Mobility-, orientation-, and airframe-aware channel modeling

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Half-day Tutorial Session at ICUAS 2026 (09:00 – 13:00), 15th June 2026
Room Calypso A – Divani Corfu Palace

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Channel Model

INPUT–OUTPUT MODEL → $y(t) = \mathcal{H}(\mathbf{q}_r(t), \mathbf{q}_t(t), t)\, x(t) + n(t)$

CHANNEL GAIN MODEL

$$\mathcal{H}(\mathbf{q}_r(t), \mathbf{q}_t(t), t) = \frac{G(\mathbf{q}_r(t), \mathbf{q}_t(t)) \cdot s(\mathbf{p}_r(t), \mathbf{p}_t(t)) \cdot h(\mathbf{p}_r(t), \mathbf{p}_t(t), t)}{L_P(\mathbf{p}_r(t), \mathbf{p}_t(t))}$$

Propagation Terms:

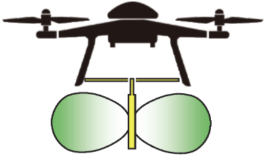
- $G(\mathbf{q}_r, \mathbf{q}_t)$: antenna gain product
- $s(\mathbf{p}_r, \mathbf{p}_t)$: large-scale shadowing
- $h(\mathbf{p}_r, \mathbf{p}_t, t)$: small-scale fading
- $L_P(\mathbf{p}_r, \mathbf{p}_t)$: path loss

Signals and States:

- $x(t)$: transmitted signal
- $y(t)$: received signal
- $n(t)$: receiver noise
- $\mathbf{q}_r(t)$, $\mathbf{q}_t(t)$: receiver and transmitter *poses*
- $\mathbf{p}_r(t)$, $\mathbf{p}_t(t)$: receiver and transmitter *positions*

Antenna Gain and Pose Coupling

- The antenna gain depends on the **full pose** (the position and the orientation).
- For a quadrotor, the antenna is body-fixed and the antenna gain changes because:
  - Translation requires pitch/roll change
  - Pitch/roll rotates the antenna boresight

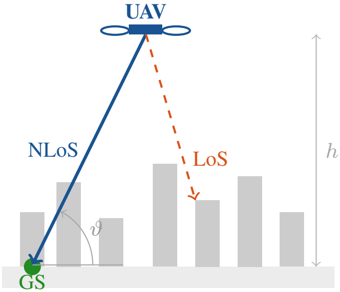


Decoupling position and orientation $\Rightarrow$ adds additional control on the antenna gain.

UAV Air-to-Ground (A2G) Channel Model

Why A2G differs from terrestrial

- UAV elevation angle θ improves LoS probability
- Ground-level clutter (buildings, trees) causes NLoS
- Channel properties vary *continuously* with altitude h and horizontal distance d



LoS probability

$$P_{\text{LoS}}(\vartheta) = \frac{1}{1 + C\ \exp\big[-B(\vartheta - C)\big]}$$

where $\vartheta = \arctan(h/r)$ is the elevation angle, B, C are environment-dependent constants (urban, suburban..).

At high altitude, $\vartheta \uparrow \Rightarrow P_{\text{LoS}} \uparrow \Rightarrow$ better channel, but path distance increases. An **optimal altitude** h^* exists.

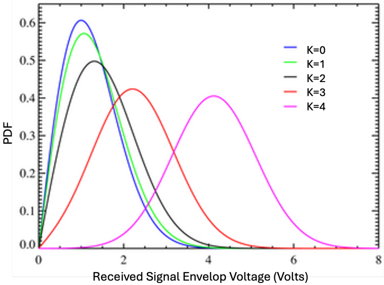
H. El Hammouti et al. "Air-to-ground channel modeling for UAV communications using 3D building footprints," International Symposium on Ubiquitous Networking. Springer International Publishing, 2018.

A2G Channel: Rician Modeling

- A2G fading is well modelled by the **Rician distribution**:

$$f(r) = \frac{2r(K+1)}{\Omega}\exp\left(-K - \frac{(K+1)r^2}{\Omega}\right) I_0\left(2r\sqrt{\frac{K(K+1)}{\Omega}}\right)$$

- K: Rician K-factor (ratio of LoS power to scattered power)
- Ω: total average power



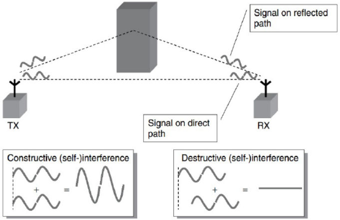
- At low altitude: K small (NLoS-dominated, Rayleigh-like)
- At high altitude: $K \gg 1$ (LoS-dominant, nearly deterministic)

Small-Scale Fading

Multipath Interference: LoS and reflected waves arrive with different phases, causing:

- **Constructive interference** → signal boost
- **Destructive interference** → signal fading

Effects vary over distances $\sim$ wavelength (cm-scale at GHz).

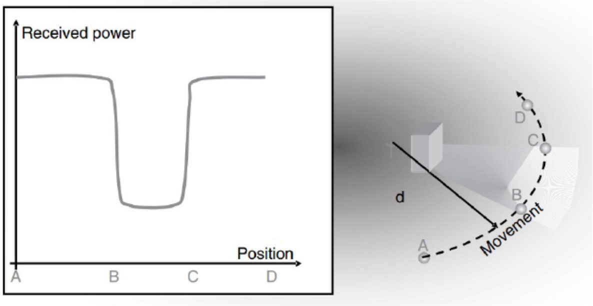


A. F. Molisch, *Wireless Communications,* John Wiley & Sons, 2011.

In general, **Rayleigh distribution** is used to model multipath fading in wireless communications.

Shadowing (Large-Scale Fading)

- Shadowing: occurs when large objects (e.g., buildings, terrain) obstruct the LoS path, causing a significant drop in received power over large distances.



A. F. Molisch, *Wireless Communications,* John Wiley & Sons, 2011.

LoS between nodes B and C is blocked → reduced signal strength due to shadowing.

Shadowing (Large scale fading)

Shadowing model

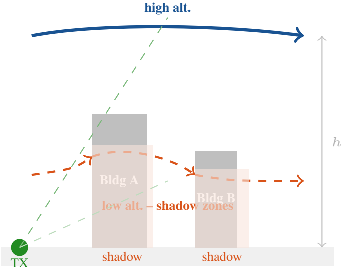
- Log-normal shadowing: received power P_r in dB satisfies

$$P_r(\mathrm{dB}) = \overline{P}_r(\mathrm{dB}) - \underbrace{X_\sigma}_{\text{shadow}}, \qquad X_\sigma \sim \mathcal{N}(0, \sigma_s^2)$$

- Spatial correlation (Gudmundson model):

$$\mathbb{E}[X_\sigma(\mathbf{p}_1) X_\sigma(\mathbf{p}_2)] = \sigma_s^2 \exp^{-\|\mathbf{p}_1 - \mathbf{p}_2\|/d_c}$$

d_c: decorrelation distance (∼10–50 m in urban areas).

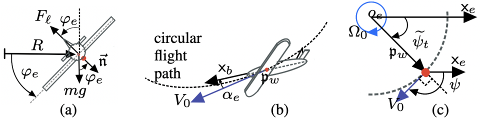


Key trade-off: flying high avoids shadowing but increases path loss and propulsion energy. **Pose-aware planning** must account for both simultaneously.

Gudmundson M. "*Correlation model for shadow fading in mobile radio systems*", IEEE Letters 1991; 27:2145–2146.

Airframe Self-Shadowing in UAV Communications

- The UAV's own **mechanical structure** (frame arms, motor mounts, battery, payload) physically obstructs the antenna radiation pattern, creating **attitude-dependent signal blockage**



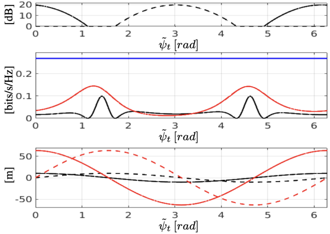
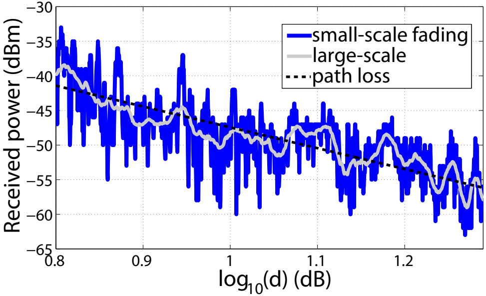
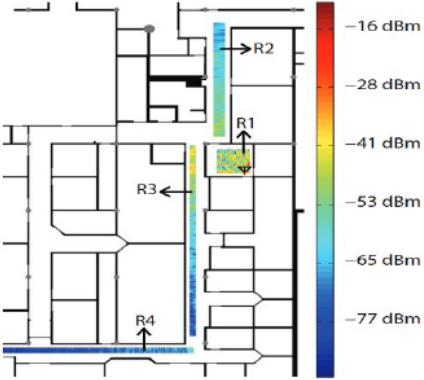


Figure right: Illustration of airframe shadowing; Figure left: Top: airframe shadowing loss of each link for the benchmark trajectory; $L_{S_{GU}}$ (continuous line) and $L_{S_{BS}}$ (dashed line). Middle: normalized end-to-end bit rate $r(\widetilde{\psi}_t)/B$ for the benchmark trajectory (black), the ASA trajectory (red), and the multirotor UAV (blue). Bottom: benchmark trajectory (black), and ASA trajectory (red); x components in continuous lines, and y components in dashed lines.

Licea DB, Bonilla M, Ghogho M, Saska M. "*Energy-efficient fixed-wing UAV relay with considerations of airframe shadowing*", IEEE Communications Letters. 2023 Apr 5;27(6):1550-4.

Path Loss, Shadowing, and Fading in Wireless Channels

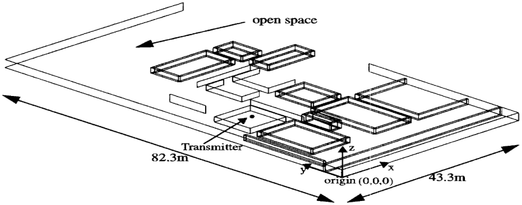




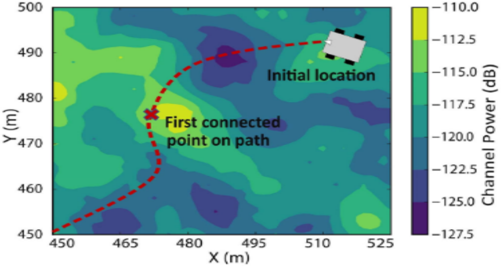
A. M. Malmichrgini et al., "*On the Spatial Predictability of Communications Channels*," IEEE Transactions on Communication, 2012.

Prior Knowledge of the Communication Channel

Physical Map Available



RF Map Available



Other Possible Scenarios:

- Only sparse RF measurements are available.
- A purely analytical model is used.

A. Muralidharan et al., "*Path Planning for Minimizing the Expected Cost Until Success*," IEEE Trans. Robotics, 2019.

C. M. P. Ho et al., "*Wireless Channel Prediction in a Modern Office Building Using an Image-Based Ray Tracing Method*," Proc. IEEE GLOBECOM, 1993.

Summary: Channel Effects and Their Impact on UAV Planning

Effect	Physical Cause	Scale	Impact on UAV Planning
Path loss	Geometric spreading	$\propto d^n$	Drives 3D placement: optimal altitude h^*
Shadowing	Obstacle blockage	10–100 m	Shadow-aware trajectory
Small-scale fading	Multipath	$\sim\lambda$ (cm)	Statistical margin in link budget
Antenna gain	Directional pattern + attitude coupling	Instantaneous	**Pose** optimisation required

Thank you

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