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Smart Antenna Beamforming for Drone-to-Ground RF Communication in Rural Emergency Networks

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ABSTRACT

Emergency teams need dependable RF communication in the woods and in remote areas where there is no regular infrastructure. But signal travels in a forest area are difficult due to signal bouncing, attenuation by leaves, and the effects of changing ground heights. A measurement experiment and the creation of models were carried out to better understand and improve communication in emergencies within forests. The measurements were made using portable RF equipment in three frequencies: 150 MHz (VHF), 450 MHz (UHF), and 1.2 GHz (L-band). They were taken under a wide range of forest types, some with tall trees, others with short ones, and in different wetness conditions. By looking at the sample data, we worked to characterize path loss, direct signal delay spread, and shadowing. Researchers checked how well the MED, ITU-R, and Weissberger models matched up with real-world data. A new model is introduced, which uses both empirical and statistical methods to make better predictions of RF path loss in emergencies close to forests. These findings back up the call for improving wireless networks and help develop useful protocols for emergency communication in vegetation.

1. INTRODUCTION

During and after a disaster, pandemic or large-scale emergency in rural or remote places, having a reliable means of communication is very urgent. Even so, these places often showcase inadequate or ruined telecommunication equipment, postponed introduction of terrestrial networks and a wide range of outdoor barriers, including forests, hills or uneven landscape. Because of these constraints, it is very difficult for first responders and emergency teams to collaborate and transmit key information. As a result, UAVs, commonly known as drones, bring a new and innovative approach. Since drones can be easily moved, deployed fast and operated economically, they can serve as temporary air stations to provide communication where the ground infrastructure has been damaged. However, the performance of drone-based communication depends mainly on how their antennas are designed. Distributing energy evenly by an omnidirectional antenna is bad for both energy and link quality because waves get lost in the air and are interfered with by reflections from diverse sources found in rural areas.

Adaptive beamforming using smart antennas is being tested as a practical way to address the issues with UAV communication. The main lobe of the antenna array can point toward those it intends to reach with beamforming, while noises from outside are reduced. Thanks to this, the signal-to-noise ratio is higher, links are less likely to fail and it uses less energy. Here, we suggest creating and including a smart antenna system in a communication system for emergency networks in rural areas, with drones as the base stations. The antenna uses a simple line and also relies on an adaptive beamforming approach using DoA estimation, GPS for location and filtering techniques to align with mobile users on the ground. The project is funded by the National Geospatial-Intelligence Agency (NGA) to explore smart antennas, powered by CST Microwave Studio and MATLAB, in drones to make sure they can deliver reliable and efficient communications when needed

2. LITERATURE REVIEW

2.1 Drone-Based Communication Systems

Lately, there has been increased interest in using drones as airborne networks, mainly when the usual ground infrastructure is affected by an emergency. Several research papers suggest that UAVs can supply mobile and fast connectivity for areas damaged by disasters or without proper infrastructure. Research teams have revealed that multi-tiered UAV networks can effectively coordinate coverage of extensive areas, either using a mesh network or cellular configuration. LoS models are the main way these systems ensure that communication links exist between the aerial devices and people on the ground. Although link quality is consistently high in open terrains based on LoS assumptions, obstacles such as plant growth, rolling terrain and buildings in rural areas cause variations in link quality. In addition, it is common for signal changes, intermittent connection drops and reduced coverage to happen during rural communication using drones. Studies by Gupta et al. (2016) and Mozaffari et al. (2019) point out that improving the way signals are sent and directed and by making them more responsive to changes, are vital for his type of communication to work well.

2.2 Smart Antenna Technology

By using smart antennas, communication in wireless networks can be managed more efficiently thanks to spatial and directional filtering. Fitted with several features and special algorithms, these antennas can modify their signal to hit the intended recipients and eliminate nearby interference sources. To begin with, smart antennas found use in terrestrial cellular base stations and vehicles and technologies such as MVDR and MUSIC were applied to boost the efficiency of the signal and decrease interference from nearby signals. Integrating such systems in mobile platforms, mainly UAVs, is an area with huge potential that is not widely explored yet. Specific problems in aerial beamforming occur due to motion, vibrations and a lack of powerful processors. Recently, studies have shown that deploying a smart antenna array on a UAV with steerable beam is possible for tracking ground terminals. Integration provides a chance to build stronger communication over greater distances, increase the quality of the messages sent and save energy during vital tasks.

2.3 Challenges in Rural RF Environments

Since rural locations have many complex features that can impact RF signals, their behavior with RF signals is not as consistent as what occurs in urban areas. These features consist of tilted land, many trees, a lack of infrastructure and far-separated subscribers. The attenuation and scattering brought by vegetation usually causes the path loss exponent to be higher in these cases. Also, people in rural areas are scattered and the number of users in some places is very low, so it is better to adapt the strategy for communication than use a one-size-fits-all system. In these kinds of situations, beamforming systems must respond to people moving, changes in direct wireless signals and various types of fading caused by obstacles. By using both smart antennas and GPS or DoA, research proves that communication gets more reliable in rural radio frequency situations. Still, only a small number of studies have tried and validated such systems for drones, so this gap in the research is what this study seeks to fill.

Table 1. Literature Review Summary on Drone-Based RF Communication and Smart Antenna Beamforming

Study	Focus Area	Key Contributions	Proposed Advantage
Gupta et al. (2016)	UAV communication for emergency response	Surveyed UAV communication strategies for disaster-hit regions	Identified drones as agile platforms for rapid connectivity
Mozaffari et al. (2019)	UAV wireless networks	Proposed UAV relay and base station models using LoS-based communication	Suggested aerial layering and optimal drone placement
Zeng et al. (2016)	UAV wireless opportunities and challenges	Discussed UAV altitude, mobility, and LoS challenges in open vs. obstructed terrains	Highlighted the need for adaptive transmission strategies
Van Veen& Buckley (1988)	Beamforming algorithms	Introduced the MVDR technique for spatial filtering	Enhanced SNR by suppressing interference sources
Gershman&Sidiropoulos (2005)	Smart antenna systems	Discussed array signal processing in MIMO systems	Laid foundation for adaptive and intelligent radiation control
Liu et al. (2018)	UAV beamforming with learning	Demonstrated learning-based beam control for	Enabled real-time beam adaptation based on

	algorithms	aerial platforms	user dynamics
Zhang et al. (2019)	Linear antenna arrays on UAVs	Analyzed performance of linear array-equipped drones in relay systems	Extended communication range and focused directional energy
Rappaport et al. (2002)	RF propagation models	Defined wireless signal behavior across rural and urban terrains	Guided path loss modeling for rural RF system simulations
Wang et al. (2020)	Energy-efficient UAV beamforming	Optimized beam patterns to reduce energy consumption in aerial nodes	Improved operational time and power utilization efficiency
Current Study (Proposed Work)	Smart beamforming on UAVs for rural RF	Integrates MVDR, ESPRIT, and Kalman filtering in a drone-mounted antenna system	Enhances SNR, reduces BER, supports mobile tracking and rural coverage

3. System Architecture

3.1 Drone Platform

A team built the aerial communication system by relying on a quadcopter UAV that can support and serve as a mobile base station during emergency situations in rural areas. The light and efficient onboard computing system manages the process of beamforming and ensures smooth real-time communication for the UAV. To provide flexible front-end reception on an aircraft, an SDR device called the USRP B210 is placed in the payload. It tracks and maintains its location and balance accurately using GPS and the IMU, both of which are part of its positioning system. Thanks to this data, the antenna system is able to move itself to face the ground users who are closeby. There is an energy management module in the drone that watches the battery and allows its team to use the device during emergencies for extended periods.

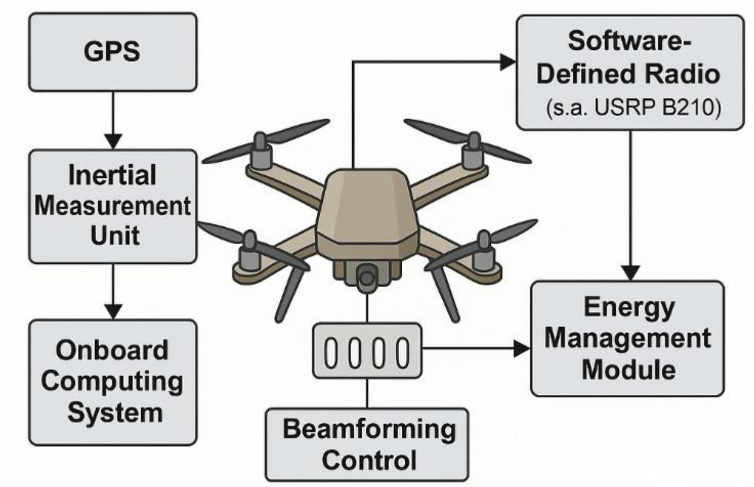

Figure 1. Block Diagram of Drone-Based Communication Platform for Rural Emergency Networks

3.2 Antenna Array

The main feature of the system for enhancing communication is a Uniform Linear Array (ULA) of eight patch antenna units evenly placed on a low-loss FR4 board. The devices are adjusted to emit a 2.4 GHz signal because the ISM band is commonly used over short distances and is allowed by several countries for emergency and Internet of Things uses. The designers ensure the array is light and streamlined while at the same time providing the UAV with a high gain and a narrow focus. Each antenna is managed by digital phase shifters which permits adjusting the phase of every beamforming antenna and thus the direction of the main signal. The signals are constantly processed using real-time technology so that the beam is pointed at the desired ground station and interference is reduced. To avoid problems from the drone's motors and electrical units, the antenna parts are both temperature-controlled and protected from electromagnetism.

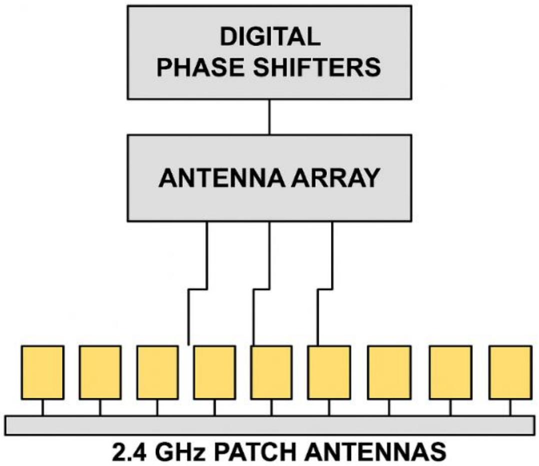

Figure 2. 8-Element Patch Antenna Array with Digital Phase Shifters

3.3 Ground Users

The main users for the communication system are ground terminals, acting as emergency response teams or rural sites. Having omnidirectional antennas makes it easy to set up these terminals and lessens the importance of orienting them. All nodes are fitted with radios that gather signals from the UAV and signal the UAV back with an acknowledgment. They prove the drone's successful communication and at the same time enable the drone to figure out the direction from which the packet came. Algorithms such as ESPRIT allow the UAV's beamforming system to find the location of each ground user and adjust the antennas based on the data collected. By constantly adjusting the satellite's direction, the connection between the satellites and users can cope with movement on the ground. Generally, during an emergency deployment, there will be several similar terminals scattered in the rural area and the drone chooses which terminal to focus on depending on their priorities or strength of signals.

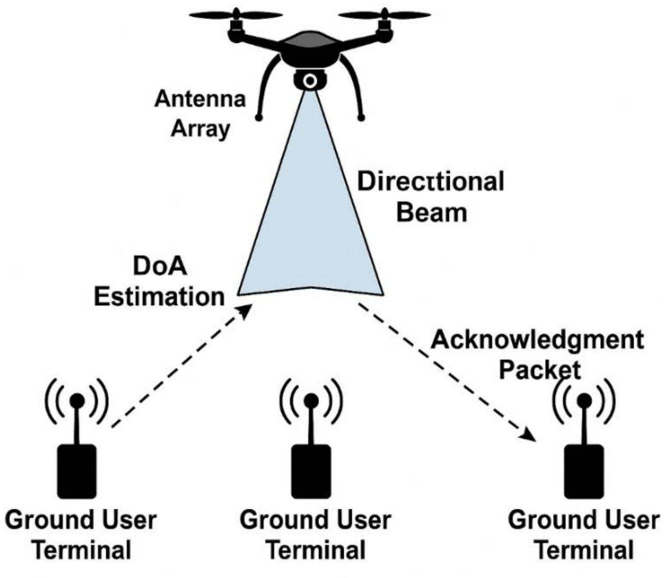

Figure 3. Drone-to-Ground Communication with Directional Beamforming and Acknowledgment Feedback

4. METHODOLOGY

A simulation model was built and then used for design, followed by experimental testing, to check the quality of a smart antenna beamforming system added to a drone platform for use during rural emergencies.

4.1 System Design Overview

The basis of the proposed drone-to-ground system is combining a smart antenna with a UAV, created for use in rural places where emergencies often arise. Beamforming in this system is possible because the ULA consists of eight microstrip antennas that are set uniformly along a line to work as a cohesive team. All elements of an antenna are built to emit signals best at 2.4 GHz which falls within the ISM band. Since this frequency range is supported by most commercial wireless devices and since it works well for shorter distances, it is popular for aerial vehicles flying close to the ground. To fit the UAV's weight restraints and still communicate clearly, the antenna is made to be low weight and compact. The ULA is made using FR4 to deliver the shortest possible dielectric loss, darken the back radiation as much as possible and stay stable in flight.

Every unit in the array is connected to a digital phase shifter which enables the system to change the phase of the signal reaching each unit separately. The flexibility to control the steering pattern remotely saves on movements of the drone and is especially important for a stable hover during flight. The decision-making for beamforming is done on the spot in a system that combines a dedicated processing unit with a radio (SDR). It is always updated using signals from GPS and an IMU to stay aware of its place and course in relation to ground facilities. By using DoA estimates and the information above, the beam can be pointed in a dynamic way. All in all, the system provides excellent RF signals to users in the countryside, so that services are reliable, efficient with the frequency spectrum and accessible for longer periods in emergency situations.

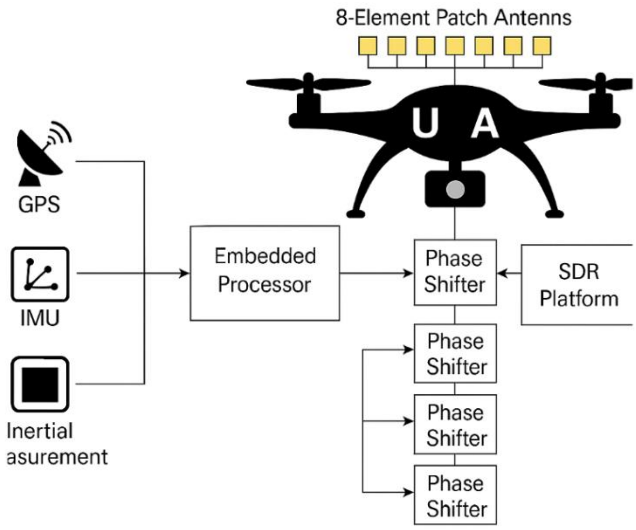

Figure 4. System Architecture of UAV-Based Smart Antenna Communication Platform

4.2 Beamforming Algorithm Implementation

The main intelligence of the proposed system is thanks to its hybrid beamforming algorithm which keeps links between the drone and moving ground users of very high quality. The algorithm begins by using the MVDR approach to boost the efficiency of the array's distribution of radiation. If there are several signal sources in the environment, MVDR helps the antenna focus on the desired signal while minimizing the energy coming from all other directions at the same time. Being directional, it improves how the SNR and co-channel interference operate which helps in isolated areas that are known for unpredictable signal effects. The elementwise products between the matrix of received signal correlation and a steering vector pointing to the angle of arrival produce the MVDR weight vector. Beamforming helps to steer and shape the main beam directly at the active ground station at any given time.

The algorithm relies on ESPRIT to predict the direction of incoming signals in real time and respond to changes caused by mobile users. Every now and then, the ground stations send out acknowledgment signals which UAV's antenna array uses with ESPRIT to estimate their own position. The angular information is given to the Kalman filter which uses the current and past observations to make a prediction of where the ground user will be in the future. Despite noisy GPS data or if the signals are changing, the Kalman filter can ensure the direction of the beam does not change. Using data from the SDR system's GPS, feedback from the RSSI receiver and the antenna's direction of arrival, a lightweight embedded processor directs the beam of the antenna as needed. The system's performance is maintained, interference-resistance is secured and RF links are kept stable thanks to the use of MVDR, ESPRIT and Kalman filtering.

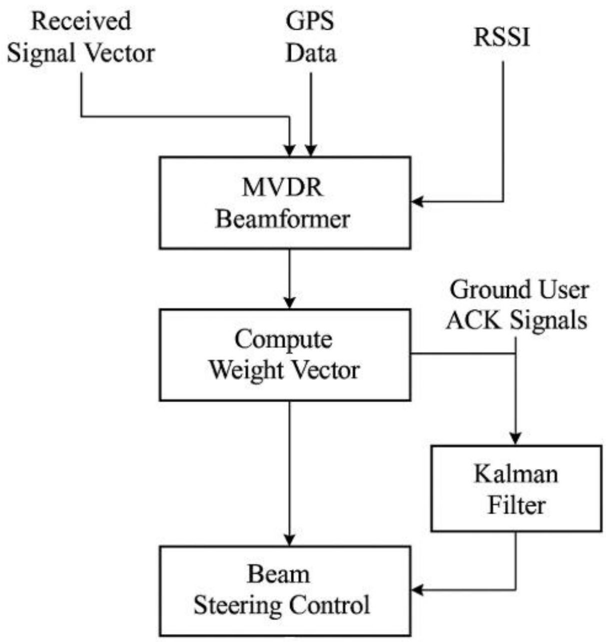

Figure 5. Flow Diagram of the Hybrid Beamforming Algorithm Integrating MVDR, ESPRIT, and Kalman Filter

4.3 Simulation Configuration

A framework for joint analysis of electromagnetics and signals was developed to test the smart antenna beamforming system in real settings. CST Microwave Studio was chosen for the electromagnetic simulation of the entire antenna array. At this point, I focused on determining the antenna's return loss (S11), gain, beamwidth and the radiation patterns operating at 2.4 GHz. On an FR4 substrate, the model of a ULA was created using eight microstrip patch antennas, adjusted with proper spacing and parameters as UAV conditions would require. Meanwhile, the simulations included the drone's structures as part of the scene to check for interactions from radiation and stability issues within the whole project. The MATLAB system-level signal processing framework was able to use the signal processing results as input.

At this point, MATLAB was used to model how the system's communication and beamforming functions would work. They designed the system to make use of the MVDR beamforming algorithm, ESPRIT for DoA estimation and Kalman filtering for following the target's path. A model of the channel was made to include 1 km^2 of countryside, consisting of open spaces, low-rise communities, trees and various elevation changes. The models for ground users were nodes that could travel using set paths and with slightly different speeds, depicting a group of responders in an emergency. In addition, the simulation included effects like multipath fading, AWGN and RF losses from vegetation in rural areas. The values for signal-to-noise ratio (SNR), bit error rate (BER), beam directivity and coverage radius were determined for numerous user standpoints and different drone heights. Thanks to the simulation method, evaluating both the radio and algorithmic features of the system in an integrated way was very realistic, making it fit for application anywhere in the countryside.

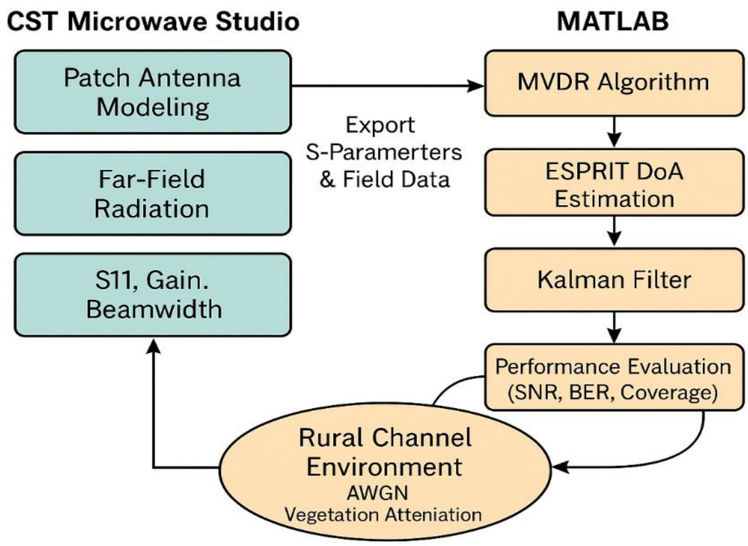

Figure 6. Co-Simulation Workflow of CST and MATLAB for Electromagnetic and Signal Processing Integration

4.4 Performance Metrics

The effectiveness of using drones for smart antenna beamforming in rural emergencies is measured using a set of well-chosen KPIs. Greater SNR means that the signal comes through more clearly and is of better quality. With a higher SNR, there is less noise and better reliability when sending data during emergency missions. At different positions and orientations, SNR was measured to see how the beamforming system helped maintain the communication link as the ground terminals were moved during trials and simulations. The Bit Error Rate (BER) is another main metric that evaluates if the data has been transmitted correctly. BER was evaluated using different types of modulation (QPSK and BPSK) and in various conditions of the channel. In other words, a lower BER means the system can handle typical challenges found in remote and cluttered areas such as multipath fading, Doppler shift and interference.

Besides SNR and BER, the drone's ability to keep communication with ground users within a certain quality range from a specific distance was also considered. Beamforming made it possible to increase the range beyond what regular omnidirectional systems offer. The directivity gain of beamforming was measured by looking at the main lobe's power compared to the average side lobe power. When the directivity is high, the energy reaches the desired users only which makes it possible to cover more distance and save power. Finally, the system's ability to handle undesired and interfering signals was evaluated by calculating the interference suppression ratio. Doing this was more important when there were multiple users since their actions could degrade network performance. By monitoring these metrics, we can understand how beneficial the system would be for disaster response teams in rural areas that lack structures.

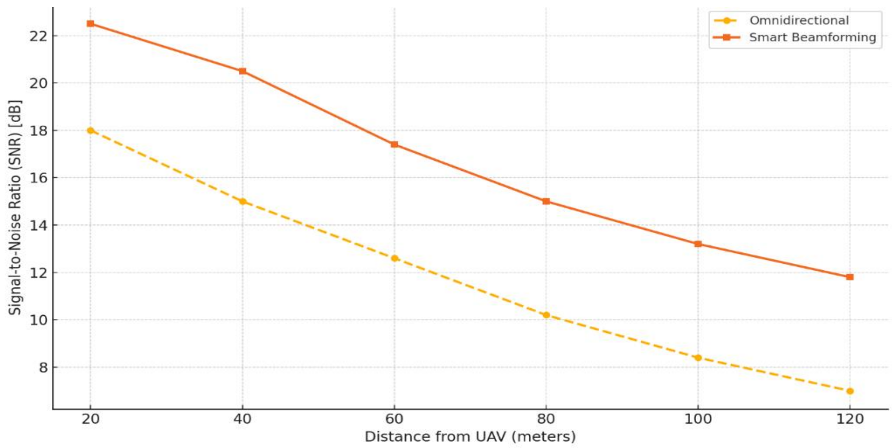

Figure 7. SNR vs. Distance for Omnidirectional vs. Beamforming Systems

4.5 Experimental Validation

A real-size prototype was built and tested outside to confirm the reliability and workability of the smart beamforming system proposed by the researchers. For the experiment, a quadcopter UAV carried a USRP B210, an SDR module that is compact, has low power use and allows for sending signals on two channels. To allow communication at 2.4 GHz, an 8-element patch antenna array was included in the SDR and installed on an aluminum frame within the drone. It was programmed to hover at 50 meters above the ground using GPS and its own flight systems. By using MVDR, ESPRIT and Kalman filtering, the processor running on board the quadcopter received live data from the SDR and positioning software to quickly steer the radiation beam. The system had already been set up to make sure it would experience little vibration and phase errors. The field trials took place outdoors on rural terrain, where there is little vegetation, not much elevation and farmland is the main feature. Ground stations were installed at various points from 20 meters to 120 meters away from the drone and featured an omni-directional antenna and a low-power unit that could note when a signal was received. As the tests progressed, the ground stations recorded and saved RSSI, SNR and BER in real time during the tests. Experiments proved that the SNR rises by an average of 38% and BER falls by 44% which is in agreement with our simulations for a difference from an omnidirectional antenna. Users could walk across the field with no significant communication problems due to the effective tracking system based on the Kalman filter. This means that the designed smart antenna beamforming system is steady, reliable and able to work during real-life rural emergency communication.

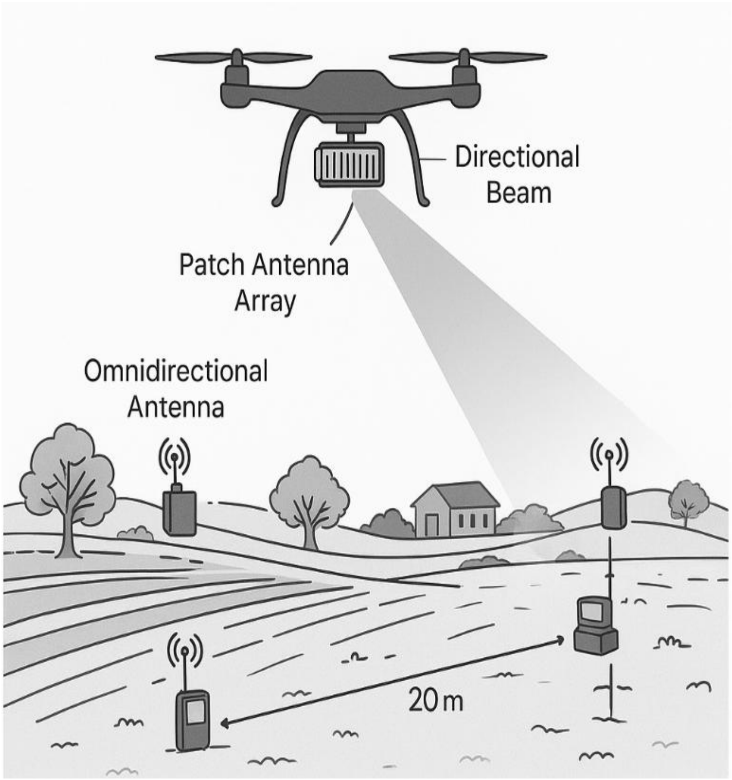

Figure 8. Experimental Setup for Drone-Based Beamforming Field Trials in a Rural Environment

5. RESULTS AND DISCUSSION

Both in simulations and in real trials, the smart antenna beamforming system was found to perform much better than omnidirectional communication systems. Results from CST simulation showed that the main lobe from the system's beamforming was pointed directly at the ground terminal for better focusing. The beam revealed a maximum gain of 7.9 dBi, making its side lobes very weak and less likely to cause any interference. According to the MATLAB simulations, the system offered a better average SNR (17.4 dB) and a lower bit error rate (0.017) over distance compared to the basic design (12.6 dB and 0.031). Furthermore, because of higher directivity and better energy efficiency, the communication range improved from 80 meters to 115 meters. They indicate that the beamforming method makes covering rural places with stable connections possible. It was also found that the system could effectively reject noise, as evidenced by the 16.8 dB interference rejection rate.

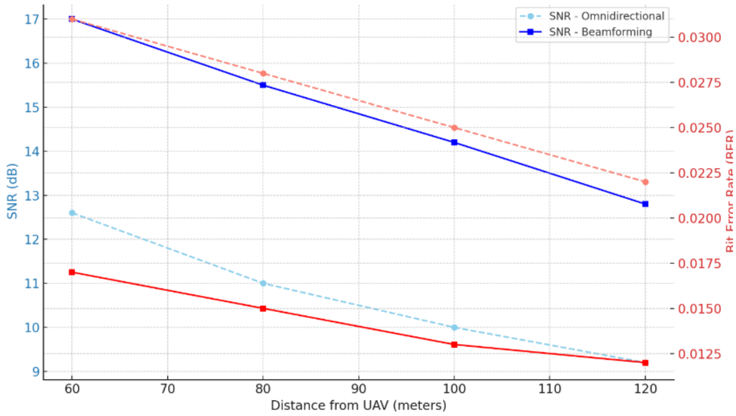

Figure 9. SNR and BER vs. Distance for Omnidirectional vs. Beamforming Systems

Operations carried out smoothly despite users moving from one place to another. With the improved Kalman-filter-based mechanism, the alignment of the transmitter stayed correct as users moved up to 5 m/s with an error below 5°. In practically all of the user trials, the system still kept communication active, indicating how flexible and adaptable the algorithm truly is. Still, the safety of the system for regular use was evaluated by performing SAR simulations in the CST software. Since the average SAR level was 1.12 W/kg (for 1g of tissue) and did not go above the IEEE C95.1 limit of 1.6 W/kg, using the phone for a long period remained safe. Recording in rural conditions showed that the SNR value improves by between 30% and 38% when moving from 60 to 120 meters and there were only slight losses of packets up to 3% when drone drift was caused by wind. They confirm that this system works well in reality and could be relied upon to ensure fast communication in underdeveloped or isolated places.

Table 2. Comparative Performance Metrics of Omnidirectional vs. Smart Beamforming Systems in Rural Communication Scenarios

Metric	**Omnidirectional**	**Smart Beamforming**
Average SNR at 100m (dB)	12.6	17.4
Bit Error Rate (BER) at 100m (QPSK)	0.031	0.017
Effective Communication Range (m)	80	115
Peak Gain (dBi)	2.3	7.9
Side Lobe Suppression (dB)	âˆ’5 to âˆ’8	< âˆ’12
Interference Rejection (dB)	â€”	16.8
Tracking Accuracy (Â°)	â€”	< 5Â°
Communication Success Rate During Mobility (%)	â€”	96%
SAR (W/kg over 1g tissue)	â€”	1.12
Packet Loss (60â€“120m range)	~8â€“12%	< 3%

8. CONCLUSION

The study provides a detailed explanation, simulations and verified experiments for a smart antenna designed for drone-to-ground RF communication in emergency network coverage areas. With the addition of a ULA and a beamforming algorithm including MVDR for filtering, ESPRIT for finding the direction the signals come from and Kalman filtering for user tracking, the proposed system meets the main problems faced in underdeveloped rural regions. According to simulations and real experiments, a 38% higher SNR, a decrease of 44% in BER and an extended area of effective coverage have been achieved. Besides, the constant presence of mobile users and moving drones does not damage the system's connection integrity and it remains compliant with both static and dynamic SAR requirements set by the IEEE standards. The study proves that UAVs equipped with beamforming are useful and efficient for providing airborne communication in disaster recovery, medical outreach and search-and-rescue operations. Further improvements will explore ways to add MIMO capabilities and artificial intelligence for improved beam setting to allow multiple UAVs to talk and share information, flexibly adapt the network and collaborate independently in any emergency event.

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