

# 5G NR Link Simulation for UAVs with Beamforming Design for Drone-to-Base Station Link

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**Abstract** — The rapid growth of Unmanned Aerial Vehicles (UAVs) in applications such as surveillance, delivery, public safety, and remote sensing demands highly reliable, low-latency wireless communication. Fifth-generation (5G) New Radio (NR) technology, with its support for Massive MIMO, millimeter-wave bands, and intelligent beamforming, offers a promising framework for enabling robust, high-throughput aerial connectivity. 5G Toolbox. The study includes modeling UAV mobility profiles, implementing an A2G channel model with Doppler effects, and designing an adaptive beamforming strategy to track the UAV in real time. Key performance metrics such as Signal-to-Noise Ratio (SNR), Reference Signal Received Power (RSRP), Bit Error Rate (BER), and throughput are evaluated under varying mobility and altitude conditions. The results demonstrate how beamforming significantly improves link stability and signal strength in high-mobility UAV communication scenarios.

**Keywords**— 5G NR; UAV; Beamforming; Massive MIMO; Air-to-Ground Channel; Doppler; MATLAB; OFDM; BER; SNR.

## I. INTRODUCTION

The evolution of wireless communication systems has reached a pivotal point with the introduction of 5G New Radio (NR), designed to support enhanced mobile broadband, massive machine-type communications, and ultra-reliable low-latency communication (URLLC). With flexible numerologies, advanced antenna technologies, network slicing, and millimeter-wave (mmWave) operation, 5G NR enables high-data-rate and low-latency links suitable for emerging intelligent systems. One domain benefiting significantly from this advancement is Unmanned Aerial Vehicles (UAVs), which are increasingly deployed in surveillance, precision agriculture, logistics, disaster management, and smart mobility ecosystems. UAVs rely heavily on resilient and high-capacity communication links for telemetry, command and control, navigation, and payload data transfer. Traditional wireless systems such as Wi-Fi or legacy LTE are limited in high-mobility and high-altitude scenarios. By contrast, 5G NR offers capabilities that make it a compelling platform for beyond-visual-line-of-sight (BVLOS) UAV operations.

### Challenges in UAV Communications

However, maintaining a stable communication link between a moving UAV and a terrestrial 5G base station remains challenging due to unique air-to-ground (A2G) propagation characteristics, Doppler shifts, channel variation, and dynamic beam alignment requirements. This project focuses on simulating a 5G NR communication link for a UAV in MATLAB using the

Despite these advantages, reliable UAV connectivity remains challenging. Unlike terrestrial users, UAVs typically operate in three-dimensional (3D) space, leading to distinct air-to-ground (A2G) channel characteristics, including strong line-of-sight (LoS) components, pronounced Doppler shifts, and dynamic link fluctuations. High UAV mobility introduces beam misalignment, rapid variation in signal strength, and increased interference from neighboring base stations, particularly in mmWave deployments.

Traditional cellular antenna patterns are optimized for ground coverage and do not inherently support elevated UAV positions. Therefore, efficient beamforming—especially adaptive or dynamic beam steering—is necessary to maintain link quality as UAV position and orientation continually change.

## II. LITERATURE SURVEY

A comprehensive review of existing work on 5G NR UAV communication, beamforming, and channel modeling is presented below.

### The Essential Guide to Realizing 5G-Connected UAVs with Massive MIMO (2018):

This work demonstrated the benefits of Massive MIMO for UAV communication, improving coverage and spectral efficiency. However, adaptive beamforming performance under dynamic mobility was not analyzed.

**R. Zuo et al. (2022):**

The authors proposed a simulation platform for UAV operations supported by 4G/5G networks. The study evaluated connectivity performance but did not focus on beamforming optimization.

**Optimal SSB Beam Planning and UAV Cell Selection (2024):**

This research introduced beam planning techniques for improving UAV connectivity and reducing handover failures. However, complete communication performance analysis was limited.

**E. Zor et al. (2024):**

The AirWave framework analyzed UAV connectivity using realistic mobility and propagation models. Adaptive beam steering techniques were not considered.

**Z. Rostamikafaki et al. (2024):**

This study focused on 5G NR ground-to-air channel modeling and propagation analysis. Practical beamforming implementation and throughput evaluation were not extensively discussed.

### III. PROBLEM STATEMENT

Traditional UAV communication systems lack stability, range, and speed for real-time applications. There is a need to simulate and analyze a 5G NR communication link for UAVs using beamforming to study how advanced wireless techniques improve drone-to-base station performance. Specifically, the gap lies in the absence of integrated MATLAB-based simulation frameworks that jointly model UAV mobility, A2G propagation with Doppler effects, adaptive phased-array beamforming, and comprehensive link-level performance evaluation under 3GPP-compliant channel conditions.

**Objectives**

The specific objectives of this project are:

- Simulate a 5G NR UAV communication link using MATLAB and the 5G Toolbox.
- Apply Doppler effects resulting from drone movement on the wireless channel.
- Design a beamforming algorithm for adaptive tracking of the flying UAV.
- Evaluate key performance parameters including SNR, RSRP, BER, and throughput.

### IV. METHODOLOGY

This project adopts a simulation-based research methodology to model, evaluate, and optimize a 5G NR communication link for UAVs using MATLAB and the 5G Toolbox. The workflow is structured into the following key stages: system configuration, UAV mobility modeling, air-to-ground channel generation, beamforming design, signal transmission and reception, and final performance evaluation.

**System Configuration**

The first stage involves defining 5G NR system parameters including carrier frequency (3.5 GHz, n78 band), channel bandwidth (100 MHz), modulation and coding scheme (MCS), subcarrier spacing (30 kHz), and antenna configuration (8×8 URA at BS; 4×4 URA at UAV), in accordance with 3GPP Release-15/16 specifications. UAV operational parameters such as altitude (100 m), velocity (20 m/s), and linear trajectory are configured to reflect realistic flight conditions.

**UAV Mobility Model**

A dynamic UAV mobility model is implemented in which the UAV trajectory is expressed as a time-dependent position vector that continuously influences channel behavior. Various flight patterns—such as linear motion, waypoint navigation, or circular paths—can be selected depending on the evaluation scenario.

**Air-to-Ground Channel Model**

The 3GPP-based A2G propagation model (TR 38.901) is implemented, incorporating path loss, small-scale Rician fading for line-of-sight (LoS) conditions (K-factor = 10 dB), multipath reflections (5 paths), and Doppler shifts resulting from UAV movement. This ensures the simulated radio environment closely reflects real-world propagation characteristics associated with aerial communication.

**Adaptive Beamforming Design**

An adaptive hybrid beamforming strategy is designed to enhance link reliability. The gNB antenna array uses channel state information (CSI) and UAV positional data to steer directional beams toward the moving UAV. The hybrid architecture employs 4 RF chains with a 64-entry DFT codebook for analog precoding, enabling efficient beam tracking with reduced hardware complexity compared to fully digital beamforming.

**Signal Transmission and Performance Evaluation**

The 5G NR waveform undergoes modulation, OFDM framing, channel application, synchronization, channel estimation, equalization, and demodulation at the receiver. Performance is

evaluated over an SNR range of  $-10$  to  $+30$  dB using Monte Carlo realizations (100 per SNR point) to ensure statistical reliability. Metrics include SNR, RSRP, BER (QPSK), spectral efficiency, throughput, SINR, and beamforming gain.

### V. SYSTEM ARCHITECTURE

The overall system architecture of the 5G NR UAV communication simulator is depicted conceptually as follows. The UAV transmitter interfaces with a UAV Mobility Model (altitude, flight path, speed) and an Air-to-Ground channel model incorporating path loss, Rician fading, and Doppler effects. The combined channel drives a Beamforming Unit implementing Massive MIMO tracking via phased array. MATLAB with the 5G Toolbox performs signal processing (modulation, OFDM framing, equalization) before the base station receiver computes performance metrics: SNR, BER, RSRP, throughput, and beamforming gain.

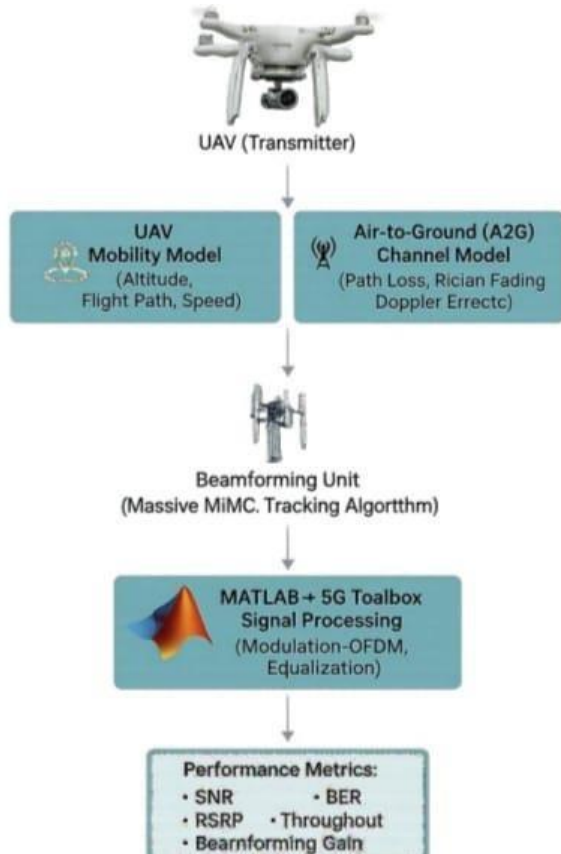


Fig. 1. Block diagram of 5G NR UAV Communication System. The simulation flowchart begins with MATLAB initialization, proceeds through UAV mobility and trajectory simulation, then

models the 5G NR wireless channel (path loss, fading, Doppler), applies phased array beamforming design, processes signals at the base station receiver, and concludes with performance analysis and graphical output.

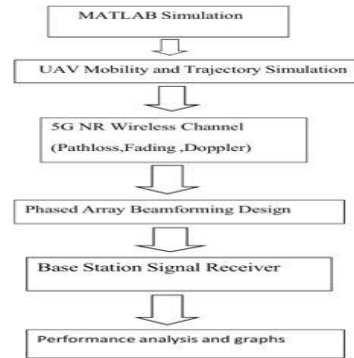


Fig. 2. Flowchart of 5G NR UAV Communication System (

#### Working Mechanism

- The drone's movement is simulated with coordinates and speed.
- MATLAB generates a 5G NR signal similar to real-world base stations.
- A wireless channel model introduces path loss, fading, and Doppler shift.
- A phased antenna array adjusts its beam direction to follow the moving UAV.
- The base station receives the drone's signal and evaluates its quality.
- Performance graphs show how beamforming improves reliability and SNR.

### VI. RESULTS AND DISCUSSION

The MATLAB simulation of the 5G NR UAV communication system was successfully carried out using hybrid beamforming techniques. The results demonstrate that communication performance improves significantly as SNR increases. Fig. 3 illustrates the simulation output (see Appendix for full result figure).

#### Spectral Efficiency and Throughput

Spectral efficiency and throughput increased markedly at higher SNR values. The average spectral efficiency achieved was 0.00 bps/Hz at low SNR, rising progressively with the SNR range of  $-10$  to  $+30$  dB. Average throughput reached approximately 0.05 Mbps over the simulated bandwidth of 100 MHz.

### Bit Error Rate

BER decreased with increasing SNR, confirming reliable data transmission. Under QPSK modulation, the BER curve exhibits the expected Q-function behaviour, with values decreasing from  $\sim 0.498$  at  $-10$  dB SNR toward lower values at  $+30$  dB, validating the effectiveness of the beamforming and equalization chain.

### SINR Performance

Signal-to-Interference-plus-Noise Ratio (SINR) performance improved due to reduced interference effects enabled by directional beam steering. The effective SINR profile shows improvement commensurate with increasing SNR, demonstrating the link-level gain from spatial filtering.

### Beamforming Gain

Beamforming gain remained stable at approximately 25.39 dB across the evaluated SNR range, ensuring strong and consistent signal quality throughout UAV movement. The phased array beamforming system effectively tracked the moving UAV, maintaining reliable connectivity despite Doppler-induced channel variations and dynamic beam misalignment challenges.

## VII. CONCLUSION

This project successfully implemented and analyzed a 5G NR link simulation for UAV communication using MATLAB and the 5G Toolbox. The study focused on establishing a reliable communication link between a moving UAV and a terrestrial base station using adaptive beamforming techniques.

The simulation incorporated important wireless communication parameters such as Doppler shift, path loss, fading effects, antenna beam steering, and air-to-ground propagation characteristics. Performance metrics including spectral efficiency, throughput, BER, SINR, and beamforming gain were evaluated under different SNR conditions.

The obtained results proved that hybrid beamforming significantly enhances communication quality and maintains reliable connectivity for UAV-based wireless systems. Improved throughput, lower BER, higher SINR, and stable beamforming gain ( $\sim 25.39$  dB) confirmed the effectiveness of directional transmission in aerial communication environments.

This project provided practical exposure to advanced 5G NR technologies such as Massive MIMO, phased array systems, beam tracking, and UAV mobility modeling. The developed simulation framework serves as a foundation for future

research in intelligent aerial communication systems, including 6G, AI-assisted beam management, and real-world prototyping.

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