

Bridging Physical and Virtual World Using New Digital Twin Approach for 6G UAV Performance

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Abstract—As 6G networks continue to advance, they cater to various new key use cases, Unmanned Aerial Vehicle (UAV) communications being one of them. However, integrating UAV systems into these networks still faces the significant challenge of maintaining ultra-reliable, low-latency connections. This study investigates how Digital Twins (DTs) can evaluate the performance of the UAV network within the 6G environment by leveraging Unreal Engine as a tool to replicate real-world conditions. The paper centers on developing a UAV communication digital twin, enabling the assessment and enhancement of critical Quality of Service (QoS) factors—namely latency, signal strength, path loss and carrier-to-noise ratio —across urban landscapes. Through the exploration of QoS monitoring using the raytracing method, the paper underscores the potential of Digital Twins to provide a transformative solution for designing and deploying robust, next-generation aerial networks, offering vital insights for researchers and industry professionals.

Index Terms—Digital Twins, 6G Communication, UAV Networks, Quality of Service, Raytracing

I. INTRODUCTION

The rapid evolution of 6G networks envisions unprecedented connectivity standards, necessitating innovative approaches to address dynamic quality of service (QoS) challenges [1]–[3]. Digital twins (DT) have emerged as transformative tools in this context, offering virtual replicas of physical systems for real-time analysis, and predictive insights [4]–[6]. Various studies have been conducted to explore the role of DTs in UAV use cases such as intrusion detection [7], interference mitigation [8], manoeuvring target tracking [9] and airspace management [10].

One of the key use cases of 6G is UAV communications [11], [12]. This is a critical use case that requires low latency, high reliability, and adaptive network performance and resource allocation [13]. Accurate QoS assessment and prediction are essential to enable these capabilities, aligning with key 6G Key Performance Indicators (KPIs) such as ultralow latency, support for a large number of connected devices, and energy efficiency [14].

DTs have become a cornerstone in addressing the complexities of 6G/5G networks, finding applications in network optimization, testing AI algorithms, and synthetic data generation or testing [4]. While the specific implementations vary based on use cases—such as optimising resource allocation for enhanced mobile broadband (eMBB) or ensuring low-latency communication for ultra-reliable low-latency communication

(URLLC) [15], their underlying structure remains consistent. At their core, DTs consist of three fundamental layers: the physical entity, the virtual representation, and the connection interface [16]. This architecture ensures that real-time data from physical systems is accurately mirrored in the digital model, enabling simulations and analysis that inform actionable insights. The physical entity represents the actual network components, such as base stations, user devices, and IoT sensors. The virtual representation models these components using advanced algorithms, AI-driven simulations, and real-time data integration to replicate the system's behaviour. The connection interface bridges the two, enabling bidirectional communication for continuous updates and feedback.

In future 6G networks, O-RAN is expected to enable significant cost reduction and enhanced scalability by leveraging its open, modular architecture, cloud-native operations, and AI-driven intelligent control to efficiently manage increasingly complex and resource-intensive communication environments [17], [18]. Therefore, DTs can be used to simulate O-RAN's dynamic operations and its architecture is presented in Figure 1. O-RAN DT can predict as near-real-time resource allocation and energy efficiency strategies, through AI-driven control from O-RAN's RAN Intelligent Controller (RIC).

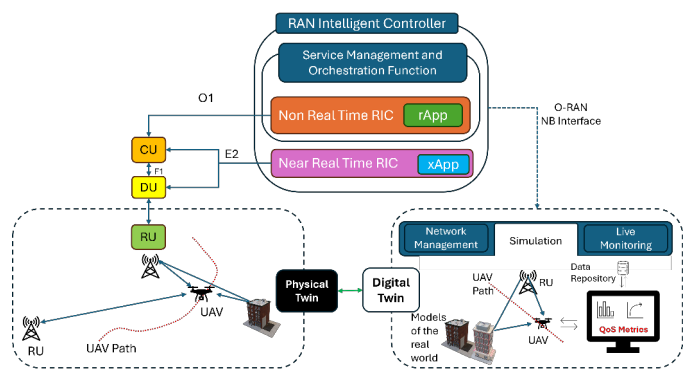


Fig. 1. Proposed O-RAN Centered Digital Twin Architecture

Integrating DTs into the open radio access network (O-RAN) architecture further amplifies their importance, enabling real-time network orchestration, efficient resource utilisation, and enhanced decision-making. The modularity and flexibility of o-RAN align seamlessly with DT-driven insights, foster-

ing innovations that are essential for 6G's distributed and intelligent network paradigm [19]. Tools such as NVIDIA Aerial Omniverse [20], SIONNA [21], and Unreal Engine [22] are widely recognized for their role in building digital twins, providing scalable and realistic simulation environments for testing complex communication scenarios, including those involving UAVs [23], [24].

The main contribution of this research is the development of a framework for constructing digital twins capable of live QoS data acquisition and generating synthetic datasets for enhanced network analysis. The proposed approach is designed to be scalable and modular, enabling the integration of additional functionalities such as beamforming optimization [25], [26] and advanced 6G physical layer investigations in the future [27]. Aligned with the ITU-T Y.3090 framework for digital twin networks [28], this work underscores the technical requirements and architectural considerations essential to build DTs in 6G systems. By addressing real-world QoS challenges in UAV communication, this study demonstrates how DTs can serve as pivotal enablers in achieving 6G's ambitious goals, providing actionable insights and fostering advancements in future network architectures. For this study, the primary objective is to generate a live QoS dashboard to monitor Signal Strength, latency and Signal to Noise Ratio along the UAV path.

II. DEVELOPED SYSTEM ARCHITECTURE

This section provides a detailed overview of the framework designed to simulate and analyze UAV operations within a controlled and dynamic environment. The architecture integrates multiple layers, each contributing to a holistic approach for modeling, testing, and validating UAV systems.

A. System Design

The overall system design of the DT is represented in Figure 2. At the foundation, there is a static layer, which establishes the baseline scenario and reference models. This includes static geographical maps and building layouts, drawn from geospatial data repositories such as Cesium 2.0 plugin and Google Maps API. Cesium is used for building and terrain integration while Google imagery serves as a base mesh of the environment. The study area is Central Milton Keynes, United Kingdom where tall buildings are taken into account to analyse QoS parameters using the raytracing method during UAV flight. The Digital Environment Layer, realised in Unreal Engine, renders UAVs, vehicles, and infrastructure in real-time. It applies physics-based flight dynamics, lighting, and weather conditions, while MATLAB and Simulink process sensor data and flight trajectories. This ensures UAV behaviour matches the realistic constraints set by the static layer data.

The physical layer links the simulation to actual hardware, enabling hardware-in-the-loop testing. Real flight controllers can inject commands for manual flight, and simulation results refine real-world operational strategies. For autonomous flight, QGround Station software is used to generate and import a '.plan' file as a flight path into Simulink.

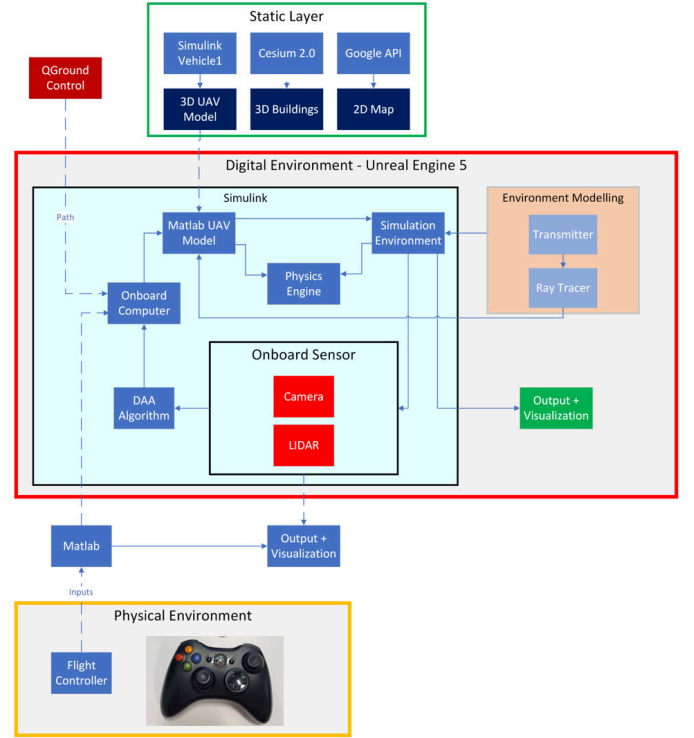


Fig. 2. Digital Twin Framework

The developed DT environment relies on the following software tools, each serving a distinct purpose within the system's layered architecture. As indicated in Table I, the primary tools are Unreal Engine 5.3, MATLAB, and Simulink. Unreal Engine 5.3 provides the 3D visualization capabilities necessary to create immersive, photorealistic virtual worlds. Its advanced rendering engine, combined with customizable plugins and assets, allows for the realistic representation of terrains, buildings, urban environments, and dynamic objects like UAVs and communication towers. MATLAB serves as a platform for communication analysis. It facilitates the modelling and performance assessment of wireless links, antenna patterns, and signal propagation within the DT. Through MATLAB's extensive signal processing and mathematical toolboxes, it becomes possible to conduct Link Budget Analysis (LBA) and evaluate QoS parameters such as SNR at various distances. Simulink complements this setup by providing a model-based design framework that enables the development and testing of advanced algorithms, including Detect and Avoid (DAA) strategies for UAVs. In Simulink, the control logic can be graphically modelled, simulated, and iteratively refined, ensuring that complex autonomy functions—such as path planning, obstacle recognition, and collision avoidance. This synergy between Simulink's control logic simulations and Unreal Engine's 3D environments results in a high-fidelity feedback loop, where simulated UAV navigation is informed by realistic environmental and communication parameters from MATLAB. The Simulink logic used for this study is an updated version of the MathWorks UAV Package Delivery

example [29].

Therefore, UAV's behaviour and control logic is developed and fine-tuned in Simulink before being output and rendered in the Unreal Engine environment. In contrast, the antenna is a static object imported into Unreal via Simulink, allowing for accurate visualization and integration of both the UAV's dynamics and the antenna's precise placement and orientation. A raytracer block was used within Simulink for the analysis to evaluate the QoS metrics using the raytracing method.

TABLE I
SOFTWARES UTILIZED FOR DT

Software/plugin	Role
Unreal Engine 5.3	3D Visualization
Matlab	Communication Analysis
Simulink	Detect and Avoid

In the ray tracing process, the antenna emits a configurable number of rays (5000 in the current setup), scattered uniformly in random directions. Each ray may undergo up to five bounces (reflections) before terminating. While increasing the number of rays or the number of bounces can yield a more detailed and realistic model of the propagation environment, it also significantly raises the computational complexity and processing time. To balance fidelity and performance, the chosen parameters (5000 rays and five bounces) represent a practical compromise for the current simulation scenario. The laptop's characteristics are found in Table II

TABLE II
LAPTOP HARDWARE SPECIFICATIONS

Component	Specification
CPU	Intel Core i7-13700H
RAM	32 GB
GPU	NVIDIA GeForce RTX 4060 Laptop

B. Link Budget Analysis

In the context of UAV-based communication systems, a comprehensive link budget analysis is critical for determining the feasibility and robustness of aerial links under diverse operational and environmental conditions. By quantifying factors such as transmitter power, receiver sensitivity, propagation losses, and environmental attenuations, it provides crucial insights that guide system design, resource allocation, and performance optimization. The mathematical model for Link Budget Analysis (LBA) used in this DT framework follows approaches similar to those described in [30]–[32]. The primary objective is to evaluate the signal strength and communication latency between the transmitting antenna and the UAV under various conditions such as different UAV heights, distances, and environmental factors (e.g., atmospheric attenuation and rain). Ray-tracing techniques are employed to model the propagation of electromagnetic waves and to capture reflections, refractions, and diffractions encountered by the signals.

In the considered DT scenario, the link budget calculation begins with the determination of the Free Space Path Loss

(FSPL). This term quantifies the reduction in power density of an electromagnetic wave as it propagates through a vacuum or ideal free-space environment. It represents how much the signal attenuates solely due to the geometric spreading of the wavefronts, without considering additional losses from obstacles, atmospheric effects, or absorption.

$$\text{FSPL (dB)} = 20 \log_{10}(d) + 20 \log_{10}(f) + 20 \log_{10}\left(\frac{4\pi}{c}\right) \quad (1)$$

In this equation, d is the total distance between the antenna and the UAV (in meters) calculated using the Pythagorean theorem, f is the carrier frequency (in Hz), and c is the speed of light in vacuum (m/s).

The received power P_{rx} equation determines how much of the originally transmitted signal power remains after propagation losses, antenna gains, and other environmental factors are accounted for. Starting from the transmitted power P_t one must consider the transmitter and receiver antenna gains, the free space path loss, transmitter-side losses, and additional environmental losses (e.g., rain attenuation, atmospheric absorption). The equation of the P_{rx} in dBm is:

$$P_r = P_t + G_t + G_r - \text{FSPL} - L_{tx} - L_{env} \quad (2)$$

where:

- P_t : Transmitter output power (dBm)
- G_t, G_r : Transmitter and receiver antenna gains (dBi), respectively
- L_{tx} : Transmitter-side losses (dB)
- L_{env} : Environmental losses (dB)

Atmospheric attenuation primarily arises from the interaction of electromagnetic waves with atmospheric gases. It becomes increasingly significant as frequency increases, adding to the total path loss and ultimately diminishing the received signal strength. To quantify this effect, the total atmospheric attenuation coefficient γ in dB/km) is expressed as the sum of the specific attenuation due to dry air γ_0 and the specific attenuation due to water vapor γ_w :

$$\gamma = \gamma_0 + \gamma_w \quad (3)$$

Once γ is determined, the total atmospheric attenuation L_{atm} over d in km is given by:

$$L_{atm} = \gamma d \quad (4)$$

Rain attenuation, on the other hand, is the weakening of the signal caused by rain along the communication path. The rain attenuation A_{rain} can be modeled as

$$A_{rain} = kR^\alpha \quad (5)$$

Here, k and α are parameters dependent on frequency and polarization, while R is the rain rate (in mm/h). This relationship enables estimation of the signal degradation experienced under varying rainfall conditions.

The Carrier-to-Noise (C/N) ratio measures the received signal's strength relative to the background noise level, providing a key indicator of communication quality and link robustness. The noise power N is derived based on thermal noise calculations that use Boltzmann's constant in a dB scale. The relevant equations are as follows:

$$N = -228.6 + 10 \log_{10}(T) + 10 \log_{10}(B) \quad (6)$$

Here, T is the system noise temperature in K, and B is the bandwidth in Hz. Once N is computed, the C/N ratio is given by:

$$\frac{C}{N} = P_r - N - M_{\min} \quad (7)$$

Latency (τ) represents the propagation delay that a signal experiences when traveling from the transmitter to the receiver. It is essentially the time it takes for electromagnetic waves, which propagate at or near the speed of light, to cover the physical distance between two points and it is given by the formula:

$$\tau = \frac{d}{c} \quad (8)$$

Shooting and Bouncing Rays (SBR) method was employed for raytracing for computing the propagation paths and QoS metrics along the path in a 3D environment. This method traces each ray emitted from the transmitter and models various interactions between the rays and the environment, such as reflections and edge diffractions until the ray reaches the receiver's reception sphere. The computational complexity of the SBR method increases linearly with the number of reflections as opposed to an exponential increase in computational complexity with number of reflections as observed in Image Theory Method [33].

III. SIMULATION AND ANALYSIS

This section details the UAV mission scenario, its simulation environment, and the corresponding analysis of communication performance through QoS metrics.

A. Mission Definition

The simulation scenario location is set in central Milton Keynes, which is a city in the United Kingdom. The UAV path has a 250 m length and is shown in Figure 3. The transmit antenna is placed at the location marked by an antenna icon. The UAV departs from the take-off point, marked as 'T'. It travels through the waypoints marked and lands in the location marked as 'L'. The entire path was divided into 50 equal segments and hence we have 51 waypoints at which the QoS was analysed. The resulting segments have approximately 5 meters and the important waypoints are listed in Table III.

The ray tracing model was used to evaluate the QoS metrics: path loss, received signal strength, carrier-to-noise ratio, and latency. The list of ray tracer configurations is listed in Table IV.

TABLE III
IMPORTANT LOCATIONS ALONG THE PATH

Waypoint ID	Description
1	Take-off location
18	Closest to antenna
33	90 degree left turn
51	Landing location

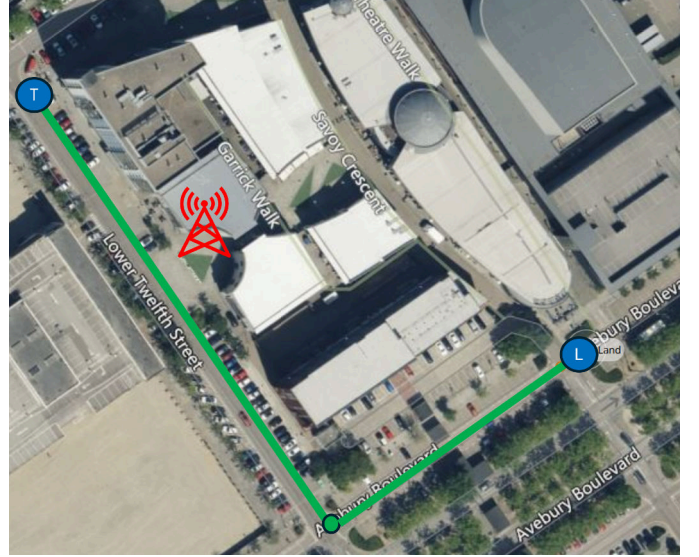


Fig. 3. UAV mission through Milton Keynes, UK

TABLE IV
RAY TRACER CONFIGURATION

Parameter	Value
Obstacles Considered	Buildings, Ground, Trees, Cars
Number of Rays	5000
Number of Bounces	5
Length of Rays	1000 m

Figure 4 illustrates the UAV's initial phase within the digital twin environment. In this setting, urban features like buildings, cars, and trees can reflect and scatter the transmitted signals. To visualize these interactions, a blue cube marker is used to indicate the locations where rays hit obstacles. Rays that undergo one or more reflections are coloured in red, allowing them to be easily distinguished from the direct, unreflected beams, which are depicted in green.

The UAV is equipped with both a Light Detection and Ranging (LIDAR) and camera sensor (Figure 5). The LIDAR data supports a Detect-and-Avoid (DAA) algorithm, ensuring safe navigation by continuously monitoring and maintaining separation from surrounding structures and terrain. Although the camera currently provides a basic visual feed for situational awareness, its functionality will be expanded as the digital twin evolves. Future enhancements may leverage the camera for advanced navigation, scene interpretation, and real-time decision-making to further improve the UAV's operational capabilities in complex urban settings.

The parameters considered for QoS are listed below, in

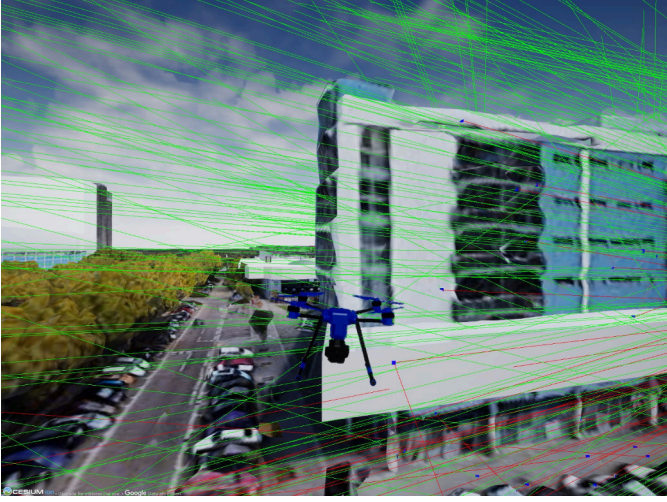


Fig. 4. UAV in take-off phase - Scenario Configuration mode

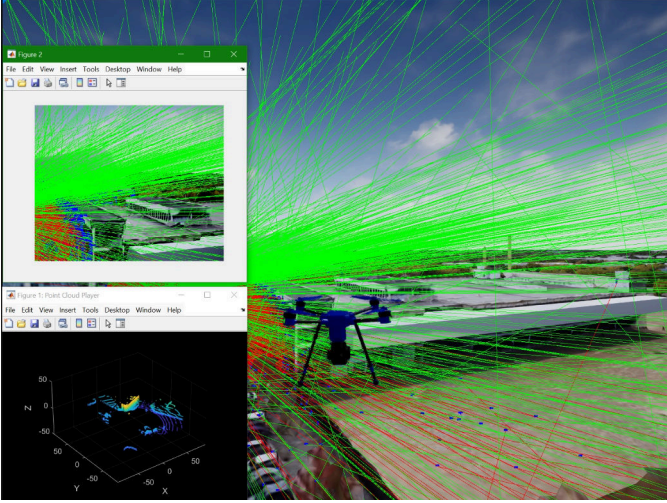


Fig. 5. UAV with sensor view - Full Mission Flight

Table V.

TABLE V
SYSTEM PARAMETERS.

System Parameters	Specification
Operating (center) frequency	100 GHz
Antenna gain (UAV-mounted)	10 dBi
UAM vehicle velocity	25 m/s
Transmitter Antenna Height	10 m
UAV Height	15 m
Base station power	38 dBm
Noise temperature	300 K
Minimum required C/N	-120 dB (for 6G)

B. Results and Discussion

Figure 6 shows the free space path loss (FSPL) along the UAV path defined in the previous subsection. The result shows an expected trend. FSPL is inherently dependent on

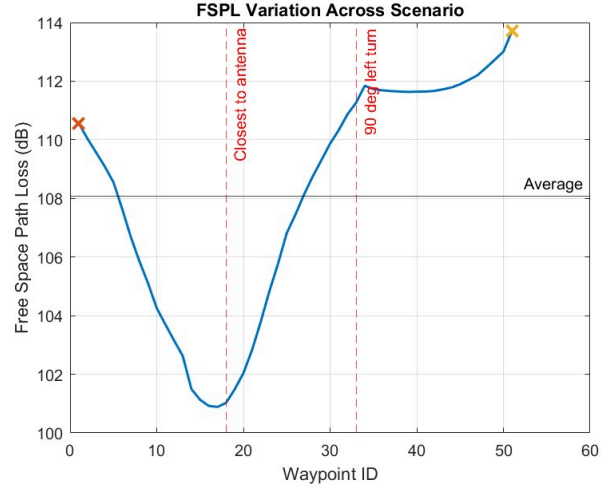


Fig. 6. Free Space Path Loss along the mission path using raytracing

the distance travelled by the ray from the antenna to the UAV. Hence, it decreases in the first 18 points as it moves closer to the transmitting antenna. As it continues along the decided path, it moves away from the antenna hence the path loss increases again. The UAV takes a 90° turn at the 33rd point, after which no more strong Line of sight component of the signal reaches the UAV directly. The rays reaching the UAV are the reflected rays. Hence the free space path loss varies very less near the bend and increases less gradually after the bend when moving away from the UAV.

Figure 7 shows the variation of the received signal strength at the UAV receiver along the UAV path evaluated using the digital twin. This is calculated using raytracing which uses the shooting and bouncing rays (SBR) method. Multipath interference is also taken into account in this method by evaluating the phasor sum. The received signal strength increases as it moves closer to the transmitting antenna and reduces as it moves further. The UAV moves closer to the antenna from waypoint 1 to waypoint 18 and moves away from waypoint 19 to 33, where it takes a left turn. The effect of multipath can be seen clearly after waypoint 33 (denoted by position 33 on X-axis).

Latency, dependent solely on the distance travelled by the signal from the transmit antenna on network tower to the receiver antenna mounted on the UAV, follows the same trend as FSPL. This can be seen in Figure 8.

Finally, the carrier-to-noise ratio was evaluated as discussed in methodology and was measured at each position through the UAV path. This is shown in Figure 9. Since carrier-to-noise ratio is dependent on received signal strength at the corresponding point, the trend observed in the graph is identical to the one observed in Figure 7.

The results show how the Digital Twin when run in the simulation mode can generate synthetic data which can be used to train models to optimise path, transmitter and receiver antenna configurations, and also the resource allocation for a

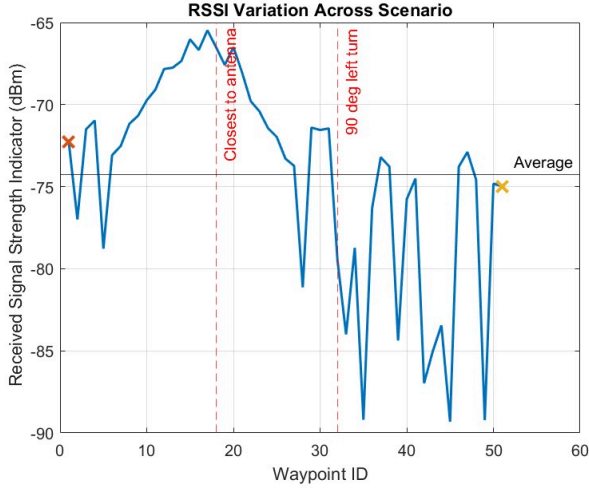


Fig. 7. Received Signal strength using raytracing

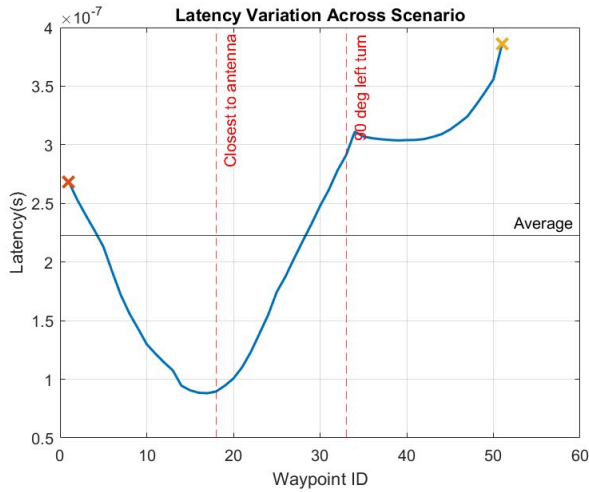


Fig. 8. Latency variation along the mission path

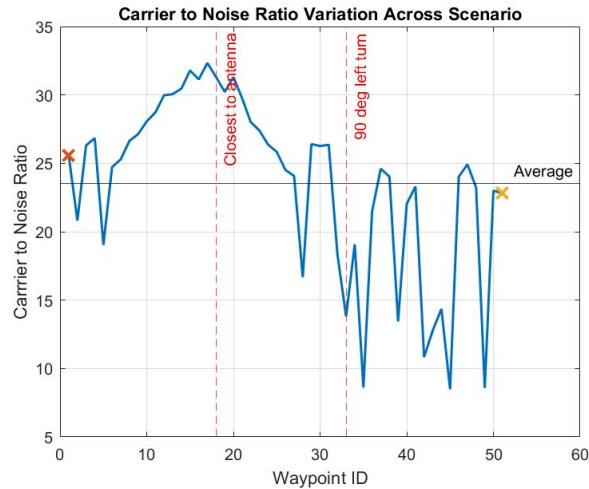


Fig. 9. Carrier to Noise ratio along the mission path

particular use case. While this is an innovative approach to evaluate and optimise QoS metrics in the real world, there are certain limitations of this approach. The accuracy of the results (as compared to real-world trials) would depend on how well the virtual world is designed. While it is impossible to create the exact real world within the virtual environment, it is important to make it as close to the real world as possible.

Raytracing is a computationally intensive method where the optimal path(s) is evaluated out of numerous paths which are possible between the transmitter and the receiver. The raytracing simulation becomes closer to the real-world trial by adding more and more actors which would affect the propagation of the ray from the transmitter to the receiver. But more actors (buildings, trees, pavement etc) added into the simulation would also mean more reflections and more computation required to evaluate the optimal path of the ray. The material properties of the actors added must also be close to the actual value to get results that are close to real-world trials.

IV. CONCLUSION

This paper presented a framework for integrating DTs into UAV communication systems, focusing on the evaluation of key QoS metrics such as path loss, received signal strength, latency, and carrier-to-noise ratio in a simulated 6G environment. Using Unreal Engine for high-fidelity visualization and MATLAB/Simulink for communication analysis and control logic, we demonstrated the ability to emulate real-world UAV communication scenarios within a digital twin. The results highlight the DT's capability to generate synthetic data for performance evaluation, optimization of flight paths, and resource allocation. This study represents the initial phase of our DT development, laying the foundation for advanced functionalities. Further enhancements, including integration with O-RAN architectures and intelligent handover management through xApps, are detailed in the next section.

V. FUTURE WORK

While the current version of the Network Digital Twin primarily evaluates QoS metrics in a simulation environment, future work will align it more closely with the O-RAN architecture for next-generation (6G) networks by integrating intelligent handover algorithms through specialized xApps in the near-real-time RAN Intelligent Controller (near-RT RIC). These xApps, functioning like microservices, use historical and real-time network data to optimize and control RAN functions—such as dynamic handover management, load balancing, and interference mitigation—at near-real-time scales. In subsequent iterations of the digital twin, dedicated xApps will predict network conditions, orchestrate handover events, and optimize end-to-end QoS, transforming the twin from a passive observer of QoS into an active, data-driven participant in closed-loop decision-making. This evolution positions the digital twin as a crucial component in future O-RAN-based networks, harnessing advanced analytics to enhance performance, reliability, and user experience.

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