Pinching-Antenna Systems: A New Paradigm for Wireless Transceiver Designs

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Outline

A Motivation from the Futuristic Perspective

An ultimate goal of wireless communications:
Providing **fiber-like**, **user-centric**, **cheap** connections

Outdoor Communications

Indoor Communications

Generated by ChaptGPT 4o

A Motivation from the Historic Perspective (1/2)

Shannon's formula is key to the evolution of modern communication systems

$$C = W \cdot \log\left(1 + \gamma_{\mathrm{h}} \cdot \frac{P_s}{P_n}\right)$$

- MIMO creates parallel channels between the transceivers, and increases the effective bandwidth to $\min\{N_{\mathrm{TX}}, N_{\mathrm{RX}}\}W$
- NOMA encourages spectrum sharing among multiple users and hence introduces extra degrees of freedom to configure W and P_s
- Even the noise term, P_n, can be treated as a configurable system parameter - Noise Modulation
- Conventionally, a user's wireless channel, i.e., γ_h, has been viewed as a fixed system parameter that cannot be adjusted.

A Motivation from the Historic Perspective (2/2)

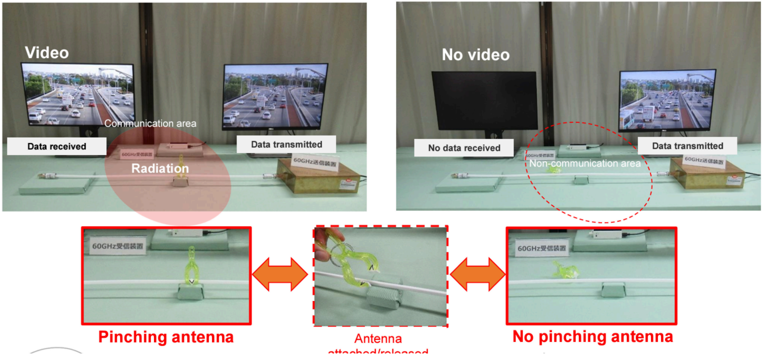
Flexible-antenna systems are to treat wireless channels as tunable system parameters

- RIS/IRS
  - Mitigate the line-of-sight (LoS) blocking issue by reflecting signals around obstacles
  - Drawback: suffering double attenuation.
- Fluid antennas and movable antennas
  - Change the locations of antennas at the wavelength scale to combat fading
  - Drawback: moving the antennas of the transceivers a few wavelengths is not helpful to combat LoS blockage
- In addition, most existing flexible-antenna systems are also
  - Expensive to build
  - Lack of array reconfigurability (adding/removing antennas is not trivial)

Outline

Pinching-Antenna Systems

- An innovative, flexible and low-complexity way to implement flexible-antenna systems

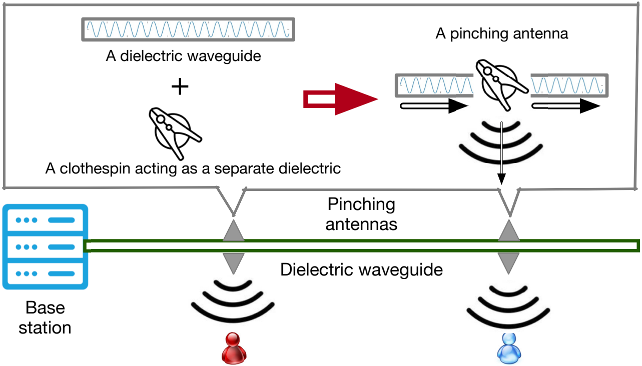


A. Fukuda, H. Yamamoto, H. Okazaki, Y. Suzuki, and K. Kawai, "Pinching antenna - using a dielectric waveguide as an antenna," NTT DOCOMO Technical J., vol. 23, no. 3, pp. 5–12, Jan. 2022.

Pinching-Antenna Systems

So what exactly are pinching-antenna systems?

- Leaky wave antennas + dielectric waveguides



Z. Ding, R. Schober and H. V. Poor, Flexible-Antenna Systems: A Pinching-Antenna Perspective, IEEE Transactions on Communications, to appear in 2025

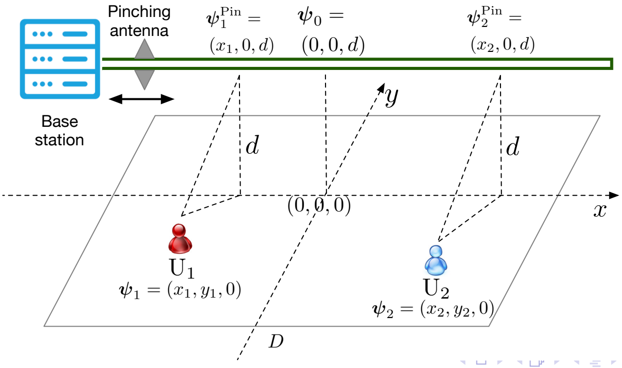
Pinching-Antenna Systems - Key Features

- Capability to support LoS communication:
  - Create a new LoS transceiver link
  - Make an existing LoS link stronger
  - Because the location of a pinching antenna can be flexibly adjusted over a large scale .
- Flexibility to reconfigure the antenna system:
  - Increasing (or decreasing) the size of the pinching antenna system flexibly
  - New types of MIMO with reconfigurable channels
  - Achieving upper bounds which are not possible for conventional cases

Z. Ding, R. Schober and H. V. Poor, Flexible-Antenna Systems: A Pinching-Antenna Perspective, IEEE Transactions on Communications, to appear in 2025

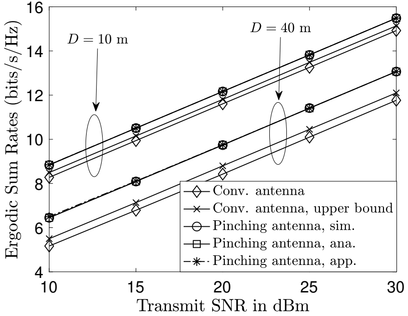
Case I - SPSW (1/2)

- Users are served by a single pinching antenna on a single waveguide (SPSW) via TDMA
- Applying stochastic geometry, the throughput of pinching antennas is shown to be strictly larger than that of conventional ones.

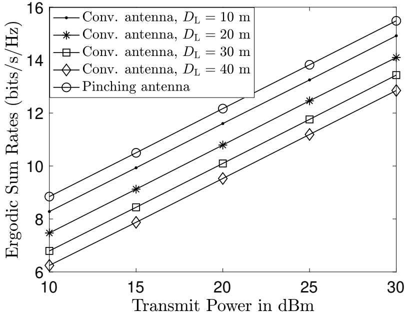


Case I - SPSW (2/2)

- This simple case study demonstrates the key features of pinching antennas to create strong LoS links



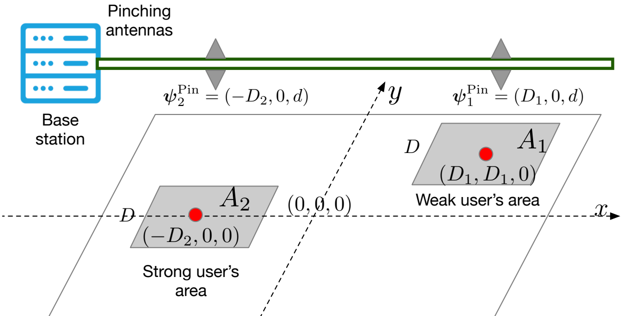
(a) Square User Deploymeng



(b) Rectanglar User Deploymeng

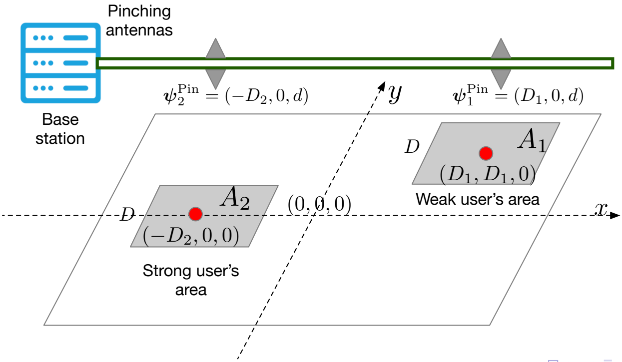
Case II - MPSW (1/2)

- Pinching antennas are cheap and easy to be installed
- So why not to activate multiple pinching antennas on a single waveguide (MPSW)?
- A catch: more antennas there are, less transmit power each can have
- TDMA case: we show that indeed the use of more antennas yields better performance.



Case II - MPSW (2/2)

- These pinching antennas are on the same waveguide.
- Similar to hybrid beamforming with one RF chain
- Multiple users' signals need to be superimposed first
- It is natural to consider the application of NOMA



Case III - MPMW (MIMO) (1/3)

Recap for two-user interference channels

$$\mathrm{SINR}_1 = \frac{\rho|\mathbf{h}_1^H\mathbf{p}_1|^2}{\rho|\mathbf{h}_1^H\mathbf{p}_2|^2+1}, \quad \mathrm{SINR}_2 = \frac{\rho|\mathbf{h}_2^H\mathbf{p}_2|^2}{|\mathbf{h}_2^H\mathbf{p}_1|^2+1},$$

- Zero-forcing:

$$\mathrm{SINR}_1^{\mathrm{ZF}} = \rho|\mathbf{h}_1^H\mathbf{p}_1^{\mathrm{ZF}}|^2, \quad \mathrm{SINR}_2^{\mathrm{ZF}} = \rho|\mathbf{h}_2^H\mathbf{p}_2^{\mathrm{ZF}}|^2.$$

- Maximum ratio combining:

$$\mathrm{SINR}_1^{\mathrm{MRC}} = \frac{\rho|\mathbf{h}_1|^2}{\rho\frac{|\mathbf{h}_1^H\mathbf{h}_2|^2}{|\mathbf{h}_2|^2}+1}, \mathrm{SINR}_1^{\mathrm{MRC}} = \frac{\rho|\mathbf{h}_2|^2}{\rho\frac{|\mathbf{h}_2^H\mathbf{h}_1|^2}{|\mathbf{h}_1|^2}+1}.$$

- A holy-grail upper bound:

$$\mathrm{SINR}_1 \leq \rho|\mathbf{h}_1|^2, \quad \mathrm{SINR}_2 \leq \rho|\mathbf{h}_2|^2,$$

Case III - MPMW (MIMO) (2/3)

- A holy-grail upper bound:

$$\mathrm{SINR}_1 \leq \rho|\mathbf{h}_1|^2, \quad \mathrm{SINR}_2 \leq \rho|\mathbf{h}_2|^2,$$

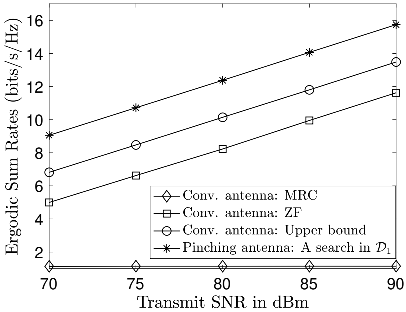
- Two necessary conditions for realizing the upper bound are as follows:
  - Phase-Matching Condition: For U_m, the phase of $p_{m,m}$ matches the phase of $h_{m,m}$, i.e., the difference between the phases of $p_{m,m}$ and $h_{m,m}$ must be multiples of 2π and hence the numerator of SINR_m can be $|\mathbf{h}_m|^2$.
  - Orthogonality Condition: Each user does not experience interference from the other user, which ensures the denominator of SINR_m is 1, $m \in \{1, 2\}$, i.e.,

$$h_{1,1}p_{2,1} + h_{1,2}p_{2,2} = 0, h_{2,1}p_{1,1} + h_{2,2}p_{1,2} = 0. \tag{1}$$

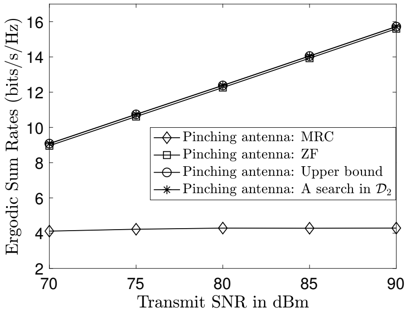
- They are achievable by pinching antennas since both $p_{m,i}$ and $h_{m,i}$ are adjustable.

Case III - MPMW (MIMO) (3/3)

- The ideal upper bound can be achievable in pinching-antenna systems



(c) Pinching antennas vs fixed antennas



(d) Low-complexity pinching-antenna methods

Outline

Fundamentals of Pinching-Antenna Systems (1/2)

LoS blockage becomes beneficial in pinching-antenna systems.

- For two-user interference channels with conventional antennas:

$$\bar{R}_1^{\rm Conv} = \mathcal{E}\left\{\log_2\left(1+\frac{\alpha_1 \left|h_{11}\right|^2 P}{\alpha_1 \left|h_{12}\right|^2 P + M\sigma^2}\right)\right\} \approx \mathcal{E}\left\{\log_2\left(1+\frac{\left|h_{11}\right|^2}{\left|h_{12}\right|^2}\right)\right\}.$$

- For pinching antennas:

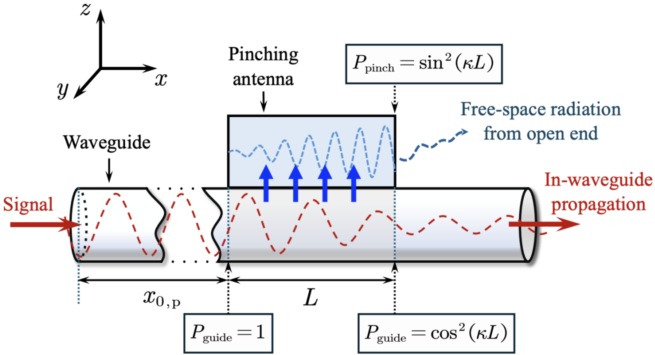
$$R_1^{\rm Pin} = \log_2\left(1+\frac{\frac{\alpha_{11}\eta P}{|\psi_1^{\rm Pin}-\psi_1|^2}}{\frac{\alpha_{12}\eta P}{|\psi_2^{\rm Pin}-\psi_1|^2}+M\sigma^2}\right) \rightarrow \infty$$

if $\alpha_{11} \neq 0$, $\alpha_{12} = 0$ and $P \rightarrow \infty$.

Z. Ding and H. V. Poor, LoS Blockage in Pinching-Antenna Systems: Curse or Blessing?, IEEE CL, submitted.

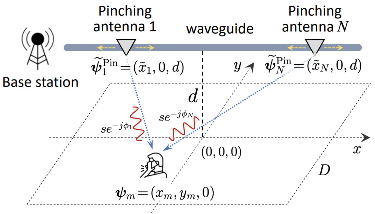
Fundamentals of Pinching-Antenna Systems (2/2)

The phase of the signal from a pinching antenna can be controlled by its position, and its amplitude can also be tuned.

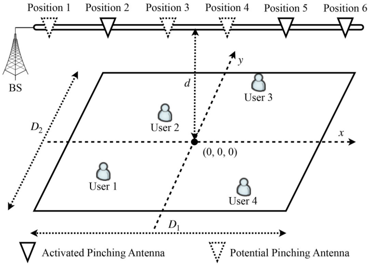


Z. Wang, C. Ouyang, X. Mu, Y. Liu, Z. Ding, Modeling and Beamforming Optimization for Pinching-Antenna Systems, IEEE Trans. Wireless Commun., submitted.,

Topology and Network Optimization



(e) Optimizing the positions of pinching antennas



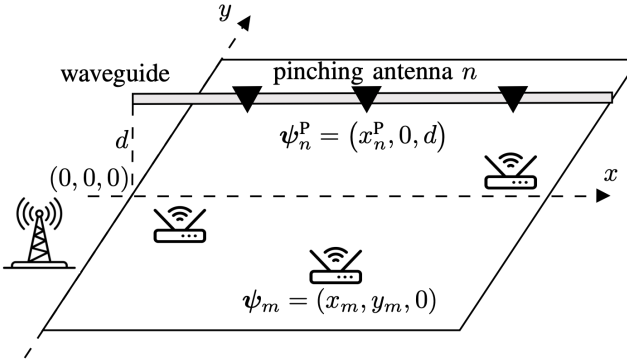
(f) Antenna activation instead of moving

And there are more parameters offering extra degrees of freedom to design the system

Y. Xu, Z. Ding and G. Karagiannidis, Rate Maximization for Downlink Pinching-Antenna Systems, IEEE CL, appear in 2025.
K. Wang, Z. Ding and R. Schober, Antenna Activation for NOMA Assisted Pinching-Antenna Systems, IEEE Wireless Commun. Lett., to appear in 2025.

Uplink Pinching-Antenna Systems

Many existing works about pinching-antenna systems focused on downlink, but its uplink design is equally interesting



S. A. Tegos, P. D. Diamantoulakis, Z. Ding, G K. Karagiannidis, Minimum Data Rate Maximization for Uplink Pinching-Antenna Systems, IEEE Wireless Commun. Lett., to appear in 2025,

Vairious Applications of Pinching Antennas

- Pinching antennas are a general communication technology that is compatible with many other communication techniques
- NGMA, SAGIN, V2X
- A case study of ISAC is focused here
- The CRLB for a user's location can be expressed as follows:

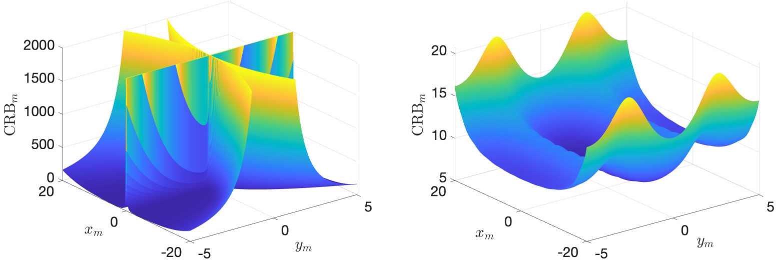
$$\mathrm{CRB}_m = \frac{\frac{K_E}{(2K_E+1)}}{\sum_{n=1}^{N} \frac{\left(x_m - x_n^{\mathrm{Pin}}\right)^2}{\left(\left(x_m - x_n^{\mathrm{Pin}}\right)^2 + \left(y_m - y_n^{\mathrm{Pin}}\right)^2 + d_{\mathrm{H}}^2\right)^2}} + \frac{\frac{K_E}{(2K_E+1)}}{\sum_{n=1}^{N} \frac{\left(y_m - y_n^{\mathrm{Pin}}\right)^2}{\left(\left(x_m - x_n^{\mathrm{Pin}}\right)^2 + \left(y_m - y_n^{\mathrm{Pin}}\right)^2 + d_{\mathrm{H}}^2\right)^2}}.$$

- Three interesting properties of pinching-antenna assisted positioning can be revealed.

Z. Ding, Pinching-Antenna Assisted ISAC: A CRLB Perspective, IEEE WCL, submitted.

Pinching-Antenna Assisted ISAC: Property 1

Pinching antennas - uniform positioning accuracy
Conventional antennas - a significant disparity in accuracy

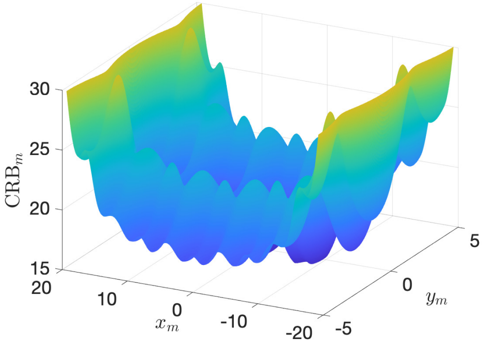


(g) Conventional Antennas (h) Pinching Antennas

Z. Ding, Pinching-Antenna Assisted ISAC: A CRLB Perspective, IEEE WCL, submitted.

Pinching-Antenna Assisted ISAC: Property 2

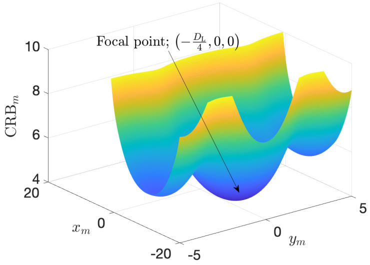
Local maximum of CRLB - Conflict between sensing and communications



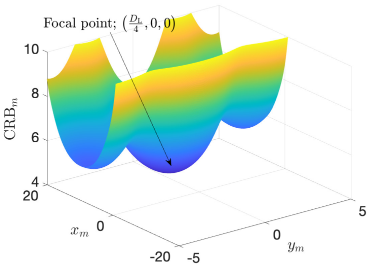
Z. Ding, Pinching-Antenna Assisted ISAC: A CRLB Perspective, IEEE WCL, submitted.

Pinching-Antenna Assisted ISAC: Property 3

Supporting user-centric flexible positioning



(i) Positioning with a focal point at $\left(-\frac{D_L}{4}, 0, 0\right)$



(j) Positioning with a focal point at $\left(\frac{D_L}{4}, 0, 0\right)$

Z. Ding, Pinching-Antenna Assisted ISAC: A CRLB Perspective, IEEE WCL, submitted.

Outline

Conclusions

- Capability to create strong LoS links between the transceivers - large-scale path losses and LoS blockage can be effectively mitigated by activating antennas close to users.
- Reconfigurability of pinching-antenna systems - the topology of a pinching-antenna array, e.g., the locations and the number of pinching antennas, can be flexibly adjusted.
- Practicality - DOCOMO's prototype shows that pinching antennas can be flexibly deployed in a low-cost manner.

Thank you for your attention!
Articles and their codes are available at GitHub

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Z. Yang, N. Wang, Y. Sun, Z. Ding, R. Schober, G. K. Karagiannidis, V. W. S. Wong, O. A. Dobre, Pinching Antennas: Principles, Applications and Challenges, IEEE Wireless Commun., revised.
Z. Wang, C. Ouyang, X. Mu, Y. Liu, Z. Ding, Pinching-Antenna Systems (PASS): Architecture Designs, Opportunities, and Outlook, IEEE Commun. Magazine, submitted.