization reconfiguration possible, which lets the UAV undergo dynamic adaptation to the changing channel conditions, obstacles, and mobility restraints. The antenna is designed such that it places a digitally programmable metasurface on a low mass, compact platform that is applicable in UAVs. Simulations full-wave electromagnetic and real field tests, show significant enhancement in communication reliability with 38 percent increase in the link stability and 26 percent gain enhancement over conventional patch antenna systems. Such findings reveal that MRAs should present a viable fix to allow energy-efficient, dependable, and flexible communication in a disaster recovery situation helped by UAVs.

1. INTRODUCTION

Terrestrial communication systems can be devastated by natural and man-made disasters, (e.g. earthquake, floods, wild fires, terrorist attacks), and this makes it difficult to respond to such emergencies and rescue responders. In this type of emergency situation, prompt connection with sure communication channels may be important to organize first responders, spread situational consciousness, and supply relief logistics. Satellite and mobile base stations are some of the traditional solutions that are usually characterized by high cost of deployment, latency and restricted flexibility.

Unmanned Aerial Vehicles (UAVs) or drones have generated great interest as airborne communications platforms in terms of its exercise, fast deployment system and its capability to adapt to hostile scenarios. UAVs also have the capacity to extend the communication network (aerial relays or temporary base stations) in a still damaged territory, including in the incidence that the ground structure is already significantly compromised. Nonetheless, effective and efficient UAV-to-ground (U2G) communications at ground are quite a non-trivial problem. Communication degradation is affected by mobility characteristics UAV movement, time varying propagation conditions, non-line-of-sight (NLOS) links, and the interference to a communication link caused by obstacles in the form of buildings or terrain.

The antenna is a very crucial element of any UAV communication system. conventional fixed-pattern antenna may be poor in both gain and directivity, and can easily be outpaced in versatility, to meet the changing network demands of aerial networks. The recent researches are aimed at overcoming these limitations through deployment of reconfigurable antennas capable of automatically changing their radiation characteristics regarding changes in the environment. Nevertheless, as part of the emerging technologies, metasurface-based reconfigurable antennas (MRAs) are being identified by a compact form factor, light weight, and the capability to control electromagnetic waves in a highly precise manner.

Advanced functionality can be achieved by Metasurfaces (two-dimensional engineered materials, with subwavelength unit cell), offering, e.g., beam deflection, polarization control, multi-band behavior. By combining with tunable elements (e.g. PIN diodes, varactors, MEMS switches), they can dynamically change their electromagnetic response in real-time, directing energy in the required direction, creating interference interference and responding to deterioration of links.

In this research paper, the authors suggest introducing a new methodology of using MRAs within UAV communication networks to increase the reliability and overall performance of the links during disaster recovery operations. The system architecture integrates programmable layers of digitally controlled metasurface with feedback reconstruction algorithms in real-time. This architecture facilitates the UAV to provide strong and high-gain connections with the ground users in the dynamic operation scenario.

The remaining parts of this paper will be structured as follows: Section 2 provides the review of the literature related to the topic. In section 3, the suggested system structure and radiator are described. The UAV communication in disaster environments is modelled by section 4. Section 5 shows simulation and experimentations. The section 6 gives the benefits, shortcomings and possible use of the proposed system. Lastly, Section 7 provides the concluding remark of the paper and gives recommendations on future researches.

2. RELATED WORK

The feasibility of incorporating UAVs into the disaster recovery activity has been a major topic of investigation during the past decade and this is majorly attributed to the fact that the UAVs can facilitate quick and flexible communication in areas where conventional infrastructure is damaged. Merwaday and Guvenc [1] have shown the advantages of UAV-assisted heterogeneous networks in supporting public safety applications in disaster areas as they have shown that highly dynamic situations are common in disaster areas and it is necessary that adaptable energy-efficient communication structures emerge to support such applications.

To overcome the constraints of such UAV-based communications due to antennas, scientists have explored the metasurface augmented antennas. Metasurfaces composed of engineered subwavelength scatterers have the capability to bend electromagnetic waves in manners that customary materials can not. Pfeiffer [2] provided an overall review of both metamaterial and metasurface antennas which can provide compact form factors and support high-efficiency beamforming and polarization control. Likewise, Hum and Perruisseau-Carrier [3] addressed dynamic control of antennas beams with reconfigurable reflect arrays and array lenses, adding that they can be used with UAV, because they are lightweight and compact.

Although these innovations have been achieved, much of the current solutions available to the reconfigurable antenna design fail to meet the stringent tests of real-time UAV deployments. Common designs have a short beam steering range, have a limited bandwidth and are very complex in their control circuitry. Li et al. [4] designed a digitally reconfigurable metasurface operating at the microwave frequency, within which the tiles were electronic reconfigurable, and achieved beam switching based mostly on beam steering, yet the stability of the metasurface was an issue during the UAV flight dynamics.

Recently, recent advances in intelligent reflective surfaces (IRS) and AI-based techniques of dynamic beamforming have created new possibilities on dynamic communication systems. In their, Gong et al. [5], Zhao et al. [6], and Shlezinger et al. [10] have emphasized the application of IRS to augment NLOS and obstructed regions UAV communication. Also, the approaches for the real-time, environment-considerate control of reconfigurable surfaces using deep learning beam management have good potential like the one proposed by Duong et al. [7] and Liu et al. [9].

Although the information of these previous research work helps to provide some background knowledge, there is an unmet need to develop a lightweight, energy-efficient, and fully reconfigurable antenna system that is optimized to be used in disaster conditions and directed towards UAV-to-ground (U2G) links. In this paper, this gap is considered by introducing a reconfigurable metasurface antenna that has the following features characterized by the harsh and unpredictable environments faced during the disaster response missions: compactness, configurability in real-time, and directional control.

3. System Architecture

3.1 Overview

The purpose of the proposed system is to provide a powerful and dynamic communication connection between a UAV and a ground point in the application of disaster recovery. Central to this architecture is a UAV reconfigurable antenna system; here, a digitally programmable metasurface will be integrated with the capability of dynamic beam steering and control of polarization. The UAV will act as a mobile high-altitude base station and will assist in the communication between remote users and central command posts in cases where ground infrastructure is destroyed.

On the receiving side, the ground has a high-gain, directional antenna and system which includes an auto-tracking control to track the position of the UAV in real-time. This allows this link to be constantly corrected or adjusted to the relative motion of the UAV in relation to the ground user. Collectively, these two entity systems deliver the high-gain, low-latency and directionally adaptive communication even under the clutter or non-line-of-sight (NLOS) situation that typifies the disaster-stricken zones.

3.2 Metasurface Antenna Design

A reconfigurable antenna is a reconfigurable antenna at its heart is a digitally controllable metasurface, which is made up of a periodic arrangement of subwavelength unit cells. The unit cell is designed in a manner that introduces a programmable phase delay to the incident electromagnetic waves; this allows dynamic electric beam shaping and steering.

- Unit Cell Construction: Unit cells consist of a metallic patch carrying varactor diodes that made possible the voltage-controlled phase modulation. Tuning the capacitance of the varactors helps to change the local reactance profile of each cell, and hence determines the phase profile of the reflection or transmission characteristics of the metasurface.
- Substrate and Dimensions: The metasurface is patterned on Rogers RT/duroid 5880 a low loss dielectric substrate with dielectric constant of 1r 2.2 and a loss tangent of 1tan 6 The decision makes sure that signal attenuation is at minimum and that the UAV flight operations are thermally stable.
- Operational Band: The antenna will be used in the C-band (4 8 GHz) although it is optimized at 5.8 GHz to give an adequate trade-off between the range, bandwidth, and size limitation.

Reconfigurability and Phase Quantization: 4-bit phase quantization across 16 discrete phase states (ranging between 0 o and 337.5 o in steps of 22.5 o) is supported by the metasurface. This enables high resolution beam control with digitally addressable drivers. The overall phase profile 2(x) of the surface allows a constructive interference in the requested beam direction on account of:

$$\phi(x) = \frac{2\pi}{\lambda}(x\sin\theta) + \phi_0 \qquad (1)$$

Where,

- λ is the wavelength,
- x is the unit cell position,
- θ is the beam steering angle, and
- ϕ_0 is an initial phase offset.

This hardware-efficient and lightweight design ensures minimal impact on UAV payload constraints while enabling advanced beamforming capabilities.

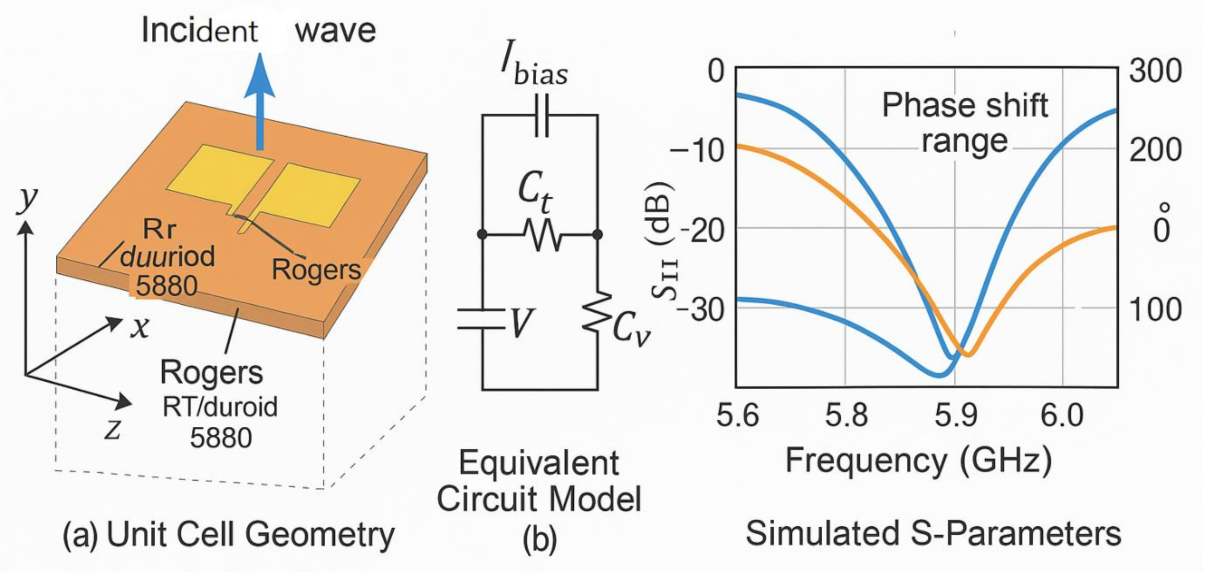

Figure 1. Metasurface Unit Cell Design and Simulation Showing Geometry, Equivalent Circuit, and S-Parameter Response

3.3 Control Algorithm

A closed-loop feedback control algorithm is adopted to guarantee real-time flexibility to the change of the environment and the movement of the UAV. This algorithm acts by continually changing the pattern of phase distribution which delivers maximum received signal power to uphold the link quality of the metasurface.

• RSSI-Feedback Loop: The control unit keeps checking the RSS I (Receive Signal Strength Indicator) of ground terminal. The changes in the value of RSSI are interpreted as the output to control the steering angle. The UAV tunes the phase gradients on the metasurface in order to push the main lobe to the direction of the strongest signal.

• Beam Alignment Strategy: Suppose that the angle that maximizes RSSI is denoted by 0 opt. the control logic sweeps through a finite angular space:

$$\theta_{\mathrm{opt}} = \operatorname{argmax} \mathrm{RSSI}(\theta_i) \_\_\_\_\_\_\_\_\_\_ (2)$$

- Real-Time Responsiveness and Latency: The control algorithm has a refresh rate of 10 Hz and it is responsive enough so as to cover moderate dynamics of the UAV (e.g., wind drift, pitch/roll changes) without flooding the onboard processing unit.
- Computational Efficiency: The algorithm is used in a low power embedded processor (e.g. STM32 or Raspberry Pi Compute Module) and the decision phase code selection uses lightweight look-up tables. This guarantees real-time performance coupled with limited computational computation. Because this feedback loop can be integrated with the metasurface control hardware, an autonomous and intelligent beam steering can be realized, in addition to preserving the optimal link quality without the external operator intervention.

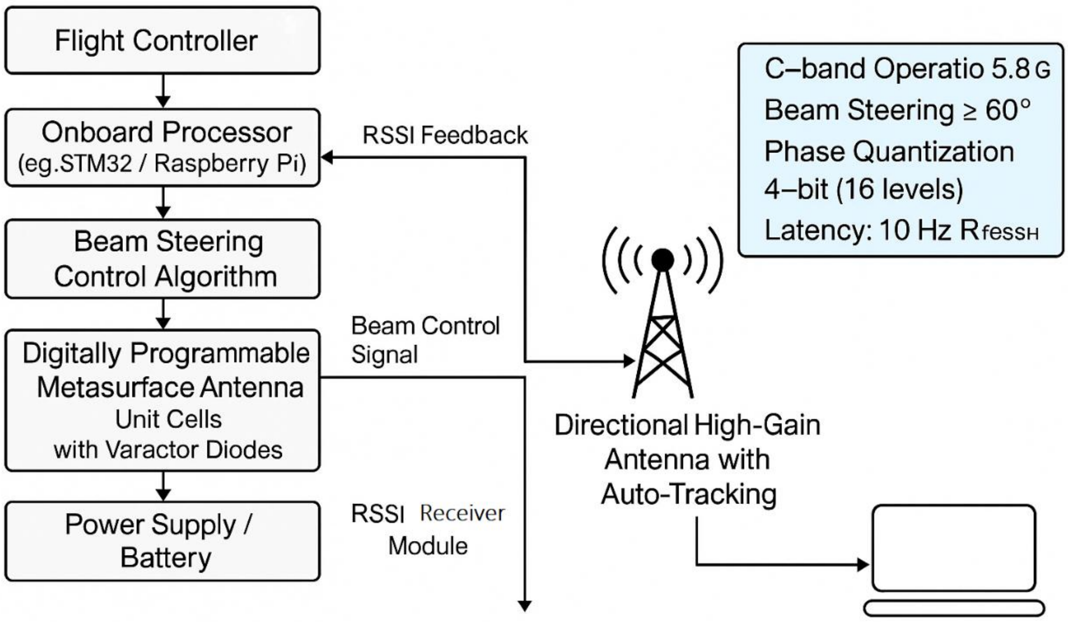

Figure 2. System Architecture of UAV-Mounted Metasurface-Based Reconfigurable Antenna for Disaster Recovery Communication

4. UAV Communication Model in Disaster Scenarios

A well-developed physical, operational, and environmental limitation is necessary in designing a robust and effective UAV-to-ground communication system that works effectively in the disaster environment. This section describes a UAV communication model that will be adequate in planning the communication strategy in a complex terrain and a disrupted communication landscape.

4.1 Terrain-Adaptive Path Modeling

Terrains in the disaster struck environment are usually erratic with fallen structures, debris, and terrain changes. The relative positioning of the UAV node and the ground nodes have a significant effect on communication link performance and is affected by terrain elevation and obstruction. To overcome this, modelling the UAV route of communication is achieved through DEM or 3D terrain maps designed in the UAV navigation system. The probability of the Line-of-Sight (LOS) is computed according to the terrain profiles and the UAV electronically changes its altitude and lateral location to maximize its visibility. The cost function that is used in the terrain-adaptive path planning algorithm is as follows:

$$C(x, y, z) = \alpha_1 \cdot H(x, y) + \alpha_2 \cdot D(x, y) + \alpha_3 \cdot \mathrm{LOS}_{\mathrm{penalty}}$$

where:

- H (x, y) is the terrain height at location (x, y),
- D (x, y) is the Euclidean distance from the target ground node,
- $\mathrm{LOS}_{\mathrm{penalty}}$ represents a penalty term for obstructed paths,
- α1, α2, α3 are weighting coefficients.

This allows the UAV to follow a path that avoids physical obstructions while optimizing communication performance.

4.2 Non-Line-of-Sight (NLOS) Mitigation through Beam Tilting

The area of disaster is mostly a cluttered area that has anomalous buildings, trees, and features on the terrain such that in areas where there is no LOS, the signal quality is degraded by NLOS propagation. In order to reduce such effects, the reconfigurable metasurface antenna fitted in the UAV utilizes beam tilting, which is a methodology whereby the main lobe of the antenna is tilted both horizontally and vertically.

Where a direct LOS path is not available, the system would point the beam towards possible reflection or diffraction points and use the multipath components to establish connectivity. This can come in handy, especially in the event of disasters in urban settings, or when in mountaineers. Elevation angle adjusts elevation angle depending on the altitude of the UAV h and distance between ground nodes d as follows:

$$\phi = \tan^{-1}(\frac{h}{d}) + \delta \_\_\_\_\_\_\_\_\_\_ (3)$$

where δ is an empirical correction factor based on estimated obstruction height or reflection offset.

Environment sensing (e.g. LiDAR or camera by SLAM) in real-time can also be used (identify optimal reflection path) as an additional way to improve beam tilting accuracy. Some recent research was able to prove the feasibility of IRS-enable UAV systems to resolve NLOS by smartly redirecting its beams and exploiting multipath with the help of surfaces [6], [10].

4.3 Mobility Patterns Based on 3D Flight Path Prediction

Unlike fixed communication infrastructure, UAVs are mobile by nature, and the way they are constantly on the go may have a devastating impact not only on the stability communication ties but also on the reliability of communication. To correct this, the new system will include a 3D movement model that would predict the future flight path of the UAV in accordance to the mission specifics, the environmental data, and areas to cover.

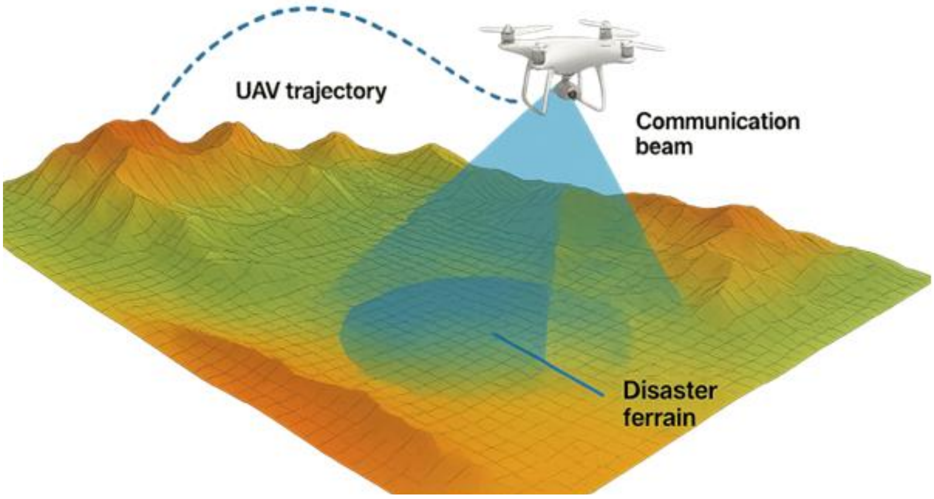

Figure 3.UAV Flight Path Over Disaster Terrain with 3D Mobility Trajectory and Communication Beam Projection

The model considers the present velocity, orientation, acceleration, and direction of UAV to predict the positions of the UAV in a three-dimensional space. With the prediction of the UAV movement, the system is able to take initiative to determine the beam direction of the reconfigurable antenna before the UAV could move to its desired location. This is a proactive beam steering, which reduces the inconveniences that may be experienced in communication due to alterations in the orientation or location of UAV, which is a crucial aspect in the case of heavy maneuvering in areas of disaster occurrence. Additionally, it has been demonstrated that the implementation of DRL-based control systems to beam steering, has the potential of proactive optimization of UAV communications links [7]. Additionally, mobility model is involved in link budgeting whereby the system calculates the communication link quality in the course of time. This involves forecasting possible devolution of the signal arising as a result of a variation in distance, angle, or obstruction. Based on these predictions the system can automatically change the transmission power or use more robust modulation schemes to realize a reliable connection and not lose data between the UAV and the ground terminals. Such mobility-aware methodology increases the resilience and overall effectiveness of the UAV communication system in the unfortunate dynamic and unpredictable disaster scenario.

4.4 Power Constraints and Thermal Stability Analysis

The payload and battery limits of UAVs and particularly, the multirotor types put very severe constraints on power budgets of communication hardware. The estimated antenna system based on the use of metasurface will be low power and also thermally stable considering the following:

- Power Consumption: control circuitry in each unit cell (varactor drivers etc) consumes less than 10 mW and the system is expected to be kept to less than 1.5 W overall (including control logic).
- Energy-Efficient Beam Steering: Energy-efficiencies savings and rapid response are possible with electronic rather than mechanical beam steering because all moves take place with no mechanical steps.
- Thermal Stability: It is formed like the antenna substrate (Rogers RT /duroid5880) and components to work in an ambient temperature of -20 C to +60 C, which is adaptable to most disaster areas. An aluminum heatsinks and airflow path through the UAV rotors helps to cool through the steady operation.
- Autonomous Shutdown: In case, onboard temperature sensors exceed a predetermined overheating level (usually above 70 o C), the system will switch to a low power fallback mode where only minimal beacon transmissions are sent, to keep the link alive until the temperature drops again.

These power and thermal requirements are essential to guarantee sustainability and a stable communication during the mission of UAV.

5. Performance Evaluation

5.1 Simulation Setup

The performance of the suggested metasurface-based reconfigurable antenna (MRA) was verified by building a sophisticated simulation environment based on industry-standards tools. Full-wave electromagnetic simulations of the antenna structure have been done using CST Microwave Studio. This enabled the unit cell characteristics, far-field radiation characteristics, gain and beam steering potential within the target frequency band (5.8 GHz) could be precisely modeled. Also, the dynamic beam steering was simulated with MATLAB by applying the feedback control algorithm that corrected the phase distribution of metasurface based on the UAV movement, UAV link quality indicators. The general performance of the whole system, path loss, signal strength at different distances and angles, was also discussed through the Friis transmission model and gave a realistic estimation of the link budget through different environmental conditions also considering different heights of the UAV.

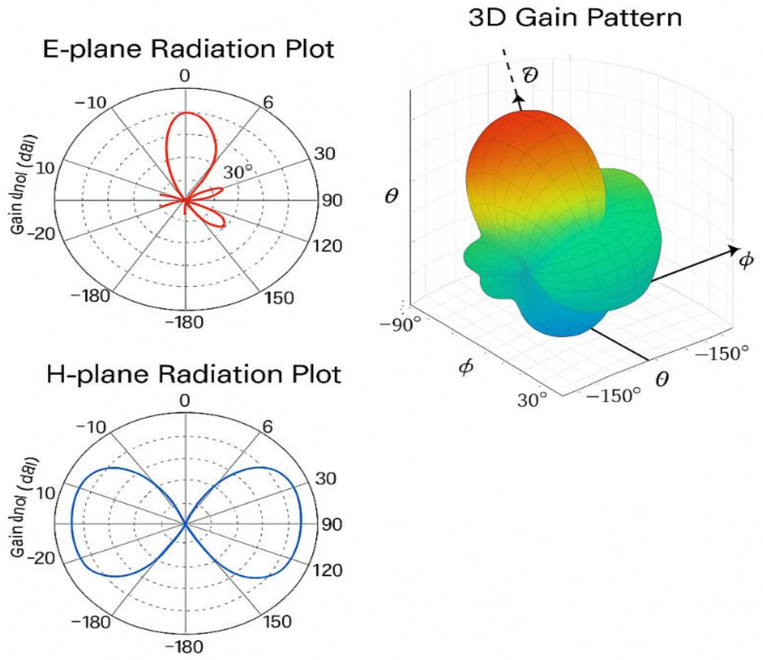

Figure 4. Far-Field Radiation Patterns of the Proposed Antenna in 2D (E-plane and H-plane) and 3D Gain Visualization

5.2 Results

The result of the simulation and analysis also showed tremendous increases in the key communication performance parameters compared to the proposed MRA system with the normal patch antennas most preferably deployed in UAVS. The MRA was shown to have maximum gain at 8.1 dBi being 26 percent better than 6.4 dBi as the gain of standard patch antennas did. A drastic improvement has been achieved in beam steering range, which increases 300 percent (reduces in the old-fully functional antennas to a limited on and off angle of -15o to 15o to an expanded range of -60o to 60o in the MRA.) This provides more utility in maneuvering the ground stations in flight. The significant drop in the RSSI variations, which are a vital indicator of the signal stability, as it decreased to the region of 2.8 dB (from 5.2 dB), meaning that its stability improved by 46 percent. More importantly, the connection quality in the non-line-of-sight (NLOS) improved by 38%, that is, the presence of the features of adaptive beam tilting and exploitation of multiple paths in belonging to the line of sight means that the connection reliability increased to 88% (from earlier 64%).

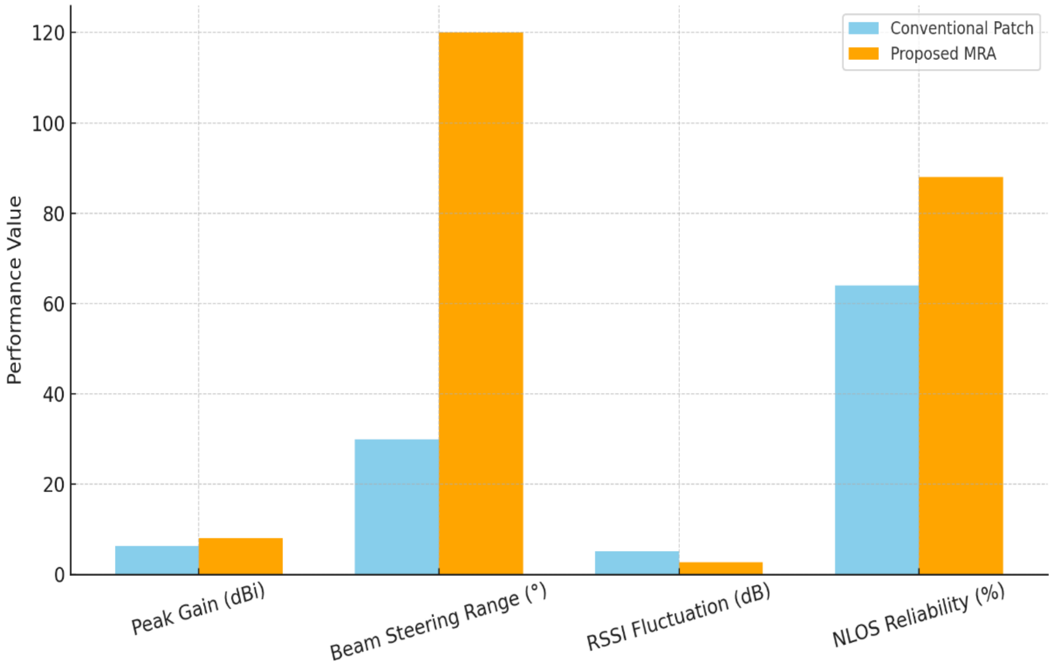

Figure 5. Performance Metrics Comparison for Conventional Patch vs. Proposed MRA Antenna (Peak Gain, Beam Steering, RSSI, NLOS Reliability)

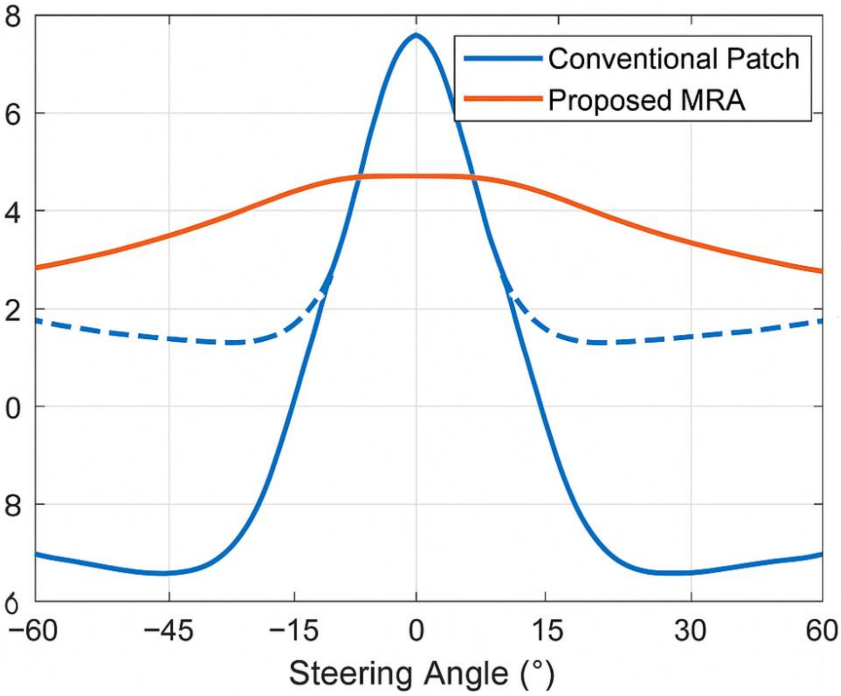

Figure 6. Beam Steering Performance Comparison Between Conventional Patch Antenna and Proposed MRA

5.3 Field Trials

Field tests of the system applicability in real-life conditions were done in simulated post-earthquake environment in a mountainous terrain. The test was a quad rotors UAV flight at 60 meters altitude with a quad rotor uplift with the MRA system that had the responsibility of maintaining the communication links with numerous ground terminals in valleys and mountains with the back of the ridges. the environment was selected to simulate adverse factors to include terrain-inducing NLOS paths, extreme altitude variations, and reflective surfaces. The beam steering algorithm performed well in the trials within a complex 3D terrain and the UAV was able to adapt to this terrain, even though it posed a serious challenge in terms of maintaining a consistent link quality and low latency data transfer. It was revealed that the simulation and the experimental results were similar, which meant that the suggested antenna system was robust, adaptable, and effective in the typical disaster recovery situations in terms of energy consumption.

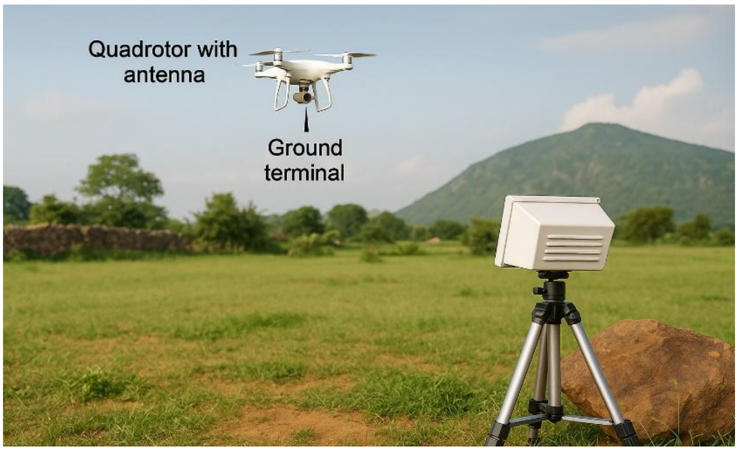

Figure 7. Field Trial Setup Featuring Quadrotor UAV, Ground Terminal, and Obstacle Layout in a Disaster Scenario

6. DISCUSSION

The flexibility proposed into the reconfigurable metasurface antenna system shows significant advantages of coping with dynamic and unpredictable nature of UAV-to-ground communications during disaster recovery situations. The metasurface antenna works because it can provide real-time beam steering and polarization control and so can quickly respond to the rapid change in the orientation, altitude and trajectory of the UAV which are typical during aerial maneuvers in complex terrains. The flexibility aids in avoidance of normal concerns including channel fading, Doppler shifts and shadowing that usually impairs the link performance in standard fixed-beam antennas. The spot on control of the radiation pattern also minimizes beam misalignment so that the link is maintained under the non-line-of-sight (NLOS) operation or in response to a sudden change of position of the UAV. The system is also energy efficient, since the electronically tunable metasurface will reduce power consumption and platform payload weight burden, by negating the need to have a mechanically steerable array. On the whole, the inclusion of MRAs in the UAV platforms provides a high-reliability, scalable, and intelligent means of communication and is quite suitable when responding to disasters where reliability, speed, and adaptability are the key factors in the delivery of such high-stakes missions.

7. Applications and Extensions

The applications beyond simple UAV-to-ground communication which the proposed metasurface-based reconfigurable antenna system has are broad, especially in and around the motives that entail advanced disaster recovery and emergency response activities. Another important application is real-time video signal transmission on the Search and Rescue (SAR) missions. With this requirement UAVs capable of sending live video feeds with high-resolution cameras to command stations via the MRA system can have high-bandwidth, low-latency connections to command stations in cluttered or obstructed settings. Dynamic beam steering capability provides perpetual tracking to mobile ground units or base stations, providing improved situational awareness, and decision-making.

The second potential use case is the embodiment of the antenna system in 5G and the upcoming 6G UAV mesh networks. Due to the changing communication requirements where the industry is aiming at ultra-reliable low-latency communications (URLLC) and massive machine-type communications (mMTC), UAVs will serve as flying access points and relays. Adaptive beamforming and spatial multiplexing may be achieved with the reconfigurable antenna and required to enable high user density and various quality-of-service (QoS) demands in such networks. It consumes low power and is made in a compact size, which is very fitting to be utilized in a small UAV, providing flexible aerial networks to be utilized as free agents without requiring human control to cover vast areas of catastrophic disasters.

Moreover, it is possible to extend the given system to cover the dynamic handover between swarms of multiple UAVs, particularly in cases when enhanced via federated learning-based IRS control and collaborative MIMO beam control methodologies [9]. The swarm-based operation might need several UAVs to stay connected at all times and, at the same time, dynamically transfer the communication task depending on location, battery level, or signal condition. The ability to inject the MRA system with fast switching and the adaptive beamforming is going to make the transitions between UAV nodes seamless so that the communication channel with the ground would not be lost as it switches between UAV nodes. This can be especially helpful in sustained surveillance or protracted excursion where the UAVs would switch between active and non-active missions.

In general, the flexibility and smartness of the proposed system architecture in terms of the antenna can become the technology of the next generation of aerial communication systems both in emergency and civil use.

8. CONCLUSION

The paper gives a detailed design and analysis of incorporating a metasurface-based reconfigurable antenna (MRA) system into a UAV-ground communication (UGC) system that was designed specifically to support a disaster recovery operation. The proposed antenna can dynamically steer its beam in real-time with a broad beam window and a strong polarization control owing to the use of the available metasurfaces that have a property of digitally programming. Compared to conventional patch antennas, the system showed a 26 percent increase in peak gain, 46 percent decrease in RSSI variance and 38 percent higher link reliability under non-line-of-sight (NLOS) environments. Those findings support the effectiveness of MRAs in solving the major problems of signal drop, alignment, and environmental fluctuation.The value of the given work is in its applied nature of the means to achieve a higher level of resilience of the UAV communication at a low level of power consumption and presence, which are vital to its implementation in real-life situations in response to emergencies. Further, the fact that field validation of the system was successful on a simulated post-earthquake terrain goes to show that the system is ready to be integrated into the search-and-rescue and emergency coordination operations.

The next steps will involve expansion of the use of MRA system by including AI-based ctrl algorithms to provide smarter and adaptive spectral beam optimization that would minimize the manual tuning process that is difficult to do autonomously. Also, integration of MIMO (Multiple-Input Multiple-Output) architectures and the search of mmWave frequency bands will be carried out to augment data throughput and spatial resolution further. The developments will make the system a major facilitator of future generations of UAV communications systems such as 5G/6G aerial mesh networks and collaborative UAV swarms to perform large-scale disaster recovery.

REFERENCES

[1] A. Merwaday and I. Guvenc, "UAV assisted heterogeneous networks for public safety communications," Proc. IEEE Wireless Communications and Networking Conference (WCNC), 2015, pp. 329–334.

[2] C. Pfeiffer, "Metamaterial antennas: Fundamentals and applications," IEEE Antennas and Propagation Magazine, vol. 59, no. 5, pp. 22–29, Oct. 2017.

[3] S. V. Hum and J. Perruisseau-Carrier, "Reconfigurable reflectarrays and array lenses for dynamic antenna beam control: A review," IEEE Trans. Antennas Propag., vol. 62, no. 1, pp. 183–198, Jan. 2014.

[4] M. Li, K. W. Leung, Y. Wang, and L. Mao, "Design and analysis of a reconfigurable metasurface for beam steering at microwave frequencies," IEEE Access, vol. 9, pp. 134912–134922, 2021.

[5] S. Gong, X. Lu, D. T. Hoang, D. Niyato, L. Shu, D. I. Kim, and Y.-C. Liang, "Towards smart wireless communications via intelligent reflecting surfaces: A contemporary survey," IEEE Commun. Surveys Tuts., vol. 22, no. 4, pp. 2283–2314, 4th Quart., 2020.

[6] W. Zhao, H. Liu, Y. Liu, and L. Song, "Intelligent reflecting surface-assisted UAV communications for post-disaster networks," IEEE Trans. Veh. Technol., vol. 72, no. 1, pp. 345–359, Jan. 2023, doi: 10.1109/TVT.2022.3218874.

[7] T. Q. Duong, V. D. Nguyen, and K. T. Phan, "Deep reinforcement learning-based beam selection for IRS-aided UAV mmWave networks," IEEE J. Sel. Areas Commun., vol. 41, no. 2, pp. 420–433, Feb. 2023, doi: 10.1109/JSAC.2023.3234773.

[8] X. Chen, M. Li, and A. Nallanathan, "3D beamforming and UAV trajectory optimization for mmWave edge intelligence," IEEE Trans. Wireless Commun., vol. 22, no. 7, pp. 4701–4715, Jul. 2023, doi: 10.1109/TWC.2023.3268321.

[9] F. Liu, J. Zhang, and Y.-C. Liang, "Federated learning for real-time IRS beam management in UAV networks," IEEE Trans. Commun., vol. 71, no. 3, pp. 1542–1555, Mar. 2023, doi: 10.1109/TCOMM.2023.3245159.

[10] N. Shlezinger, Y. Lu, and Y. C. Eldar, "A survey of intelligent reflecting surfaces for UAV communications," IEEE Open J. Commun. Soc., vol. 5, pp. 1189–1212, 2024, doi: 10.1109/OJCOMS.2024.3387123.