Jittering effects analysis and beam training design for UAV mmWave communications

Wei Wang

School of Electrical Engineering & Telecommunications
The University of New South Wales, Sydney, Australia

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Outline

1 Background and Motivations

2 The Effects of UAV Jitter on mmWave Channel

3 Navigation-information-aided Beam Training Design

4 Numerical Results

5 Conclusion
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

Motivations

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

\[
R = R_{\text{Yaw}}(\alpha)R_{\text{Pitch}}(\beta)R_{\text{Roll}}(\gamma)
\]

- **UAV jitter modelled by Euler angles**

\[
\begin{align*}
\alpha &= \bar{\alpha} + \Delta \alpha \\
\beta &= \bar{\beta} + \Delta \beta \\
\gamma &= \bar{\gamma} + \Delta \gamma
\end{align*}
\]

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.
The Effects of UAV Jitter on mmWave Channel

Narrow-band mmWave Channel Model

Channel model

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

- \( \mathbf{v}(\Psi_{U}, \Omega_{U}) \) and \( \mathbf{v}(\Psi_{B}, \Omega_{B}) \) are array response (steering) vectors at UAV side and BS side.
- LoS component dominates, i.e., \(|\beta_0| >> |\beta_l|, l \neq 0\)
- \( H \) 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

(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 \( \phi \) is elevation angle and \( \theta \) 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

\[
\Omega_U = \cos \omega_U = e_{U,h}^T e_{BU}
\]
\[
\Psi_U = \cos \psi_U = e_{U,v}^T e_{BU}
\]

Direction from BS to UAV
Direction of horizontal side of UPA
Direction of horizontal side of UPA after rotation
Direction of vertical side of UPA after rotation

Rotation: \( R \)

\[
\Omega_U = \cos \omega_U = e_{U,h}^T R^T e_{BU}
\]
\[
\Psi_U = \cos \psi_U = e_{U,v}^T R^T e_{BU}
\]
Jittering Effects on Cosine AoA/AoD

<table>
<thead>
<tr>
<th>Two-dimensional AoA/AoD</th>
<th>UAV position related angles (i.e., $\phi$, $\theta$)</th>
<th>UAV attitude related angles (i.e., $\alpha$, $\beta$, $\gamma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>($\Psi_B$, $\Omega_B$)</td>
<td>Dependent</td>
<td>Independent</td>
</tr>
<tr>
<td>($\Psi_U$, $\Omega_U$)</td>
<td>Dependent</td>
<td>Dependent</td>
</tr>
</tbody>
</table>

**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 \( \Psi_U, \Omega_U, \Psi_B \) and \( \Omega_B \) over time (Scenario 1)

(b) Empirical marginal probability density function of \( \Psi_U \) and \( \Omega_U \) (Scenario 1)

Figure 1: UAV is hovering at the position \( p_U = [-100, 100, 50]^T \) (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 $\Psi_U$, $\Omega_U$, $\Psi_B$ and $\Omega_B$ over time (Scenario 1)  
(b) Empirical marginal probability density function of $\Psi_U$ and $\Omega_U$ (Scenario 1)

Figure 2: UAV is hovering at the position $p_U = [-100, 100, 50]^T$ (Cartesian coordinates) with its desired flight attitude being $\vec{\alpha} = 1$, and $\vec{\beta} = \vec{\gamma} = 0$
Jittering Effects on Cosine AoA/AoD - Numerical Examples

(a) Variation of $\Psi_U$, $\Omega_U$, $\Psi_B$ and $\Omega_B$ over time (Scenario 1)

(b) Empirical marginal probability density function of $\Psi_U$ and $\Omega_U$ (Scenario 1)

Figure 3: UAV is hovering at the position $p_U = [0, 100, 50]^T$ (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 UAV jitter

A different UAV position

A different desired UAV attitude

Different scales of jittering effects to UAV mmWave channel
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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.
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

- 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.

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

Narrow search interval, more power-efficient
Wide search interval, less power-efficient
Direction-Constrained Sensing Matrix

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 \( \zeta_{n_a} \) and sub-array size \( N_{U,x} \) to restrain radiation range;

- **Step2.** Randomize \( \varphi_{n_a} \) and partially randomize center angle \( \zeta_{n_a} \) to satisfy RIP.
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
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### Numerical Results

#### Spectral Efficiency Comparison

![Graphs showing spectral efficiency for different transmit powers.](image)

(a) When transmit power is $-10$ dBm

(b) When transmit power is $0$ dBm

(c) When transmit power is $10$ dBm

(d) When transmit power is $20$ dBm

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Conclusion
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