Wideband Beam Tracking Based on Beam Zooming for THz Massive MIMO

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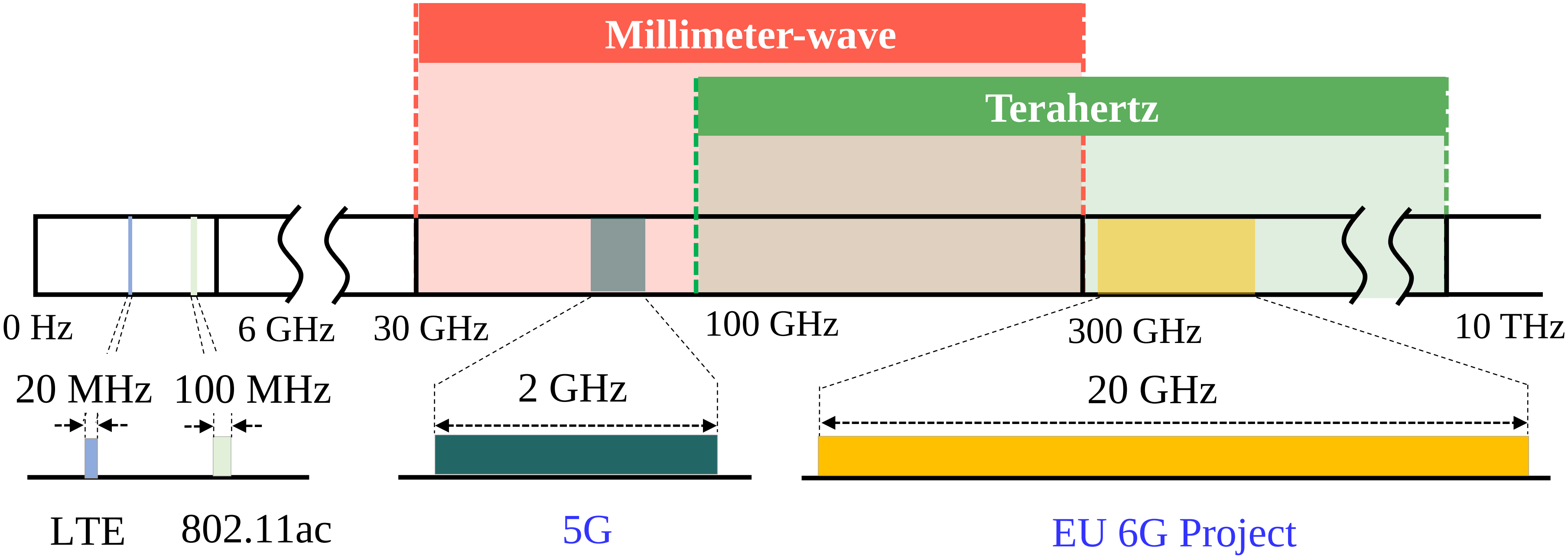
2020.12.10

- **Background**
- **Beam zooming based beam tracking**
- **Simulation results**
- **Conclusions**

Background

THz communication

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

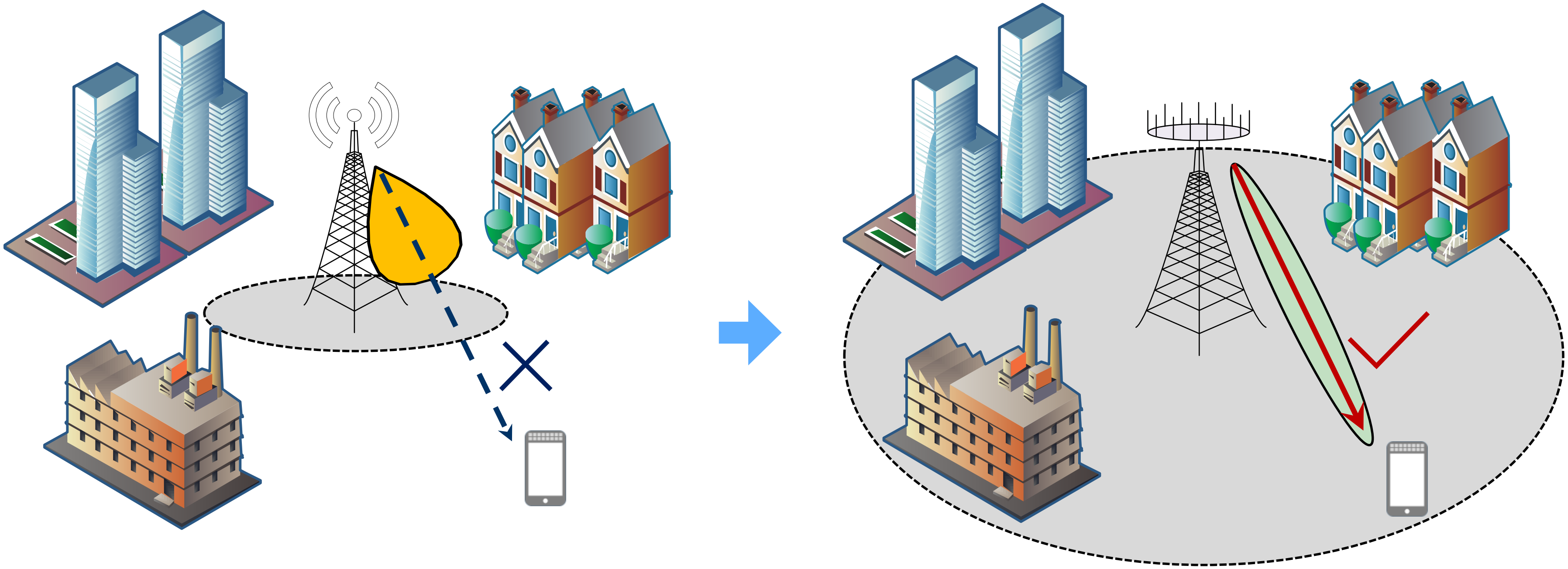


T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, A. Alkhateeb, and G. C. Trichopoulos, “Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond,” *IEEE Access*, vol. 7, pp. 78 729–78 757, Jun. 2019.

Background

THz massive MIMO

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



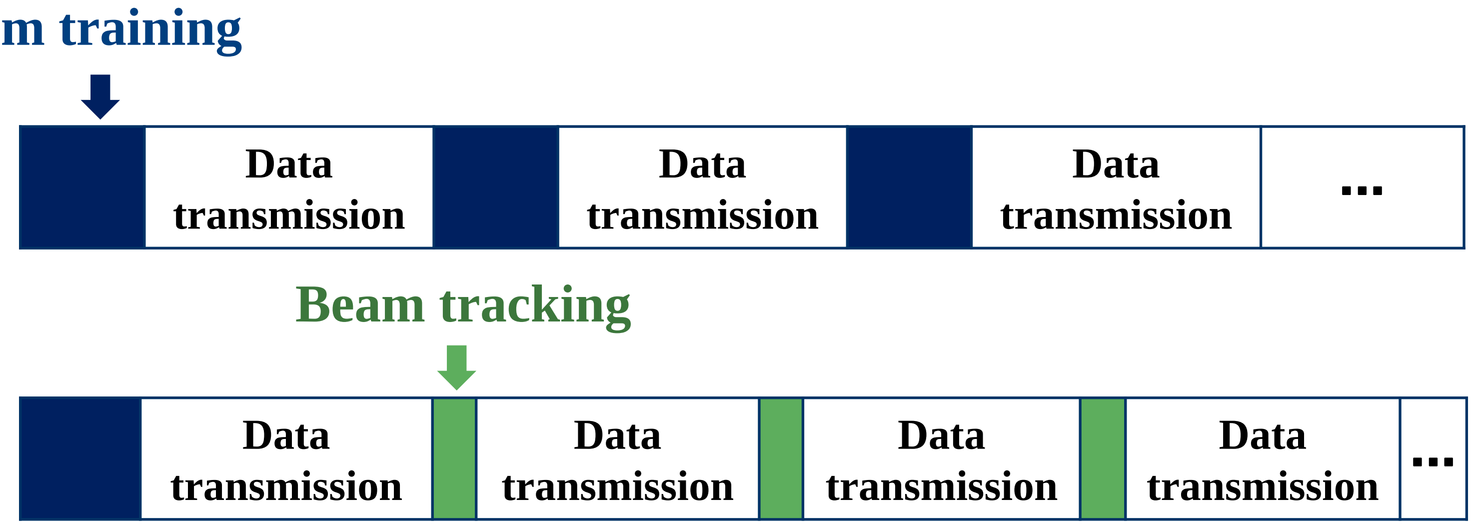
THz massive MIMO is the key technique in future 6G communciations

T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, A. Alkhateeb, and G. C. Trichopoulos, “Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond,” *IEEE Access*, vol. 7, pp. 78 729–78 757, Jun. 2019.

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



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

D. Zhu, J. Choi and R. W. Heath, "Auxiliary Beam Pair Enabled AoD and AoA Estimation in Closed-Loop Large-Scale Millimeter-Wave MIMO Systems," *IEEE Trans. Wireless Commun.*, vol. 16, no. 7, pp. 4770-4785, July 2017.

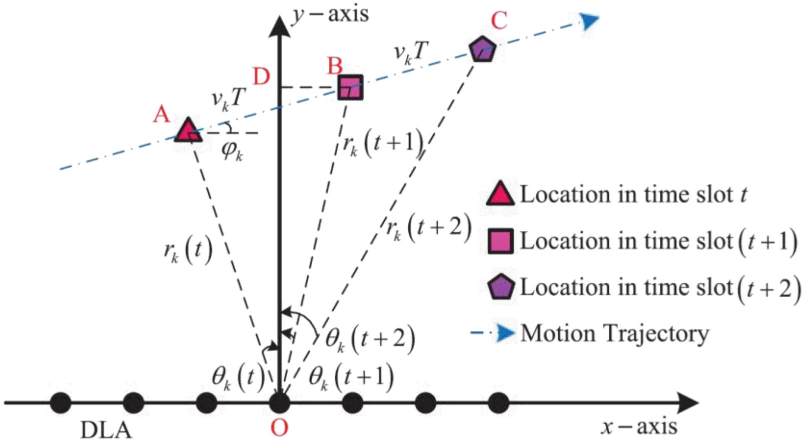
Existing beam tracking schemes

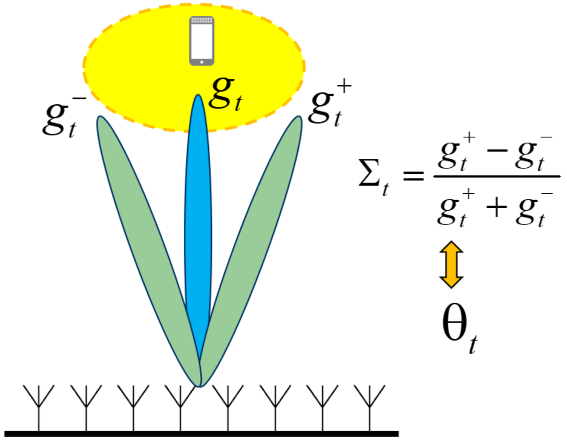
Beam tracking based on channel prediction

- 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





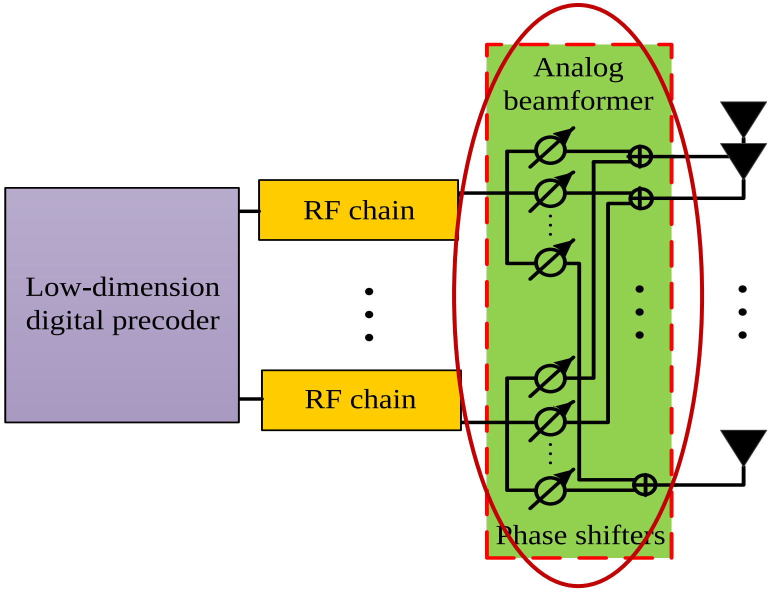
[1] X. Gao, L. Dai, Y. Zhang, T. Xie, X. Dai and Z. Wang, “Fast channel tracking for terahertz beamspace massive MIMO systems,” *IEEE Trans. Veh. Technol.*, vol. 66, no. 7, pp. 5689-5696, July 2017.

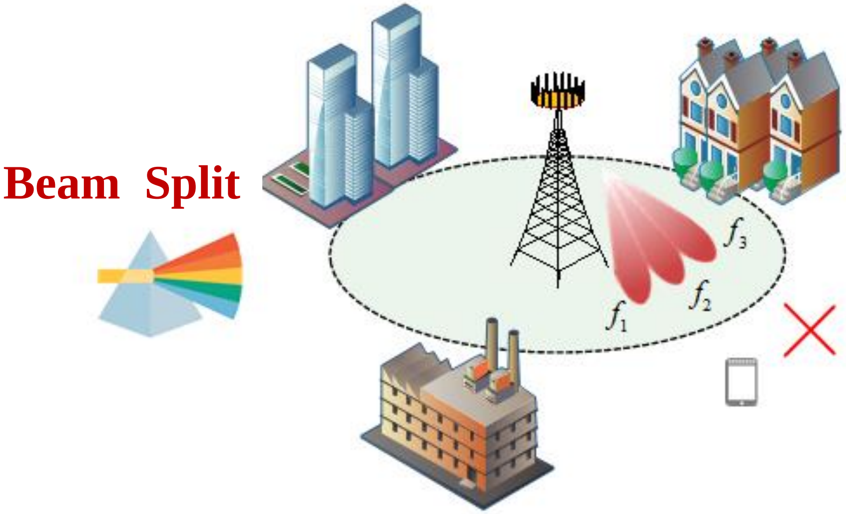
[2] D. Zhu, J. Choi, Q. Cheng, W. Xiao and R. W. Heath, “High-resolution angle tracking for mobile wideband millimeter-wave systems with antenna array calibration,” *IEEE Trans. Wireless Commun.*, vol. 17, no. 11, pp. 7173-7189, Nov. 2018.

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

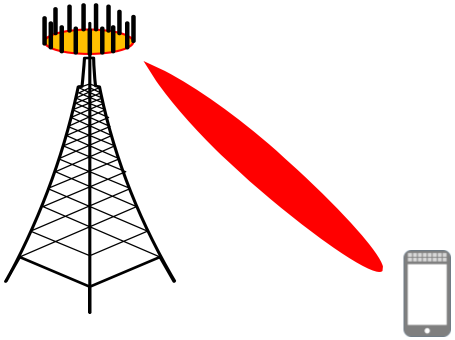
Beam zooming based beam tracking scheme

Challenges

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

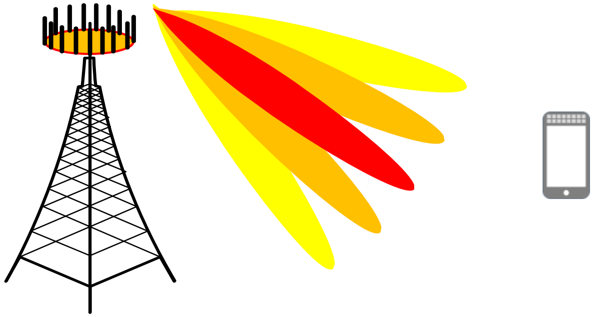
Solution

- 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



Track one direction

Beam Zooming



Track multiple directions simultaneously

System model

Delay-phase precoding

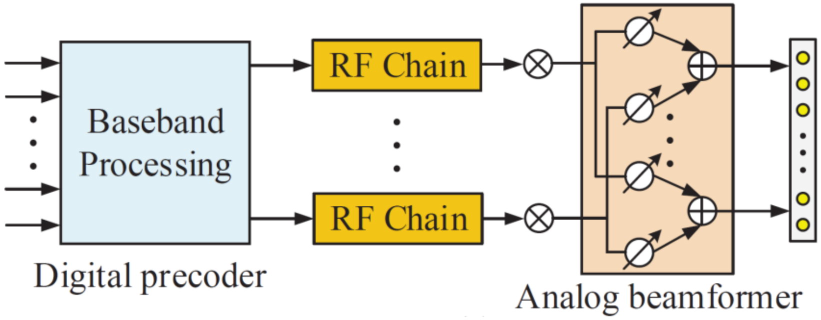
- N-antenna BS serves K single-antenna user
- Delay-phase precoding: introduce K_{d} time-delayers (TDs) for each RF chain

$$\mathbf{y}_m = \mathbf{H}_m \mathbf{A}_m \mathbf{D}_m \mathbf{s} + \mathbf{n}$$

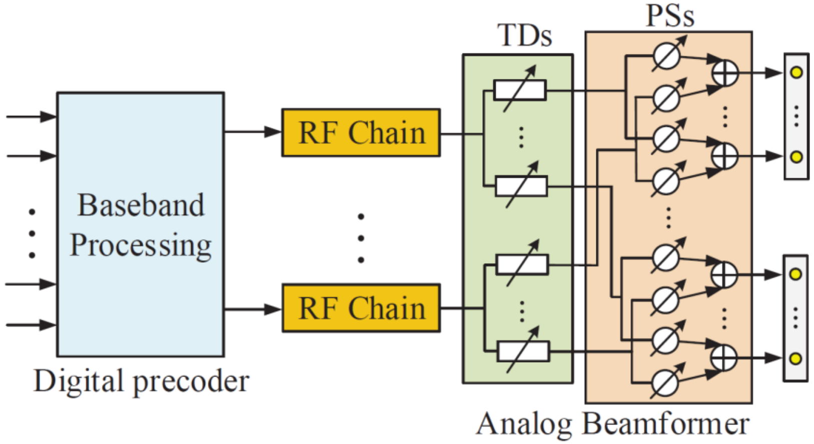
- Analog beamformer $\mathbf{A}_m = \mathbf{A}^{\mathrm{s}} \mathbf{A}^{\mathrm{d}}_m$

$$\mathbf{A}^{\mathrm{s}} = [\mathbf{A}^{\mathrm{s}}_1, \mathbf{A}^{\mathrm{s}}_2, \cdots, \mathbf{A}^{\mathrm{s}}_K] \qquad \mathbf{A}^{\mathrm{d}}_m = \mathrm{diag}\left([e^{-j2\pi f_m \mathbf{t}_1}, e^{-j2\pi f_m \mathbf{t}_2}, \cdots, e^{-j2\pi f_m \mathbf{t}_K}]\right)$$

- Beamforming vector for the k-th user $\mathbf{f}_{k,m} = \mathbf{A}^{\mathrm{s}}_k e^{-j2\pi f_m \mathbf{t}_k}$



Classical hybrid precoding



Delay-phase precoding

J. Tan and L. Dai, “Delay-phase precoding for THz massive MIMO with beam split,” in *Proc. IEEE GLOBECOM’19*, Dec. 2019, pp. 1–6.

System model

Channel model

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

$$\mathbf{h}_{k,m}=\sum_{l=0}^{L-1}\beta_{k,m}^{(l)}\mathbf{a}_N\left(\psi_{k,m}^{(l)}\right)$$

$$\mathbf{a}_N(\psi_{k,m}^{(l)})=\frac{1}{\sqrt{N}}[1,e^{j\pi\psi_{k,m}^{(l)}},e^{j\pi 2\psi_{k,m}^{(l)}},\cdots,e^{j\pi(N-1)\psi_{k,m}^{(l)}}]^T$$

- 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 α_k

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

Beam tracking problem: Track $\boldsymbol{\theta}_{k,i+1}^{(0)}$ based on $\boldsymbol{\theta}_{k,i}^{(0)}$

Beam zooming mechanism

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 $\mathbf{t}_k = s_k T_c \mathbf{p}(K_\mathrm{d})$ where $s_k = -\frac{P}{2}\left(\phi_k + \frac{2\xi_M \xi_1 \alpha_k}{\xi_M - \xi_1}\right)$ and $\mathbf{p}(K_\mathrm{d}) = [0,1,\cdots K_\mathrm{d}-1]^T$, and phase shifts provided by the PSs have the following form as $\mathbf{A}_k^\mathrm{s} = \mathrm{blkdiag}\left(\mathbf{a}_P(\phi_k) e^{j\pi(P\phi_k + 2s_k)\mathbf{p}^T(K_d)}\right)$, the beamforming vector $\mathbf{f}_{k,m}$ will point to

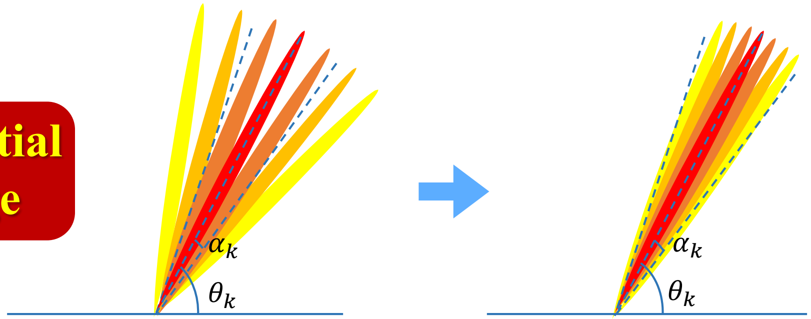
$$\boxed{\bar{\theta}_{k,m} = \theta_k + (1-\xi_1)\alpha_k + \frac{2\xi_M \xi_1 (\xi_m - 1)}{\xi_m(\xi_M - \xi_1)}\alpha_k}$$

monotonously increasing over ***m***

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

$$m = M \quad \bar{\theta}_{k,M} = \theta_k + \alpha_k$$

Cover the user potential angle-domain range



Beam zooming based beam tracking scheme

Channel model

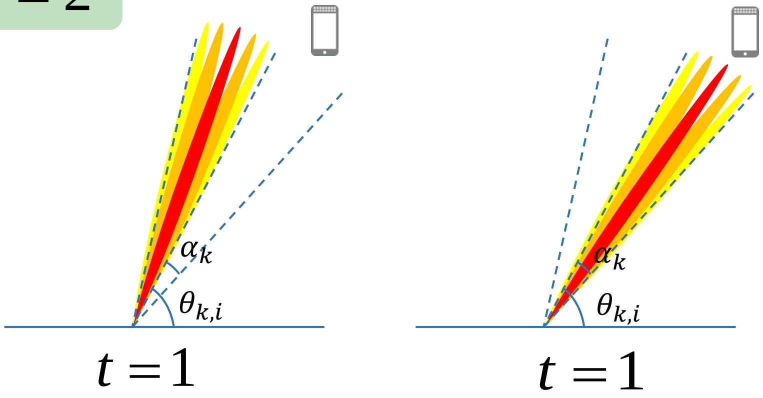
- Generate target angle set in T time slots
- Design analog beamforming matrix based on beam zooming mechanism
- Transmit training pilots

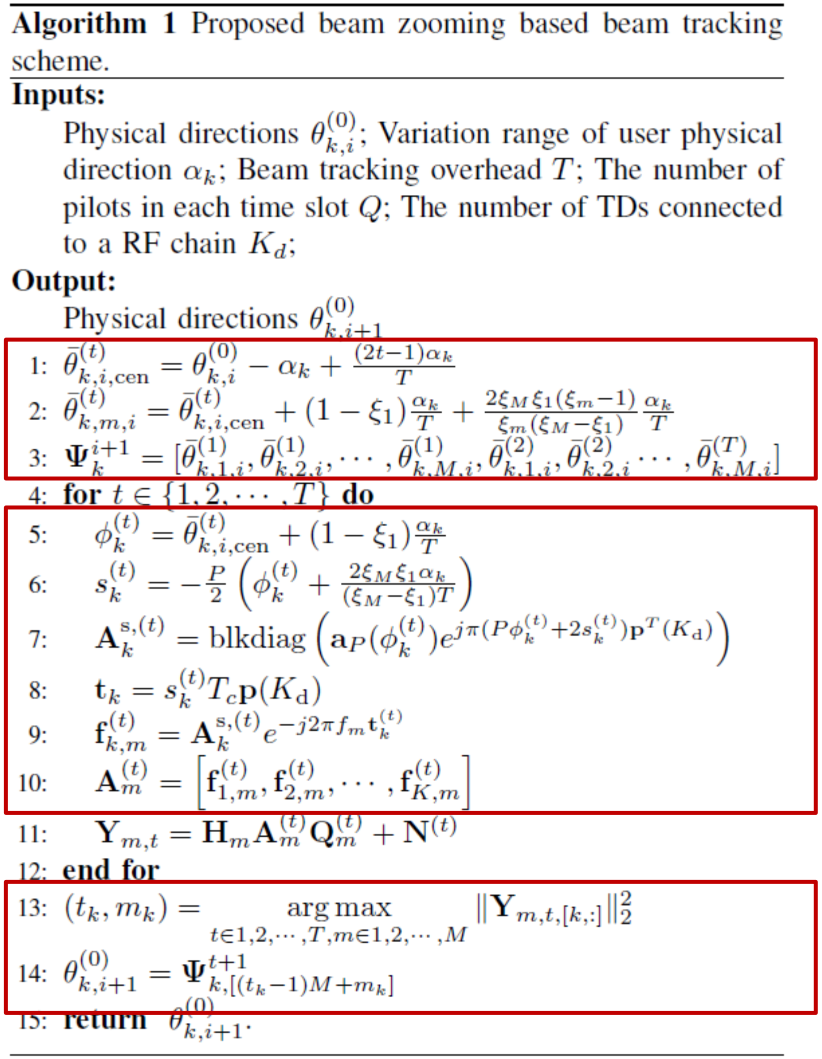
$$\mathbf{Q}_m^{(t)} = [\mathbf{q}_{1,m}^{(t)}, \mathbf{q}_{1,m}^{(t)}, \cdots \mathbf{q}_{K,m}^{(t)}]^T$$

- Detect tracking result

$$(t_k, m_k) = \arg\max \left\| \mathbf{Y}_{m,t,[k,:]} \right\|_2^2$$

$T = 2$





Algorithm 1 Proposed beam zooming based beam tracking scheme.

Inputs:

Physical directions $\theta_{k,i}^{(0)}$; Variation range of user physical direction α_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 $\theta_{k,i+1}^{(0)}$

```
$\bar{\theta}_{k,i,\mathrm{cen}}^{(t)} = \theta_{k,i}^{(0)} - \alpha_k + \frac{(2t-1)\alpha_k}{T}$
$\bar{\theta}_{k,m,i}^{(t)} = \bar{\theta}_{k,i,\mathrm{cen}}^{(t)} + (1-\xi_1)\frac{\alpha_k}{T} + \frac{2\xi_M \xi_1(\xi_m - 1)}{\xi_m(\xi_M - \xi_1)}\frac{\alpha_k}{T}$
$\mathbf{\Psi}_k^{i+1} = [\bar{\theta}_{k,1,i}^{(1)}, \bar{\theta}_{k,2,i}^{(1)}, \cdots, \bar{\theta}_{k,M,i}^{(1)}, \bar{\theta}_{k,1,i}^{(2)}, \bar{\theta}_{k,2,i}^{(2)} \cdots, \bar{\theta}_{k,M,i}^{(T)}]$
for $t \in \{1, 2, \cdots, T\}$ do
    $\phi_k^{(t)} = \bar{\theta}_{k,i,\mathrm{cen}}^{(t)} + (1-\xi_1)\frac{\alpha_k}{T}$
    $s_k^{(t)} = -\frac{P}{2}\left(\phi_k^{(t)} + \frac{2\xi_M \xi_1 \alpha_k}{(\xi_M - \xi_1)T}\right)$
    $\mathbf{A}_k^{\mathrm{s},(t)} = \mathrm{blkdiag}\left(\mathbf{a}_P(\phi_k^{(t)}) e^{j\pi(P\phi_k^{(t)} + 2s_k^{(t)})\mathbf{p}^T(K_\mathrm{d})}\right)$
    $\mathbf{t}_k = s_k^{(t)} T_c \mathbf{p}(K_\mathrm{d})$
    $\mathbf{f}_{k,m}^{(t)} = \mathbf{A}_k^{\mathrm{s},(t)} e^{-j2\pi f_m \mathbf{t}_k^{(t)}}$
    $\mathbf{A}_m^{(t)} = \left[\mathbf{f}_{1,m}^{(t)}, \mathbf{f}_{2,m}^{(t)}, \cdots, \mathbf{f}_{K,m}^{(t)}\right]$
    $\mathbf{Y}_{m,t} = \mathbf{H}_m \mathbf{A}_m^{(t)} \mathbf{Q}_m^{(t)} + \mathbf{N}^{(t)}$
end for
$(t_k, m_k) = \arg\max_{t \in 1,2,\cdots,T, m \in 1,2,\cdots,M} \|\mathbf{Y}_{m,t,[k,:]}\|_2^2$
$\theta_{k,i+1}^{(0)} = \mathbf{\Psi}_{k,[(t_k-1)M+m_k]}^{t+1}$
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

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

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: $N = 256$, $K_{\mathrm{d}} = 4$, $\mathrm{M} = 128$, $f_c = 100\,\mathrm{GHz}$, $f = 10\,\mathrm{GHz}$ $\alpha_k = 0.1$

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

- Achievable sum-rate

$$R_{k,m} \geq \log_2\left(1 + \frac{\rho\beta_{k,m}^2}{\sigma^2 N^2} \Xi_{K_{\mathrm{d}}}^2\left(\frac{\xi_m P \alpha_k}{TM} \right) \Xi_P^2\left(\left(1 - \xi_M\right)\theta_{k,i} + \frac{\alpha_k}{TM} \right) \right)$$

Proposed scheme can achieve near-optimal achievable sum-rate with low overhead

- Background
- Beam zooming based beam tracking
- Simulation results
- Conclusions

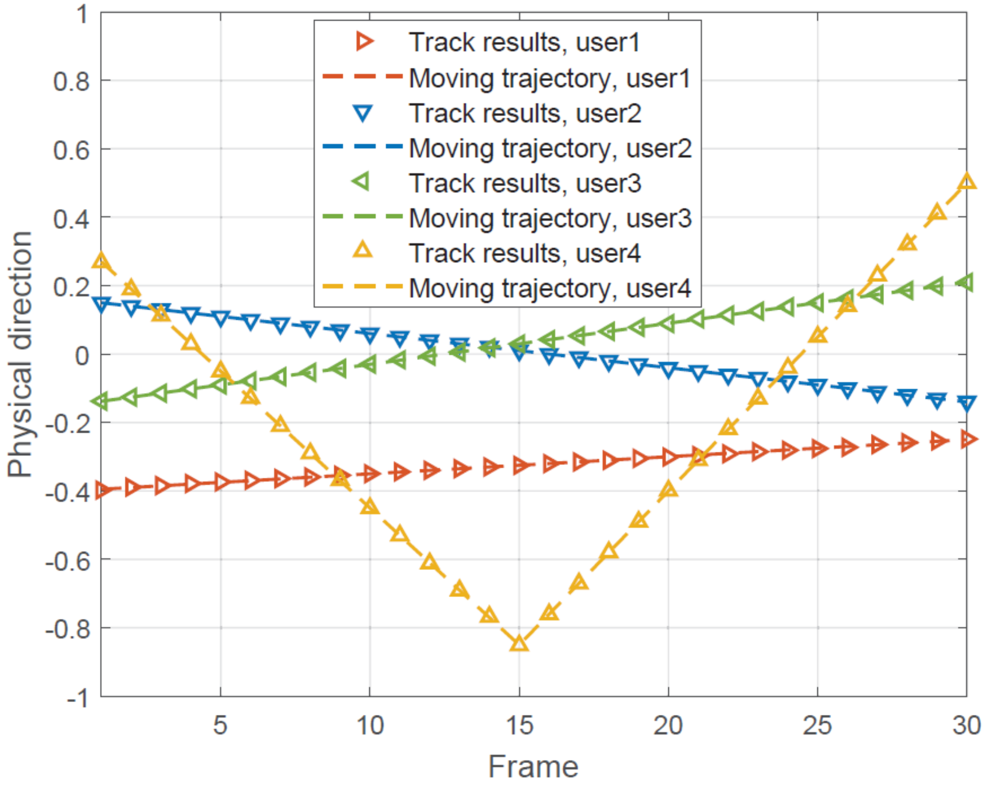
Simulation results

Tracking accuracy

- Parameters:

$$N=256,\ N_{RF}=4,\ K=4,\ K_{\mathrm{d}}=4,\ M=128,\ f_c=100\,\mathrm{GHz},\ B=10\,\mathrm{GHz}$$

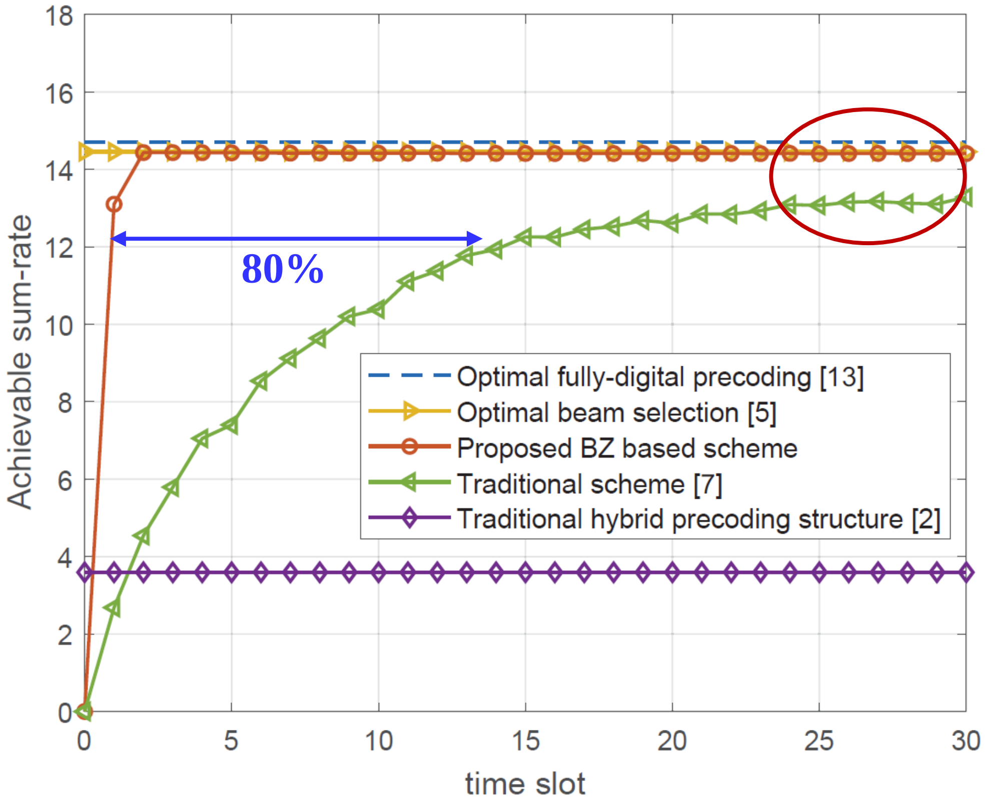
- Proposed scheme could track the user accurately



Simulation results

Beam tracking overhead

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



S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas, and A. Ghosh, "Millimeter wave beamforming for wireless backhaul and access in small cell networks," *IEEE Trans. Commun.*, vol. 61, no. 10, pp. 4391–4403, Oct. 2013.

- Background
- Beam zooming based beam tracking
- Simulation results
- Conclusions

Conclusions

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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