ISAC with Backscattering RFID Tags: Joint Beamforming Design

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IEEE International Conference on Communications (ICC), 2024

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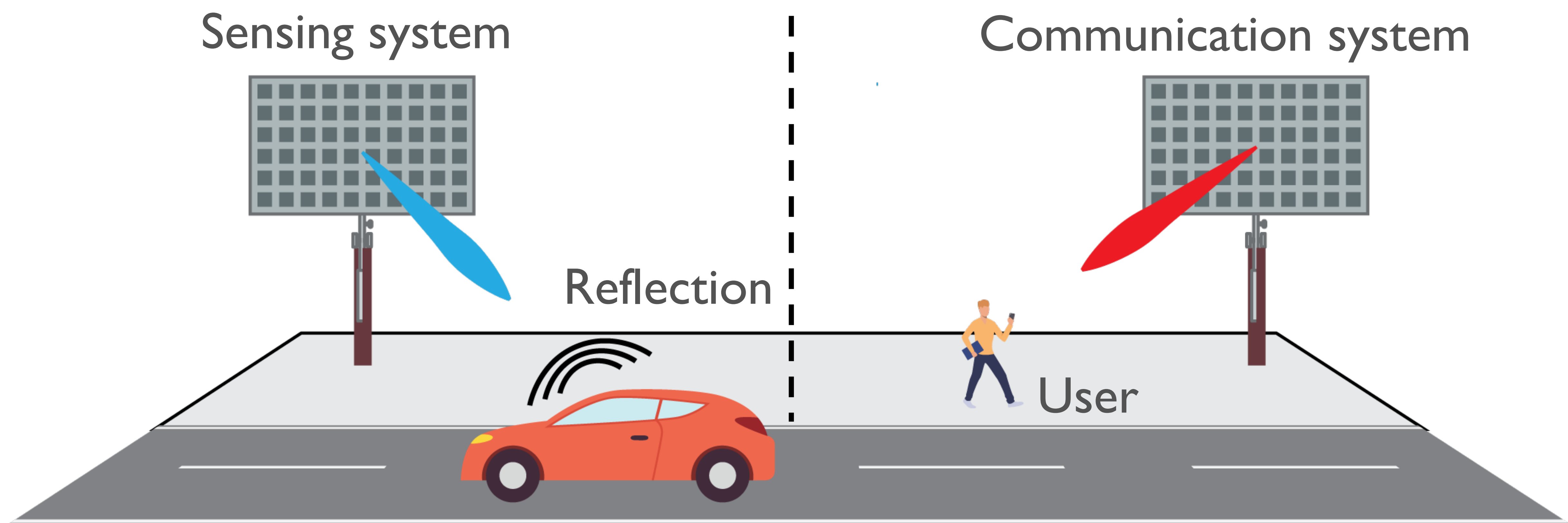
Motivation of ISAC

- Sensing and communication systems have developed independently over the past few decades



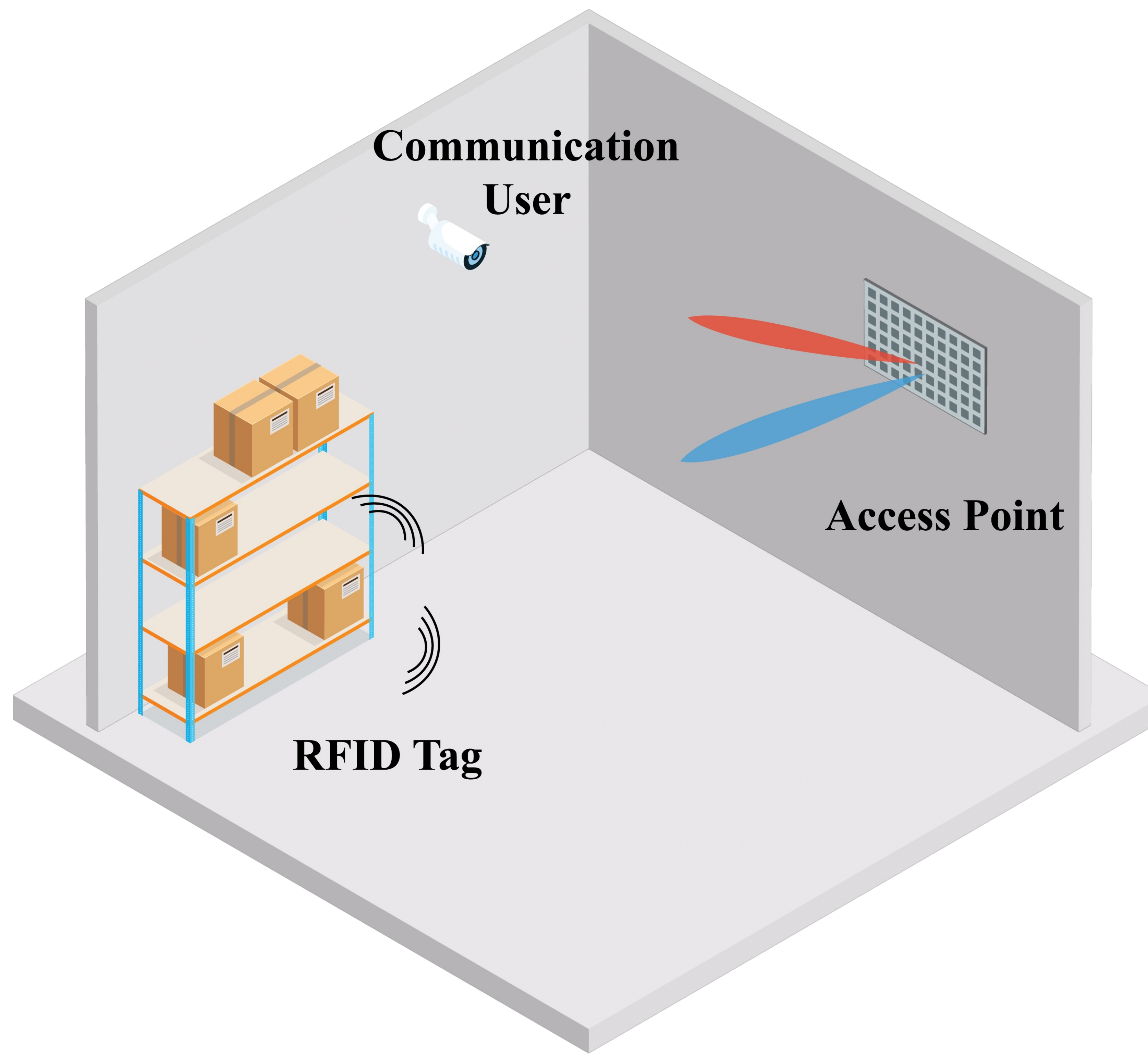
- Recently, emerging applications, such as smart city/industry, have motivated the study of integrated sensing and communication (ISAC) systems
  - The coexistence of two functions in a single system
  - Resource efficiency (spectrum/energy/hardware)
  - Mutual benefits between sensing and communication

Interest in ISAC is growing in both academia and industry

[Liu'22] Liu, F., et al. (2022). Integrated sensing and communications: Toward dual-functional wireless networks for 6G and beyond. *IEEE journal on selected areas in communications*, *40*(6), 1728-1767.

Motivation of ISAC-backscattering system

- Radio frequency identification (RFID)
  - Replace barcodes with low-cost passive RFID tags
  - Inventory management in warehouse or retail store
- RFID is a potential scenario of ISAC
  - Smart inventory management
  - Track goods by reading passive RFID tags
  - Transmit signals to comm. users, e.g. camera
- Challenges
  - Limited reading range (lack of build-in power)
  - Mutual interference between sensing and comm.



Can we address these challenges with joint MIMO beamforming design?

Prior work

- MIMO beamforming design for ISAC system [Liu'20, Zhao'22]
  - Leverage the spatial degrees of freedom provided by MIMO to reduce the interference
- MIMO beamforming design for RFID system [Chen'16, Wang'19]
  - Utilize the beamforming gain provided by multiple antennas to enhance the reading range of the tags
- Integrated sensing and backscattering communication [Gal'23]
  - Employ beamforming to communicate with a user, while broadcasting sensing signal to read a tag
  - Analyze comm. and sensing performance under different power allocation

Neglect the requirements of reading RFID tag, e.g., sensitivity

Transmit beamforming is not applied to RFID reading

[Liu'20] Liu, X., et al. (2020). Joint transmit beamforming for multiuser MIMO communications and MIMO radar. *IEEE Transactions on Signal Processing*, *68*, 3929-3944.

[Zhao'22] Zhao, N., et al. (2022). Joint transmit and receive beamforming design for integrated sensing and communication. *IEEE Communications Letters*, *26*(3), 662-666.

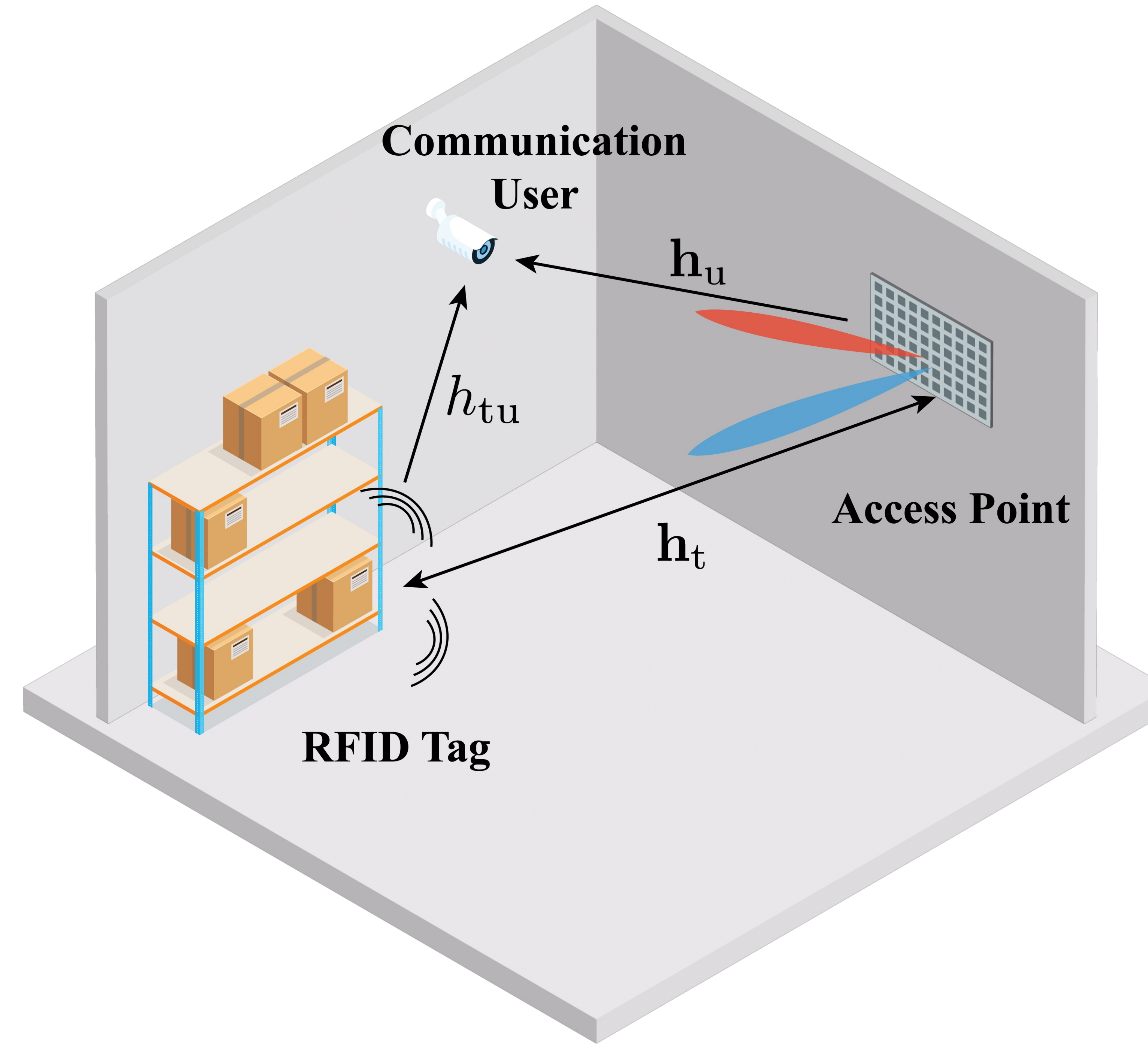
[Chen'16] Chen, S., Zhong, S., Yang, S., & Wang, X. (2016). A multiantenna RFID reader with blind adaptive beamforming. *IEEE Internet of Things Journal*, *3*(6), 986-996.

[Wang'19] Wang, J., et al. (2019). Pushing the range limits of commercial passive RFIDs. In *16th USENIX Symposium on Networked Systems Design and Implementation (NSDI 19)* (pp. 301-316).

[Gal'23] Galappaththige, D., Tellambura, C., & Maaref, A. (2023). Integrated sensing and backscatter communication. *IEEE Wireless Communications Letters*.

System model:

- Access point (reader)
  - N_t transmitter antennas
  - N_r receiver antennas
  - Assume no signal leakage [Saad'14]
- A passive RFID tag
  - Single antenna
  - Backscatter the incident signal from the access point
  - Assume the position is known
- A communication user
  - Single antenna
  - Assume the position is fixed and known



[Saad'14] Saad, W., Zhou, X., Han, Z., & Poor, H. V. (2014). On the physical layer security of backscatter wireless systems. *IEEE transactions on wireless communications*, *13*(6), 3442-3451.

System model:

- **Signal model**
  - Transmit signal: $\mathbf{x} = \mathbf{f}_t s_t + \mathbf{f}_u s_u$
    - Beamforming vectors: $\mathbf{f}_t$, $\mathbf{f}_u$
    - s_t → Sensing symbol
    - s_u → Comm. symbol

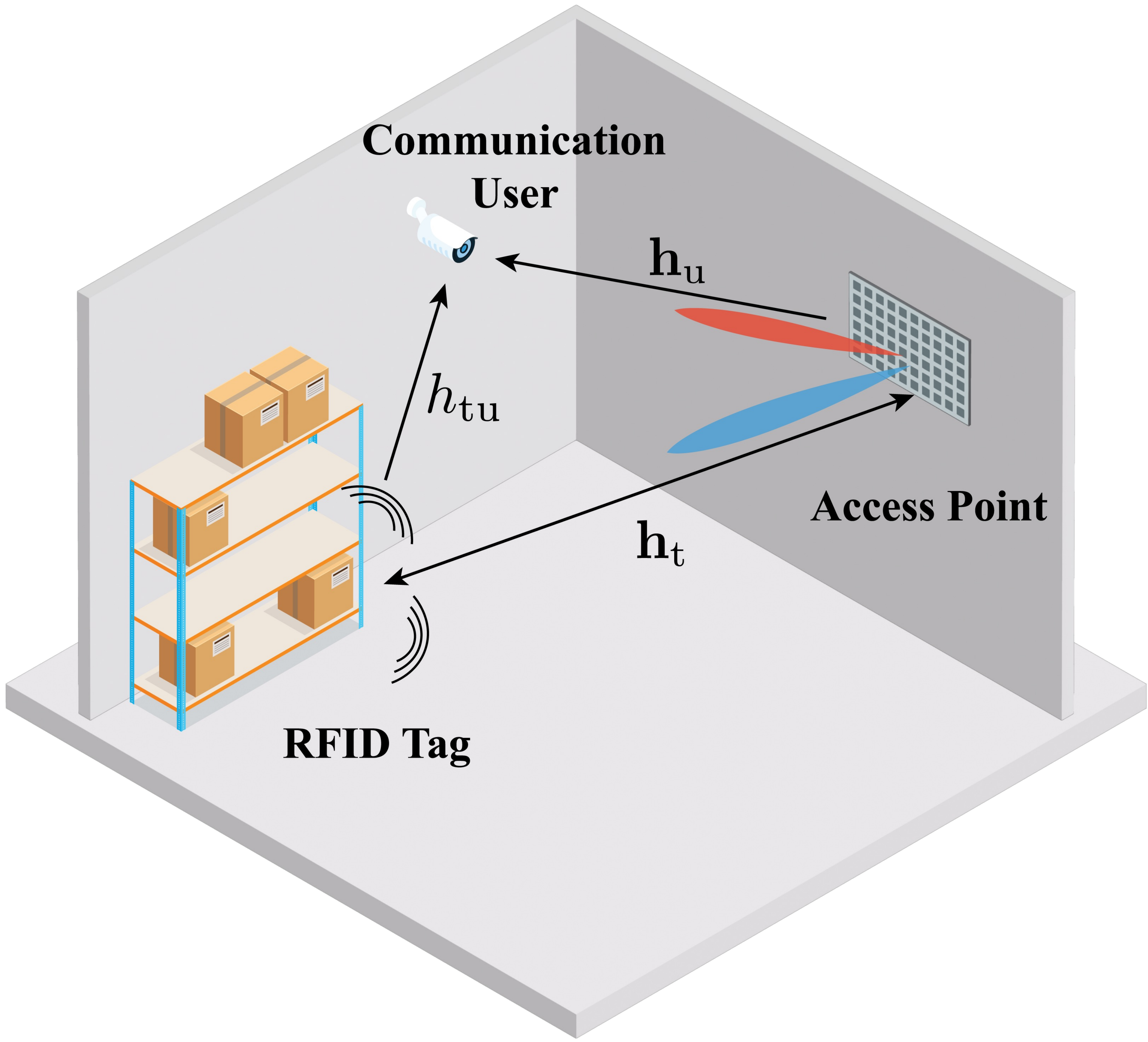
- **Backscattering model**
  - Received signal at the tag:

$$y_t = \mathbf{h}_t^H \mathbf{f}_t s_t + \mathbf{h}_t^H \mathbf{f}_u s_u + n_t$$

    - $\mathbf{h}_t^H$ → Channel between access point and tag
    - n_t → Normal Gaussian noise
  - Backscatter-modulated signal: $r = \sqrt{\eta}\, y_t\, d$
    - d → Tag's data
    - η → Backscatter modulation efficiency
  - Received signal at the reader:

$$y_r = \mathbf{w}^H \mathbf{h}_t\, r + \mathbf{w}^H \mathbf{n}_r$$
$$= \mathbf{w}^H \mathbf{h}_t \sqrt{\eta}\, d(\mathbf{h}_t^H \mathbf{f}_t s_t + \mathbf{h}_t^H \mathbf{f}_u s_u + n_t) + \mathbf{w}^H \mathbf{n}_r$$

    - $\mathbf{w}$ → Combining vector



System model:

- Tag reading requirements
  - Received SINR at the tag

$$\mathrm{SINR_t} = \frac{|\mathbf{h}_t^H \mathbf{f}_t|^2}{|\mathbf{h}_t^H \mathbf{f}_u|^2 + \sigma_t^2}$$

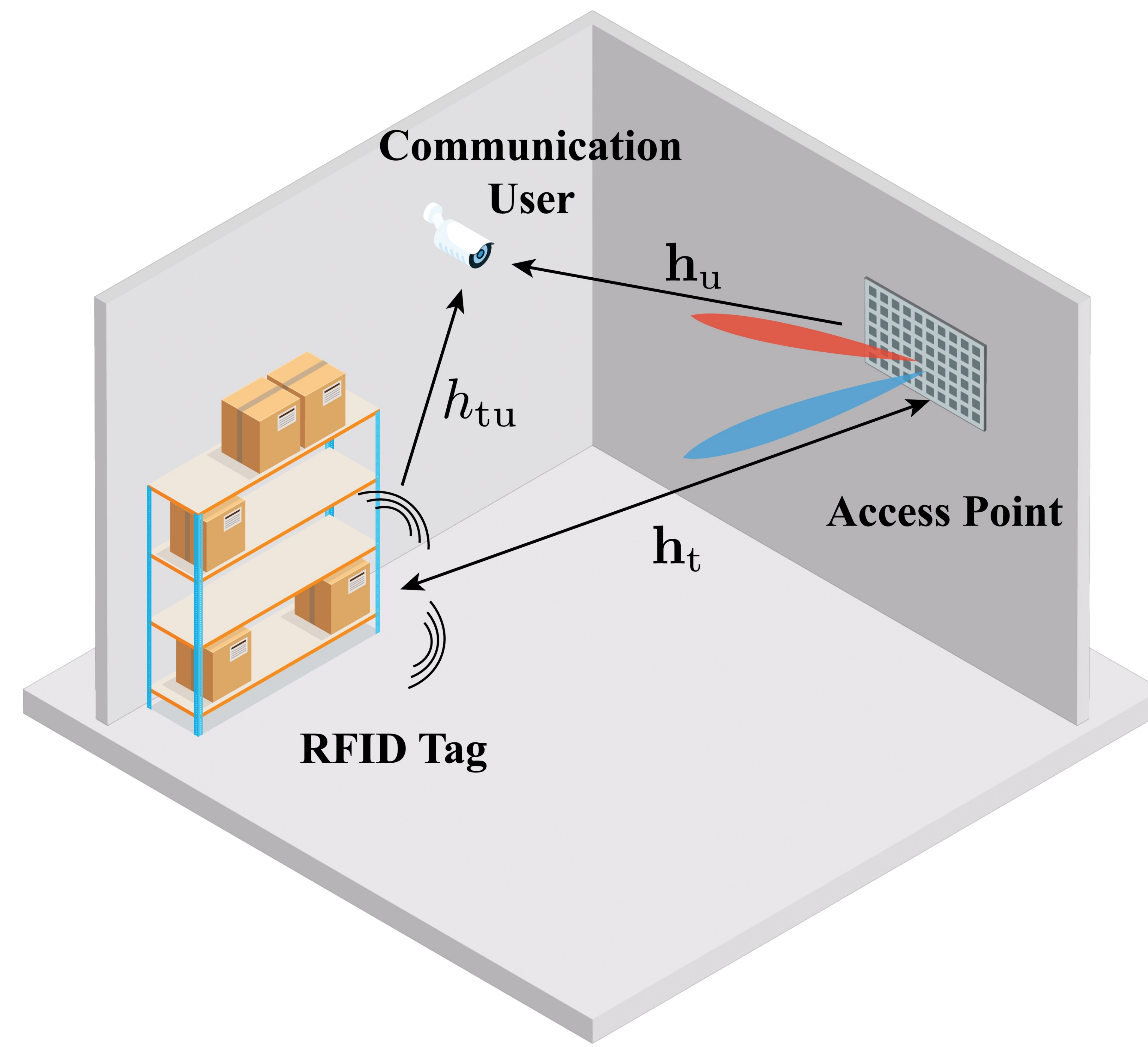
  - Received SINR at the reader

$$\mathrm{SINR_r} = \frac{\eta |\mathbf{w}^H \mathbf{h}_t|^2 |\mathbf{h}_t^H \mathbf{f}_t|^2}{\eta |\mathbf{w}^H \mathbf{h}_t|^2 |\mathbf{h}_t^H \mathbf{f}_u|^2 + \eta\, \sigma_t^2 |\mathbf{w}^H \mathbf{h}_t|^2 + \sigma_r^2}$$

  - Successful tag reading

$\mathrm{SINR_t} \geq \gamma_\mathrm{t}$ ⟶ Tag's sensitivity constraint

$\mathrm{SINR_r} \geq \gamma_\mathrm{r}$ ⟶ Reader's sensitivity constraint



[Chen'16] Chen, S., Zhong, S., Yang, S., & Wang, X. (2016). A multiantenna RFID reader with blind adaptive beamforming. *IEEE Internet of Things Journal*, *3*(6), 986-996.

System model:

Communication model

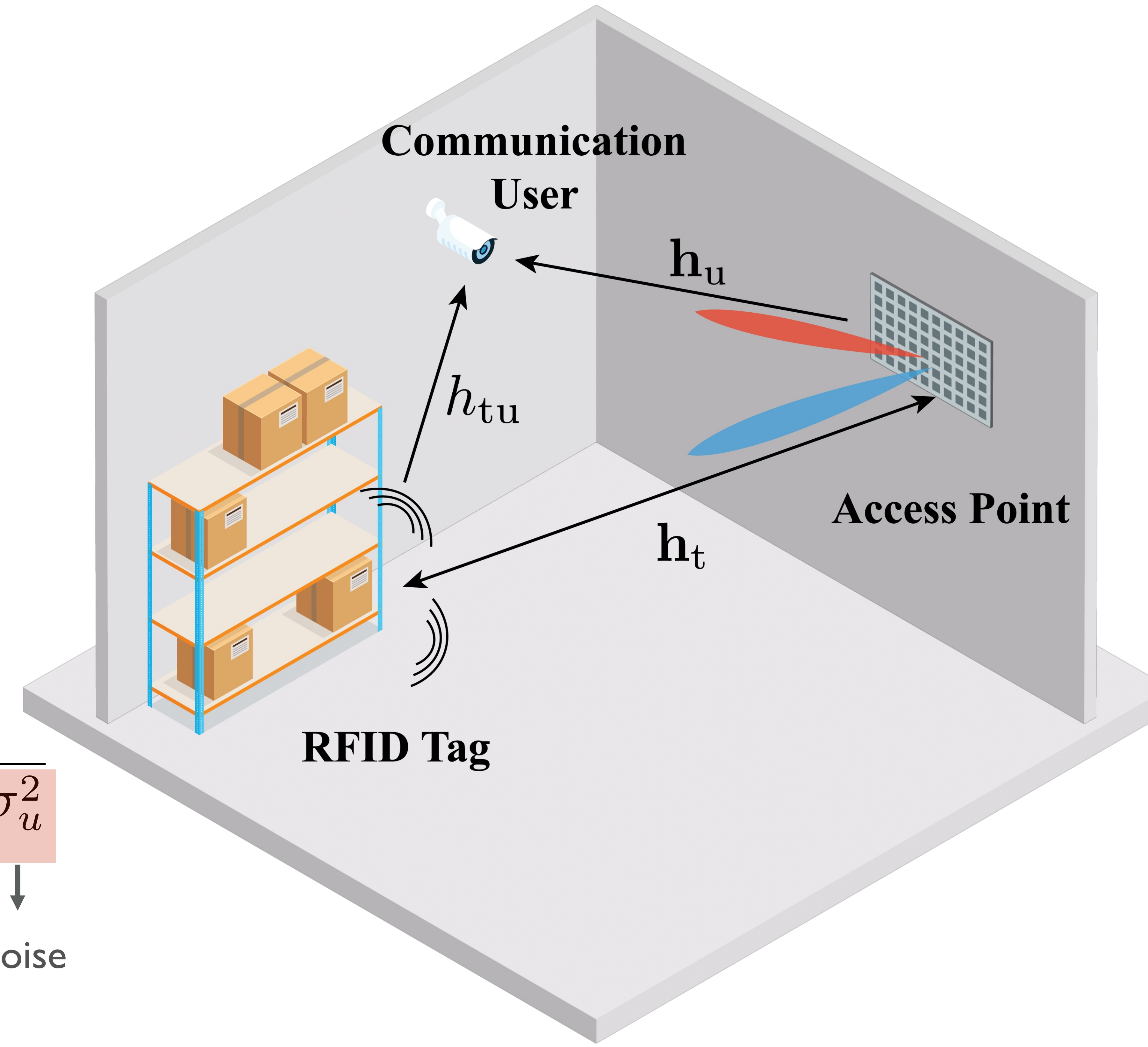
- Received signal at the user

$$y_u = \mathbf{h}_u^H \mathbf{x} + h_{tu} r + n_u$$
$$= \mathbf{h}_u^H \mathbf{f}_u s_u + \mathbf{h}_u^H \mathbf{f}_t s_t$$
$$+ h_{tu}\sqrt{\eta}\, d(\mathbf{h}_t^H \mathbf{f}_t s_t + \mathbf{h}_t^H \mathbf{f}_u s_u + n_t) + n_u.$$

- Received SINR at the user

$$\mathrm{SINR_u} = \frac{|\mathbf{h}_u^H \mathbf{f}_u|^2}{|\mathbf{h}_u^H \mathbf{f}_t|^2 + \eta |h_{tu}|^2 (|\mathbf{h}_t^H \mathbf{f}_t|^2 + |\mathbf{h}_t^H \mathbf{f}_u|^2 + \sigma_t^2) + \sigma_u^2}$$

Sensing signal — Backscattered signal — Noise



Problem formulation

- Assumptions
  - The communication channel and the tag's position are known to the access point

- Problem formulation

$$\begin{aligned} \text{find} \quad & \{\mathbf{f}_t, \mathbf{f}_u\} \\ \text{s.t.} \quad & \text{SINR}_u \geq \gamma_u, \\ & \text{SINR}_t \geq \gamma_t, \\ & \text{SINR}_r \geq \gamma_r, \\ & \|\mathbf{f}_t\|^2 + \|\mathbf{f}_u\|^2 \leq P. \end{aligned}$$

Feasibility check of beamforming vectors

Communication requirement ($\text{SINR}_u \geq \gamma_u$)

Tag reading requirement ($\text{SINR}_t \geq \gamma_t$, $\text{SINR}_r \geq \gamma_r$)

Transmit power constraint ($\|\mathbf{f}_t\|^2 + \|\mathbf{f}_u\|^2 \leq P$)

- The feasibility problem above may have multiple solutions, and the most desirable is the one with the minimal power

We propose two approaches to solve this problem

Approach I: Zero-forcing beamforming with power allocation

- Zero-forcing beamforming
  - Project the tag's channel on the null-space of the user's channel, and vice versa

$$[\mathbf{f}_t^{\mathrm{ZF}}, \mathbf{f}_u^{\mathrm{ZF}}] = \mathbf{H}(\mathbf{H}^H\mathbf{H})^{-1}$$

Stacked channel $\mathbf{H} = [\mathbf{h}_t, \mathbf{h}_u]$

Leverage zero-forcing to design beamforming vectors

$$\mathbf{f}_t = \sqrt{P_t}\,\bar{\mathbf{f}}_t = \sqrt{P_t}(\mathbf{f}_t^{\mathrm{ZF}}/\|\mathbf{f}_t^{\mathrm{ZF}}\|)$$

$$\mathbf{f}_u = \sqrt{P_u}\,\bar{\mathbf{f}}_u = \sqrt{P_u}(\mathbf{f}_u^{\mathrm{ZF}}/\|\mathbf{f}_u^{\mathrm{ZF}}\|)$$

Allocated power

- Power minimization problem

$$\begin{aligned} \min_{P_t, P_u} \quad & P_t + P_u \\ \text{s.t.} \quad & \mathrm{SINR_u} \geq \gamma_\mathrm{u}, \\ & \mathrm{SINR_t} \geq \gamma_\mathrm{t}, \\ & \mathrm{SINR_r} \geq \gamma_\mathrm{r}, \\ & P_t + P_u \leq P. \end{aligned}$$

Optimization of power allocation

Communication requirement ($\mathrm{SINR_u} \geq \gamma_\mathrm{u}$)

Tag reading requirement ($\mathrm{SINR_t} \geq \gamma_\mathrm{t}$, $\mathrm{SINR_r} \geq \gamma_\mathrm{r}$)

Transmit power constraint ($P_t + P_u \leq P$)

The problem is a linear programming, which can be solved by convex solvers

Approach II: Joint beamforming optimization

- Problem formulation

$$\min_{\mathbf{f}_t,\mathbf{f}_u} \quad \|\mathbf{f}_t\| + \|\mathbf{f}_u\|$$
$$\text{s.t.} \quad \mathrm{SINR_u} \geq \gamma_\mathrm{u},$$
$$\mathrm{SINR_t} \geq \gamma_\mathrm{t},$$
$$\mathrm{SINR_r} \geq \gamma_\mathrm{r},$$
$$\|\mathbf{f}_t\|^2 + \|\mathbf{f}_u\|^2 \leq P.$$

Optimization of beamforming vectors

$$\frac{|\mathbf{h}_u^H\mathbf{f}_u|^2}{|\mathbf{h}_u^H\mathbf{f}_t|^2 + \eta|h_{tu}|^2(|\mathbf{h}_t^H\mathbf{f}_t|^2 + |\mathbf{h}_t^H\mathbf{f}_u|^2 + \sigma_t^2) + \sigma_u^2} \geq \gamma_u$$

$$\frac{1}{\gamma_u}|\mathbf{h}_u^H\mathbf{f}_u|^2 \geq |\mathbf{h}_u^H\mathbf{f}_t|^2 + \eta|h_{tu}|^2(|\mathbf{h}_t^H\mathbf{f}_t|^2 + |\mathbf{h}_t^H\mathbf{f}_u|^2 + \sigma_t^2) + \sigma_u^2$$

$$|\mathbf{h}_u^H\mathbf{f}_u| = \mathrm{Re}\left\{\mathbf{h}_\mathrm{u}^\mathrm{H}\mathbf{f}_\mathrm{u}\right\}$$

$$\sqrt{\frac{1}{\gamma_u}}\mathrm{Re}\left\{\mathbf{h}_u^H\mathbf{f}_u\right\} \geq \left\| \begin{matrix} \mathbf{h}_u^H\mathbf{f}_t \\ \sqrt{\eta}\,h_{tu}\,\mathbf{h}_t^H\mathbf{f}_t \\ \sqrt{\eta}\,h_{tu}\,\mathbf{h}_t^H\mathbf{f}_u \\ \sqrt{\eta}\,h_{tu}\,\sigma_t \\ \sigma_u \end{matrix} \right\|$$

Note: Arbitrary phase rotation can be added to the expression in an absolute w/o affecting the value. $|\mathbf{h}_u^H\mathbf{f}_u| = |\mathbf{h}_u^H\mathbf{f}_u e^{j\theta}|$

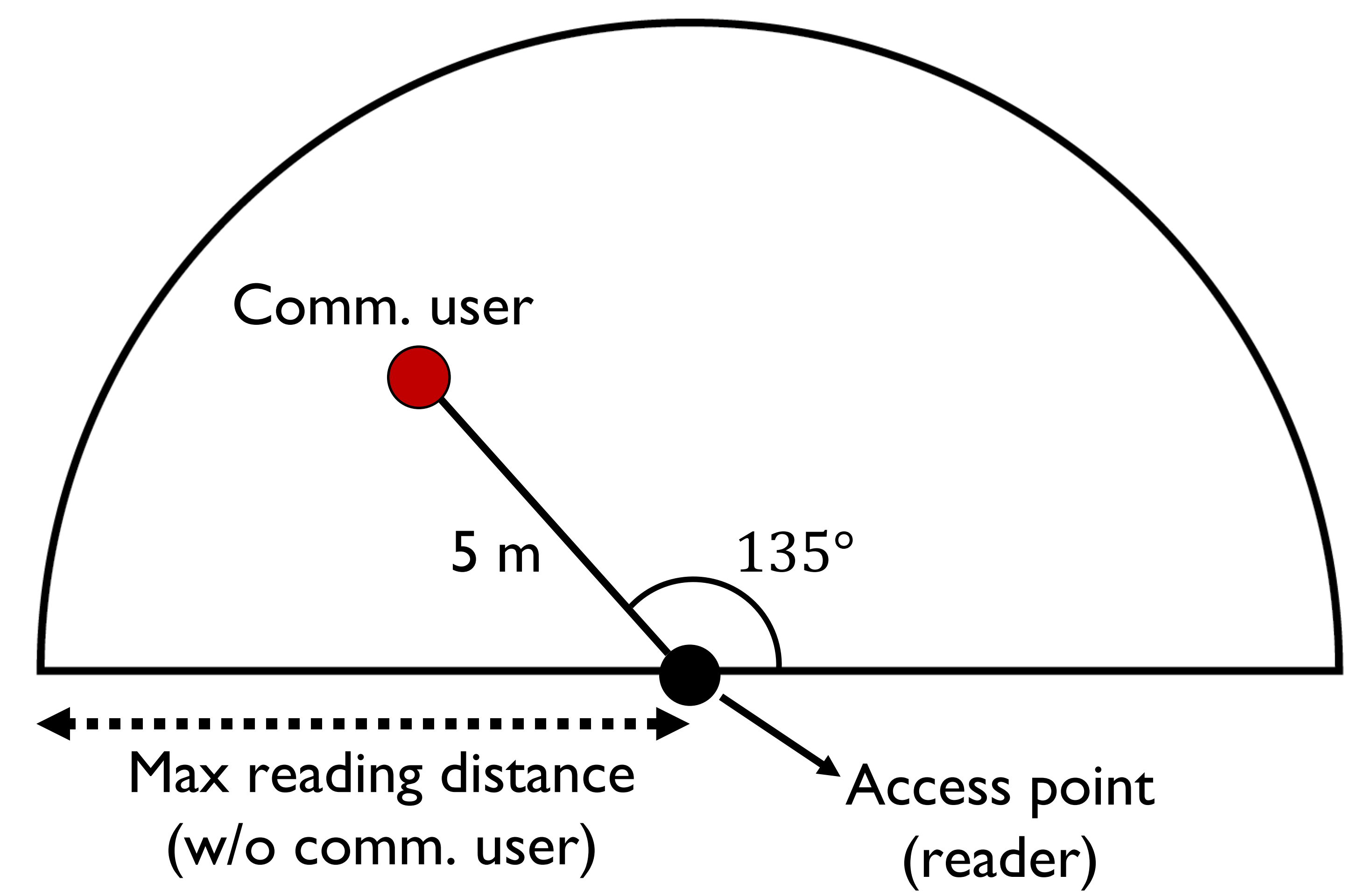
The problem can be transformed to SOCP and solved by convex solvers

[Bjö'14] Björnson, E., Bengtsson, M., & Ottersten, B. (2014). Optimal multiuser transmit beamforming: A difficult problem with a simple solution structure [lecture notes]. *IEEE Signal Processing Magazine*, *31*(4), 142-148.

Simulation setup

- System parameters
  - Uniform linear arrays at the access point
  - Operating frequency: 2.4 GHz
  - Total transmit power: 30 dBm
  - Noise power: $10\log_{10}(kTB) + N_f$ dBm
    - k: Boltzmann's constant
    - $T = 270$ Kelvvin
    - $B = 10$ MHz
    - $N_f = 7$ dB
  - Tag's sensitivity: -25.5 dBm
  - Reader's sensitivity: -94 dBm
  - Backscatter modulation efficiency: 0.16

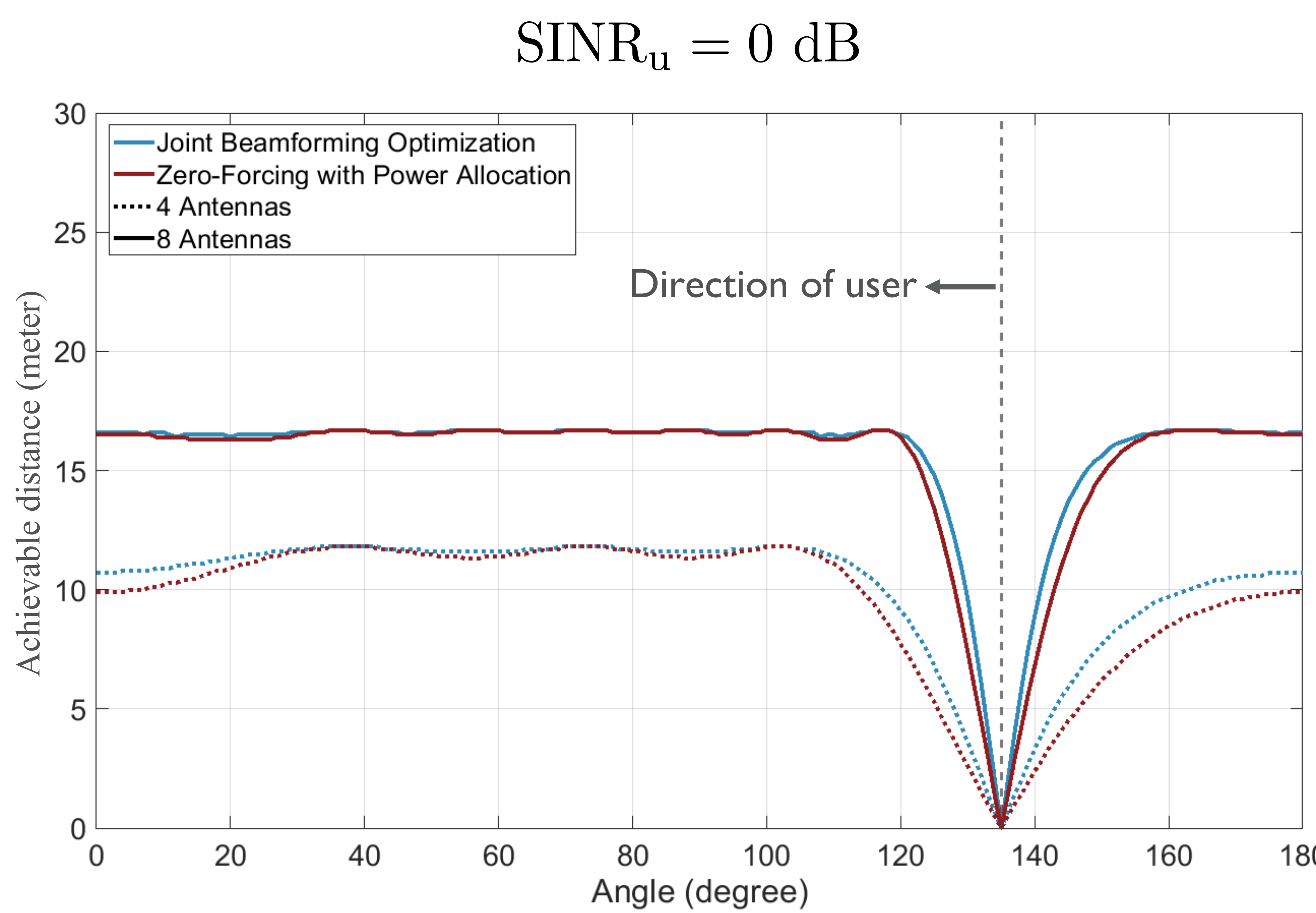
- Adopted environment layout



What is the achievable reading distance for a given tag's direction?

[RFIDTag] Impinj, RAIN RFID Tag Chips, M830/M850, 2023. [Online]. Available: https://support.impinj.com
[RFIDReader] Impinj, RAIN RFID Reader Chips, E910, 2023. [Online]. Available: https://support.impinj.com
[Nik'08] Nikitin, P. V., & Rao, K. S. (2008, April). Antennas and propagation in UHF RFID systems. In *2008 IEEE international conference on RFID* (pp. 277-288). IEEE.

Simulation results: Achievable reading distance

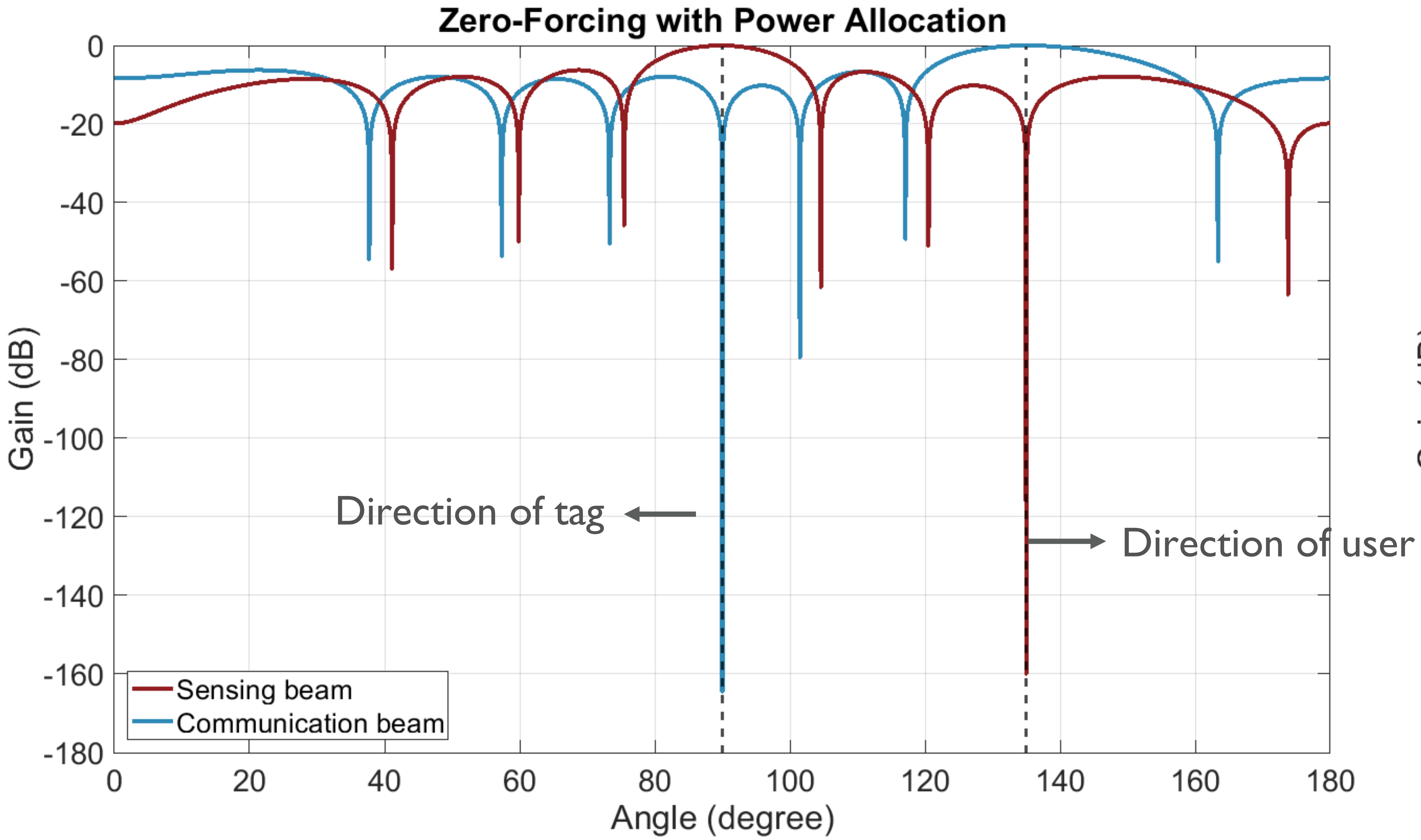


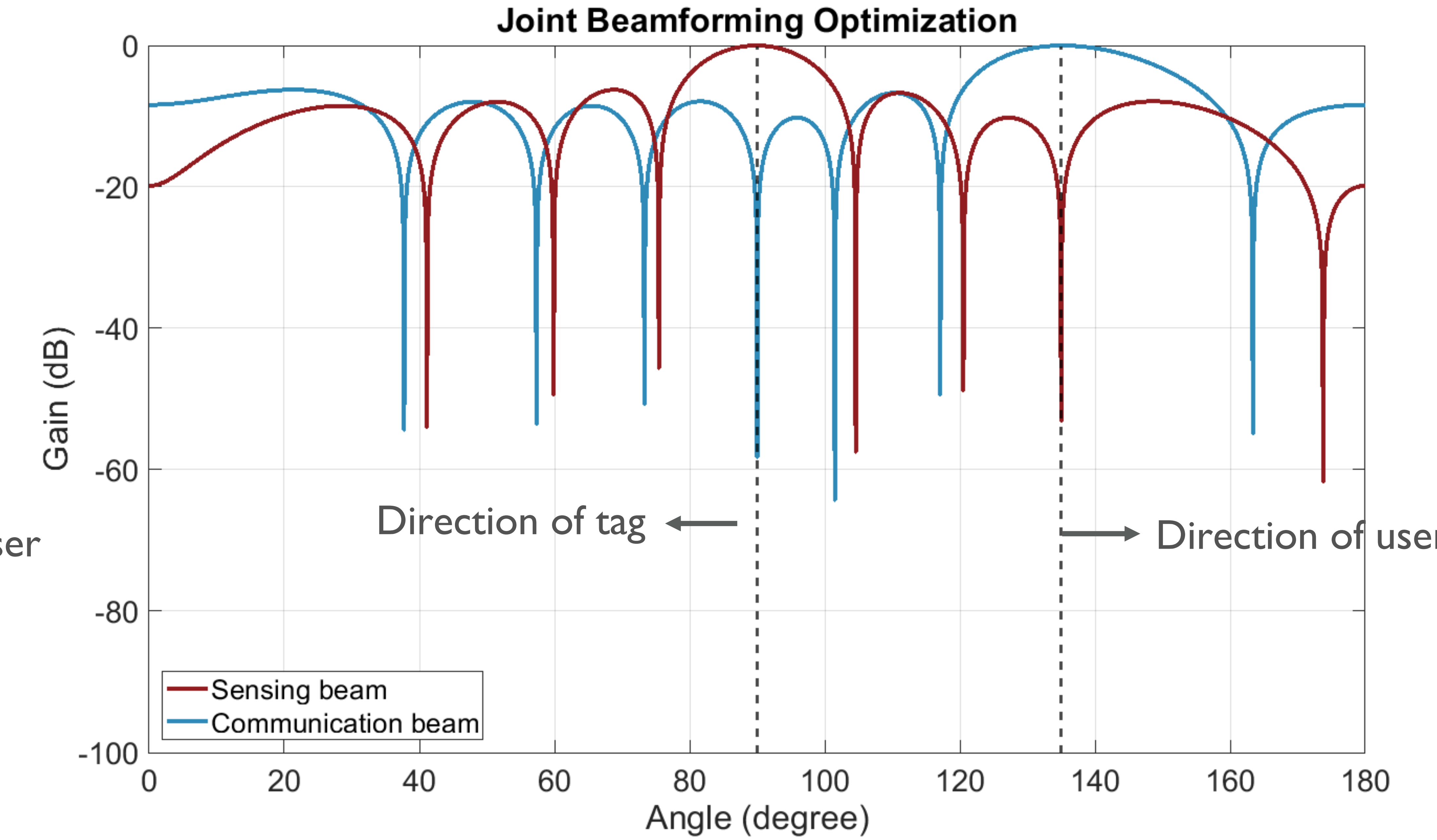
- The number of antenna is set to {4, 8}
- When the tag and user directions are close, the reading distance decreases due to high interference
- The achievable reading distance increases with the growing number of antennas

Beamforming gain can benefit the tag reading range

Joint beamforming opt. has better overall performance

Simulation results: Beamforming pattern





- The number of antenna is 8
- The directions of the tag and the user remain fixed at $90°$ and $135°$, respectively.
- The interference between sensing and comm. is suppressed by the designed beams

Joint BF opt. allows more freedom in the BF design

Conclusion and future work

- Explore the interplay between ISAC and RFID
  - ISAC allows sensing and comm. to coexist in a single system
  - Smart inventory management with RFID is a potential scenario of ISAC
- Address the challenges in the ISAC system with RFID tags
  - Limited reading range (beamforming)
  - Mutual interference (joint beamforming optimization)
- For the beamforming design, the results show that
  - Beamforming can benefit the reading range
  - Joint beamforming design is better than zero-forcing based method
- Future work
  - Extending the current work by considering unknown tag position
  - Considering the scenario with multiple users and multiple tags

The implementation of this paper is available at www.wi-lab.net

Q&A

Thank you!