Jittering effects analysis and beam training design for UAV mmWave communications

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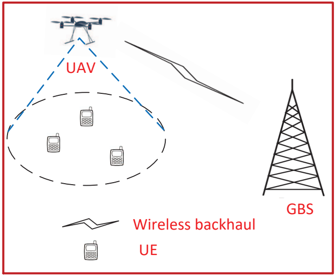
Outline

UAV communications

Background

- UAV communications
  - High operational flexibility and controllable mobility
- MmWave communications
  - Directional transmission and high throughput
- UAV + mmWave communications
  - An on-demand solution to high-capacity wireless backhaul in cellular networks

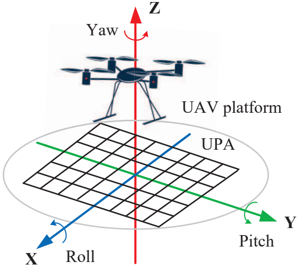


Movitations

- Jittering effects are a key factor that characterizes UAV communications
  - Detrimental to UAV mmWave backhaul with a directional narrow beam

Outline

What is UAV jitter?



- UAV jitter: The unintended high-frequency change of UAV attitude/orientation;
- Euler angles describe the orientation of a rigid body with respect to a fixed coordinate system

$$\mathbf{R} = \mathbf{R}_{Yaw}(\alpha)\mathbf{R}_{Pitch}(\beta)\mathbf{R}_{Roll}(\gamma)$$

- UAV jitter modelled by Euler angles

$$\alpha = \bar{\alpha} + \Delta\alpha$$
$$\beta = \bar{\beta} + \Delta\beta$$
$$\gamma = \bar{\gamma} + \Delta\gamma$$

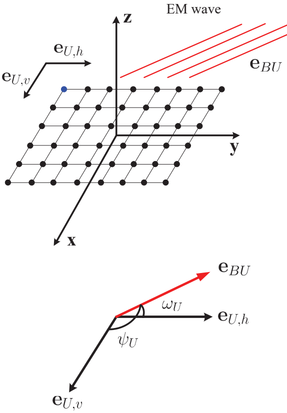
where $\bar{\alpha}, \bar{\beta}, \bar{\gamma}$ are the desired attitude angles, and $\Delta\alpha, \Delta\beta, \Delta\gamma$ refer to the fluctuations caused by UAV jitter.

Narrow-band mmWave Channel Model

Channel model

$$\mathbf{H} = \sum_{l=0}^{L-1} \beta_l \mathbf{v}(\Psi_{U,l}, \Omega_{U,l}) \mathbf{v}^H(\Psi_{B,l}, \Omega_{B,l})$$

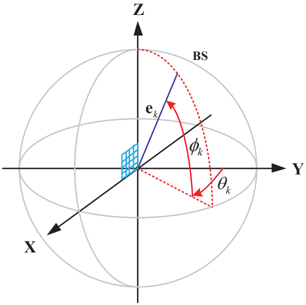
- $\mathbf{v}(\Psi_U, \Omega_U)$ and $\mathbf{v}(\Psi_B, \Omega_B)$ are array response (steering) vectors at UAV side and BS side.
- LoS component dominates, i.e., $|\beta_0| >> |\beta_l|, l \neq 0$
- $\mathbf{H}$ is characterized by $(\Psi_{U,0}, \Omega_{U,0})$ and $(\Psi_{B,0}, \Omega_{B,0})$, which are termed as cosine AoA/AoD or direction cosines.



$$\Omega_U = \cos\omega_U = \mathbf{e}_{U,h}^T \mathbf{e}_{BU}$$

$$\Psi_U = \cos\psi_U = \mathbf{e}_{U,v}^T \mathbf{e}_{BU}$$

A Deep Look Into Angles



ϕ_k: Elevation angle

θ_k: Azimuth angle

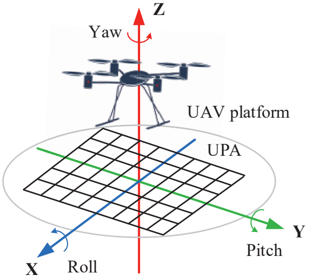
$\mathbf{e}_k$: Direction vector from user k to BS

(1) Azimuth angle & Elevation angle

- Angles in spherical coordinate that are used to identify the position of UAV
- The direction vector from UAV to BS is $\mathbf{e}_{BU} = [\cos\phi\cos\theta,\ \cos\phi\sin\theta,\ \sin\phi]^T$ where ϕ is elevation angle and θ is azimuth angle of the LoS path.
- Can be obtained via GPS and barometer.

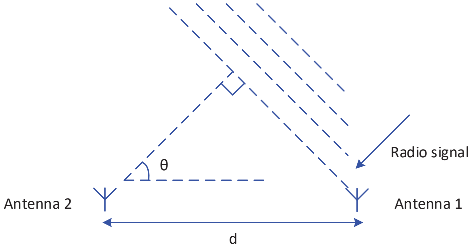
A Deep Look Into Angles

(2) Yaw, pitch & roll angles



- Can be measured via Gyroscope.

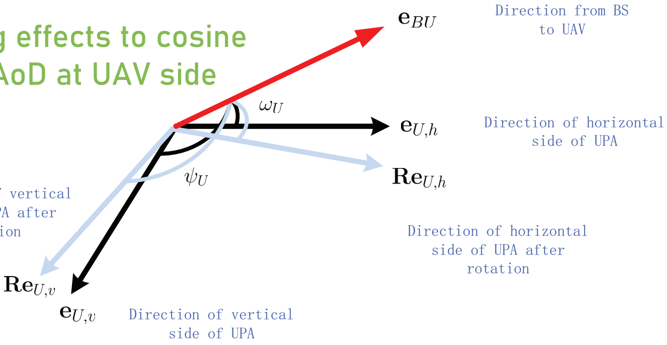
(3) Angle of arrival (AoA) & Angle of departure (AoD)



- Can be obtained through estimating phase differences of the elements of an antenna array.

A Deep Look Into Angles

Jittering effects to cosine AoA/AoD at UAV side



$$\Omega_U = \cos\omega_U = \mathbf{e}_{U,h}^T \mathbf{e}_{BU}$$
$$\Psi_U = \cos\psi_U = \mathbf{e}_{U,v}^T \mathbf{e}_{BU}$$

Rotation: R

$$\Omega_U = \cos\omega_U = \mathbf{e}_{U,h}^T \mathbf{R}^T \mathbf{e}_{BU}$$
$$\Psi_U = \cos\psi_U = \mathbf{e}_{U,v}^T \mathbf{R}^T \mathbf{e}_{BU}$$

Jittering Effects on Cosine AoA/AoD

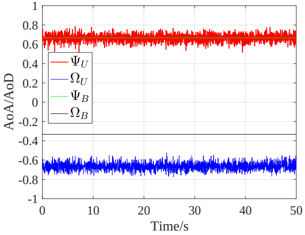
Two-dimensional AoA/AoD	UAV position related angles (i.e., ϕ, θ)	UAV attitude related angles (i.e., α, β, γ)
(Ψ_B, Ω_B)	Dependent	Independent
(Ψ_U, Ω_U)	Dependent	Dependent

Table 1: Dependency of the two-dimensional AoA/AoD (BS side and UAV side) on UAV position and UAV attitude

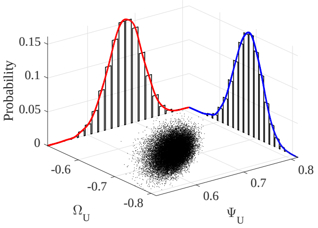
- UAV Jittering Effects on cosine AoA/AoD at UAV side cannot be ignored
- UAV Jittering Effects on cosine AoA/AoD at BS side are negligible

Jittering Effects on Cosine AoA/AoD - Numerical Examples

Modelling of UAV jitter: $\sigma_\alpha = \sigma_\beta = \sigma_\gamma = 0.05$



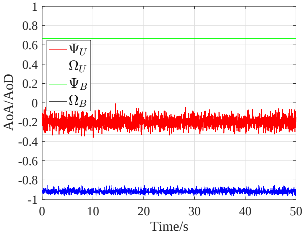
(a) Variation of Ψ_U, Ω_U, Ψ_B and Ω_B over time (Scenario 1)



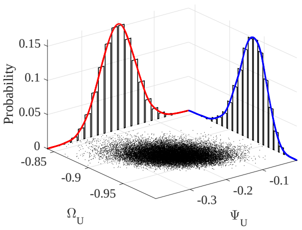
(b) Empirical marginal probability density function of Ψ_U and Ω_U (Scenario 1)

Figure 1: UAV is hovering at the position $\mathbf{p}_U = [-100, 100, 50]^T$ (Cartesian coordinates) with its desired flight attitude being $\bar{\alpha} = \bar{\beta} = \bar{\gamma} = 0$

Jittering Effects on Cosine AoA/AoD - Numerical Examples



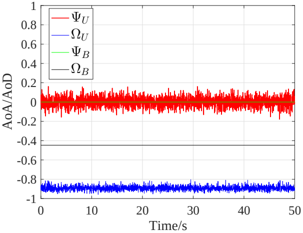
(a) Variation of Ψ_U, Ω_U, Ψ_B and Ω_B over time (Scenario 1)



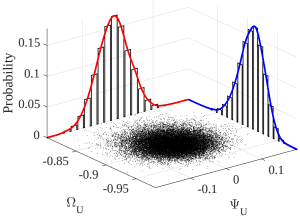
(b) Empirical marginal probability density function of Ψ_U and Ω_U (Scenario 1)

Figure 2: UAV is hovering at the position $\mathbf{p}_U = [-100, 100, 50]^T$ (Cartesian coordinates) with its desired flight attitude being $\bar{\alpha} = 1$, and $\bar{\beta} = \bar{\gamma} = 0$

Jittering Effects on Cosine AoA/AoD - Numerical Examples



(a) Variation of Ψ_U, Ω_U, Ψ_B and Ω_B over time (Scenario 1)



(b) Empirical marginal probability density function of Ψ_U and Ω_U (Scenario 1)

Figure 3: UAV is hovering at the position $\mathbf{p}_U = [0, 100, 50]^T$ (Cartesian coordinates) with its desired flight attitude being $\bar{\alpha} = \bar{\beta} = \bar{\gamma} = 0$

Jittering Effects on Cosine AoA/AoD

The same scale of of UAV jitter

+

A different UAV position

+

A different desired UAV attitude

Different scales of jittering effects to UAV mmWave channel

Outline

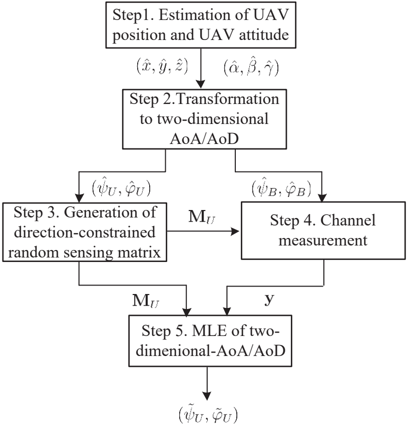
UAV Beam Training Under Jittering Effects

The Objective of Beam Training: Estimate AoA/AoD of the strongest path in mmWave channel to support the subsequent beam alignment operation.

- Ideally, with the relative position (Azimuth angle & Elevation angle) and attitude (Euler angles) of UAV, AoA/AoD can be accurately obtained.
- However, UAV platform faces the following challenges
  - Gyroscope and accelerometer are very sensitive to the jitter/vibration induced by the engine and wind gust;
  - The estimation error increases with the degree of UAV jitter.

UAV Beam Training Under Jittering Effects

Utilizing navigation information to facilitate compressed sensing (CS) based UAV beam training.



- Obtain a rough estimate of cosine AoA/AoD from navigation information according to the relationship between angles.
- Narrow down the search range of CS-based beam training

How to Design Sensing Matrix

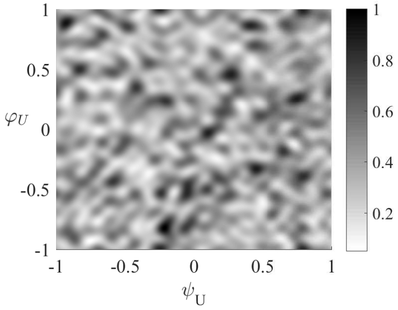
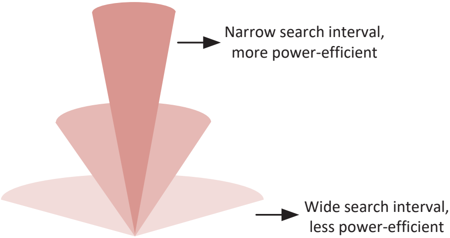


Figure 4: Fully random case with the sensing range being $\Psi_U, \Omega_U \in (-1, 1)$

- Sensing matrix needs to satisfy restricted isometry property (RIP)
- Randomly generated (under constant modulus constraint) sensing matrix satisfies RIP with high probability
- However, fully random sensing matrix is semi-omnidirectional and power inefficient and will result in heavier training overload.

How to Design Sensing Matrix

How to design the (random) CS sensing matrix within an arbitrary sensing range?



- Design of direction-constrained CS sensing matrix is challenging due to
  - Constant modulus constraint of analog array antenna
  - Restrained sensing range

Direction-Constrained Sensing Matrix

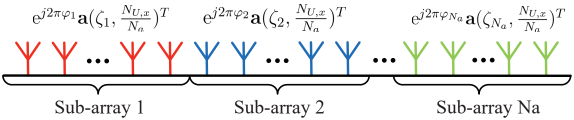


Figure 5: Visualization of sub-array partition along one dimension

Sub-array based method:

Radiation range of the sub-array: $\left(-\frac{N_a}{N_{U,x}} + \zeta_{n_a}, \frac{N_a}{N_{U,x}} + \zeta_{n_a}\right)$

- **Step1.** Restrict center angle ζ_{n_a} and sub-array size $N_{U,x}$ to restrain radiation range;
- **Step2.** Randomize φ_{n_a} and partially randomize center angle ζ_{n_a} to satisfy RIP.

Direction-Constrained Sensing Matrix

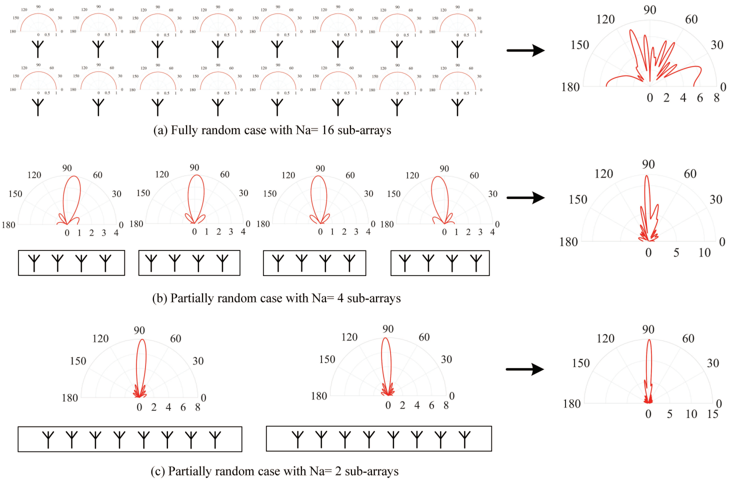
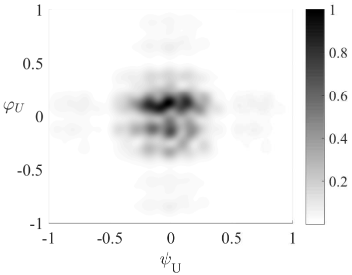
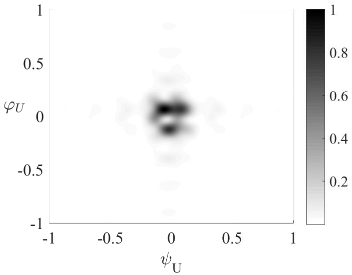


Figure 6: Visualization of sub-array based design of random sensing vector (the scale of angle is $\cos^{-1}\Psi_U$)

Direction-Constrained Sensing Matrix



(a) $N_a = 4$ sub-arrays, and the sensing range is $\Psi_U, \Omega_U \in (-0.4, 0.4)$

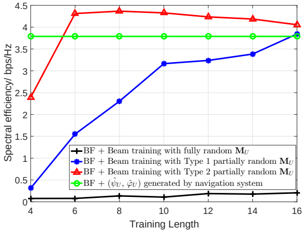


(b) $N_a = 2$ sub-arrays, and the sensing range is $\Psi_U, \Omega_U \in (-0.225, 0.225)$

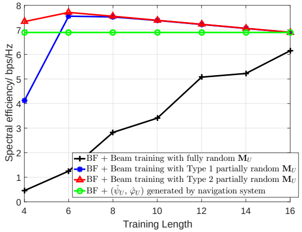
Figure 7: Beam space of partially random sensing matrices under constant modulus constraint

Outline

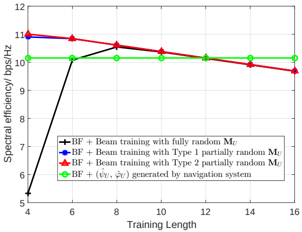
Spectral Efficiency Comparison



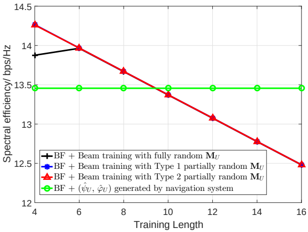
(a) When transmit power is -10dBm



(b) When transmit power is 0dBm



(c) When transmit power is 10dBm



(d) When transmit power is 20dBm

Outline

Conclusion

- We analytically build the connection between UAV jitter and its effects on mmWave channel;
- We propose a navigation-information-aided beam training for UAV mmWave communications;
- UAV beam training scheme assisted by navigation information can achieve better accuracy with reduced training length in AoA/AoD estimation.

Q&A