Massive MIMO Communications with One-Bit Quantization

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Network-on-a-Chip

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System & Circuit Architectures for Wireless Communications

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Analog Integrated Circuit Design for Communications Systems

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Multiuser Information Theory
Wireless Communications

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Coding and Communication Theory
Wireless Networks

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Network Protocols & Algorithms
Network Coding & Security

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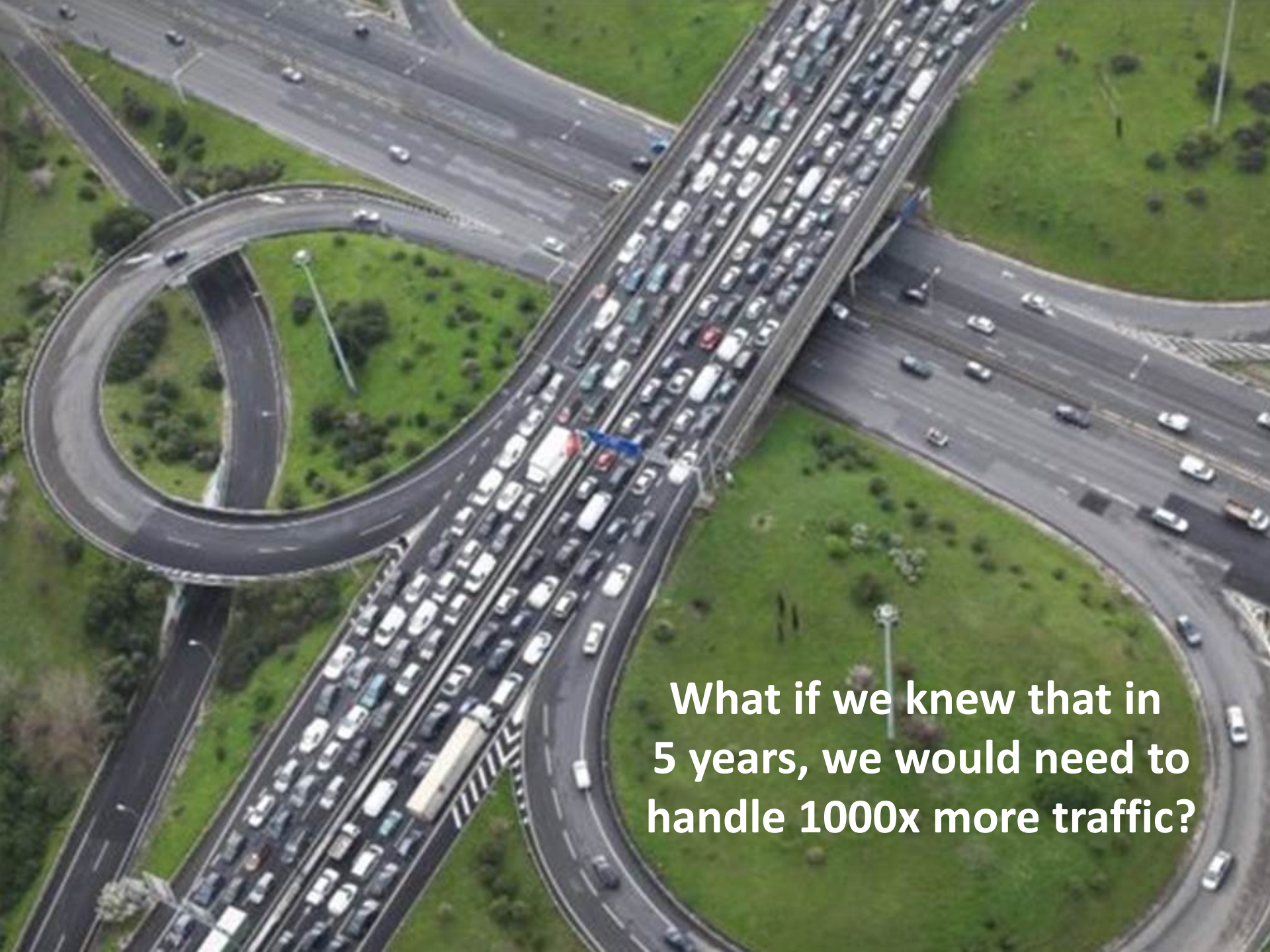
Signal Processing
Wireless Communications

Zhiying Wang
Information and Coding Theory
Data Storage, Genomic Information

The Spectral Crunch

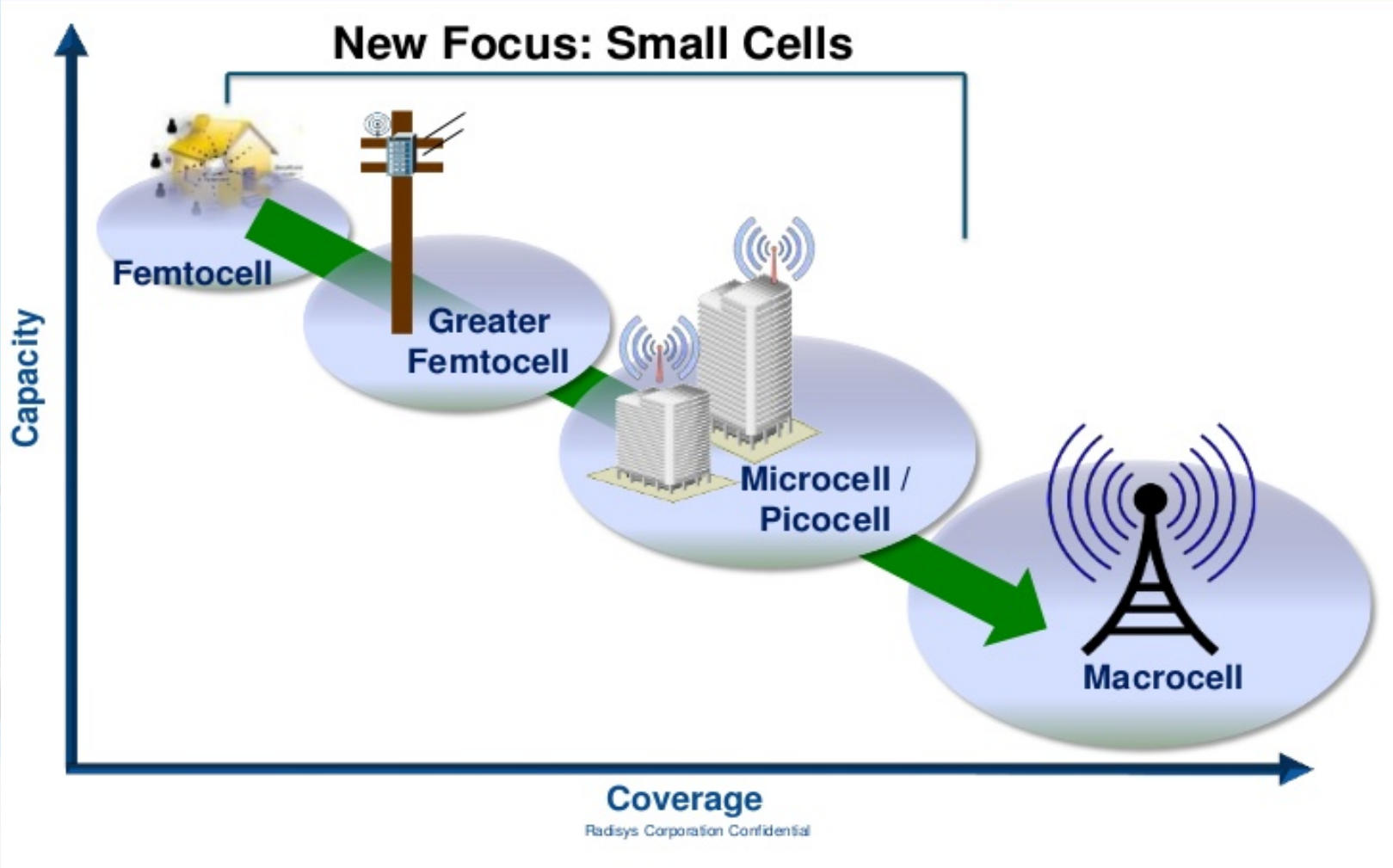
- More active mobile wireless devices than people on the planet
- Ubiquitous wireless access is now a commodity
  - emergency services
  - e-Health
  - environmental monitoring
  - smart grid
  - vehicular communications
- And private uses: communications, internet, HDTV on demand, gaming
- To meet growing needs, we need 1000x more throughput!
- Current systems don't have any more bandwidth available ....


What if we knew that in
5 years, we would need to
handle 1000x more traffic?

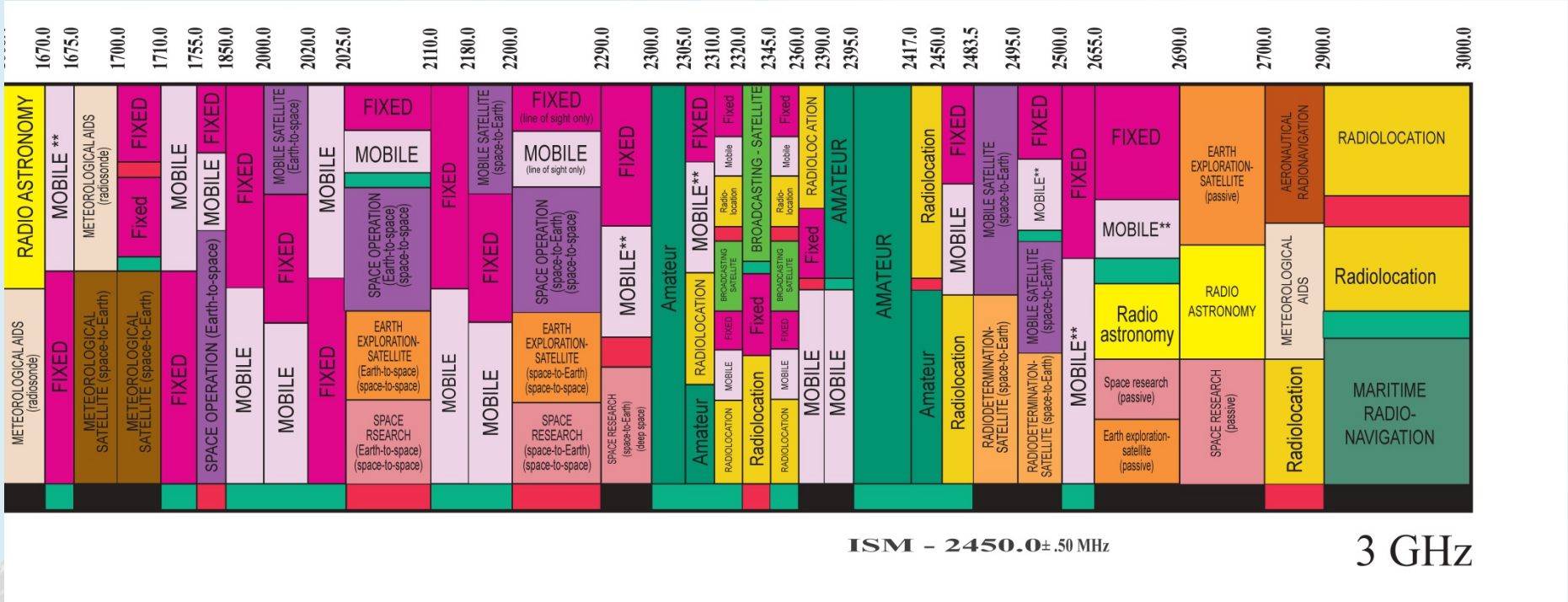
The Road to Gigabit Wireless (5G and Beyond)

- How do we get to Gb/s wireless links?
- Three symbiotic trends emerging:
  - Deployment of pico- and femto-cells (OoM decrease in cell size)
    Build more roads, closer together
  - Millimeter wave frequencies (OoM increase in bandwidth)
    Build wider roads
  - Massive MIMO (OoM increase in antennas)
    Stack the roads on top of each other!

(1) “Pico” and “Femto” Cells



(2) Millimeter Wave Frequencies (30-300 Ghz)



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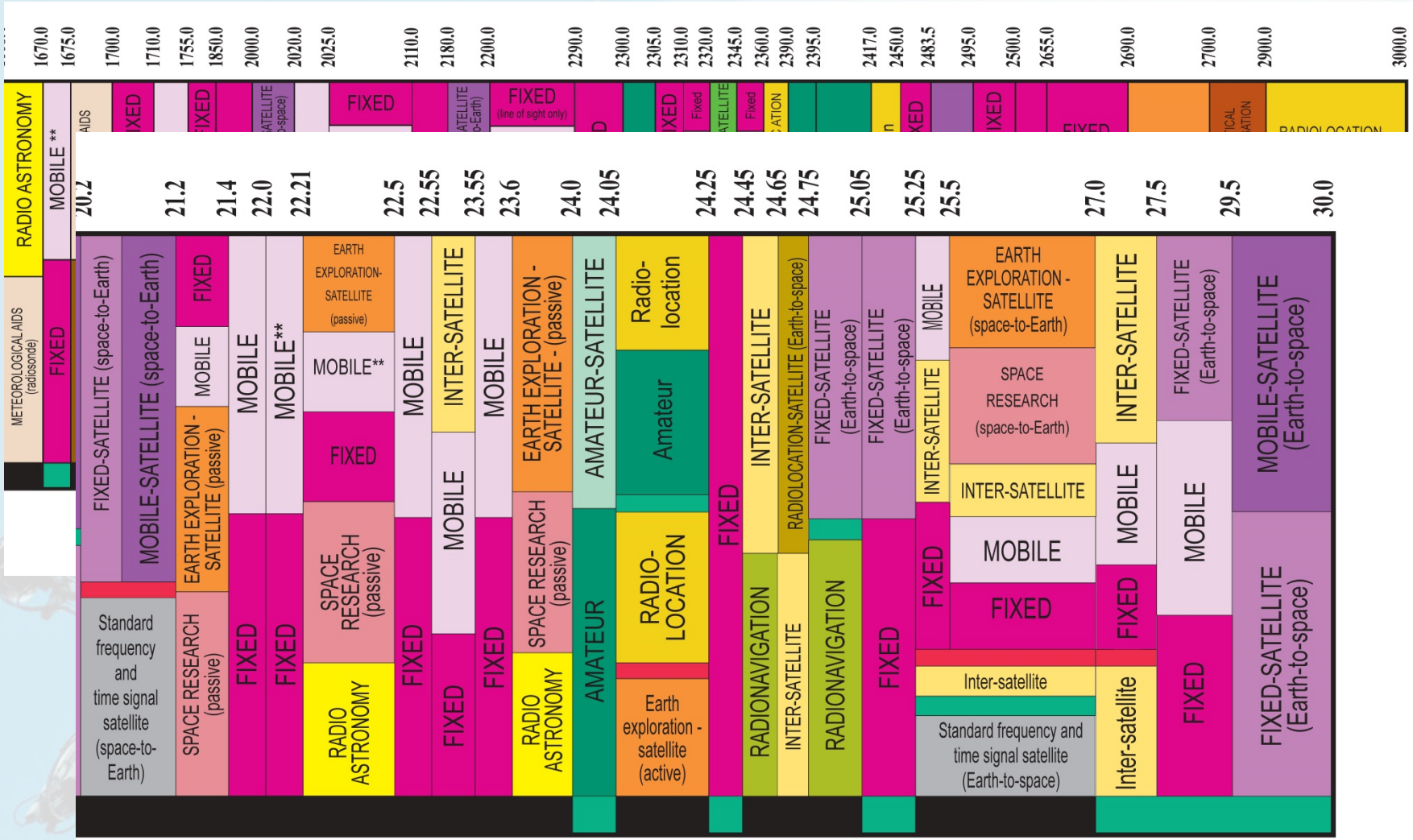

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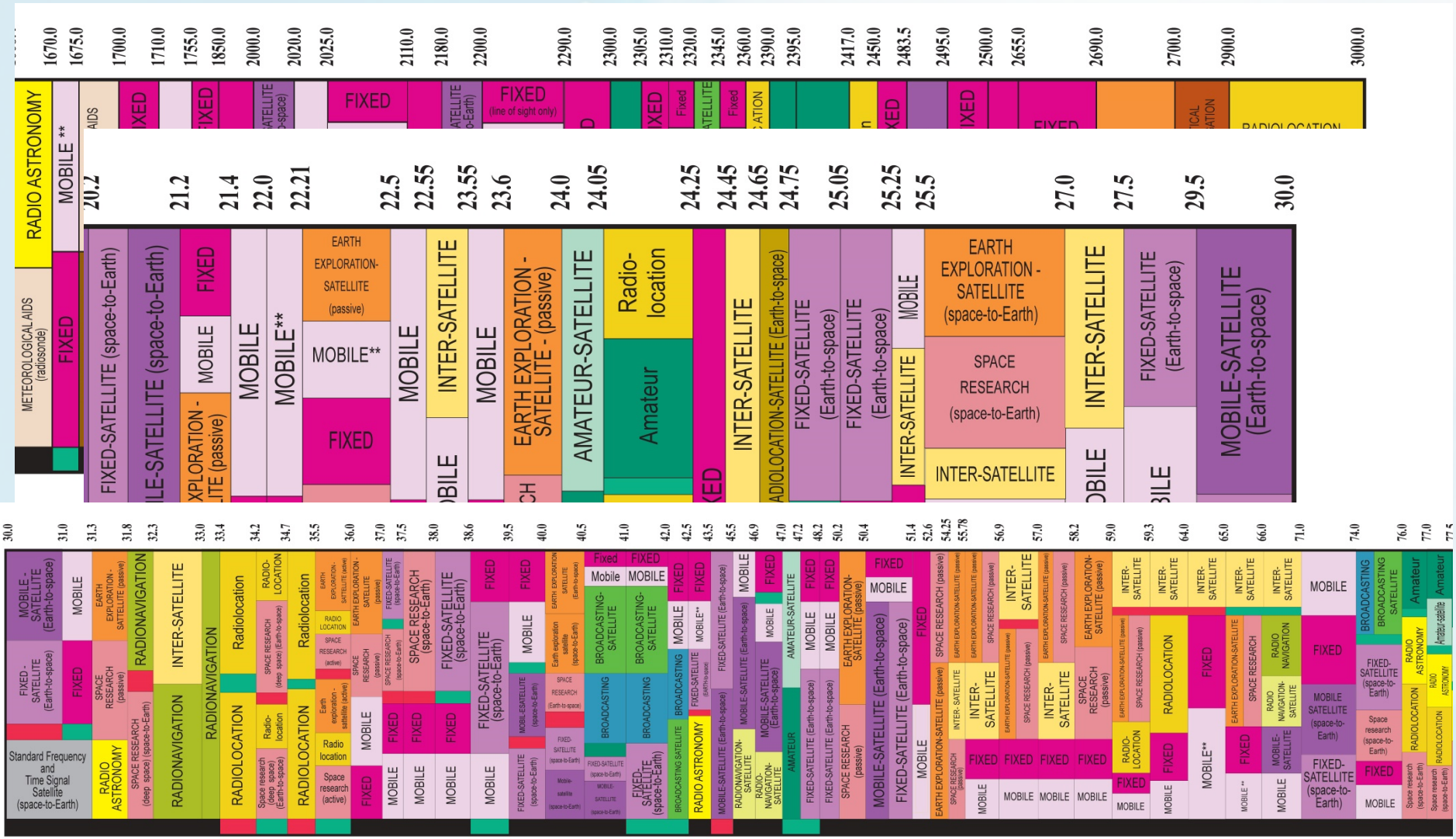
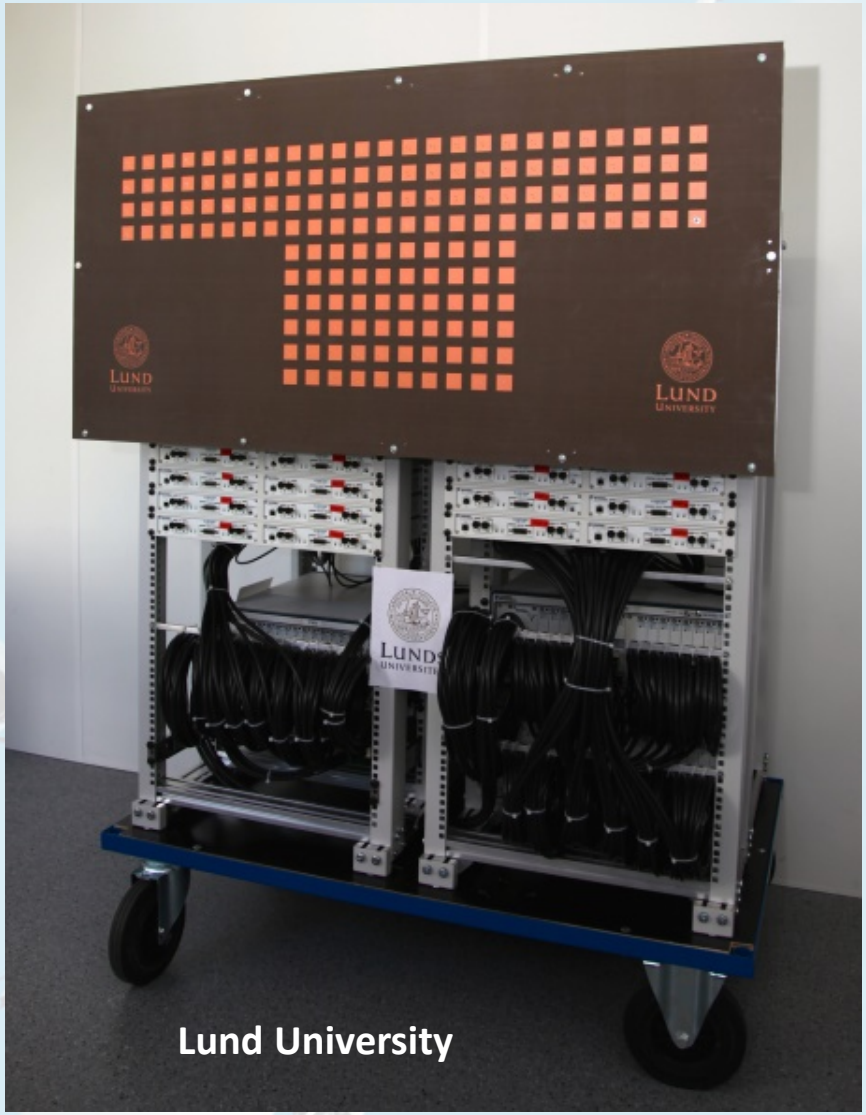
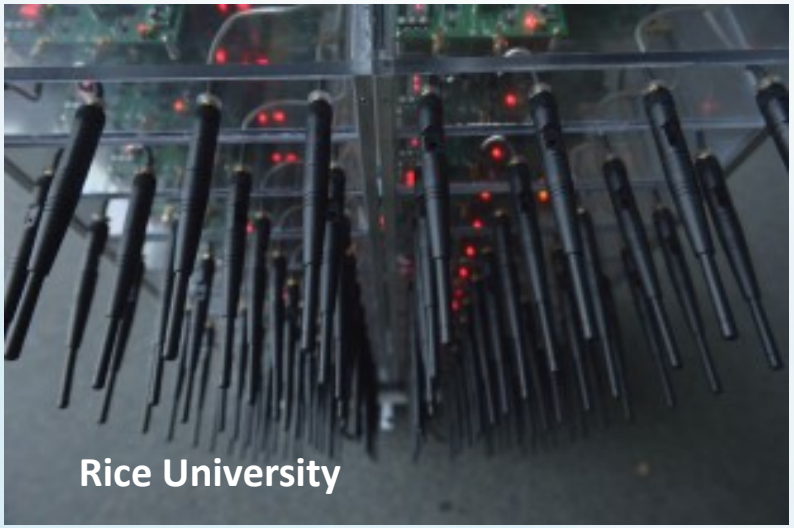


(3) Massive Multi-Input Multi-Output (MIMO) Antenna Arrays



Lund University


Rice University


Nokia/Mitsubishi

A Symbiotic Relationship

- Millimeter wave frequencies
  - short wavelengths
  - larger propagation losses, shorter range operation
  - little multipath, line-of-sight (LOS) or near-LOS
  - low SNR
  - larger Doppler shifts, more sensitive to mobility

- Massive antenna arrays
  - large array gain
  - size proportional to wavelength
  - narrow, focused beamforming

- Small cells
  - short range
  - lower power
  - low mobility
  - interference-limited

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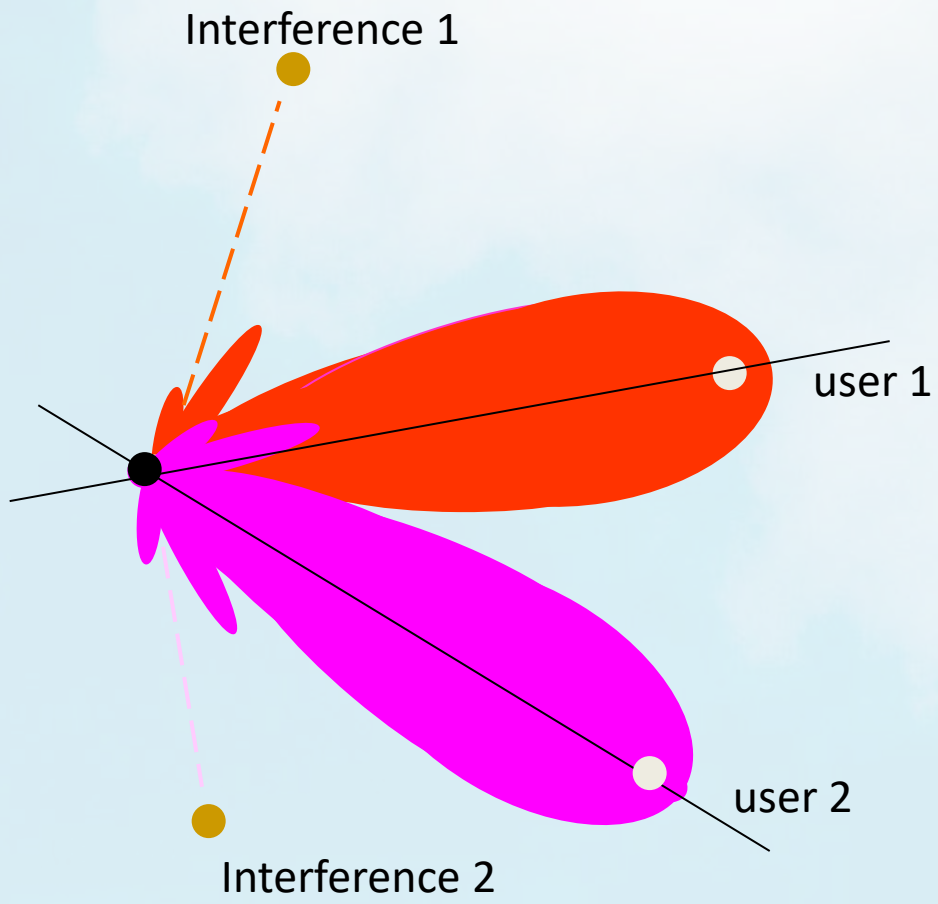
***Research Group*: Exploiting Antenna Arrays for Next-Generation Wireless Systems**

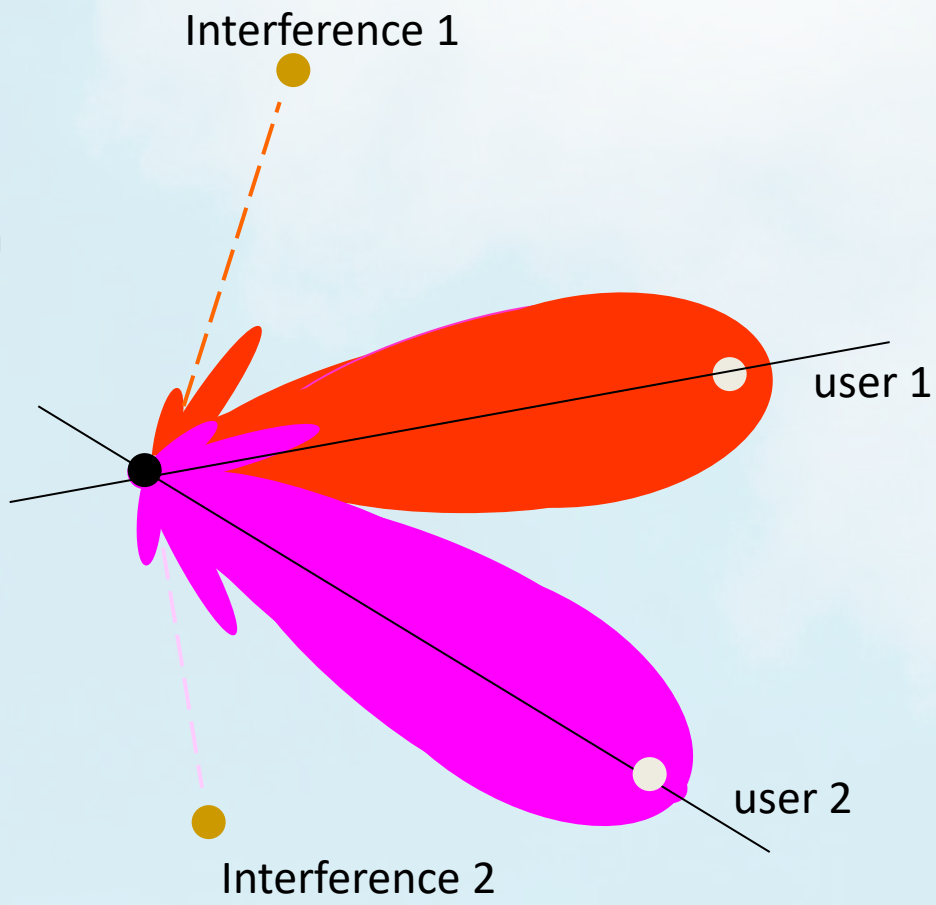
“Smart” Antenna Systems

- interference reduction



“Smart” Antenna Systems

- interference reduction
- multiplexing users in space
- at high SNR, *M* antennas can yield *M*-fold gain in rate w/out bandwidth expansion



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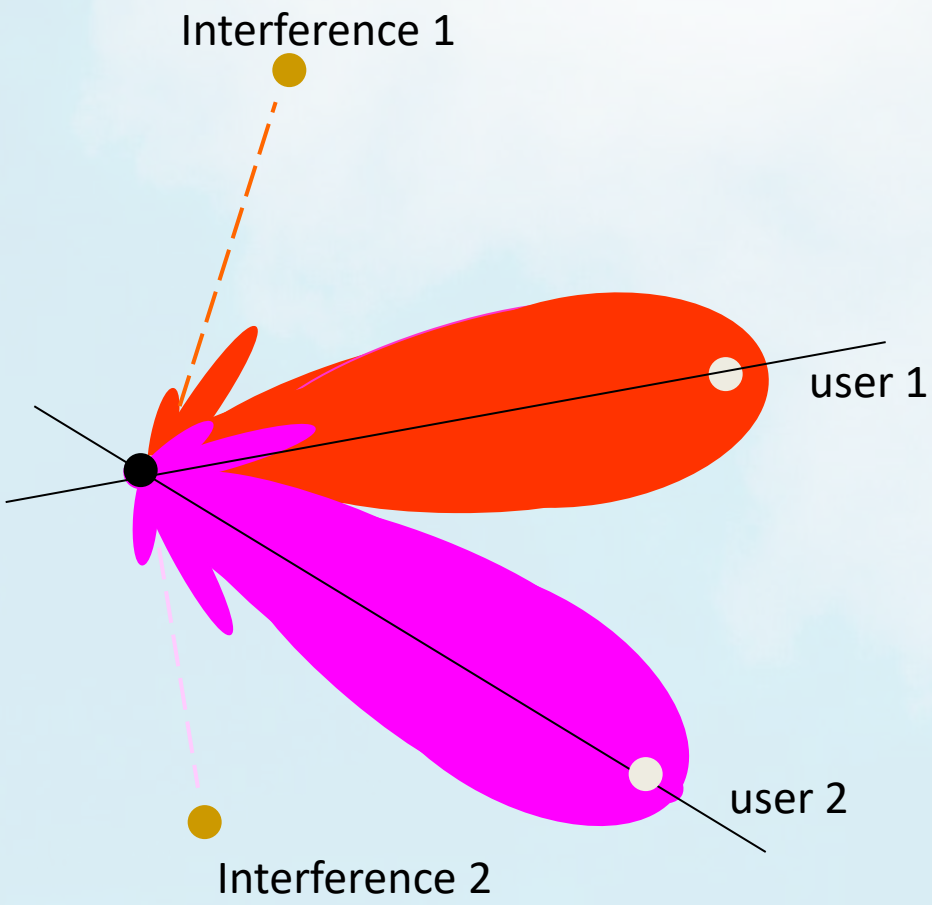

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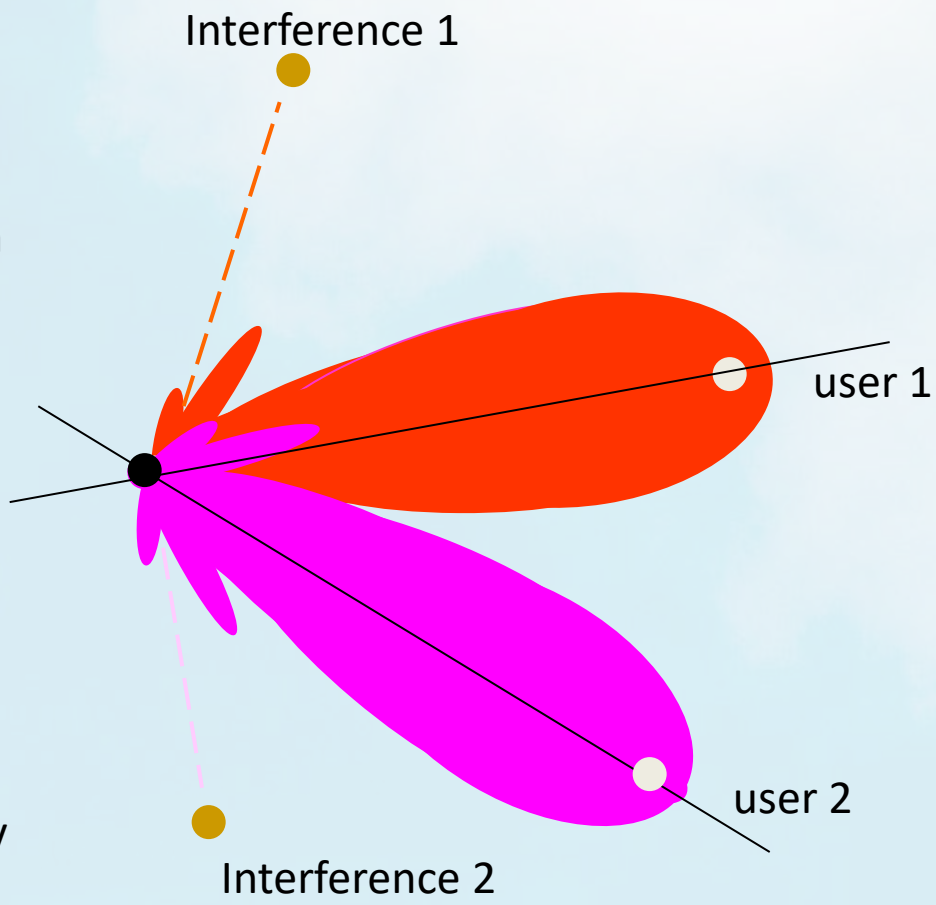

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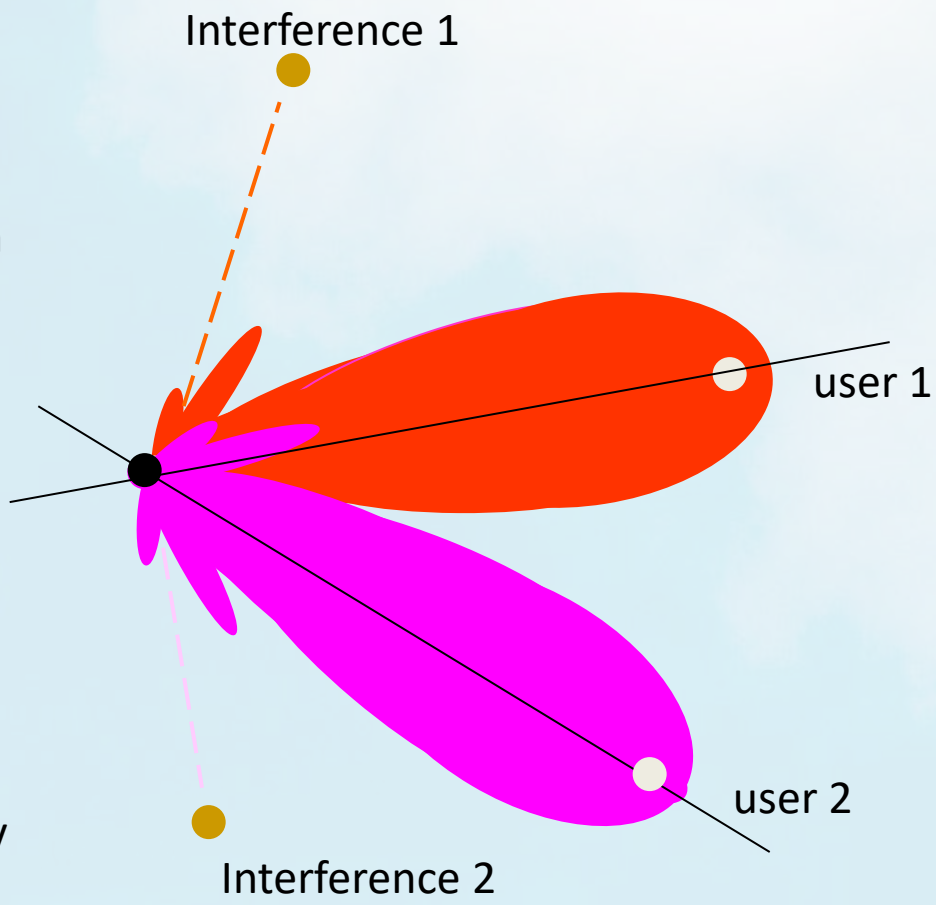
- user 1 and user 2 can be different antennas for the same user: MIMO



Massive Antenna Arrays for Wireless

The advantages of multiple antennas in wireless communications is by now well known:

- improved coverage
- improved diversity
- increased spectral efficiency
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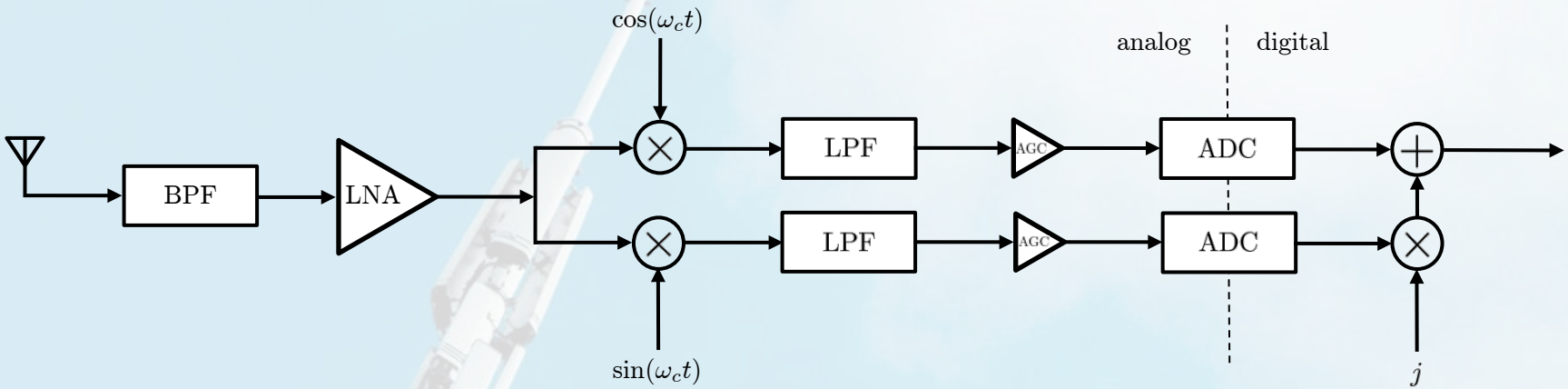
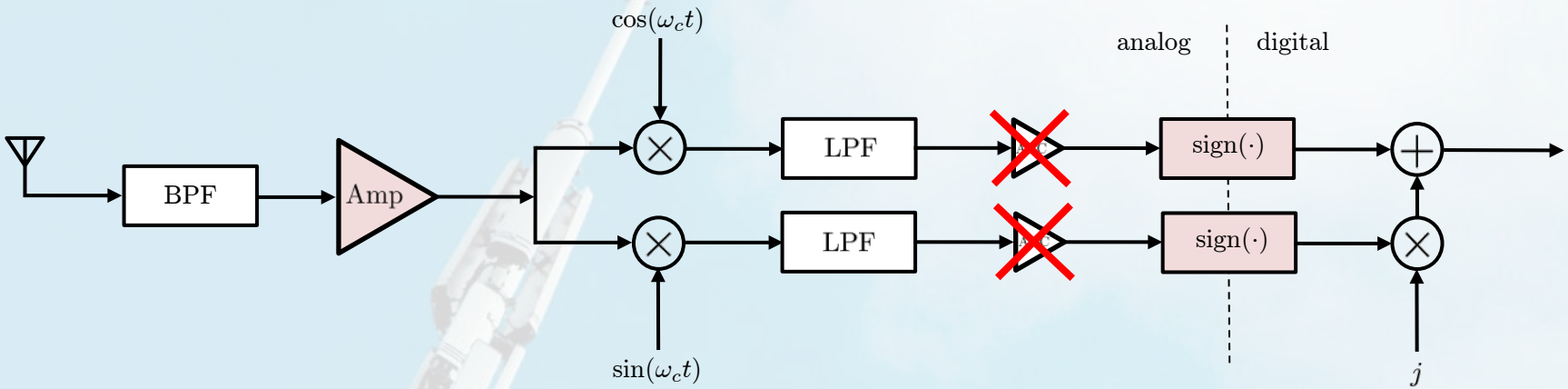
At millimeter wave frequencies, on- or near-chip antennas produce a small Footprint for large arrays; e.g., a 12x12 array @ 30 GHz is less than 6”x6”

Standard Receiver Implementation



- Full precision ADC requires linear, low-noise amplifiers and AGC
- ADC power consumption grows exponentially with resolution
- A commercial TI 1 Gs/s 12-bit ADC requires as much as 2-4W
- Not practical for ideal massive MIMO

A One-Bit Receiver



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- One-bit ADC $\Rightarrow$ simple RF, no AGC or high cost LNA
- Operates at a fraction of the power (mW)
- Compensate for quantization error with signal processing

Single Antenna Theoretical Analysis

AWGN Channel Capacity

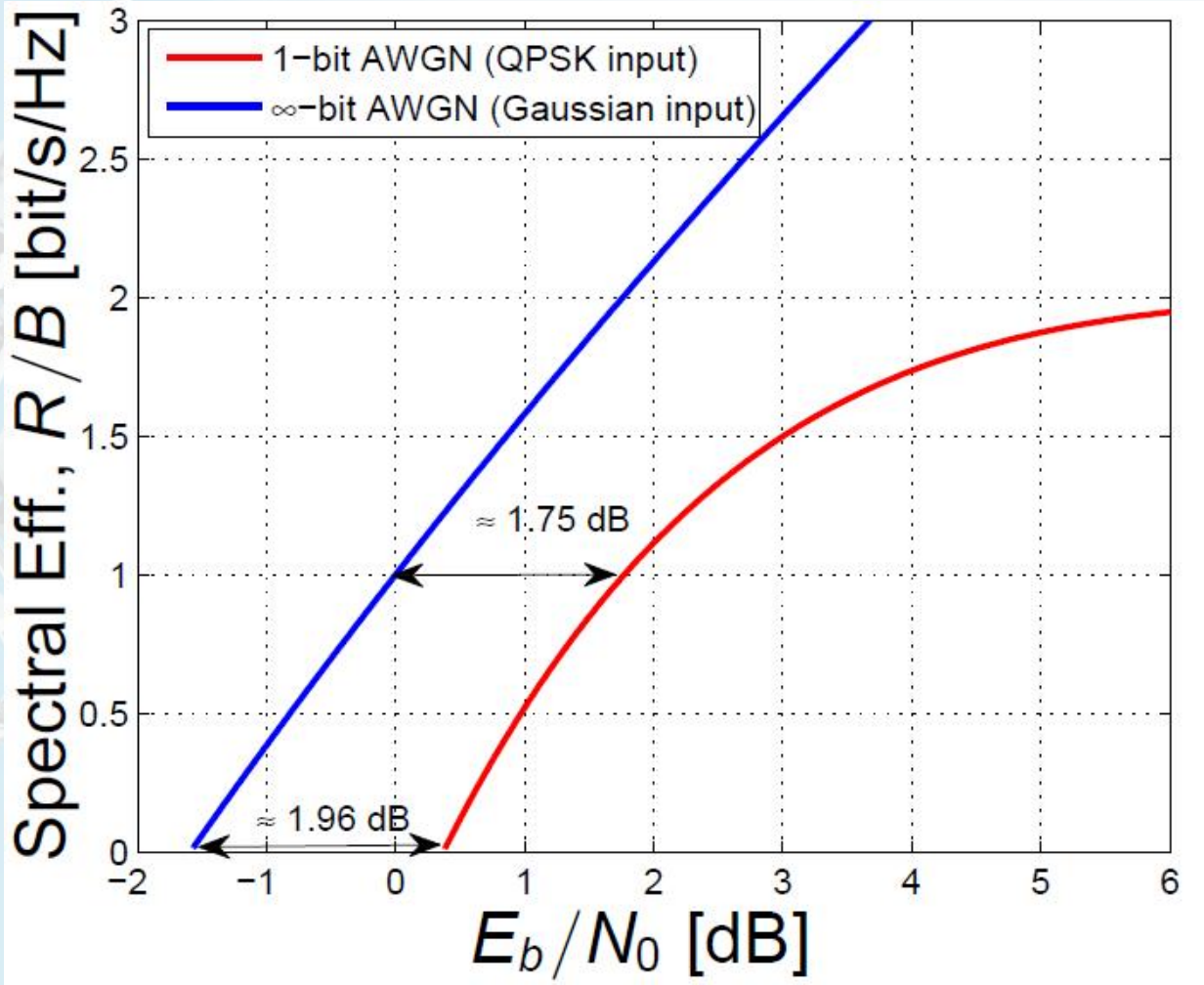
$$B \log_2(1 + \mathrm{SNR})$$

1-Bit AWGN Capacity

$$2B\left(1 - H_b(\Phi(\sqrt{\mathrm{SNR}}))\right)$$

loss in power efficiency < 2dB when SE < 1.4 bpcu

trade-off between power and energy efficiency is less apparent for 1-bit systems



Nonlinear Analysis: The Bussgang Decomposition

Consider a Gaussian signal that passes through a non-linear operator:

$$\mathbf{r} = \mathcal{Q}(\mathbf{x})$$

Bussgang (Bell Labs, 1952) showed that a statistically "equivalent" (up to second order) linear model exists for the non-linearity

$$\mathbf{r} = \mathcal{Q}(\mathbf{x}) = \mathbf{A}\mathbf{x} + \mathbf{q}$$

that results in the error $\mathbf{q}$ (here the quantization noise) and the signal $\mathbf{x}$ being uncorrelated, namely

$$\mathbf{A} = \mathcal{E}\{\mathbf{x}\mathbf{r}^T\}\mathcal{E}\{\mathbf{x}\mathbf{x}^T\}^{-1}$$

This is also the choice that minimizes the quantization noise:

$$\mathbf{A} = \arg\min_{\mathbf{A}} \|\mathbf{r} - \mathbf{A}\mathbf{x}\|^2$$

Recent Research Activities

- How many more antennas are needed with one-bit quantization?

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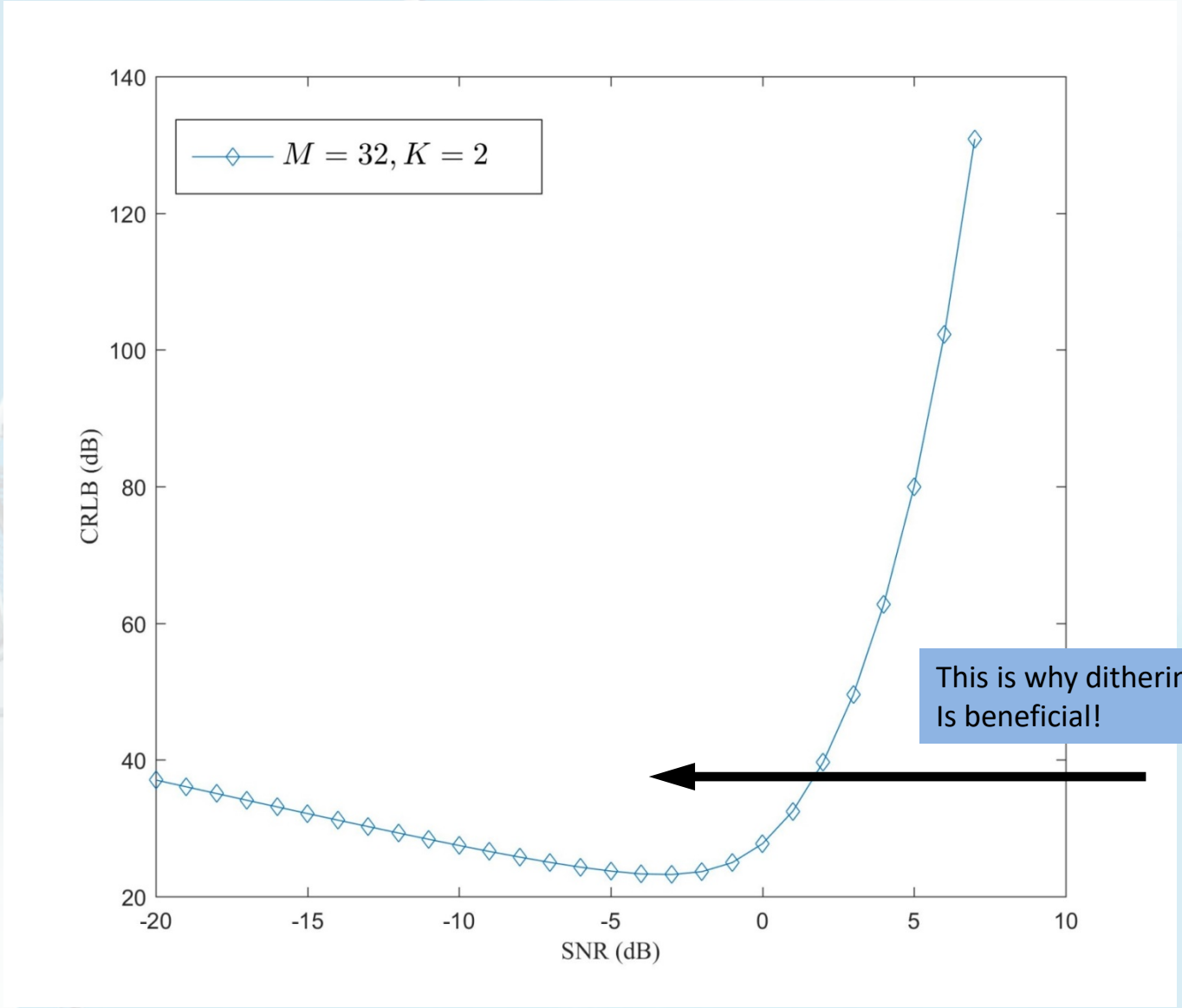
- How to estimate the wireless channel with one-bit quantization?

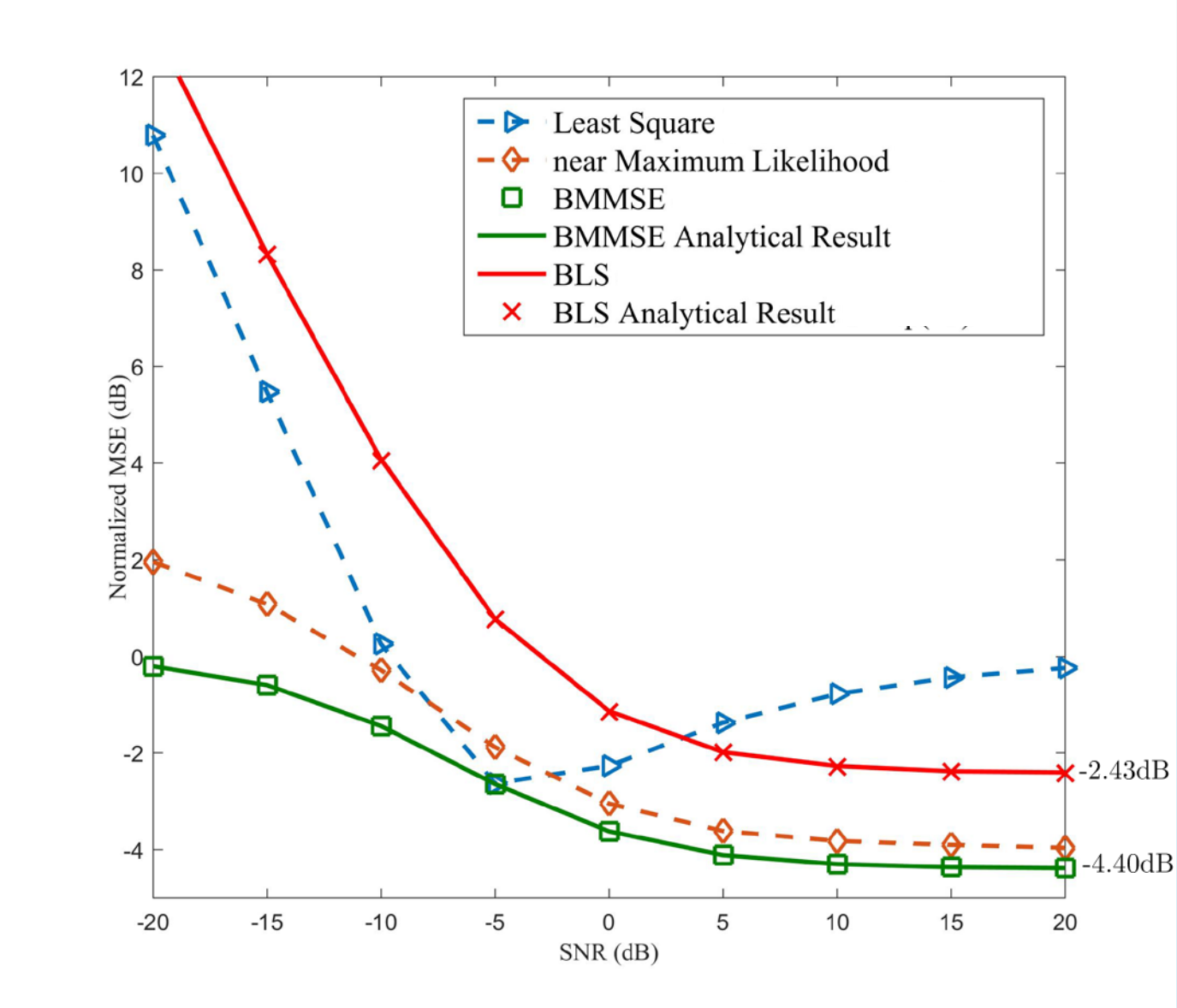
Answer: Bussgang LMMSE

Example: Channel Estimation Error Bounds



Example: Channel Estimation

- $M = 128$
- $K = 8$
- $\tau = K$
- Rayleigh fading



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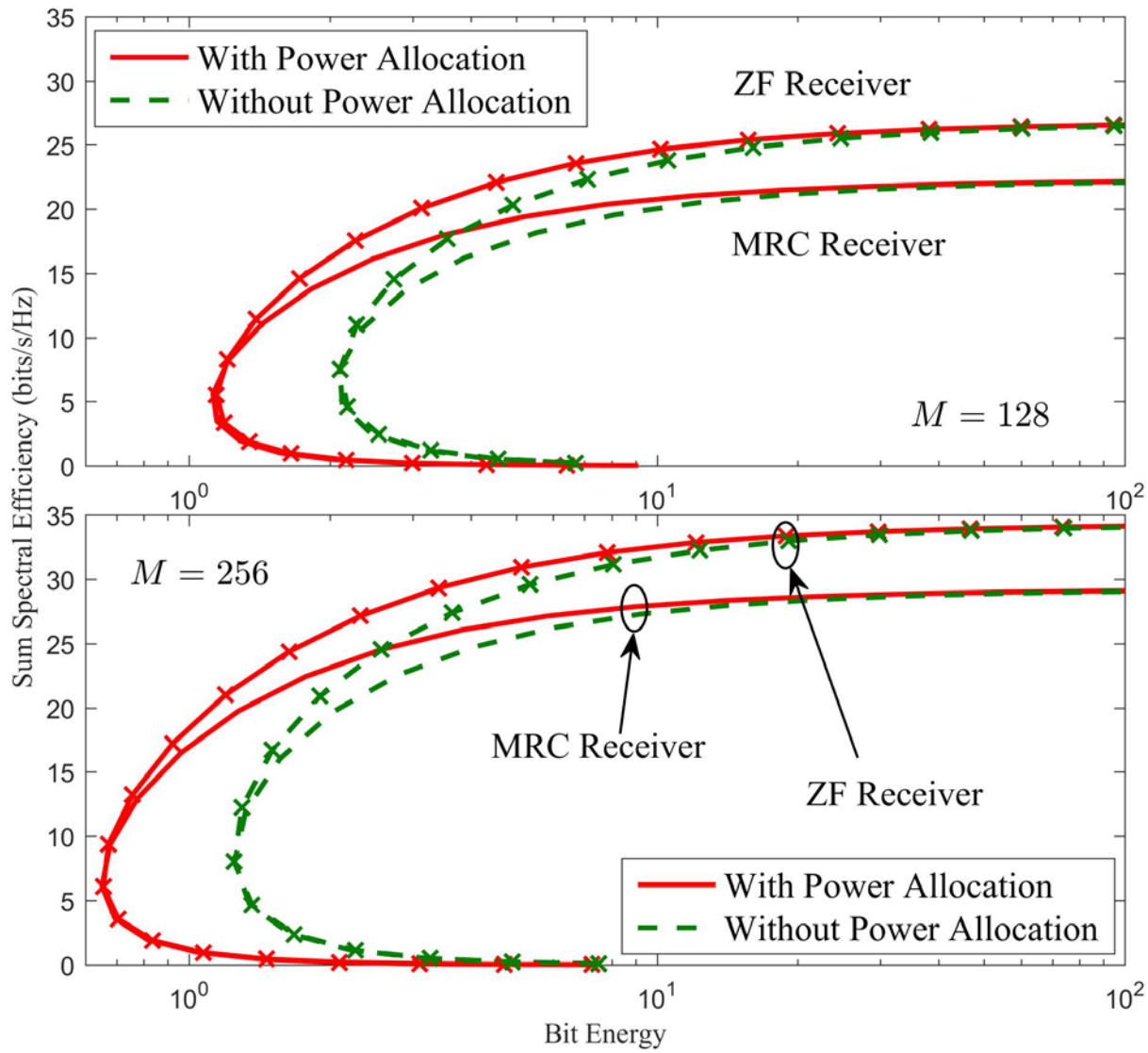
- How to maximize spectral/energy efficiency?

Answer: Convex optimization for energy-per-bit

Example: Optimizing Energy per Bit

- $K = 8$ users
- unoptimized $\rho_d = \rho_p$
- coherence interval $T = 200$
- sum spec. eff.

$$\mathcal{S} = \frac{T-K}{T} KR$$



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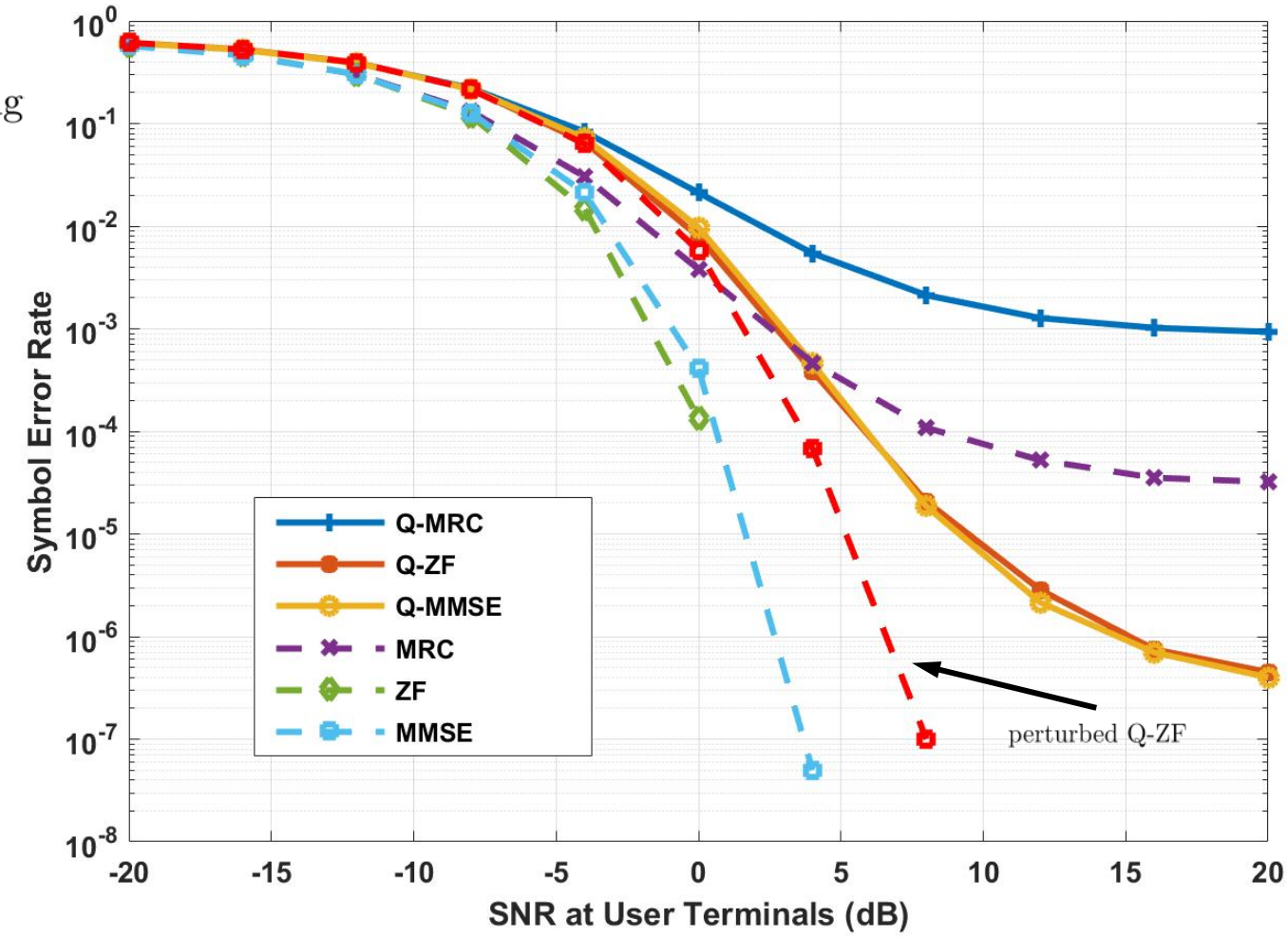
- How to precode the signals to account for one-bit DAC?

Answer: Perturbed quantized linear precoding

Example: Performance of Perturbed Quantized ZF Precoder

- $M = 128$
- $K = 8$ users
- Rayleigh fading
- Perfect CSI



Conclusion

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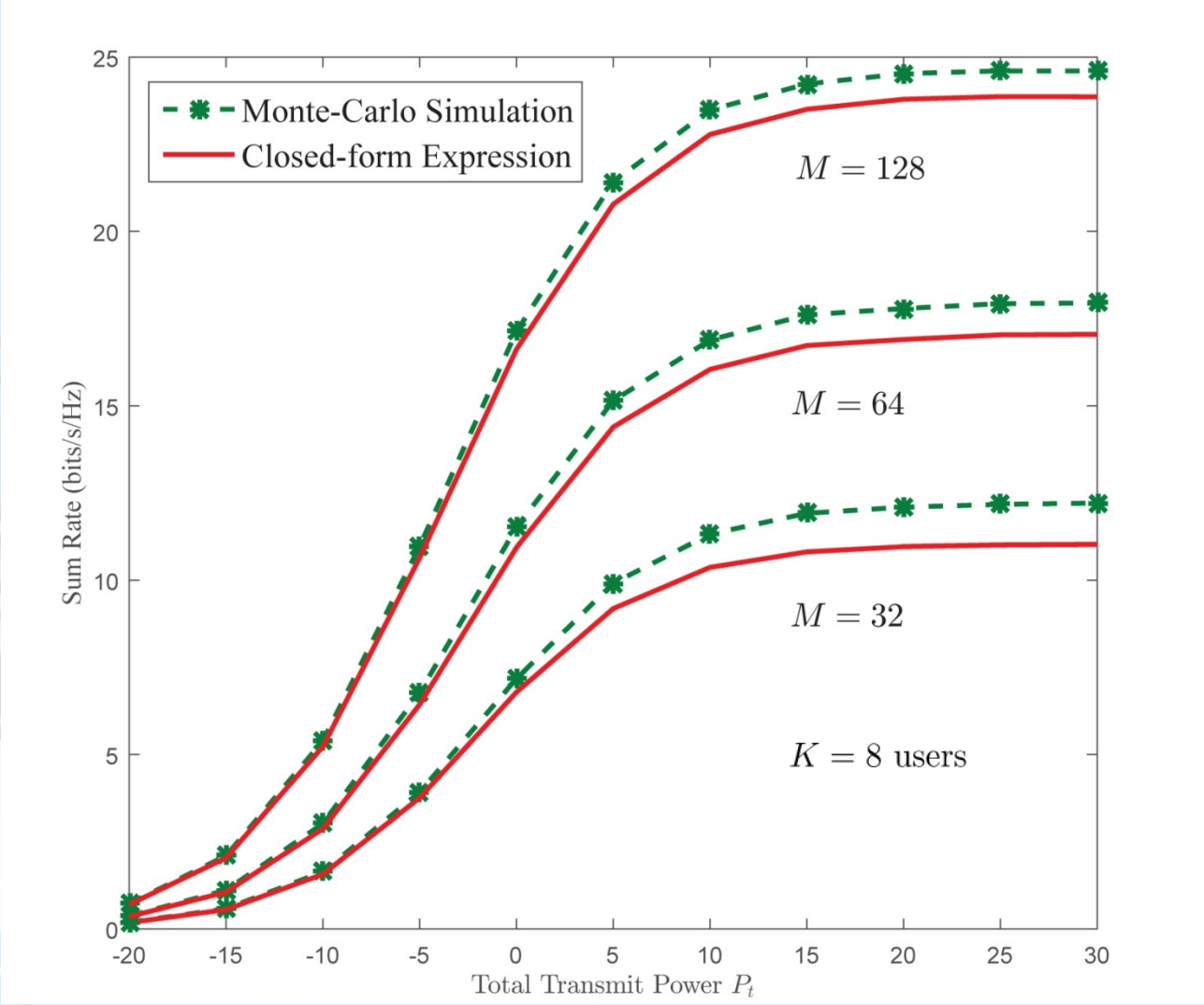

Conclusion

Can we get a 1000x improvement in throughput with only one-bit transceivers?

YES!

(with a GHz of bandwidth and the right processing)