

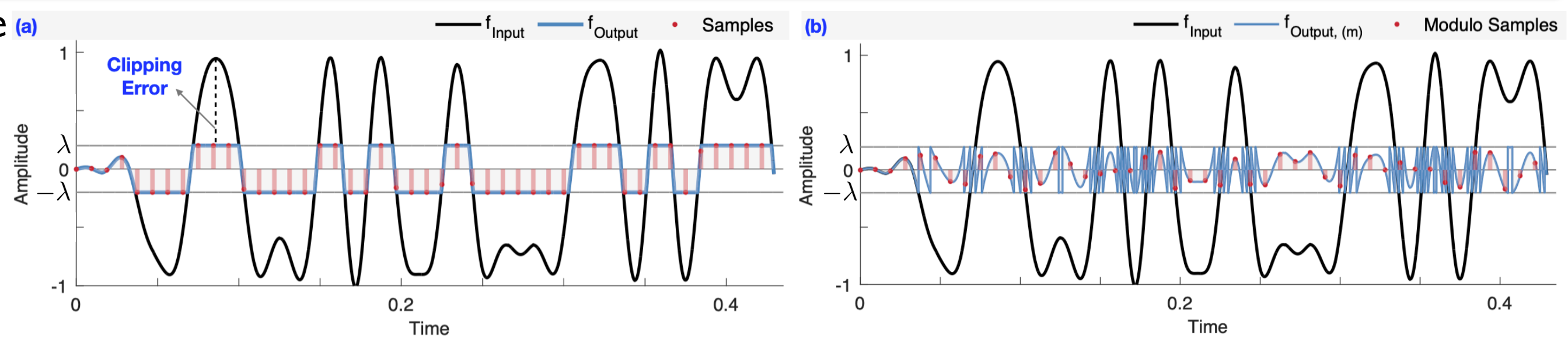


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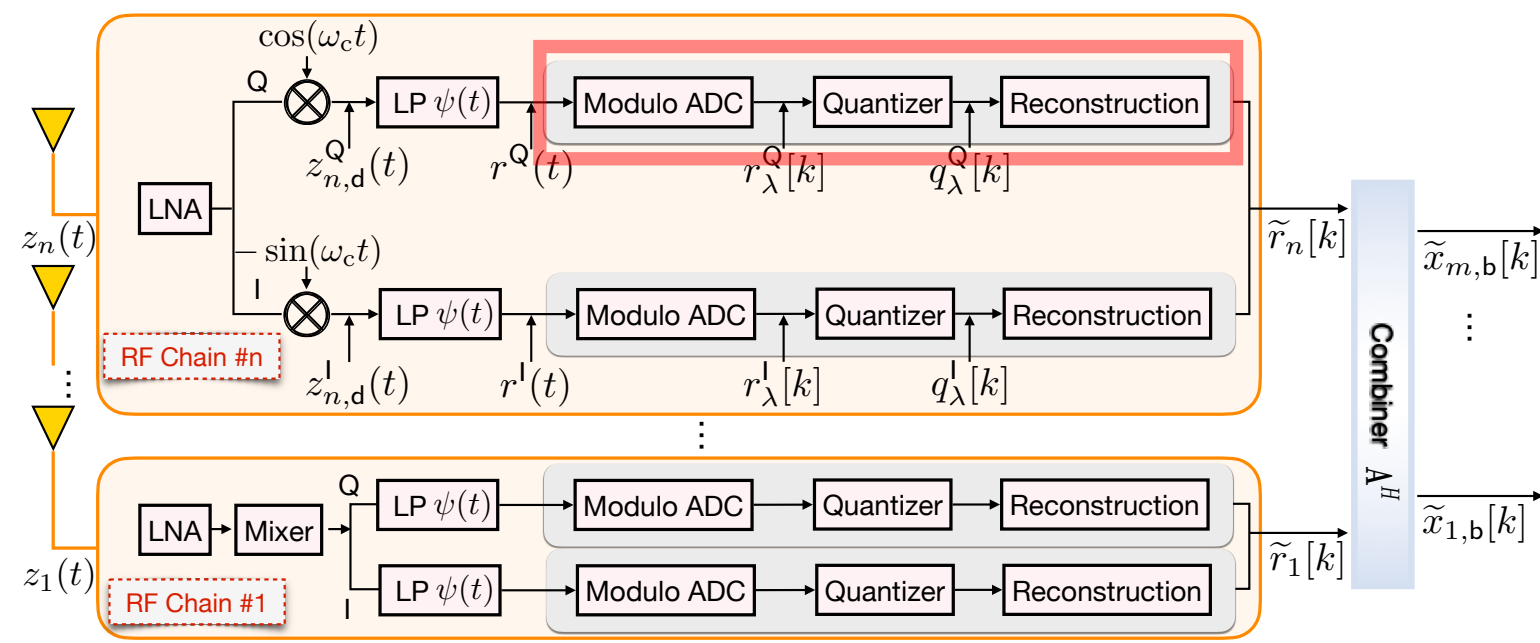
Challenges in Massive MIMO

- **Power consumption:** The power consumption of the ADC grows linearly with the sampling rate but exponentially with the number of bits b that decide the ADC's resolution.
- **Receiver saturation:** This impediment is caused by the fact that ADCs are limited by their dynamic range (DR).

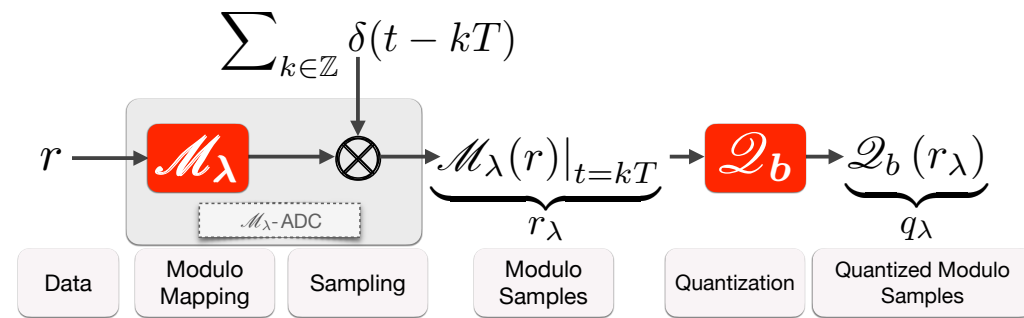


Our Approach: λ -MIMO

- Utilizing modulo ADCs ($\mathcal{M}_\lambda$ -ADC) instead of a conventional ADC.

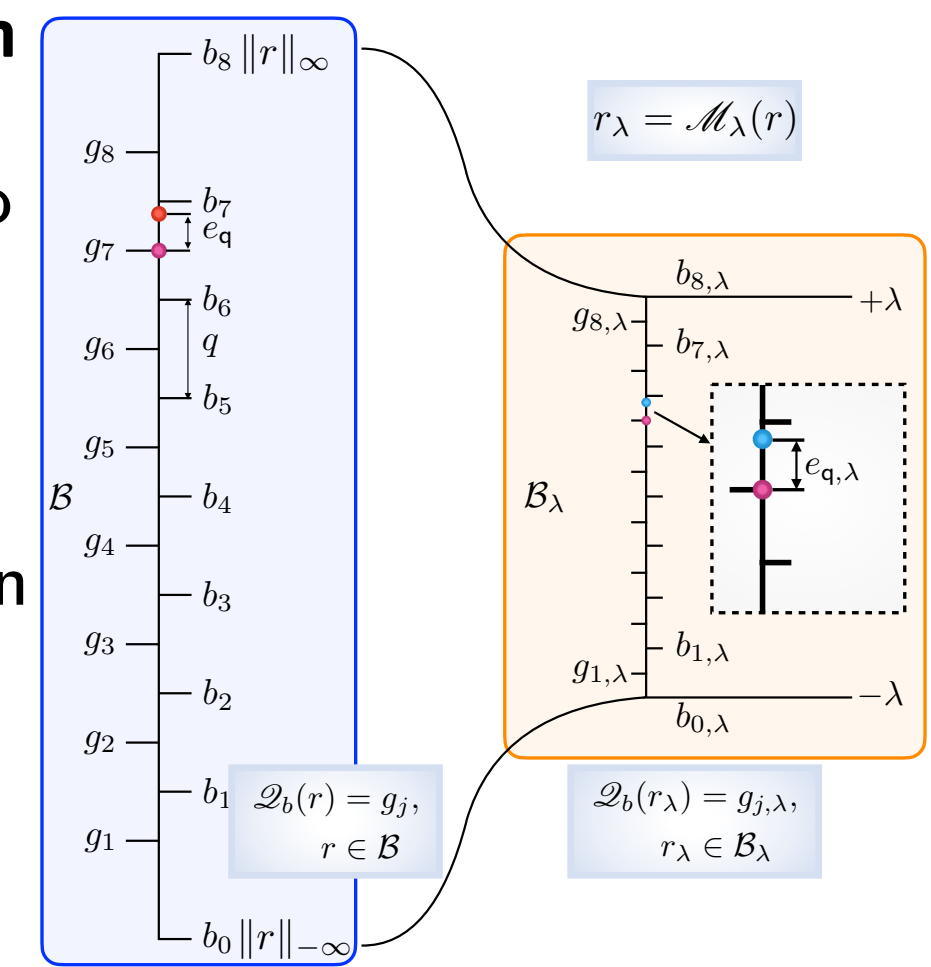


- The architecture of $\mathcal{M}_\lambda$ -ADC and quantizer.



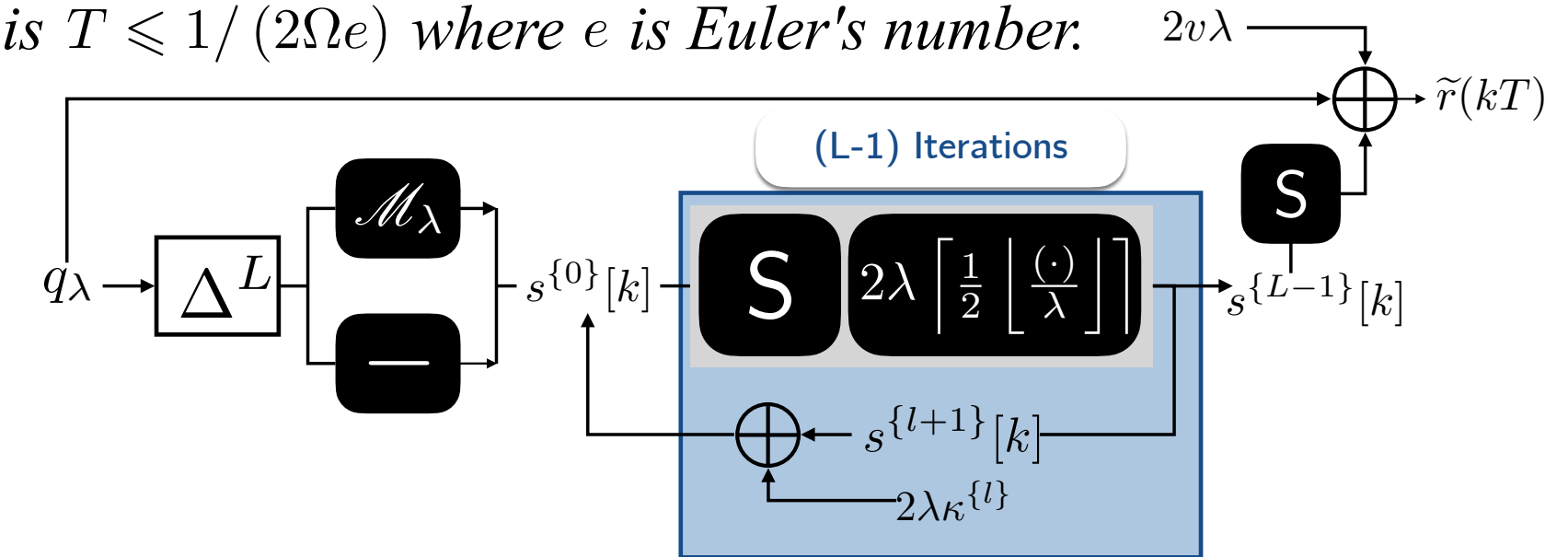
Benefits of λ -MIMO

- Our approach offers similar **detection** and **sum-rate** performances as an ∞ -resolution, conventional ADC, due to
 - **Lower** signal-to-quantization-noise ratio (SQNR),
 - No saturation.
- **Lower** power consumption for a given bit budget.
- Our approach is devoid of VGA and AGC apparatus, thus enabling **lower complexity** hardware.



Reconstruction Algorithm based on Unlimited Sampling Theorem

- Unlimited Sampling Theorem¹: Let $f(t)$ be a continuous-time function with maximum frequency Ω (rads/s). Then, a sufficient condition for recovery of $f(t)$ from its modulo samples (up to an additive constant) taken every T seconds apart is $T \leq 1/(2\Omega e)$ where e is Euler's number.
- Recovery from Modulo Samples:
 - Based on the observation that the modulo and the finite-difference operators commute in a certain sense¹.
 - Extracting the higher-order differences of unfolded signal from its modulo samples.
 - Stably inverting the difference-operator.



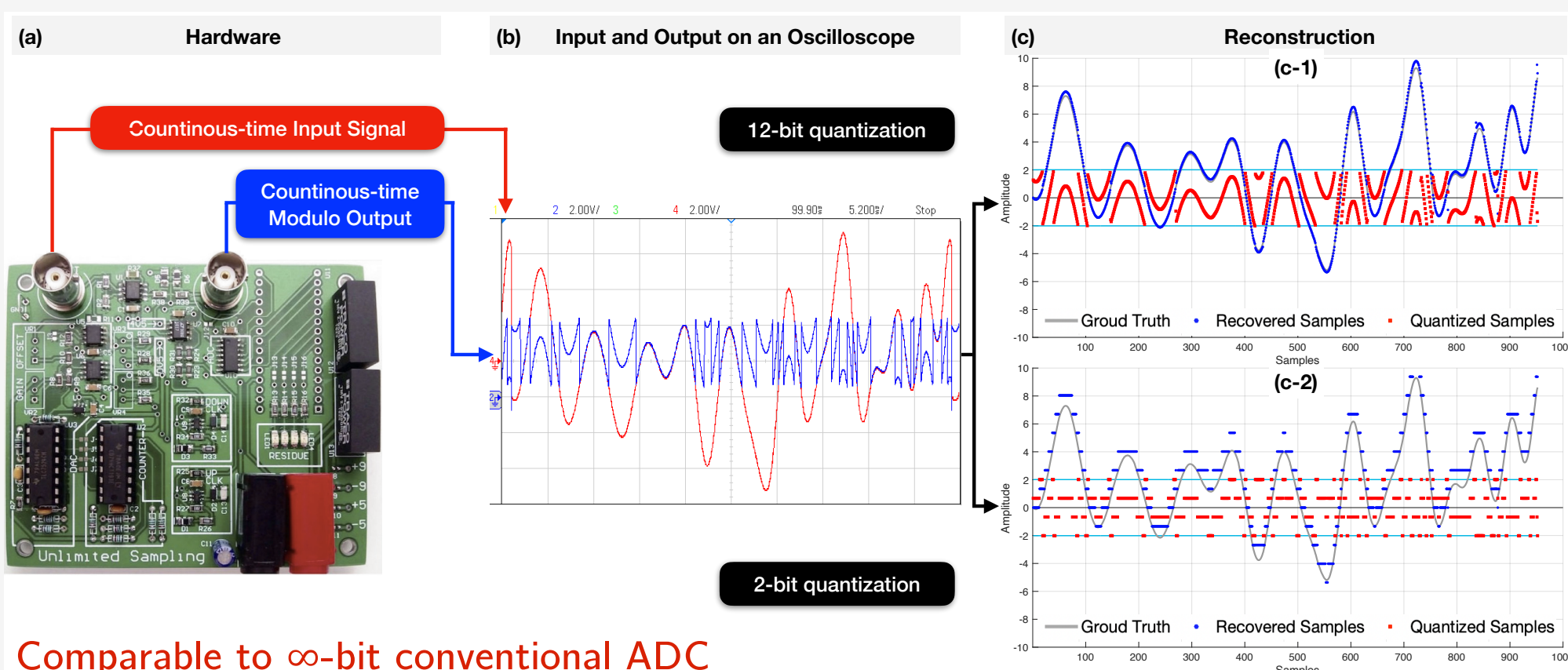
Achievable Sum-rate Analysis

- The quantized received signal is given by $\mathbf{r}_q = \gamma_\lambda \mathbf{r} + \epsilon_q = \gamma_\lambda \sqrt{p_u} \mathbf{H} \mathbf{x} + \gamma_\lambda \epsilon + \epsilon_q$,
 - p_u : average transmitted power of each user
 - ϵ_q : additive Gaussian quantization noise
 - $\epsilon_q \sim \mathcal{N}(0, (1 - \gamma_\lambda) \gamma_\lambda \sigma_r^2)$, $\gamma_\lambda = 1 - \sigma_{q,\lambda}^2 / \sigma_r^2$
 - σ_r^2 : signal power
 - $\sigma_{q,\lambda}^2 = \zeta^2 \sigma_q^2$
 - $\sigma_{q,\lambda}^2$ and σ_q^2 : quantization noise variances of $\mathcal{M}_\lambda$ -ADC and conventional ADC.
- The ergodic achievable uplink rate of the m^{th} user

$$R_m = \mathcal{E} \left\{ \log_2 \left(1 + \frac{p_u \gamma_\lambda^2 \|\mathbf{a}_m\|^4}{\mathbf{I}_H} \right) \right\}$$
 - $\mathbf{a}_m$: m^{th} column of combiner $\mathbf{A}$
 - $\mathbf{I}_H$: interference & noise

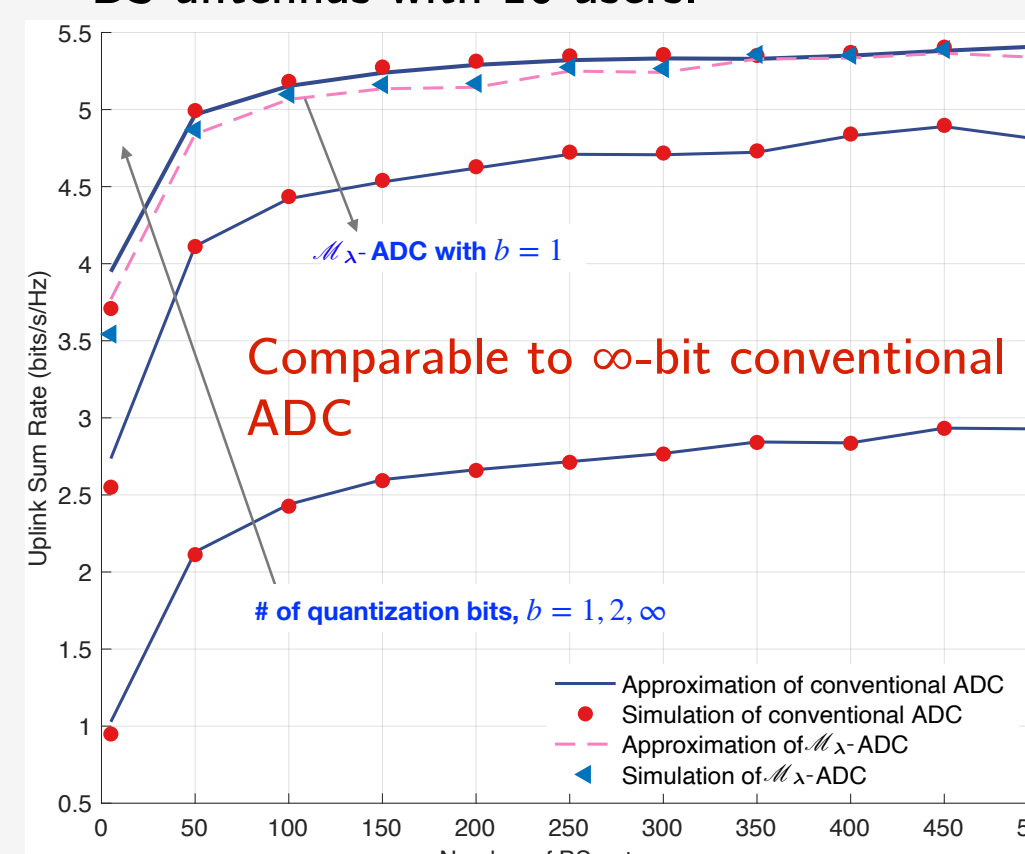
Hardware Experiments and Simulation Results

- Hardware experiments and actual recovery results.

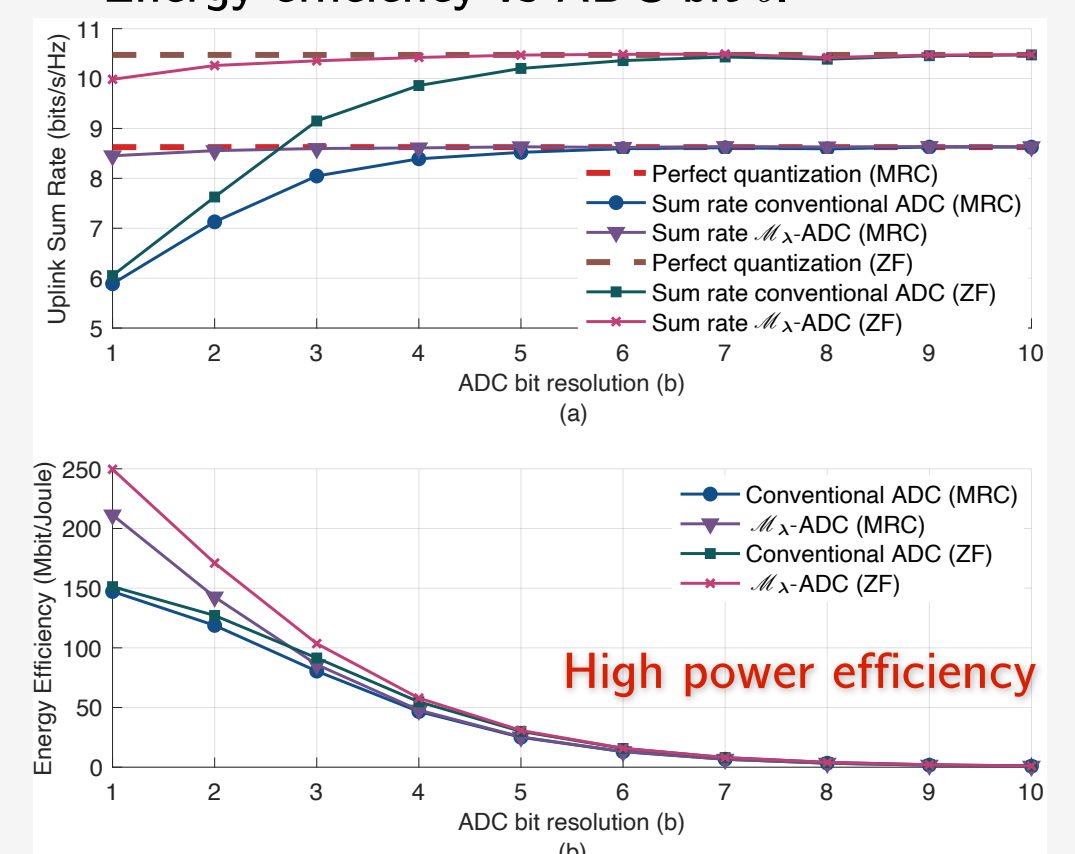


Comparable to ∞ -bit conventional ADC

- Uplink sum-rate per cell vs the number of BS antennas with 10 users.



- (a) Uplink sum-rate vs ADC bit b , (b) Energy efficiency vs ADC bit b .



Conclusion

Our λ -MIMO approach can tackle the two challenges simultaneously. The distinguishing features of our work include

- leveraging higher signal-to-quantization noise ratio (SQNR),
- approaching the detection and average uplink sum-rate performances comparable to an ∞ -bit resolution, conventional ADC, with a very few bit $\mathcal{M}_\lambda$ -ADC, This enables higher order modulation schemes (e.g., 1024 QAM) that seemed previously impossible.
- higher power efficiency attributing to a superior trade-off between energy efficiency and bit budget.

[1] A. Bhandari, F. Krahmer, and R. Raskar, "On unlimited sampling and reconstruction," *IEEE Trans. Sig. Proc.*, vol. 69, pp. 3827–3839, Dec. 2020.