Pinching-Antenna Systems (PASS): From Wireless to Near-Wired Communications

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Outline

- **PASS Basis**
  - Overview of PASS: Start with a Protype (What)
  - Advantages of PASS: From Wireless to Near-Wired (Why)
  - Physics Principle and Signal Modelling (How)
  - Activation Methods and Transmission Structures (How)
- **Case Studies**
  - Case I: Capacity Limits and Performance Analysis for PASS
  - Case II: Beamforming Design for PASS
  - Case III: Multiple Access Design for PASS
  - Case IV: Beam Training and Channel Estimation for PASS
  - Case V: Applications for PASS
- **Research Challenges and Opportunities**

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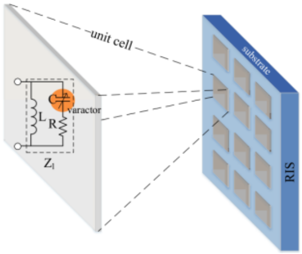
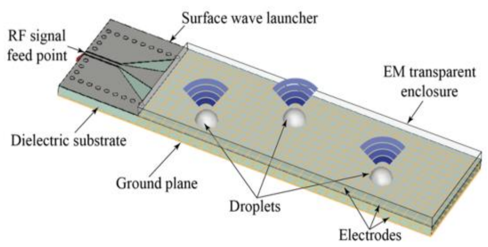
The road to Flexible-Antenna Systems towards 6G

❑ Existing Flexible-Antenna Systems

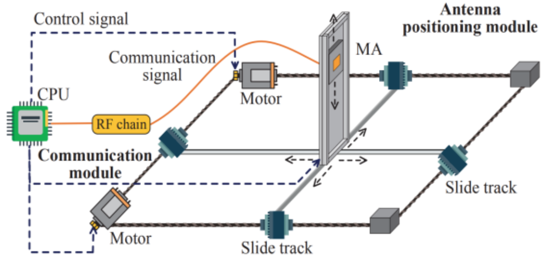
- Enabling **active reconfiguration** of channel parameters to boost the performance
- Adjusting their **positions**, **apertures**, and **electromagnetic properties**



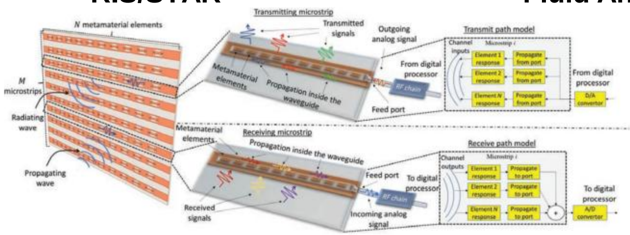
RIS/STAR



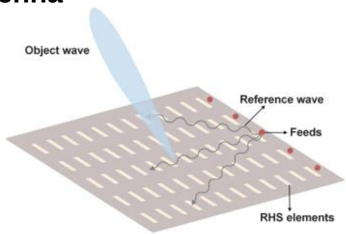
Fluid Antenna



Movable Antenna



Dynamic Metasurface Antenna



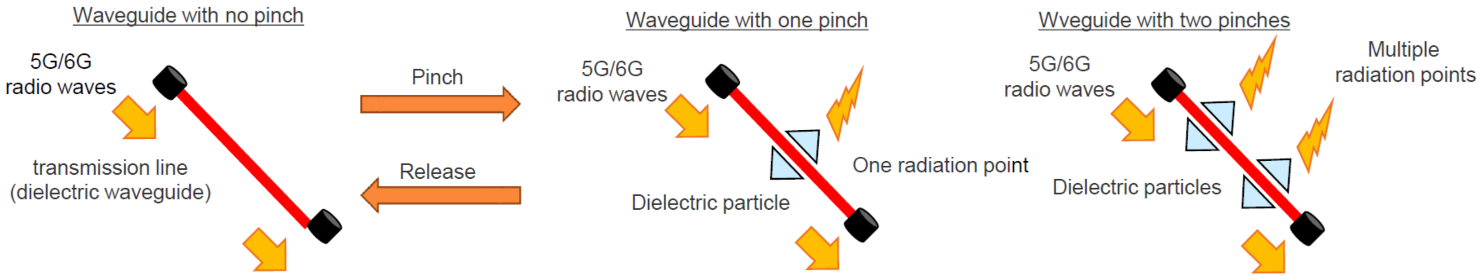
Reconfigurable Holographic Surface

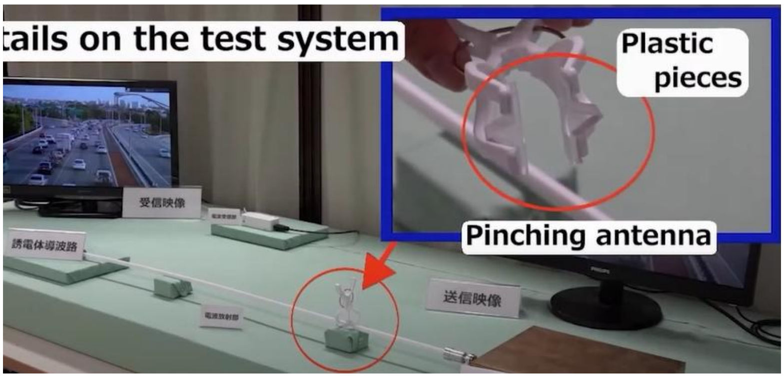
Continuous-Aperture Array (CAPA)

[1] **Y. Liu**, Z. Wang, X. Mu, C. Ouyang, X. Xu, and Z. Ding, “Pinching-antenna systems (PASS): Architecture designs, opportunities, and outlook,” *IEEE Commun. Mag.*, major revision, 2025. https://arxiv.org/abs/2501.18409

What is PASS: Start with a Prototype

❑ Pinching-Antenna System (PASS)



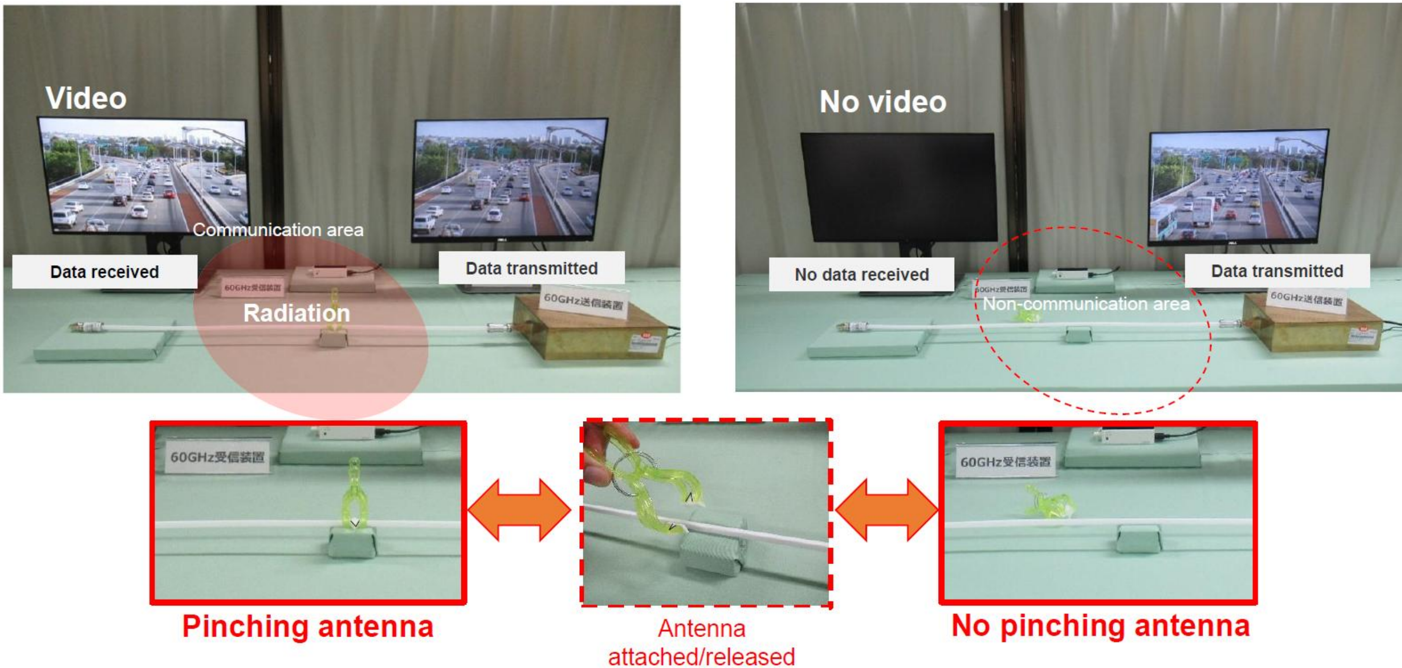


- The first **prototype** of PASS was developed and tested by NTT DOCOMO in 2021
- A pinching antenna is the dielectric waveguide that works as a leaky-wave antenna by attaching other small dielectric particles on it
- Radio waves are *transmitted/received* via (pinched) dielectric particles on a dielectric waveguide.
- One or *more transmission/reception points* can be created anywhere along the dielectric waveguide.

[1] https://www.docomo.ne.jp/english/info/media_center/event/mwc21/pdf/06_MWC2021_docomo_Pinching_Antenna_en.pdf#page=1.00
[2] A. Fukuda, H. Yamamoto, H. Okazaki, Y. Suzuki, and K. Kawai, “Pinching antenna - using a dielectric waveguide as an antenna,” NTT DOCOMO J., vol. 23, no. 3, pp. 5–12, Jan. 2022.

What is PASS: Start with a Prototype

❑ NTT DOCOMO’s Test using 60GHz Band



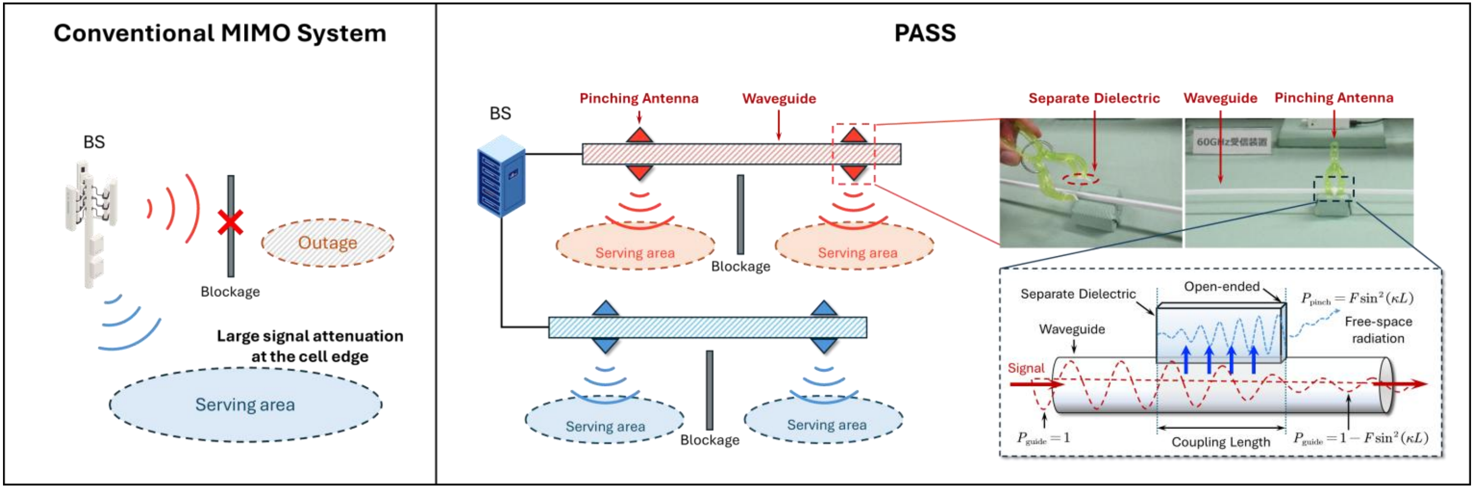
[1] https://www.docomo.ne.jp/english/info/media_center/event/mwc21/pdf/06_MWC2021_docomo_Pinching_Antenna_en.pdf#page=1.00

[2] A. Fukuda, H. Yamamoto, H. Okazaki, Y. Suzuki, and K. Kawai, “Pinching antenna - using a dielectric waveguide as an antenna,” *NTT DOCOMO J.*, vol. 23, no. 3, pp. 5–12, Jan. 2022.

Why PASS -- From “*Last Mile*” to “*Last Meter*”

❑ Key Advantages of Pinching-Antenna System (PASS)

- ➢ **Large-Scale Antenna Reconfiguration (tens or even hundreds of meters)**
- ➢ **Line-of-Sight Creation (*PASS* signals follow you 如影随形)**
- ➢ **Scalable Implementation (add/remove pinching antennas easily)**
- ➢ **Near-Field Advantages (beamfocusing, sparse deployment, sensing, etc.)**



[1] **Y. Liu**, Z. Wang, X. Mu, C. Ouyang, X. Xu, and Z. Ding, “Pinching-antenna systems (PASS): Architecture designs, opportunities, and outlook,” *IEEE Commun. Mag.*, under review, 2025. https://arxiv.org/abs/2501.18409
[2] Z. Ding, R. Schober and H. Vincent Poor, “Flexible-Antenna Systems: A Pinching-Antenna Perspective," *IEEE Trans. Commun.*, early access, Mar. 2025

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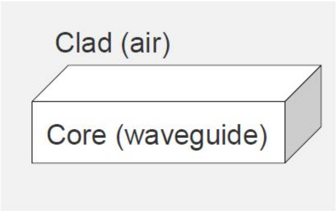
Physics Principle: Dielectric Waveguide

❑ Rod-shaped line made of fluorine resin or similar material

- No core conductor, unlike coaxial cable
- Not covered with metal, unlike basic waveguide
- Consists of core (waveguide) and clad (air or other dielectric), same as optical fiber
- Capable of transmitting millimeter waves (28 GHz band and above)

Coaxial cable

Metal waveguide



Dielectric waveguide

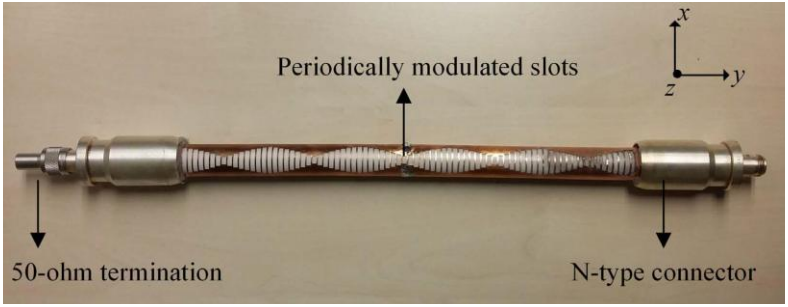
- Dielectric waveguides and pinching antennas are fabricated from ***insulating materials*** such as PolyTetraFluoroEthylene (PTFE) [2], Alumina [3], etc.

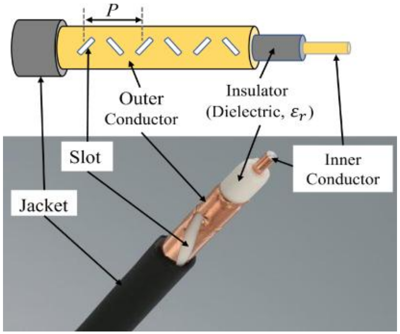
[1] https://www.docomo.ne.jp/english/info/media_center/event/mwc21/pdf/06_MWC2021_docomo_Pinching_Antenna_en.pdf#page=1.00
[2] A. Fukuda, H. Yamamoto, H. Okazaki, Y. Suzuki, and K. Kawai, "Pinching antenna - using a dielectric waveguide as an antenna," *NTT DOCOMO J.*, vol. 23, no. 3, pp. 5–12, Jan. 2022.
[3] C. Yeh et al., "Communication at millimetre–submillimetre wavelengths using a ceramic ribbon," Nature, vol. 404, no. 6778, pp. 584–588, Apr. 2000.

Similar Implementation Concepts now: LCX

❑ Leaky coaxial cable (LCX)

- Extensively used in mines, railway, and subway tunnels, shopping malls, and airports
- Example: **London Underground**
- A line-shaped cable with many slots arranged periodically over its outer layer and wireless signal can be radiated or received through these slots
- LCX can be treated as **a special case of "PASS"** where pinches are fixed (*less flexible*)
- LCX suffers from *more serious propagation loss* than PASS in for high-frequency bands



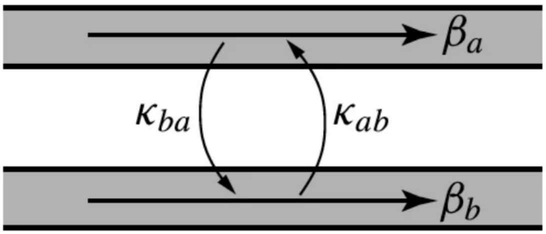


[1] Z. Siddiqui, M. Sonkki, M. Tuhkala, and S. Myllymäki, "Periodically slotted coupled mode leaky coaxial cable with enhanced radiation performance," *IEEE Trans. Antennas Propag.*, vol. 68, no. 11, pp. 7595– 7600, Nov. 2020.
[2] Z. Ji, J. Zhu, Y. Hou, S. Denno, "Theoretical analysis on localization error bound for wireless system using leaky coaxial cable," in *Proc. IEEE ICACTE*, 2024.

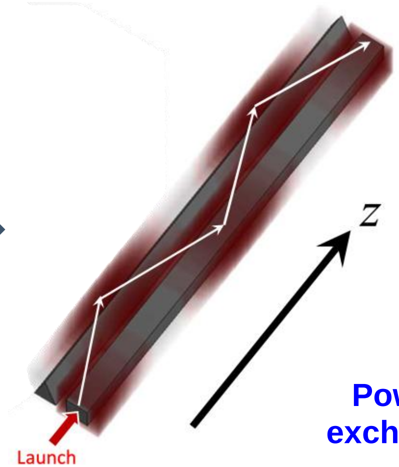
What is different? Electromagnetic Coupling

❑ Different Physical Principle

- **Conventional electronic antennas** leverage **electronic components to** convert alternating electric current into radio waves.
- **Pinching antennas** leverage **electromagnetic coupling**, occurring when a separate dielectric is placed near a dielectric waveguide.



Coupling between two waveguides/transmission lines

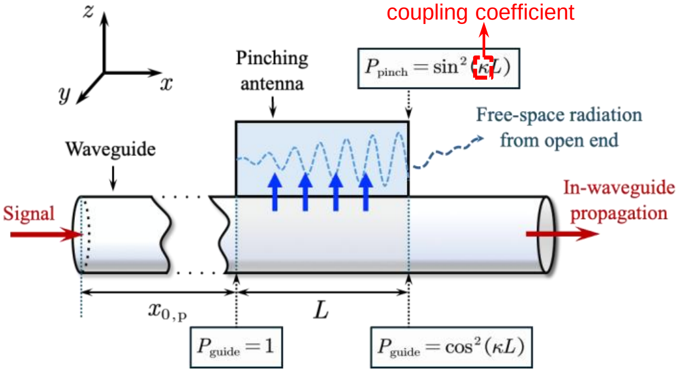


Power exchange

[1] **Y. Liu**, Z. Wang, X. Mu, C. Ouyang, X. Xu, and Z. Ding, "Pinching-antenna systems (PASS): Architecture designs, opportunities, and outlook," *IEEE Commun. Mag.*, major revision, 2025. https://arxiv.org/abs/2501.18409
[2] Z. Wang, C. Ouyang, X. Mu, **Y. Liu**, and Z. Ding, "Modeling and Beamforming Optimization for Pinching-Antenna Systems," *IEEE Trans. Commun.*, major revision, 2025. https://arxiv.org/abs/2502.05917

Physics Principle: Pinching Antennas

❑ Pinching antenna as a coupler



- **Pinching antenna:** a short open-end waveguide
- **Power Transfer & Radiation:** Energy from the original waveguide couples into the pinching antenna and radiates from its open end.

❑ Coupled-mode theory

Overall EM Field: $\mathbf{E} = A(x)\mathbf{E}_{\text{guide}} + B(x)\mathbf{E}_{\text{pinch}}$

coupling length

From Maxwell's Equations

coupling coefficient

$$\frac{dA(x)}{dx} = -j\kappa B(x) \qquad A(0) = 1$$

$$\frac{dB(x)}{dx} = -j\kappa A(x) \qquad B(0) = 0$$

Power Relationship

$$P_{\text{guide}}(x) = |A(x)|^2 = 1 - \sin^2(\kappa x)$$

$$P_{\text{pinch}}(x) = |B(x)|^2 = \sin^2(\kappa x)$$

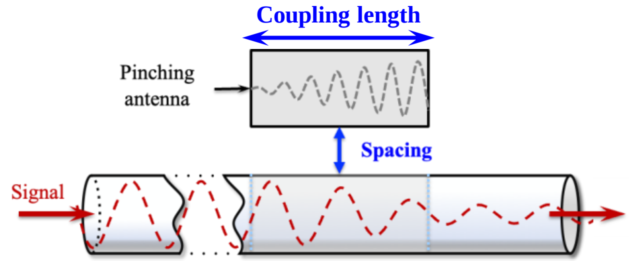
- The periodicity of the sin() function reveals the power exchange phenomenon

[1] **Y. Liu**, Z. Wang, X. Mu, C. Ouyang, X. Xu, and Z. Ding, "Pinching-antenna systems (PASS): Architecture designs, opportunities, and outlook," *IEEE Commun. Mag.*, major revision, 2025. https://arxiv.org/abs/2501.18409
[2] Z. Wang, C. Ouyang, X. Mu, **Y. Liu**, and Z. Ding, "Modeling and Beamforming Optimization for Pinching-Antenna Systems," *IEEE Trans. Commun.*, major revision, 2025. https://arxiv.org/abs/2502.05917

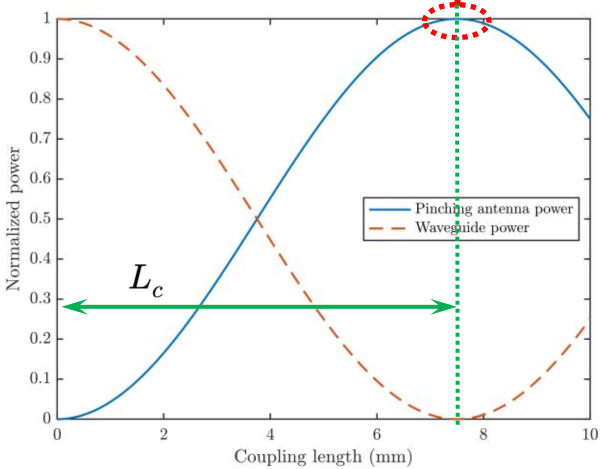
❑ Some exemplified results

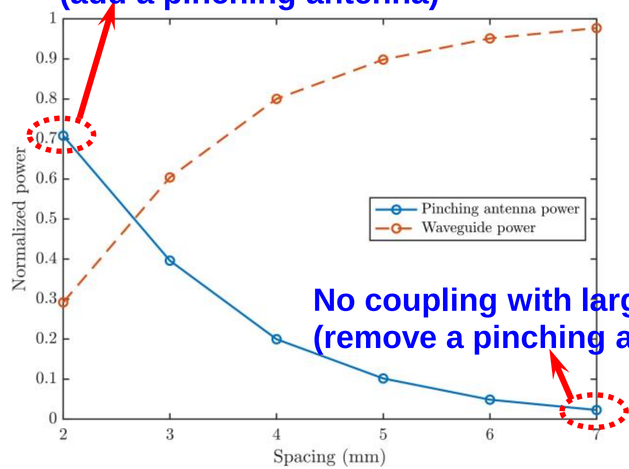
The results are generated based on [1] for two 2mm dielectric waveguides in a 50 GHz system.

Full radiation condition: Full power radiation is achievable with just a few millimeters of coupling length.



Strong coupling with small spacing (add a pinching antenna)





No coupling with large spacin
(remove a pinching antenna)

Coupling length should be several times L_c and wavelength for stable transmission, but kept compact.

[1] C. -Y. Liu, H. -E. Ding, S. -H. Wu and T. -L. Wu, "Significant Crosstalk Reduction in High-Density Hollow Dielectric Waveguides by Photonic Crystal Fence," *IEEE Trans. Microw. Theory Tech.*, vol. 69, no. 2, pp. 1316-1326, Feb. 2021

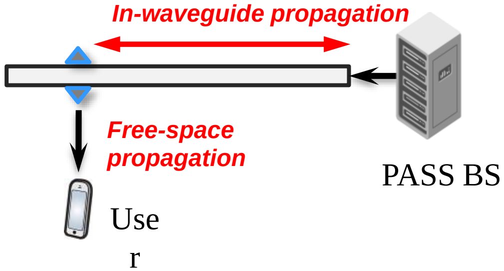
Signal Modelling

❑ Waveguide propagation and free-space propagation

$$y_n = \frac{\beta_n \sqrt{P_n}}{r_n} e^{-j\frac{2\pi}{\lambda}(r_n + n_{\mathrm{eff}} d_n)} x$$

Free-space propagation

In-waveguide propagation



❑ Power model for multiple pinching antennas on one waveguide

✓ Proportional power model

$$P_n = \delta^2 (1 - \delta^2)^{n-1}$$

$$\delta = \sin(\kappa L)$$

Each antenna have the *same coupling length* and radiates the *same ratio of power*

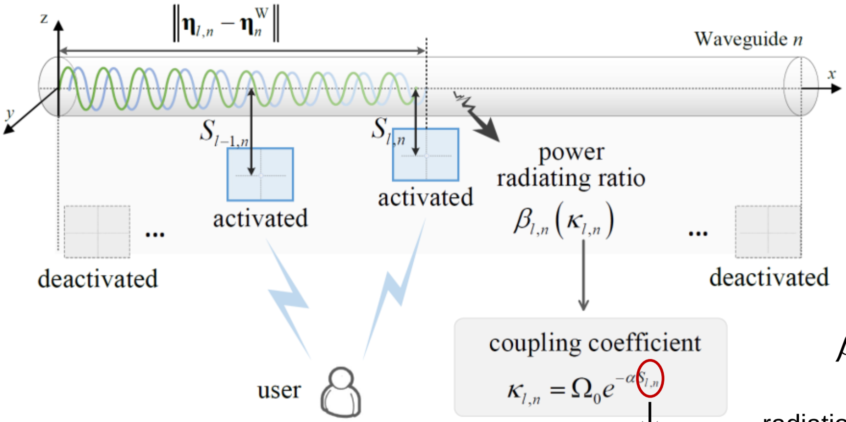
✓ Equal power model

$$P_1 = P_2 = \cdots = P_N$$

Each antenna have the *different coupling length* and radiates the *same power*

[1] Z. Wang, C. Ouyang, X. Mu, **Y. Liu**, and Z. Ding, “Modeling and Beamforming Optimization for Pinching-Antenna Systems,” *IEEE Trans. Commun.*, major revision, 2025. https://arxiv.org/abs/2502.05917
[2] Z. Ding, R. Schober and H. Vincent Poor, “Flexible-Antenna Systems: A Pinching-Antenna Perspective," *IEEE Trans. Commun.*, early access, Mar. 2025

❑ Adjustable Power Radiation Model for PASS



waveguide-antenna spacing

- **Power radiation ratio** of each pinching antenna can be **flexibly adjusted** by one-by-one configuring **spacing** $S_{l,n}$ between **waveguide** n and **antenna** l

coupling length

$$\beta_{l,n}=a_{l,n}\sin\left(\kappa_{l,n}L^{\mathrm{PA}}\right)\prod_{i=1}^{l-1}\sqrt{1-a_{i,n}\sin^2\left(\kappa_{i,n}L^{\mathrm{PA}}\right)}$$

radiation ratio **coupling coefficient** activation state

- **Element-wise power radiation control**

The **target** power radiation ratio $\beta_{l,n}^{\mathrm{target}}$ can be achieved by **one-by-one adjusted spacing**, such that

$$\sin\left(\Omega_0 e^{-\alpha S_{l,n}}\right)=\frac{\beta_{l,n}^{\mathrm{target}}}{\prod_{i=1}^{l-1}\left(1-a_{i,n}\sin^2\left(\Omega_0 e^{-\alpha S_{i,n}}\right)\right)}$$

- **Special case: equal-power radiation**

Equal power radiation ratio at waveguide n can be achieved by one-by-one adjusted spacing, such that

$$\sin\left(\Omega_0 e^{-\alpha S_{l,n}}L^{\mathrm{PA}}\right)=\frac{1}{\sqrt{L_n^{\mathrm{s}}-\rho_{l,n}}},\qquad \rho_{l,n}=\sum_{i=1}^{l-1}a_{i,n}$$

number of activated antennas

[1] X. Xu, X. Mu, Z. Wang, **Y. Liu**, and A. Nallanathan, "Pinching-Antenna Systems (PASS): Power Radiation Model and Optimal Beamforming Design," *IEEE Trans. Commun.*, under review, 2025. https://arxiv.org/abs/2505.00218

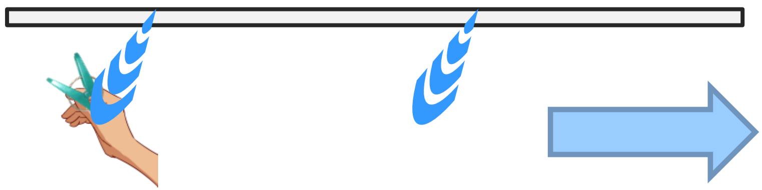
Activation Methods

❑ User-centric activation

Users can attach or remove portable PAs on the waveguide as needed to enhance local communication services.

Pros: Low complexity
Cons: Difficult to manage, security issue

Power Track Socket



Similar concept demo

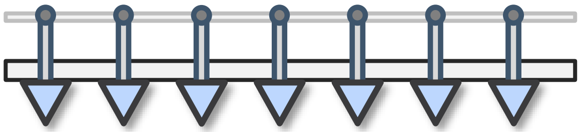
❑ BS-centric activation

BS controls the activation and positions of pinching antennas

Pros: High performance, less security issue
Cons: High complexity for coordination

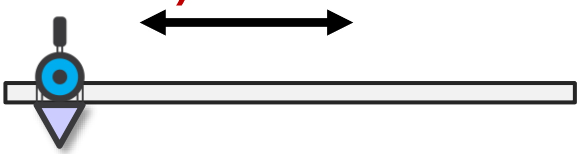
Activation Schemes

❑ Discrete Activation (Piano Keyboard)

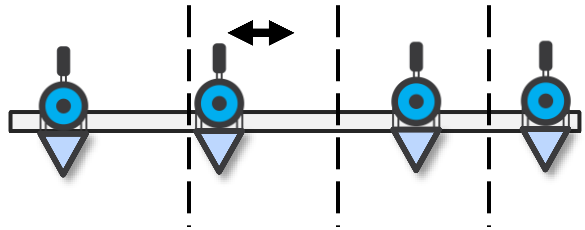


Pinching antennas

❑ Continuous Activation (Electrical Curtain)



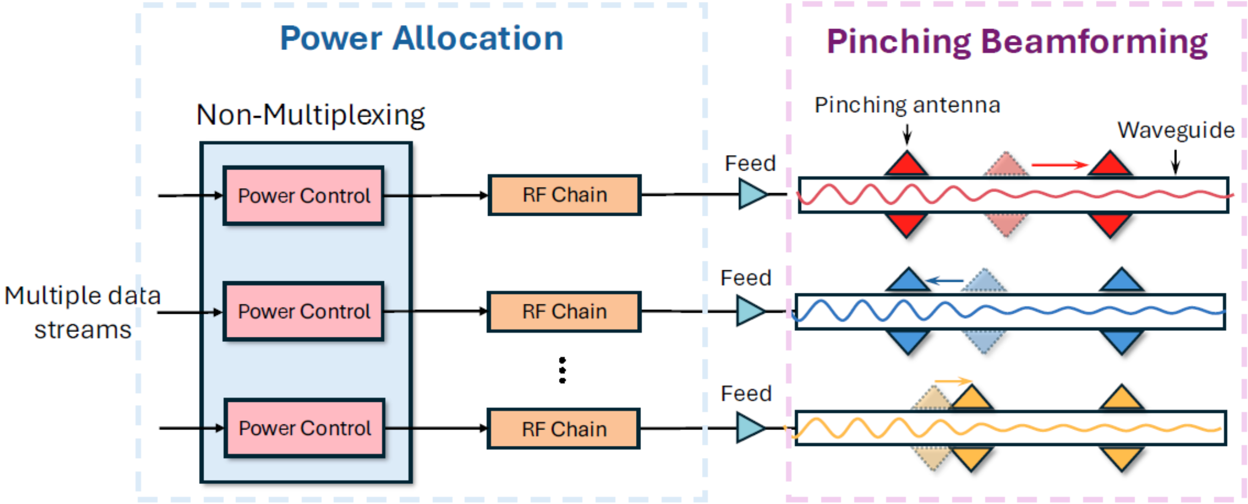
❑ Semi-Continuous Activation



Schemes	Advantages	Disadvantages
Discrete Activation	Fast response (Electrical)	Massive number of antennas; Discrete positions
Continuous Activation	Limited numbers of antennas needed; Continuous positions	Slow response (Mechanical)
Semi-Continuous Activation	A good trade-off between response time and complexity	

Transmission Architectures

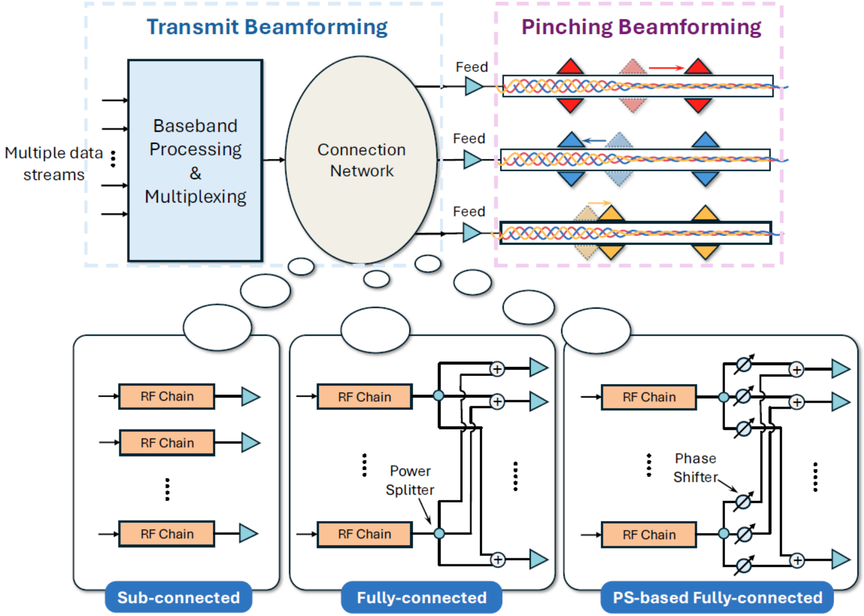
❑ Non-Multiplexing Architecture --- Waveguide Division (WD)



- Each waveguide is fed by **a single data stream**.
- Low-complexity implementation
- Pinching beamforming: optimization of the locations of the pinching antennas
- Suited for scenarios where each waveguide serves geographically isolated areas

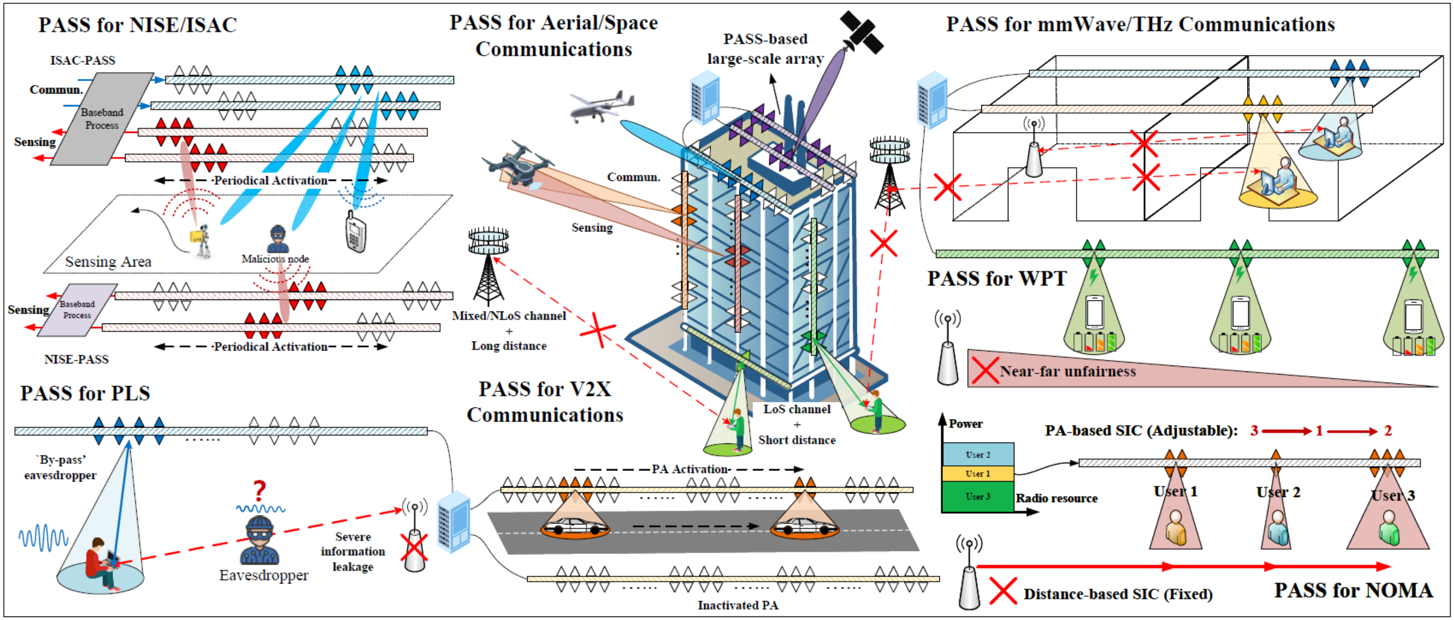
Transmission Architectures

❑ Multiplexing Architecture --- Waveguide Multiplexing (WM)



- **Sub-connected:** each waveguide is connected to a dedicated RF chain
- **Fully-connected:** each RF chain are fed into all waveguides with the aid of power splitters
- **Phase shifter-based fully-connected**: tri-hybrid beamforming

‘PASS’ Signals for 6G and Beyond



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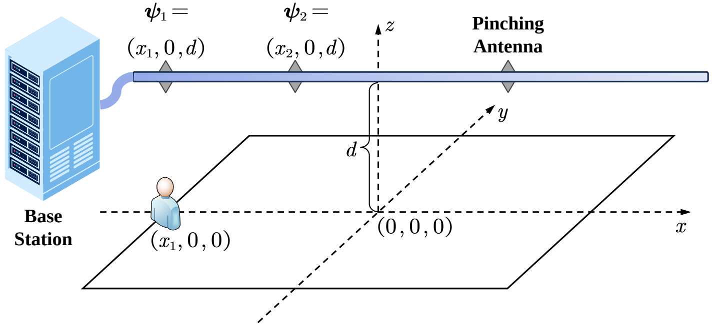
Capacity Limits for PASS: Single-User Case

❑ PASS: single waveguide with multiple pinching antennas



- A PASS using a single pinched waveguide serves a single-antenna user
- The ***capacity*** is determined by the ***array gain***
- The ***array gain*** is related with the number and locations of pinching antennas

$$a = \frac{\gamma}{P/\sigma^2} = \frac{\eta}{N}\left|\sum_{n=1}^{N} \frac{e^{\boxed{-\mathrm{j}\frac{2\pi}{\lambda}\sqrt{d^2+\Delta_n^2}}\boxed{-\mathrm{j}\frac{2\pi\Delta_n}{\lambda_g}}}}{\boxed{\sqrt{d^2+\Delta_n^2}}}\right|^2$$

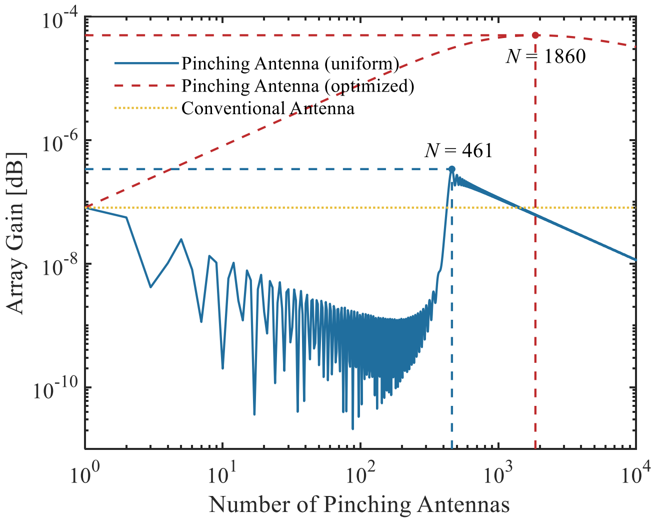
Pinching beamforming

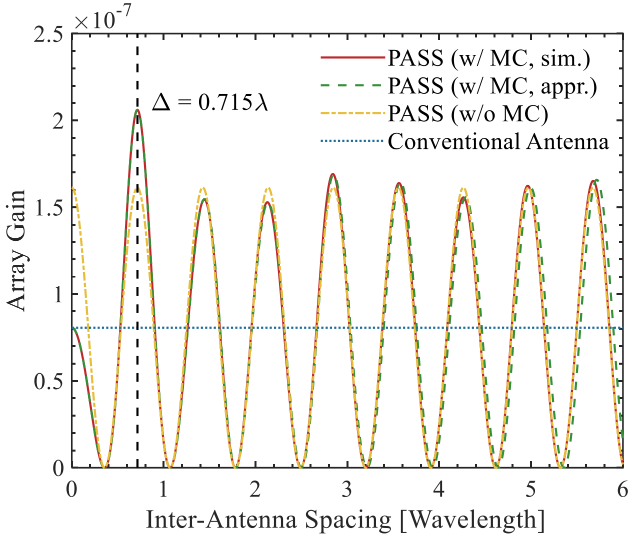
Near-field model

- *Q1: For fixed inter-antenna spacing, does the array gain increase monotonically with the number of antennas?* ***How many antennas do we need?***
- *Q2: For a fixed antenna number, does the array gain increase monotonically as the inter-antenna spacing decreases?*

[1] C. Ouyang, Z. Wang, **Y. Liu**, and Z. Ding, “Array gain for pinching-antenna systems (PASS),” *IEEE Commun. Lett.*, vol. 29, no. 6, pp. 1471-1475. Jun. 2025. https://arxiv.org/abs/2501.05657

Capacity Limits for PASS: Single-User Case





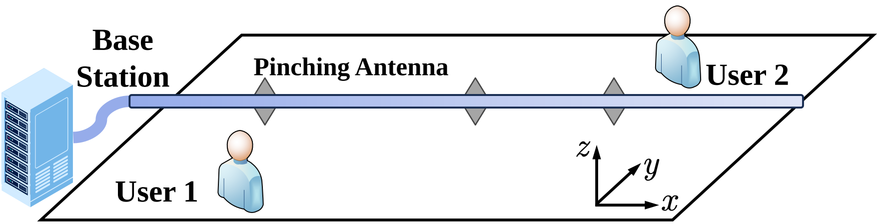
- A1: The array gain does not increase monotonically with the number of antennas
- A1: PASS requires an optimal antenna number to maximize the array gain
- A2: The array gain does not increase monotonically as the inter-antenna spacing decreases

Optimizing the number and locations of pinching antennas is important

[1] C. Ouyang, Z. Wang, **Y. Liu**, and Z. Ding, “Array gain for pinching-antenna systems (PASS),” *IEEE Commun. Lett.*, vol. 29, no. 6, pp. 1471-1475. Jun. 2025. https://arxiv.org/abs/2501.05657

Capacity Limits for PASS: Multiuser Case

❑ PASS: single waveguide with multiple pinching antennas



- A PASS using a single pinched waveguide serves two single-antenna users
- The ***capacity region*** is influenced by the ***pinching beamforming***

Uplink PASS $$y = \sum_{k=1}^{2} \sqrt{p_k}\,\mathbf{h}^{\mathrm{T}}(\mathbf{u}_k, \boxed{\mathbf{q}})\boldsymbol{\phi} s_k + z_{\mathrm{U}}$$

Pinching beamforming

Downlink PASS $$y_k = \sqrt{1/N}\,\mathbf{h}^{\mathrm{T}}(\mathbf{u}_k, \boxed{\mathbf{q}})\boldsymbol{\phi} x + z_k$$

- *Uplink: The channel capacity is achievable using **SIC Decoding**. The entire capacity region is obtained using the **rate-profile approach**.*
- *Downlink: The channel capacity is achievable using **DPC** or power-domain **NOMA (SIC decoding)**. The entire capacity region is obtained through **duality**.*

Characterizing the channel capacity limits of multiuser PASS

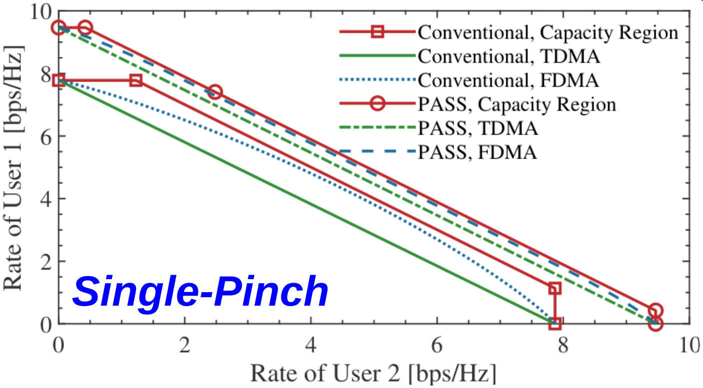
[1] C. Ouyang, Z. Wang, **Y. Liu**, and Z. Ding, "Capacity Characterization of Pinching-Antenna Systems," submitted to *IEEE TWC*, 2025, https://arxiv.org/abs/2506.14298

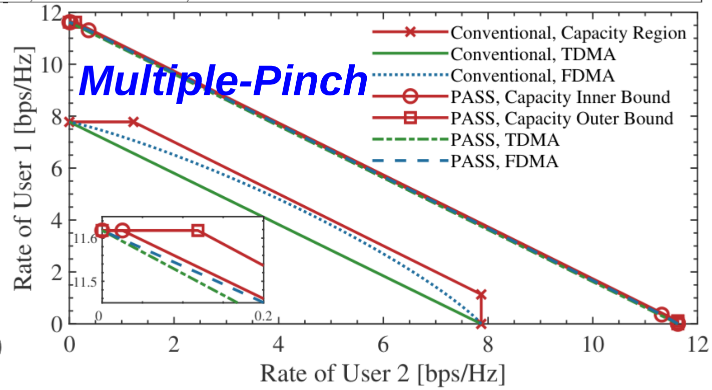
Capacity Limits for PASS: Multiuser Case

❑ Uplink PASS: rate-profile approach

- ➢ ***Single-Pinch Case:*** *Complete capacity region* and TDMA/FDMA rate region
- ➢ ***Multiple-Pinch Case:*** *Inner and outer bounds for the capacity region* and FDMA rate region, the complete TDMA rate region

	Capacity Region	TDMA Rate Region	FDMA Rate Region
Single-Pinch	$\mathcal{C}_{\mathrm{S}}^{\mathrm{U}}$ (*closed-form*, (23))	$\mathcal{R}_{\mathrm{S,T}}^{\mathrm{U}}$ (*closed-form*, (24))	$\mathcal{R}_{\mathrm{S,F}}^{\mathrm{U}}$ (*closed-form*, (27))
Multiple-Pinch	$\mathcal{C}_{\mathrm{M,IB}}^{\mathrm{U}}$ (*rate-profile*); $\mathcal{C}_{\mathrm{M,OB}}^{\mathrm{U}}$ (*relaxation*) $\mathcal{C}_{\mathrm{M,IB}}^{\mathrm{U}} \subseteq \mathcal{C}_{\mathrm{M}}^{\mathrm{U}} \subseteq \mathcal{C}_{\mathrm{M,OB}}^{\mathrm{U}}$	$\mathcal{R}_{\mathrm{M,T}}^{\mathrm{U}}$ (*method in [24]*)	$\mathcal{C}_{\mathrm{M,IB}}^{\mathrm{U}}$ (*rate-profile*); $\mathcal{C}_{\mathrm{M,OB}}^{\mathrm{U}}$ (*relaxation*) $\mathcal{R}_{\mathrm{M,F,IB}}^{\mathrm{U}} \subseteq \mathcal{R}_{\mathrm{M,F}}^{\mathrm{U}} \subseteq \mathcal{C}_{\mathrm{M,OB}}^{\mathrm{U}}$
Comparison	$\mathcal{R}_{\mathrm{S,T}}^{\mathrm{U}} \subseteq \mathcal{R}_{\mathrm{S,F}}^{\mathrm{U}} \subseteq \mathcal{C}_{\mathrm{S}}^{\mathrm{U}}$ (*single-pinch*); $\mathcal{R}_{\mathrm{M,T}}^{\mathrm{U}} \subseteq \mathcal{R}_{\mathrm{M,F}}^{\mathrm{U}} \subseteq \mathcal{C}_{\mathrm{M}}^{\mathrm{U}} \subseteq \mathcal{C}_{\mathrm{M,OB}}^{\mathrm{U}}$ (*multiple-pinch*)		





- ➢ The derived inner and outer bounds are tight
- ➢ FDMA and TDMA are nearly capacity-achieving; FDMA rate region contains TDMA rate region

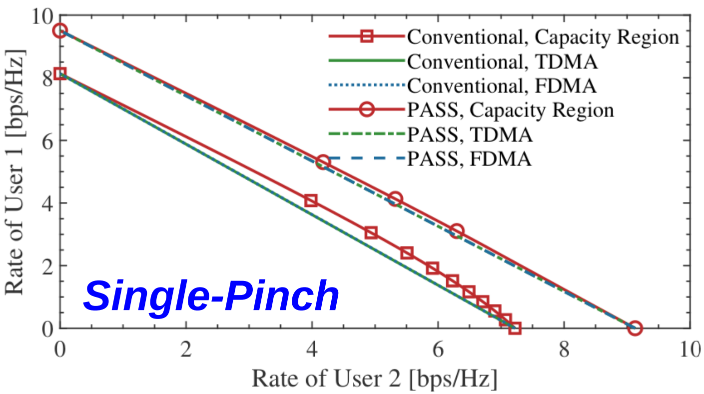
[1] C. Ouyang, Z. Wang, **Y. Liu**, and Z. Ding, "Capacity Characterization of Pinching-Antenna Systems," submitted to *IEEE TWC*, 2025, https://arxiv.org/abs/2506.14298

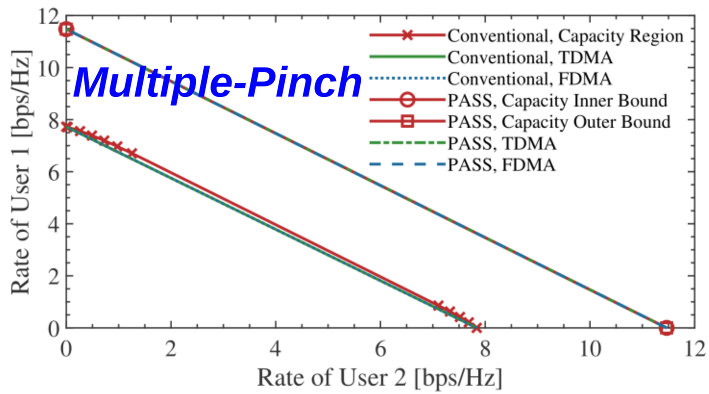
Capacity Limits for PASS: Multiuser Case

❑ Downlink PASS: uplink-downlink duality

- ➢ ***Single-Pinch:*** *Complete capacity region* and TDMA/FDMA rate region
- ➢ ***Multiple-Pinch Case:*** *Inner and outer bounds for the capacity region* and FDMA rate region, the complete TDMA rate region

	Capacity Region	TDMA Rate Region	FDMA Rate Region
Single-Pinch	$\mathcal{C}_{\mathrm{S}}^{\mathrm{D}}$ *(duality, closed-form)*	$\mathcal{R}_{\mathrm{S,T}}^{\mathrm{D}}$ *(duality, closed-form)*	$\mathcal{R}_{\mathrm{S,F}}^{\mathrm{D}}$ *(duality, closed-form)*
Multiple-Pinch	$\mathcal{C}_{\mathrm{M,IB}}^{\mathrm{D}}$ *(duality)*; $\mathcal{C}_{\mathrm{M,OB}}^{\mathrm{D}}$ *(duality)* $\mathcal{C}_{\mathrm{M,IB}}^{\mathrm{D}} \subseteq \mathcal{C}_{\mathrm{M}}^{\mathrm{D}} \subseteq \mathcal{C}_{\mathrm{M,OB}}^{\mathrm{D}}$	$\mathcal{R}_{\mathrm{M,T}}^{\mathrm{D}}$ *(duality, method in [24])*	$\mathcal{C}_{\mathrm{M,IB}}^{\mathrm{D}}$ *(duality)*; $\mathcal{C}_{\mathrm{M,OB}}^{\mathrm{D}}$ *(duality)* $\mathcal{R}_{\mathrm{M,F,IB}}^{\mathrm{U}} \subseteq \mathcal{R}_{\mathrm{M,F}}^{\mathrm{U}} \subseteq \mathcal{C}_{\mathrm{M,OB}}^{\mathrm{U}}$
Comparison	$\mathcal{R}_{\mathrm{S,T}}^{\mathrm{D}} \subseteq \mathcal{R}_{\mathrm{S,F}}^{\mathrm{D}} \subseteq \mathcal{C}_{\mathrm{S}}^{\mathrm{D}}$ *(single-pinch)*; $\mathcal{R}_{\mathrm{M,T}}^{\mathrm{D}} \subseteq \mathcal{R}_{\mathrm{M,F}}^{\mathrm{D}} \subseteq \mathcal{C}_{\mathrm{M}}^{\mathrm{D}} \subseteq \mathcal{C}_{\mathrm{M,OB}}^{\mathrm{D}}$ *(multiple-pinch)*		





- ➢ The derived inner and outer bounds are tight
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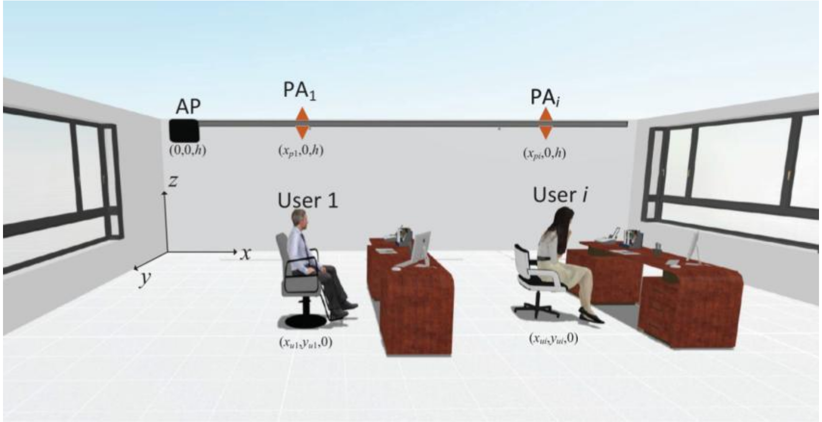
Performance Analysis for PASS

PASS: multiple/single pinching antennas for multiple/single users



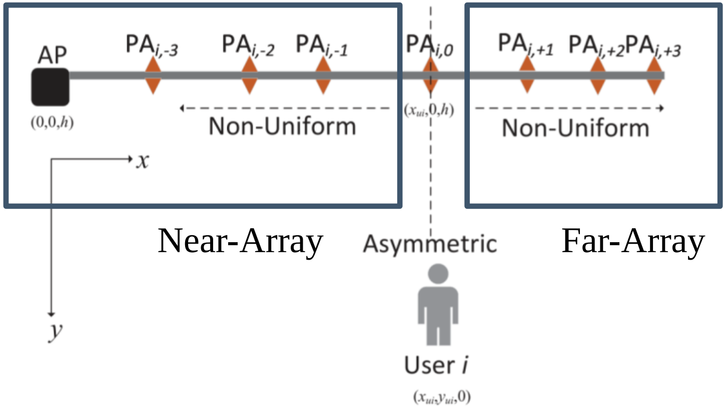
- MPSU: Multiple pinching antennas for a single user
- SPSU: A single pinching antenna for a single user
- SPMU: A single pinching antenna for multiple users
- The optimize location of PAs is related to the number of PAs and user’s location

$$x_n = \frac{n\lambda(2d_0 + n\lambda)}{2(d_0 + n\lambda)}, n = -N, ..., 0, ..., N,$$

[1] T. Hou, **Y. Liu**, and A. Nallanathan, “On the Performance of Uplink Pinching Antenna Systems (PASS),” *IEEE Trans. Commun.*, under review, 2025. https://arxiv.org/abs/2502.12365

Performance Analysis for PASS

❑ MPSU: Multiple pinching antennas for a single user

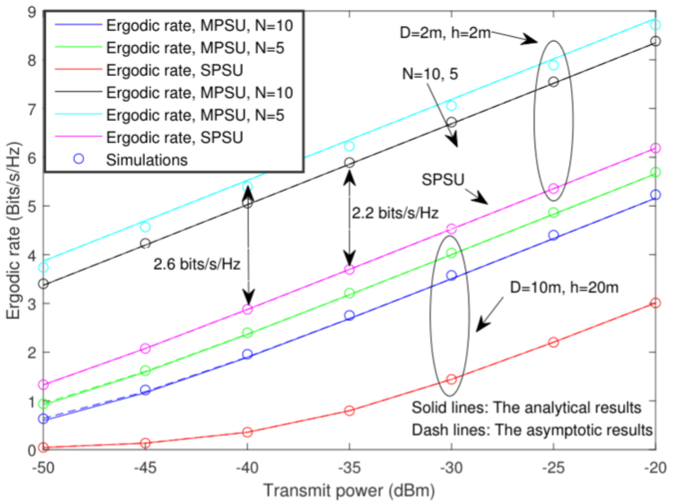


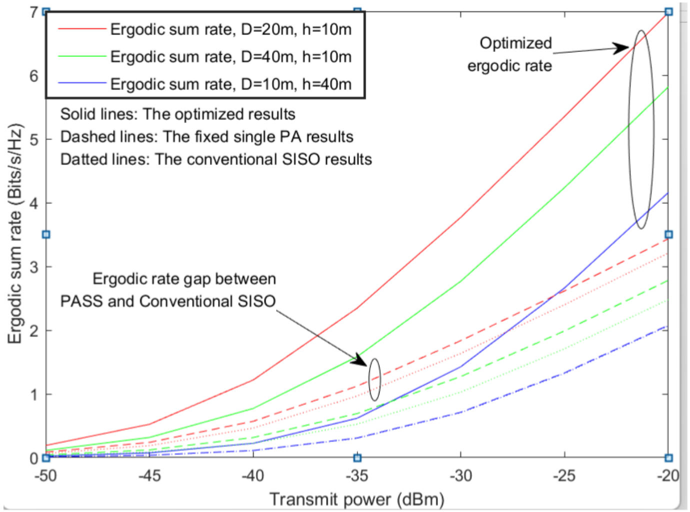
- Far-zone (larger than 10 wavelength)
  - The optimized location approximate **a symmetric uniform distribution**

- Near-zone (lower than 10 wavelength)
  - The optimized location exhibit **an asymmetric non-uniform distribution**
  - Near-Array: the antenna spacing becomes more **sparse**
  - Far-Array: the antenna spacing becomes more **dense**
- Both UL and DL obey this distribution

[1] T. Hou, **Y. Liu**, and A. Nallanathan, "On the Performance of Uplink Pinching Antenna Systems (PASS)," *IEEE Trans. Commun.*, under review, 2025. https://arxiv.org/abs/2502.12365

Performance Analysis for PASS





- The approximated antenna gains
  - MPSU: ***2N***
  - SPSU: 1
  - SPMU: 1

Perfect Antenna Gain!

- When the **number of PAs is lower than the number of users**, the optimized location of PA obey:

$$\frac{(x-x_{u1})}{(x_{u2}-x)} = \frac{(x-x_{u1})^2 + y_{u1}^2 + h^2}{(x-x_{u2})^2 + y_{u2}^2 + h^2}$$

Better Fairness

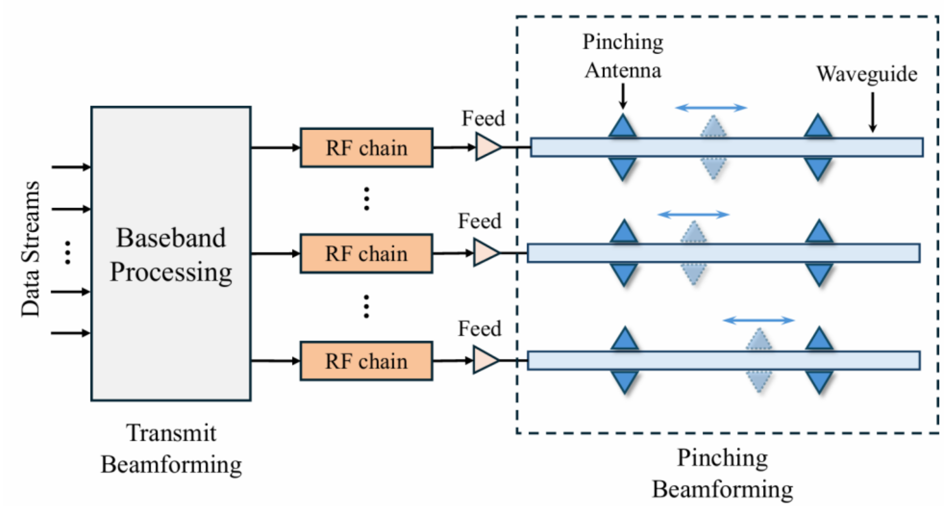
[1] T. Hou, **Y. Liu**, and A. Nallanathan, "On the Performance of Uplink Pinching Antenna Systems (PASS)," *IEEE Trans. Commun.*, under review, 2025. https://arxiv.org/abs/2502.12365

Outline

- ❑ **PASS Basis**
  - ❑ Overview of PASS: Start with a Protype (What)
  - ❑ Advantages of PASS: From Wireless to Near-Wired (Why)
  - ❑ Physics Principle and Signal Modelling (How)
  - ❑ Activation Methods and Transmission Structures (How)
- ❑ **Case Studies**
  - ❑ Case I: Capacity Limits and Performance Analysis for PASS
  - ❑ Case II: Beamforming Design for PASS
  - ❑ Case III: Multiple Access Design for PASS
  - ❑ Case IV: Beam Training and Channel Estimation for PASS
  - ❑ Case V: Applications for PASS
- ❑ **Research Challenges and Opportunities**

Beamforming Design for PASS

- **Joint transmit and pinching beamforming design**

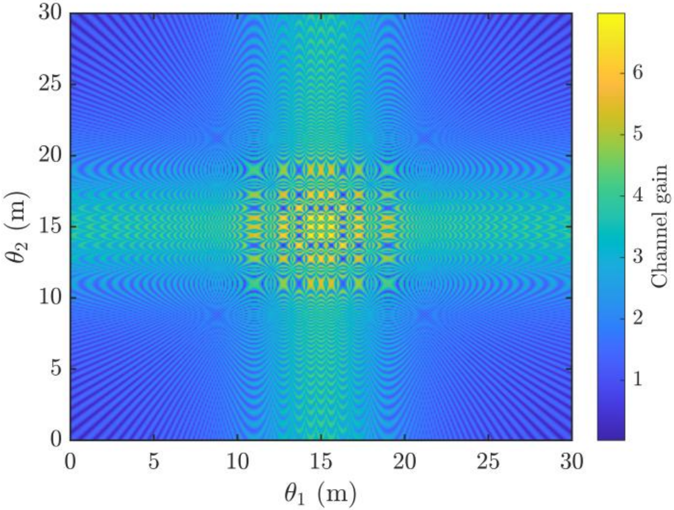


- Sub-connected multiplexing architecture
- Power model: equal power model and proportional power model
- Activation model: continuous and discrete

[1] Z. Wang, C. Ouyang, X. Mu, **Y. Liu**, and Z. Ding, "Modeling and Beamforming Optimization for Pinching-Antenna Systems," *IEEE Trans. Commun.*, major revision, 2025. https://arxiv.org/abs/2502.05917

Beamforming Design for PASS

❑ Key challenges of Pinching Beamforming



Channel gain versus positions of two pinching antennas

$$\mathrm{SINR}_k(\mathbf{W},\mathbf{X}) = \frac{|\overbrace{\mathbf{h}_k^H(\mathbf{X})}^{\textit{Free-space propagation}}\overbrace{\mathbf{G}(\mathbf{X})}^{\textit{In-waveguide propagation}}\mathbf{w}_k|^2}{\sum_{i=1,i\neq k}^{K}|\underbrace{\mathbf{h}_k^H(\mathbf{X})\mathbf{G}(\mathbf{X})}_{\textit{Pinching beamforming}}\underbrace{\mathbf{w}_i}_{\textit{Transmit beamforming}}|^2+\sigma_k^2}$$

- **Highly coupled objective function** leads to *non-separable optimization variables.*
- **A large number of local optima** lead to *inefficient conventional gradient or coordinate descent.*

[1] Z. Wang, C. Ouyang, X. Mu, **Y. Liu**, and Z. Ding, "Modeling and Beamforming Optimization for Pinching-Antenna Systems," *IEEE Trans. Commun.*, major revision, 2025. https://arxiv.org/abs/2502.05917

Beamforming Design for PASS

❑ Joint transmit and pinching beamforming design

$$\min_{\mathbf{w},\mathbf{x}} \sum_{k=1}^{K} \|\mathbf{w}_k\|^2$$

Transmit power minimization

$$\text{s.t. } \mathrm{SINR}_k(\mathbf{W},\mathbf{X}) \geq \gamma_k, \ \forall k$$

$$x_{n,m} - x_{n,m-1} \geq \Delta x, \ \forall n, m \neq 1,$$

$$0 \leq x_{n,m} \leq x_{\max}$$

➢ **Proposed solution 1: Penalty-based algorithm**

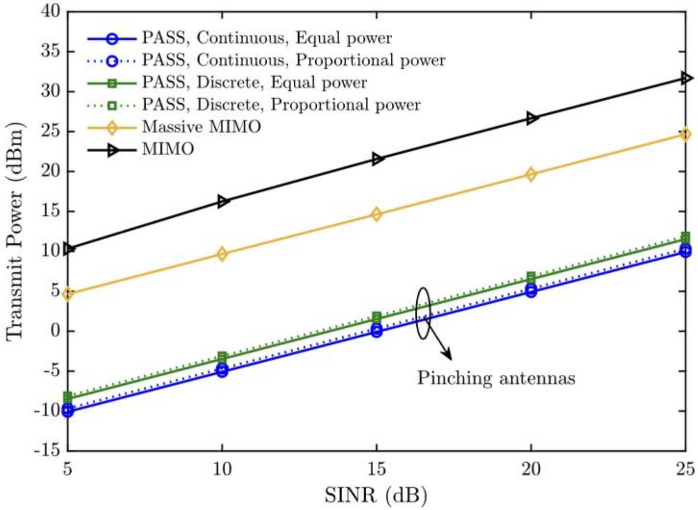
a) Using **penalty method** to **decouple** the optimization variables, which enables **one-dimensional search** to replace the inefficient gradient or coordinate descent.
b) High complexity, directly solving the original optimization problem

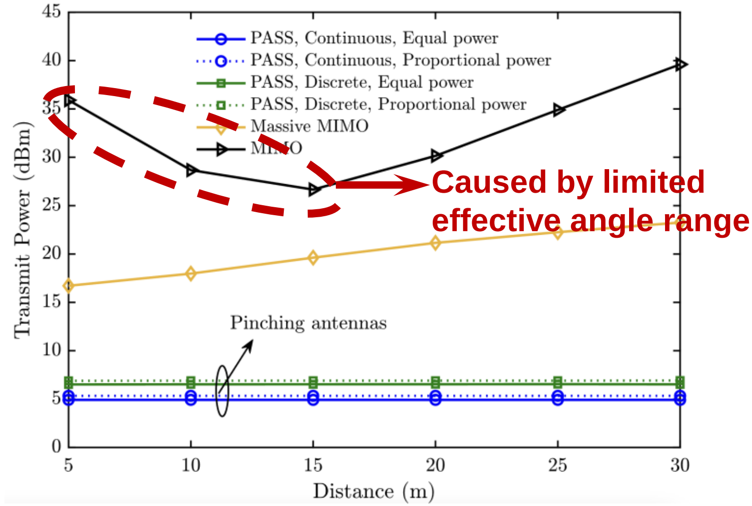
➢ **Proposed solution 2: Zero-forcing-based algorithm**

a) Using **zero-forcing beamformer** to simplified the optimization problem
b) Low complexity, solving a simplified problem

[1] Z. Wang, C. Ouyang, X. Mu, **Y. Liu**, and Z. Ding, "Modeling and Beamforming Optimization for Pinching-Antenna Systems," *IEEE Trans. Commun.*, major revision, 2025. https://arxiv.org/abs/2502.05917

Beamforming Design for PASS



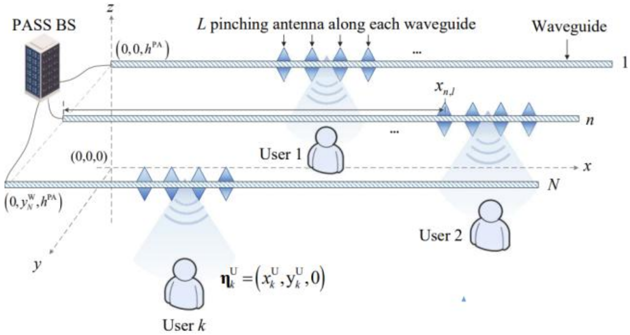


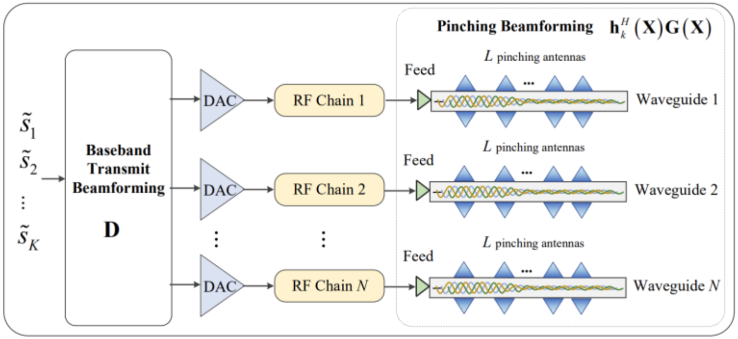
- ➢ The performance loss caused by the proportional power model is negligible compared to the equal power model.
- ➢ The performance of PASS is irrelevant to the distance between transceivers due to the high flexibility of pinching antennas

[1] Z. Wang, C. Ouyang, X. Mu, **Y. Liu**, and Z. Ding, "Modeling and Beamforming Optimization for Pinching-Antenna Systems," *IEEE Trans. Commun.*, major revision, 2025. https://arxiv.org/abs/2502.05917

Beamforming Design for PASS – LLM Method

❑ Pinching Beamforming: Optimization-Based or Learning-Based





➢ Sum rate maximization

$$\max_{\mathbf{X},\mathbf{D}} \sum_{k=1}^{K} \log_2\left(1+\frac{|\mathbf{h}_k^H(\mathbf{X})\mathbf{G}(\mathbf{X})\mathbf{d}_k|^2}{\sum_{i\neq k}|\mathbf{h}_k^H(\mathbf{X})\mathbf{G}(\mathbf{X})\mathbf{d}_i|^2+\sigma^2}\right)$$

$$\text{s.t.}\quad x_{n,l}-x_{n,l-1}\geq\Delta_{\min},\quad \forall n,l$$

$$0\leq x_{n,l}\leq S_{\mathrm{x}},\quad \forall n,l$$

$$\sum_{k=1}^{K}\|\mathbf{d}_k\|^2\leq P$$

$\mathbf{h}_k^H(\mathbf{X})\mathbf{G}(\mathbf{X})$: Pinching beamforming

$\mathbf{d}_k$: Conventional transmit beamforming (baseband)

(minimum spacing of pinches)

(deployment range)

(maximum transmit power)

[1] X. Xu, X. Mu, **Y. Liu** and A. Nallanathan, “Joint Transmit and Pinching Beamforming for PASS: Optimization-Based or Learning-Based?” *IEEE Trans. Wireless Commun.*, under review, 2025. https://arxiv.org/pdf/2502.08637

Beamforming Design for PASS – LLM Method

❑ Optimization-Based: An MM-PDD Method

MM-PDD Method

⇩

WMMSE → **(i)** **Sum rate reformulation**

↓

Majorization-Minimization (MM) → **(ii)** **Construct** **Lipschitz gradient surrogate** **for nonconvex exponential components**

$$L^{\mathrm{EXP}}_{k,n,l}\left(\theta^{(t-1)}_{k,n,l}\right) + \nabla_{\theta} L^{\mathrm{EXP}}_{k,n,l}\left(\theta^{(t-1)}_{k,n,l}\right)\left(\theta_{k,n,l} - \theta^{(t-1)}_{k,n,l}\right) + \left|\frac{\varrho^{\theta}_{k,n,l}}{2}\left(\theta_{k,n,l} - \theta^{(t-1)}_{k,n,l}\right)\right|^2$$

↓

Penalty Dual Decomposition (PDD) → **(iii)** **Decompose highly coupled problem**

⇩

Obtain KKT solutions (Stationary solutions)

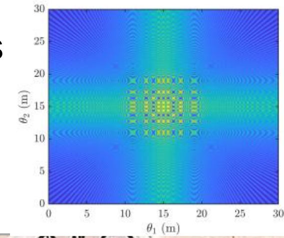
➢ **Advantage**

Strong theoretical guarantees to find locally (sub-)optimal solutions

➢ **Limitations**

(i) High complexity for a large amount of iterations

(ii) Nonconvex problem may have numerous suboptimal solutions



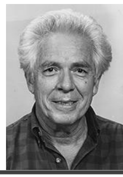
Beamforming Design for PASS – LLM Method

❑ Learning-Based: A KDL-Transformer Method

When KKT meets Large language model (LLM)

Karush-Kuhn-Tucker (KKT) solutions: Foundation of constrained optimization

Harold W. Kuhn



Albert W. Tucker

Large language model (LLM)

Model intricate dependence of elements (namely *tokens*) in sequences (e.g., natural language, audios, images)

- **KKT-guided dual learning (KDL): Recover KKT solutions** in an **iteration-free data-driven** way by **only learning dual variables ->** Guide black-box learning by KKT theory
- **KDL-Transformer:** Leveraging the **power of LLM**

CSI-to-Beamforming mapping
↓
Sequence-to-sequence generation

⇒

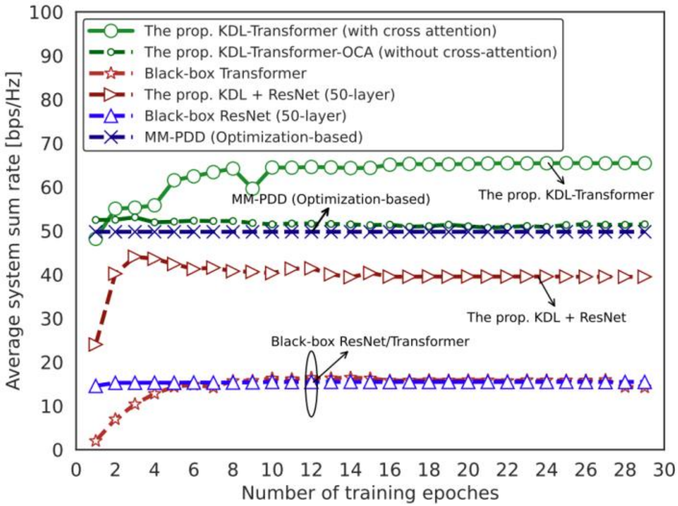
Inter-pinch/inter-user dependence → **Self-attention**

CSI-Beamforming dependence → **Cross-attention**

[1] X. Xu, X. Mu, **Y. Liu** and A. Nallanathan, "Joint Transmit and Pinching Beamforming for PASS: Optimization-Based or Learning-Based?" *IEEE Trans. Wireless Commun.*, under review, 2025. https://arxiv.org/pdf/2502.08637

Beamforming Design for PASS – LLM Method

❑ Pinching Beamforming: Optimization-Based or Learning-Based



Performance \ Method	MM-PDD ($\rho = 0.01$)	KDL-Transformer (with cross attn.)
Sum rate ($K = 4, L = 8$)	49.76	**65.83**
Execution time (second)	255.51/sample	0.0324/batch
Sum rate ($K = 4, L = 16$)	47.20	**67.68**
Execution time (second)	408.12/sample	0.0477/batch

- ➢ **Black-box ResNet/Transformer** is stuck at inferior points compared to MM-PDD
- ➢ **KDL-Transformer** increases over **20%** system performance than MM-PDD, while achieving **over 7000 times faster execution** on modern GPUs

[1] X. Xu, X. Mu, **Y. Liu** and A. Nallanathan, "Joint Transmit and Pinching Beamforming for PASS: Optimization-Based or Learning-Based?" *IEEE Trans. Wireless Commun.*, under review, 2025. https://arxiv.org/pdf/2502.08637

Beamforming Design for PASS – GNN Method

❑ Joint transmit and pinching beamforming design

- ➢ Downlink system, a BS with *N* waveguides transmits to *K* users, *M* pinching antennas on each waveguide
- ➢ Optimize pinching and transmit beamforming to maximize spectral efficiency

$$\max_{\Phi^p,\mathbf{W}} \sum_{k=1}^{K} \log_2\left(1+\frac{\left|\overbrace{\boxed{\mathbf{h}_k^H\mathbf{V}}}^{\text{Pinching beamforming}}\overbrace{\boxed{\mathbf{w}_k}}^{\text{Transmit beamforming}}\right|^2}{\sum_{j=1,j\neq k}^{K}\left|\mathbf{h}_k^H\mathbf{V}\mathbf{w}_j\right|^2+\sigma_0^2}\right)$$

$$\text{s.t.}\quad 0 \le \underbrace{\boxed{x_{m,n}^p}}_{\text{Position of pinching antennas}} \le D,\ \forall m,n,$$

$$x_{m,n}^p - x_{m-1,n}^p \ge \Delta_{\min},\ \forall m,$$

$$\|\mathbf{W}\|^2 \le P$$

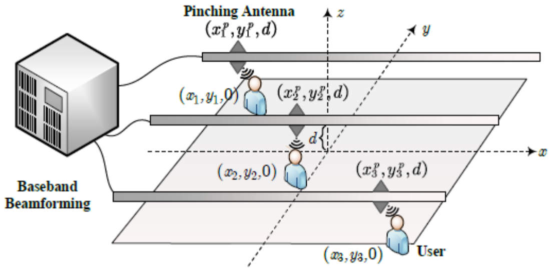


Fig. 1. Illustration of PASS, $K = N = 3$.

- ➢ Beamforming policy: mapping from users' positions to optimal beamforming
- ➢ Permutation property: The policy is not affected by permuting the **users**, **waveguides**, and **pinching antennas on each waveguide**

[1] J. Guo, **Y. Liu** and A. Nallanathan "Deep Learning for Beamforming of PASS" *IEEE Wireless Commun. Lett.*., under revision, https://arxiv.org/abs/2502.01438.

Beamforming Design for PASS – GNN Method

GNN for Learning Beamforming Policy

- Graph modeling: two types of vertices: users, pinching antennas
- Simultaneously outputting pinching and transmit beamforming leads to inferior performance due to coupling between the two beamforming
- Staged architecture:
  - **Stage 1:** learn pinching beamforming
  - **Stage 2:** learn traditional beamforming with optimal solution structure:

$$\mathbf{W}^{\star} = \widetilde{\mathbf{H}}\left(\Lambda\widetilde{\mathbf{H}}^{H}\widetilde{\mathbf{H}} + \sigma_0^2\mathbf{I}_K\right)^{-1}\mathbf{P}^{\frac{1}{2}},$$

Sub-GNN for learning pinching beamforming

Sub-GNN for learning transmit beamforming

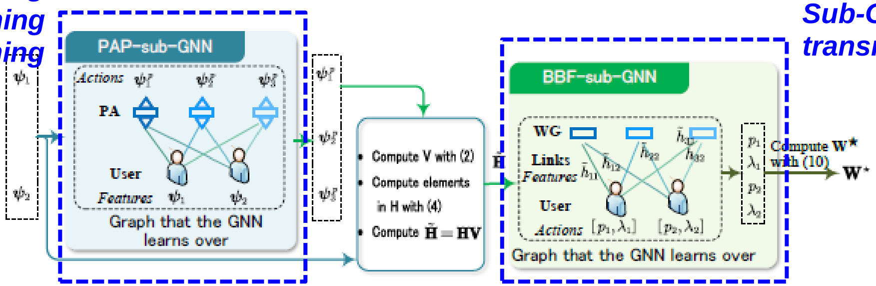


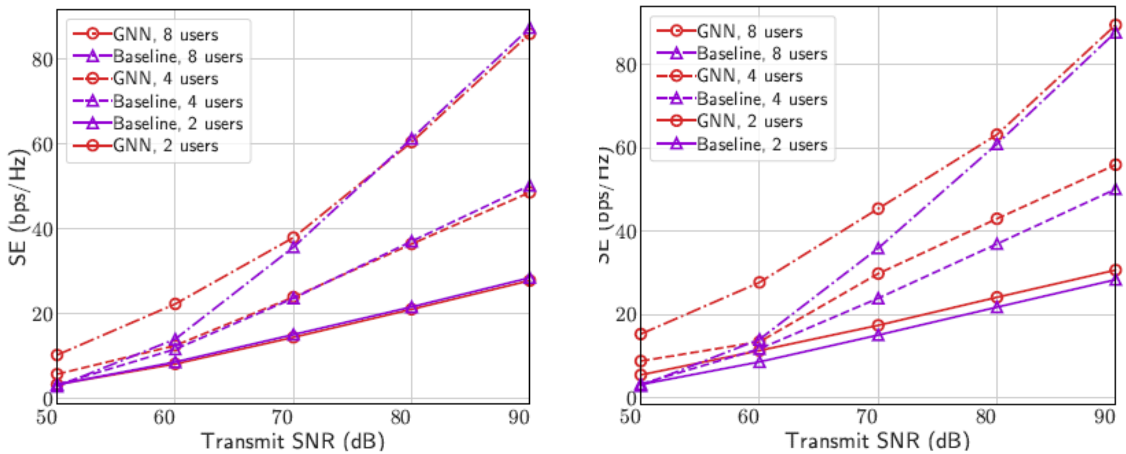
Fig. 2. GNN architecture for learning beamforming policy in PASS.

[1] J. Guo, **Y. Liu** and A. Nallanathan "Deep Learning for Beamforming of PASS" *IEEE Wireless Commun. Lett.*., under revision, https://arxiv.org/abs/2502.01438.

Beamforming Design for PASS – GNN Method

❑ Simulation Results

- 8 users in 10 x 10 m^2 region, 8 waveguides, GNN trained with 10000 samples.
- Baseline: Every pinching antenna is deployed to the closest user, ZF beamforming



(a) $M = 1$ (b) $M = 3$

- The proposed GNN can achieve SE that is close to or higher than the baseline method, especially when the SNR is low.

[1] J. Guo, **Y. Liu** and A. Nallanathan "Deep Learning for Beamforming of PASS" *IEEE Wireless Commun. Lett.*., under revision, https://arxiv.org/abs/2502.01438.

Beamforming Design for PASS – Optimal Solution

❑ Globally Optimal Beamforming (Discrete Activation)

- **How to find the optimal PASS design,** so that we can **justify suboptimal ones?**
- For discrete activation structure, we jointly optimize the pinching beamforming, transmit beamforming, and numbers of activated antennas at waveguides

Globally Optimal Beamforming by BnB

Construct McCormick envelope based convex relaxation for coupled variables

↓

Branch-and-Bound (BnB)

↓

Converge to global optimum

Near-optimal Beamforming: Low-complexity Matching

Model pinching beamforming as a many-to-many matching game

↓

Digital beamforming by KKT

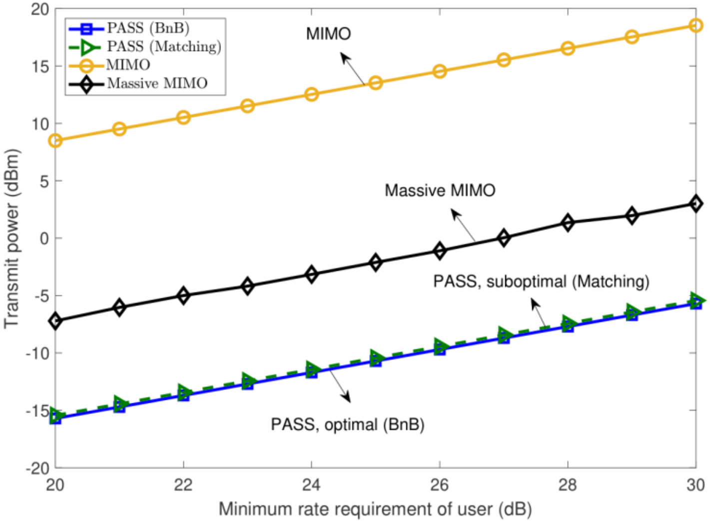
↓

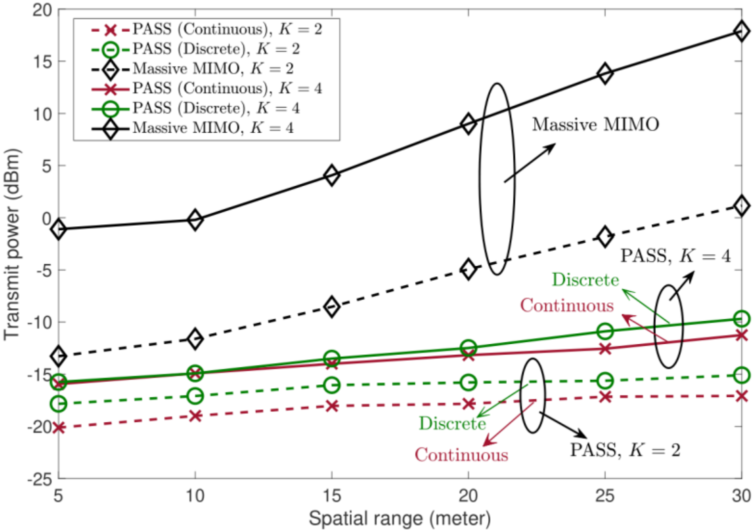
Locally optimal & pairwise stable solution by welfare-driven matching

[1] X. Xu, X. Mu, Z. Wang, **Y. Liu**, and A. Nallanathan, "Pinching-Antenna Systems (PASS): Power Radiation Model and Optimal Beamforming Design," *IEEE Trans. Commun.*, under review, 2025. https://arxiv.org/abs/2505.00218

Beamforming Design for PASS – Optimal Solution

❑ Globally Optimal Beamforming (Discrete Activation)





- **Many-to-many matching incurs only a marginal loss compared to the globally optimal BnB**
- The performance gain over conventional MIMO increases with the number of users and spatial range

[1] X. Xu, X. Mu, Z. Wang, **Y. Liu**, and A. Nallanathan, "Pinching-Antenna Systems (PASS): Power Radiation Model and Optimal Beamforming Design," *IEEE Trans. Commun.*, under review, 2025. https://arxiv.org/abs/2505.00218

Outline

- ❑ **PASS Basis**
  - ❑ Overview of PASS: Start with a Protype (What)
  - ❑ Advantages of PASS: From Wireless to Near-Wired (Why)
  - ❑ Physics Principle and Signal Modelling (How)
  - ❑ Activation Methods and Transmission Structures (How)
- ❑ **Case Studies**
  - ❑ Case I: Capacity Limits and Performance Analysis for PASS
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  - ❑ Case III: Multiple Access Design for PASS
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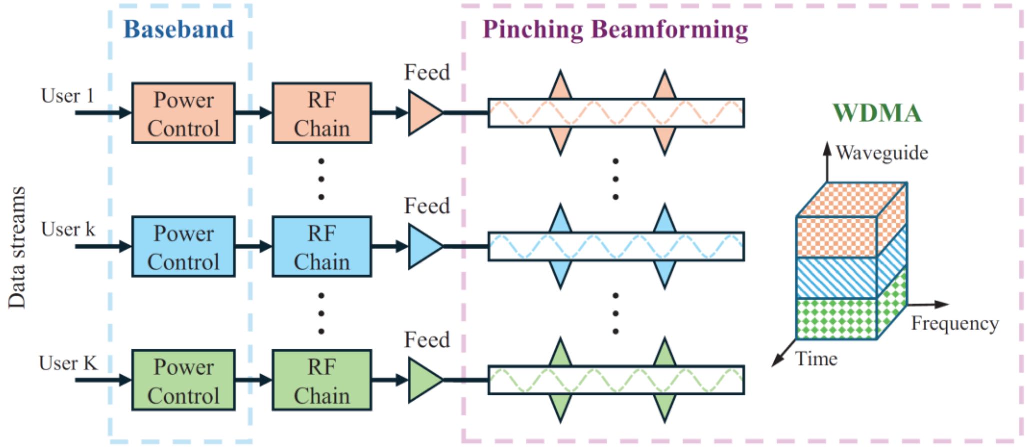
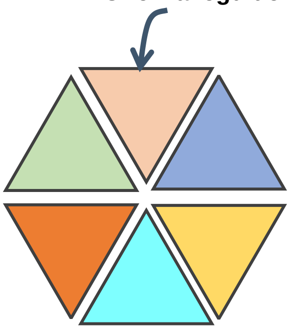
  - ❑ Case V: Physical Layer Security for PASS
- ❑ **Research Challenges and Opportunities**

Multiple Access Design for PASS

❑ Waveguide Division Multiple Access (WDMA)





- **WDMA:** Allocate each user with a dedicated waveguide (like a new type of radio resources) to facilitate multi-user communications.
- **Simple Implementation:** baseband power allocation + pinching beamforming.
- **Pinching Beamforming:** desired signal enhancement and interference mitigation to achieve *(near) orthogonality* in the free space

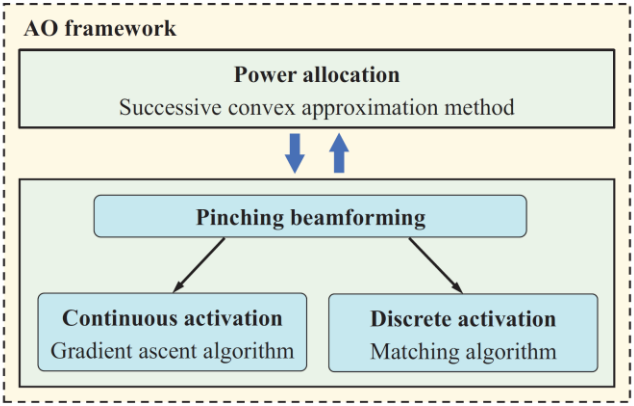
[1] J. Zhao, X. Mu, K. Cai, Y. Zhu, and **Y. Liu**, "Waveguide Division Multiple Access for Pinching-Antenna Systems (PASS)," *IEEE Trans. Wireless Commun.*, under review, 2025. https://arxiv.org/pdf/2502.17781

Multiple Access Design for PASS

❑ Waveguide Division Multiple Access (WDMA)

$$\max_{\mathbf{x},\mathbf{p}} \ \sum\nolimits_{k=1}^{K} R_k$$

$$\begin{aligned} s.t.\ \ & R_k \geq \overline{R}_k, \forall k, \\ & \mathbf{x}_p^k \in \mathcal{F}^C / \mathbf{x}_p^k \in \mathcal{F}^D, \\ & \sum\nolimits_{k=1}^{K} p_k \geq P_{\max}. \end{aligned}$$



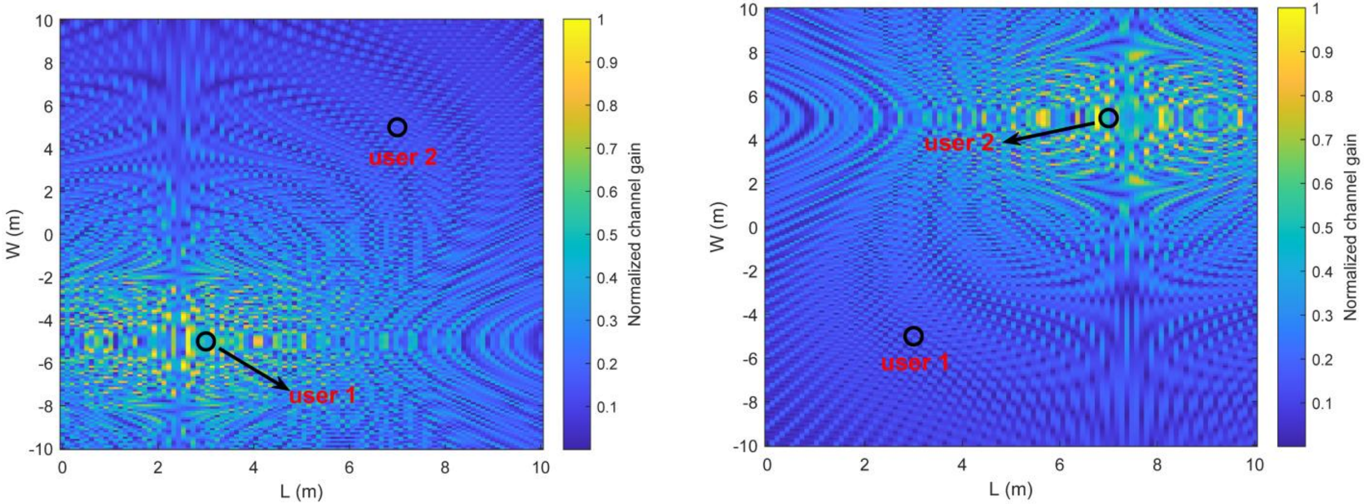
- ❑ **Sum-rate Maximization:** Joint *power allocation* and *pinching beamforming* design

- ❑ **Solution:** An alternating optimization algorithm
- ➢ **Continuous Activation Case:** Gradient ascent algorithm for pinching beamforming
- ➢ **Discrete Activation Case:** Matching theory for pinching beamforming

[1] J. Zhao, X. Mu, K. Cai, Y. Zhu, and **Y. Liu**, "Waveguide Division Multiple Access for Pinching-Antenna Systems (PASS)," *IEEE Trans. Wireless Commun.*, under review, 2025. https://arxiv.org/pdf/2502.17781

Multiple Access Design for PASS

❑ Effectiveness of the Pinching Beamforming

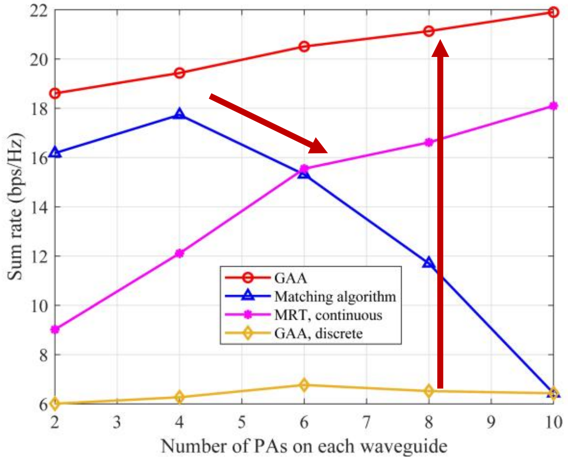


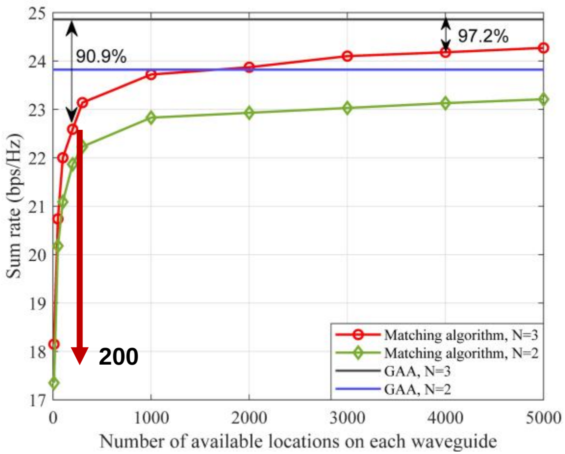
➢ Only using the pinching beamforming, high channel gain can be achieved for the intended user, while much lower channel gain is observed at the interfering user, i.e., ***near orthogonality in free space***:

[1] J. Zhao, X. Mu, K. Cai, Y. Zhu, and **Y. Liu**, "Waveguide Division Multiple Access for Pinching-Antenna Systems (PASS)," *IEEE Trans. Wireless Commun.*, under review, 2025. https://arxiv.org/pdf/2502.17781

Multiple Access Design for PASS

❑ Impact of Discrete Pinching Antenna Positions





- When the number of discrete candidate positions is limited (e.g., 10), (i) ***significant performance loss*** occurs by quantizing the continuous positions into discrete ones, (ii) it is ***harmful*** to further increase number of pinching antennas.
- Practically feasible numbers of discrete candidate positions (e.g., 200 in 10 meter) can achieve **90%** performance of the ideal continuous case.

[1] J. Zhao, X. Mu, K. Cai, Y. Zhu, and **Y. Liu**, "Waveguide Division Multiple Access for Pinching-Antenna Systems (PASS)," *IEEE Trans. Wireless Commun.*, under review, 2025. https://arxiv.org/pdf/2502.17781

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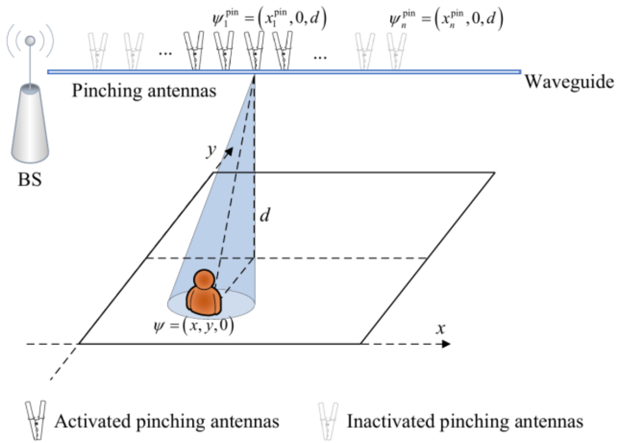
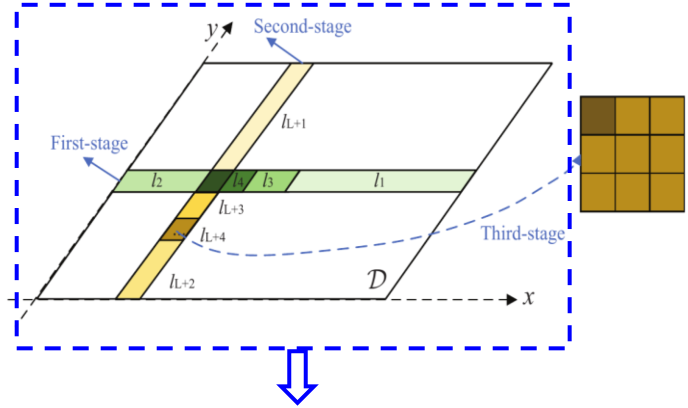
Beam Training for PASS

❑ Single-Waveguide-Single-User PASS (SWSU-PASS)





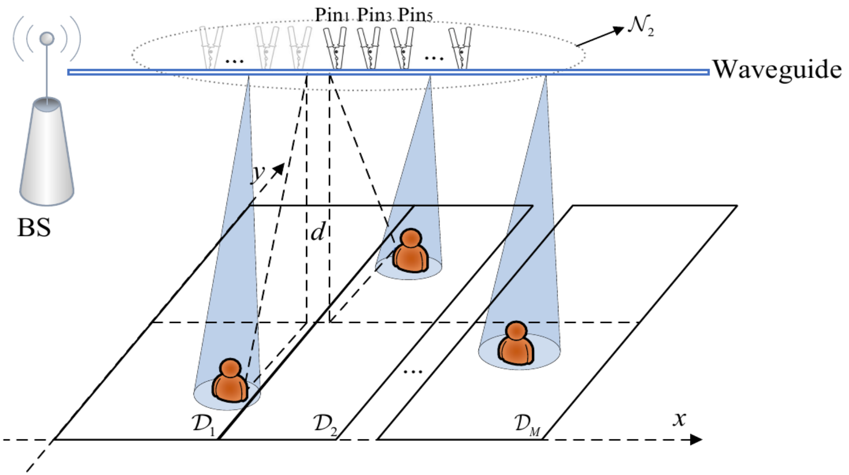
Reduce the 2D search to two 1D searches

- **Scalable Codebook Design**: Scalability, Flexibility and Efficiency
- **3 - Stage Beam Training (3SBT) Scheme**:
  - **Stage-1: Coarse-grained estimation** to roughly locate the user along *x*-dimension
  - **Stage-2: Fine-grained estimation** to refine the user's location along *y*-dimension
  - **Stage-3: Partial exhaustive search** to achieve precise beam alignment

[1] S. Lv, **Y. Liu** and Z. Ding, "Beam Training for Pinching Antenna Systems (PASS)," *IEEE Trans. Wireless Commun.*, major revision, 2025. https://arxiv.org/abs/2502.05921

Beam Training for PASS

❑ Single-Waveguide-Multi-User PASS (SWMU-PASS)

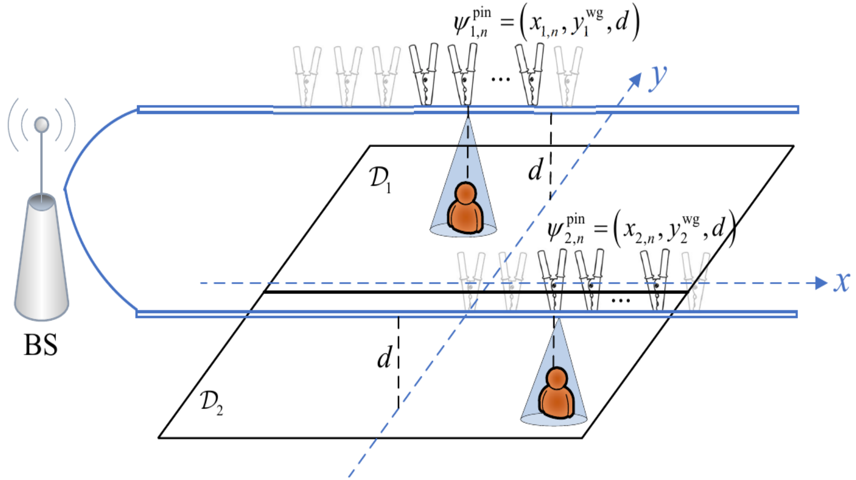


- **Support NOMA-based transmission.**
- **Improved 3SBT Scheme:**
  - **Stage-1: Separated user training** to locate each user's location.
  - **Stage-2: Partial antenna reclustering** to avoid overlapping.
  - **Stage-3: Joint multi-user training** to maximize sum rate.

[1] S. Lv, **Y. Liu** and Z. Ding, "Beam Training for Pinching Antenna Systems (PASS)," *IEEE Trans. Wireless Commun.*, major revision, 2025. https://arxiv.org/abs/2502.05921

Beam Training for PASS

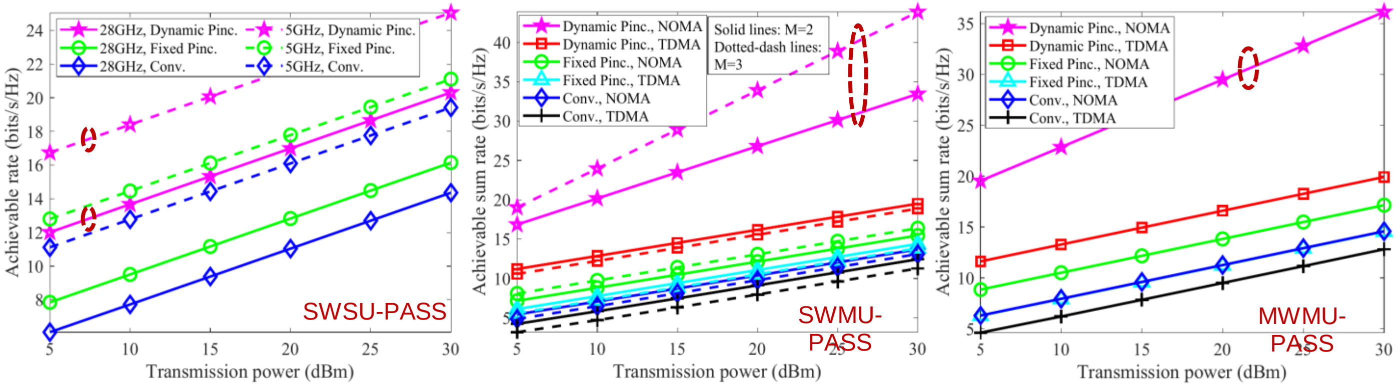
❑ Multi-Waveguide-Multi-User PASS (MWMU-PASS)



- **Increased-dimensional codebook design**
- **Increased-dimensional 3SBT scheme:**
  - **Stage-1: Waveguide determination** to associate user with its closest waveguide
  - **Stage-2: Separated user training** to roughly determine each user's location
  - **Stage-3: Multi-user joint training** to optimize sum rate

[1] S. Lv, **Y. Liu** and Z. Ding, "Beam Training for Pinching Antenna Systems (PASS)," *IEEE Trans. Wireless Commun.*, major revision, 2025. https://arxiv.org/abs/2502.05921

Beam Training for PASS



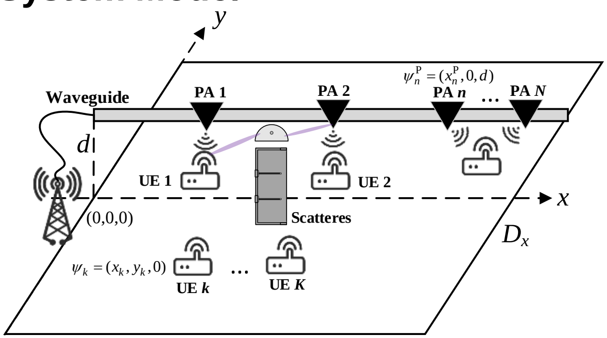
Beam training scheme	Total training overhead	In our set up
SWSU, 2D exhaustive search	$K^{L_1+L_2} \cdot K_1 K_2$	2^{20}
SWSU, proposed	$K(L_1+L_2)+K_1K_2$	48
SWMU, 2D exhaustive search	$K^{M(L_1+L_2)} \cdot \prod_{m=1}^{M}(K_{m,1}K_{m,2})$	$2^{40}, M=2;\ \ 2^{60}, M=3$
SWMU, proposed	$MK(L_1+L_2)+\prod_{m=1}^{M}(K_{m,1}K_{m,2})$	$320, M=2;\ \ 4192, M=3$
MWMU, 2D exhaustive search	$K^{M(L_1+L_2)} \cdot \prod_{m=1}^{M}(K_{m,1}K_{m,2})$	2^{40}
MWMU, proposed	$MK(L_1+L_2)+\prod_{m=1}^{M}(K_{m,1}K_{m,2})$	320

- Reduced training overhead while maintaining reasonable rate performance.
- Better flexibility and improved system performance compared to fixed-location pinching antennas and conventional array antennas.

[1] S. Lv, **Y. Liu** and Z. Ding, "Beam Training for Pinching Antenna Systems (PASS)," *IEEE Trans. Wireless Commun.*, major revision, 2025. https://arxiv.org/abs/2502.05921

Channel Estimation for PASS

❑ System Model



❑ Received Signal at the BS:

$$y_t = \sum_{k=1}^{K} \mathbf{g}^{\top} \mathbf{h}_k s_{k,t} + n_t$$

- ➢ $\mathbf{g}$ -- in-waveguide channel (deterministic component)
- ➢ $\mathbf{h}_k$ --wireless propagation channel between PAs and UE *k*
- ➢ $s_{k,t}$ -- pilot signal transmitted by UE k,
- ➢ n_t -- random noise

All PAs are hard to provide the full coverage of LoS services for all UEs

$$\mathbf{g} = \left[\alpha_1 e^{-j\frac{2\pi}{\lambda_g}|\psi_0^p - \psi_1^p|}, \ldots, \alpha_N e^{-j\frac{2\pi}{\lambda_g}|\psi_0^p - \psi_N^p|} \right]^{\top}$$

depends on positions and coupling lengths of PAs

$$\mathbf{h}_k = \Upsilon_k \odot \mathbf{h}_k^{\mathrm{LoS}} + \mathbf{h}_k^{\mathrm{NLoS}}$$

$$\mathbf{h}_k^{\mathrm{NLoS}} = \sqrt{\frac{1}{S}} \sum_{s=1}^{S} \beta_{k,s} \mathbf{a}_{k,s} e^{j\eta_{k,s}}$$

Υ_k -- the existence of a LoS link

$\mathbf{a}_{k,s}$-- near-field array response

❑ Channel estimation at the arbitrary positions and numbers of PAs

- ➢ Estimate equivalent cascaded channel scalar $h_k = \mathbf{g}^{\top}\mathbf{h}_k$ (not enough for PA optimization)
- ➢ Estimate individual channels $\mathbf{g}$ and $\mathbf{h}_k \in {}^{N \times 1}$ (underdetermined recovery problem)

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Channel Estimation for PASS

❑ Challenges for Conventional Channel Estimation Solutions

- The deterministic in-waveguide analog combining (fixed PA positions) results in:
  - Limited measurement diversity
  - Inadequate matrix rank
  - Ineffective multi-user orthogonal pilot utilization

❑ Antenna Switching-based LS and LMMSE Estimators

- Introducing binary switching matrix to selects subsets of PAs in different time slots

$$\mathbf{y}_k = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_T \end{bmatrix} = \begin{bmatrix} \mathbf{w}_1^T \\ \mathbf{w}_2^T \\ \vdots \\ \mathbf{w}_T^T \end{bmatrix} \mathbf{b}_k + \mathbf{n} = \mathbf{W}^T \mathbf{b}_k + \mathbf{n}$$

$$\hat{\mathbf{b}}_k^{\mathrm{LS}} = (\mathbf{W}\mathbf{W}^T)^{-1}\mathbf{W}\mathbf{y}_k \qquad \hat{\mathbf{h}}_k(n) = \frac{\hat{\mathbf{b}}_k(n)}{\mathbf{g}(n)}$$

$$\hat{\mathbf{b}}_k^{\mathrm{LMMSE}} = \mathbf{R}_b \mathbf{W}(\mathbf{W}^T \mathbf{R}_b \mathbf{W} + \sigma^2 \mathbf{I}_T)^{-1} \mathbf{y}_k$$

$$\mathbf{b}_k = \mathbf{g} \odot \mathbf{h}_k \qquad \mathbf{W} = [\mathbf{w}_1, \ldots, \mathbf{w}_T] \in \{0, 1\}^{N \times T}$$

  - Limited estimation accuracy (Lost spatial diversity)
  - Unnecessary hardware overhead
  - Extended measurement time ($T \geq N$ for single-waveguide and $T \geq N/M$ for *M* waveguides)
  - Potential switch losses

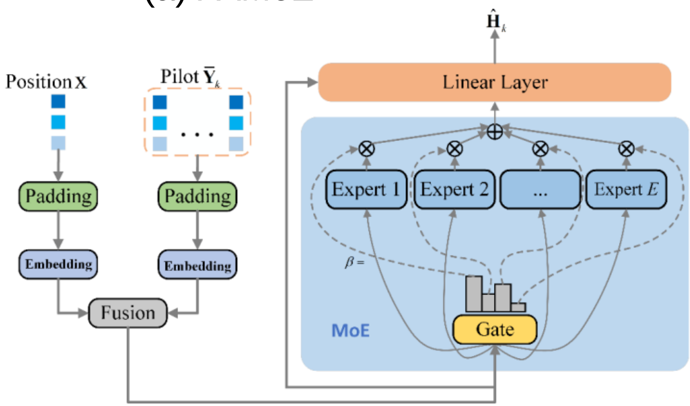
[1] J. Xiao, J. Wang, and **Y. Liu**. "Channel estimation for pinching-antenna systems (PASS)." *IEEE Commun. Lett.*, early access https://arxiv.org/abs/2503.13268.

Channel Estimation for PASS

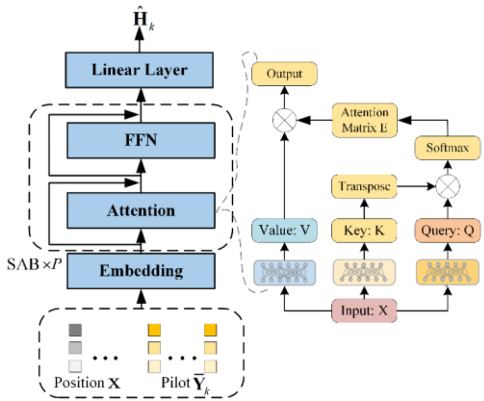
- **Challenges for Deep Learning (DL)-based Channel Estimation Solutions**
  - Extended channel state space (far larger than typical movable antennas)
  - Dynamically activated PA counts (depend on real-time QoS)

- **Proposed DL Solutions**

(a) *PAMoE*



(b) *PAformer*



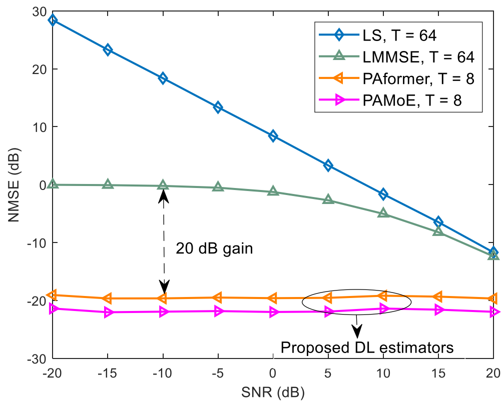
- Leveraging mixture of experts (MoE) to extend the network capacity
- Employing self-attention mechanism to deal with vary PAs

[1] J. Xiao, J. Wang, and **Y. Liu**. "Channel estimation for pinching-antenna systems (PASS)." *IEEE Commun. Lett.*, early access https://arxiv.org/abs/2503.13268.

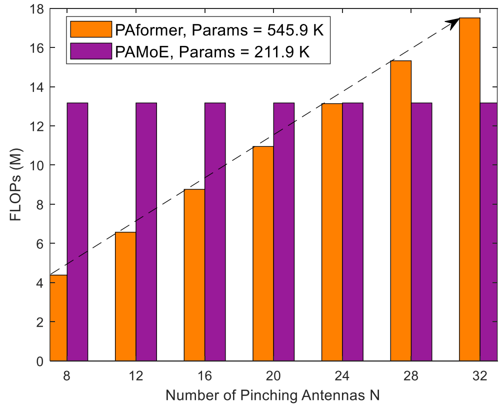
Channel Estimation for PASS

❑ Numerical Results

- **In the offline training stage:** Fixed SNR and PA configurations (N =16)
  - NMSE of different estimators



  - Complexity of different DL estimators



- **In the online test stage:**
- Robust estimation accuracy for dynamic SNR range (*PAMoE>PAformer*)
  - Excellent zero-shot learning capability for unknown PA counts (*PAMoE>PAformer*)
  - Trade off between complexity and flexibility (*PAformer offer better flexibility for N*)

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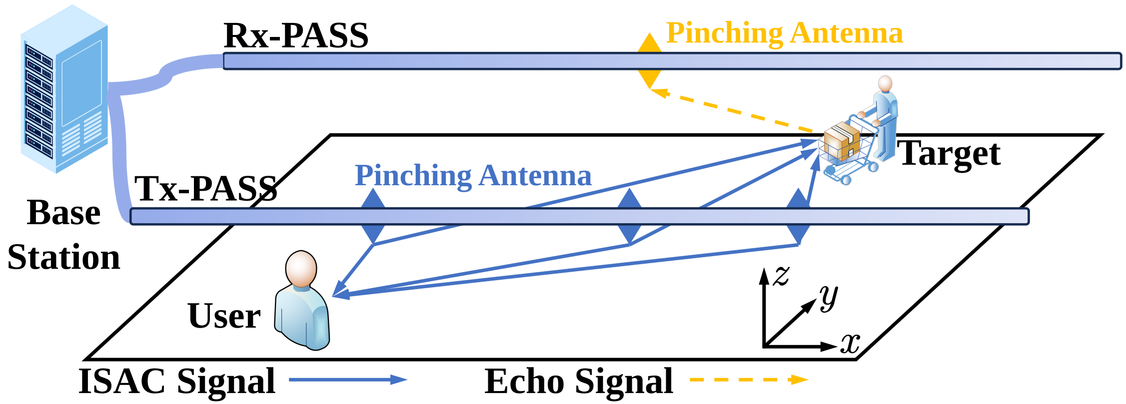
PASS-Enabled ISAC

❑ PASS for ISAC



- **PASS: One waveguide for transmission, one waveguide for receiving**
  TX-PASS: A single pinched waveguide with multiple pinching antennas
  RX-PASS: A single pinched waveguide with a single pinching antenna
- **Dual-Functional ISAC pinching beamforming design**
  Communications-centric design: maximizing the communication rate (CR)
  Sensing-centric design: maximizing the sensing rate (SR)
  Pareto-optimal design: characterizing the CR-SR rate region

[1] C. Ouyang, Z. Wang, **Y. Liu**, and Z. Ding, "Rate Region of ISAC for Pinching-Antenna Systems," *IEEE Trans. Commun.*, under review. https://arxiv.org/2505.10179

PASS-Enabled ISAC

❑ Rate-Region Characterization

➢ **Rate-Profile Approach**

$$
\begin{aligned}
\max_{R,\underbrace{\mathbf{t}}_{\text{Pinching Beamforming}}} \quad & R \\
\text{s.t.} \quad & \underbrace{\log_2(1+\gamma_{\rm c}(\mathbf{t}))}_{\text{CR}} \geq \alpha R \\
& \underbrace{\log_2(1+\gamma_{\rm s}(\mathbf{t}))/L}_{\text{SR}} \geq (1-\alpha) R
\end{aligned}
$$

➢ **Single-Pinch Case:**
Closed-Form Rate Region

➢ **Multiple-Pinch Case: Inner and Outer Bounds of the Rate Region**
Inner Bound: Alternating Optimization
Outer Bound: Cauchy-Schwarz and Karamata's inequalities

	Communications-Centric	Sensing-Centric	Pareto-Optimal (Rate Region)
Single-Pinch	$\mathcal{C}_{\rm S}(t_1^\star)$ (*closed-form*, $t_1 = x_{\rm c}$)	$\mathcal{C}_{\rm S}(t_0^\star)$ (*closed-form*, $t_1 = x_{\rm s}$)	$\mathcal{C}_{\rm p}^{\rm S}$ (*closed-form*, $t_1 = t_\alpha^\star$)
Multiple-Pinch	$\mathcal{C}_{\rm M}(\mathbf{t}_1^\star)$ (*method in [26]*, $\mathbf{t} = \mathbf{t}_{\rm c}$)	$\mathcal{C}_{\rm M}(\mathbf{t}_0^\star)$ (*method in [26]*, $\mathbf{t} = \mathbf{t}_{\rm s}$)	$\mathcal{C}_{\rm p}^{\rm IB}$ (*rate-profile*); $\mathcal{C}_{\rm p}^{\rm OB}$ (*closed-form*) $\mathcal{C}_{\rm p}^{\rm IB} \subseteq \mathcal{C}_{\rm p} \subseteq \mathcal{C}_{\rm p}^{\rm OB}$

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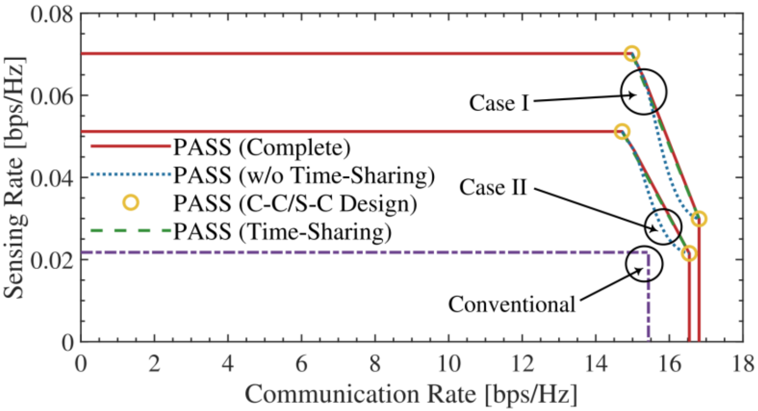
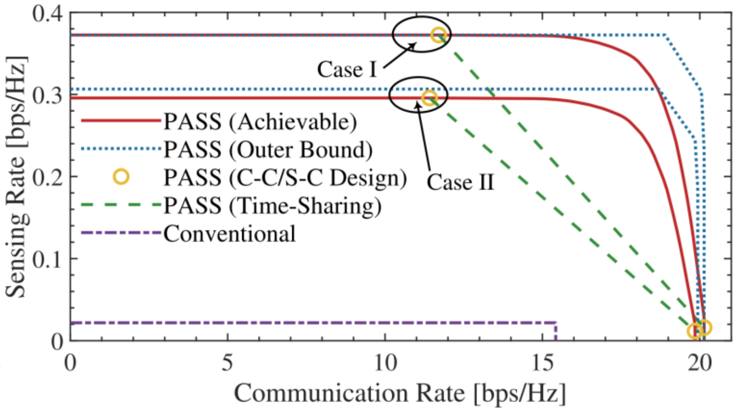
PASS-Enabled ISAC

❑ Rate-Region Characterization



Single-Pinch Case



Multiple-Pinch Case

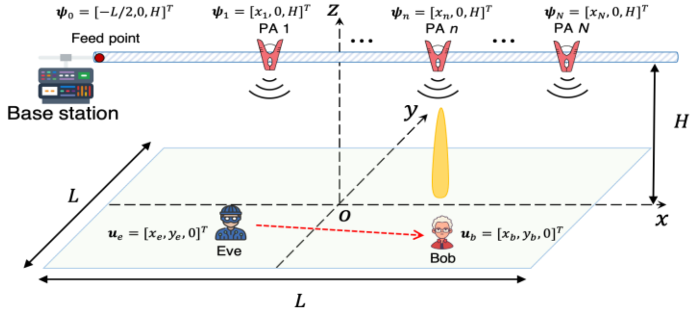
- Case II: PASS with in-waveguide loss; Case I: PASS with no in-waveguide loss
- The in-waveguide propagation loss has negligible impact on the performance of PASS
- PASS yields a larger rate region than conventional fixed-antenna systems

[1] C. Ouyang, Z. Wang, **Y. Liu**, and Z. Ding, "Rate Region of ISAC for Pinching-Antenna Systems," *IEEE Trans. Commun.*, under review. https://arxiv.org/2505.10179

Physical Layer Security for PASS

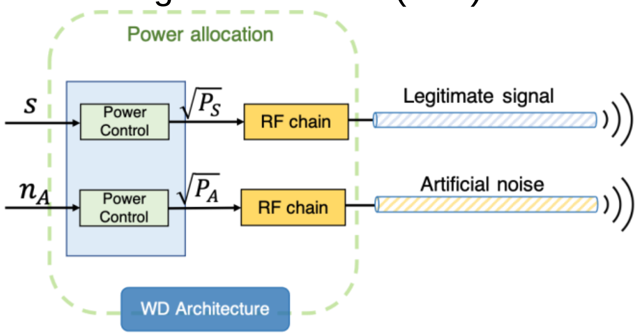
❑ Secure Architecture Design

➢ Single-waveguide PASS Security Enhancement

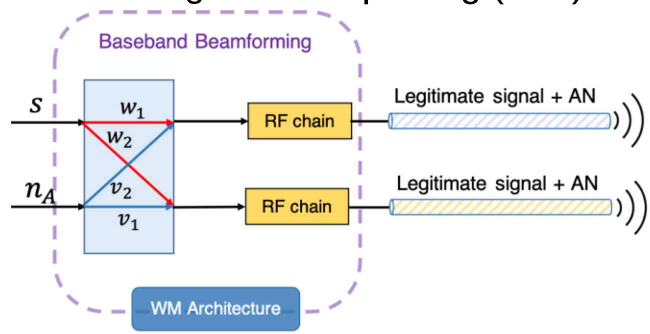


➢ Multiple-waveguide PASS Security Enhancement with *Artificial Noise*

❖ Waveguide Division (WD)



❖ Waveguide Multiplexing (WM)



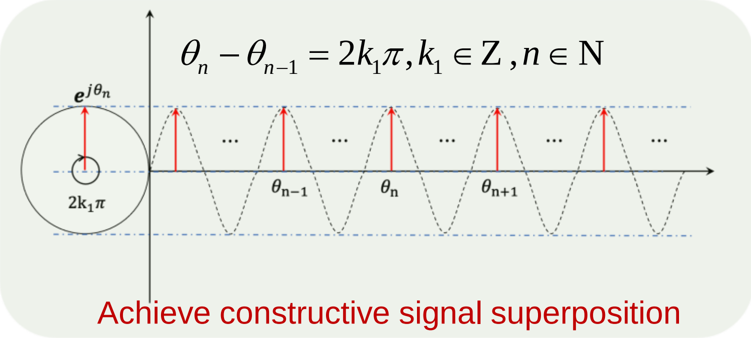
[1] G. Zhu, X. Mu, L. Guo, S. Xu, **Y. Liu**, and N. Al-Dhahir, "Pinching-Antenna Systems (PASS)-enabled Secure Wireless Communications", https://arxiv.org/abs/2504.13670

Physical Layer Security for PASS

❑ Single-waveguide PASS Security Enhancement

➢ **Secrecy Rate Maximization**

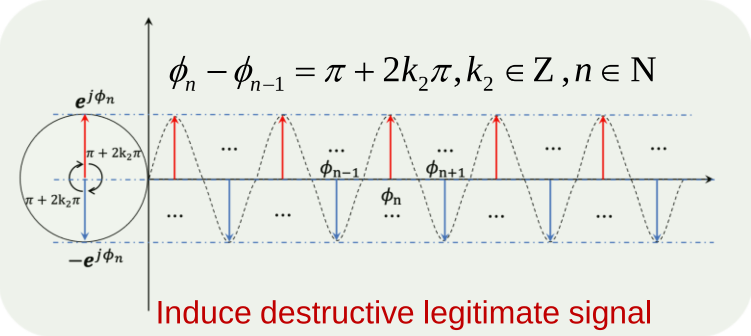
$$\begin{aligned} \max_{\mathbf{x},P} \quad & R_S \\ s.t. \quad & P \le P_{\max}, \\ & -\frac{L}{2} < x_1 < \cdots < x_N < \frac{L}{2}, \\ & x_n - x_{n-1} \ge \Delta, \forall n \in \mathrm{N}. \end{aligned}$$



➢ **Proposed PA-wise Successive Tuning (PAST) Solution**

- **Step-1: Coarse PA Distribution** by minimizing large-scale path loss for the legitimate user

- **Step-2: Successive Fine-Tuning** to constructively combine signals at the legitimate user while inducing destructive legitimate signal at the eavesdropper



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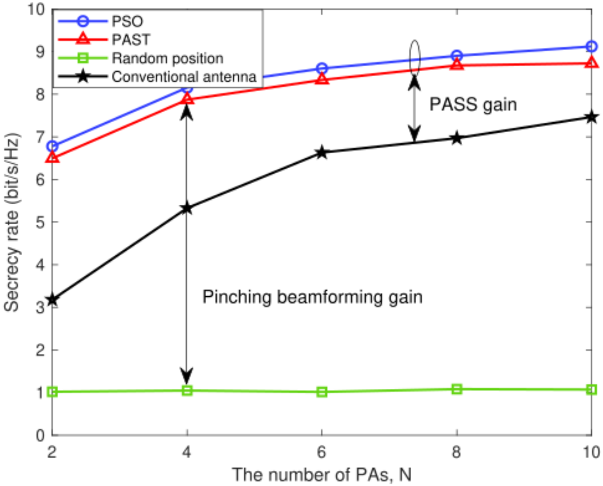
Physical Layer Security for PASS

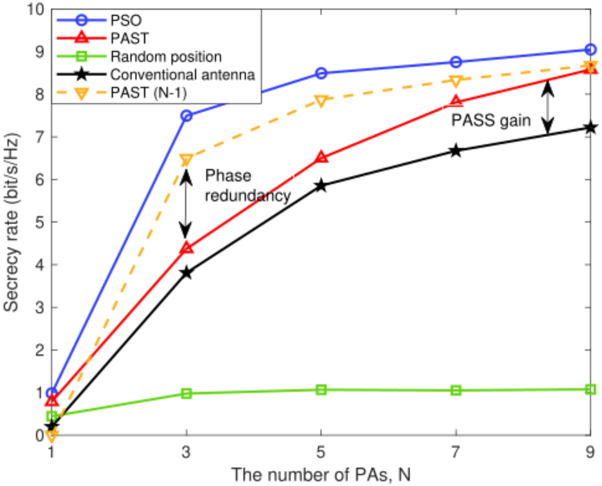
❑ Single-waveguide PASS Security Enhancement

➢ **Numerical Results**

Even case



Odd case



➢ PASS achieve notable secrecy gains over conventional multiple-antenna systems;

➢ Proposed PAST algorithm delivers competitive performance with *low complexity*, particularly when the number of PAs is *even* or *large*.

[1] G. Zhu, X. Mu, L. Guo, S. Xu, **Y. Liu**, and N. Al-Dhahir, "Pinching-Antenna Systems (PASS)-enabled Secure Wireless Communications", https://arxiv.org/abs/2504.13670

Physical Layer Security for PASS

❑ Multiple-waveguide PASS Security Enhancement with Artificial Noise

➢ **Secrecy Rate Maximization**

$$\begin{aligned} \max_{P_A, P_S, \{\mathbf{x}_1, \mathbf{x}_2\}} \quad & R_S^{\mathrm{WD}} \\ s.t. \quad & P_A + P_S \le P_{\max}, \\ & -\frac{L}{2} \le x_{m,n} \le \frac{L}{2}, n \in \mathrm{N}, m \in \{1,2\}, \\ & x_{m,n} - x_{m,n-1} \ge \Delta, n \in \mathrm{N}, m \in \{1,2\}. \end{aligned}$$

$$\begin{aligned} \max_{\mathbf{w}, \mathbf{v}, \{\mathbf{x}_1, \mathbf{x}_2\}} \quad & R_S^{\mathrm{WM}} \\ s.t. \quad & \|\mathbf{w}\| + \|\mathbf{v}\| \le P_{\max}, \\ & -\frac{L}{2} \le x_{m,n} \le \frac{L}{2}, n \in \mathrm{N}, m \in \{1,2\}, \\ & x_{m,n} - x_{m,n-1} \ge \Delta, n \in \mathrm{N}, m \in \{1,2\}. \end{aligned}$$

➢ **Proposed Solutions**

➢ **A Two-Stage Algorithm for WD**

- **Stage-1: Pinching beamforming** is designed with **PAST** algorithm
- **Stage-2: Baseband power allocation** among legitimate signal and AN is solved using SCA

➢ **An AO Algorithm for WM**

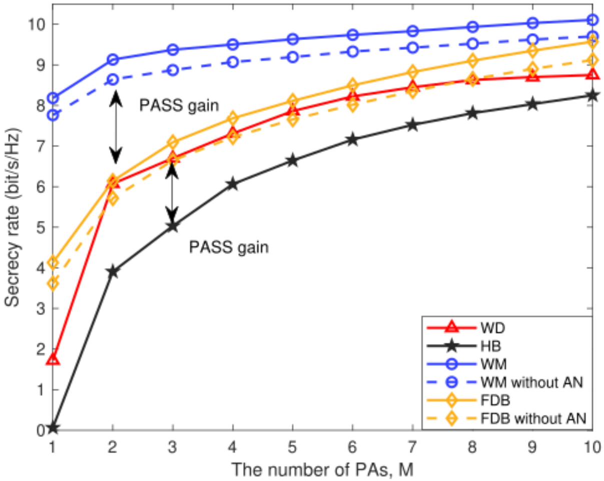
- **Subproblem-1: Pinching beamforming** is designed employing **PSO** method
- **Subproblem-2: Baseband beamforming** is optimized with SCA

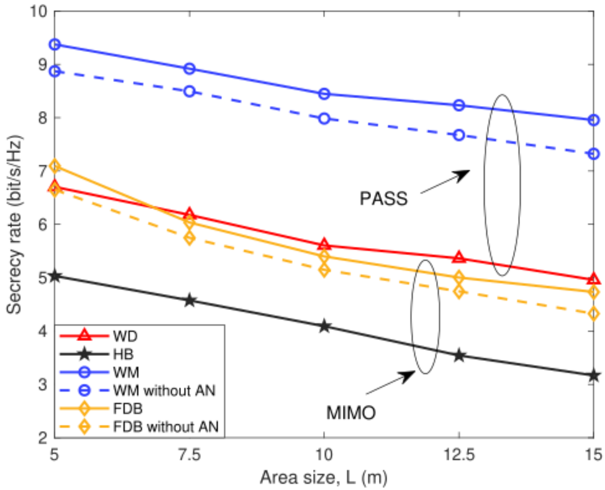
[1] G. Zhu, X. Mu, L. Guo, S. Xu, **Y. Liu**, and N. Al-Dhahir, "Pinching-Antenna Systems (PASS)-enabled Secure Wireless Communications", https://arxiv.org/abs/2504.13670

Physical Layer Security for PASS

❑ Multiple-waveguide PASS Security Enhancement

➢ **Numerical Results**





- ➢ The WM architecture provides the *best* performance at the cost of increased complexity;
- ➢ The WD architecture enables a *low complexity* and scalable option with *competitive* performance achieved.

[1] G. Zhu, X. Mu, L. Guo, S. Xu, **Y. Liu**, and N. Al-Dhahir, “Pinching-Antenna Systems (PASS)-enabled Secure Wireless Communications”, https://arxiv.org/abs/2504.13670

Physical Layer Security for PASS

- **Single-Bob and single-Eve scenario**
  - **BS Configuration**
    A BS with *N* waveguides, only *one* pinching antenna on each waveguide.
  - **Joint transmit and pinching beamforming** to maximize secrecy rate.

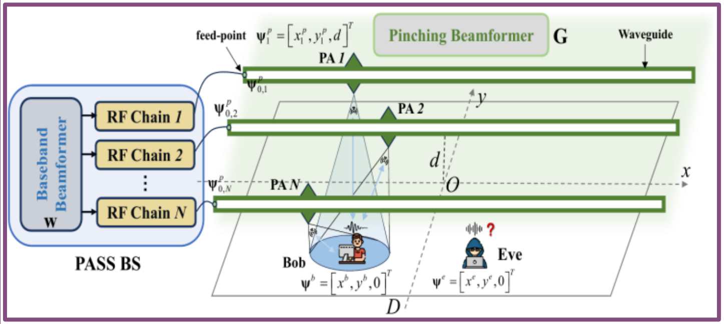
Legitimate channel

$$\max_{\mathbf{w},\mathbf{x}^p}\ \max\left\{\log_2\left(\frac{1+\left|\boxed{\mathbf{h}^{bT}}(\mathbf{x}^p)\mathbf{w}\right|^2/\sigma_b^2}{1+\left|\boxed{\mathbf{h}^{eT}}(\mathbf{x}^p)\mathbf{w}\right|^2/\sigma_e^2}\right),0\right\}$$

Wiretap channel

$$\text{s.t.}\ \ \|\mathbf{w}\|^2\le P_T,$$

antenna positions $\boxed{x_n^p}\in\left[-\frac{D}{2},\frac{D}{2}\right],\forall n=1,\ldots,N.$



- The **optimal** transmit beamformer: **Generalized Rayleigh quotient**
- The pinching beamformer: A **gradient-based** method

[1] M. Sun, C. Ouyang, S. Wu and **Y. Liu**, "Physical Layer Security for Pinching-Antenna Systems (PASS)" *IEEE Trans. Commun.*, under review, 2025. https://arxiv.org/abs/2503.09075

Physical Layer Security for PASS

❑ Multiple-Bob and multiple-Eve scenario

- **System Configuration**

  A BS with N waveguides; M pinching antenna on each waveguide; K Bobs and J Eves coexist.

- **Joint transmit and pinching beamforming** to maximize the weighted secrecy sum-rate (WSSR).

$$\max_{\{\mathbf{w}_k\}_{k=1}^{K},\mathbf{x}^p} \max\left\{\log_2\left(\frac{1+\boxed{\gamma_k}}{1+\boxed{\Gamma_k}}\right),0\right\}$$

$$\text{s.t.} \sum_{k=1}^{K}\|\mathbf{w}_k\|^2 \le P_T,$$

Pinching antennas' positions

$$\boxed{x_{m,n}^p} \in \left[-\frac{D}{2},\frac{D}{2}\right], \forall n=1,\ldots,N,$$

$$|x_{m,n}^p - x_{m',n}^p| > \Delta_{\min}, \forall m \neq m', \forall n.$$

Legitimate channel

$$\gamma_k = \frac{|\boxed{\mathbf{h}_k^{bT}}(\mathbf{x}^p)\mathbf{w}_k|^2}{\sum_{i\neq k}|\mathbf{h}_k^{bT}(\mathbf{x}^p)\mathbf{w}_i|^2+\sigma_{b,k}^2}$$

$$\Gamma_k = \sum_{j=1}^{J}\frac{|\boxed{\mathbf{h}_j^{eT}}(\mathbf{x}^p)\mathbf{w}_k|^2}{\sigma_{e,j}^2}$$

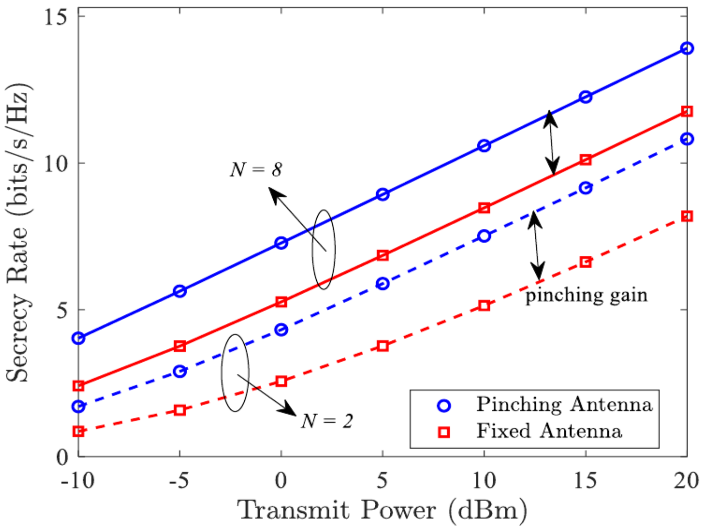
Wiretap channel

- The transmit beamformer: A **fractional programming-based** BCD algorithm.
- The pinching beamformer: A **one-dimensional search** method

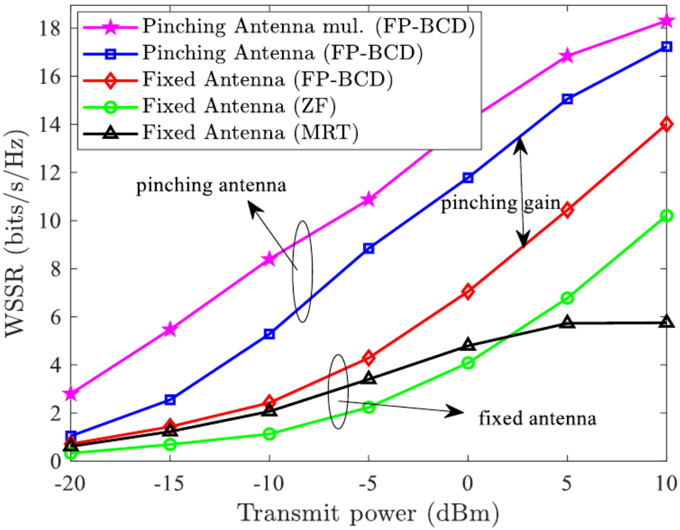
[1] M. Sun, C. Ouyang, S. Wu and **Y. Liu**, "Physical Layer Security for Pinching-Antenna Systems (PASS)" *IEEE Trans. Commun.*, under review, 2025. https://arxiv.org/abs/2503.09075

Physical Layer Security for PASS

❑ Simulation Results



single-Bob single-Eve



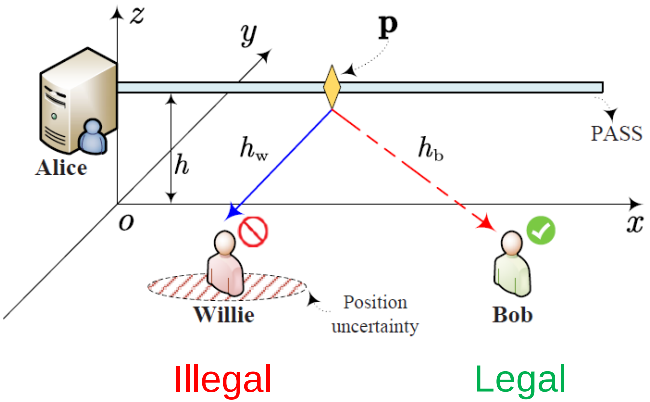
multiple-Bob multiple-Eve

- Simulation results show that PASS consistently achieves significantly higher system WSSR compared to the conventional fixed-antenna system under various configurations, highlighting its performance advantages.

PASS Enhanced Covert Communications

❑ Using A Single Pinching Antenna on A Single Waveguide (SWSP):

- **Motivation:** Hiding the legitimate transmission from a watchful warden



a) An illustration of the SWSP PASS scenario.

OBJ: Maximize Transmission Rate at Bob

$$\max_{x,P} \quad \log_2\left(1+\gamma_b(x,P)\right)$$
$$\text{s.t.} \quad 0 \le x \le L,$$
$$0 \le P \le P_{\max},$$
$$\xi \ge 1-\rho_w, \quad \forall \xi \in \mathcal{E},$$

Covertness Constraint at Willie

[1] H. Jiang, Z. Wang and **Y. Liu**, "Pinching-Antenna System (PASS) Enhanced Covert Communications," *submitted to IEEE Journals*, under review, 2025 https://arxiv.org/abs/2504.10442

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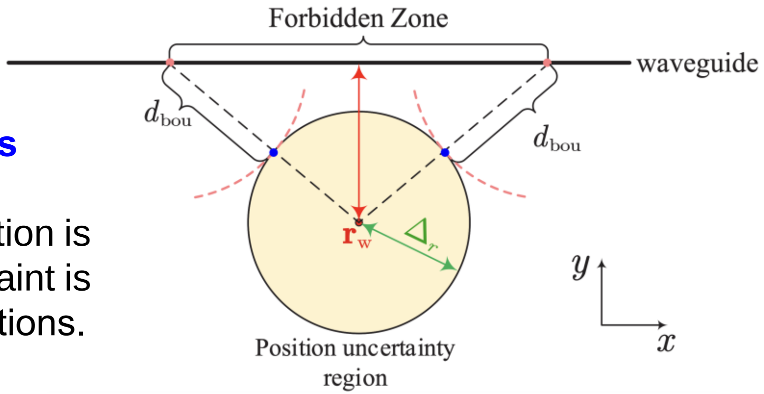
PASS Enhanced Covert Communications

❑ Remarks:

- To deal with the **uncertainty of Willie's position**, we propose the concept of **forbidden zones.** When antenna position is within this zone, the covertness constraint is violated by some possible Willie's positions.



- Based on the definition of forbidden zones and feasible positions on waveguide, **the closed-form optimal antenna position is derived** .

$$x^{\mathrm{opt}} = \begin{cases} \emptyset, & \text{if } \mathcal{S} \subseteq \mathcal{D}, \\ x_{\mathrm{b}}, & \text{if } \mathcal{S} \nsubseteq \mathcal{D} \text{ and } x_{\mathrm{b}} \in \mathcal{F}, \\ \arg\min\limits_{x \in \mathcal{A}} |x - x_{\mathrm{b}}|, & \text{if } \mathcal{S} \nsubseteq \mathcal{D} \text{ and } x_{\mathrm{b}} \notin \mathcal{F}. \end{cases}$$

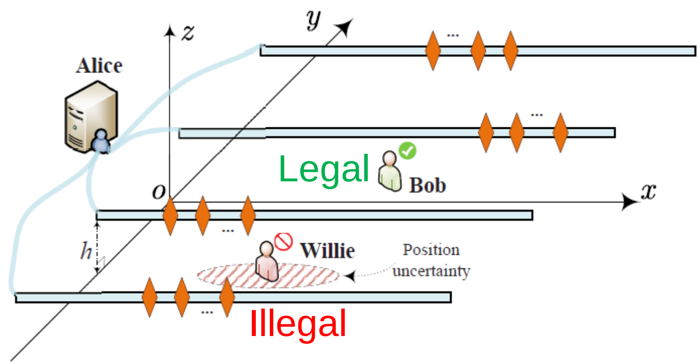
- Finally, a low-complexity **1D linear search algorithm** is proposed for **transmit power optimization**.

[1] H. Jiang, Z. Wang and **Y. Liu**, "Pinching-Antenna System (PASS) Enhanced Covert Communications," *submitted to IEEE Journals*, under review, 2025 https://arxiv.org/abs/2504.10442

PASS Enhanced Covert Communications

❑ Using Multiple Pinching Antennas on Multiple Waveguides (MWMP):

➢ **Motivation:** The flexibility of the SWSP case is limited due to lower coverage area.



b) An illustration of the MWMP PASS scenario.

OBJ: Maximize Transmission Rate at Bob

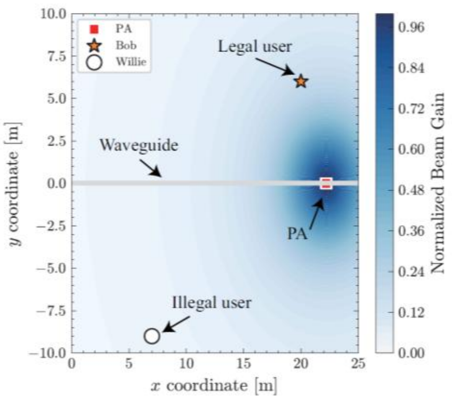
$$
\begin{aligned}
\max_{\mathbf{X},\mathbf{w}} \quad & \log_2\left(1+\gamma_{\mathrm{b}}\left(\mathbf{X},\mathbf{w}\right)\right) \\
\text{s.t.} \quad & 0 \le x_{n,m} \le L, \forall m \in \mathcal{M}, n \in \mathcal{N} \\
& \Delta_{n,m} \triangleq x_{n,m} - x_{n,m-1} \ge \Delta_{\min}, \forall m \in \mathcal{M}, \\
& \|\mathbf{w}\|^2 \le P_{\max}, \\
& \xi \ge 1 - \rho_{\mathrm{w}}, \quad \forall \xi \in \mathcal{E}
\end{aligned}
$$

Covertness Constraint at Willie

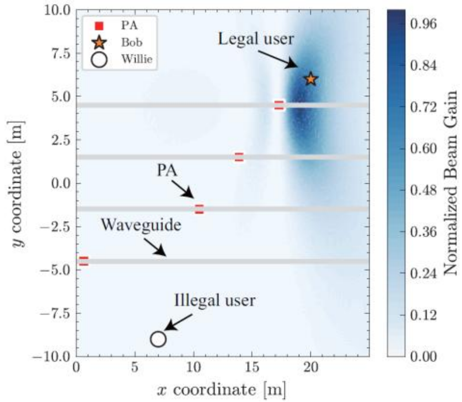
➢ **Solution:** Due to the complexity for deriving the optimal solution, we present a TwinPSO method to solve this problem with a moderate computational complexity.

PASS Enhanced Covert Communications

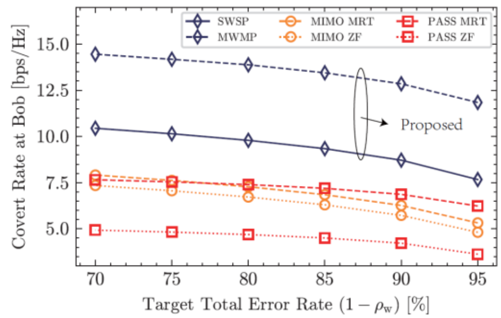
❑ Simulation Results:



(a) SWSP Case



(b) MWMP Case



- The high beam gain region is closer to the legitimate user (Bob).
- The MWMP setup can achieve **higher beam gain via enhanced flexibility**.
- The **PASS outperforms the conventional fixed-position benchmarks**, i.e., “MIMO MRT” and “MIMO ZF”.
- As **covertness constraint becomes more stringent**, the **covert rate decreases** correspondingly.

[1] H. Jiang, Z. Wang and **Y. Liu**, “Pinching-Antenna System (PASS) Enhanced Covert Communications,” *submitted to IEEE Journals*, under review, 2025 https://arxiv.org/abs/2504.10442

Outline

- ❑ **PASS Basis**
  - ❑ Overview of PASS: Start with a Protype (What)
  - ❑ Advantages of PASS: From Wireless to Near-Wired (Why)
  - ❑ Physics Principle and Signal Modelling (How)
  - ❑ Activation Methods and Transmission Structures (How)
- ❑ **Case Studies**
  - ❑ Case I: Performance Analysis for PASS
  - ❑ Case II: Beamforming Design for PASS
  - ❑ Case III: Multiple Access Design for PASS
  - ❑ Case IV: Beam Training and Channel Estimation for PASS
  - ❑ Case V: Physical Layer Security for PASS
- ❑ **Research Challenges and Opportunities**

Research Challenges and Opportunities

- Hardware implementation for PASS
- Channel measurement for PASS Modelling
- Uplink receiving design for PASS
- Beamforming design under practical/complicated constraints
- Flexible pinching power allocation for PASS
- Multiple access/NOMA design for PASS design
- Tri-hybrid MIMO-PASS design
- PASS for non-terrestrial and satellite communications
- Spatial analysis of PASS using stochastic geometry
- Channel estimation for PASS
- Machine learning/edge intelligence for PASS
- PASS enabled ISAC
- PASS enabled THz communications
- PASS enabled near-field sensing/localization
- Sparse/Distributed antenna design for PASS

Thanks for your attention ;-)
Q & A

Download the slides at:
https://www.eee.hku.hk/~yuanwei/research.html

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