Key Challenges of THz Communications for 6G Era:

Tbps Communications and Energy Efficient System

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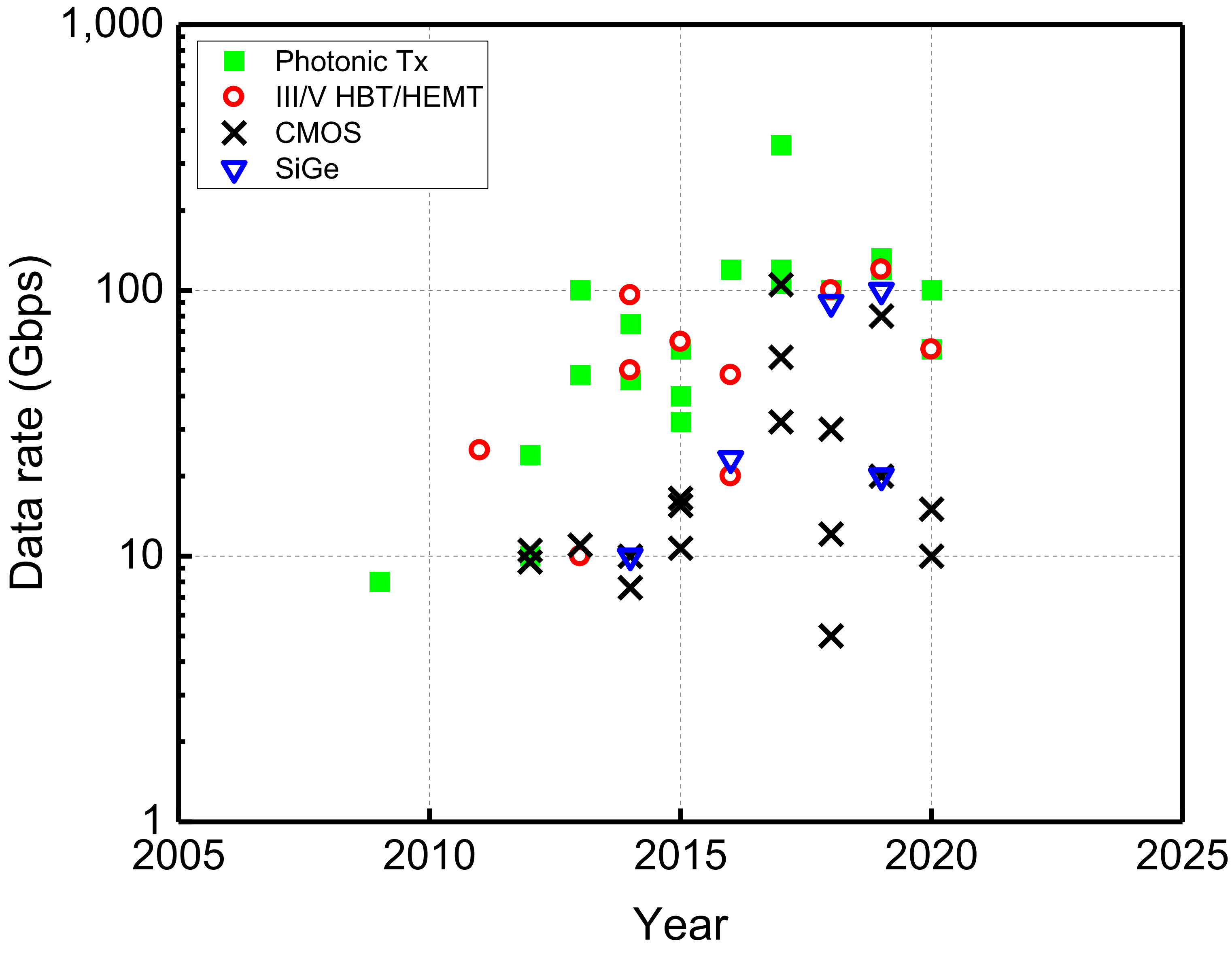
Overview

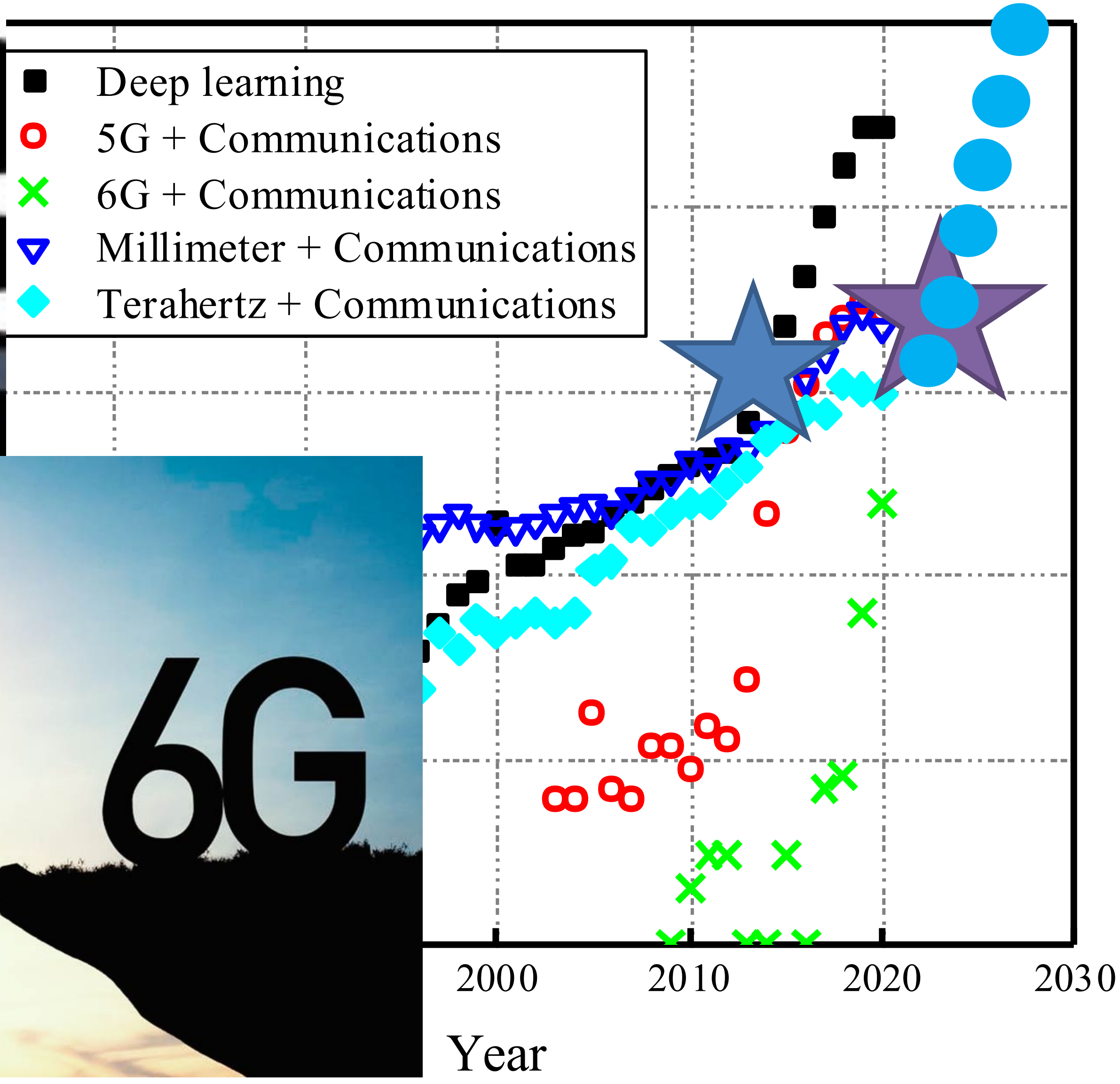
- **Introduction: Challenges in past**
- **Ultimate challenges we are already aware of**
  - Data rate
  - Power dissipation
  - ~~Applications~~
- **Conclusion**

Why THz?

Progress in Data Rate



Community Growth



(2021)

Key Challenges in Past (and even now)

Circuit Design
- Various functionality
- High power/ low noise

Devices
- Toward 2-THz f_{max} HEMTs
- RTD, UTC-PD, SBD, etc..
- Advanced fabrication tech. (passive)

PHY design
- Target application
- Channel modeling
- Study on wave-propagation
- PHY architecture

Packaging and Antenna
- Compact packaging
- Interconnection
- On-Chip or In-Package antenna

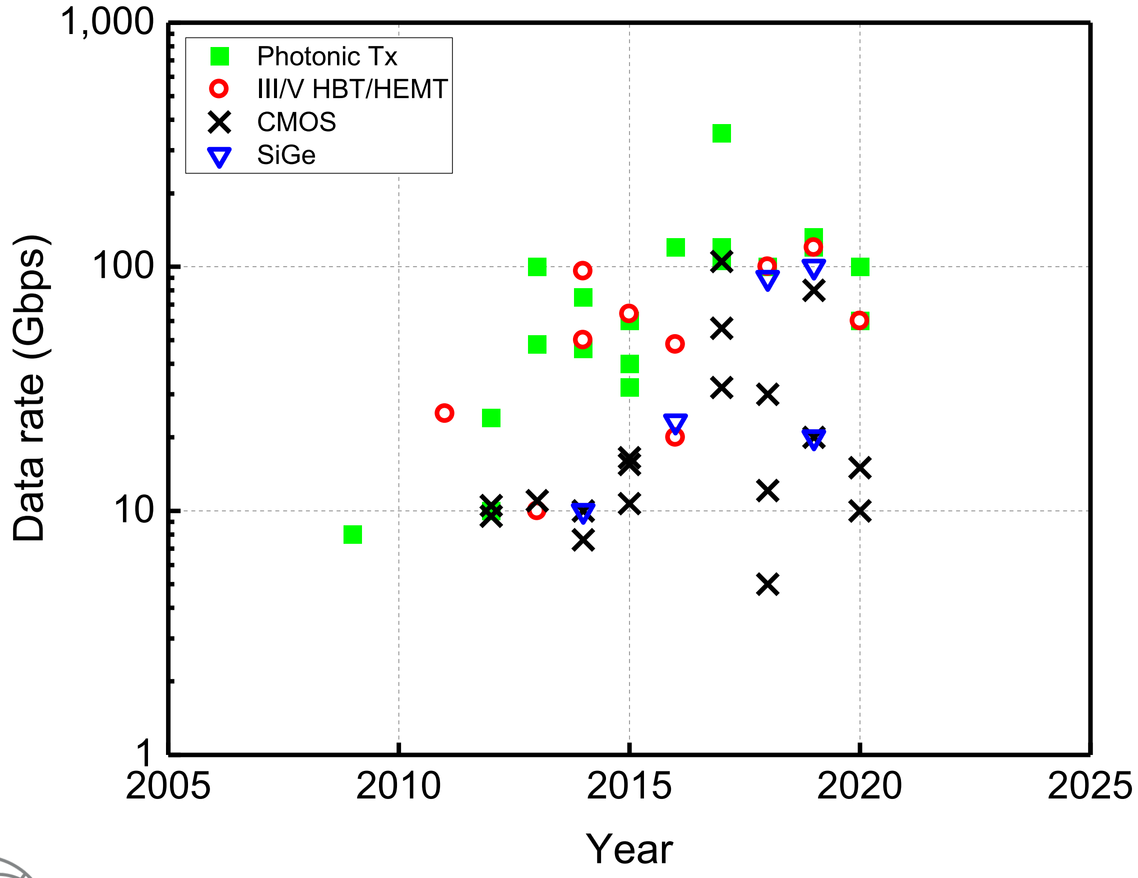
What is Key Challenges Now?

- Two of the most frequency questions about THz communications.

- **How large data rate will be achievable? or 1Tbps**
- **Power dissipations of devices?**

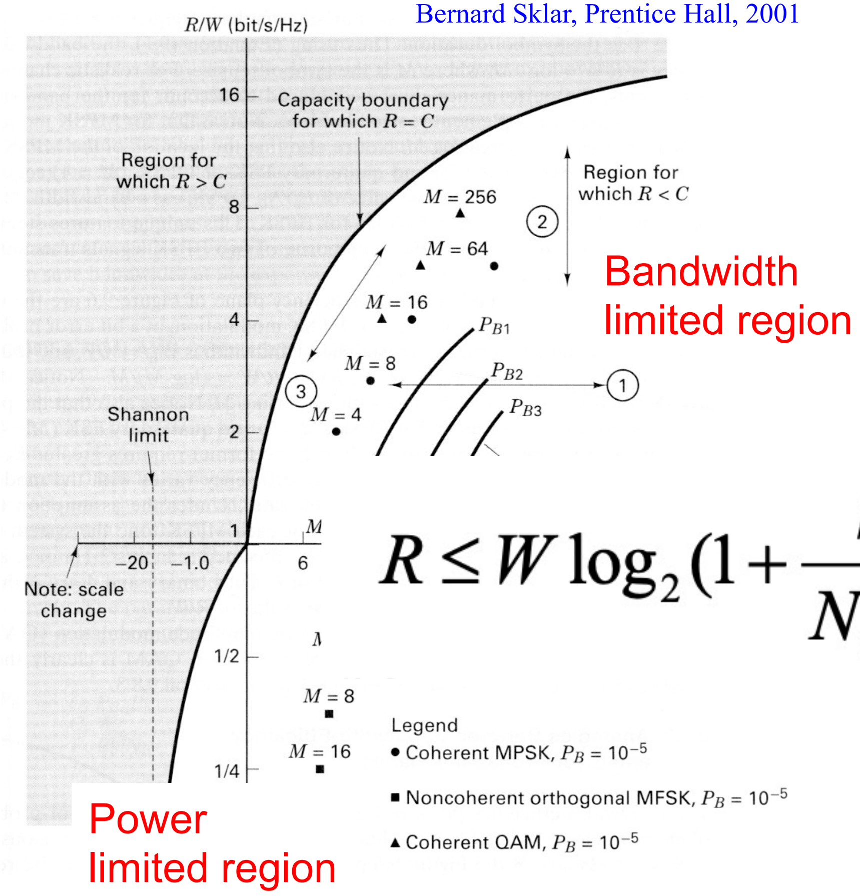
How to achieve 1 Tbps at THz frequencies?

Max Data Rate is around 100 Gbps



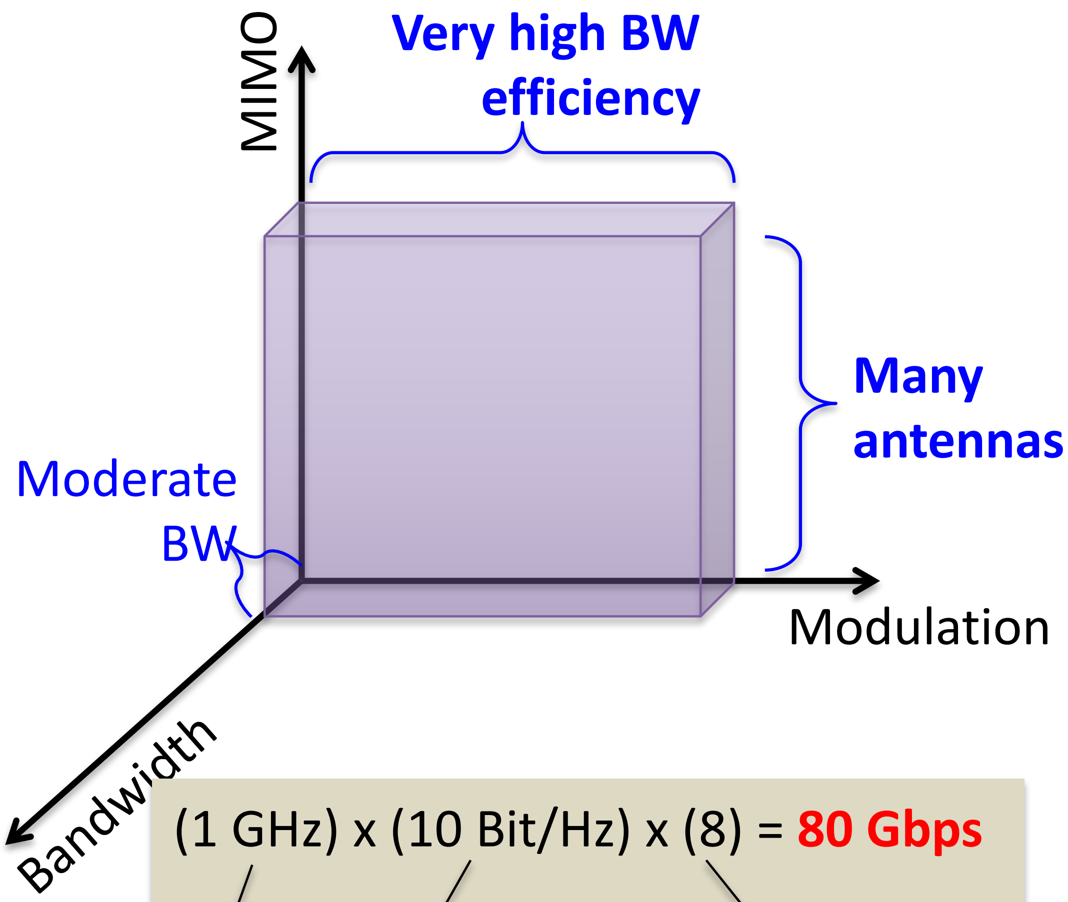
THz communications are working with narrowband waveform that requires large power

From 'Digital Communications 2/e'
Bernard Sklar, Prentice Hall, 2001



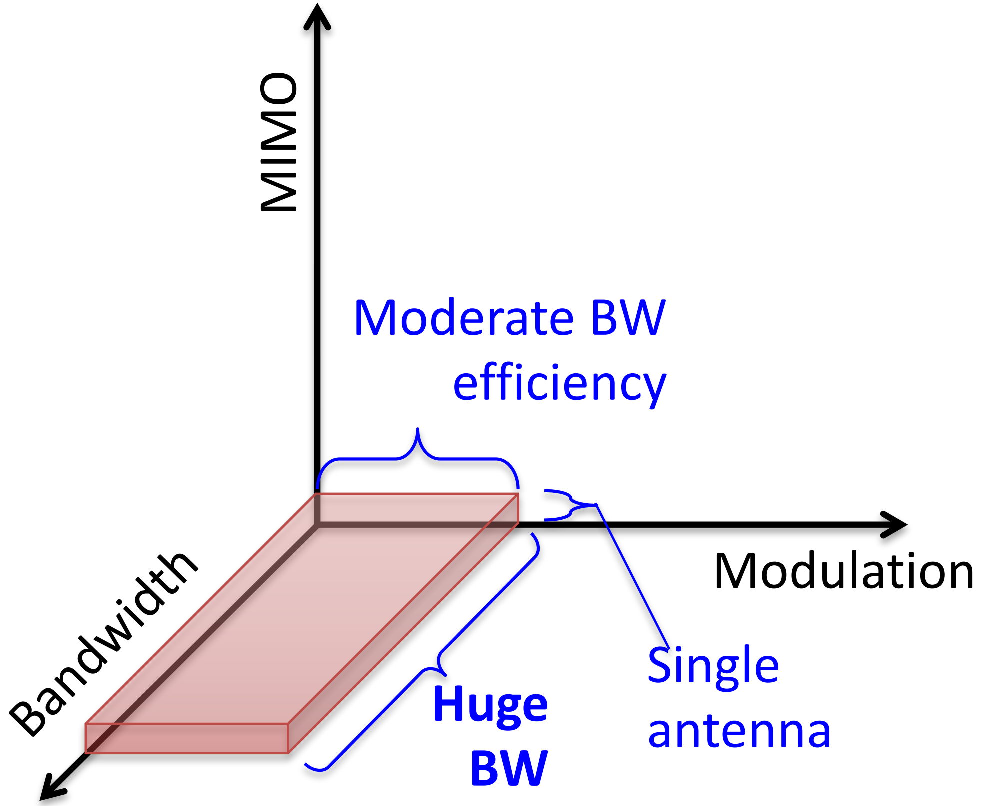
$$R \le W \log_2\left(1 + \frac{S}{N_0 W}\right)$$

Data Rate = BW x modulation x Beams



(1 GHz) x (10 Bit/Hz) x (8) = **80 Gbps**

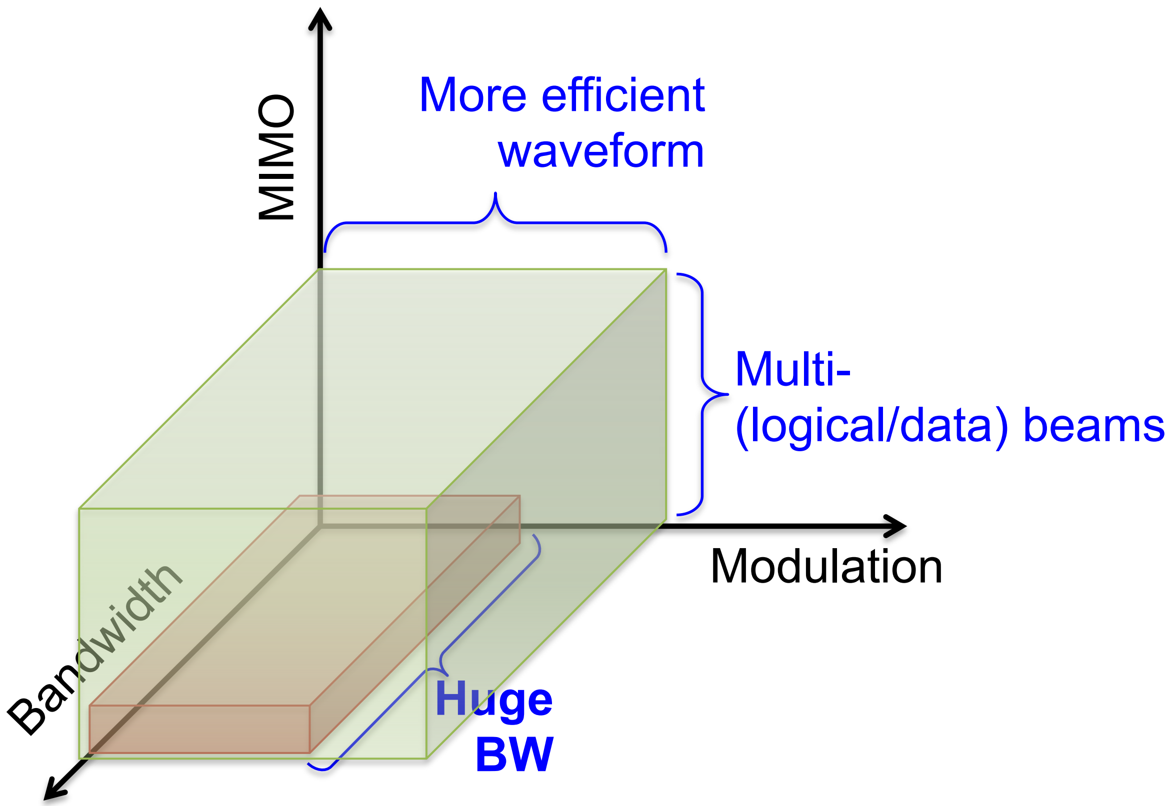
BW 1024 QAM *MIMO* $min(N_{tx}, N_{rx})$



(50 GHz) x (2 Bit/Hz) x (1) = **100 Gbps**

BW QPSK *SISO*

1 Tbps?

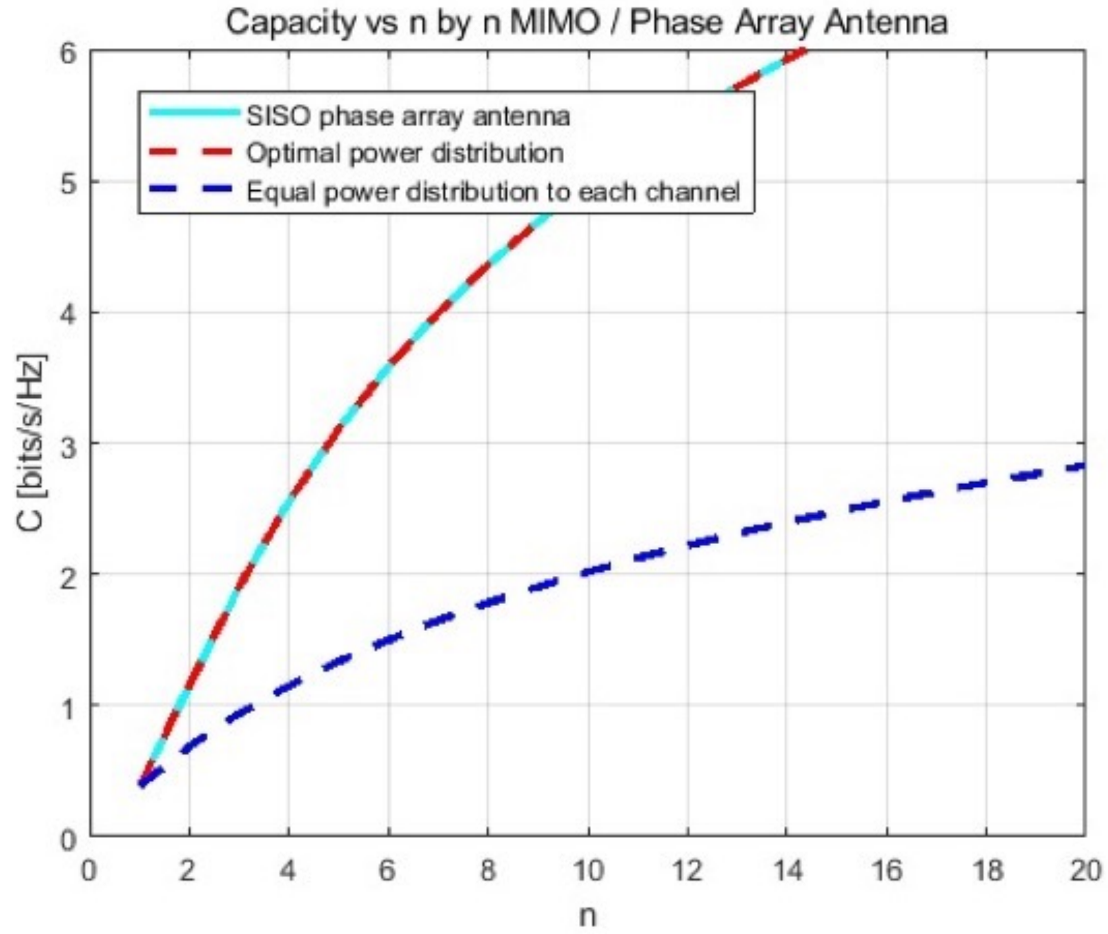


(50 GHz) x (4 Bit/Hz) x (5) = **1000 Gbps**

BW — 16AQM — *5-layer MIMO*

MIMO at LOS Channel?

If there are multiple signal paths which are orthogonal ($\lambda_{i>2} \neq 0$), we can transmit more

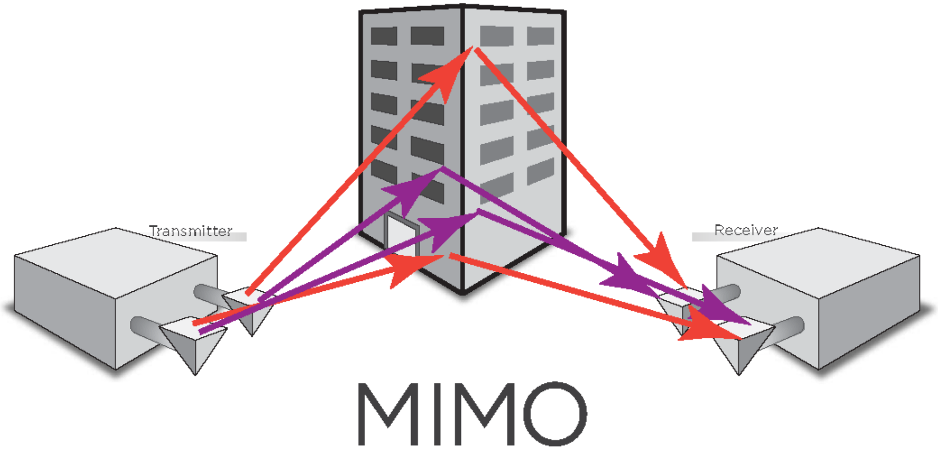


$$C_{MIMO,opt} = \Sigma_i log_2\left(1+\frac{{\lambda_i}^2 P_i}{{\sigma_n}^2}\right) = log_2\left(1+\frac{{\lambda_1}^2 P_1}{{\sigma_n}^2}\right) + log_2\left(1+\frac{{\lambda_2}^2 P_2}{{\sigma_n}^2}\right) + \cdots + \left(1+\frac{{\lambda_n}^2 P_n}{{\sigma_n}^2}\right)$$

$$\approx log_2\left(1+\frac{{\lambda_1}^2 P}{{\sigma_n}^2}\right)$$

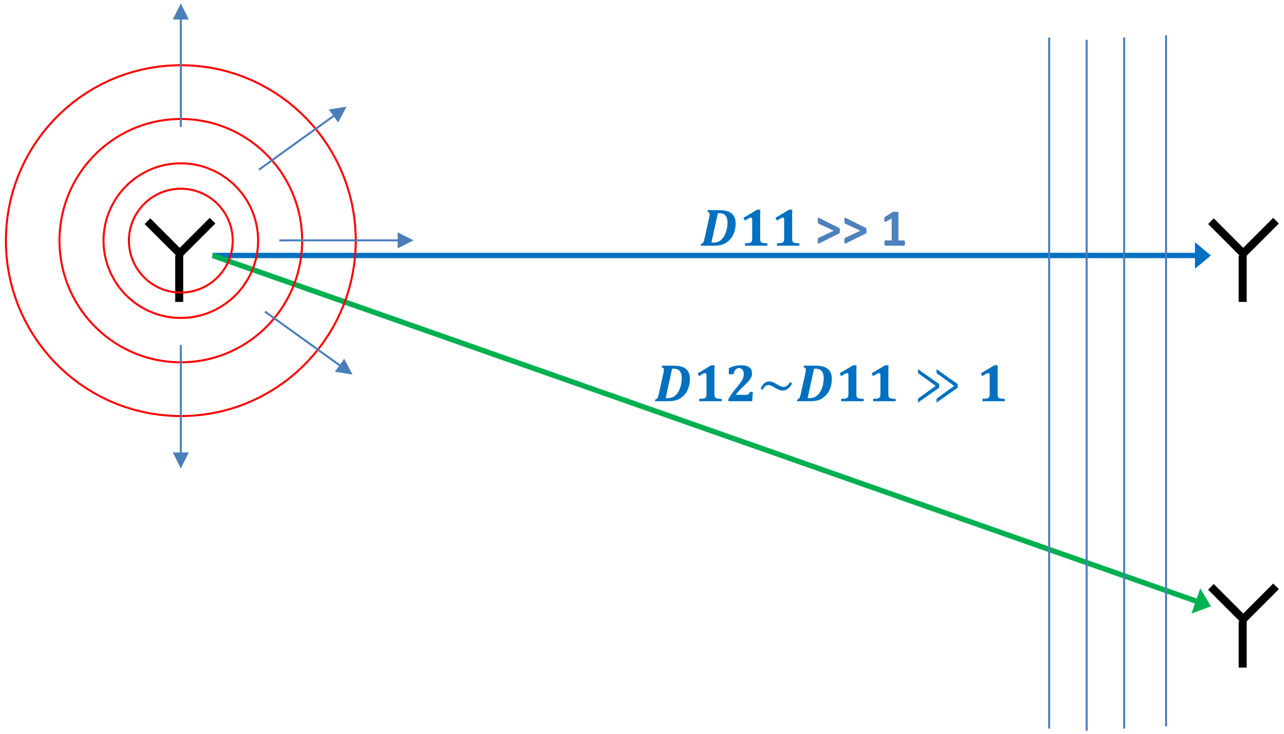
$$= log_2\left(1+\frac{n^2 P}{{\sigma_n}^2}\right)$$

$= C_{SISO}$ w/ arrayed antenna in TRx (# of antenna = n)



Wavefront Approximation

approximate



→ We don't have a change to send more date due to D11 and D12 are identical.

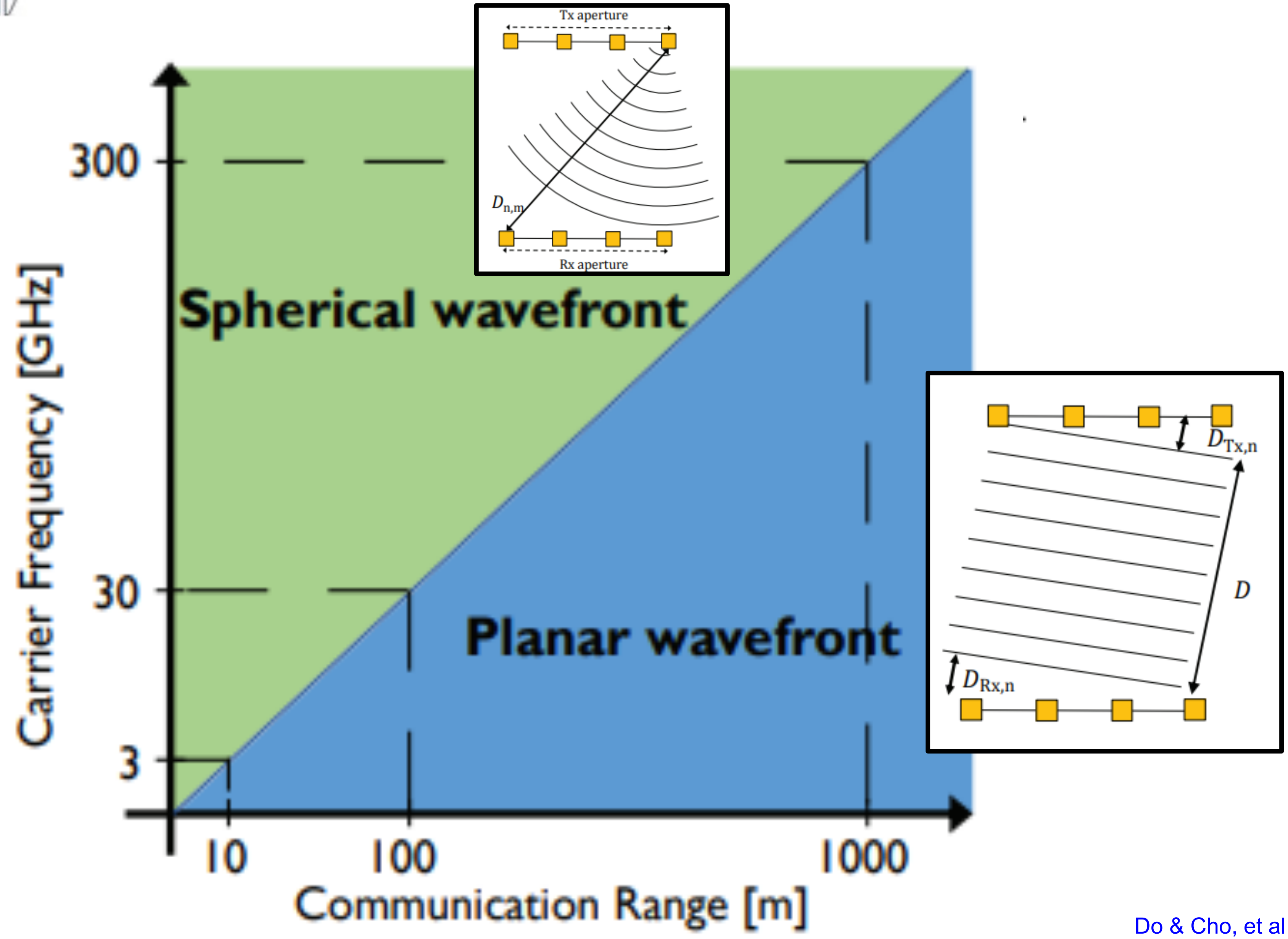
Wavefront at THz frequency

The planar wavefront is an accurate approximation for *a surface-segment of a very large spherical wavefront*.

it is valid when the *effective antenna array area normalized by the wavelength* is smaller than the *communication distance*.

$$D > 4\frac{(\text{array width})^2}{\lambda}$$

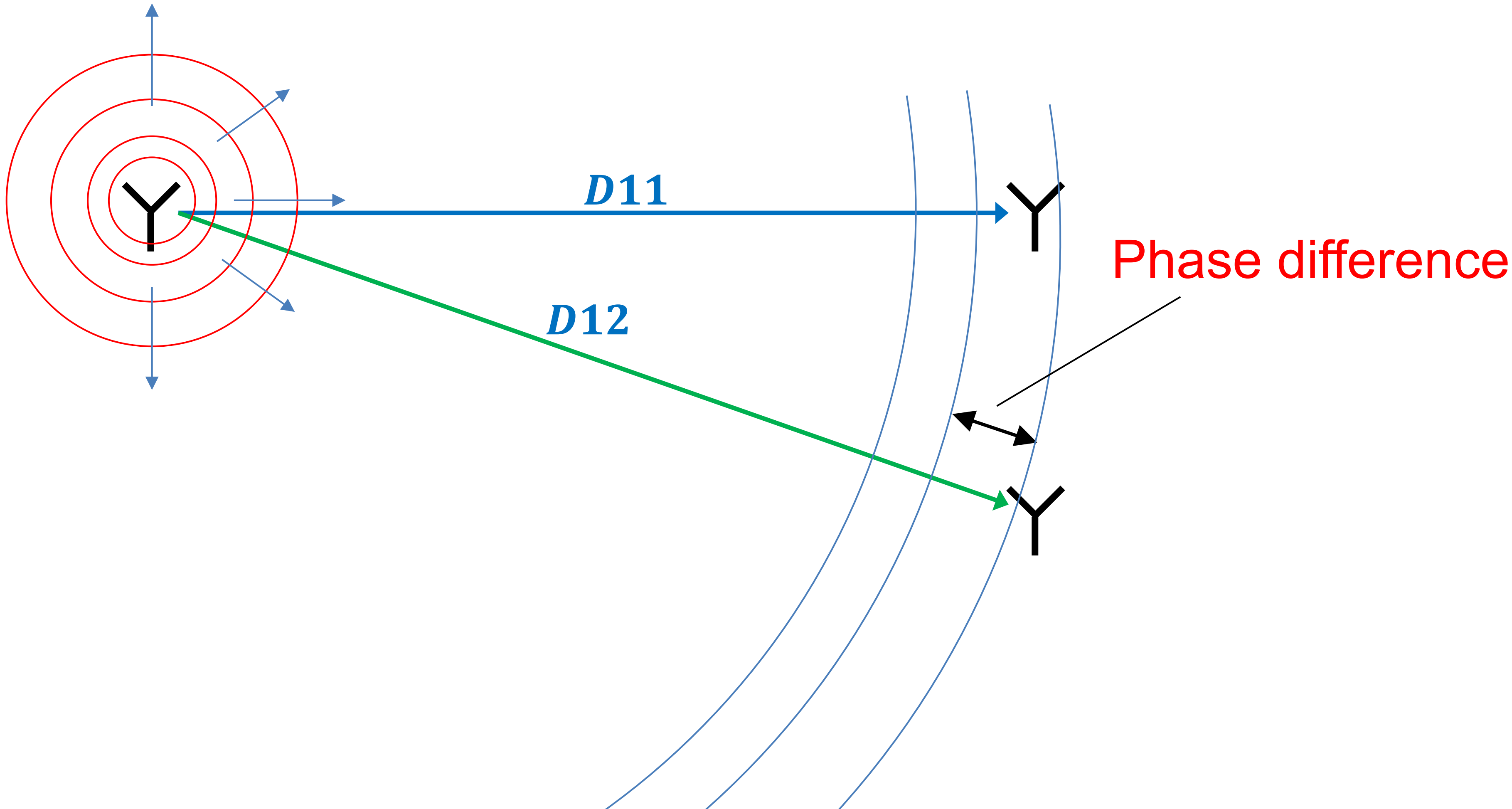
Assuming antenna aperture = 0.5 x 0.5 m^2



Do & Cho, et al., IEEE ComMag 2021

Spherical Wavefront

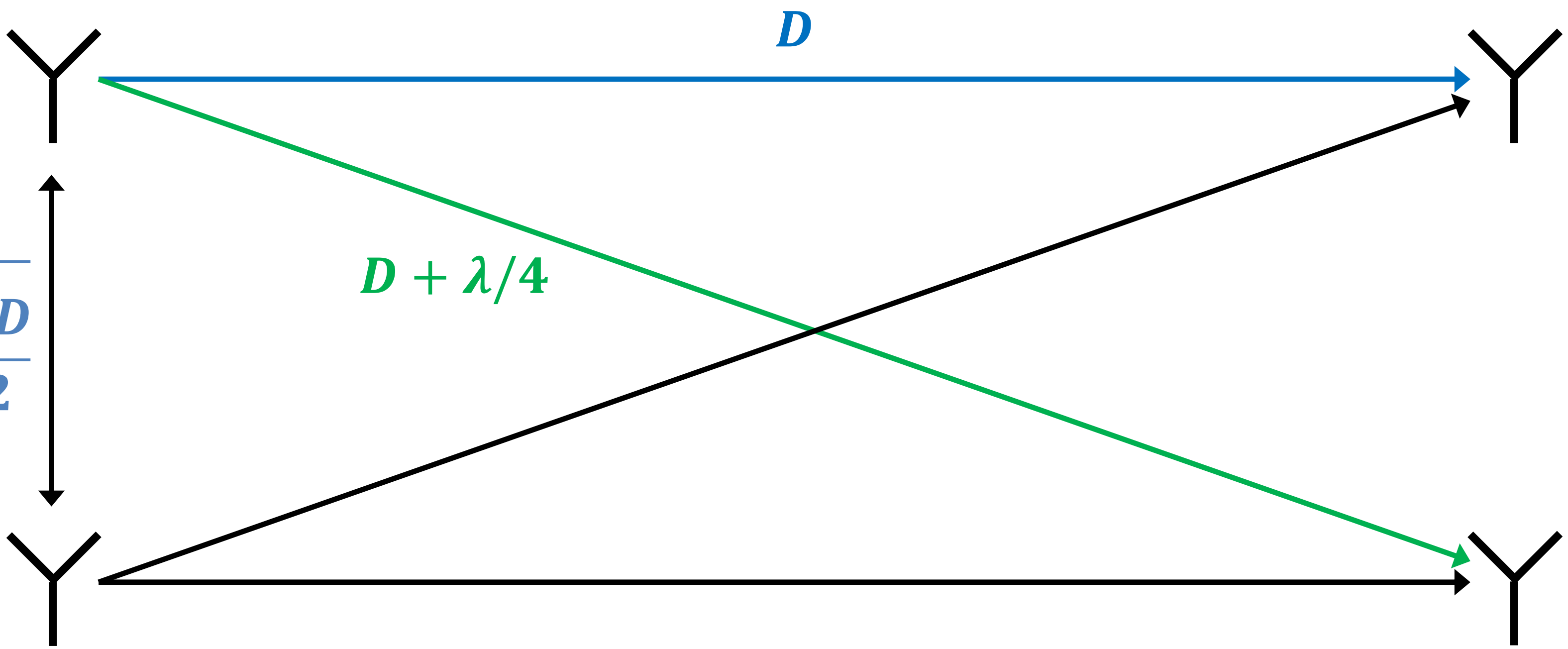
At least, two paths are not identical!



LOS-MIMO

One can have orthogonality between signal paths with appropriate antenna spacing for given distance. (MIMO rank > 1)

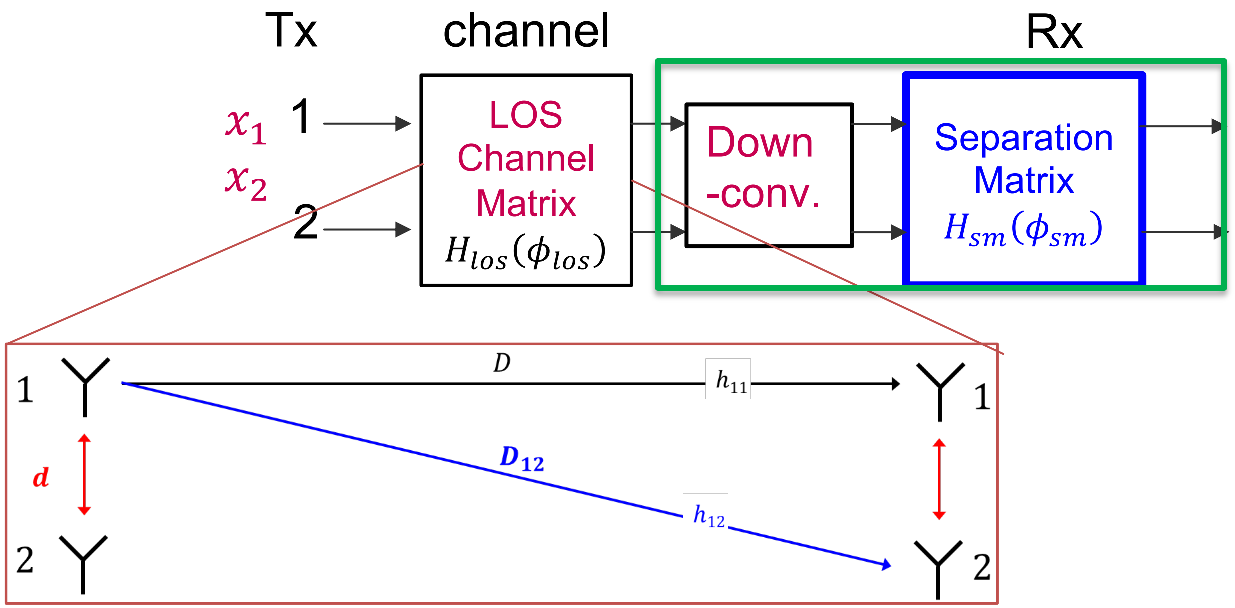
Rayleigh Criterion $d = \sqrt{\frac{\lambda D}{2}}$



$$a\begin{bmatrix} e^{-j2\pi\frac{D}{\lambda}} & e^{-j2\pi\frac{D+\lambda/4}{\lambda}} \\ e^{-j2\pi\frac{D+\lambda/4}{\lambda}} & e^{-j2\pi\frac{D}{\lambda}} \end{bmatrix} = ae^{-j2\pi\frac{D}{\lambda}}\begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix}$$

How to Do This?

$$M = \boldsymbol{H_{sm}(\phi_{sm})}H(\phi_{los}), |M(2,1)| = 0$$



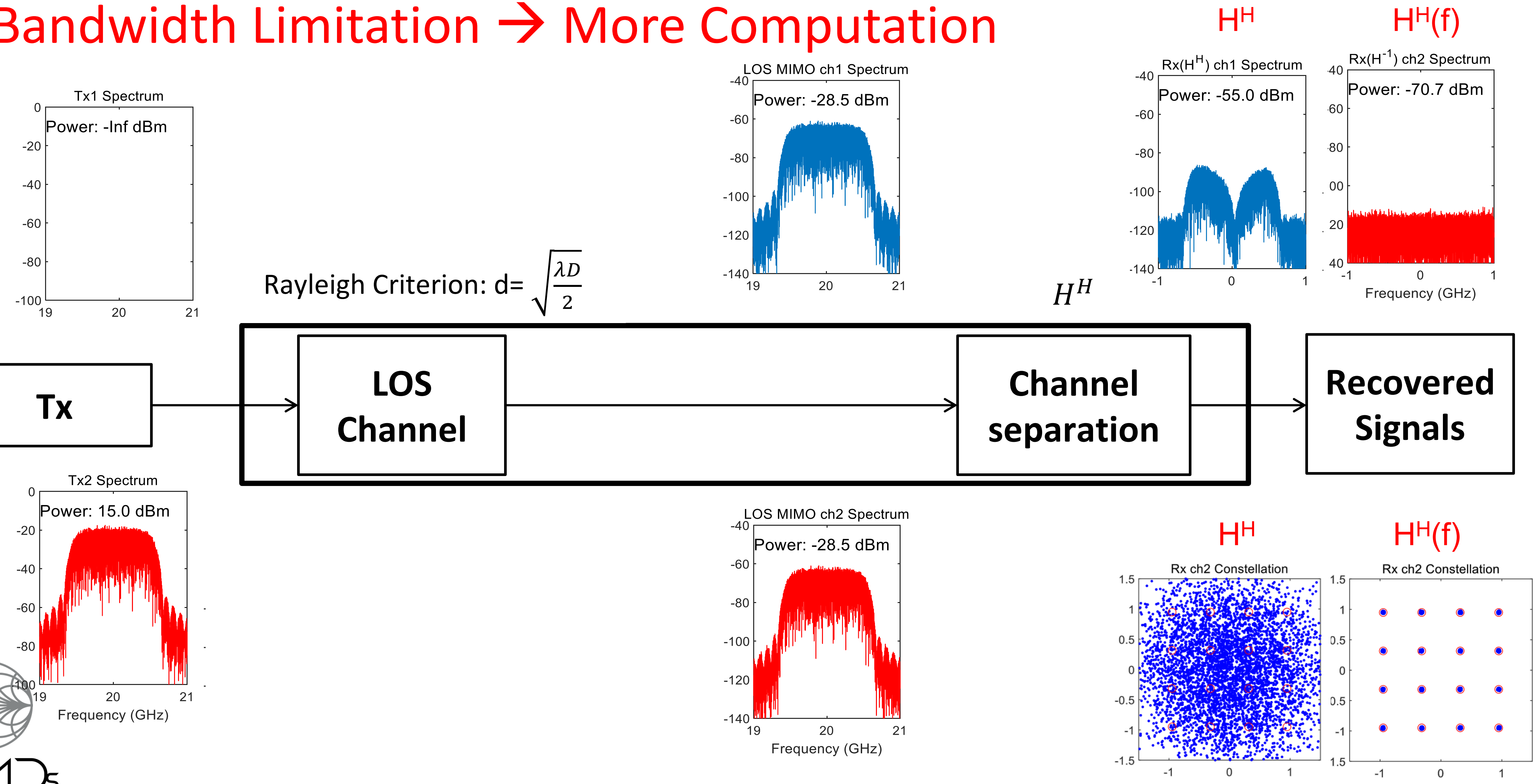
$$\underbrace{\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \boldsymbol{H_{sm}(\phi_{sm})}H(\phi_{los}) \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}}_{\text{Received signal}}$$

➔ You may set Rx matrix $\boldsymbol{H_{sm}(\phi_{sm})} = H(\phi_{los})^{\mathbf{H}}$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \boldsymbol{H_{sm}(\phi_{sm})H(\phi_{los})} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

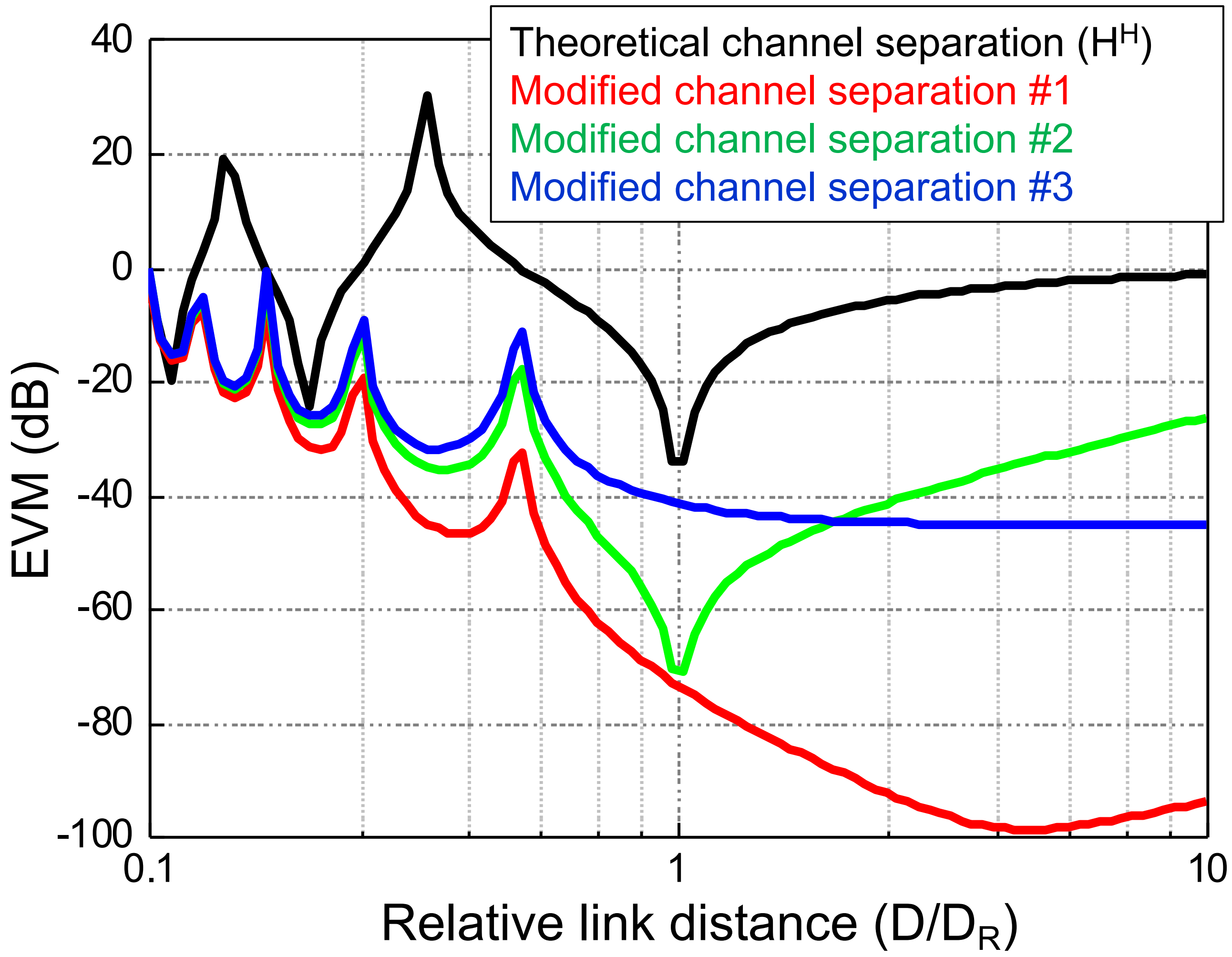
Two Technical Issues with THz LOS-MIMO (1)

- Bandwidth Limitation → More Computation



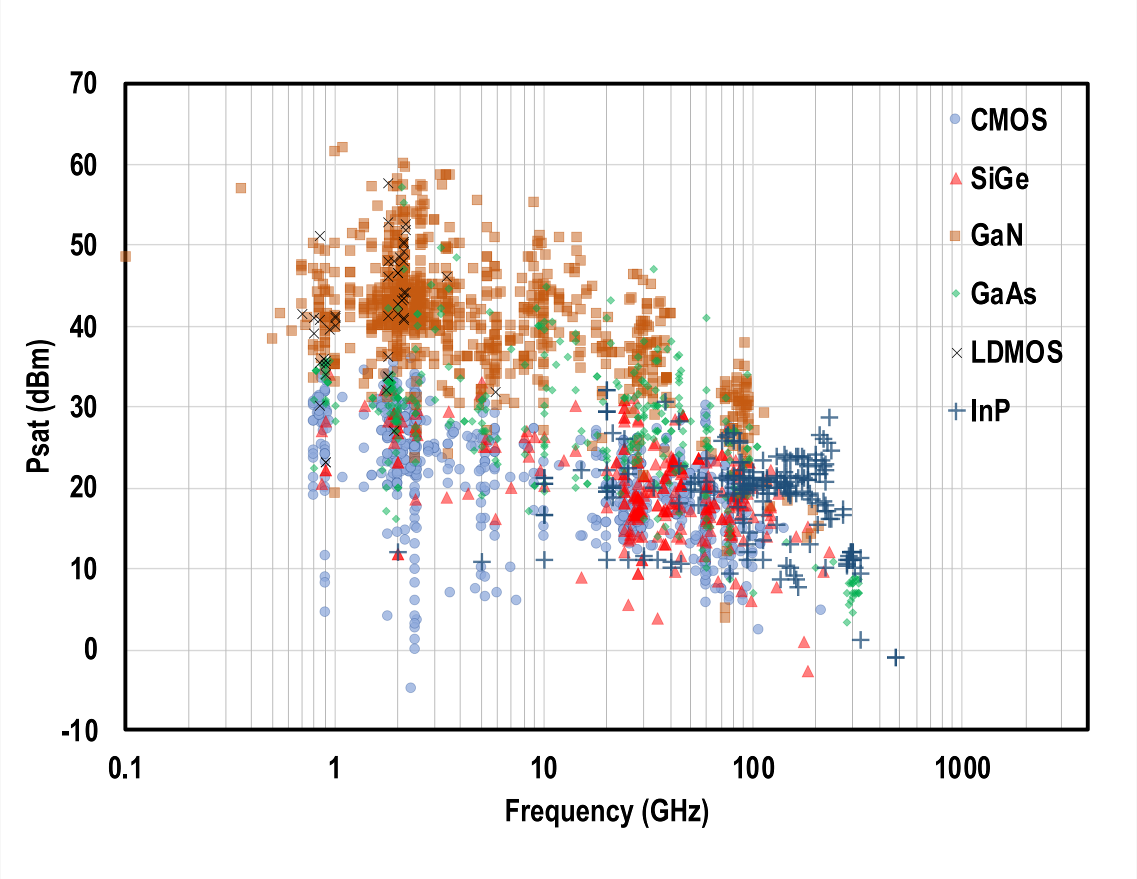
Two Technical Issues with THz LOS-MIMO (2)

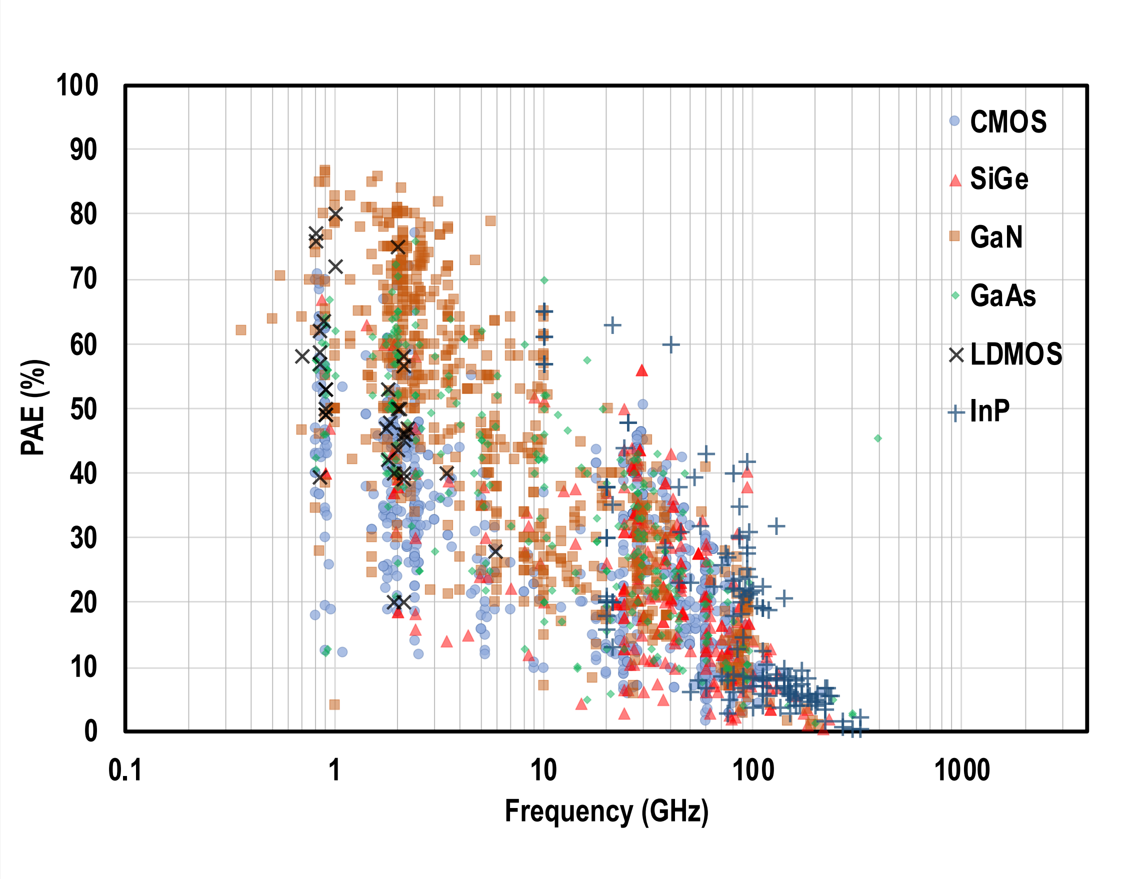
- Fixed communication range



Power Dissipation of Beamformer Transceiver

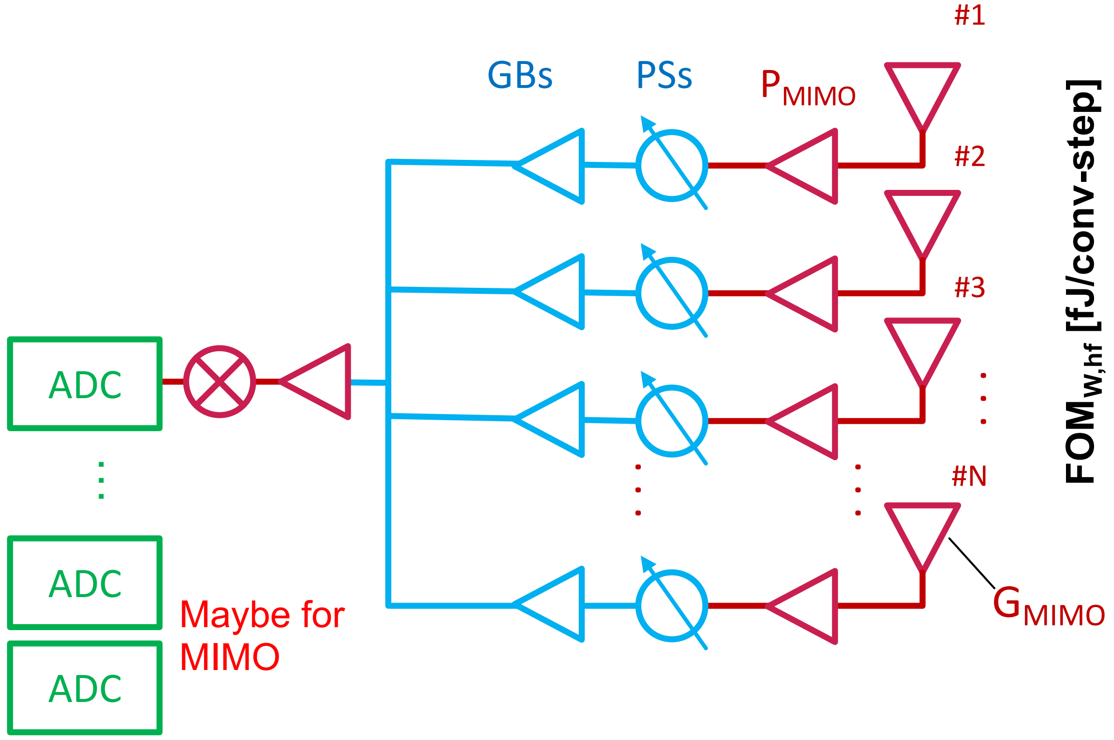
Energy Efficiency at THz

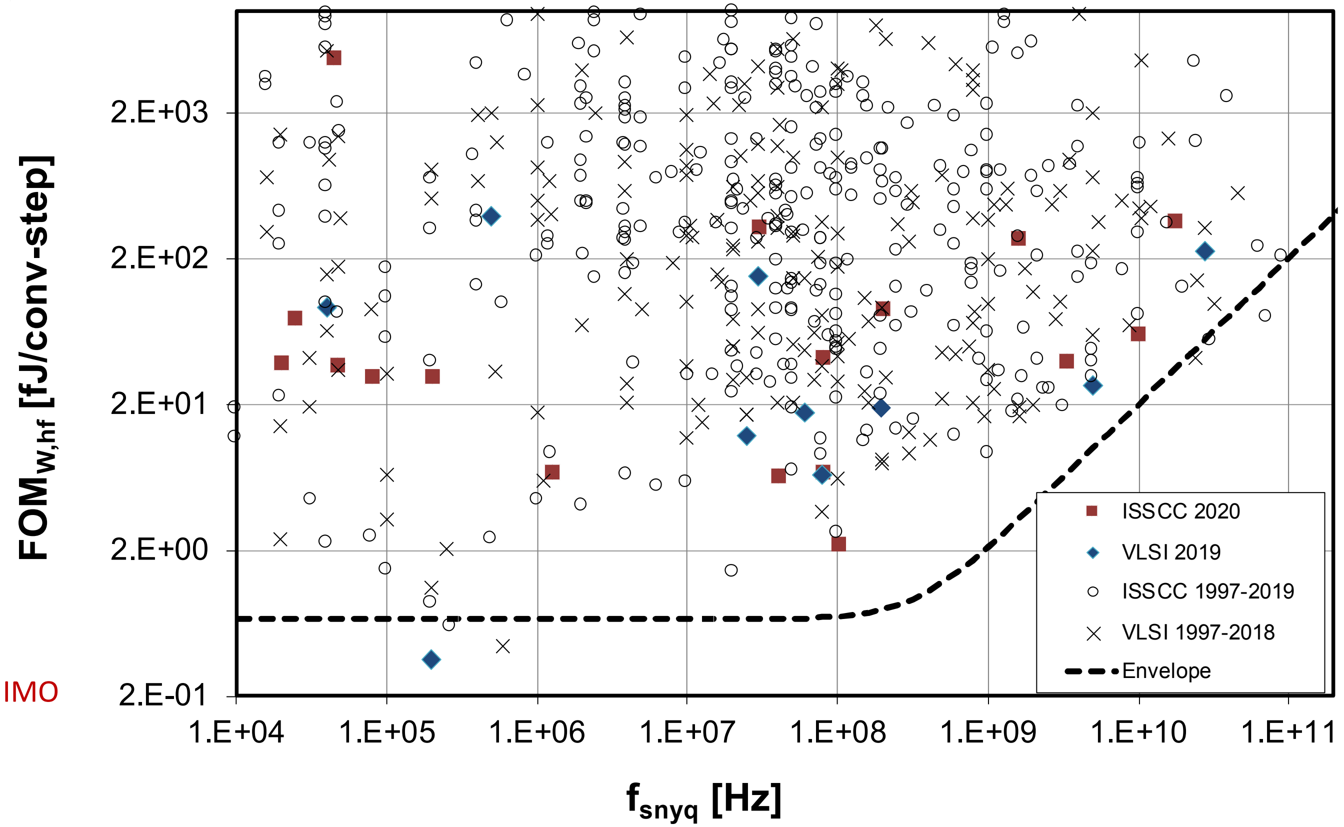




Source: Hua Wang, Tzu-Yuan Huang, Naga Sasikanth Mannem, Jeongseok Lee, Edgar Garay, David Munzer, Edward Liu, Yuqi Liu, Bryan Lin, Mohamed Eleraky, Sensen Li, Fei Wang, Amr S. Ahmed, Christopher Snyder, Sanghoon Lee, Huy Thong Nguyen, and Michael Edward Duffy Smith, "Power Amplifiers Performance Survey 2000-Present," **[Online]. Available: https://gems.ece.gatech.edu/PA_survey.html**

In Addition to PA

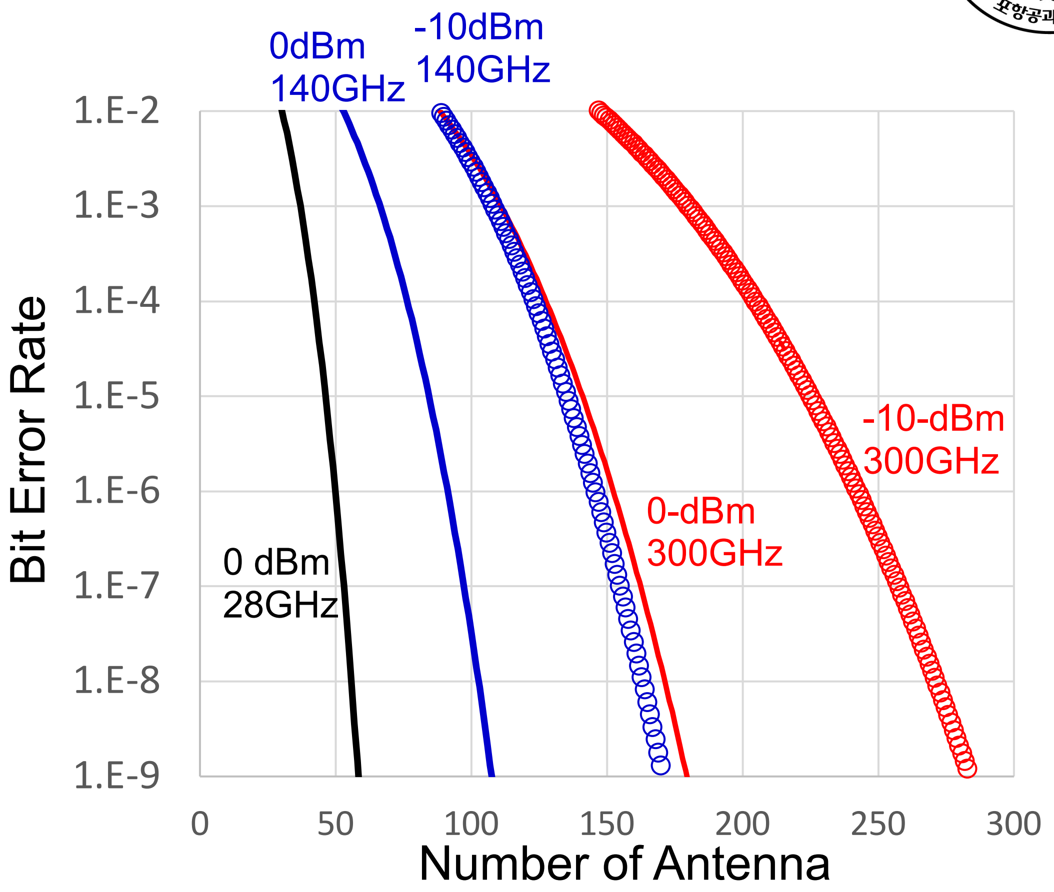




Graph showing how the energy efficiency of ADCs by Walden's figure-of-merit (FOM) is altered as the sampling rate increases.
(B. Murmann. *ADC Performance Survey 1997-2021*. Available: https://web.stanford.edu/~murmann/adcsurvey.html)

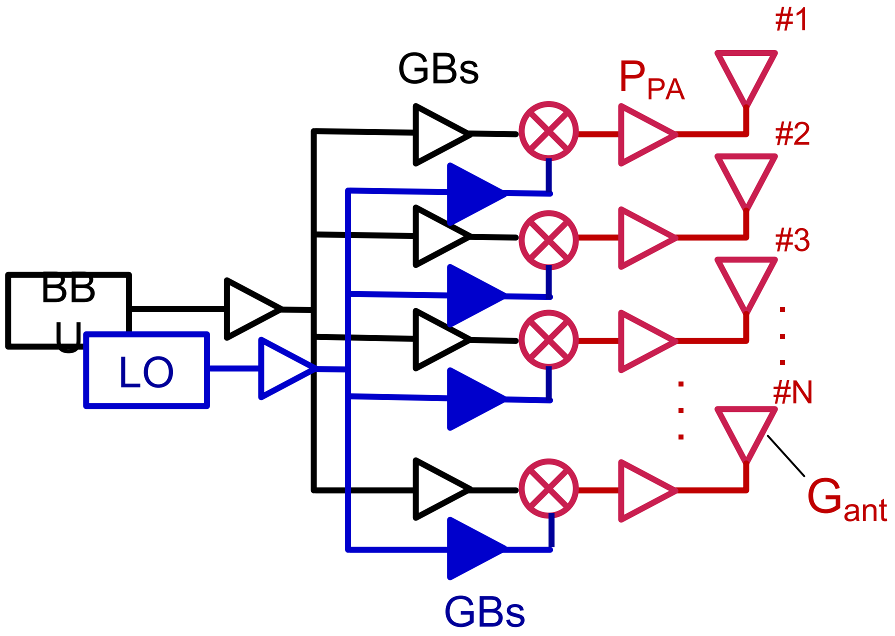
Simple Link-Budget

parameters	value
Modulation	16QAM
Baud rate (Gsps)	20
Distance	**100 m**
Unit antenna gain (dBi)	7
Average output power per PA (dBm)	-10 or 0
Noise figure (dB)	10



- 200+ antennas are necessary for 100 meter at 300 GHz

Assumptions



- For fixed EIRP,

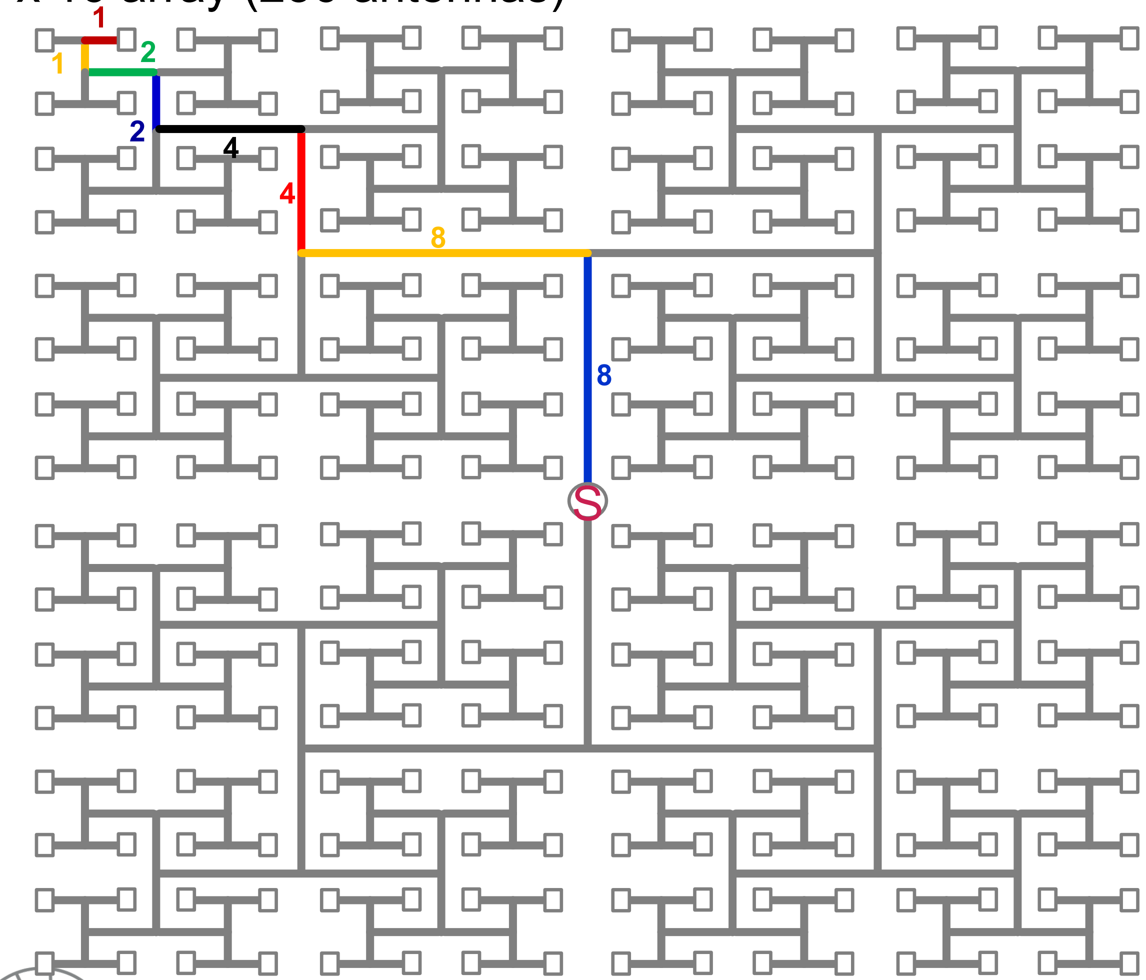
$$P_{PA} = \frac{EIRP}{N^2 G_{ant}}$$

$$\text{Total } P_{DC,PA} = \frac{EIRP}{N^2 G_{ant}} \cdot PAE \cdot N \propto \frac{1}{N}$$

- More antennas
  - Less energy for Less PA output power

Loss in LO Distribution

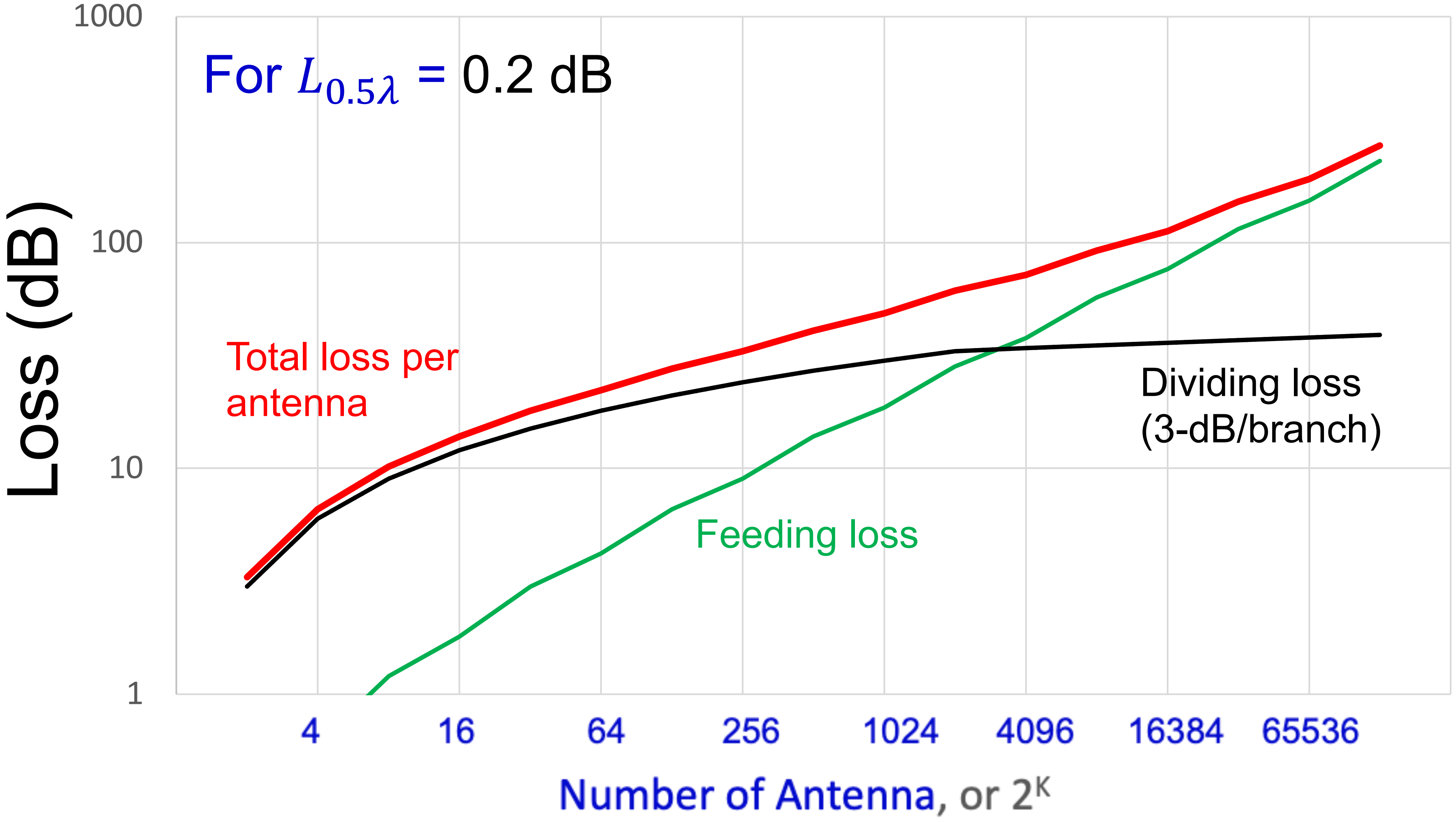
16 x 16 array (256 antennas)

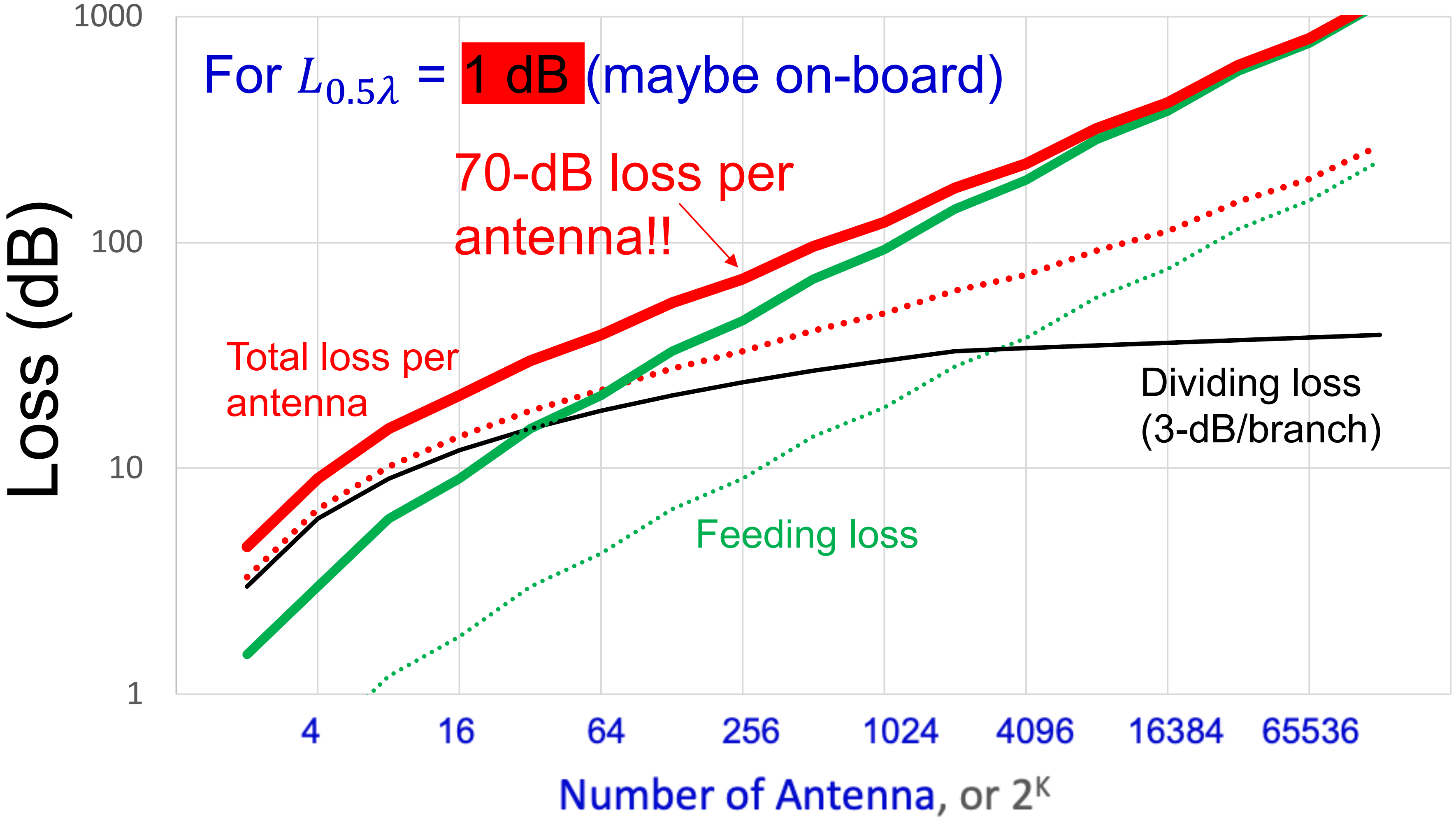


- Assuming
  - Half-wavelength separation
  - 0.2-dB loss for $\lambda/2$-length feeding line
- **Divide** loss: $3 \cdot \log_2(N)$ dB loss
- **Feeding** loss for $N=2^K$ antennas will be

$$L_{0.25\lambda} \cdot \gamma \cdot \sum_{i=0}^{K} 2^\wedge \left\lceil \frac{i}{2} \right\rceil$$

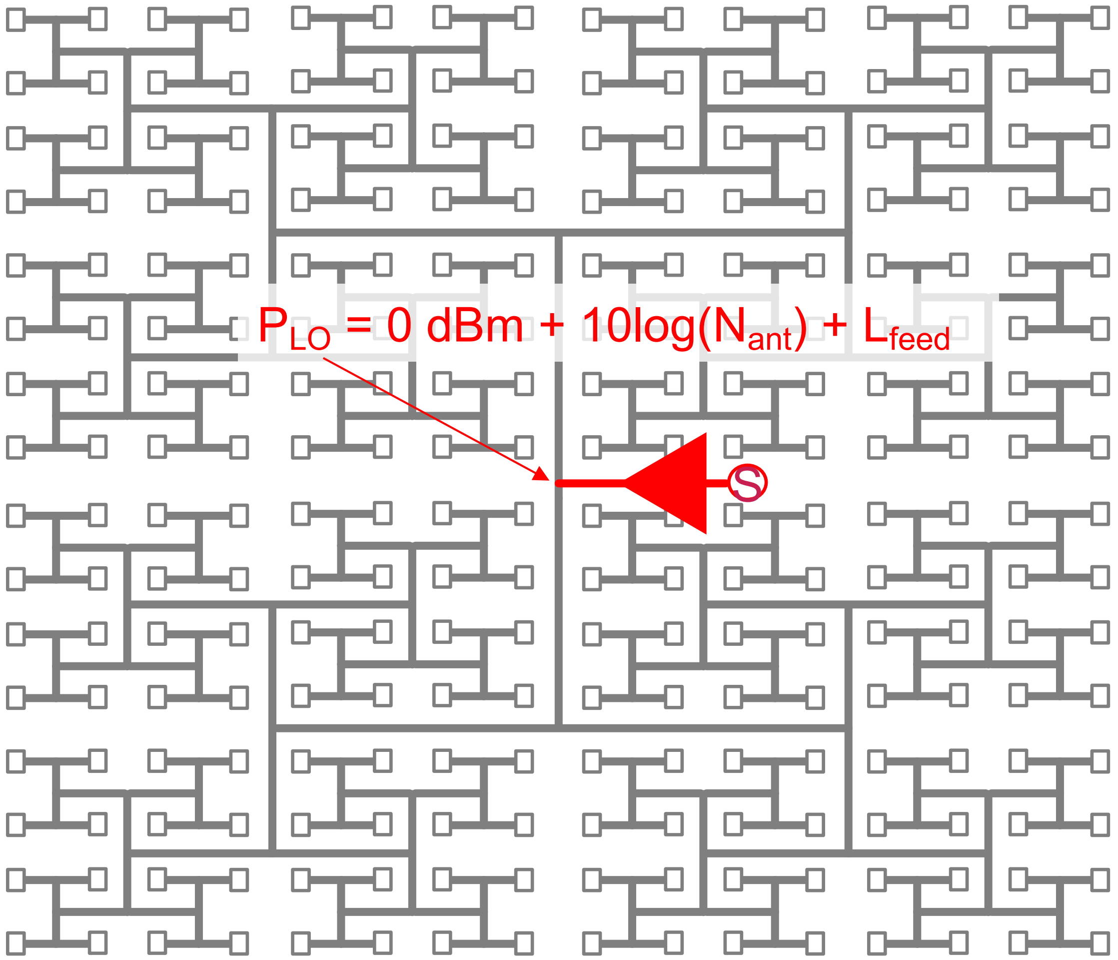
Loss in LO Distribution

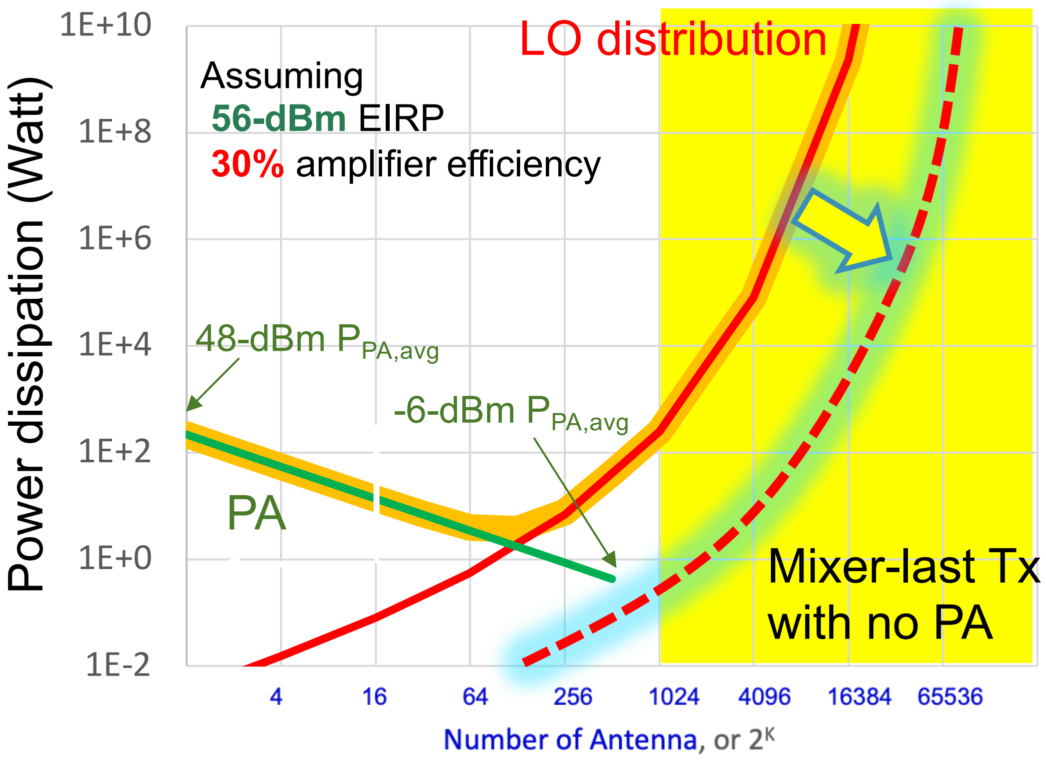




For $L_{0.5\lambda}$ = 1 dB (maybe on-board)
70-dB loss per antenna!!
Total loss per antenna
Dividing loss (3-dB/branch)
Feeding loss
Loss (dB)
1000
100
10
1
4
16
64
256
1024
4096
16384
65536
Number of Antenna, or 2^K

Total Power Dissipation in Massive Beamforming Tx



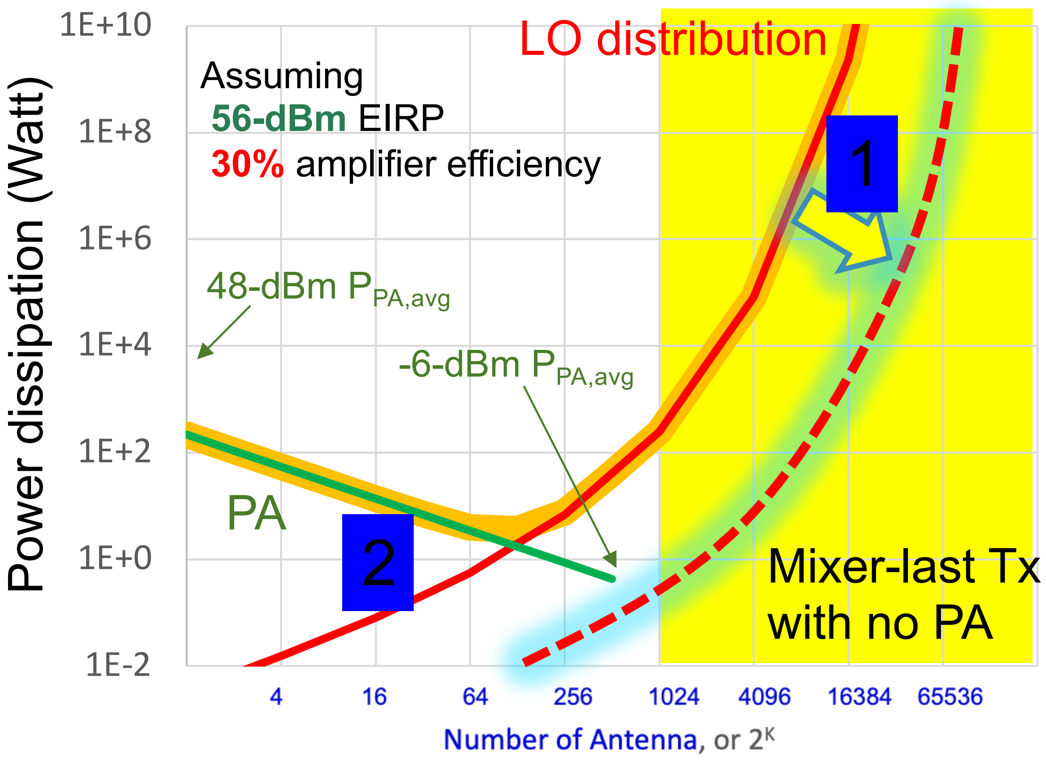


Note, PA Pout was varied to meet the target EIRP.

One May See Two Directions

1. How to minimize LO feeding loss
   → integration of massive antenna and TRxs

2. Enhance PAE of PA, maybe with InP devices but with RF CMOS core
   → integration of InP + CMOS



Remarks

- We have made significant advances in THz technologies.
  - Problems associated with lack of device technologies have been relaxed a lot.

- Key challenges we need to response for 6G would be about
  - How to realize 1 Tbps. → LOS-MIMIO → BW and Coverage issue
  - How to deal with energy efficiency. → Matter of Integration issue

- Do you think we are effectively utilizing the large number of antenna system and beamsteering functionality is sufficient for 6G?

Thank you for kind attention !!!

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