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DYNAMIC CHANNEL MODELING AND PERFORMANCE ANALYSIS FOR UAV COMMUNICATIONS

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Abstract. This paper presents a comprehensive dynamic channel modeling and simulation framework for unmanned aerial vehicle (UAV) air-to-ground communication systems. Starting from fundamental AWGN and Rayleigh fading channels, we progressively incorporate large-scale path loss (distance-dependent) and Doppler shift (velocity-dependent) to construct a realistic time-varying channel model. The performances of BPSK and QPSK modulations are compared under both line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. Simulation results quantitatively reveal the impact of flight distance and velocity on bit error rate (BER), and provide optimal modulation switching thresholds under different SNR conditions. An interactive GUI tool is developed to visualize the dynamic BER variation and constellation diagrams in real time. The work offers theoretical insights and practical guidelines for UAV communication system design.

Keywords: UAV communications, channel modeling, path loss, Doppler shift, Rayleigh fading, BER analysis.

Introduction

Unmanned Aerial Vehicles (UAVs) have become essential in various applications such as surveillance, delivery, and emergency communications [1]. Reliable air-to-ground communication is critical for these missions, as it enables real-time data transmission and command control [2]. Unlike terrestrial communication links, UAV channels exhibit high dynamics due to platform mobility, altitude variations, and complex environmental interactions [3]. Accurate and comprehensive channel modeling is therefore fundamental for the design, simulation, and performance evaluation of robust UAV communication systems [4].

Existing studies have investigated UAV channel characteristics through field measurements and statistical modeling approaches [5-7]. However, most prior works focus on either static scenarios or simplified path loss models, lacking a systematic simulation framework that integrates both large-scale fading (path loss) and small-scale fading (Rayleigh fading) with real-time UAV trajectory dynamics [8]. Moreover, the joint effect of flight distance and velocity on modulation performance, particularly under varying line-of-sight (LOS) and non-line-of-sight (NLOS) conditions, is often treated separately rather than analyzed as a coupled system [9].

In this paper, we develop a step-by-step dynamic channel simulation framework that progresses from a basic additive white Gaussian noise (AWGN) channel to a complete time-varying model incorporating distance-dependent path loss, velocity-dependent Doppler shift, and Rayleigh fading. We compare the performance of binary phase-shift keying (BPSK) and quadrature phase-shift keying (QPSK) modulations under both LOS and NLOS scenarios, derive quantitative relationships between flight parameters and bit error rate (BER), and propose adaptive modulation switching thresholds based on channel conditions. An interactive graphical user interface (GUI) is implemented to facilitate real-time parameter adjustment, dynamic visualization of BER curves, and constellation diagram display. The work provides both theoretical validation and practical guidelines for adaptive modulation and link budget design in UAV communication systems.

System Model

We consider a UAV flying horizontally at a constant altitude $h = 100m$ with constant velocity $v = 20m/s$ along the x-axis. The ground station is fixed at the origin. The UAV starts at (0,0,100) and moves to (1000,0,100). The instantaneous distance between UAV and ground station is

$$\mathrm{d}(t) = \sqrt{(x(t))^2 + h^2}\ , \tag{1}$$

where $x(t) = vt$ is the horizontal displacement of the UAV at time t; $v = 20m/s$ is the constant flight velocity of the UAV.

The free-space path loss in dB is given by

$$PL(d) = 20\log10(d) + 20\log10(fc) - 147.55\ , \tag{2}$$

where $fc = 2.4Hz$ is the carrier frequency. The linear power gain is $g_{PL}(t) = 10^{-PL(d(t))/10}$.

The radial velocity component is

$$v_r(t) = \frac{x(t)v}{d(t)}\ . \tag{3}$$

The Doppler frequency shift is

$$f_d(t) = \frac{v_r(t)}{\lambda}, \lambda = \frac{c}{f_c}\ , \tag{4}$$

where $c = 3 \times 10^8$ m/s. The Doppler-induced phase rotation is incorporated as $e^{j2\pi f_d(t)t}$.

For NLOS scenarios, we adopt a flat Rayleigh fading model with independent realizations per symbol

$$h_{ray}(t) = \frac{1}{\sqrt{2}}(N(0,1) + jN(0,1))\ , \tag{5}$$

ensuring $E[|h_{ray}|^2] = 1$, where $\alpha(t)$ follows Rayleigh distribution and $\theta(t)$ follows uniform distribution in $[0, 2\pi]$.

Two modulation schemes are considered: BPSK and QPSK. Both are normalized to unit average power. The transmitted symbols are generated from random bits. The received signal after the channel is

$$r(t) = \sqrt{g_{PL}(t)}h(t)e^{j2\pi f_d(t)t}s(t) + n(t)\ , \tag{6}$$

where $h(t) = 1$ for LOS, and $h(t) = h_{ray}(t)$ for NLOS, and $n(t)$ is AWGN with power spectral density N_0. The noise power is fixed based on a reference SNR at distance 100 m.

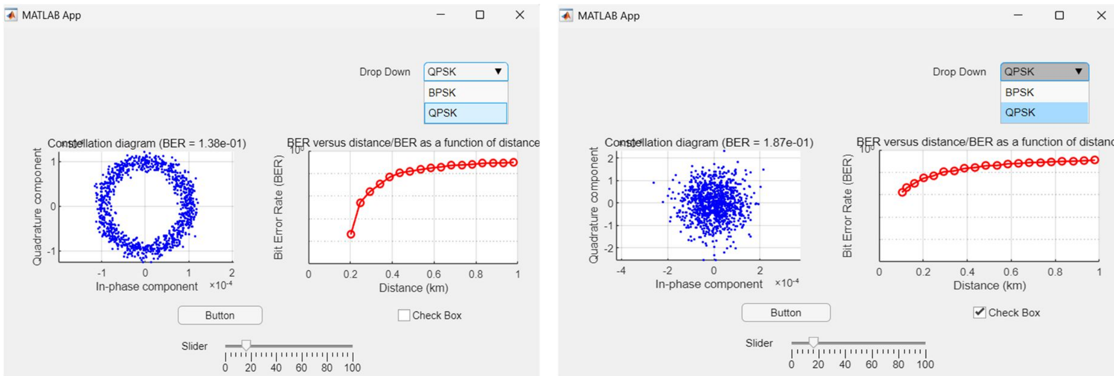
Simulation

Key simulation parameters are listed in Table 1.

Table 1. **Simulation parameters**

Parameter	Value
Carrier frequency	2.4 GHz
UAV velocity	20 m/s
UAV altitude	100 m
Flight distance range	0 – 1000 m
Symbol rate	1 kHz
Reference distance	100 m
Reference SNR range	0 – 30 dB
Number of symbols	50,000

A graphical user interface (GUI) is built using MATLAB App Designer, as shown in Figure 1. The GUI allows users to select modulation (BPSK/QPSK), enable/disable Rayleigh fading, adjust reference SNR via a slider, and instantly view the constellation diagram and BER-vs-distance curve. This tool facilitates intuitive understanding of how flight parameters affect communication performance.



a *b*

Figure 1. GUI for UAV channel simulation: a – close Check Box; b – open Check Box

Figure 2 shows the BER as a function of flight distance for BPSK and QPSK under LOS conditions (reference SNR = 30 dB at 100 m). As the UAV moves away, path loss increases, reducing received SNR and elevating BER. BPSK maintains lower BER than QPSK at all distances; at 1 km, BPSK BER is about 1.5×10^{-2}, while QPSK BER exceeds 10^{-1}. This indicates that QPSK is more sensitive to distance due to its higher SNR requirement.

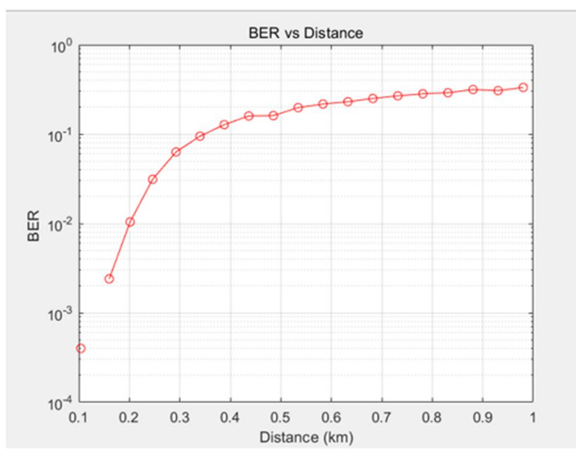


Figure **2.** BER versus distance for BPSK and QPSK (LOS, reference SNR = 30 dB)

To isolate velocity effect, we fix the distance at 500 m and vary UAV speed from 10 to 50 m/s, with reference SNR = 20 dB. Figure 3 illustrates BER growth with increasing speed, especially for QPSK. The Doppler shift causes phase rotation that challenges coherent detection; without ideal channel tracking, higher speeds degrade performance more severely.

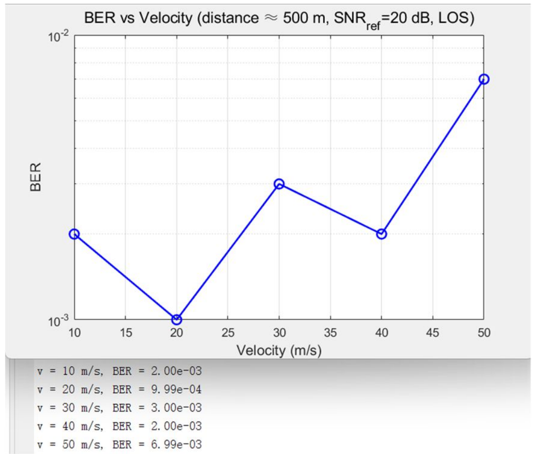


Figure 3. Situations that cannot be measured under a binocular system

Figure 4 compares BPSK and QPSK BER versus reference SNR under both LOS and NLOS (Rayleigh) channels. In LOS, BPSK achieves BER 10−310−3 at about 7 dB, while QPSK requires 10 dB. In NLOS, both suffer severe degradation: BPSK needs 18 dB, QPSK needs 22 dB for the same BER. This leads to the following modulation selection guideline:

1. SNR < 10 dB: use BPSK (reliability priority).
2. 10 dB ⩽ SNR < 22 dB: use QPSK (higher data rate while meeting BER target).
3. SNR ⩾ 22 dB: higher-order modulations (e.g., 16QAM) may be considered.

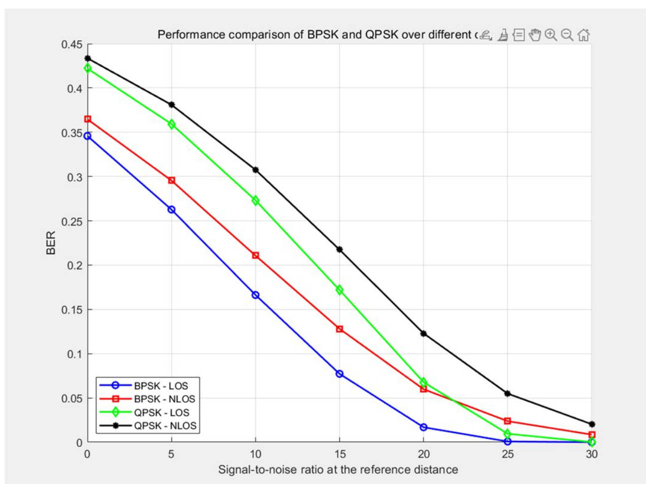


Figure 4. BER versus reference SNR for BPSK and QPSK under LOS and NLOS channels

Conclusion

This paper presented a comprehensive dynamic channel modeling and simulation framework for UAV communications. By progressively incorporating path loss, Doppler shift, and Rayleigh fading, we systematically analyzed the impact of flight distance and velocity on BER for BPSK and QPSK modulations. Key findings include: Distance significantly degrades BER, with QPSK being more sensitive than BPSK.Velocity-induced Doppler shift causes performance loss, especially for QPSK.SNR thresholds for modulation switching are identified: BPSK below 10 dB, QPSK between 10 and 22 dB.

An interactive GUI tool was developed to visualize these effects in real time, serving both educational and engineering design purposes. The work provides theoretical validation and practical insights for adaptive modulation and link budget in UAV communication systems. Future work may extend to more complex environments (e.g., urban canyon) and advanced modulations (e.g., OFDM).

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