Data-Modulating Reconfigurable Intelligent Surfaces via Spatial $\Sigma\Delta$ Modulation

An Alternative Way to Implement Massive MIMO Downlink Economically

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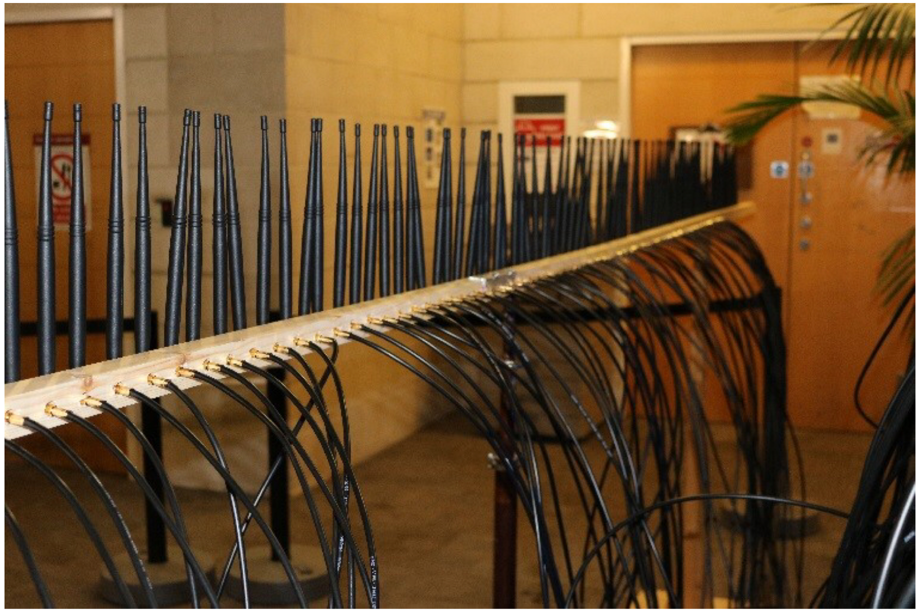
October 27, 2023

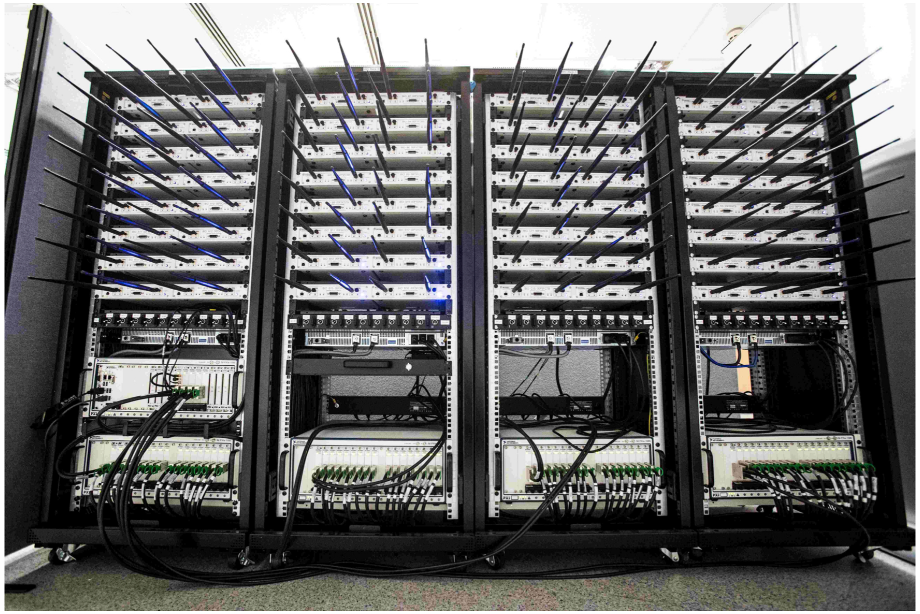
Agenda

- massive MIMO downlink: problem set-up & the challenge
- one-bit MIMO downlink via spatial $\Sigma\Delta$ modulation
- our work: spatial $\Sigma\Delta$ modulation for data-modulating RIS
- summary, acknowledgement, & conclusions

Massive MIMO Downlink

Massive MIMO

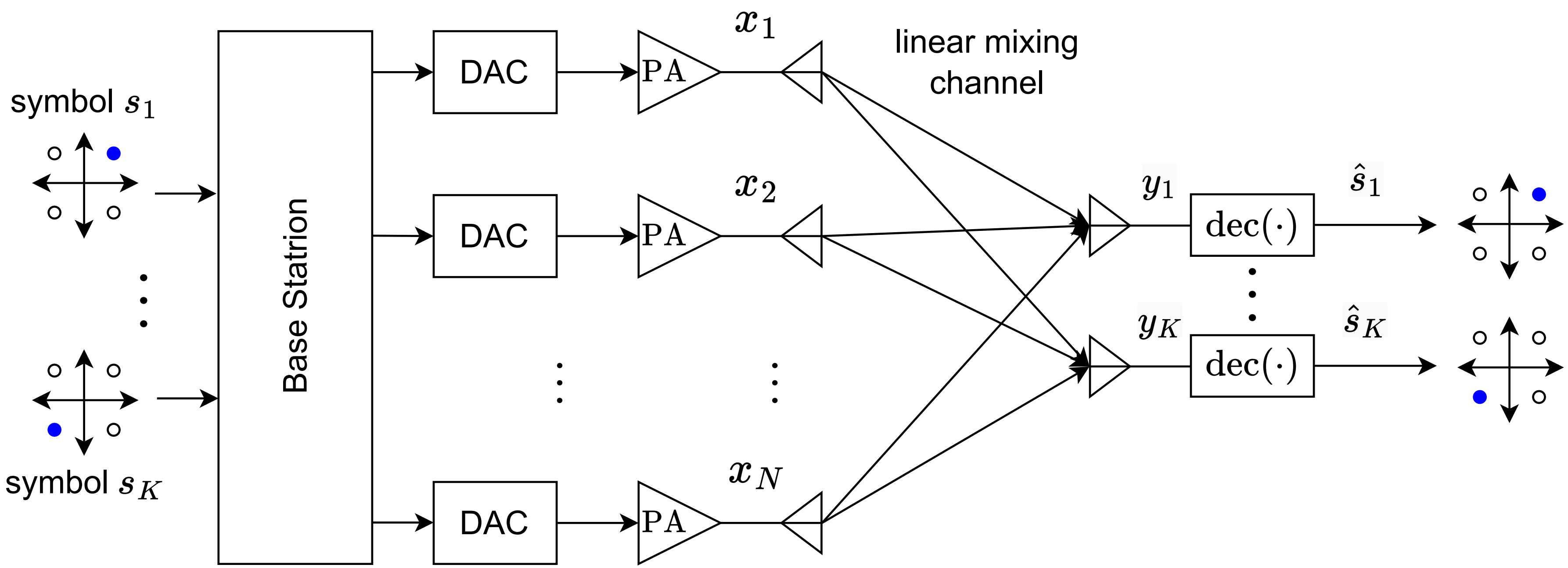




Source: P. Harris et al., "*An overview of massive MIMO research at the University of Bristol*," Radio Propagation and Technologies for 5G (2016), Durham, UK, 2016, pp. 1-5.

- massive MIMO promises many nice things for future gen. comm. sys.
- more antenna allows faster transmission, wider coverage and better QoS.

Classical MIMO Downlink Precoding



- a simple MU-MISO downlink system

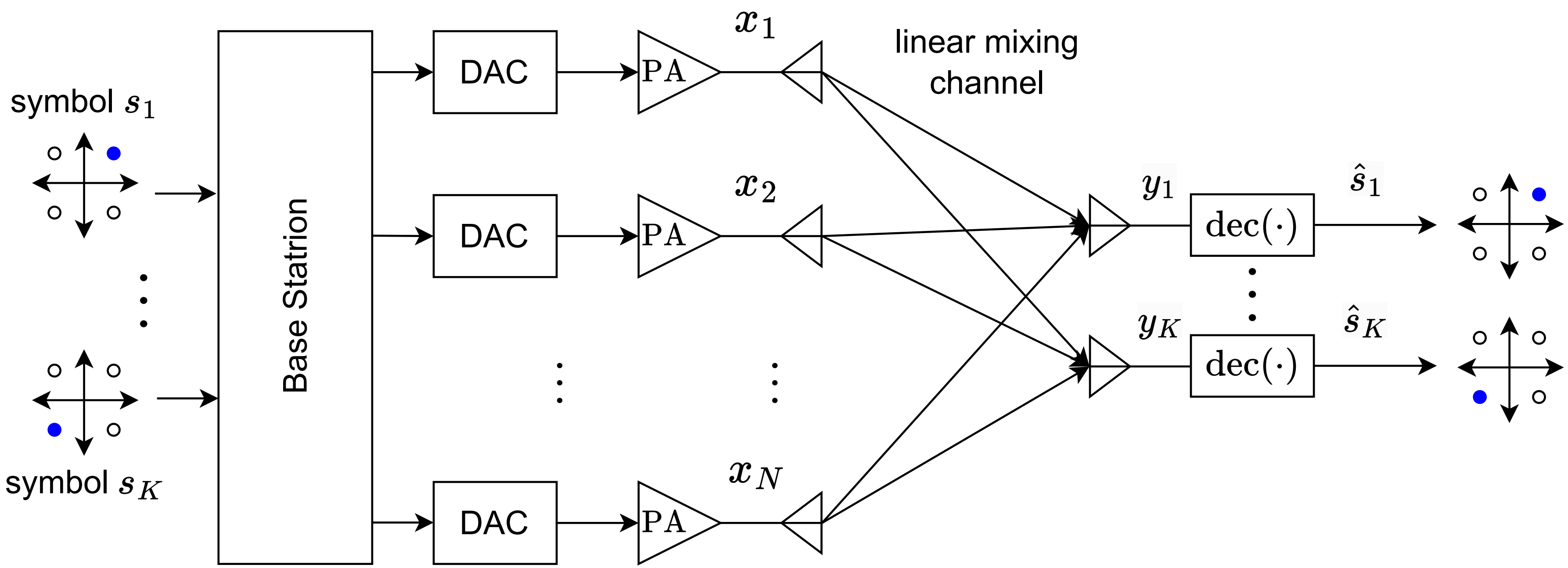
$$y_k = \boldsymbol{h}_k^\top \boldsymbol{x} + \text{noise}, \qquad k = 1, \ldots, K,$$

  is the received symbol; $\boldsymbol{h}_k$ is the channel gain vector

- precoding: given $\boldsymbol{h}_k$ and tx. symbol s_k at the BS, design a signal vector $\boldsymbol{x} \in \mathbb{C}^N$ such that the rx. symbol $y_k \approx c_k \cdot s_k$ (well studied)

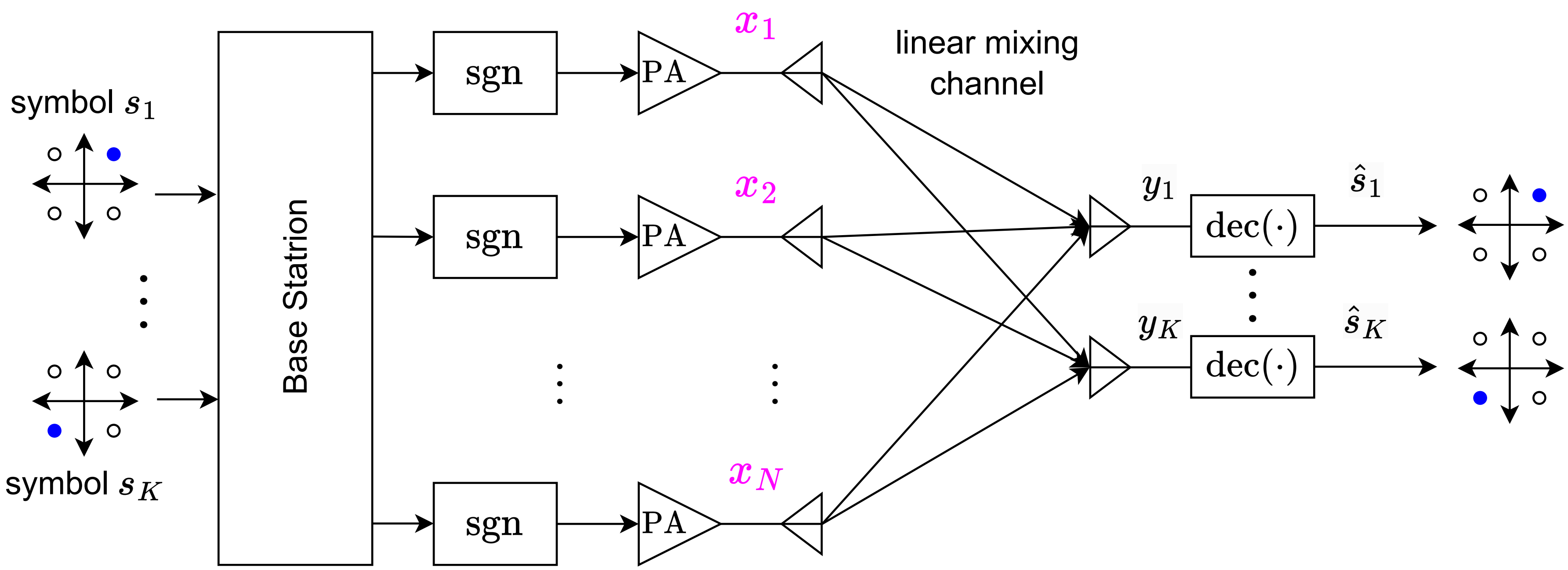
- hidden assumption: both DACs and PAs are assumed to be ideal

Massive MIMO Downlink: Challenges



- number of DACs and PAs increases as we go massive
- high res. DACs are not cheap to build
- PAs are power-hungry if they have a wide dynamic input range
- soln.: one-bit (or few-bit) MIMO precoding

One-Bit Massive MIMO Downlink



- rx. signal model: $y_k = \boldsymbol{h}_k^\top \boldsymbol{x} + \text{noise}$
- one-bit precoding: given $\boldsymbol{h}_k$ and a tx. symbol s_k at the BS, design a binary signal vector $\boldsymbol{x} \in \mathcal{X}^N = \{\pm 1 \pm \mathrm{j}\}^N$ such that the rx. symbol $y_k \approx c_k \cdot s_k$

One-Bit Massive MIMO Downlink: Existing Solutions

Precode-then-quantize

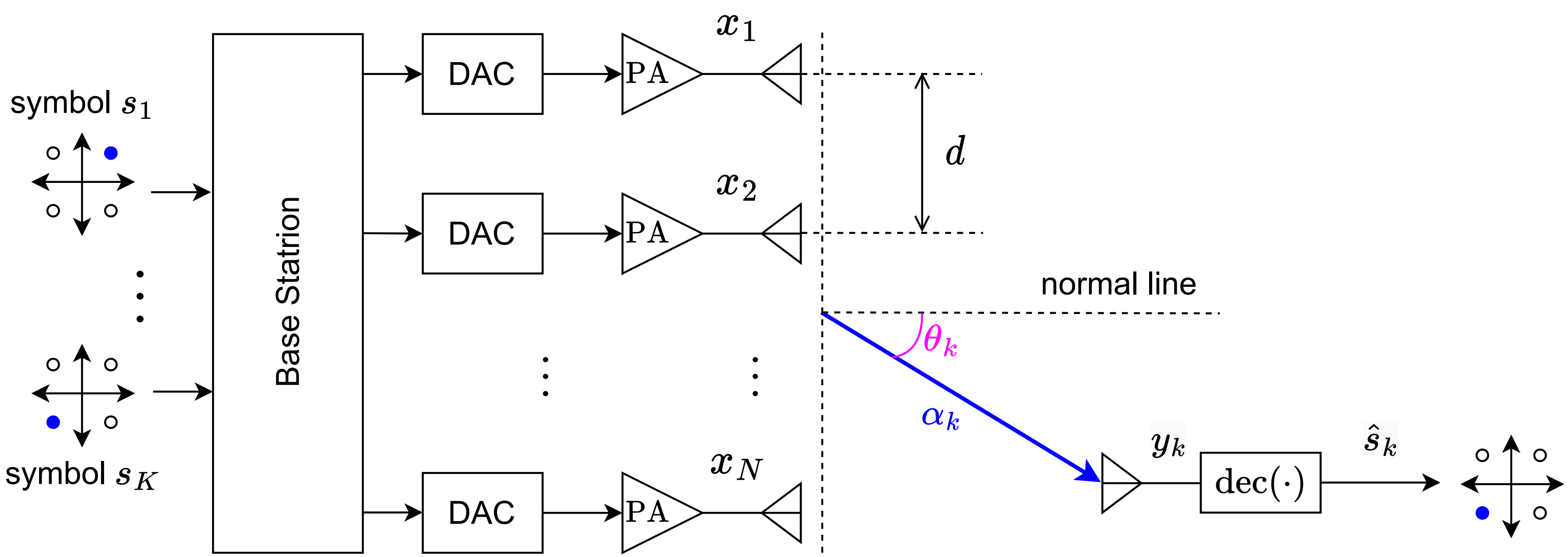
- put a conventional precoder in $\mathbb{C}^N$ (e.g. zero-forcing) through a one-bit quantizer
- results in heavy quantization error that causes performance loss
- easy to understand, fast in implementation

Direct Signal Design

- designs the one-bit signal by opt., needs to solve for large-scale binary problem
- typically requires higher computation complexity
- performance generally outperforms precode-then-quantize

Spatial $\Sigma\Delta$ mod.: a precode-then-quantize approach which, under some assumptions, gives a reasonable performance with limited complexity

Assumption: Uniform Linear Array



- assumption: **uniform linear array (ULA)**

$$\boldsymbol{h}_k = \alpha_k \, \boldsymbol{a}_k, \qquad \boldsymbol{a}_k = (0, e^{-\mathrm{j}\omega_k}, \ldots, e^{-\mathrm{j}\omega_k(N-1)}), \qquad \omega_k = \frac{2\pi d}{\lambda} \sin(\theta_k)$$

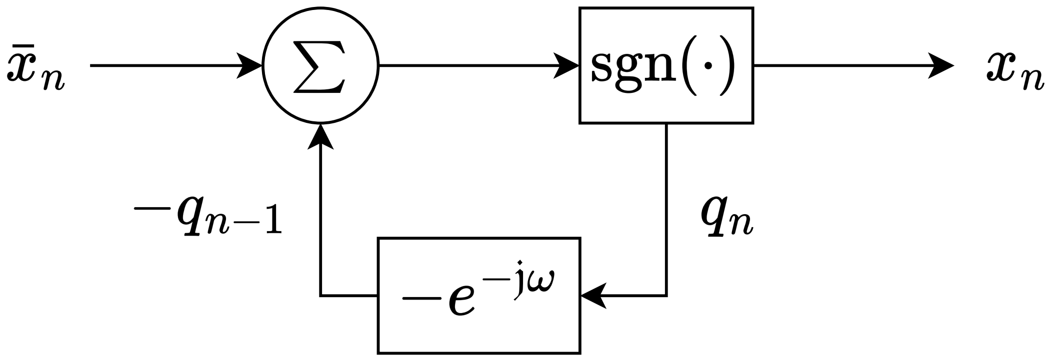
  where α_k is the channel gain, θ_k is the AoD; d is the antenna dist. and λ is the wavelength used

- observation: the noiseless rx signal model turns into a DTFT-like form

$$y_k = \alpha_k \cdot \boldsymbol{a}_k^\top \boldsymbol{x} = \alpha_k \textstyle\sum_{n=0}^{N-1} x_n e^{-\mathrm{j}\omega_k n}$$

Spatial Sigma Delta Modulation

Temporal Sigma Delta Modulation



- we first study a classical DAC: $\Sigma\Delta$ modulator[1]

- principle: given continuous-valued sequence $\bar{x}_n$, generate one-bit sequence x_n by

$$x_n = \operatorname{sgn}(\bar{x}_n - q_{n-1}) = \bar{x}_n - q_{n-1} + q_n$$

  where q_n is the quant. error incurred by the one-bit quantizer $\operatorname{sgn}(\cdot)$

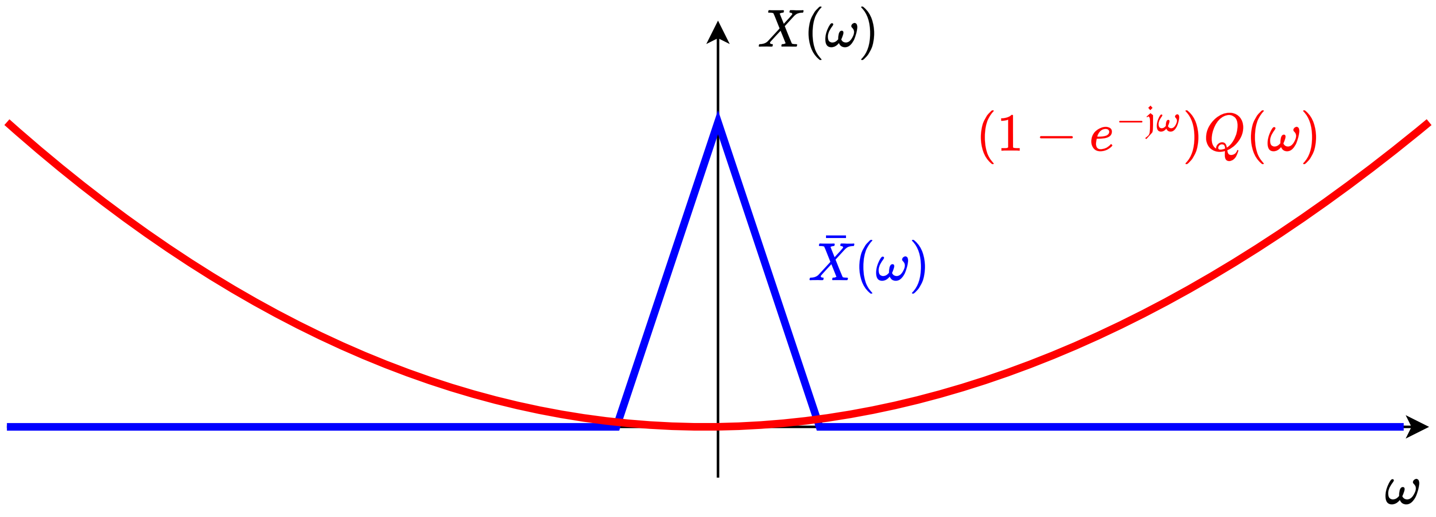
- observation: the DTFT of x_n follows:

$$\underbrace{X(\omega)}_{\text{one-bit output}} = \underbrace{\bar{X}(\omega)}_{\text{full res. input}} + \underbrace{(1 - e^{-j\omega})}_{\text{HPF}} \underbrace{Q(\omega)}_{\text{quant. error}}$$

[1] PM Aziz, HV Sorensen, and JVD Spiegel, *An overview of Sigma-Delta converters: How a 1-bit ADC achieves more than 16-bit resolution*, IEEE Sig. Proc. Mag. 13 (1996), no. 1, 61–84.

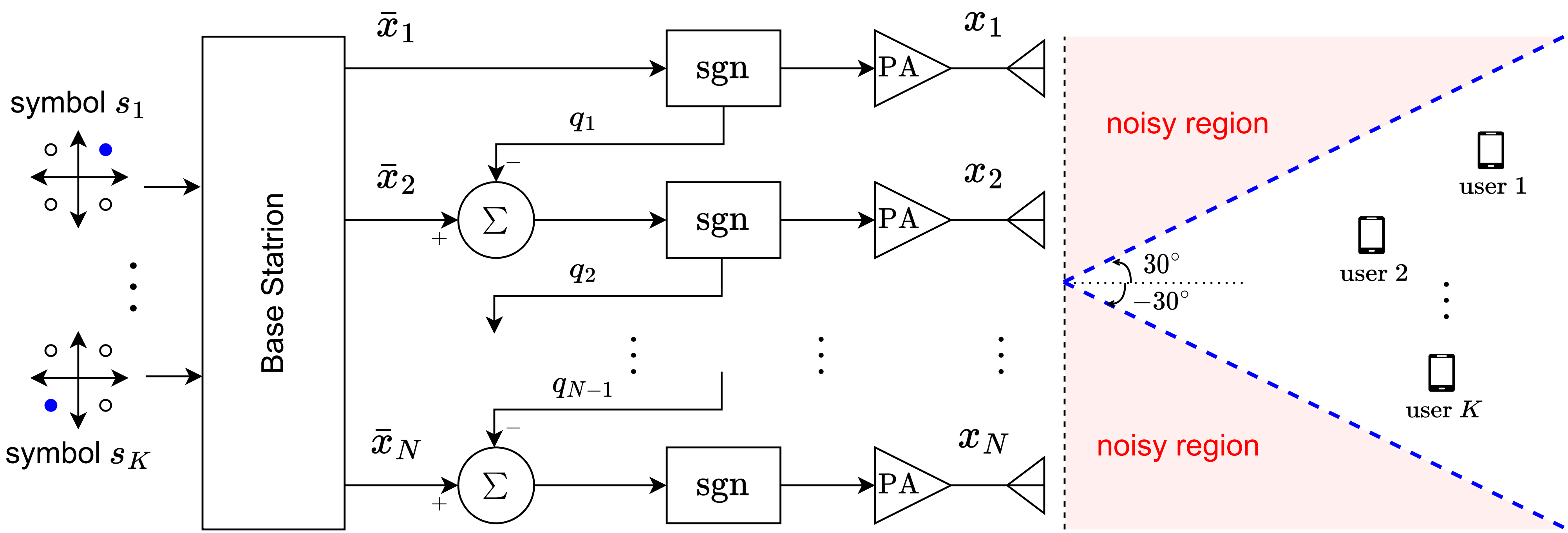
ΣΔ Principle: A Spectrum Illustration

$$\underbrace{X(\omega)}_{\text{one-bit output}} = \underbrace{\bar{X}(\omega)}_{\text{full res. input}} + \underbrace{(1 - e^{-\mathrm{j}\omega})}_{\text{HPF}} \underbrace{Q(\omega)}_{\text{quant. error}}$$



- assumptions: i) $\bar{X}(\omega)$ is low-pass and ii) $Q(\omega)$ is bounded and flat
- observation: quant. noise is shaped toward the high-pass region
- implication: apply LPF to recover the full res. $\bar{x}_n$ from the one-bit signal x_n

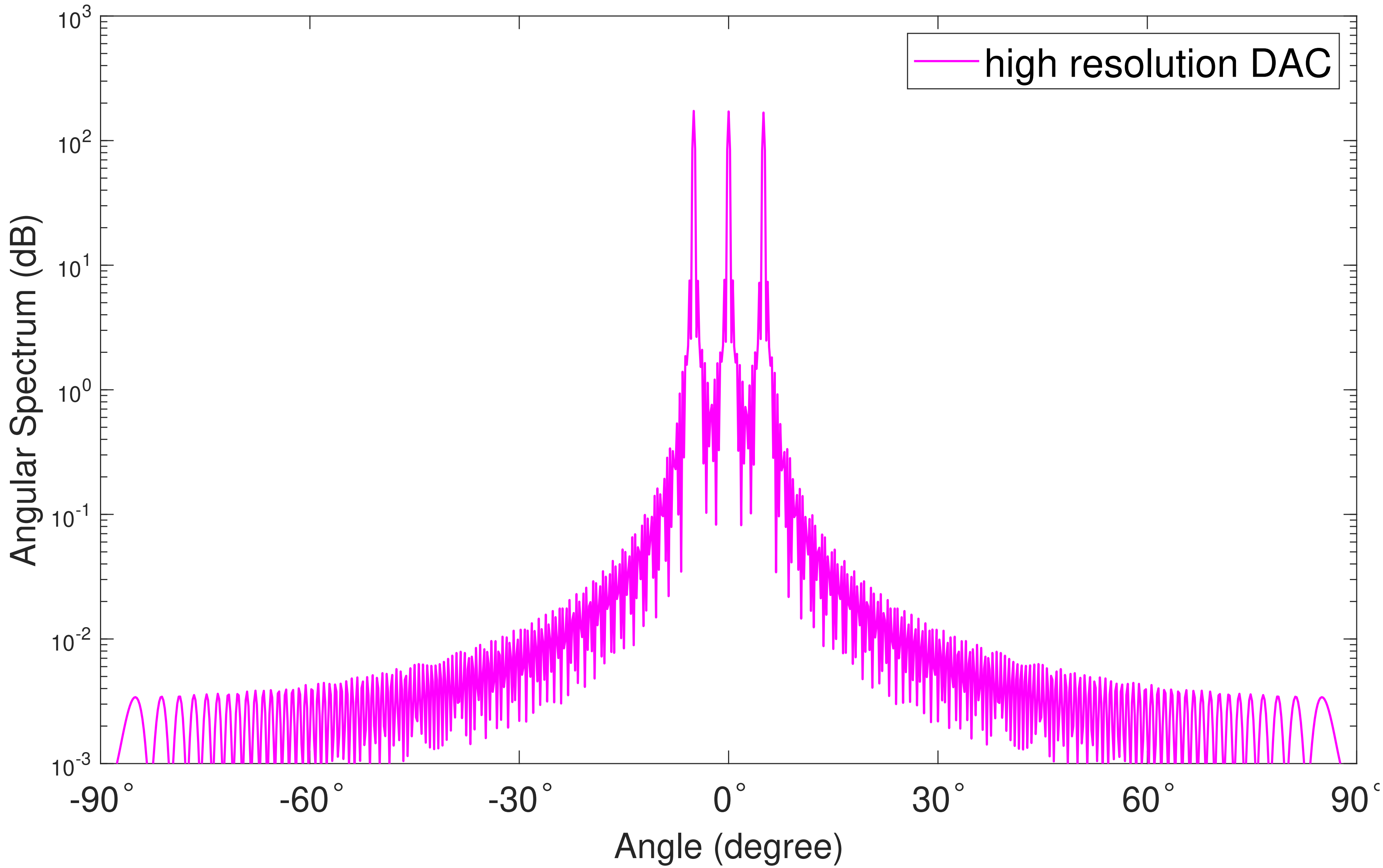
Spatial $\Sigma\Delta$ Modulator in MIMO Downlink[2]



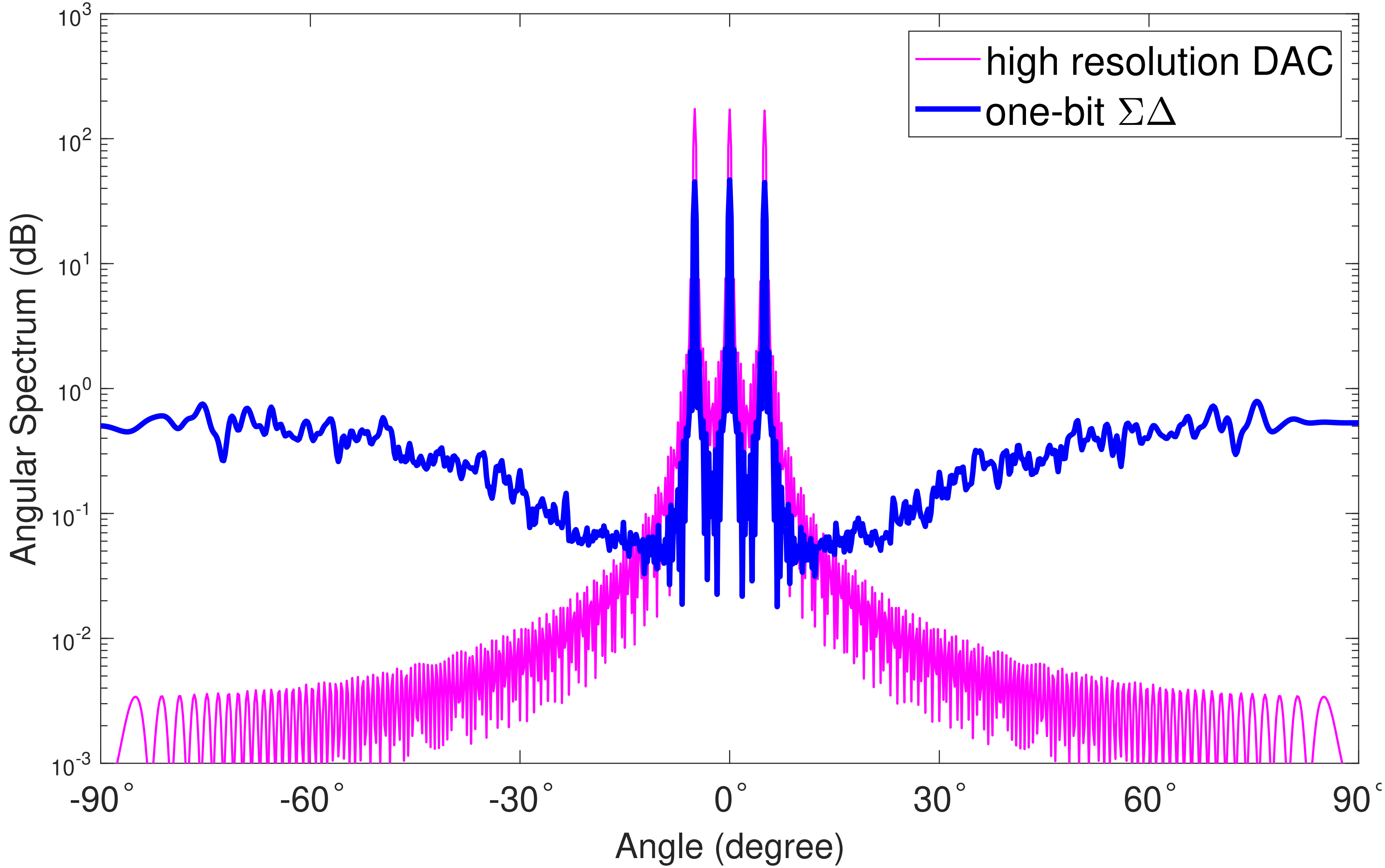
- putting $\Sigma\Delta$ to MIMO precoding we observe the following duality
  - signal at the time index n = tx. signal at the n-th antenna element
  - error feedback in temp. $\Sigma\Delta$ = passing q. error to the next antenna element
  - LPF in temp. $\Sigma\Delta$ = restrict users to lie in low angular region

[2]Mingjie Shao, Wing-Kin Ma, Qiang Li, and A Lee Swindlehurst, *One-bit Sigma-Delta MIMO precoding*, IEEE J. Sel. Topics Sig. Proc. 13 (2019), no. 5, 1046–1061.

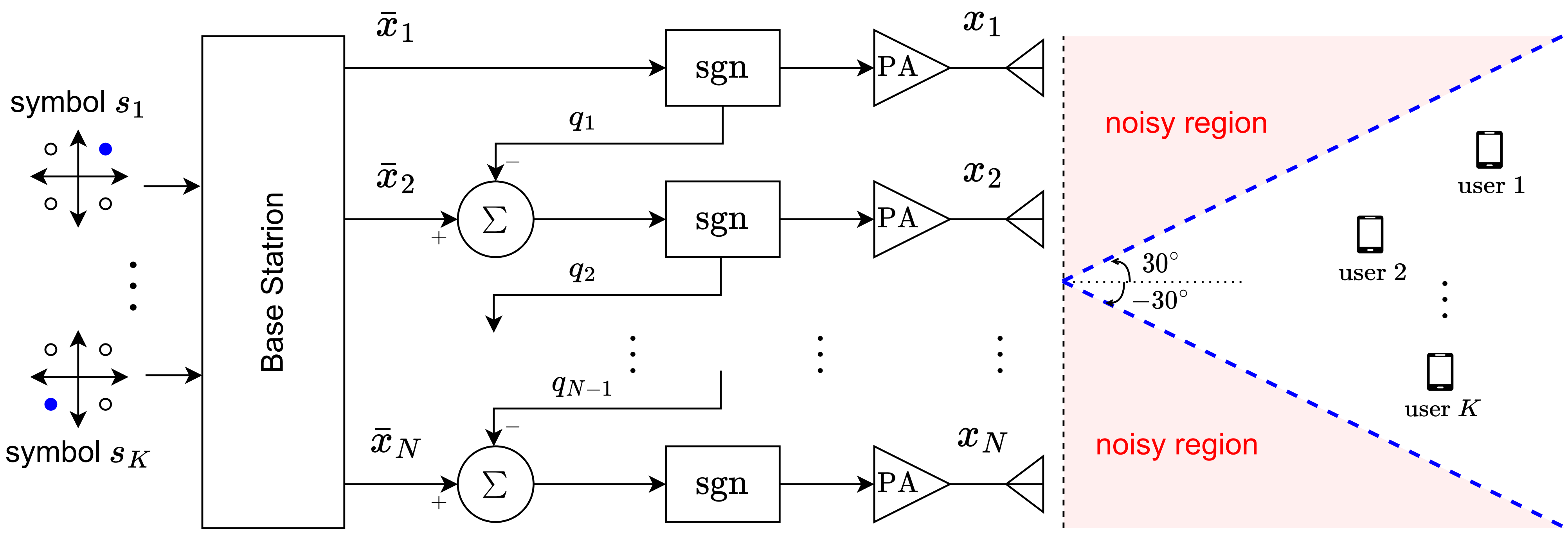
Proof of Concept: Angular Power Spectrum



Proof of Concept: Angular Power Spectrum



Spatial ΣΔ Modulator in MIMO Precoding

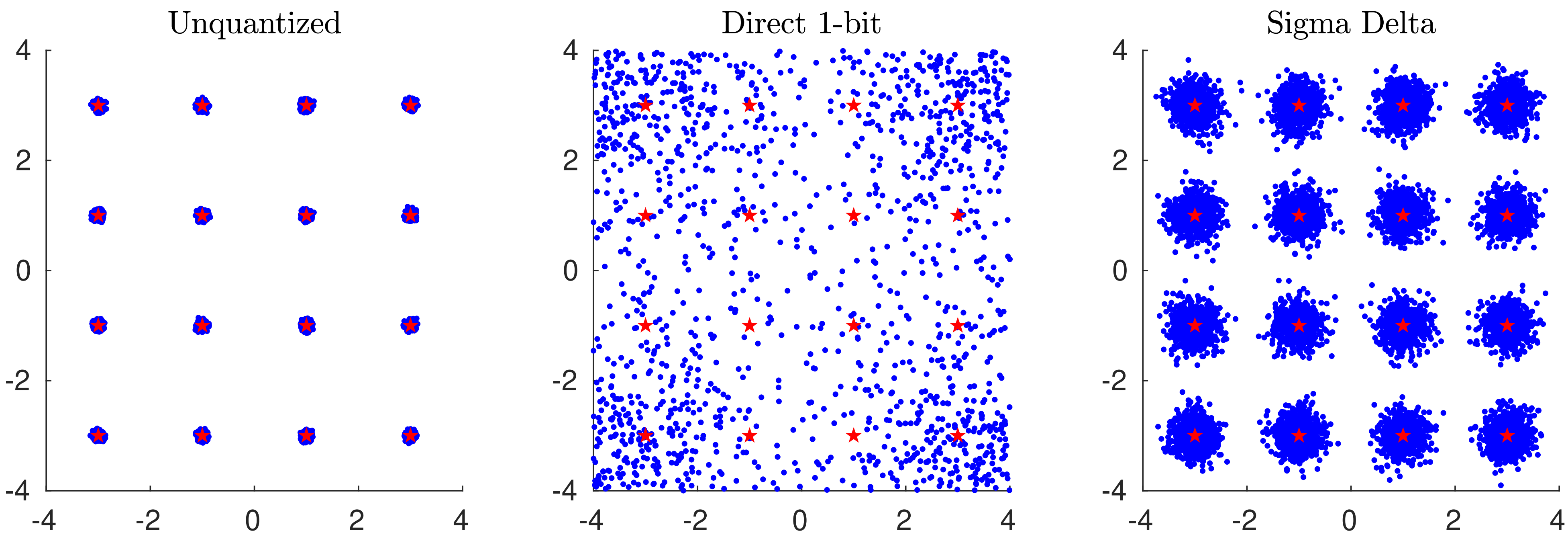


- rx signal model (when $\alpha_k = 1$ and noiseless):

$$
\begin{aligned}
y_k &= \sum_{n=0}^{N-1} (\bar{x}_n + q_n - q_{n-1}) e^{-\mathrm{j}\omega_k n} \\
&= \left[\sum_{n=0}^{N-1} \bar{x}_n e^{-\mathrm{j}\omega_k n}\right] + \left[\sum_{n=0}^{N-1} (q_n - q_{n-1}) e^{-\mathrm{j}\omega_k n}\right] \\
&\approx \bar{X}(\omega_k) + (1 - e^{-\mathrm{j}\omega_k}) Q(\omega_k) \qquad \text{(holds when } N \text{ is large)}
\end{aligned}
$$

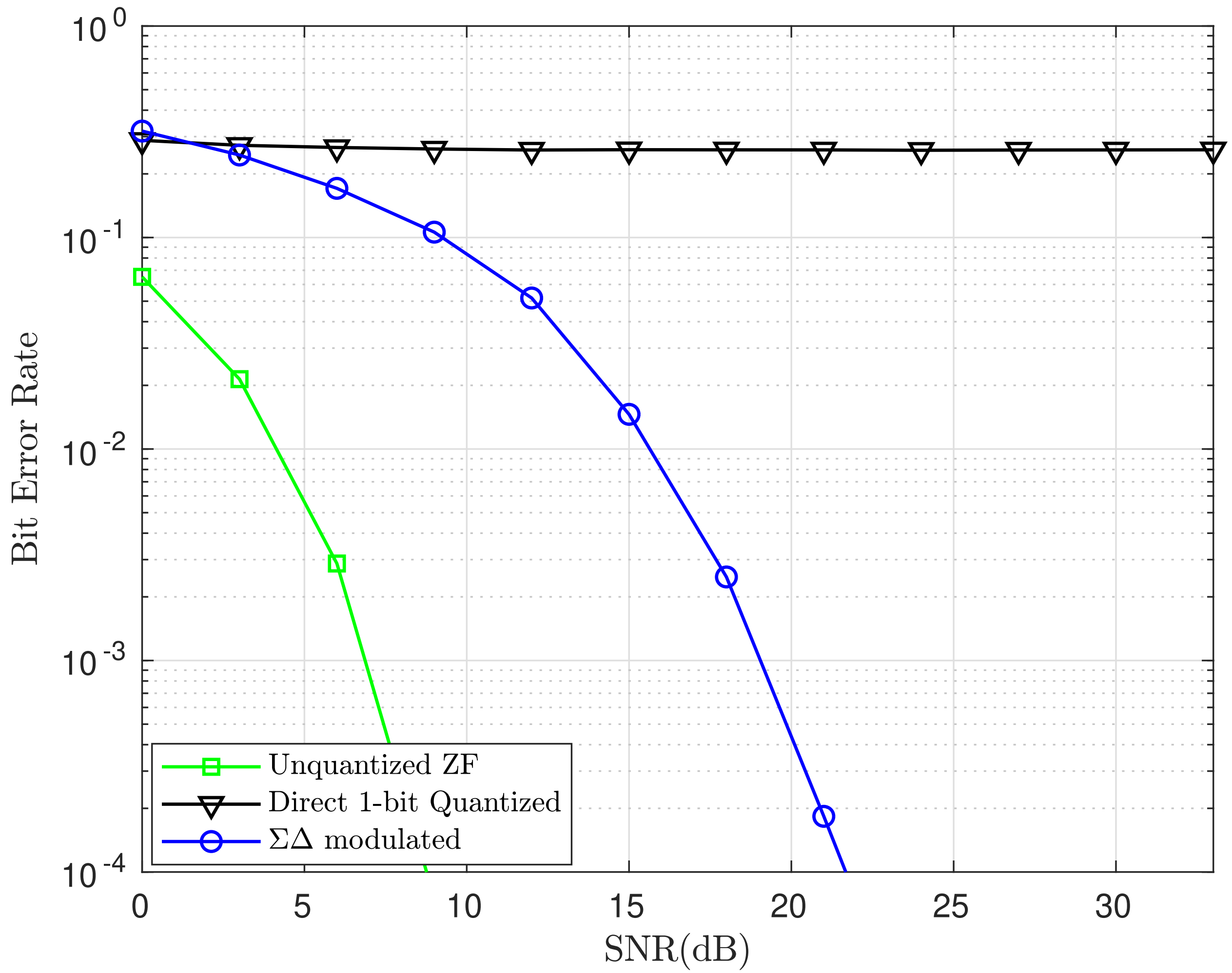
- recall $\omega_k = \frac{2\pi d}{\lambda} \sin(\theta_k)$, this means the red term zeros out when $\theta_k = 0^\circ$

Simulation: Scatter Plot



- settings: $N = 512$ Tx antenna; $K = 12$ users with $\theta_k \in [-30^\circ, 30^\circ]$; the antenna spacing is set as $d = \lambda/8$; the background SNR is fixed to 20dB

Simulation: Bit Error Rate Performance



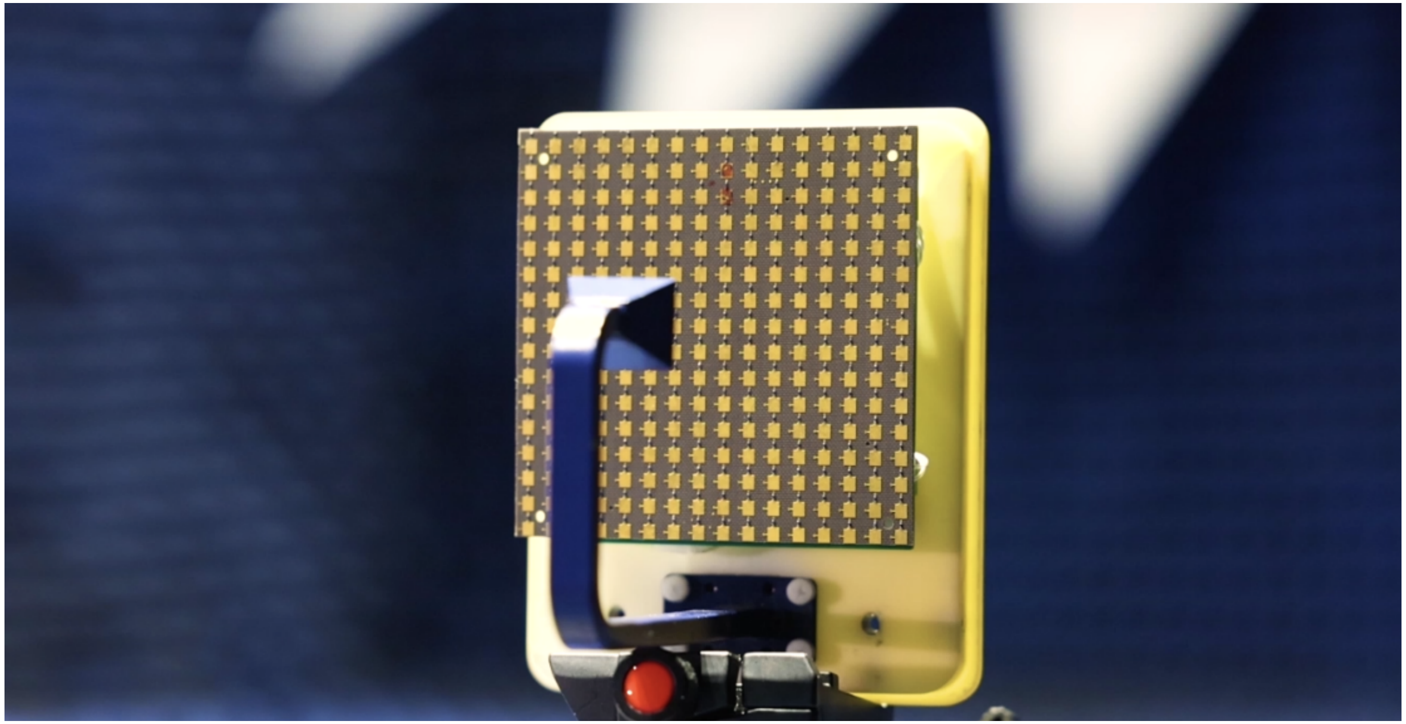
- settings: $N = 512$ Tx antenna; $K = 12$ users with $\theta_k \in [-30^\circ, 30^\circ]$; the antenna spacing is set as $d = \lambda/8$.

Some Technical Remarks

- we made two assumptions: i) $\bar{X}(\omega)$ is low-pass and ii) $Q(\omega)$ is bounded and flat
- i) is done by restricting $|\theta_k|$ in a small angular region, so that $\omega_k = \frac{2\pi d}{\lambda}\sin(\theta_k)$ will also be small
- as for ii), we use —
  - **no-overload condition**: avoid $q_n \to \infty$ by limiting $|\bar{x}_n| \leq 1$; we have $|q_n| \leq 1$, i.e. $Q(\omega)$ is bounded
  - **assumption**: assume q_n is uniformly i.i.d. over $[-1, 1]$ and is independent of $\bar{x}_n$, i.e. $Q(\omega)$ is flat

Data-Modulating RIS w/ $\Sigma\Delta$ Modulation

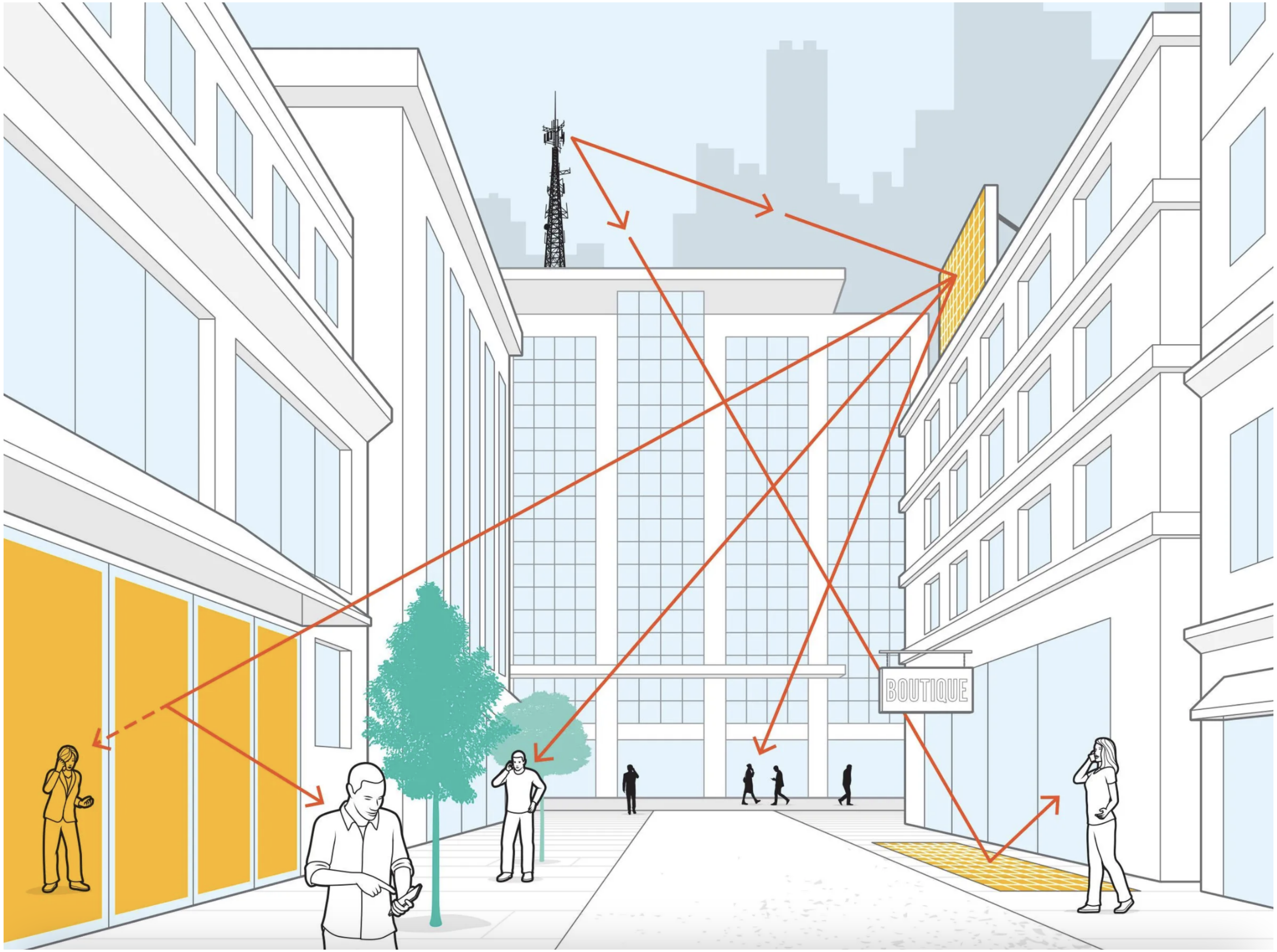
Reconfigurable Intelligent Surface



Source: M. Cui, Z. Wu, Y. Chen, S. Xu, F. Yang, and L. Dai, "*Demo: Low-power communications based on RIS and AI for 6G*," in Proc. IEEE ICC, Dec. 2022.

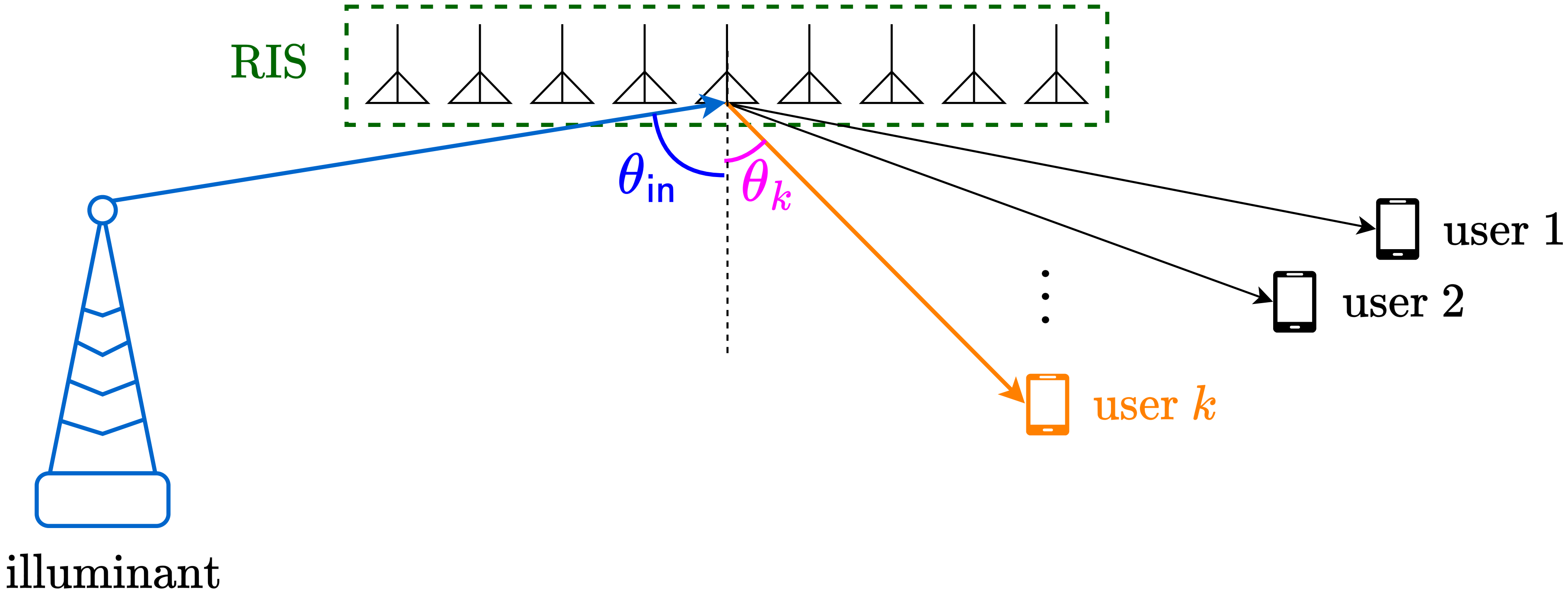
- metasurface that reflects EM wave; expected to play a role in future comm. sys.
- no RF process (incl. DAC & PA) needed when used as a pure reflector
- **cheap!**

Reconfigurable Intelligent Surface



Source: `https://spectrum.ieee.org/metamaterials-could-solve-one-of-6gs-big-problems`

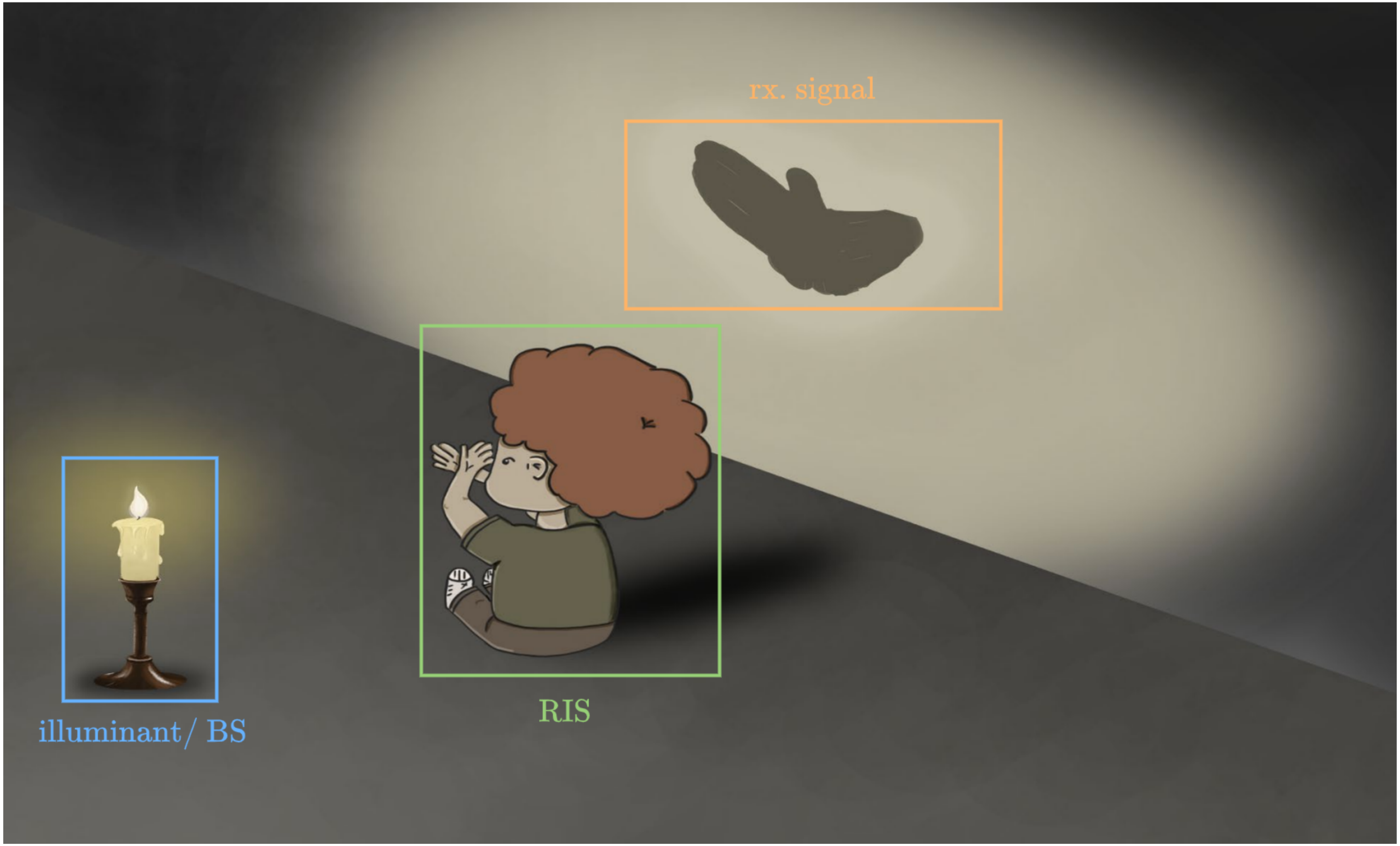
Data-Modulating RIS for MIMO Downlink



- recent researches suggest RIS can be used as info. source
- one antenna BS + RIS = MIMO downlink BS
  - requires only one PA + one DAC to implement massive MIMO
- SOTA: a SLP soln. has been done, but the computation cost is too high[3];

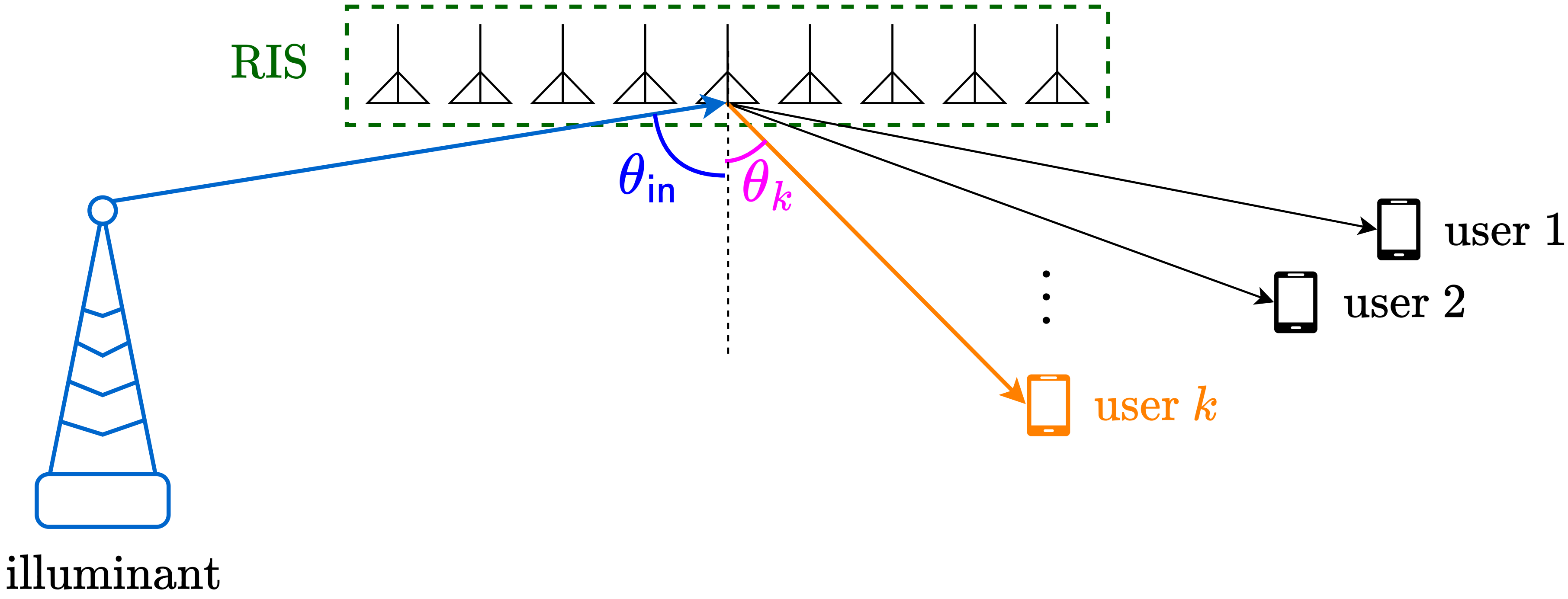
[3] H. V. Cheng and W. Yu, "Modulating Data Using Reconfigurable Intelligent Surface by Symbol Level Precoding," Proc. ISWCS2022, Hangzhou, China, 2022, pp. 1-6

Data-Modulating RIS for MIMO Downlink



Credit: Victor's designer friend, who drew this picture for a pint.

Data-Modulating RIS for MIMO Downlink



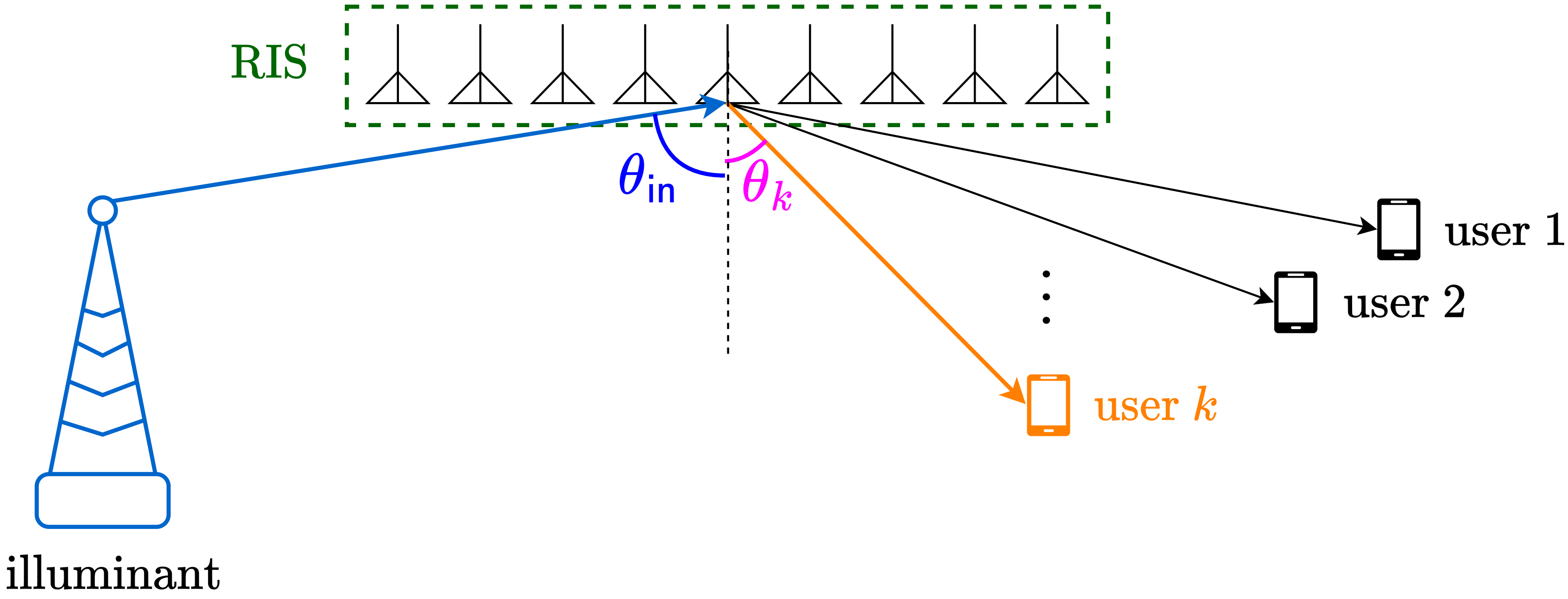
- rx signal model:

$$y_k = \sum_{n=0}^{N-1} e^{-\mathrm{j}\omega_{\text{in}} n} \underbrace{e^{\mathrm{j}\psi_{n+1}}}_{:=x_n,\text{the phase shifts of the RIS}} e^{-\mathrm{j}\omega_k n} + \text{noise}$$

$$= \left(\boldsymbol{a}(\omega_{\text{in}}) \odot \boldsymbol{a}(\omega_k)\right)^{\top} \boldsymbol{x} + \text{noise}$$

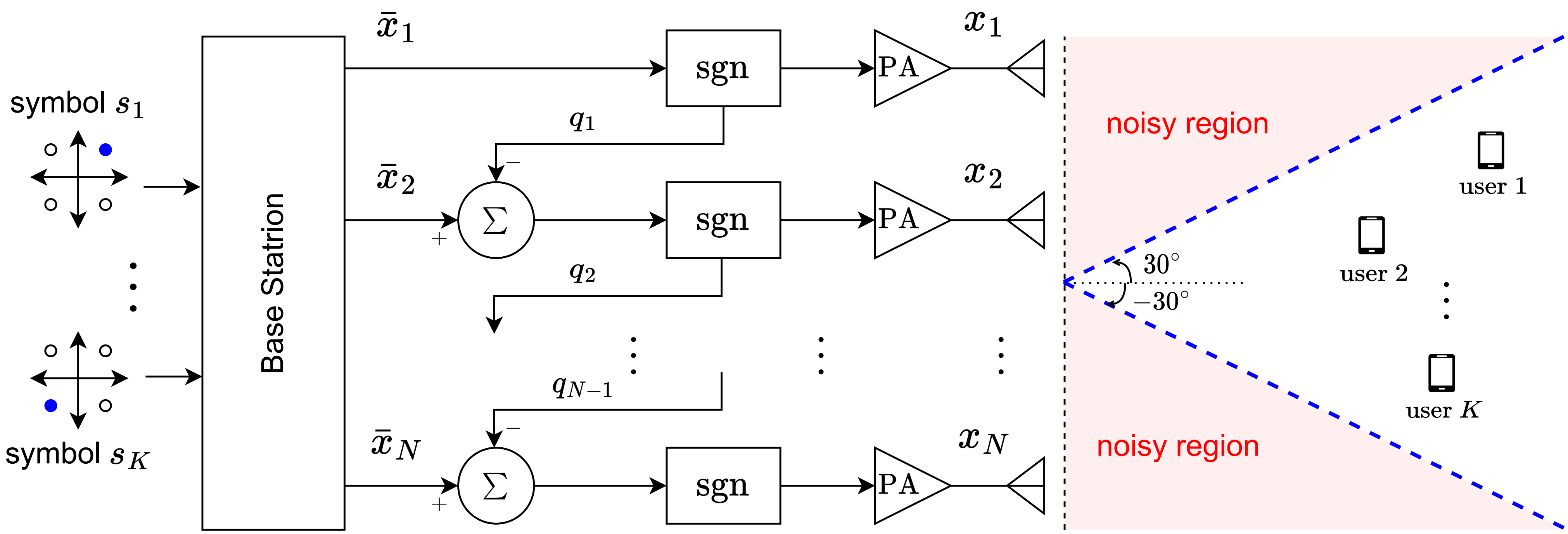
where $\boldsymbol{x} = (e^{-\mathrm{j}\psi_1}, e^{-\mathrm{j}\psi_2}, \ldots, e^{-\mathrm{j}\psi_N})$

Data-Modulating RIS for MIMO Downlink



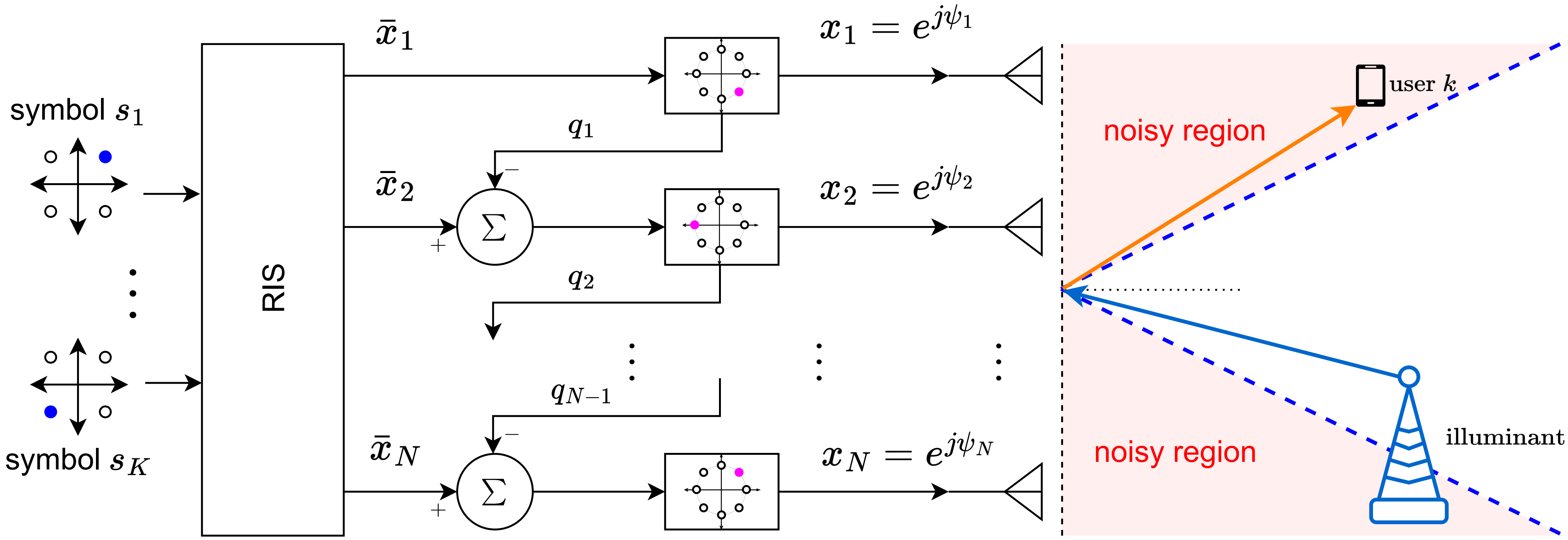
- rx signal model: $y_k = [\boldsymbol{a}(\omega_{\text{in}}) \odot \boldsymbol{a}(\omega_k)]^\top \boldsymbol{x} + \text{noise}$
- aim: manipulate the phases $(\psi_1, \ldots, \psi_N)$ at the RIS to convey info. to users

Spatial ΣΔ Approach for Data-Modulating RIS



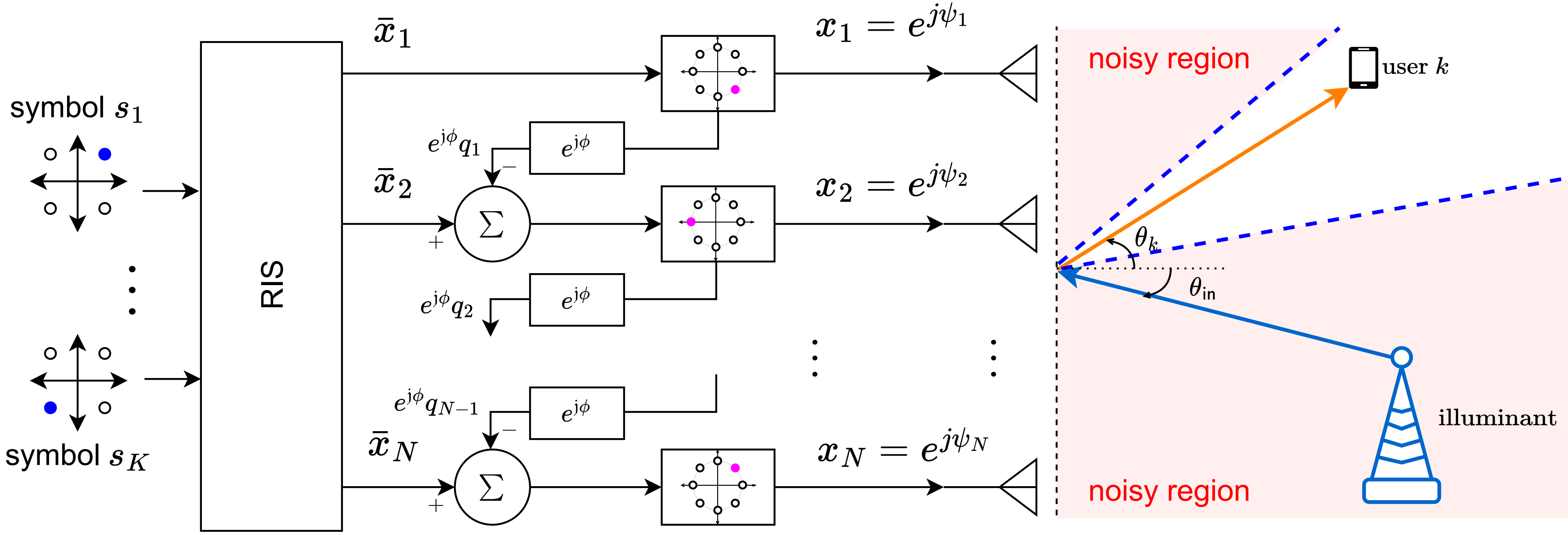
- recall the basic spatial ΣΔ modulation that sends one-bit data
- RIS reflects phases only, we need to replace the sgn by a phase quant.
- no need to take care of the PAs, as there is no PA at the RIS (unlike a relay)

Spatial ΣΔ Approach for Data-Modulating RIS



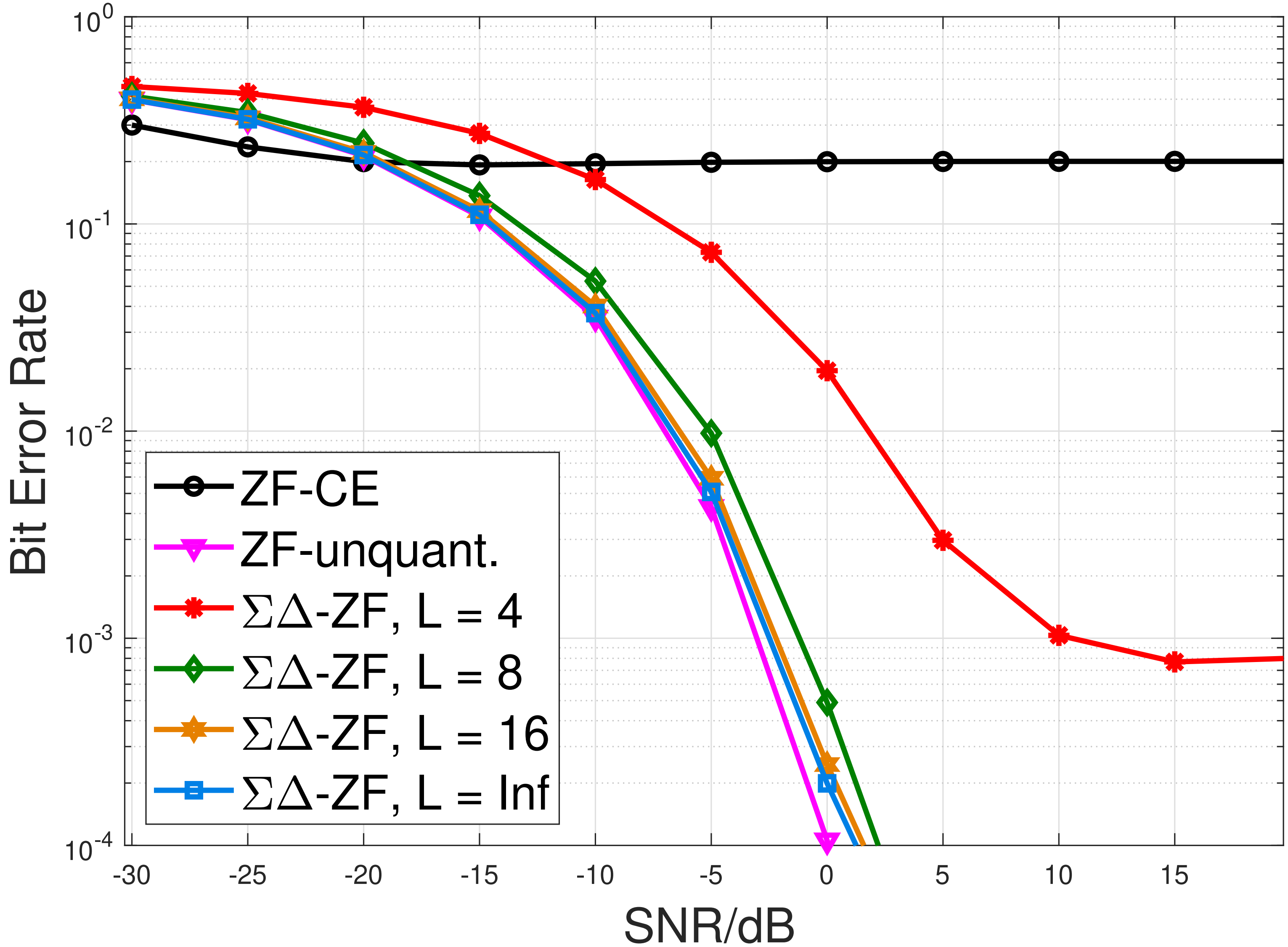
- now we have the ΣΔ modulated output x_n being discrete-phased only
- but users maybe beyond broadside of the RIS

Spatial ΣΔ Approach for Data-Modulating RIS



- angle-steering: use phasors at the spatial feedback loop
- the corresponding DTFT: $X(\omega) = \bar{X}(\omega) + \underbrace{\left(1 - e^{j(\omega-\omega_0)}\right)}_{\textbf{band-pass}} Q(\omega)$

Simulation: Bit Error Rate Performance



$(N, K) = (512, 8)$, $d = \lambda/8$, $\theta_{\text{in}} = -60°$, $\theta_k \in [20°, 40°]$, 16-QAM; L is the number of discrete phases used

Some Technical Remarks

- **no-overload condition**: modulator input amplitude should be bounded by

$$A \leq \frac{\sin(2\pi/L)}{\sin(\pi/L)} - 1$$

where L is no. of discrete phases[4]

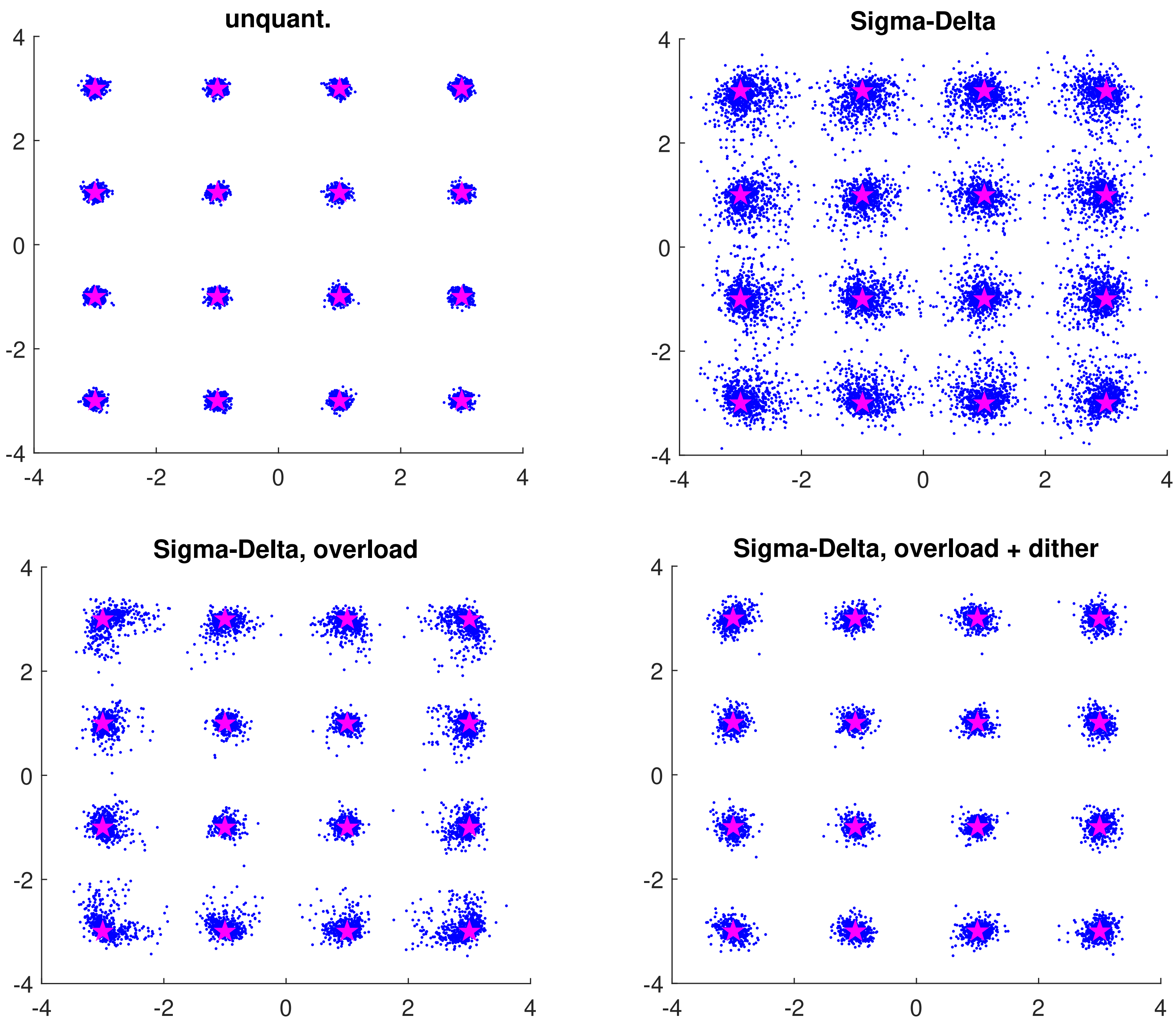
  – conservative guarantee; overloading might be able to help

- **white q. noise assumption:** does not hold on phase quant. empirically...

  – we try to use subtractive dithers to "whiten" the q. noise[5]

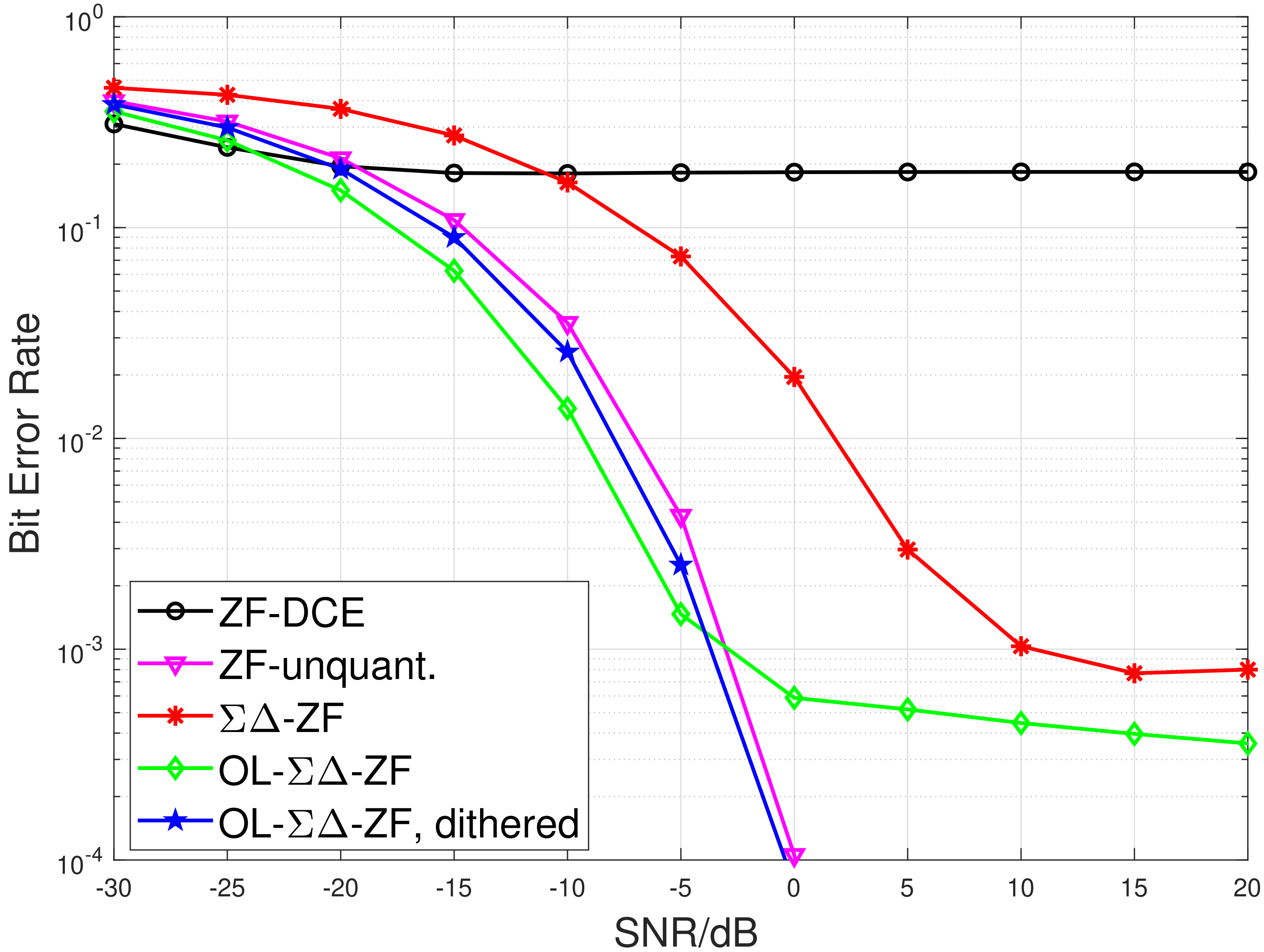
[4] W.-Y. Keung, H. V. Cheng, and W.-K. Ma, "*Transmitting data through reconfigurable intelligent surface: A spatial Sigma-Delta modulation approach*," arXiv preprint, arXiv:2310.16347, Oct 2023, https://arxiv.org/abs/2310.16347.

[5] Wannamaker, R.A., "*Subtractive and Non-Subtractive Dithering: A Comparative Analysis*," J. Audio Eng. Soc., vol. 52 (Dec. 2004), 1211–27.



$(N, K, d) = (256, 4, \lambda/4)$, $\theta_{\text{in}} = -60^\circ, \theta_k \in [0^\circ, 40^\circ]$; number of discrete phases $L = 4$; , SNR $= 10$dB

BER w/ Overloading and Subtractive Dither



$(N, K) = (512, 8)$, $d = \lambda/8$, $\theta_{\text{in}} = -60°$, $\theta_k \in [20°, 40°]$, 16-ary QAM; overloaded by $A = \sqrt{2}$; $L = 4$ discrete phases; dither strength is $0.2A$

Summary, Acknowledgement and Conclusions

Quick Summary of My Journey So Far...

- publications/pre-prints:
  - 1x ICASSP23' workshop paper on ISAC
  - 1x GlobeCom23' workshop paper on one-bit MIMO detection
  - 2x ICASSP24' submissions (one is this talk; another on robust SLP)
  - 1x OJSP submission (another $\Sigma\Delta$ paper)

Acknowledgement

- Supervisor: Prof. Wing-Kin Ma
- Examiners: Prof. Thierry Blu and Prof. Tan Lee
- Collaborators:
  - Prof. Hoi-To Wai @SEEM
  - Prof. Victor Hei Cheng @Aarhus Univ.
  - Dr. Umair Qureshi @CSE
- Lab mates: Yuening Li, Junbin Liu, Ya Liu, Dr. Yatao Liu, Dr. Herman Ng & Prof. Mingjie Shao
- Colleagues from ODLE and CSE
- my unreasonably annoying cat, who yells me up to start working at 6am sharp everyday

Take-home Points

- spatial $\Sigma\Delta$ mod. is a classical technology that has been applied on one-bit massive MIMO downlink (**reduced** cost for DACs/PAs)
- we use it for RIS-assisted phase-only MIMO downlink, wherein the BS can have only one active antenna (**negligible** cost for DACs/PAs)
- the presented work demonstrates a good potential as an alternative physical layer scheme for massive MIMO downlink
- **thank you!**

Questions?