Analytical Beam Training for RIS-Assisted Wideband THz Communication

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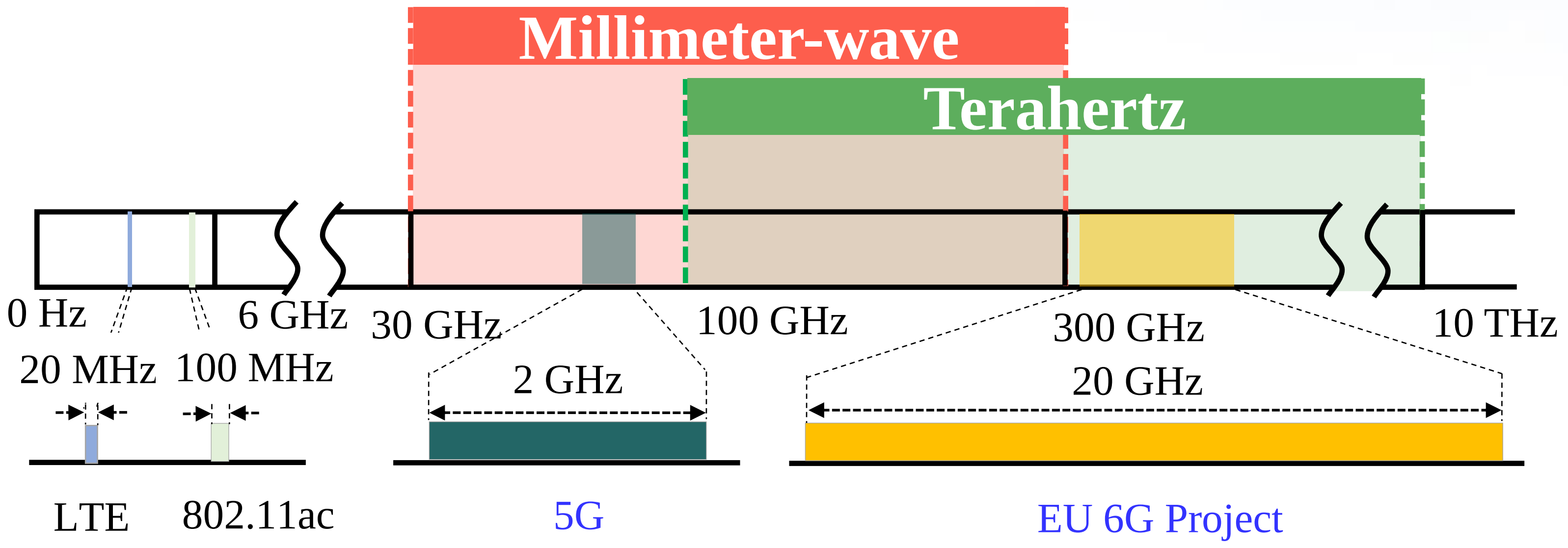
5th December, 2023

Outline

- Background
- Proposed analytical beam training
- Simulation results
- Conclusions

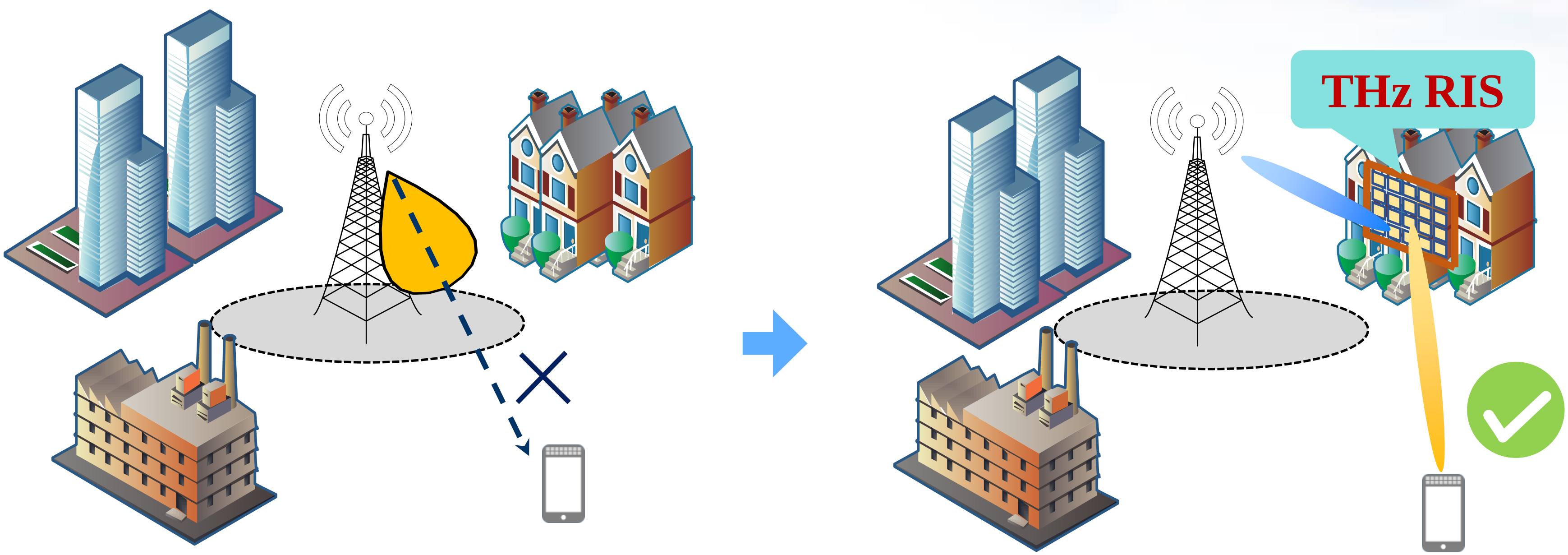
Background

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



Background

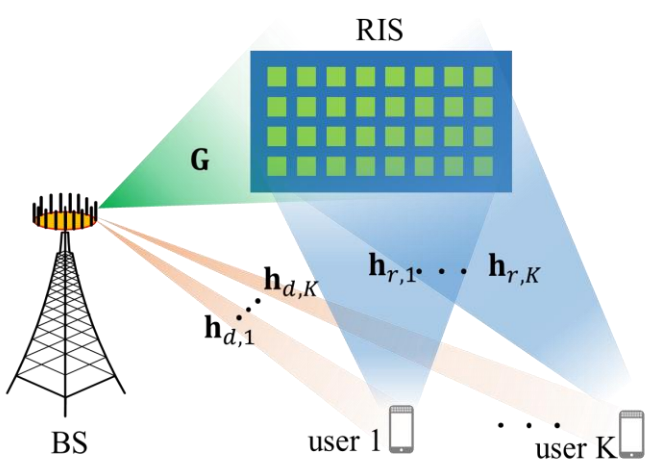
- **THZ reconfigurable intelligent surface (RIS)**
  - **Higher attenuation** in THz frequency (160GHz: ~80dB/km）
  - THz RIS: Intelligently control the propagation of electromagnetic wave



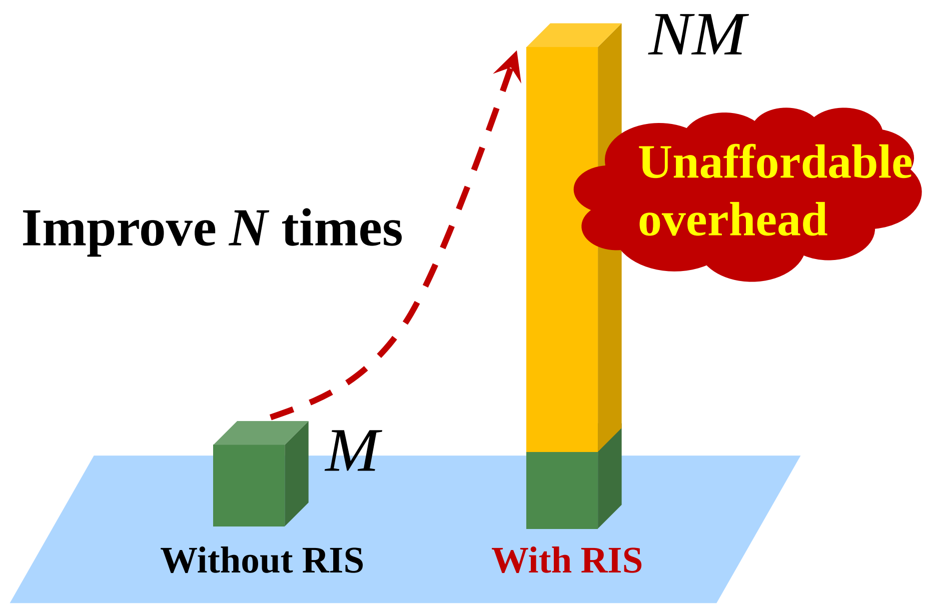
THz RIS is the key technique in future 6G communications

Beam Training for THz RIS

- **The main challenge for RIS CSI acquisition**
  - **Without the deployment of RF chain, RIS can not receive/transmit the pilot**
  - **To design the RIS beamforming, it is essential to estimate the CSI for cascaded channel with pretty high overhead**
- **Beam training: An effective alternative**
  - **It is effective to directly determine the angle of user with a pre-designed codebook via beam training**



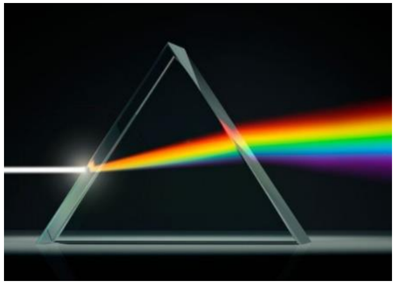
$$\mathbf{H}_k \triangleq \mathbf{G}\,\mathrm{diag}\left(\mathbf{h}_{r,k}^H\right)$$



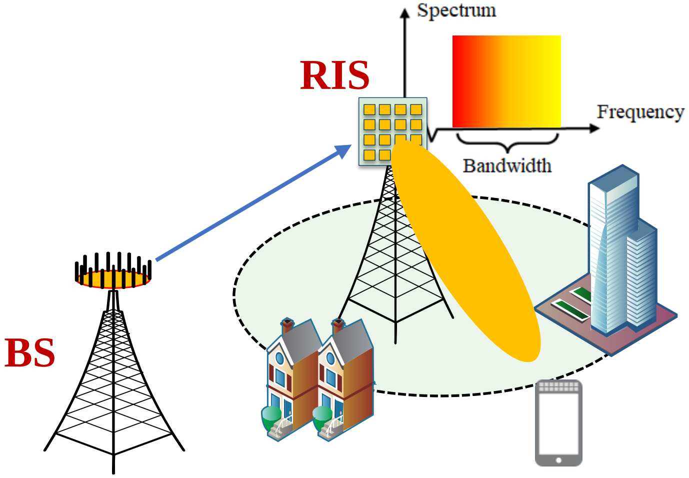
Beam Split

- **Beam split effect induced in wideband RIS systems**
  - **For narrowband, beamforming is generally designed according to the central carrier f_c**
  - **In wideband systems, the beams at different frequencies will split towards different angles, where $f_c \sin\theta_0 = f \sin\theta$**

Prism



dispersion of light



W. Hao, F. Zhou, M. Zeng, O. A. Dobre, and N. Al-Dhahir, "Ultra wideband THz IRS communications: Applications, challenges, key techniques, and research opportunities," *IEEE Netw.*, vol. 36, no. 6, pp. 214–220, Jul. 2022.

Beam Split

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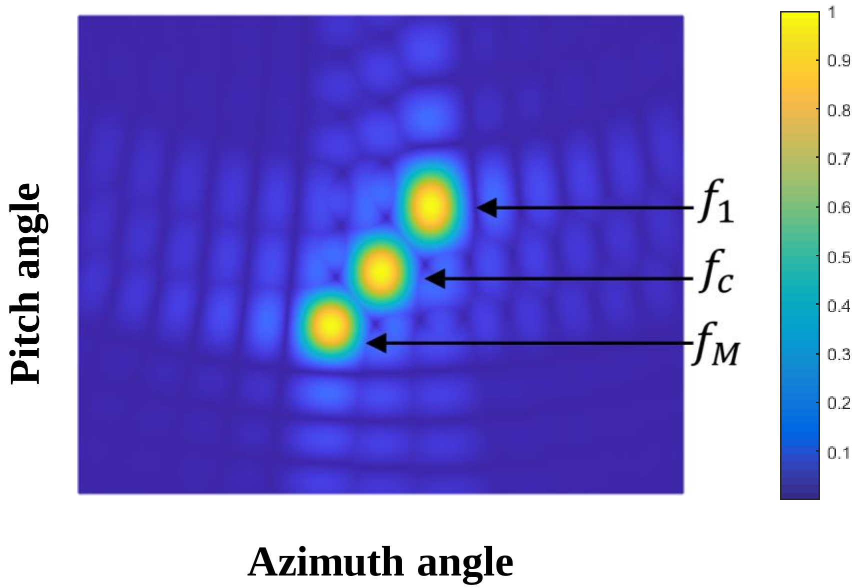
System parameters	Beam width	Beam split	Relative split
Carrier 30 GHz, bandwidth 2 GHz, RIS array 16×16	11.25°	3°	26%
Carrier 30 GHz, bandwidth 2 GHz, RIS array 60×60	3°	3°	100%
Carrier 100 GHz, bandwidth 20 GHz, RIS array 16×16	11.25°	9°	80%
Carrier 100 GHz, bandwidth 20 GHz, RIS array 60×60	3°	9°	300%

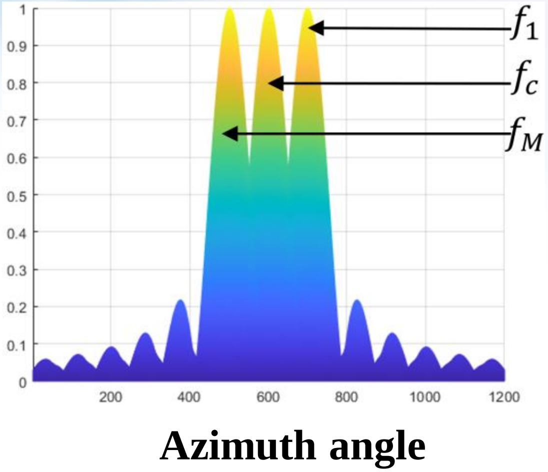
THz wideband RIS introduces a severe beam split effect

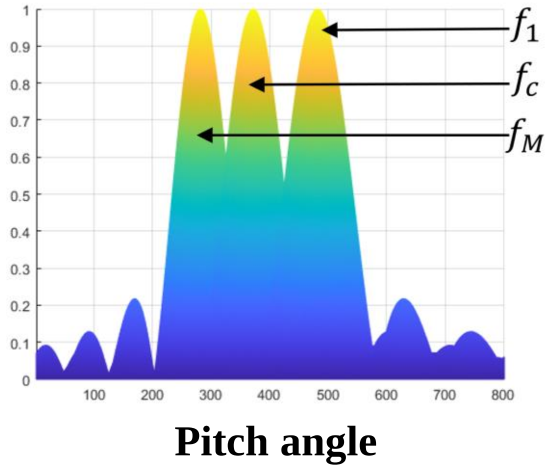
W. Hao, F. Zhou, M. Zeng, O. A. Dobre, and N. Al-Dhahir, "Ultra wideband THz IRS communications: Applications, challenges, key techniques, and research opportunities," *IEEE Netw.*, vol. 36, no. 6, pp. 214–220, Jul. 2022.

Beam Split

- **Negative effects of beam split on the beam training accuracy**
  - **Beam split makes it hard to generate narrow beams, leading to the decrease in beam training accuracy**

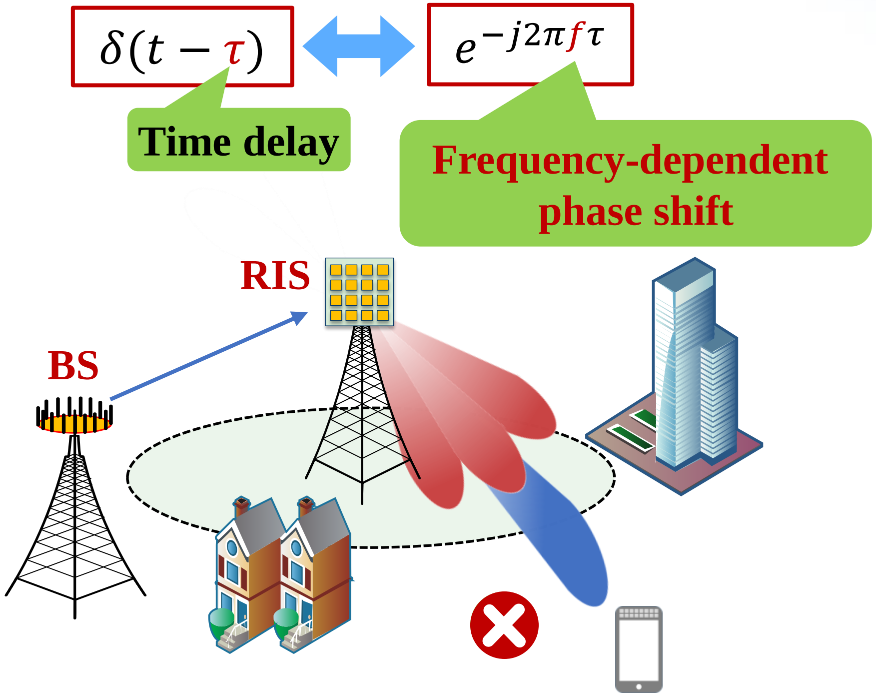


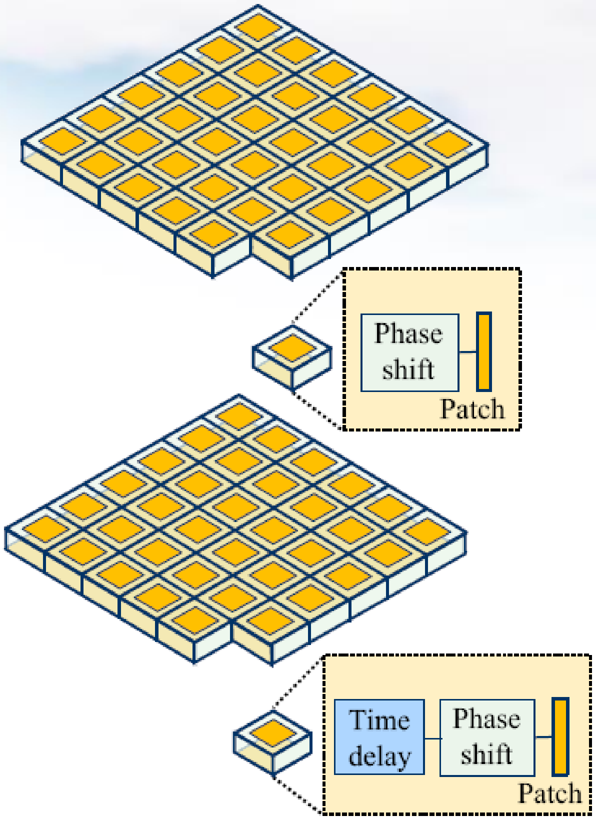




Existing Schemes: Beam split mitigation

- **Deploy time-delay units to provide frequency-dependent phase shift**





High cost of time-delay units is unpractical in RIS systems

K. Dovelos, S. Assimonis, H. Ngo, B. Bellalta, and M. Matthaiou, "Intelligent reflecting surface-aided wideband THz communications: Modeling and analysis," in *25th International ITG Workshop on Smart Antennas*, Sep. 2021.

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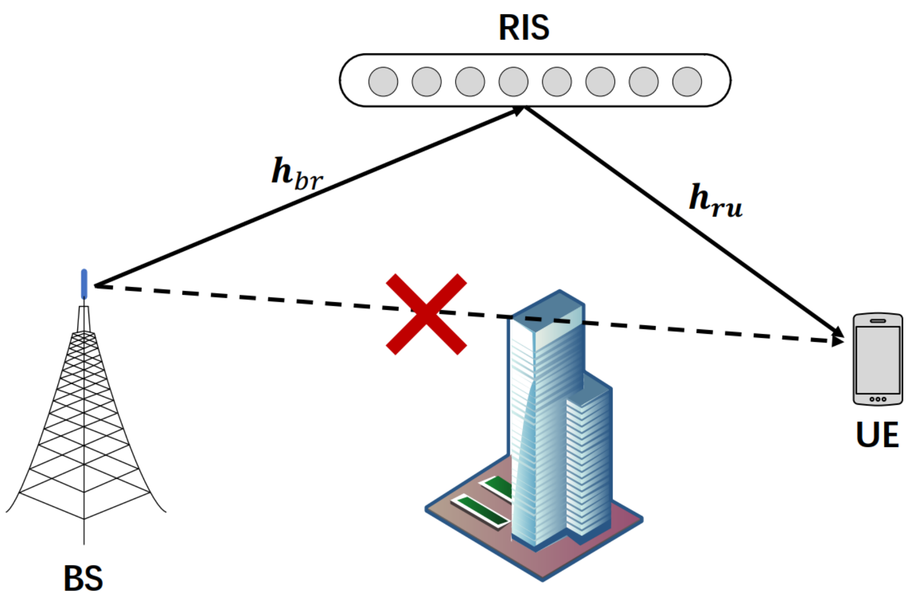
- Simulation results
- Conclusions

System Model

- **System model**
  - **The THz system is aided by an RIS with *N* elements**
  - **We adopt the assumption that the direct BS-UE transmission link is blocked by the obstacles**
  - **For high-frequency transmission, only the line-of-sight (LoS) path from the RIS to the BS or UEs is considered**



System Model

- **Signal model**
  - **The received signal at the *m*-th subcarrier**

$$y_m = \mathbf{h}_{ru,m}^{H} \boldsymbol{\Theta} \mathbf{h}_{br,m} s + n$$

  - $\boldsymbol{\Theta} \triangleq \mathrm{diag}\left(\beta_1 e^{j\theta_1}, \beta_2 e^{j\theta_2}, ..., \beta_N e^{j\theta_N}\right)$ **represents the reflecting diagonal matrix, and the *n*-th element can be expressed as** $\theta_n = e^{jp_n}$ **(constant modulus)**

- **Channel model**
  - **The channel between the base station and RIS**

$$\mathbf{h}_{br,m} = g_{br,m} e^{-j2\pi\tau_{br,m} f_m} \mathbf{a}_N\left(\varphi_m\right)$$

  - **The channel between RIS and users**

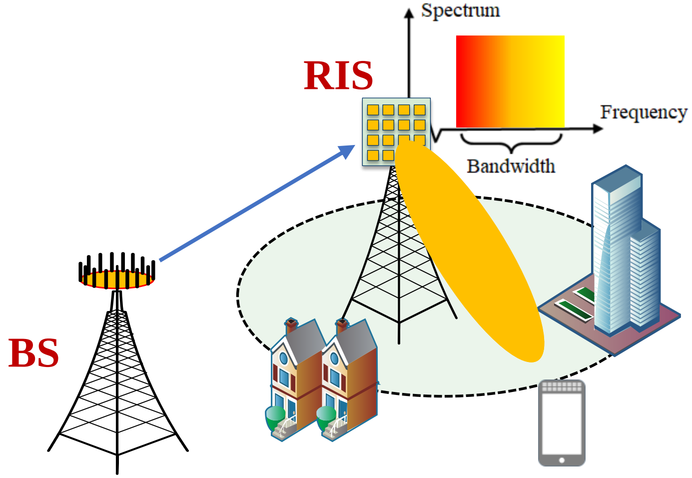
$$\mathbf{h}_{ru,m} = g_{ru,m} e^{-j2\pi\tau_{ru,m} f_m} \mathbf{a}_N\left(\psi_m\right)$$

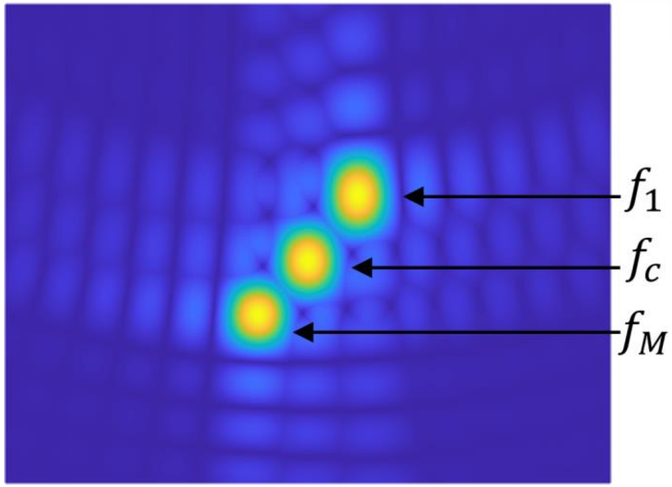
  - **The steering vector**

$$\mathbf{a}_N\left(\varphi_m\right) = \frac{1}{\sqrt{N}}\left[1, e^{j\pi\varphi_m}, e^{2j\pi\varphi_m}, \cdots, e^{(N-1)j\pi\varphi_m}\right]^T$$

Power Distribution Pattern

- **Rethink the beam split effect**
  - ➢ **Is the beam split effect necessarily a drawback?**
  - ➢ **More information in the angular domain!**





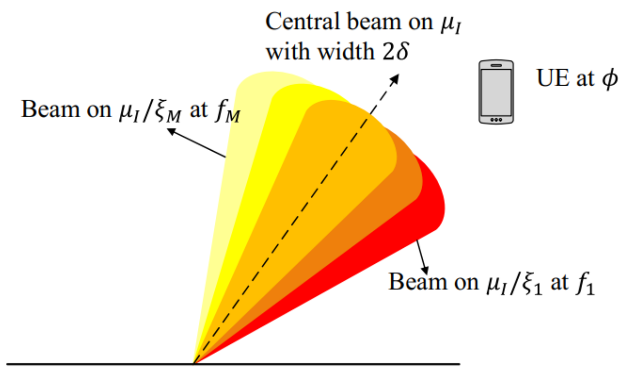
How to exploit the information in the angular domain?

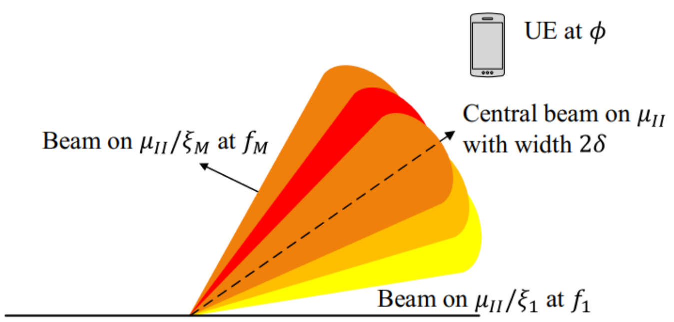
Power Distribution Pattern

- **Analyze the power distribution in the angular domain**

$$|g_I(\phi)|^2 = \left| \sum_{m=1}^{M} \left[\mathbf{a}_N^H(\phi_m) \boldsymbol{\Theta}(\mu_I) \right] \right|^2 \approx \mathcal{C} \frac{\sin^2\left(\frac{\pi N_s(\phi - \bar{\mu} + \delta)}{2}\right)}{\sin^2\left(\frac{\pi(\phi - \bar{\mu} + \delta)}{2}\right)}$$

- **How to choose the proper metric?**
  - ➢ **Set a pair of beams to eliminate the impact of propagation distance**

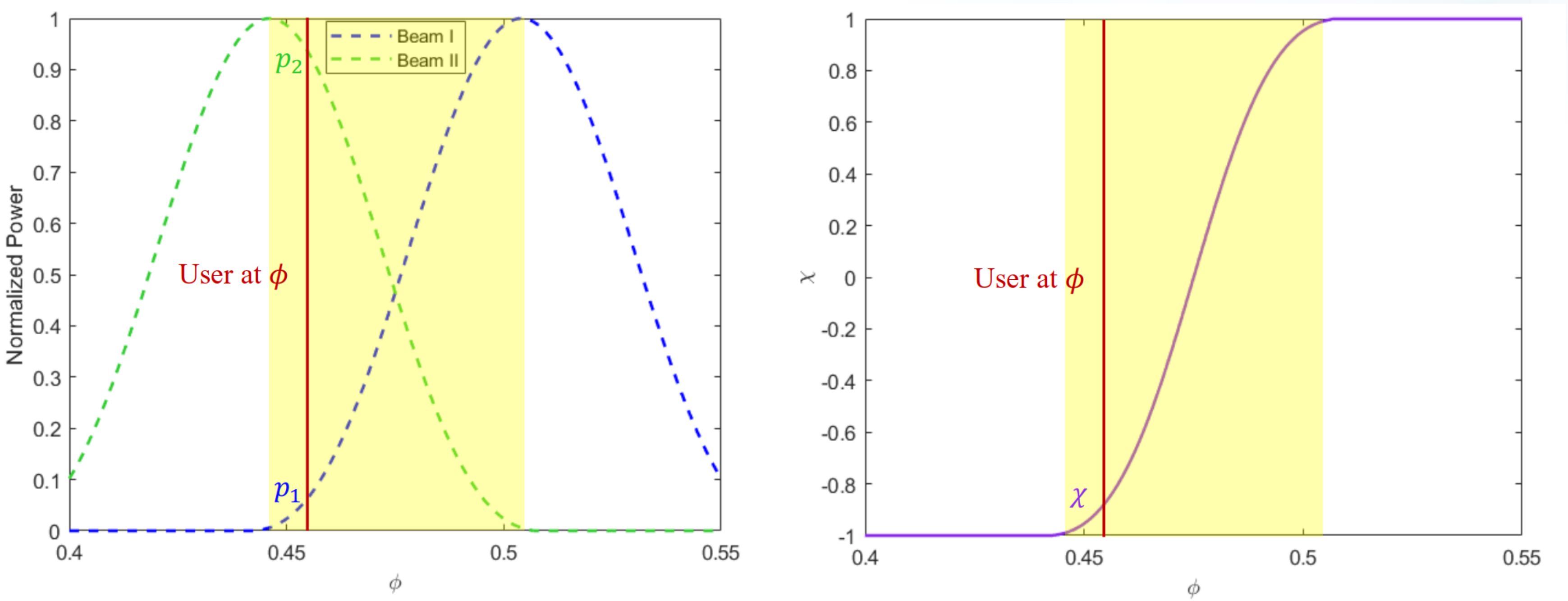




Power Distribution Pattern

- **Ratio metric of the beam pair**

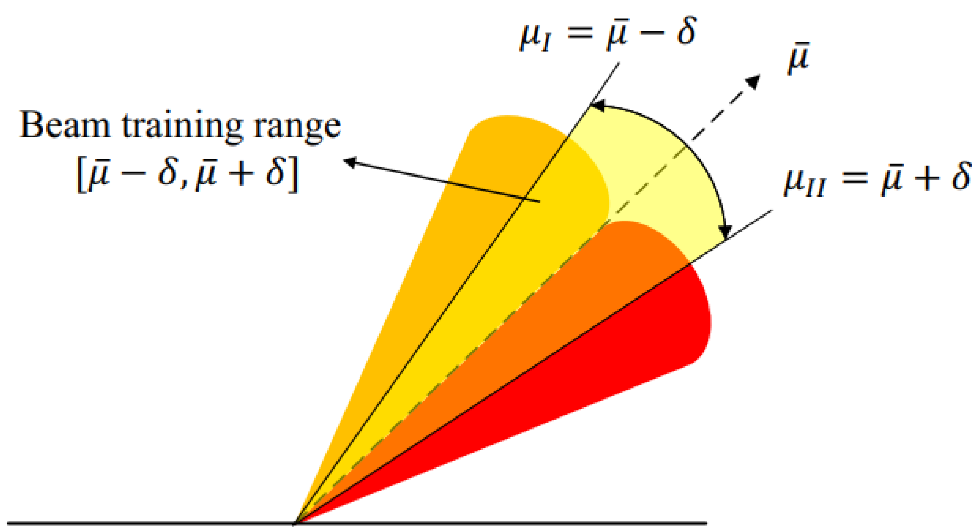
$$\chi = \frac{|g_I(\phi)|^2 - |g_{II}(\phi)|^2}{|g_I(\phi)|^2 + |g_{II}(\phi)|^2}$$



Ratio metric is a monotonic function w.r.t. the angle of user!

Analytical Codebook Design

- **Estimation range**
  - ➢ **Utilize the beam width to determine the estimation range**
- **Power normalization**
  - ➢ **Introduce the power normalization coefficient to compensate for different beam gains**



Analytical Codebook Design

- **Analytical codebook design procedure**

Algorithm 1 Proposed Analytical Codebook Design

Input: Number of units on RIS N; bandwidth B, central frequency f_c; range parameter κ; dividing parameter β

Output: Central directions of the beam pairs $\boldsymbol{\mu}$; estimation range $\boldsymbol{\rho}$; power normalization coefficient $\boldsymbol{\zeta}$; designed analytical codebook $\mathbf{W}$

Initialization:
$\boldsymbol{\mu} = [-\frac{1}{N}, \frac{1}{N}]$; $\boldsymbol{\rho} = [-\frac{1}{N}, \frac{1}{N}]$; $\boldsymbol{\zeta} = [\frac{2}{N}, \frac{2}{N}]$;
while $B\boldsymbol{\mu}[0]/f_c > -\beta$ **do**
  $\boldsymbol{\mu} = \left[\boldsymbol{\mu}[0] - \frac{2}{N}, \boldsymbol{\mu}, -\boldsymbol{\mu}[0] + \frac{2}{N}\right]$;
  $\boldsymbol{\rho} = \left[\boldsymbol{\rho}[0] - \frac{2}{N}, \boldsymbol{\rho}, -\boldsymbol{\rho}[0] + \frac{2}{N}\right]$;
  $\boldsymbol{\zeta} = \left[\frac{2}{N}, \boldsymbol{\zeta}, \frac{2}{N}\right]$;
end while
while $\boldsymbol{\rho}[0] > -1$ **do**
  $\bar{\mu} = -\frac{2\boldsymbol{\rho}[0] f_c}{2f_c - \kappa B}$;
  $\delta = \frac{B}{f_c}\bar{\mu}$;
  $\boldsymbol{\mu} = [-\bar{\mu}, \boldsymbol{\mu}, \bar{\mu}]$;
  $\boldsymbol{\rho} = [-\bar{\mu} - \kappa\delta, \boldsymbol{\rho}, \bar{\mu} + \kappa\delta]$;
  $\boldsymbol{\zeta} = \left[\frac{B\bar{\mu}}{f_c}, \boldsymbol{\zeta}, \frac{B\bar{\mu}}{f_c}\right]$;
end while
Generate the codebook $\mathbf{W}$ by Eq. (8) based on $\boldsymbol{\mu}$
return $\boldsymbol{\mu}, \boldsymbol{\rho}, \boldsymbol{\zeta}, \mathbf{W}$

Initialization

Update the central direction

Update the power normalization coefficient

Analytical Beam Training Framework

- **Analytical beam training procedure**

Algorithm 1 Proposed Analytical Beam Training Framework

Inputs: Analytical codebook $\mathbf{W}$, central directions of the beam pairs $\boldsymbol{\mu}$; power normalization coefficient $\boldsymbol{\zeta}$; beam training overhead P

Output: The estimated UE direction $\hat{\phi}$

Training stage:
for $i = 1$ to P **do**
    $\boldsymbol{\Theta} = \text{diag}\left(\mathbf{W}\left[:, i\right]\right)$
    Transmit beam training signals based on the $\boldsymbol{\Theta}$ and save the received power as $\mathbf{p}\left[i\right]$
end for
Calculating stage:
$\tilde{\mathbf{p}} = \mathbf{p} \odot \boldsymbol{\zeta}$
Estimate the UE direction $\hat{\phi}$ by the PDP-based direction estimation scheme based on $\tilde{\mathbf{p}}$.
Date transmission stage:
Transmit data based on the estimated direction $\hat{\phi}$

Transmit the codewords sequentially

Normalize the received power

Estimate the user angle

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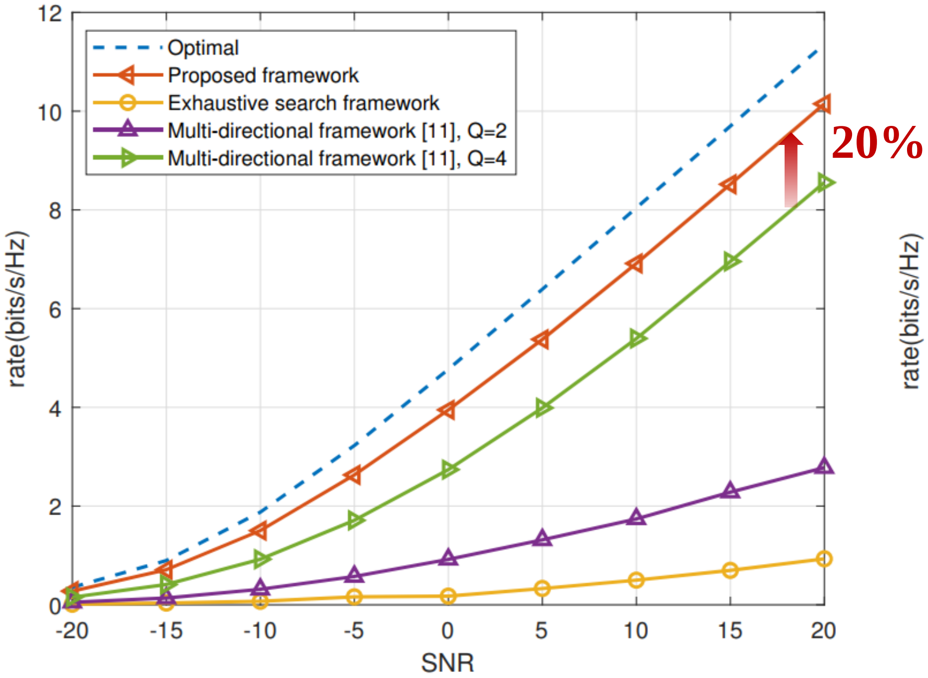
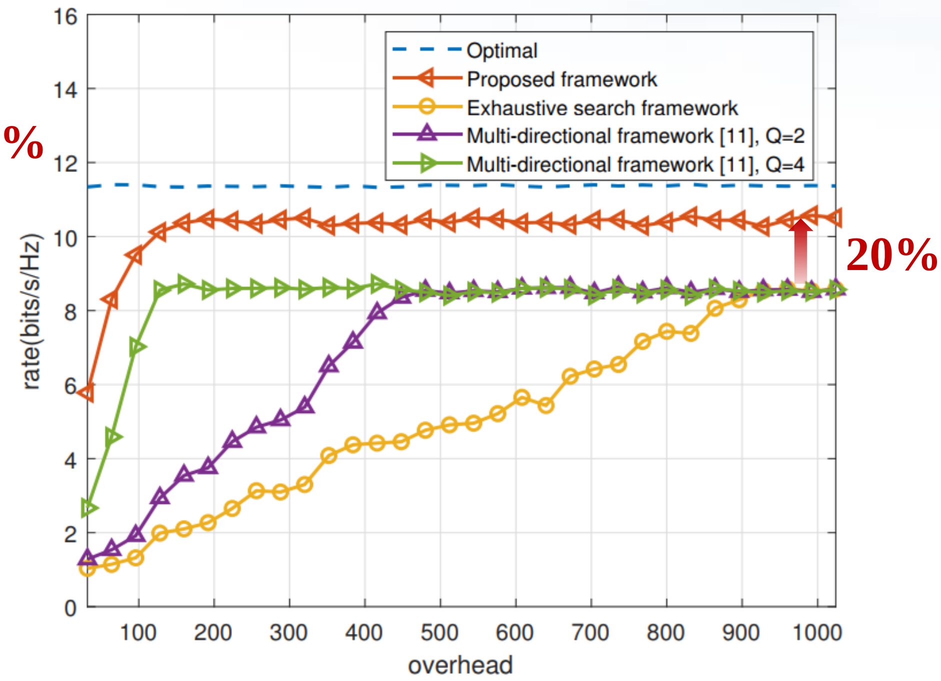
Simulation Results

- **Simulation parameters**
  - **Number of RIS elements: 1024;**
  - **Central frequency: 100 GHz;**
  - **Bandwidth: 10 GHz**





Improve the achievable rate by 20%

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Conclusions

- **RIS-assisted wideband THz communication**
  - **The beam split effect makes it hard to generate narrow beams, leading to the decrease in beam training.**
- **Power distribution pattern**
  - **Analyze the power distribution pattern w.r.t. angle**
  - **Introduce the ratio metric to eliminate the impact of propagation distance**
  - **Design the analytical codebook and propose an analytical beam training framework**
  - **Take advantage of can realize a 20% improvement in the achievable rate**

1. **Y. Chen**, J. Tan, and L. Dai, "Analytical beam training for RIS-assisted wideband terahertz communication," in *Proc. 2023 IEEE Global Commun. Conf.* (IEEE GLOBECOM'23), Kuala Lumpur, Malaysia, Dec. 2023.
2. **Y. Chen**, J. Tan, L. Dai, M. Hao, and R. MacKenzie, "Accurate beam training for RIS-assisted wideband terahertz communication," ***IEEE Trans. Commun.***, 2023.

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