Wideband Beam Tracking Based on Beam Zooming for THz Massive MIMO

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Background

Beam zooming based beam tracking

Simulation results

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Background

**THz communication**

- **C ≈ B*M*log(1+SINR):** Expand bandwidth → Increase data rate
- **Tens of GHz bandwidth in Terahertz communication**

![THz communication diagram](image)

Background

- **THz massive MIMO**
  - **Higher attenuation** in THz frequency (160GHz: ~80dB/km)
  - **Massive MIMO**: generate **narrow beams**, expand coverage

*THz massive MIMO is the key technique in future 6G communications*

Background

- **Beam tracking**
  - Time-varying channel due to **user mobility**: beam training repeatedly
  - THz massive MIMO **huge antenna number** induces **unacceptable overhead**
  - **Beam tracking**: obtain channel information with low overhead

**Beam training**

- Fast beam tracking is the key to realize mobile coverage in THz massive MIMO

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Existing beam tracking schemes

- **Beam tracking based on channel prediction**
  - Track the user based on prior information from channel prediction
  - Disadvantage: requires accurate user mobility model

- **Beam tracking based on Auxiliary Beam Pair**
  - Utilize auxiliary beam pair surrounding the user to detect user mobility
  - Disadvantage: requires extra RF chains to generate auxiliary beam pair

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Challenge from THz wideband channel

- Beam split in THz massive MIMO
  - Phase-shifters (PSs) based hybrid precoding is frequency-independent
  - The beams disperse to different directions at different frequency
  - Totally separated beams due to large bandwidth and large antenna number

The existing beam tracking schemes suffer from the severe performance degradation caused by beam split in THz massive MIMO
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Beam zooming based beam tracking scheme

**Challenges**
- Classical sweeping based tracking scheme suffers from huge overhead
- Existing low-overhead schemes cannot deal with beam split

**Solution**
- Make use of beam split, propose beam zooming based beam tracking scheme
- Reveal a beam zooming mechanism to control angle-domain coverage of beams
- Track one direction ➔ Track multiple directions, reduce the training overhead
System model

- **Delay-phase precoding**
  - \( N \)-antenna BS serves \( K \) single-antenna user
  - Delay-phase precoding: introduce \( K_d \) time-delayers (TDs) for each RF chain
  \[
y_m = H_m A_m D_m s + n
\]
  - Analog beamformer \( A_m = A_s A^d_m \)
  \[
  A_s = [A_1^s, A_2^s, \ldots, A_K^s], \quad A^d_m = \text{diag}(e^{-j2\pi f_m t_1}, e^{-j2\pi f_m t_2}, \ldots, e^{-j2\pi f_m t_K})
  \]
  - Beamforming vector for the \( k \)-th user \( f_{k,m} = A_k^s e^{-j2\pi f_m t_k} \)

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**Classical hybrid precoding**

System model

Channel model

- Ray-based **wideband channel model** with $M$-subcarrier OFDM

$$
h_{k,m} = \sum_{l=0}^{L-1} \beta_{k,m}^{(l)} a_N \left( \psi_{k,m}^{(l)} \right)
$$

$$
a_N \left( \psi_{k,m}^{(l)} \right) = \frac{1}{\sqrt{N}} [1, e^{j\pi\psi_{k,m}^{(l)}}, e^{j2\pi\psi_{k,m}^{(l)}}, \ldots, e^{j\pi(N-1)\psi_{k,m}^{(l)}}] T
$$

- **Spatial direction** $\psi_{k,m}^{(l)} = \frac{2d}{c} f_m \sin \tilde{\theta}_{k}^{(l)}$
- Define $\theta_{k}^{(l)} = \sin \tilde{\theta}_{k}^{(l)}$ represent physical direction with $\theta_{k}^{(l)} \in [-1, 1]$

Assumption

- THz channel is **LoS path dominant**, ignore NLoS path
- For LoS path, user mobility has **continuity**, angle-domain variation range $\alpha_k$

$$\theta_{k,i+1}^{(0)} \in [\theta_{k,i}^{(0)} - \alpha_k, \theta_{k,i}^{(0)} + \alpha_k]$$

**Beam tracking problem**: Track $\theta_{k,i+1}^{(0)}$ based on $\theta_{k,i}^{(0)}$
Lemma 1: Consider the $k$-th user and denote $\phi_k = \theta_k + (1 - \xi_1)\alpha_k$. When the time delays from the TDs satisfies $t_k = s_k T_c p(K_d)$ where $s_k = -\frac{P}{2} \left( \phi_k + \frac{2\xi_M \xi_1 \alpha_k}{\xi_M - \xi_1} \right)$ and $p(K_d) = [0, 1, \cdots K_d - 1]^T$, and phase shifts provided by the PSs have the following form as $A_k^s = \text{blkdiag} \left( a_p(\phi_k) e^{j\pi(P\phi_k + 2s_k)p^T(K_d)} \right)$, the beamforming vector $f_{k,m}$ will point to

$$\bar{\theta}_{k,m} = \theta_k + (1 - \xi_1)\alpha_k + \frac{2\xi_M \xi_1 (\xi_m - 1)}{\xi_m (\xi_M - \xi_1)} \alpha_k$$

monotonously increasing over $m$

$m = 1 \quad \bar{\theta}_{k,1} = \theta_k - \alpha_k$

$m = M \quad \bar{\theta}_{k,M} = \theta_k + \alpha_k$
Beam zooming based beam tracking scheme

- **Channel model**
  - Generate target angle set in $T$ time slots
  - Design analog beamforming matrix based on beam zooming mechanism
  - Transmit training pilots
    \[
    Q_m^{(t)} = [q_{1,m}^{(t)}, q_{1,m}^{(t)}, \cdots q_{K,m}^{(t)}]^T
    \]
  - Detect tracking result
    \[
    (t_k, m_k) = \arg\max \| Y_{m,t,[k,:]} \|_2^2
    \]

$T = 2$

**Algorithm 1** Proposed beam zooming based beam tracking scheme.

**Inputs:**
- Physical directions $\theta_{k,i}^{(0)}$, Variation range of user physical direction $\alpha_k$; Beam tracking overhead $T$; The number of pilots in each time slot $Q$; The number of TDs connected to a RF chain $K_d$.

**Output:**
- Physical directions $\theta_{k,i+1}^{(0)}$

1: $\hat{\theta}_{k,i,\text{cen}}^{(t)} = \theta_{k,i}^{(0)} - \alpha_k + \frac{(2t-1)\alpha_k}{T}$
2: $\hat{\theta}_{k,m,i}^{(t)} = \hat{\theta}_{k,i,\text{cen}}^{(t)} + (1 - \xi_1)\frac{\alpha_k}{T} + \frac{2\xi_2\xi_3(\xi_{m-1} - \xi_1)}{T}$
3: $\Psi_{k,i+1}^{T} = [\hat{\theta}_{k,i+1}^{(t)}(1), \hat{\theta}_{k,i+1}^{(t)}(2), \cdots, \hat{\theta}_{k,i+1}^{(t)}(M)]$
4: for $t \in \{1, 2, \cdots, T\}$ do
5: $\phi_k^{(t)} = \hat{\theta}_{k,i,\text{cen}}^{(t)} + (1 - \xi_1)\frac{\alpha_k}{T}$
6: $s_k^{(t)} = -\frac{P}{2} \left( \phi_k^{(t)} + \frac{2\xi_2\xi_3(\xi_m - \xi_1)}{T} \right)$
7: $A_{k,i}^{(t)} = \text{blkdiag}(A_P(\phi_k^{(t)}), e^{j2\pi f_{m,i}^{(t)}D})$
8: $t_k = s_k^{(t)}T_c\Phi(K_d)$
9: $f_{k,m}^{(t)} = A_k^{(t)} e^{-j2\pi f_m^{(t)}D}$
10: $A_m^{(t)} = [f_{1,m}^{(t)}, f_{2,m}^{(t)}, \cdots, f_{K,m}^{(t)}]$.
11: $Y_{m,t} = H_mA_m^{(t)}Q_m^{(t)} + N^{(t)}$
12: end for
13: $(t_k, m_k) = \arg\max_{t \in 1, 2, \cdots, T, m \in 1, 2, \cdots, M} \| Y_{m,t,[k,:]} \|_2^2$
14: $\theta_{k,i+1}^{(0)} = \Psi_{k,i+1}^{(t_k,m_k)}$
15: return $\theta_{k,i+1}^{(0)}$. 
Beam zooming based beam tracking scheme

Performance analysis

- Denote the tracking overhead $T$. If for arbitrary physical direction, the beam zooming based scheme could successfully generate required beams, we have

$$T \geq T_{\text{min}} = \left[ \max \left( \max_{m \geq M/2, \theta_{k,i,t}} \tau_1, \max_{m \leq M/2, \theta_{k,i,t}} \tau_2 \right) \right]$$

where

$$\tau_1 = -\frac{\gamma_{t,m} \alpha_k}{\left(1 + P \left(1 - \xi_m\right) \left(\theta_{k,i} - \alpha_k\right)\right)}$$

and

$$\tau_2 = \frac{\gamma_{t,m} \alpha_k}{\left(1 - P \left(1 - \xi_m\right) \left(\theta_{k,i} - \alpha_k\right)\right)}$$

- Parameters: $N=256, K_d = 4, M=128, f_c = 100 \text{ GHz}, f = 10 \text{ GHz} \alpha_k = 0.1$

$$T \geq T_{\text{min}} = 2$$

- Achievable sum-rate

$$R_{k,m} \geq \log_2 \left(1 + \frac{\rho \beta_{k,m}^2}{\sigma^2 N^2} \sum_{k=1}^{K_d} \left(\frac{\xi_m P \alpha_k}{TM}\right) \sum_{p=1}^{2} \left(1 - \frac{\xi_m}{TM} \theta_{k,i} + \frac{\alpha_k}{TM}\right)\right)$$

Proposed scheme can achieve near-optimal achievable sum-rate with low overhead
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- Tracking accuracy
  - Parameters:
    \[ N = 256, \quad N_{RF} = 4, \quad K = 4, \quad K_d = 4, \quad M = 128, \quad f_c = 100\,\text{GHz}, \quad B = 10\,\text{GHz} \]
  - Proposed scheme could track the user accurately
Simulation results

- **Beam tracking overhead**
  - Proposed scheme can **reduce overhead about 80%**
  - Proposed scheme can achieve **near optimal achievable sum-rate performance**

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- **Beam zooming based beam tracking scheme**
  - Proposed a *beam zooming mechanism* to control *angle-domain coverage* of frequency-dependent beams
  - Proposed a beam tracking scheme to *track multiple physical directions simultaneously* to realize fast beam tracking

- **Benefit**
  - Solve the problem of *huge training overhead*
  - Reduce the tracking overhead about *80%*, and could realize the near-optimal achievable sum-rate performance.
Thank you!

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