Comparison of Limited Feedback Schemes for NOMA Transmission in mmWave Drone Networks

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Motivation

- Unmanned aerial vehicles (UAVs) can be used as aerial base stations (BSs) to deliver wireless connectivity during temporary events.
- Since UAV-BSs are low power nodes, achieving higher energy efficiency (EE) and spectral efficiency (SE) are of paramount importance.
- Further, efficient placement of UAV-BSs is important to reap the maximum capacity and coverage benefits.

UAV-BSs serving during a fire

UAV-BSs serving at a stadium
Objectives

- Introduce *non-orthogonal multiple access* (NOMA) to UAVs for hot spot scenario
- Introduce NOMA *beamforming* to serve multiple users within single UAV beam
- Understand NOMA performance with angle, distance feedbacks
- Understand NOMA performance with different ordering criteria for *angle feedback*
- Investigate the impact of user region geometry on the NOMA feedback scheme
Non-Orthogonal Multiple Access (NOMA)

- BS superposes messages of both users together and generate DL signal

- Strong user first perform successive-interference-cancellation (SIC) and then decodes his data

- Weak user directly decodes his data considering strong user’s data as noise
System Model

- Each UAV-BS: $M$ elements array, Each MS: single antenna
- User region: $\Delta, L_1, L_2$ with $K$ users
- User set, $\mathcal{N}_U = \{1, \cdots K\}$
- Users are distributed following a HPPP
- MISO channel vector, $h_k$ ($M \times 1$) between UAV-BS and $k$-th MS in user region:

  $$h_k = \frac{\sqrt{M} \alpha_k a(\theta_k)}{\sqrt{\text{PL} \left( \sqrt{d_k^2 + h^2} \right)}}$$

  $\alpha_k$: Complex gain of line of sight (LoS) path
  $\theta_k$: Angle-of-departure
NOMA Operation with Beamforming

- UAV-BS generates beam $\mathbf{b} = a(\bar{\theta})$ with AoD, $\bar{\theta} \in \{0, 2\pi\}$

- $k$-th user’s effective channel gain $|\mathbf{h}_k^H \mathbf{b}|^2$, with respect to UAV-BS beam $\mathbf{b}$ is

$$|\mathbf{h}_k^H \mathbf{b}|^2 \approx \frac{|\alpha_k|^2}{M \times PL \left( \sqrt{d_k^2 + h^2} \right)} \left| \sin \left( \frac{\pi M (\bar{\theta} - \theta_k)}{2} \right) \right|^2 = \frac{\left| \alpha_k \right|^2}{PL \left( \sqrt{d_k^2 + h^2} \right)} F_M \left( \bar{\theta} - \theta_k \right)$$

Small scale fading

$F_M(\cdot)$: Fejer-Kernel

- Effective channel gain is a measure of the channel quality
NOMA for UAV-BS Downlink (1)

- Users are ordered from best to worst w.r.t their channel quality based on some criteria
  \[ q_1 > q_2 \cdots > q_K \]  
  \hspace{1cm} (2)

- UAV-BS transmits signal \( x \), by superposing messages of \( \mathcal{N}_N \subset \mathcal{N}_U \) NOMA users
  \[ x = \sqrt{P_{Tx}} \mathbf{b} \sum_{k \in \mathcal{N}_N} \beta_k s_k \]  
  \hspace{1cm} (3)

  \( \beta_k \) : \( k \)-th user power allocation coefficient
  \( s_k \) : \( k \)-th user message
  \( P_{Tx} \) : Transmit power

- \( k \)-th user receives signal \( y_k \) in the downlink
  \[ y_k = h_k^H x + v_k = \sqrt{P_{Tx}} h_k^H \mathbf{b} \sum_{k \in \mathcal{N}_N} \beta_k s_k + v_k \]  
  \hspace{1cm} (4)

  \( v_k \) : Noise at \( k \)-th user
NOMA for UAV-BS Downlink (2)

- $k$-th user, first SIC and then decode its data

\[
\text{SINR}_{m\rightarrow k} = \frac{P_{Tx}|h_k^Hb|^2\beta_m^2}{P_{Tx} \sum_{l<m, l \in \mathcal{N}_N} |h_k^Hb|^2\beta_l^2 + N_0}.
\]

- Assuming each user has a \textit{quality-of-service (QoS) based target rate} $\bar{R}_k$, outage probability at $k$-th user can be given as

\[
P^0_{k|S_K} = 1 - \Pr \left( \bigcap_{l \geq k, l \in \mathcal{N}_N} R_{l\rightarrow k} > \bar{R}_l \mid S_K \right) = 1 - \Pr \left( \bigcap_{l \geq k, l \in \mathcal{N}_N} \text{SINR}_{l\rightarrow k} > \epsilon_l \mid S_K \right),
\]

where $\epsilon_k = 2^{\bar{R}_k} - 1$ and $S_K$ captures given condition on $K$

- Outage sum rate when $S_K$ denotes range of integers

\[
\bar{R}^{\text{NOMA}} = \sum_{\tau \geq 2} \Pr \{S_{K\tau}\} \sum_{k \in \mathcal{N}_N} (1 - P^0_{k|S_{K\tau}}) \bar{R}_k = \sum_{k \in \mathcal{N}_N} (1 - P^0_k) \bar{R}_k.
\]
Limited Feedback and User Ordering Strategy for NOMA

- We consider two limited feedback schemes as captured in (1)
  - Distance
  - Angle with respect to boresight direction of the beam

- Based on above feedback schemes, three user ordering strategies are considered
  - Distance based ordering: \[ d_1 \leq d_2 \leq \cdots \leq d_K \]
  - Fejer-Kernel based ordering: \[ F_M(\theta_1) \geq F_M(\theta_2) \geq \cdots \geq F_M(\theta_K) \]
  - Absolute angle based ordering: \[ \tilde{\theta}_1 \leq \tilde{\theta}_2 \leq \cdots \leq \tilde{\theta}_K \] where \[ \tilde{\theta}_k = |\bar{\theta} - \theta_k| \]
Outage Probability with Limited Feedback

- Outage probability in (6) can be given as,

\[ P_{k|S_K}^o = P \{ |h_k^2 b|^2 < x \} = \int_{u_{\text{min}}}^{u_{\text{max}}} \int_{L_1}^{L_2} P \{ |h_k^2 b|^2 < x \mid d_k, \theta_k \} f_{d_k, \theta_k}(d, \theta) \, dd \, d\theta, \quad (8) \]

\[
\downarrow \quad \text{The distance and angle of an arbitrary user are statistically independent of each other}
\]

\[
P_k^o = \int_{u_{\text{min}}}^{u_{\text{max}}} \int_{L_1}^{L_2} P \{ |h_k^2 b|^2 < x \mid r, \theta \} f_{d_k}(r)f_{\theta_k}(\theta) \, dr \, d\theta \quad (9)
\]

- \( f_{d_k}(r), f_{\theta_k}(\theta) \) under different ordering criteria have been derived to evaluate outage probabilities analytically using (9)
Impact of Ordering Strategy on Distance and Angle Distributions

- When the user ordering criteria is a function of a particular variable, that variable alters its unordered original distribution.
- The other variable(s) follows its unordered original distribution.

Ordered $k$-th user angle and distance distribution ($k = 20$)
Simulation Settings

Two users are considered for NOMA transmission

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>User distribution</td>
<td>Uniform</td>
</tr>
<tr>
<td>Outer radius, $L_2$</td>
<td>100 m</td>
</tr>
<tr>
<td>Inner radius, $L_1$</td>
<td>85 m</td>
</tr>
<tr>
<td>Horizontal angular width, $\Delta$</td>
<td>$1^\circ, 5^\circ$</td>
</tr>
<tr>
<td>Vertical beamwidth, $\varphi_e$</td>
<td>28$^\circ$</td>
</tr>
<tr>
<td>HPPP density, $\lambda$</td>
<td>1</td>
</tr>
<tr>
<td>Number of BS antennas, $M$</td>
<td>100</td>
</tr>
<tr>
<td>Noise, $N_0$</td>
<td>$-35$ dBm</td>
</tr>
<tr>
<td>Path-loss exponent, $\gamma$</td>
<td>2</td>
</tr>
<tr>
<td>$j$th user target rate, $\bar{R}_j$</td>
<td>6 BPCU</td>
</tr>
<tr>
<td>$i$th user target rate, $\bar{R}_j$</td>
<td>0.5 BPCU</td>
</tr>
<tr>
<td>$j$th user power allocation, $\beta_j^2$</td>
<td>0.25</td>
</tr>
<tr>
<td>$i$th user power allocation, $\beta_i^2$</td>
<td>0.75</td>
</tr>
<tr>
<td>UAV-BS operation altitude, $h$</td>
<td>10 m - 150 m</td>
</tr>
</tbody>
</table>

We compare NOMA performance with orthogonal multiple access (OMA)
Sum Rates: NOMA vs OMA

Sum rates variation: $j=20$, $i=25$, $\Delta = 5$ deg
Sum Rates: Fejer-Kernel and Distance based Ordering

Sum rates variation: $j=20$, $i=25$

PDFs of Fejer-Kernel distribution
Sum Rates: Angle and Fejer-Kernel based Ordering

Sum rates variation: $\Delta = 5$ deg

PDFs of Angle Distribution
Variation of the Support of Angle PDFs

Support of the user angle PDFs: $K = 125$
Sum Rates Variation with User Region Geometry

Distance ordering

Fejer-Kernel ordering

Rate difference (Distance-Fejer-Kernel)

Sum rates with different user region geometries:

\[ h = 50 \text{ m}, P_{\text{Tx}} = 10 \text{ dBm} \]
Conclusion

- NOMA with beamforming enhances spectral efficiency of UAV-BSs
- NOMA with angle, distance feedback provide better sum rates compared to OMA
- Feedback scheme for NOMA needs to be determined considering user region geometry
- If Fejer-Kernel function is monotonically varying over the angle support of NOMA users, both Fejer-Kernel and angle based ordering provide similar sum rates