

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



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Outline

❑ PASS Basis

- ❑ Overview of PASS: Start with a Prototype (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: Applications for PASS

❑ Research Challenges and Opportunities



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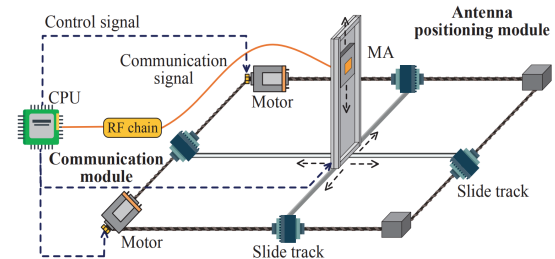
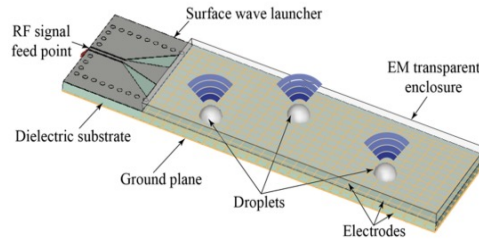
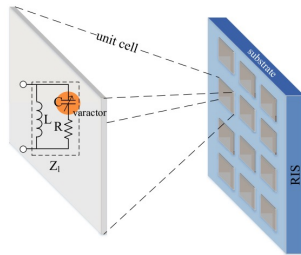
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The road to Flexible-Antenna Systems towards 6G

Existing Flexible-Antenna Systems

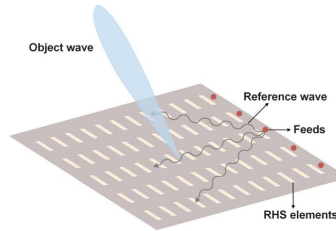
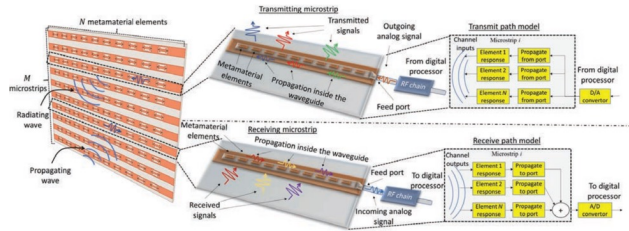
- Enabling **active reconfiguration** of channel parameters to boost the performance
- Adjusting their **positions**, **apertures**, and **electromagnetic properties**



RIS/STAR

Fluid Antenna

Movable Antenna



Dynamic Metasurface Antenna

Reconfigurable Holographic Surface

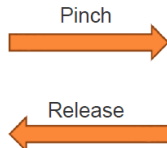
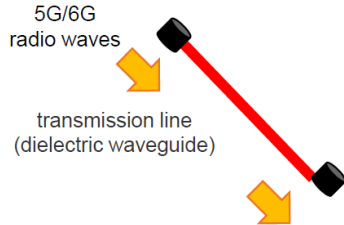
Continuous-Aperture Array

- [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.*, accepted to appear, 2025. <https://arxiv.org/abs/2501.18409>
- [2] Y. Liu et al., "Pinching-Antenna Systems (PASS): A Tutorial (Invited Paper)," *IEEE Trans. Commun.*, under review, 2025. <https://arxiv.org/abs/2508.07572>

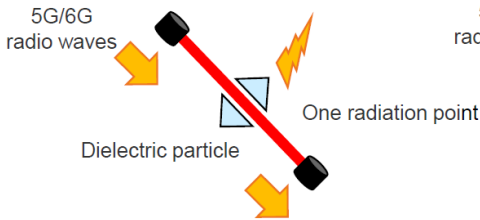
What is PASS: Start with a Prototype

❑ Pinching-Antenna System (PASS)

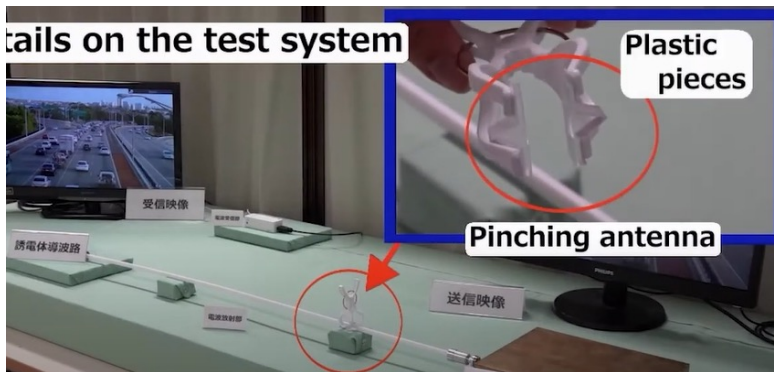
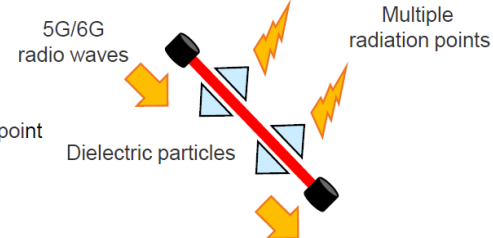
Waveguide with no pinch



Waveguide with one pinch



Waveguide with two pinches

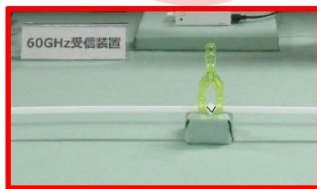
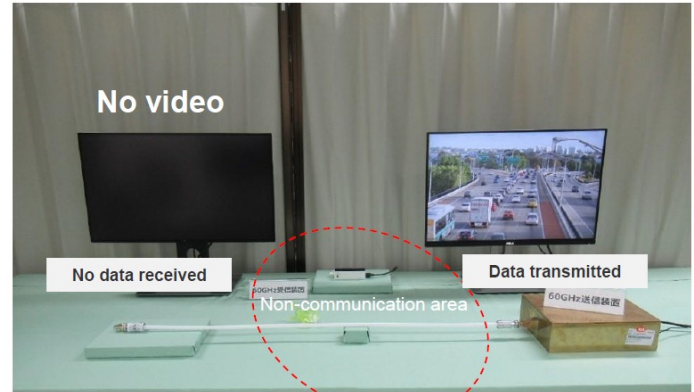
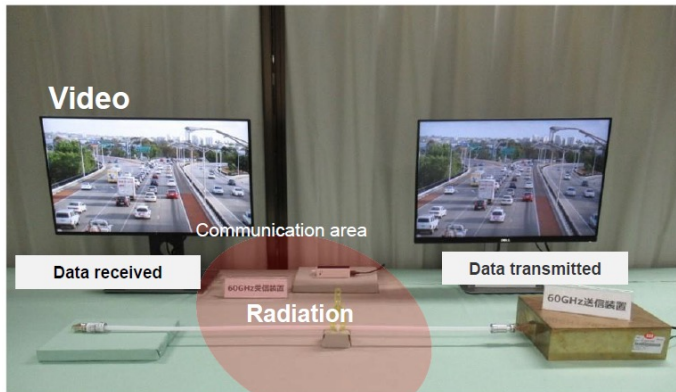


- The first **prototype** of PASS was developed and tested by NTT DOCOMO in 2021
- A pinching antenna is the dielectric waveguide that works as a leaky-wave antenna by attaching other small dielectric particles on it
- Radio waves are **transmitted/received** via (pinched) dielectric particles on a dielectric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

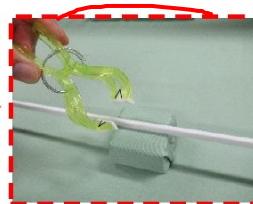
- [1] https://www.docomo.ne.jp/english/info/media_center/event/mwc21/pdf/06_MWC2021_docomo_Pinching_Antenna_en.pdf#page=1.00
- [2] A. Fukuda, H. Yamamoto, H. Okazaki, Y. Suzuki, and K. Kawai, "Pinching antenna - using a dielectric waveguide as an antenna," NTT DOCOMO J., vol. 23, no. 3, pp. 5–12, Jan.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

What is PASS: Start with a Prototype

❑ NTT DOCOMO's Test using 60GHz Band



Pinching antenna



**Antenna
attached/released**



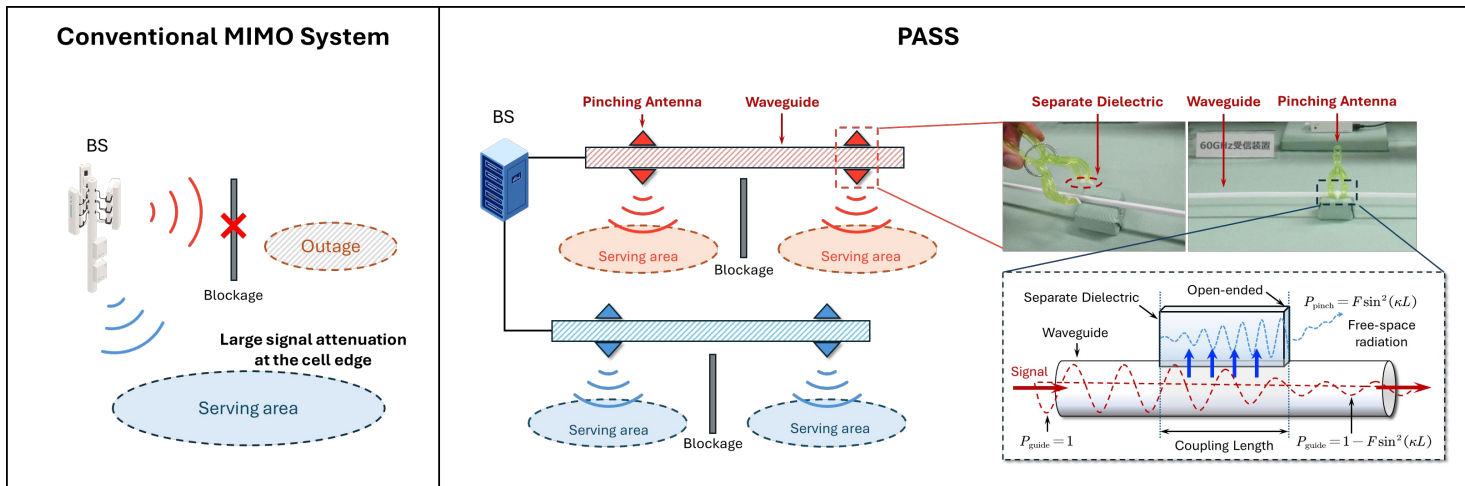
No pinching antenna

- [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)
- **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.*, accepted to appear, 2025. <https://arxiv.org/abs/2501.18409>
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❑ Research Challenges and Opportunities



Physics Principle: Dielectric Waveguide

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

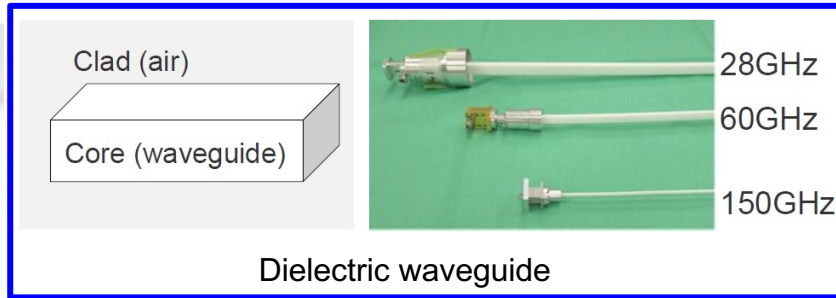
- No core conductor, unlike coaxial cable
- Not covered with metal, unlike basic waveguide
- Consists of core (waveguide) and clad (air or other dielectric), same as optical fiber
- Capable of transmitting millimeter waves (28 GHz band and above)



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

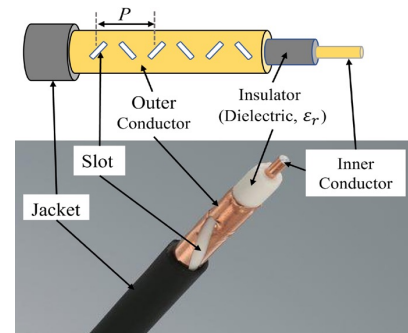
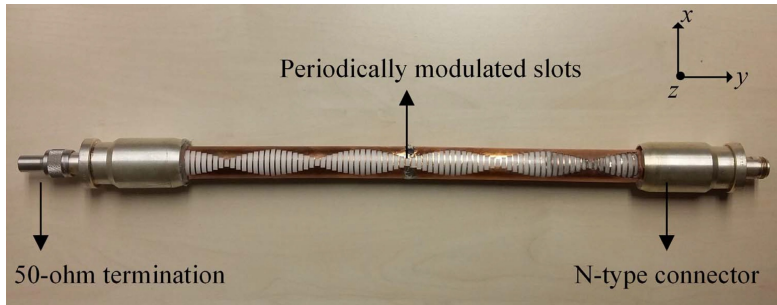
[2] A. Fukuda, H. Yamamoto, H. Okazaki, Y. Suzuki, and K. Kawai, "Pinching antenna - using a dielectric waveguide as an antenna," *NTT DOCOMO J.*, vol. 23, no. 3, pp. 5–12, Jan. 2022.

[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



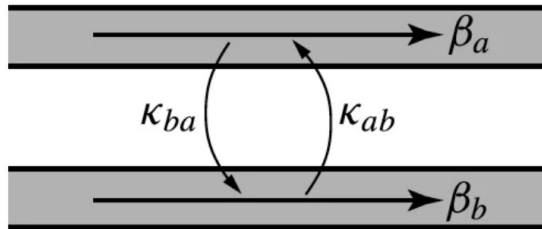
[1] Z. Siddiqui, M. Sonkki, M. Tuhkala, and S. Myllymäki, “Periodically slotted coupled mode leaky coaxial cable with enhanced radiation performance,” *IEEE Trans. Antennas Propag.*, vol. 68, no. 11, pp. 7595– 7600, Nov. 2020.

[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.

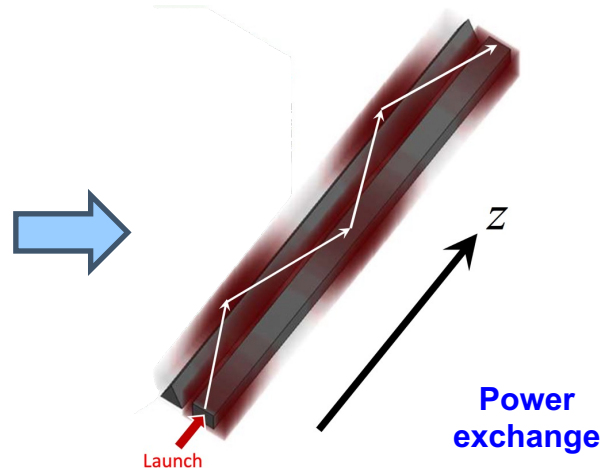
What is different? Electromagnetic Coupling

❑ 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.



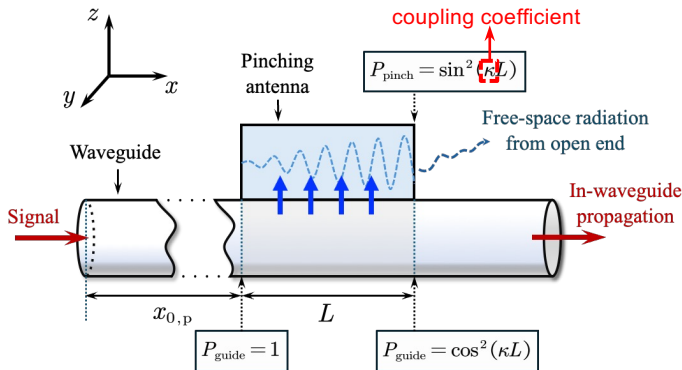
Coupling between two waveguides/transmission lines



- [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.*, accepted to appear, 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.*, minor 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

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

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

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.*, accepted to appear, 2025. <https://arxiv.org/abs/2501.18409>

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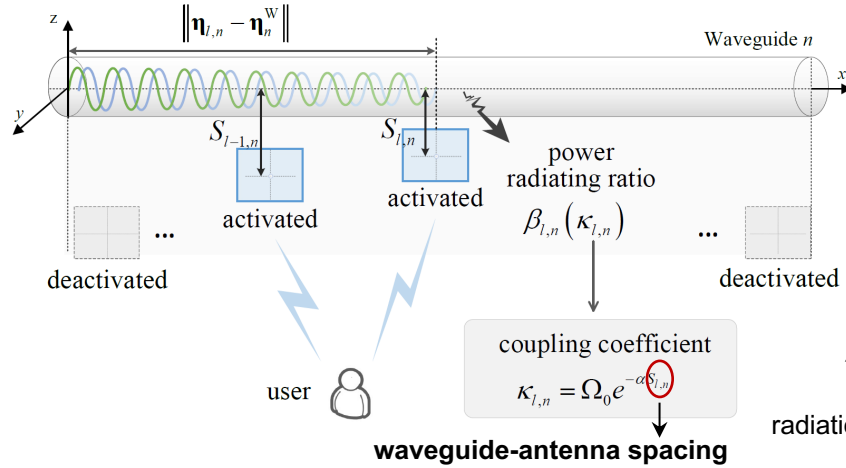


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Adjustable Power Radiation Model for PASS



- **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

$$\beta_{l,n} = a_{l,n} \sin(\underbrace{\kappa_{l,n}}_{\text{coupling coefficient}} L^{\text{PA}}) \prod_{i=1}^{l-1} \sqrt{1 - \underbrace{a_{i,n}}_{\text{activation state}} \sin^2(\kappa_{i,n} L^{\text{PA}})}$$

coupling length

radiation ratio coupling coefficient activation state

➤ Element-wise power radiation control

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

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

➤ Special case: equal-power radiation

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

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

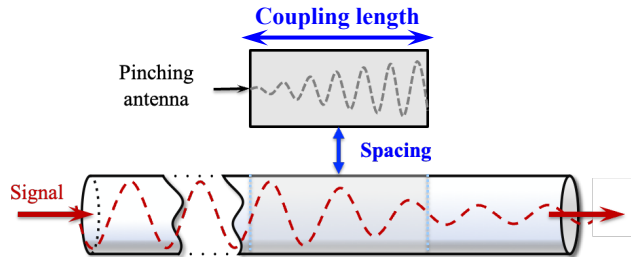
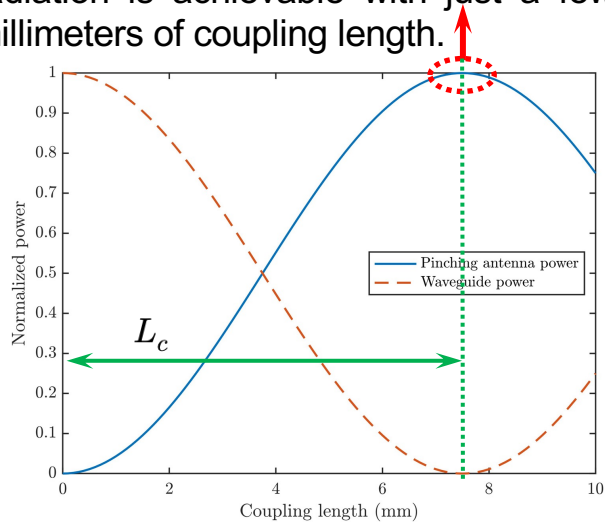
number of activated antennas

[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>

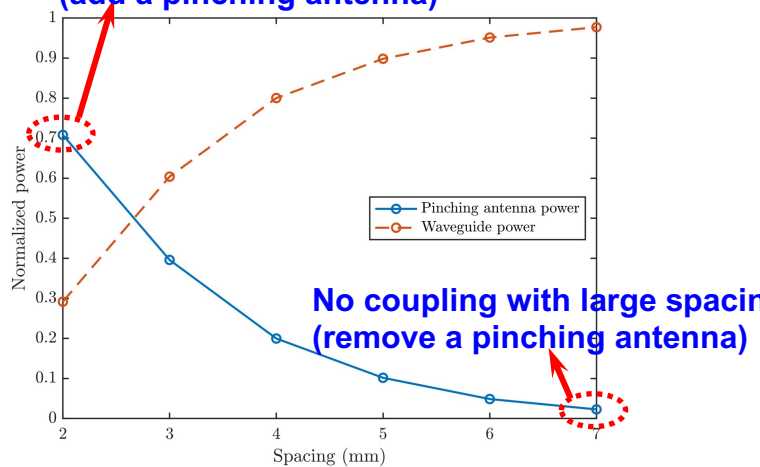
❑ Some exemplified results

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)



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

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

Free-space propagation

In-waveguide propagation

User

PASS BS

❑ 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

$$P_1 = P_2 = \dots = P_N$$

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.*, minor 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



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



❑ BS-centric activation

BS controls the activation and positions of antennas

Pros: High performance, less security issue

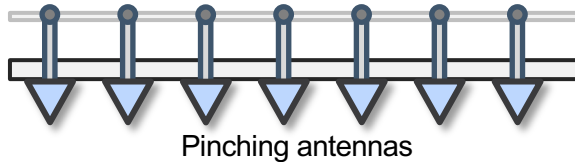
Cons: High complexity for coordination

[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.*, accepted to appear, 2025.

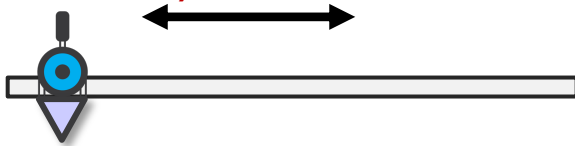
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Activation Schemes

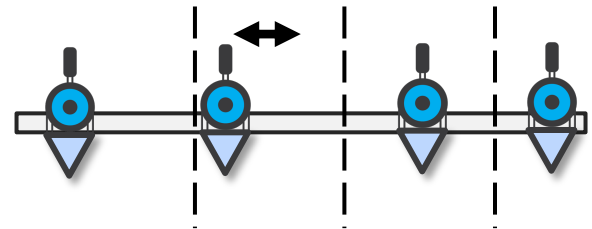
❑ Discrete Activation (Piano Keyboard)



❑ 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	

[1] Y. Liu et al., "Pinching-Antenna Systems (PASS): A Tutorial (*Invited Paper*)," *IEEE Trans. Commun.*, under review, 2025.

<https://arxiv.org/abs/2508.07572>



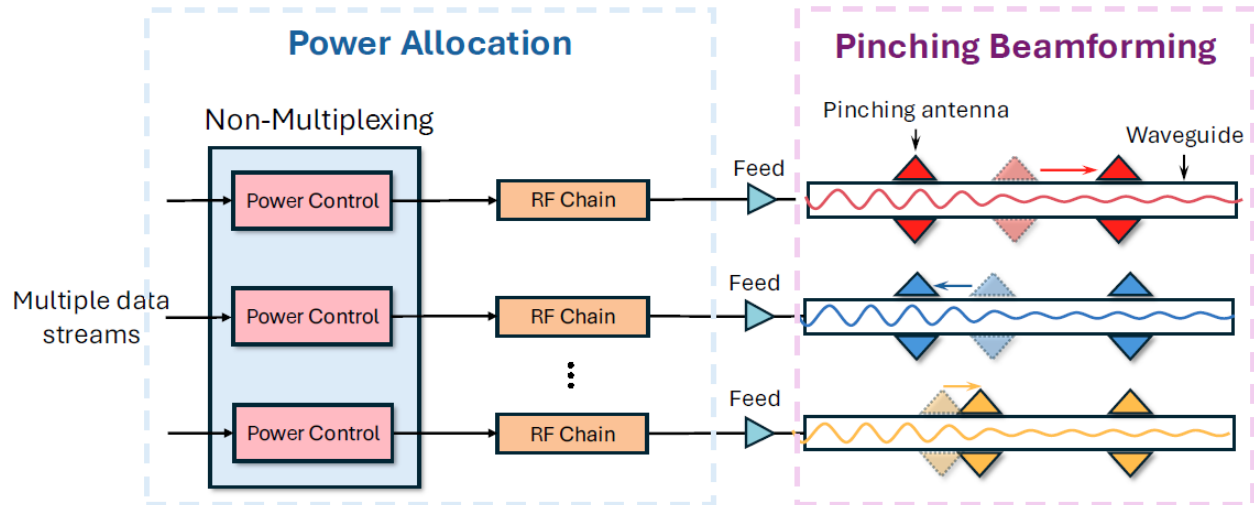
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Transmission Architectures

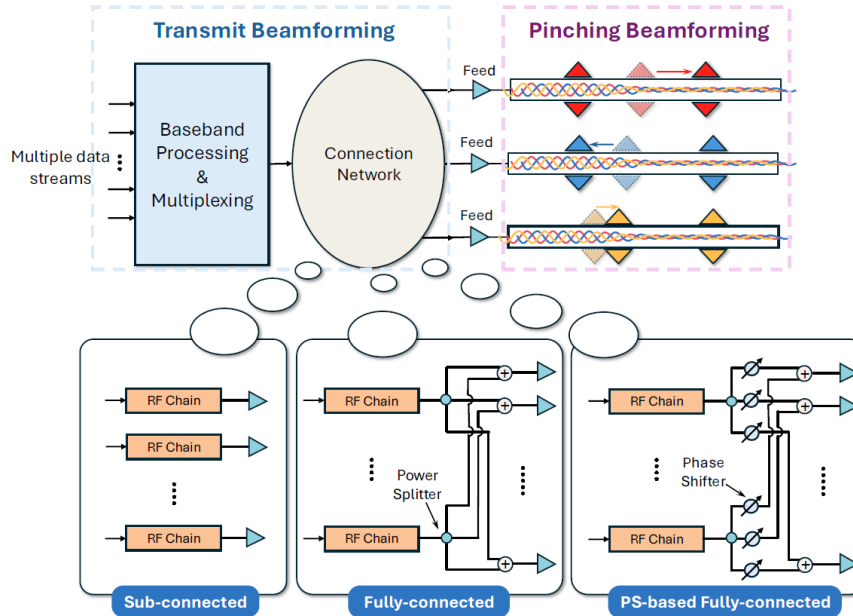
❑ Non-Multiplexing Architecture --- Waveguide Division (WD)



- 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)

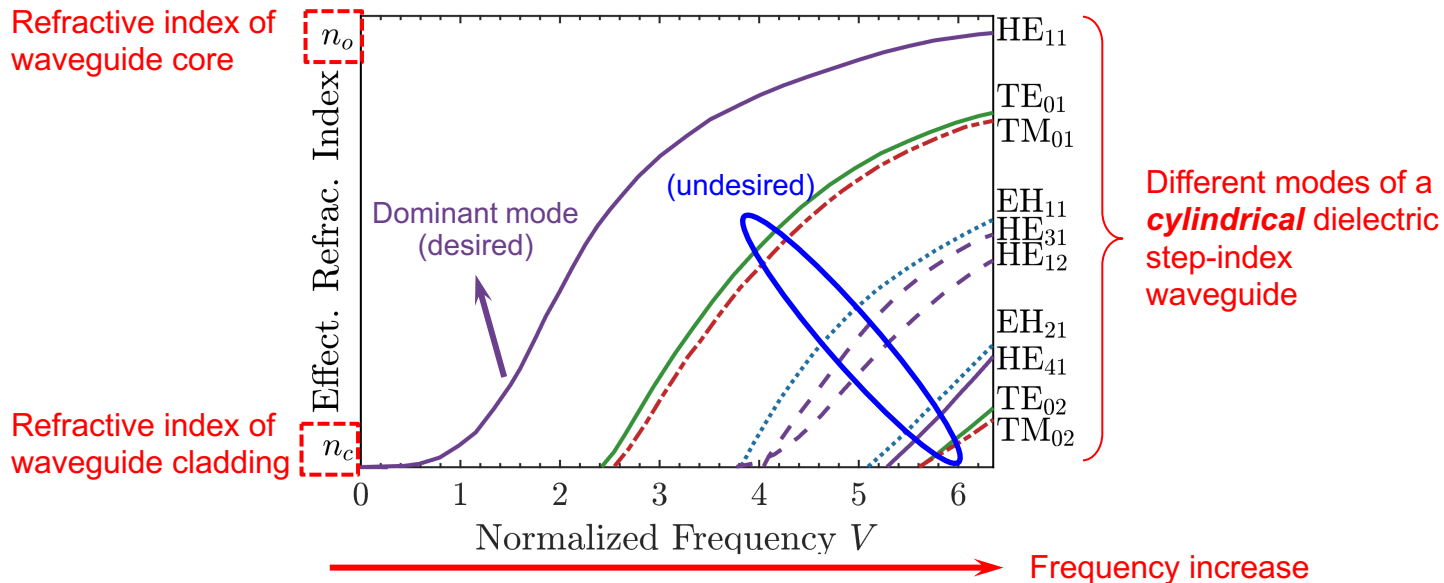


- **Sub-connected:** each waveguide is connected to a dedicated RF chain
- **Fully-connected:** each RF chain are fed into all waveguides with the aid of power splitters
- **Phase shifter-based fully-connected:** tri-hybrid beamforming

Wideband Transmission

❑ Available bandwidth – Upper limit

- Waveguide can only support **discrete electromagnetic modes**.
- Practical design often favor **single-mode operation** to simplify signal transmission and detection.



[1] Y. Liu et al., "Pinching-Antenna Systems (PASS): A Tutorial (Invited Paper)," *IEEE Trans. Commun.*, under review, 2025.

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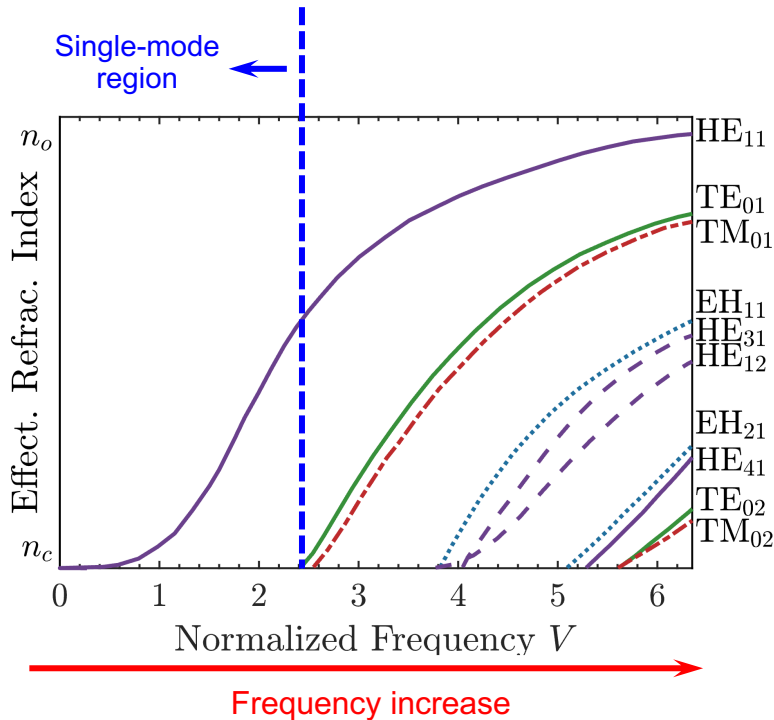
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Wideband Transmission

❑ Available bandwidth – Upper limit



Single-mode condition for cylindrical waveguide

$$f \leq \frac{0.3828c}{r_o \sqrt{n_o - n_c}}$$

Speed of light

Waveguide radius

Example: $r_o = 2 \text{ mm}$, $n_o = 1.4$, $n_c = 1$



$$f \leq 58 \text{ GHz}$$

Upper-bound frequency such that PASS can work effectively

[1] Y. Liu et al., "Pinching-Antenna Systems (PASS): A Tutorial (Invited Paper)," *IEEE Trans. Commun.*, under review, 2025.

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Wideband Transmission

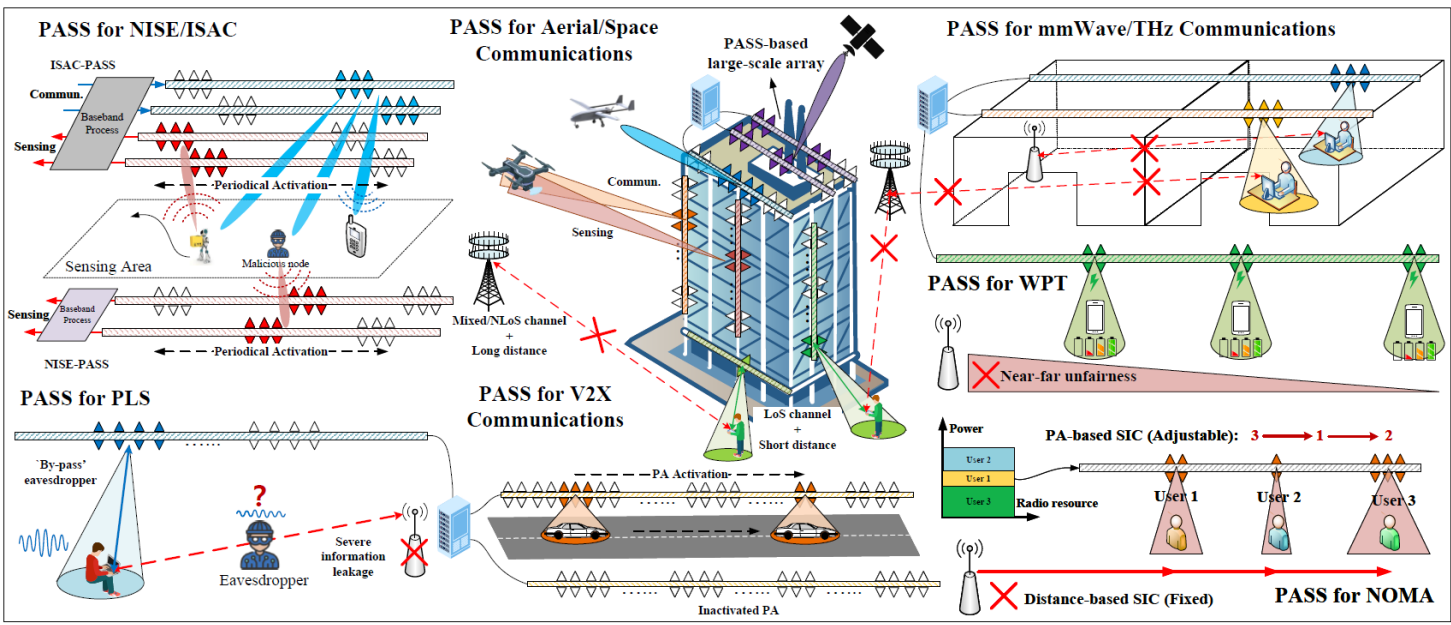
❑ Available bandwidth

- **Upper Limit:** ensure only a **single mode** to be transmitted in waveguides.
- **Lower Limit:** affected by several factors such as material losses, antenna coupling efficiency, feed structure limitations, and cut-off frequency of the dominant mode.

[1] Y. Liu et al., “Pinching-Antenna Systems (PASS): A Tutorial (*Invited Paper*),” *IEEE Trans. Commun.*, under review, 2025.
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'PASS' Signals for 6G and Beyond



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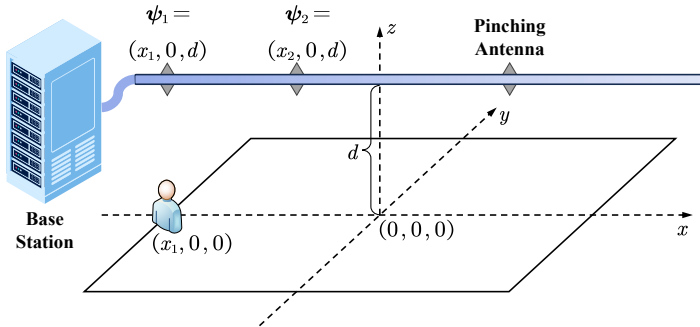
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Performance Analysis for PASS: Downlink

❑ PASS: single waveguide with multiple pinching antennas



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

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

Pinching beamforming

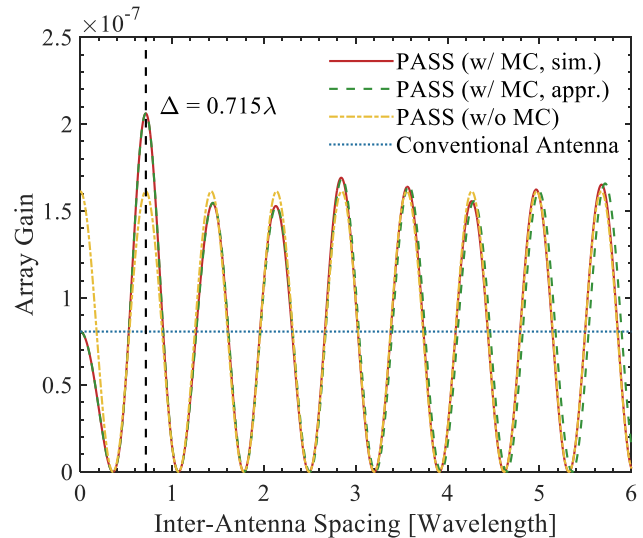
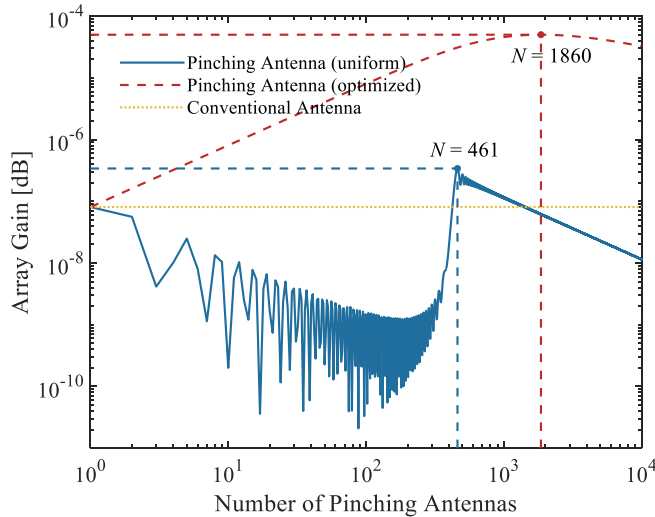
Near-field model

- 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>



Performance Analysis for PASS: Downlink



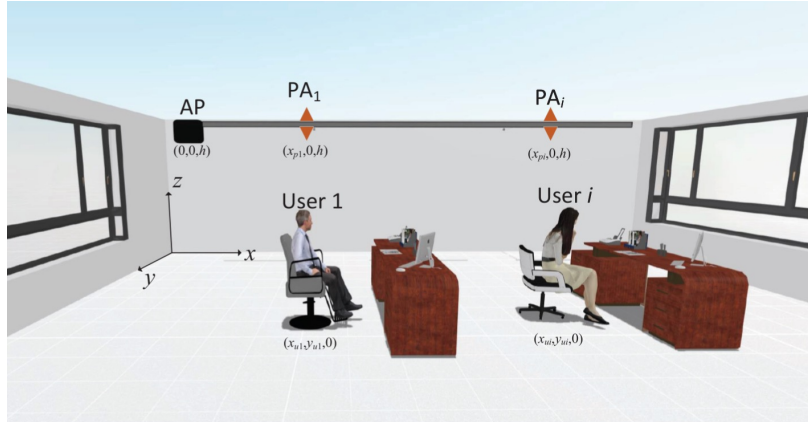
- A1: The array gain does not increase monotonically with the number of antennas
- A1: PASS requires an optimal antenna number to maximize the array gain
- A2: The array gain does not increase monotonically as the inter-antenna spacing decreases

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>

Performance Analysis for PASS: Uplink

❑ 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

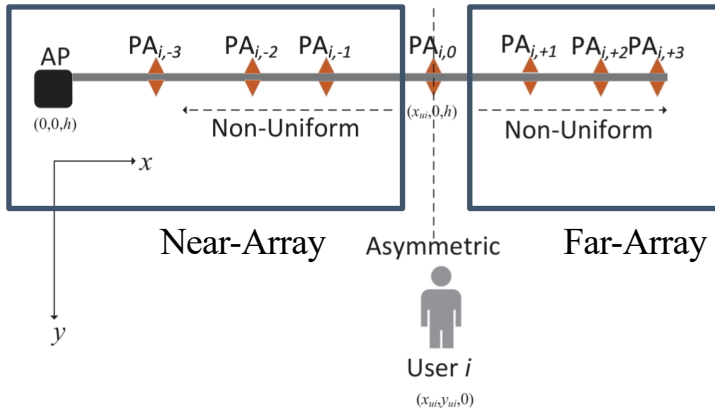
$$x_n = \frac{n\lambda(2d_0 + n\lambda)}{2(d_0 + n\lambda)}, n = -N, \dots, 0, \dots, N,$$

[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: Uplink

❑ MPSU: Multiple pinching antennas for a single user



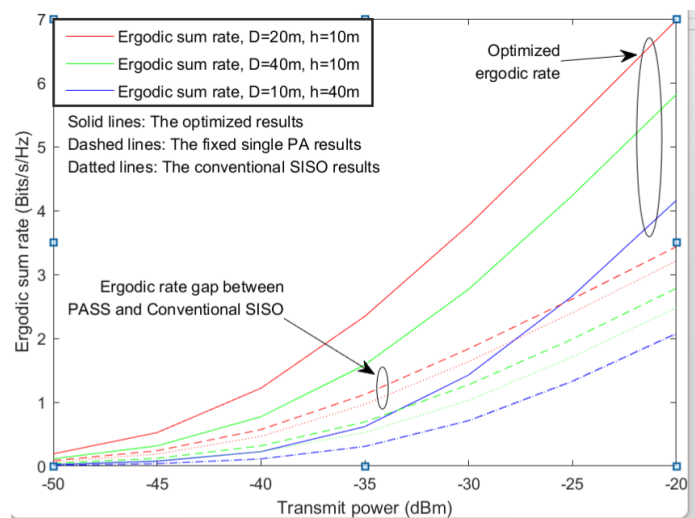
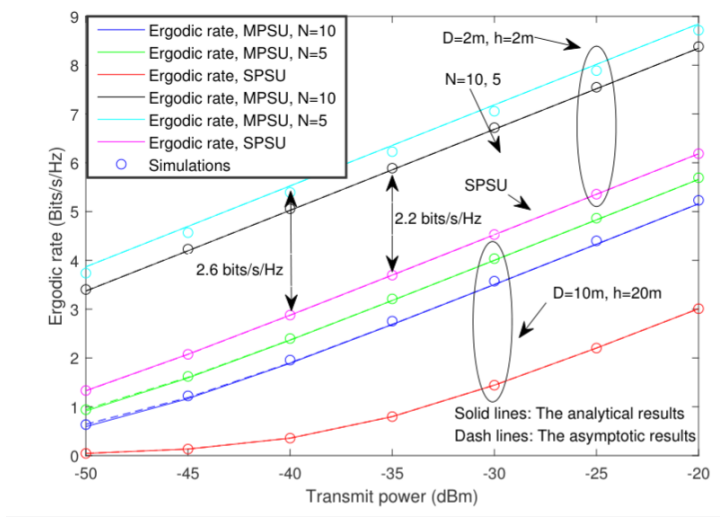
- Far-zone (larger than 10 wavelength)
 - The optimized location approximate a **symmetric uniform distribution**

- 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: Uplink



- 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 Prototype (What)
- ❑ Advantages of PASS: From Wireless to Near-Wired (Why)
- ❑ Physics Principle and Signal Modelling (How)
- ❑ Activation Methods and Transmission Structures (How)

❑ Case Studies

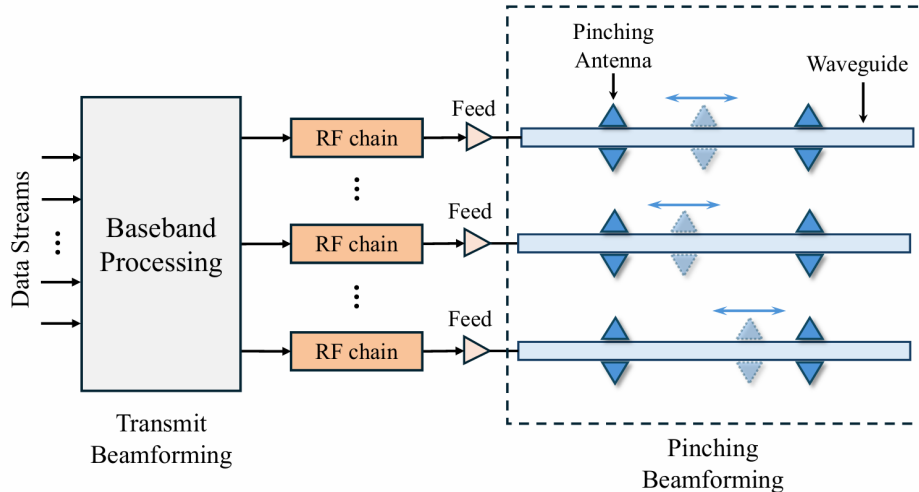
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- ❑ Case III: Multiple Access Design for PASS
- ❑ Case IV: Beam Training and Channel Estimation for PASS
- ❑ Case V: Applications for PASS

❑ Research Challenges and Opportunities



Beamforming Design for PASS

❑ Joint transmit and pinching beamforming design

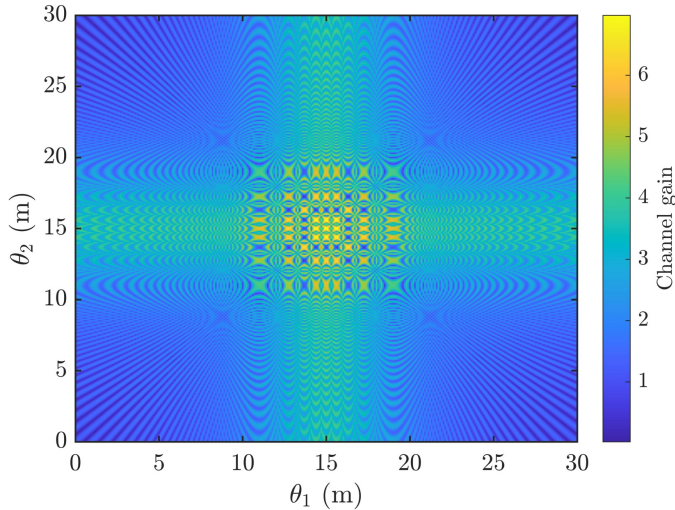


- Sub-connected multiplexing architecture
- Power model: equal power model and proportional power model
- Activation model: continuous and discrete

[1] Z. Wang, C. Ouyang, X. Mu, Y. Liu, and Z. Ding, "Modeling and Beamforming Optimization for Pinching-Antenna Systems," *IEEE Trans. Commun.*, minor 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

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

- **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.*, minor revision, 2025. <https://arxiv.org/abs/2502.05917>



Beamforming Design for PASS

❑ Joint transmit and pinching beamforming design

$$\min_{\mathbf{W}, \mathbf{X}} \sum_{k=1}^K \|\mathbf{w}_k\|^2 \quad \text{Transmit power minimization}$$

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

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

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

➤ Proposed solution 1: Penalty-based algorithm

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

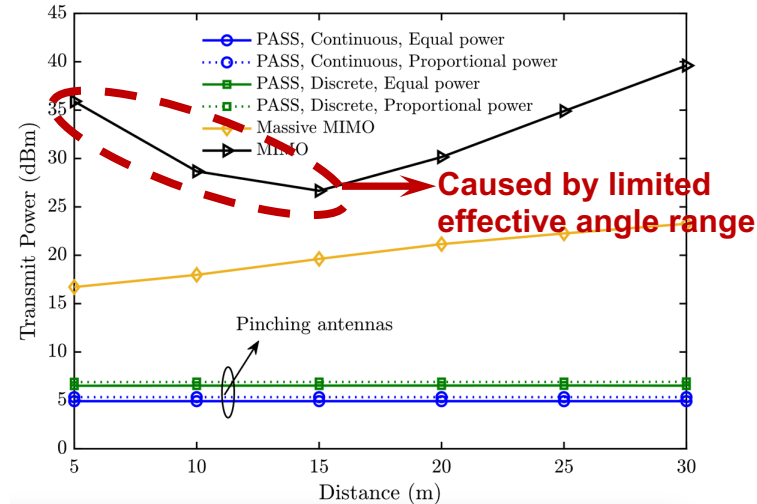
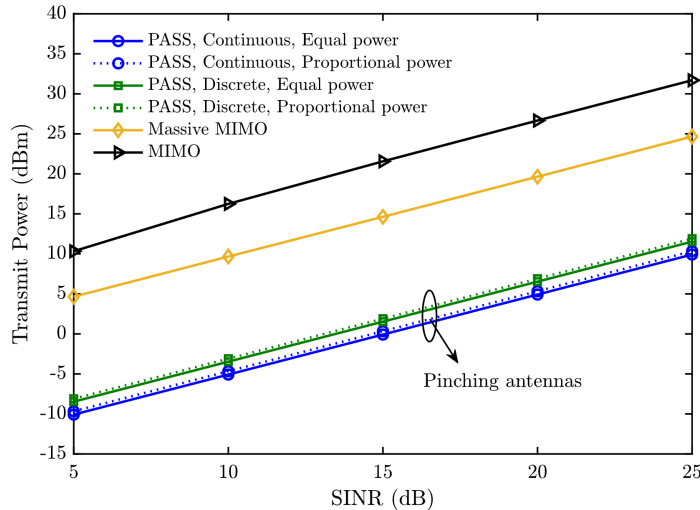
➤ Proposed solution 2: Zero-forcing-based algorithm

- Using **zero-forcing beamformer** to simplified the optimization problem
- 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.*, minor revision, 2025. <https://arxiv.org/abs/2502.05917>



Beamforming Design for PASS



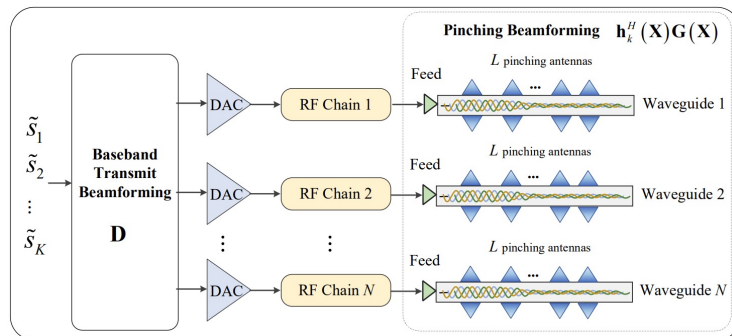
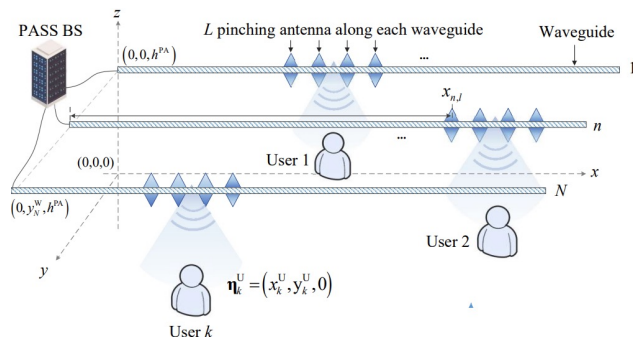
- The performance loss caused by the proportional power model is negligible compared to the equal power model.
- The performance of PASS is irrelevant to the distance between transceivers due to the high flexibility of pinching antennas

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



Beamforming Design for PASS – LLM Method

❑ Pinching Beamforming: Optimization-Based or Learning-Based



➤ Sum rate maximization

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

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

$$0 \leq x_{n,l} \leq S_x, \quad \forall n, l$$

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

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



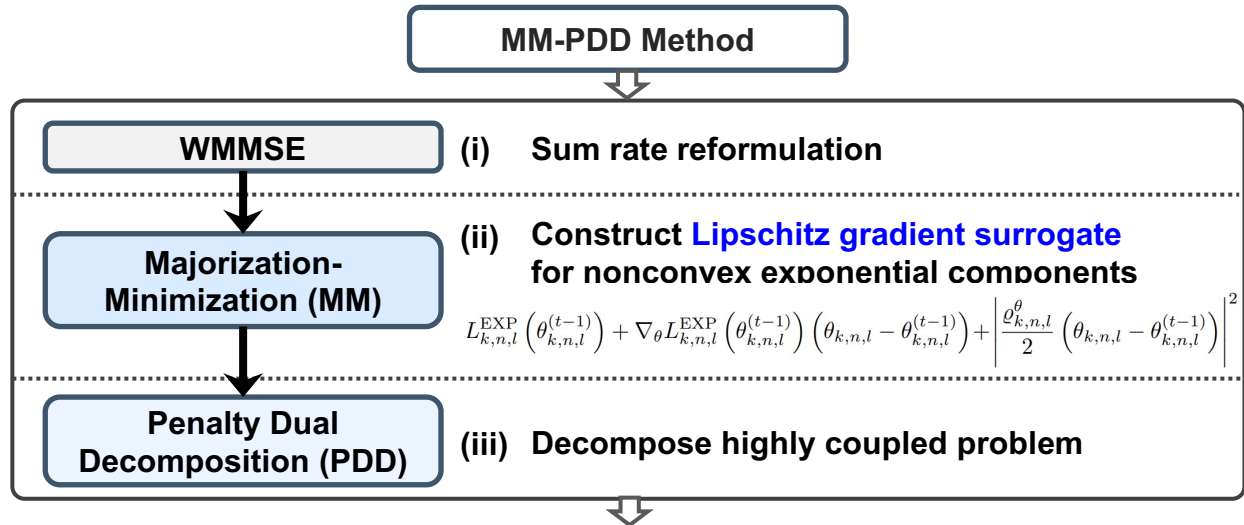
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THE UNIVERSITY OF HONG KONG



Beamforming Design for PASS – LLM Method

❑ Optimization-Based: An MM-PDD Method



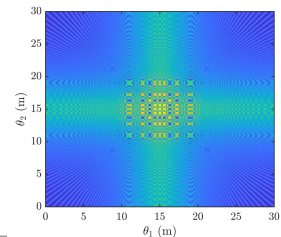
Obtain KKT solutions (Stationary solutions)

➤ Advantage

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

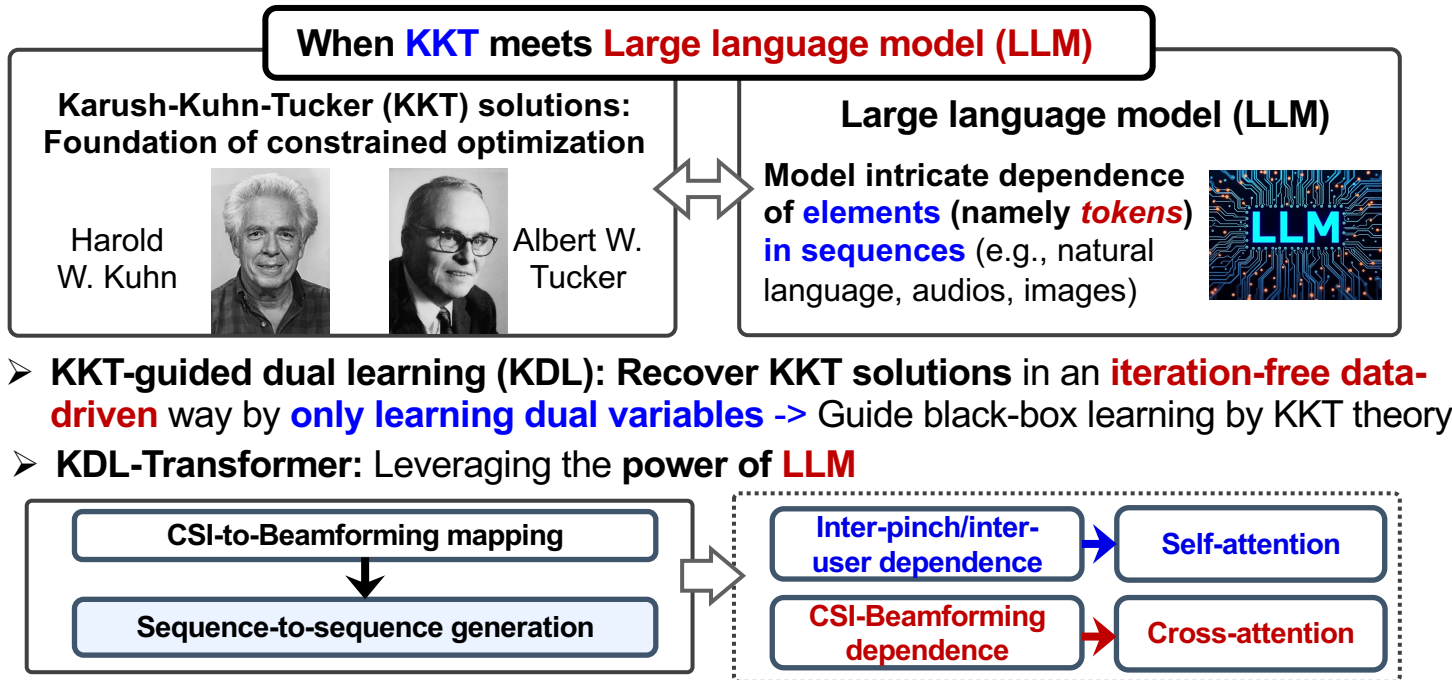
➤ Limitations

- (i) High complexity for a large amount of iterations
- (ii) Nonconvex problem may have **numerous suboptimal solutions**



Beamforming Design for PASS – LLM Method

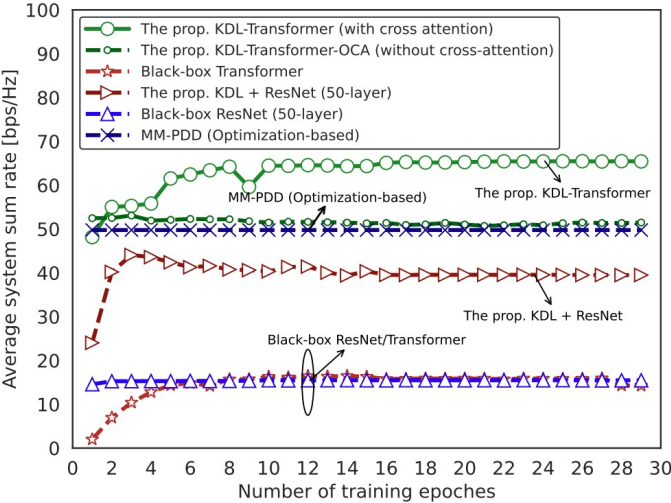
❑ Learning-Based: A KDL-Transformer Method



[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



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

$$\begin{aligned} \max_{\Phi^p, \mathbf{W}} \quad & \sum_{k=1}^K \log_2 \left(1 + \frac{\overbrace{|\mathbf{h}_k^H \mathbf{V} \mathbf{w}_k|^2}^{\text{Pinching beamforming}}}{\sum_{j=1, j \neq k}^K \underbrace{|\mathbf{h}_k^H \mathbf{V} \mathbf{w}_j|^2}_{\text{Transmit beamforming}} + \sigma_0^2} \right) \\ \text{s.t.} \quad & 0 \leq \underbrace{x_{m,n}^p}_{\text{Position of pinching antennas}} \leq D, \forall m, n, \\ & x_{m,n}^p - x_{m-1,n}^p \geq \Delta_{\min}, \forall m, \\ & \|\mathbf{W}\|^2 \leq P \end{aligned}$$

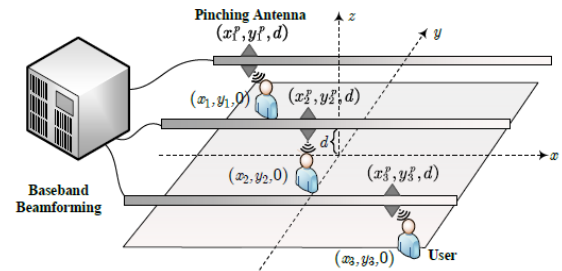


Fig. 1. Illustration of PASS, $K = N = 3$.

- 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:

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

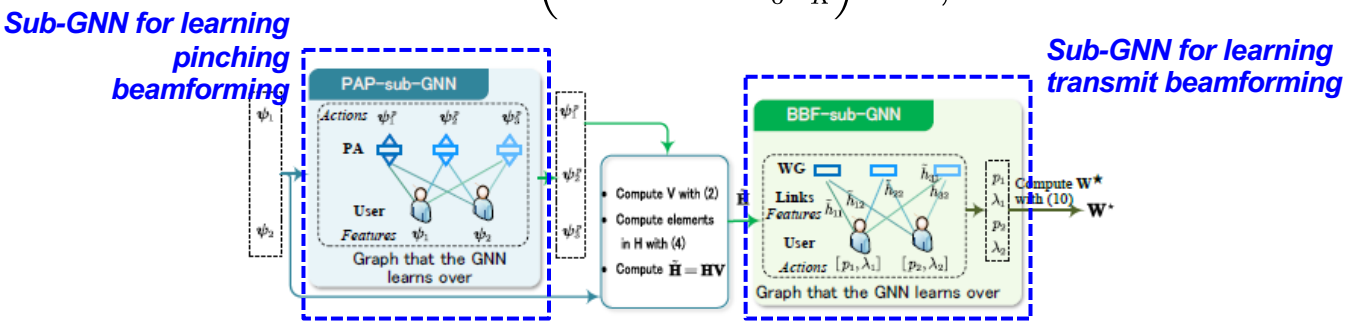


Fig. 2. GNN architecture for learning beamforming policy in PASS.

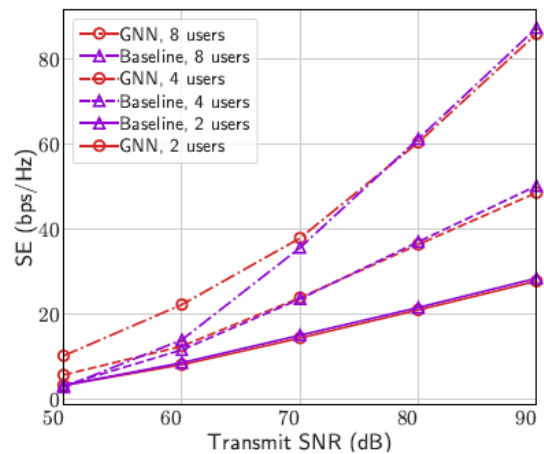
[1] J. Guo, Y. Liu and A. Nallanathan “Deep Learning for Beamforming of PASS” *IEEE Wireless Commun. Lett.*, under revision, <https://arxiv.org/abs/2502.01438>.



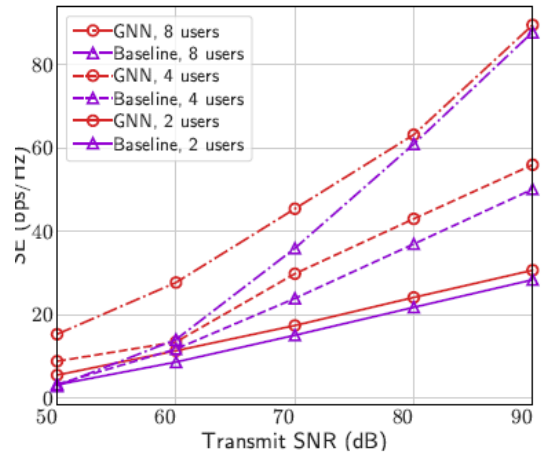
Beamforming Design for PASS – GNN Method

Simulation Results

- 8 users in 10 x 10 m² 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.

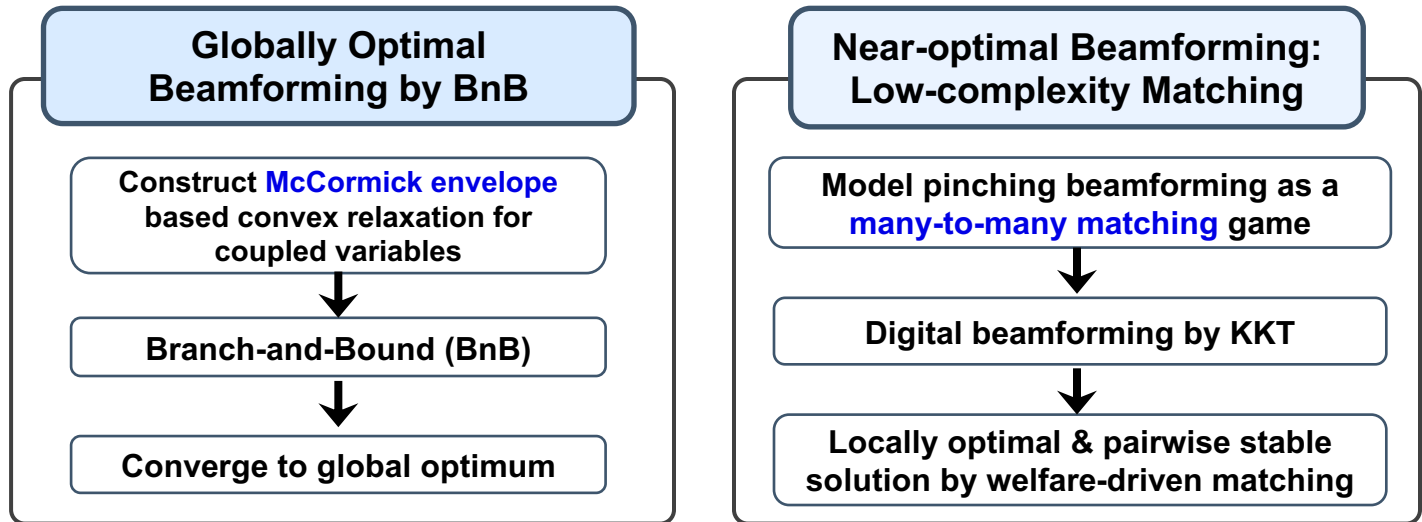
[1] J. Guo, Y. Liu and A. Nallanathan “Deep Learning for Beamforming of PASS” *IEEE Wireless Commun. Lett.*, under revision, <https://arxiv.org/abs/2502.01438>.



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

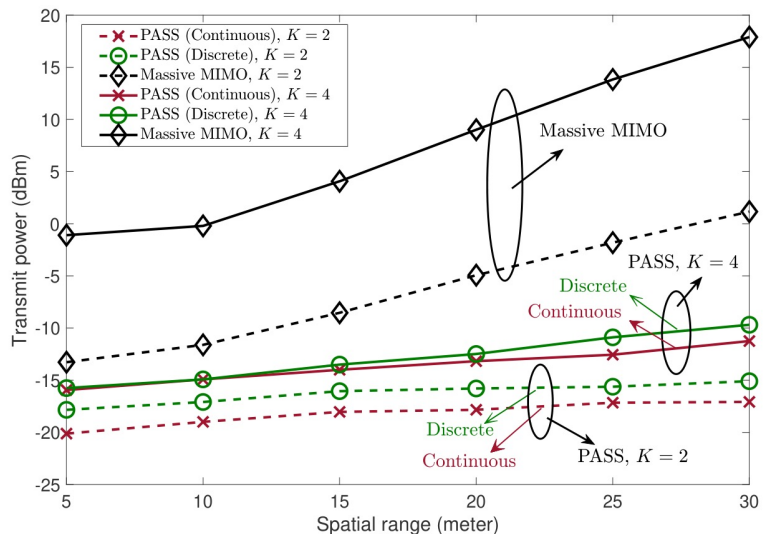
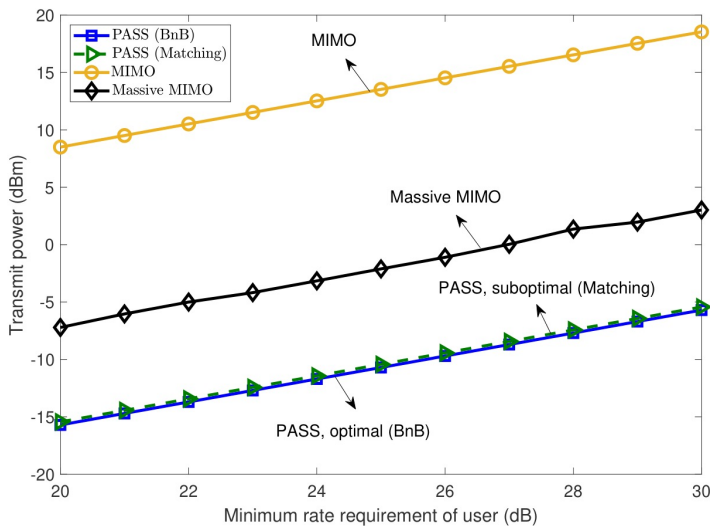


[1] X. Xu, X. Mu, Z. Wang, Y. Liu, and A. Nallanathan, "Pinching-Antenna Systems (PASS): Power Radiation Model and Optimal Beamforming Design," *IEEE Trans. Commun.*, under review, 2025. <https://arxiv.org/abs/2505.00218>



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

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- ❑ Advantages of PASS: From Wireless to Near-Wired (Why)
- ❑ Physics Principle and Signal Modelling (How)
- ❑ Activation Methods and Transmission Structures (How)

❑ Case Studies

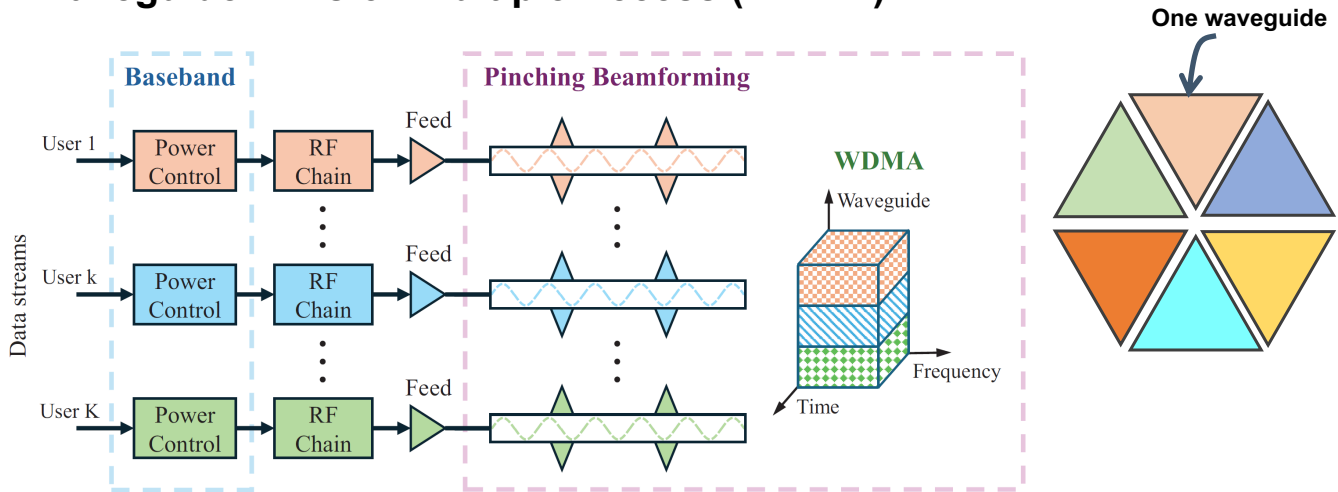
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❑ Research Challenges and Opportunities



Multiple Access Design for PASS

❑ Waveguide Division Multiple Access (WDMA)



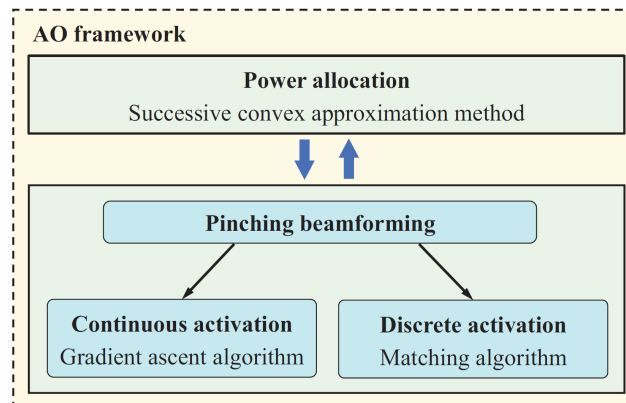
- ❑ **WDMA:** Allocate each user with a dedicated waveguide (like a new type of radio resources) to facilitate multi-user communications.
- ❑ **Simple Implementation:** baseband power allocation + pinching beamforming.
- ❑ **Pinching Beamforming:** desired signal enhancement and interference mitigation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

$$\begin{aligned} \max_{\mathbf{X}, \mathbf{p}} \quad & \sum_{k=1}^K R_k \\ \text{s.t.} \quad & R_k \geq \bar{R}_k, \forall k, \\ & \mathbf{x}_p^k \in \mathcal{F}^C / \mathbf{x}_p^k \in \mathcal{F}^D, \\ & \sum_{k=1}^K p_k \geq P_{\max}. \end{aligned}$$



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

❑ **Solution:** An alternating optimization algorithm

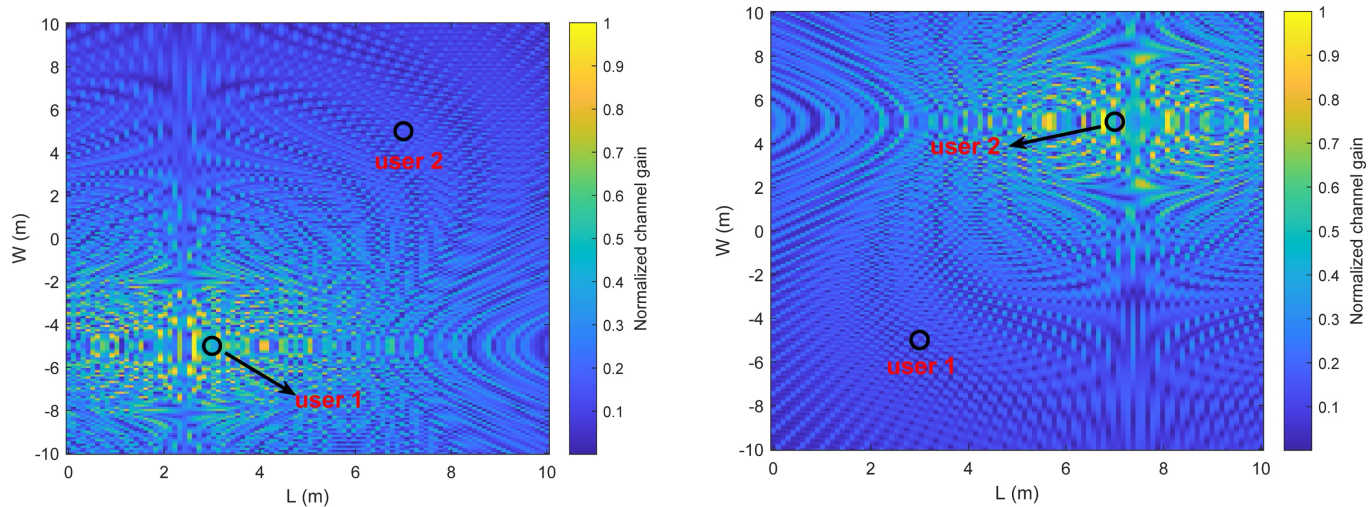
➤ **Continuous Activation Case:** Gradient ascent algorithm for pinching beamforming

➤ **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



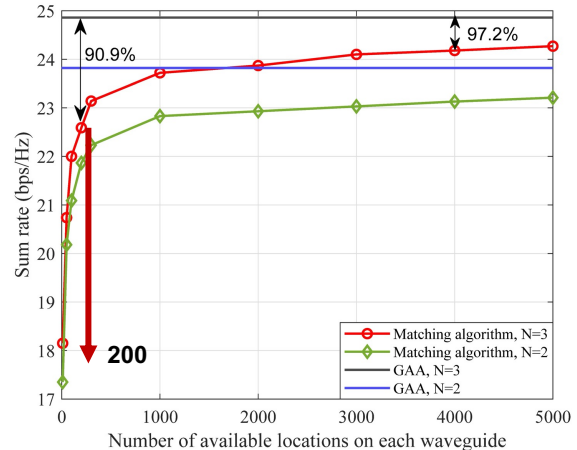
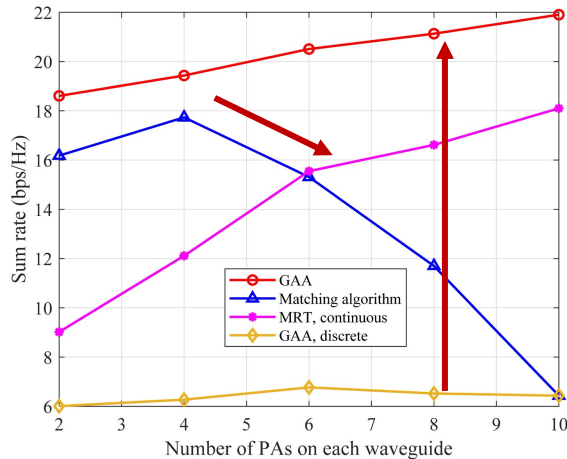
- Only using the pinching beamforming, high channel gain can be achieved for the intended user, while much lower channel gain is observed at the interfering user, i.e., ***near orthogonality in free space***:

[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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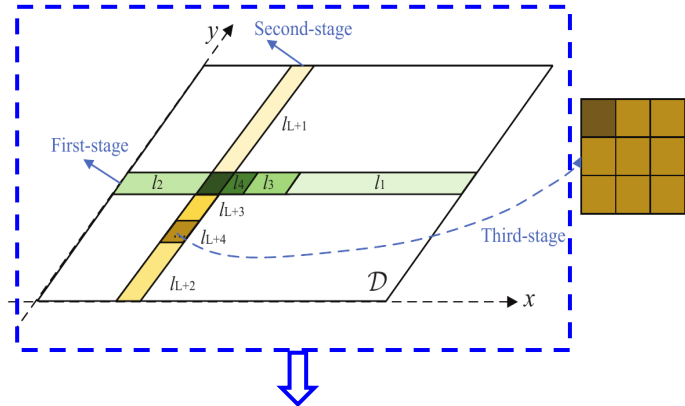
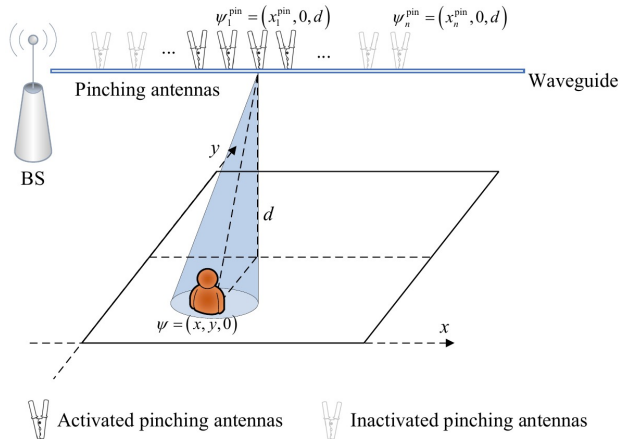
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❑ Research Challenges and Opportunities



Beam Training for PASS

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



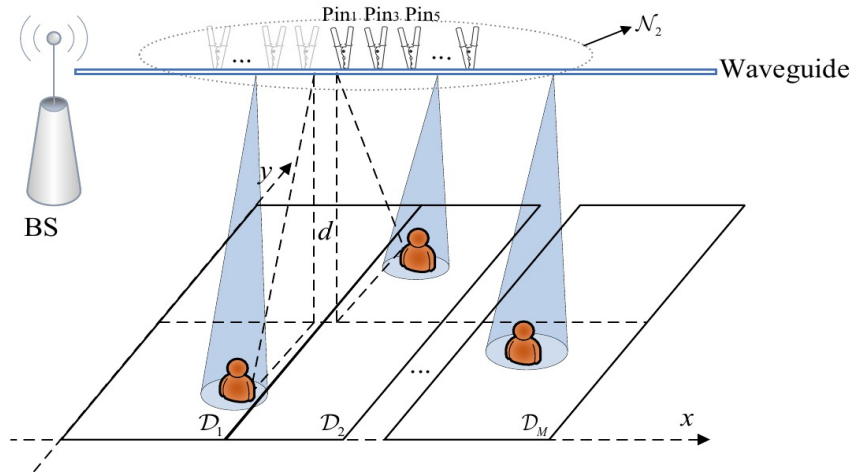
Reduce the 2D search to two 1D searches

- **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.*, under revision, 2025. <https://arxiv.org/abs/2502.05921>

Beam Training for PASS

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



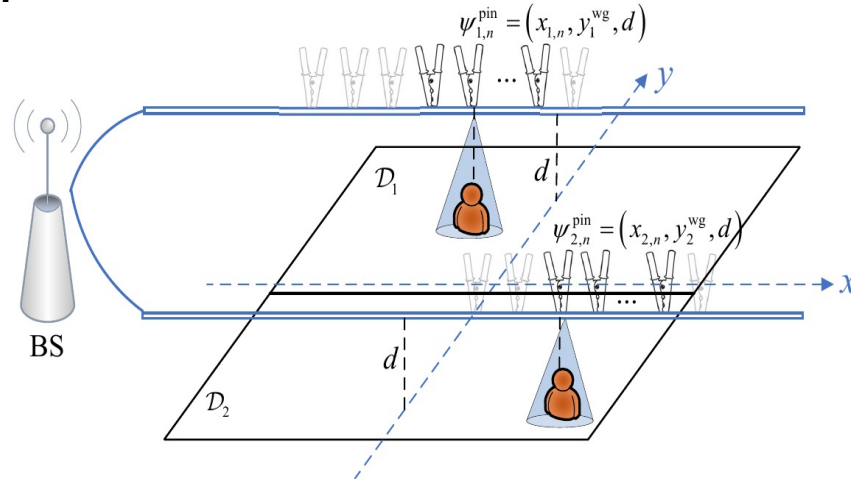
- **Support NOMA-based transmission.**
- **Improved 3SBT Scheme:**
 - **Stage-1: Separated user training** to locate each user's location.
 - **Stage-2: Partial antenna reclustering** to avoid overlapping.
 - **Stage-3: Joint multi-user training** to maximize sum rate.

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



Beam Training for PASS

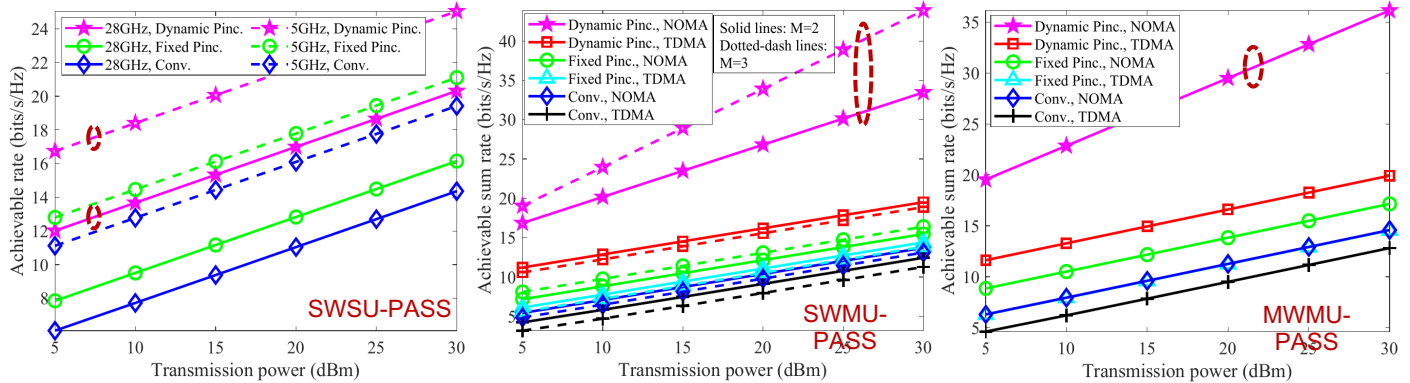
❑ Multi-Waveguide-Multi-User PASS (MWMU-PASS)



- **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.*, under revision, 2025. <https://arxiv.org/abs/2502.05921>

Beam Training for PASS



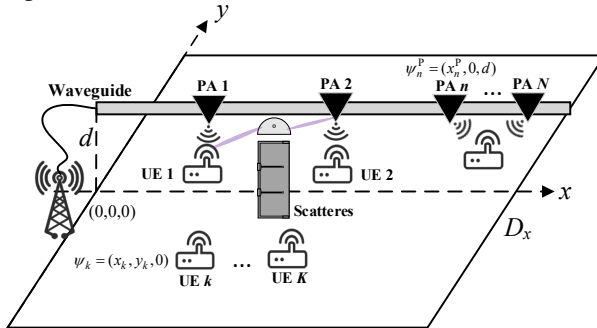
Beam training scheme	Total training overhead	In our set up
SWSU, 2D exhaustive search	$K^{L_1+L_2} \cdot K_1 K_2$	2^{20}
SWSU, proposed	$K(L_1 + L_2) + K_1 K_2$	48
SWMU, 2D exhaustive search	$K^{M(L_1+L_2)} \cdot \prod_{m=1}^M (K_{m,1} K_{m,2})$	$2^{40}, M=2; 2^{60}, M=3$
SWMU, proposed	$MK(L_1 + L_2)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

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

depends on positions and coupling lengths of PAs

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

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

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)

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 select subsets of PAs in different time slots

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

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

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

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

- 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>.



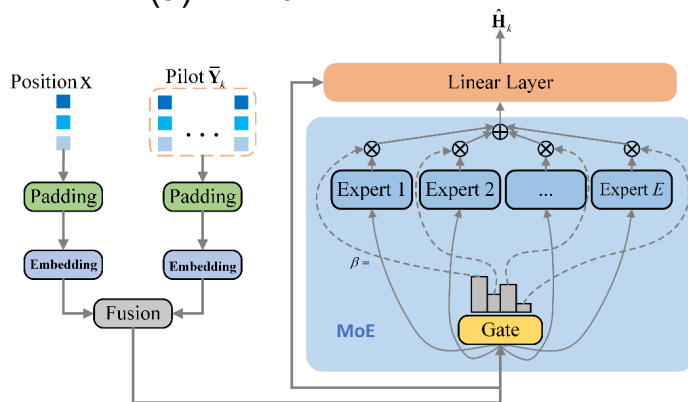
Channel Estimation for PASS

❑ 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)

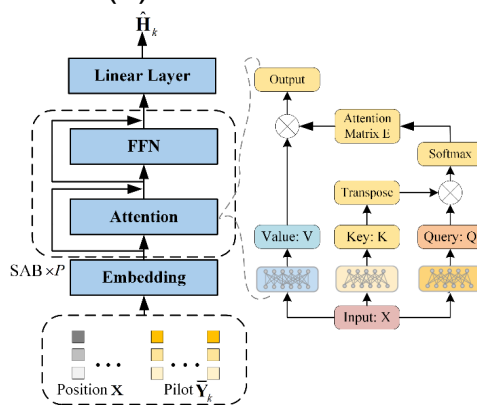
❑ Proposed DL Solutions

(a) PAMoE



- Leveraging mixture of experts (MoE) to extend the network capacity

(b) PAformer



- 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>.

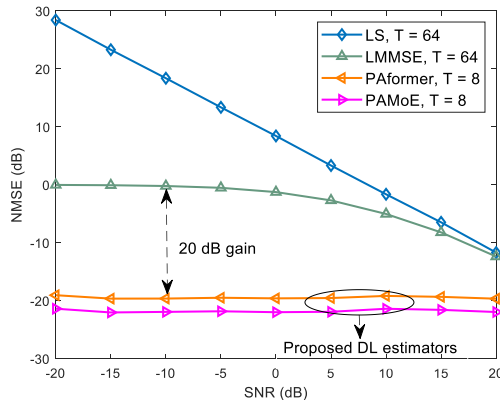


Channel Estimation for PASS

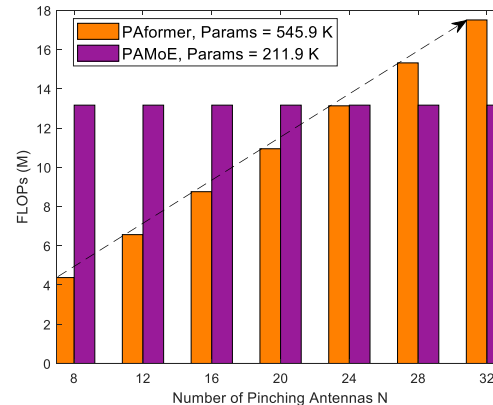
□ Numerical Results

➤ 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)

[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>.



Outline

❑ PASS Basis

- ❑ Overview of PASS: Start with a Prototype (What)
- ❑ Advantages of PASS: From Wireless to Near-Wired (Why)
- ❑ Physics Principle and Signal Modelling (How)
- ❑ Activation Methods and Transmission Structures (How)

❑ Case Studies

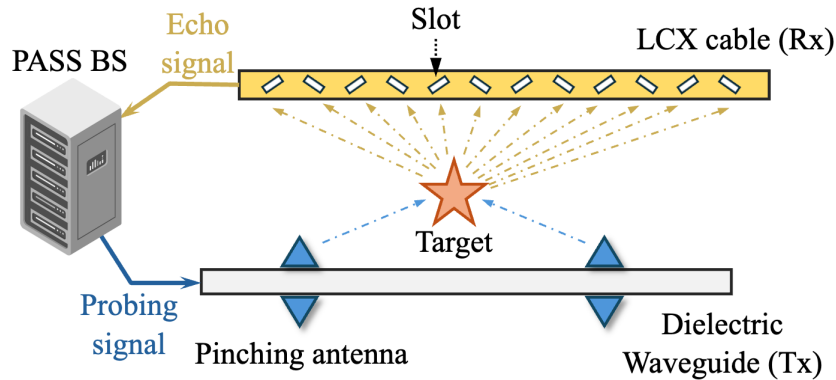
- ❑ Case I: Performance Analysis for PASS
- ❑ Case II: Beamforming Design for PASS
- ❑ Case III: Multiple Access Design for PASS
- ❑ Case IV: Beam Training and Channel Estimation for PASS
- ❑ Case V: Applications for PASS

❑ Research Challenges and Opportunities



PASS-Enabled Wireless Sensing

❑ PASS for Wireless Sensing



- **PASS: waveguide for transmission, LCX for receiving**
TX-Waveguide: focus signal power at the desired location.
RX-LCX: enlarge signal reception range.

[1] Z. Wang, C. Ouyang, Y. Liu, and A. Nallanathan, "Wireless Sensing via Pinching-Antenna Systems," *IEEE Wireless Commun. Lett.*, early access, Aug. 2025

PASS-Enabled Wireless Sensing

❑ PASS for Wireless Sensing

Pinching Beamforming ← $\min_{\mathbf{X}, \mathbf{R}_s} \text{Tr}(\text{CRB}(\boldsymbol{\theta}))$
Transmit Beamforming ← s.t. $\text{Tr}(\mathbf{R}_s) = P_t, \mathbf{R}_s \succeq 0,$
 $x_{n,m} - x_{n,m-1} \geq \Delta x, \forall n, m \neq 1,$
 $0 \leq x_{n,m} \leq L, \forall n, m,$

➤ Minimizing Cramér–Rao bound (CRB) for localizing multiple targets

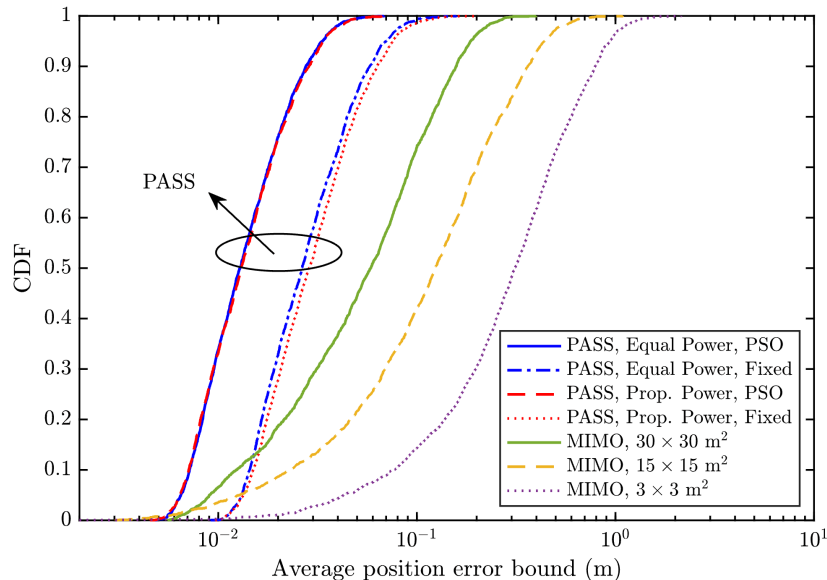
- Stage 1 optimization: **Particle swarm optimization (PSO)** for pinching beamforming based on isotropic transmit beamforming
- Stage 2 optimization: **Semidefinite programming (SDP)** for transmit beamforming based on optimized pinching beamforming

[1] Z. Wang, C. Ouyang, Y. Liu, and A. Nallanathan, "Wireless Sensing via Pinching-Antenna Systems," *IEEE Wireless Commun. Lett.*, early access, Aug. 2025



PASS-Enabled Wireless Sensing

❑ PASS for Wireless Sensing

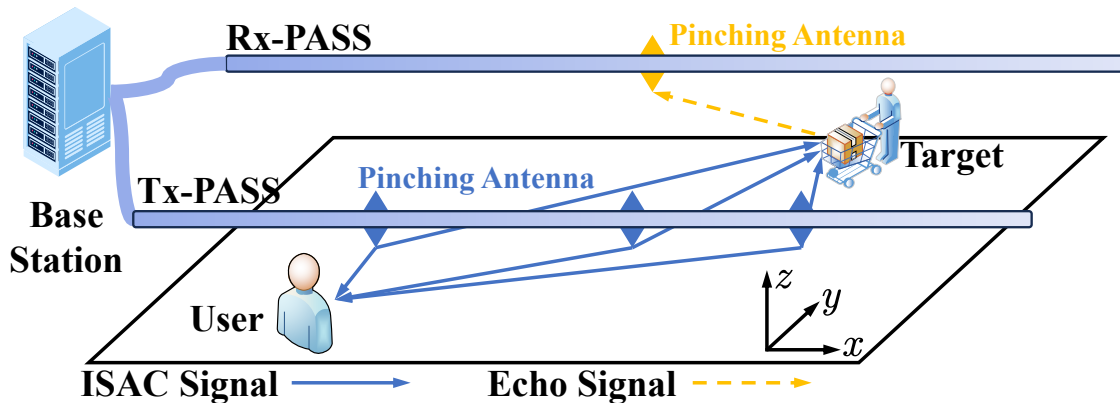


- PASS yields a lower sensing error bound than conventional fixed-antenna systems

[1] Z. Wang, C. Ouyang, Y. Liu, and A. Nallanathan, "Wireless Sensing via Pinching-Antenna Systems," *IEEE Wireless Commun. Lett.*, early access, Aug. 2025

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

$$\begin{aligned}
 & \max_{R, \mathbf{t}} R && \text{Pinching Beamforming} \\
 & \text{s.t. } \boxed{\log_2(1 + \gamma_c(\mathbf{t}))} \geq \alpha R && \text{CR} \\
 & \quad \boxed{\log_2(1 + \gamma_s(\mathbf{t}))/L} \geq (1 - \alpha) R && \text{SR}
 \end{aligned}$$

➤ 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

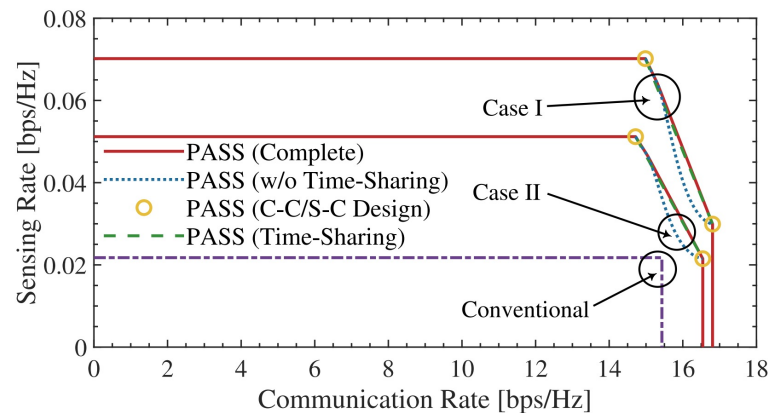
	Communications-Centric	Sensing-Centric	Pareto-Optimal (Rate Region)
Single-Pinch	$\mathcal{C}_S(t_1^*)$ (closed-form, $t_1 = x_c$)	$\mathcal{C}_S(t_0^*)$ (closed-form, $t_1 = x_s$)	$\mathcal{C}_p^S$ (closed-form, $t_1 = t_\alpha^*$)
Multiple-Pinch	$\mathcal{C}_M(t_1^*)$ (method in [26], $\mathbf{t} = \mathbf{t}_c$)	$\mathcal{C}_M(t_0^*)$ (method in [26], $\mathbf{t} = \mathbf{t}_s$)	$\mathcal{C}_p^{IB}$ (rate-profile); $\mathcal{C}_p^{OB}$ (closed-form) $\mathcal{C}_p^{IB} \subseteq \mathcal{C}_p \subseteq \mathcal{C}_p^{OB}$

[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>

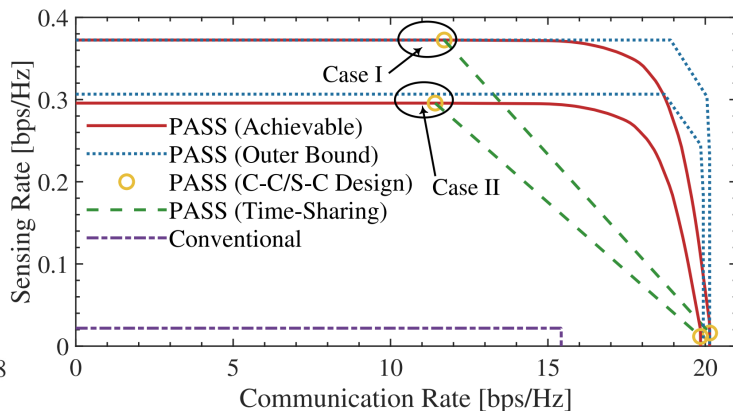


PASS-Enabled ISAC

□ Rate-Region Characterization



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

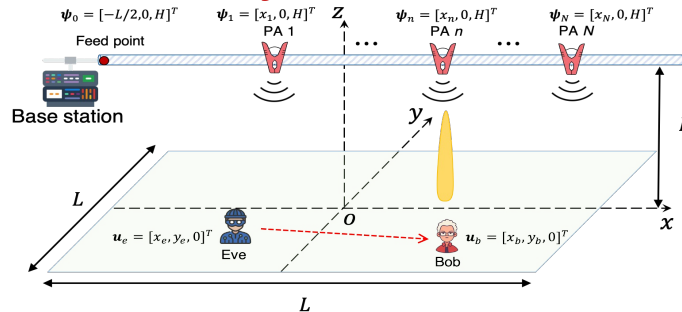
[1] C. Ouyang, Z. Wang, Y. Liu, and Z. Ding, "Rate Region of ISAC for Pinching-Antenna Systems," *IEEE Trans. Commun.*, under review. <https://arxiv.org/2505.10179>



Physical Layer Security for PASS

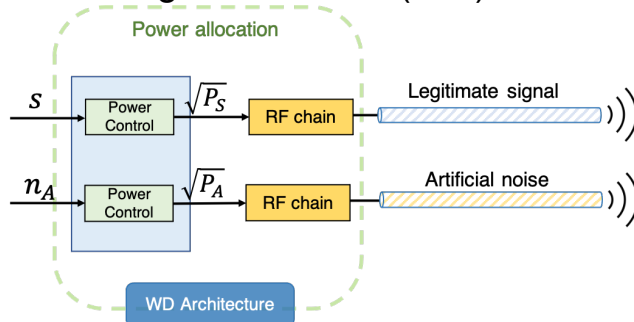
Secure Architecture Design

➤ Single-waveguide PASS Security Enhancement

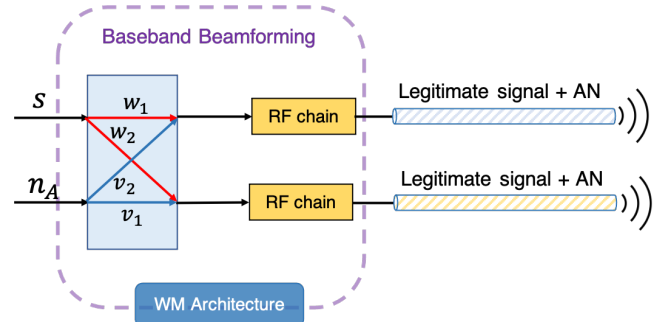


➤ Multiple-waveguide PASS Security Enhancement with Artificial Noise

❖ Waveguide Division (WD)



❖ Waveguide Multiplexing (WM)



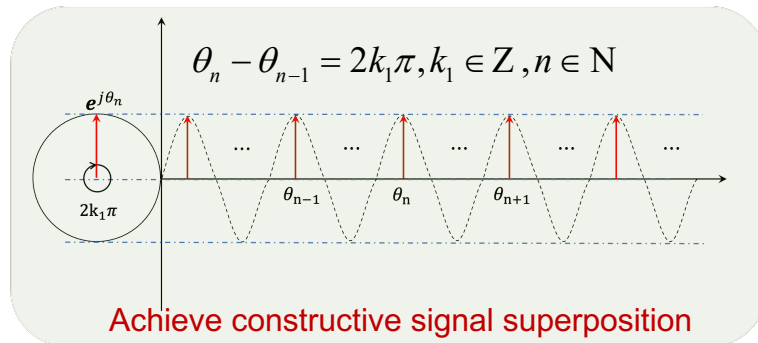
[1] G. Zhu, X. Mu, L. Guo, S. Xu, Y. Liu, and N. Al-Dhahir, "Pinching-Antenna Systems (PASS)-enabled Secure Wireless Communications", <https://arxiv.org/abs/2504.13670>

Physical Layer Security for PASS

❑ Single-waveguide PASS Security Enhancement

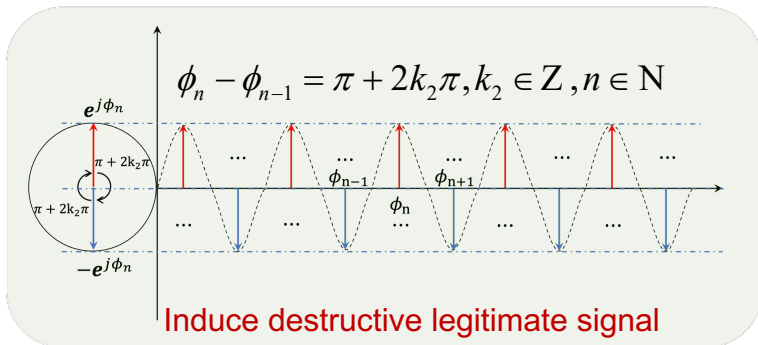
➤ Secrecy Rate Maximization

$$\begin{aligned} \max_{\mathbf{x}, P} \quad & R_S \\ \text{s.t.} \quad & P \leq P_{\max}, \\ & -\frac{L}{2} < x_1 < \dots < x_N < \frac{L}{2}, \\ & x_n - x_{n-1} \geq \Delta, \forall n \in \mathbb{N}. \end{aligned}$$



➤ 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

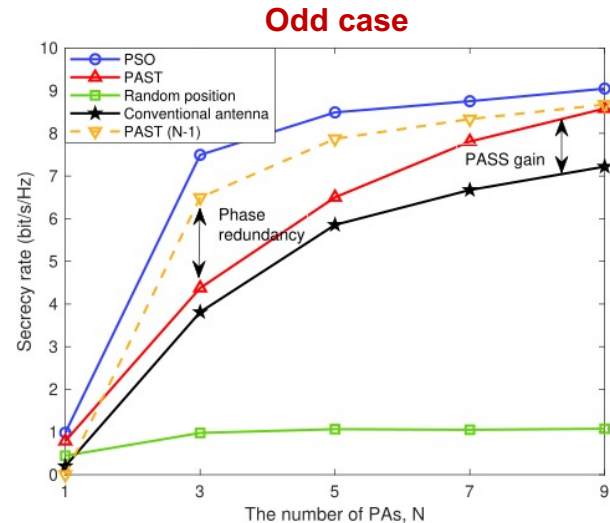
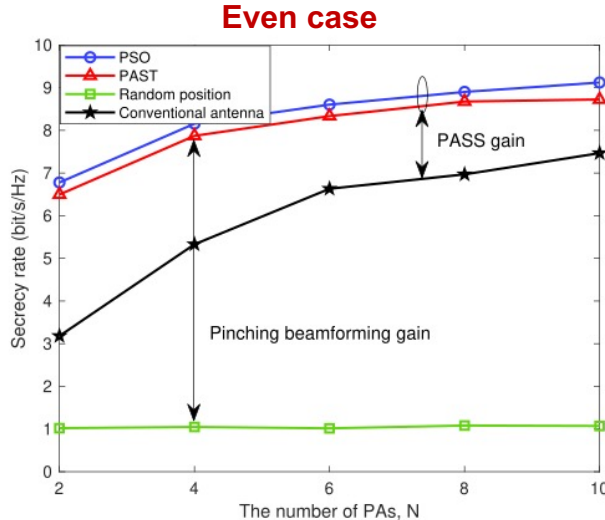


[1] G. Zhu, X. Mu, L. Guo, S. Xu, Y. Liu, and N. Al-Dhahir, "Pinching-Antenna Systems (PASS)-enabled Secure Wireless Communications", <https://arxiv.org/abs/2504.13670>

Physical Layer Security for PASS

❑ Single-waveguide PASS Security Enhancement

➤ Numerical Results



- 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

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

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

➤ 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**

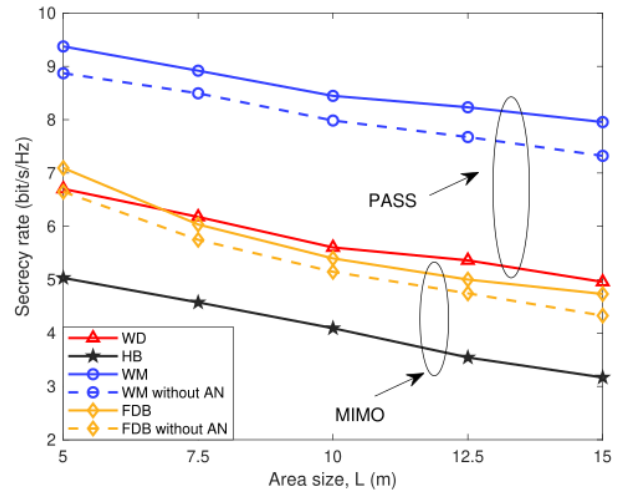
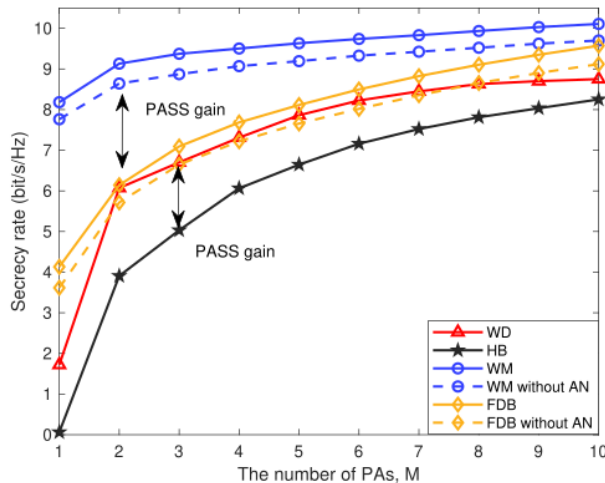
[1] G. Zhu, X. Mu, L. Guo, S. Xu, Y. Liu, and N. Al-Dhahir, "Pinching-Antenna Systems (PASS)-enabled Secure Wireless Communications", <https://arxiv.org/abs/2504.13670>



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

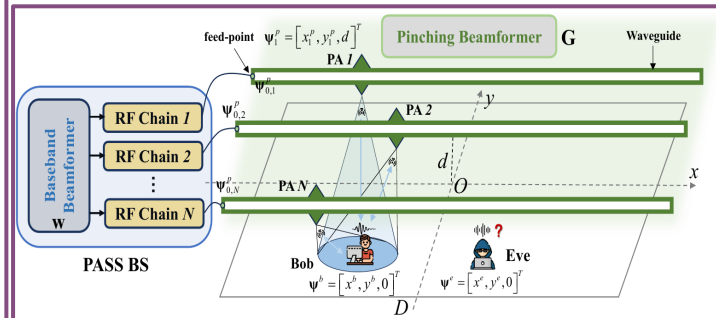
A BS with N waveguides, only *one* pinching antenna on each waveguide.

➤ Joint transmit and pinching beamforming to maximize secrecy rate.

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

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

antenna positions $\mathbf{x}_n^p \in \left[-\frac{D}{2}, \frac{D}{2} \right], \forall n = 1, \dots, N.$



➤ 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).

$$\begin{aligned} \max_{\{\mathbf{w}_k\}_{k=1}^K, \mathbf{x}^p} \quad & \max \left\{ \log_2 \left(\frac{1 + \gamma_k}{1 + \Gamma_k} \right), 0 \right\} \\ \text{s.t.} \quad & \sum_{k=1}^K \|\mathbf{w}_k\|^2 \leq P_T, \\ & \text{Pinching antennas' positions } \mathbf{x}_{m,n}^p \in \left[-\frac{D}{2}, \frac{D}{2} \right], \forall n = 1, \dots, N, \\ & |x_{m,n}^p - x_{m',n}^p| > \Delta_{\min}, \forall m \neq m', \forall n. \end{aligned}$$

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

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

Legitimate channel
Wiretap channel

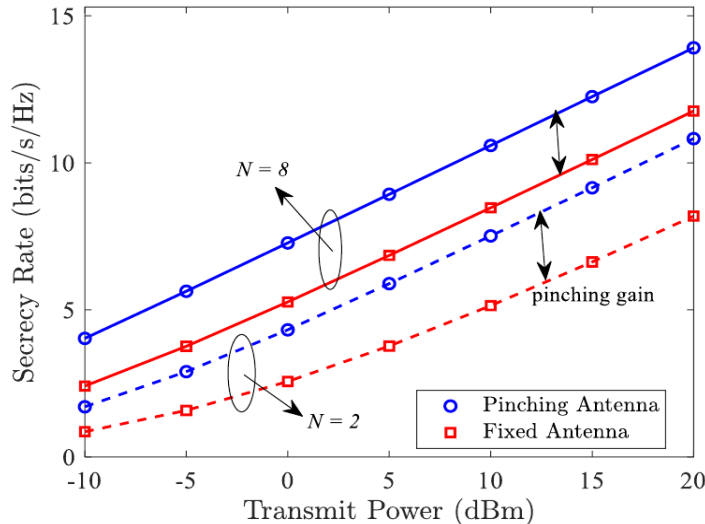
- The transmit beamformer: A **fractional programming-based** BCD algorithm.
- The pinching beamformer: A **one-dimensional search** method

[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>

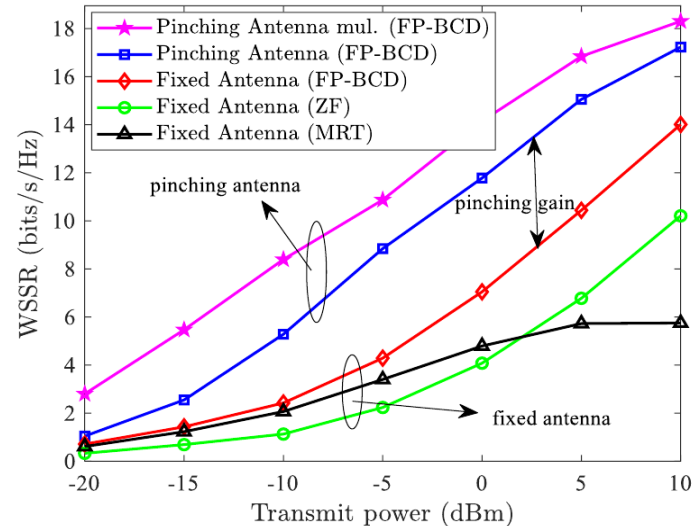


Physical Layer Security for PASS

Simulation Results



single-Bob single-Eve



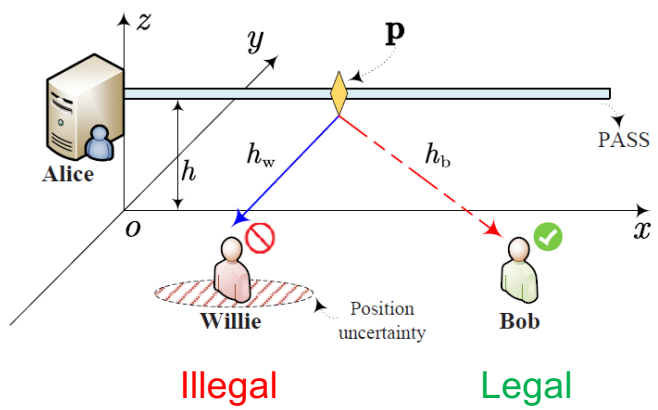
multiple-Bob multiple-Eve

- 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



OBJ: Maximize Transmission Rate at Bob

$$\begin{aligned} \max_{x,P} \quad & \log_2(1 + \gamma_b(x, P)) \\ \text{s.t.} \quad & 0 \leq x \leq L, \\ & 0 \leq P \leq P_{\max}, \\ & \xi \geq 1 - \rho_w, \quad \forall \xi \in \mathcal{E}, \end{aligned}$$

Covertiness Constraint at Willie

a) An illustration of the SWSP PASS scenario.

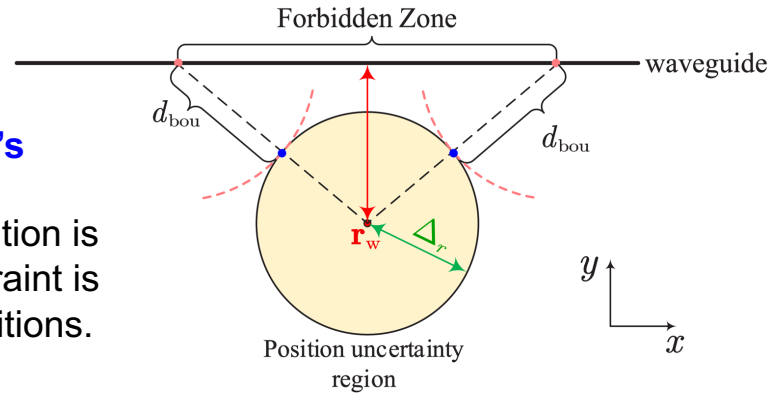
[1] H. Jiang, Z. Wang and Y. Liu, "Pinching-Antenna System (PASS) Enhanced Covert Communications," submitted to IEEE Journals, under review, 2025 <https://arxiv.org/abs/2504.10442>



PASS Enhanced Covert Communications

□ 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**.



$$x^{\text{opt}} = \begin{cases} \emptyset, & \text{if } S \subseteq \mathcal{D}, \\ x_b, & \text{if } S \not\subseteq \mathcal{D} \text{ and } x_b \in \mathcal{F}, \\ \arg \min_{x \in \mathcal{A}} |x - x_b|, & \text{if } S \not\subseteq \mathcal{D} \text{ and } x_b \notin \mathcal{F}. \end{cases}$$

- 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>

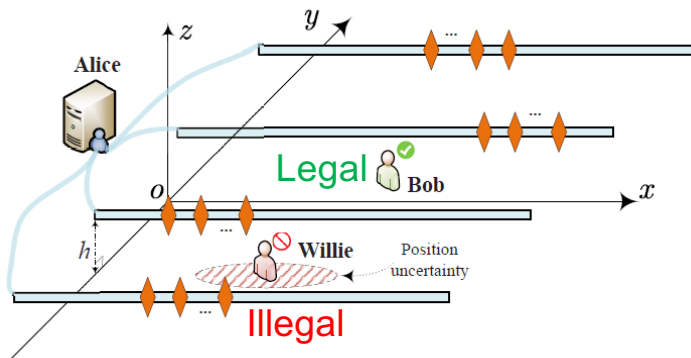


PASS Enhanced Covert Communications

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

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

OBJ: Maximize Transmission Rate at Bob



$$\max_{\mathbf{X}, \mathbf{w}} \log_2 (1 + \gamma_b (\mathbf{X}, \mathbf{w}))$$

$$\text{s.t. } 0 \leq x_{n,m} \leq L, \forall m \in \mathcal{M}, n \in \mathcal{N}$$

$$\Delta_{n,m} \triangleq x_{n,m} - x_{n,m-1} \geq \Delta_{\min}, \forall m \in \mathcal{M},$$

$$\|\mathbf{w}\|^2 \leq P_{\max},$$

$$\xi \geq 1 - \rho_w, \quad \forall \xi \in \mathcal{E}$$

Covert Constraint at Willie

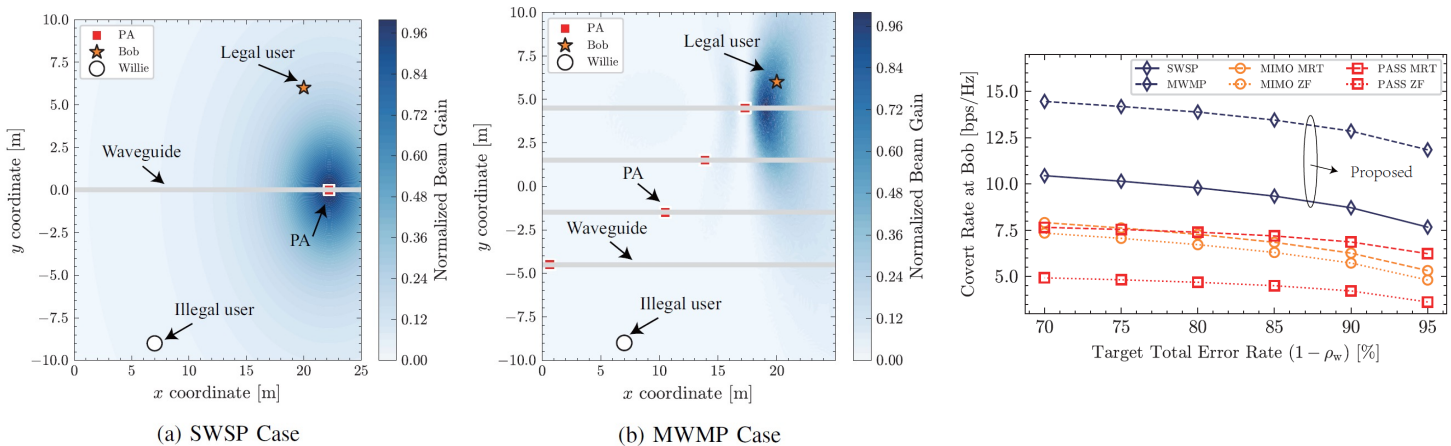
b) An illustration of the MWMP PASS scenario.

➤ **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:



- 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 **covertiness 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 Prototype (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

