# IoT at Millimeter Wave Frequencies: Finding Hope

Earl McCune
CTO, Eridan Communications

# Outline

- What is the problem?
- Why is this the way it is?
- What can be done to improve the situation?

# Wireless Link Operating Objectives

- communication distance
- power efficiency and link efficacy
- bandwidth
- directivity
- penetration of foliage
- penetration of building structures
- environmental conditions
- human safety
- Costs: capital and operational

# Key Physics

<u>Circuit Level</u>

- Linear circuit (PA) efficiency
- Signal bandwidth vs. power draw
- Circuit linearity metric
- Circuit bandwidth (multi-band)
- Ohm's Law
- Transistor speed ($f_T$)

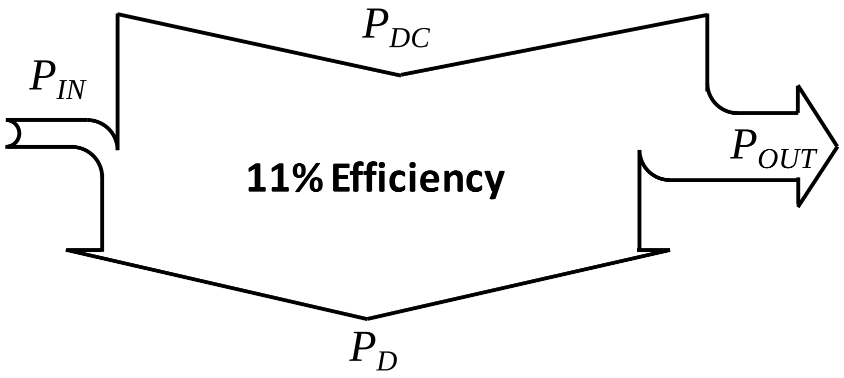
<u>System Level</u>

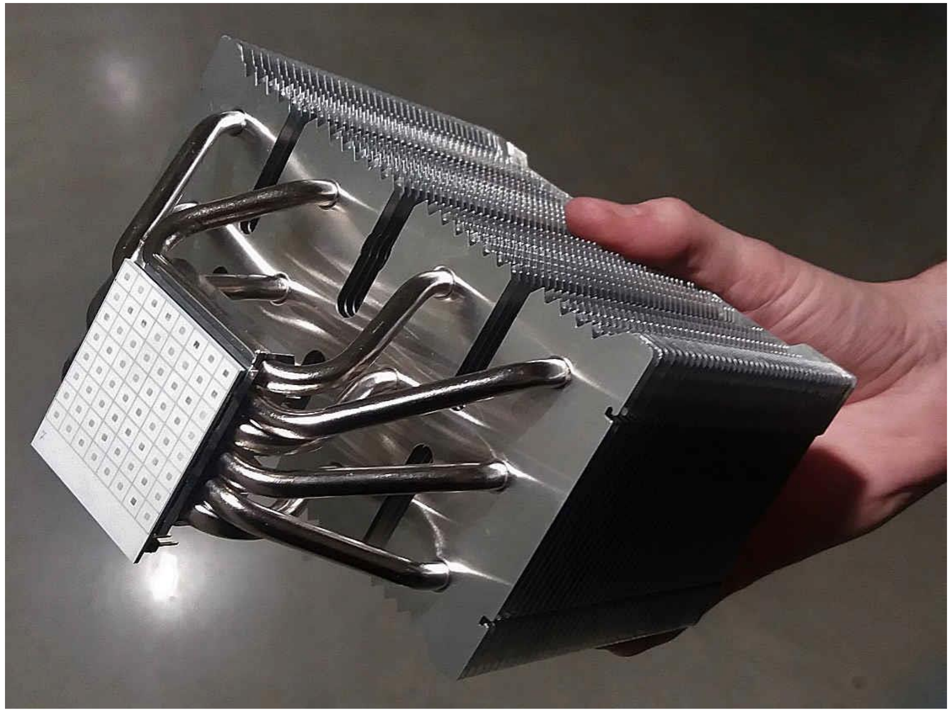
- Link Efficacy
- Antenna gain / directivity
- Modulation vs. TX power
- Bandwidth Efficiency (Efficacy)
- Human safety
- Occluded environments

# Inherent conflicts

- Modulation vs. Circuit Efficiency and Link Efficacy
- Communication distance vs. coverage
- Signal bandwidth vs. Power draw

# Circuit Efficiency

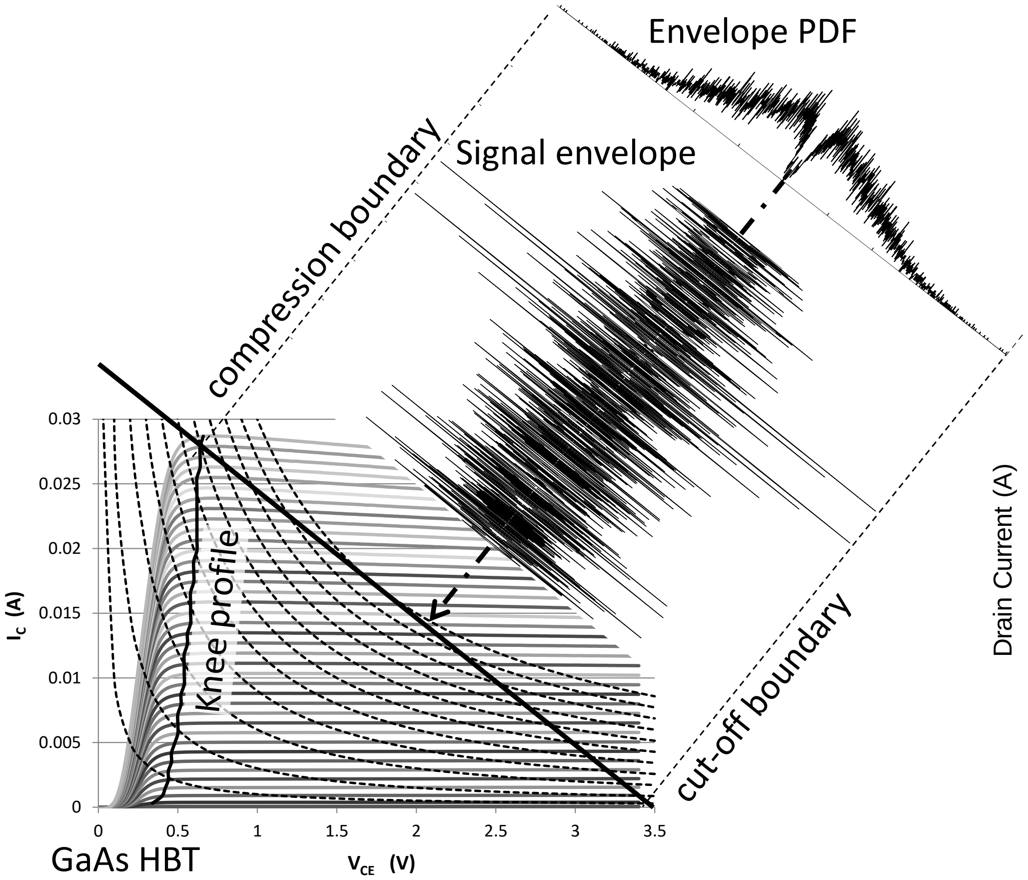


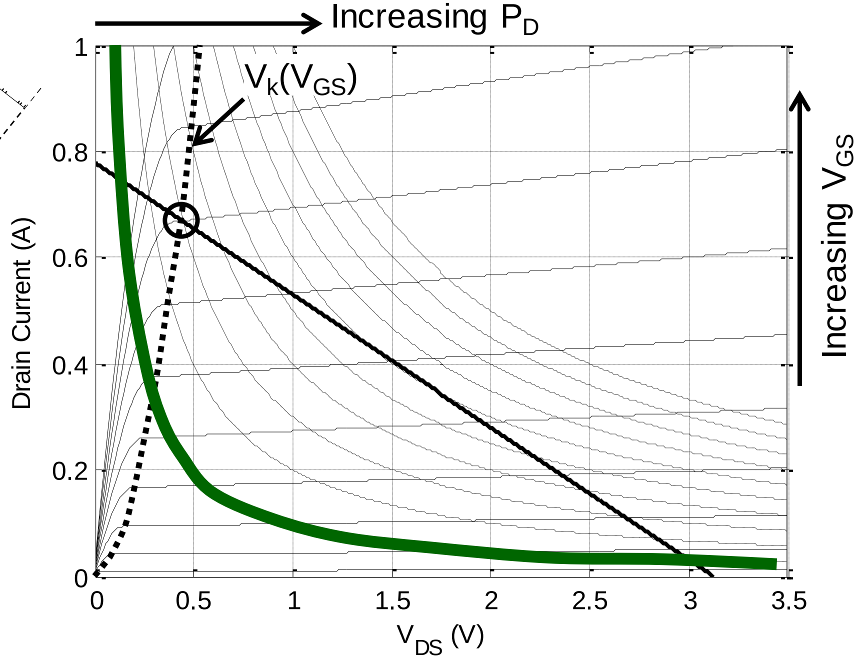
- ***Efficiency*** applies to any situation where a conservation principle applies
  - e.g. $P_{DC} + P_{IN} = P_{OUT} + P_D$
- Efficiency improvement is a solved problem below 5 GHz
  - Though it is not yet widely implemented
- This technology does NOT scale to mmW frequencies
- For the near term, we appear to be doomed……

# Transmitter Physics

## Linear Transmitter




## Efficient Transmitter




- Linear transmitters <u>*cannot be efficient*</u>
  - A direct consequence of Ohm's Law
- Efficient transmitters *cannot have circuit linearity*
  - Class-E approximates this profile
- If the amplifier transistor is too slow to follow the paths of efficient operation
  - Then all of the techniques developed for efficient operation disappear
  - Linear operation still remains (see #1)

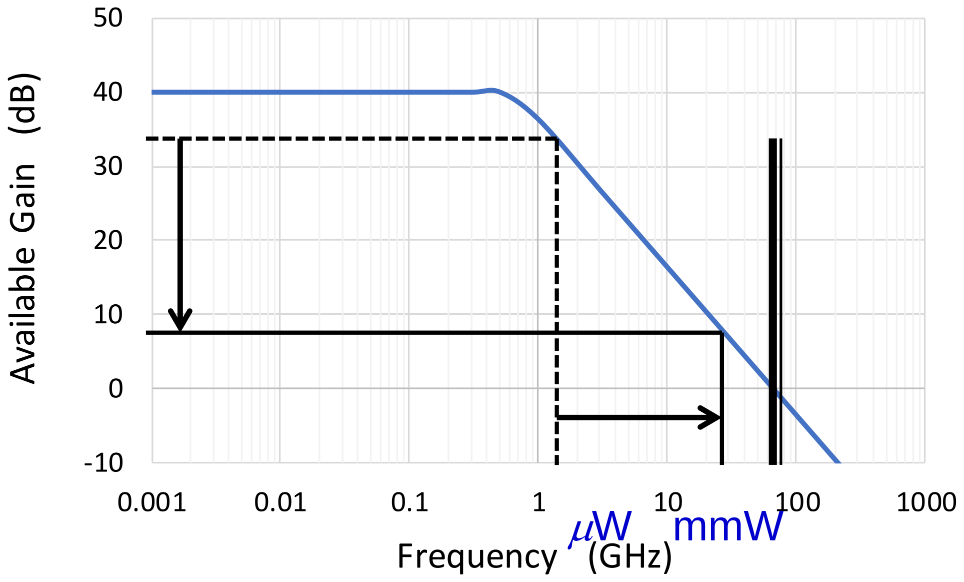
# Why is Efficiency a Special Problem at millimeter wave frequencies?

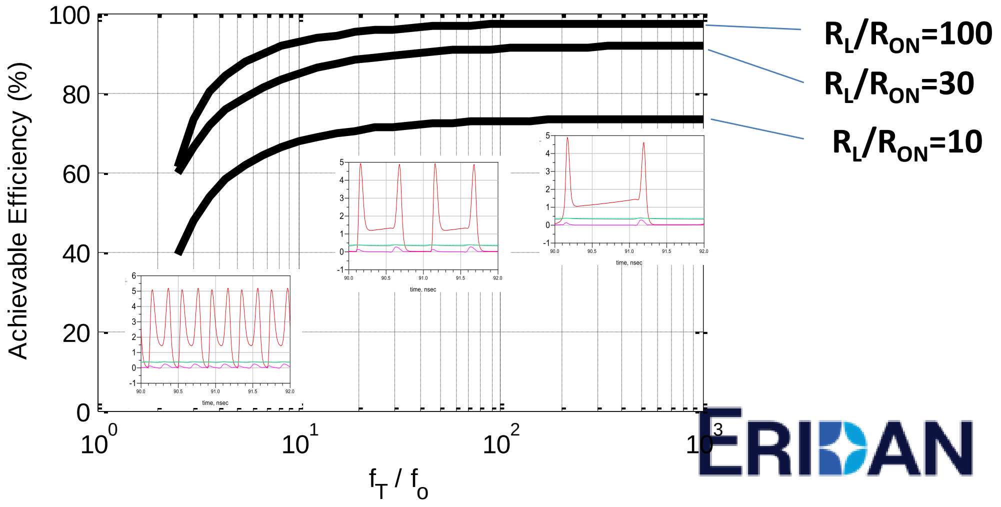
- mmWave frequencies are much closer to transistor speed boundaries

Transistor behavior changes at these frequencies

- Output power drops
- Circuit gain is lower
- Compression begins sooner
- Linear operating range shrinks

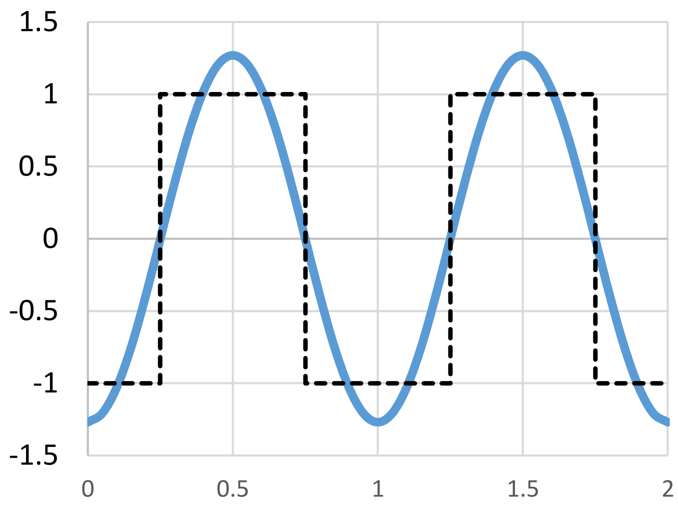
- 5G-New Radio uses identical modulation schemes at all frequencies



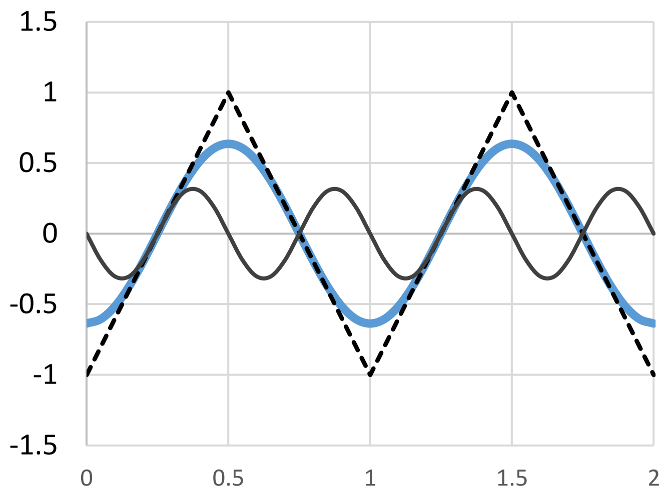



# Millimeter Wave Power Drop

As frequency increases, the transition times eventually do not settle into ON and OFF states: ***slew-rate limiting***



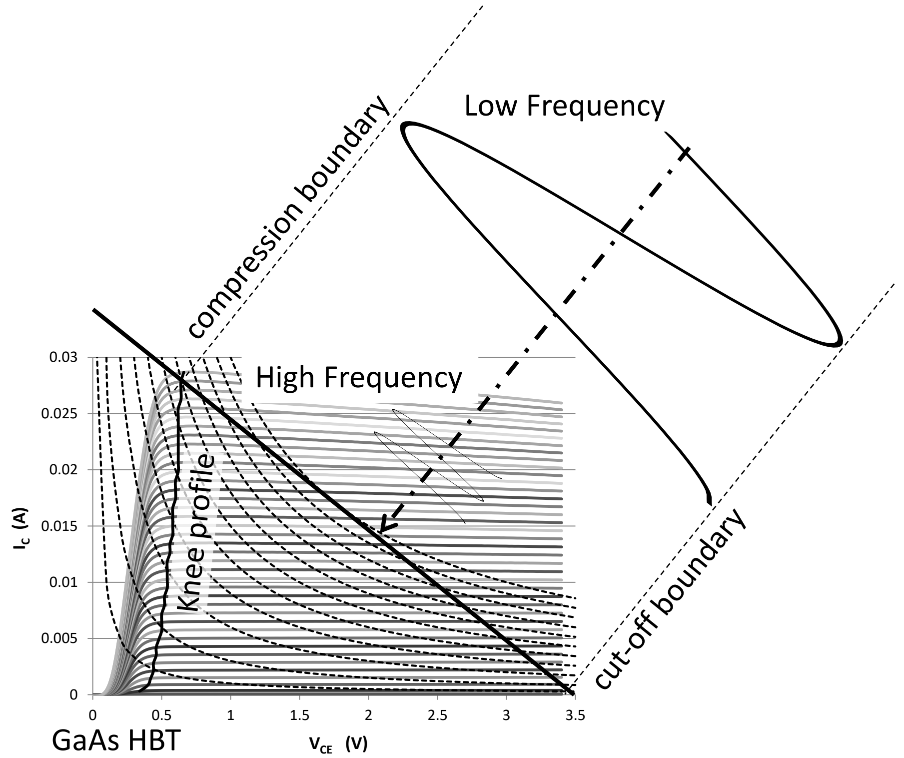

- At low frequencies, the transition time is negligibly short and the transistor does switch
- Largest possible sinewave is 2(2/π) times the squarewave magnitude (=1.27x) [+2.1 dB]



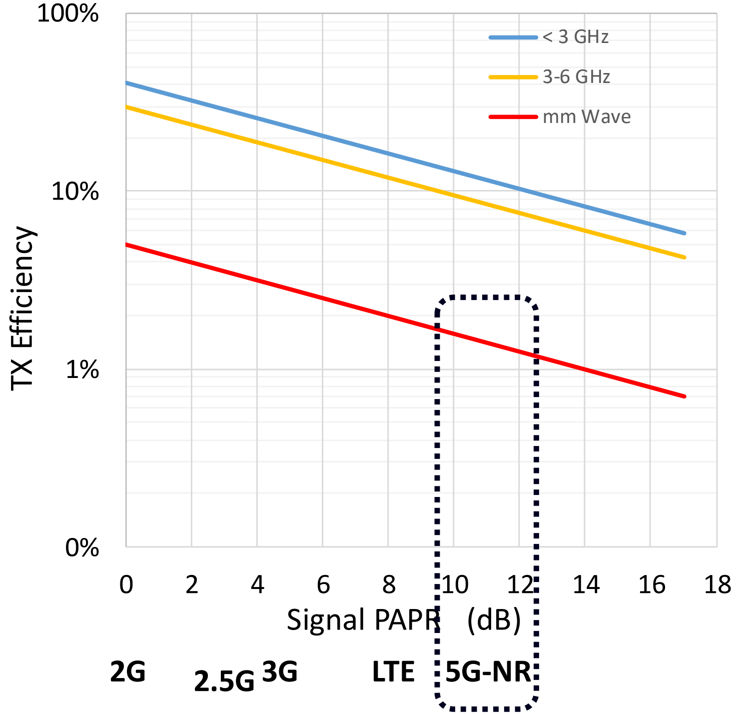

- When slew-rate limiting is reached, the largest possible sinewave output is reduced
- Largest possible sinewave is $2(2/\pi)^2$ times the squarewave magnitude (=0.81x) [-1.8 dB]

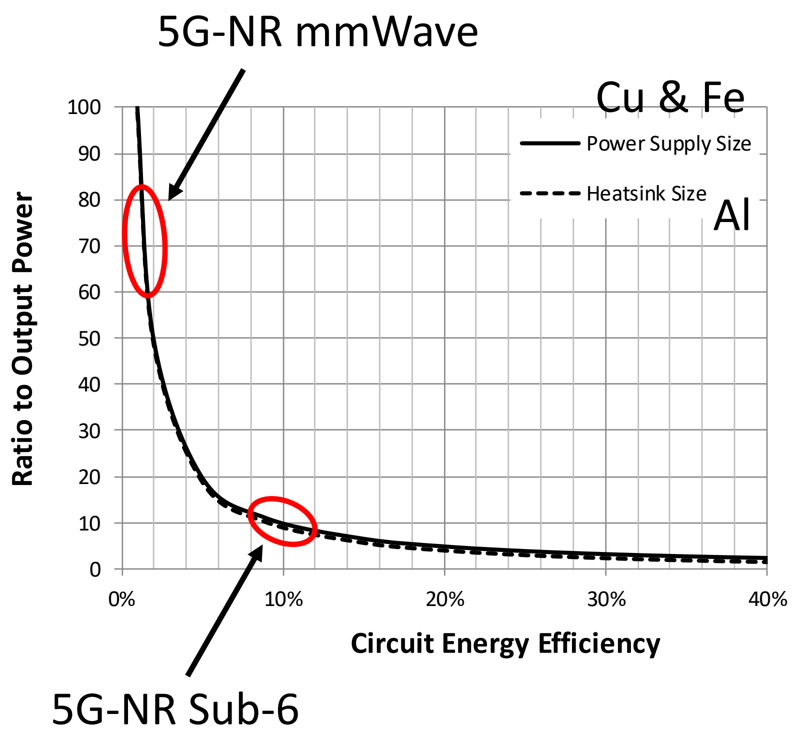
ERIDAN

# PA Thermal Management




$$\eta\left(PAPR_{dB}\right)=\eta_0 10^{-\left(\frac{PAPR_{dB}}{20}\right)}$$




- Available signal swing range is lower at mmW frequencies
- Signal PAPR further reduces output power
- More circuit stages are needed to make up total needed gain

ERIDAN

# Defining Amplifier Linear Range

$P_{1dB}$ is a poor definition of amplifier linearity range

Linearity = constant gain, independent of input value

Gain is constant only when $S = dP_{OUT}/dP_{IN}$ = 1.00 dB/dB

Gain expansion when $S > 1$

Gain compression when $S < 1$

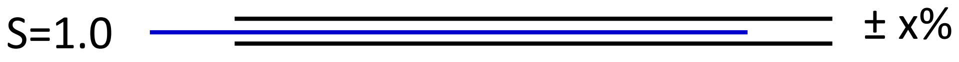
Nonlinear gain is distorting to the waveform

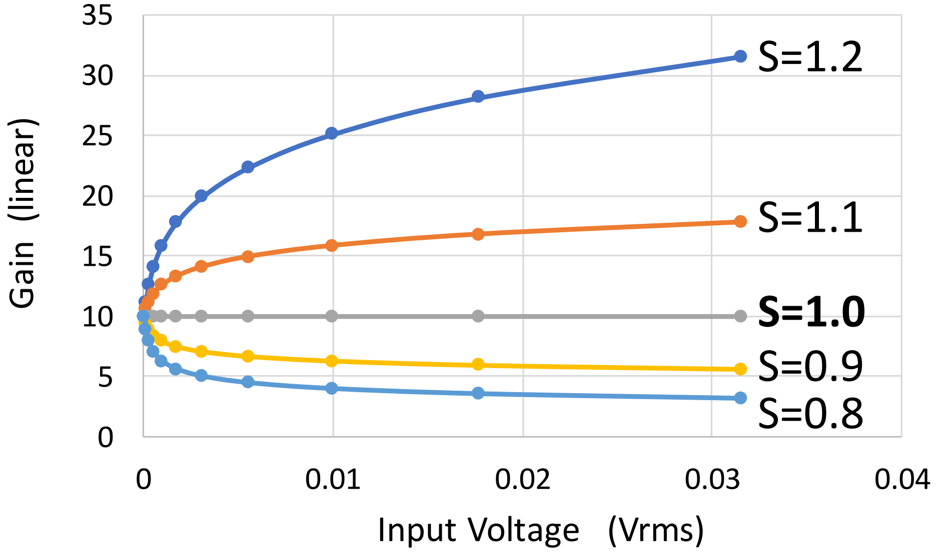
*Linearity: gain **must** be independent of the input voltage*

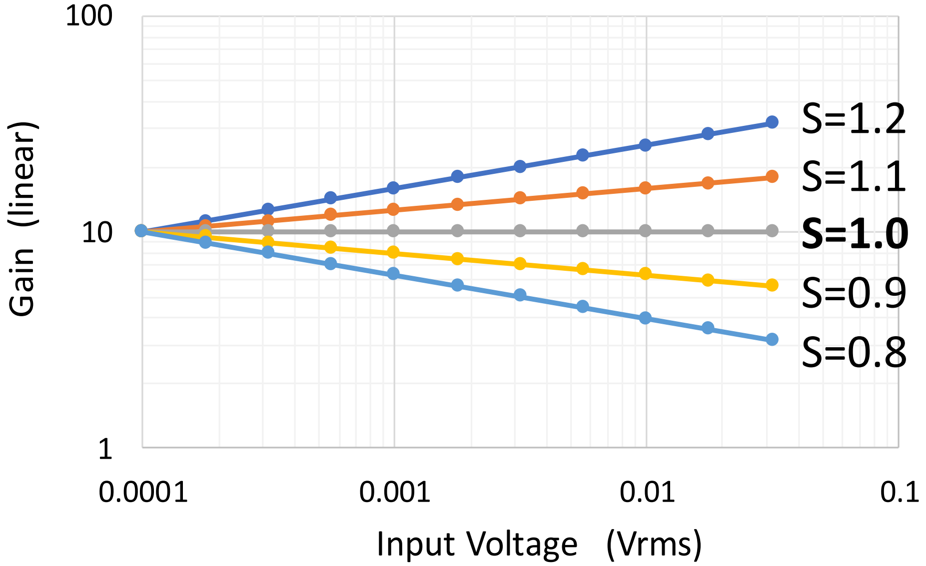
$$gain(S) = \frac{V_{out,rms}}{V_{in}} = g_0 \left( \frac{V_{in}}{V_0} \right)^{S-1}$$

Proposal:

Amplifier **linearity is defined** when S = 1.00 within an error band equal to the allowed distortion



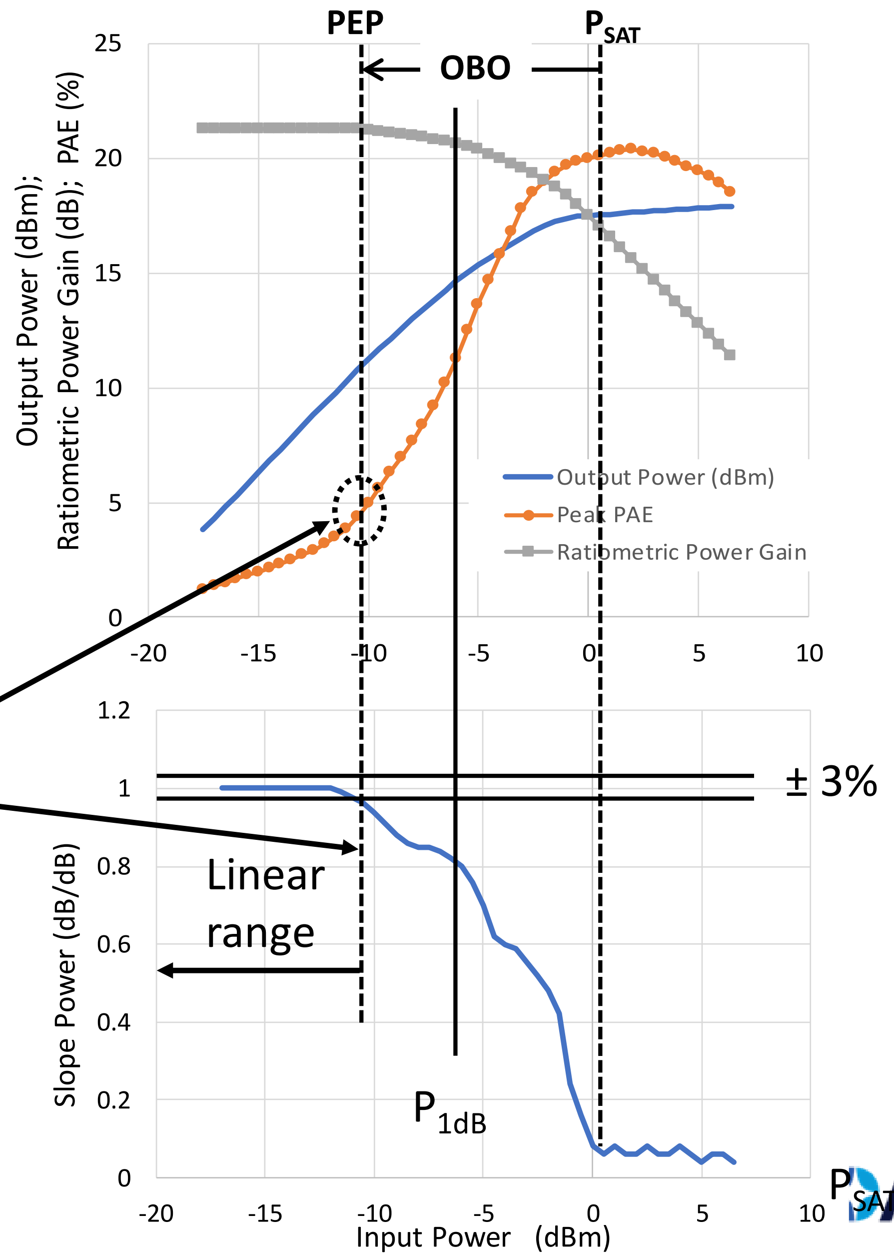
# Practical Linear PA: Range and Efficiency

5G-NR EVM spec is -30 dB
  Corresponds to 3.3% distortion
Here, this distortion limit is well below P1dB

Sets the upper limit of signal output power (PEP)
Output backoff (OBO) = $P_{SAT}$ - PEP

Also sets the peak linear efficiency
  Here $\eta_0$ = 5% at the top of the linear range

Design goal: maximize the range of S = 1
  only needs the $P_{OUT}(P_{IN})$ curve

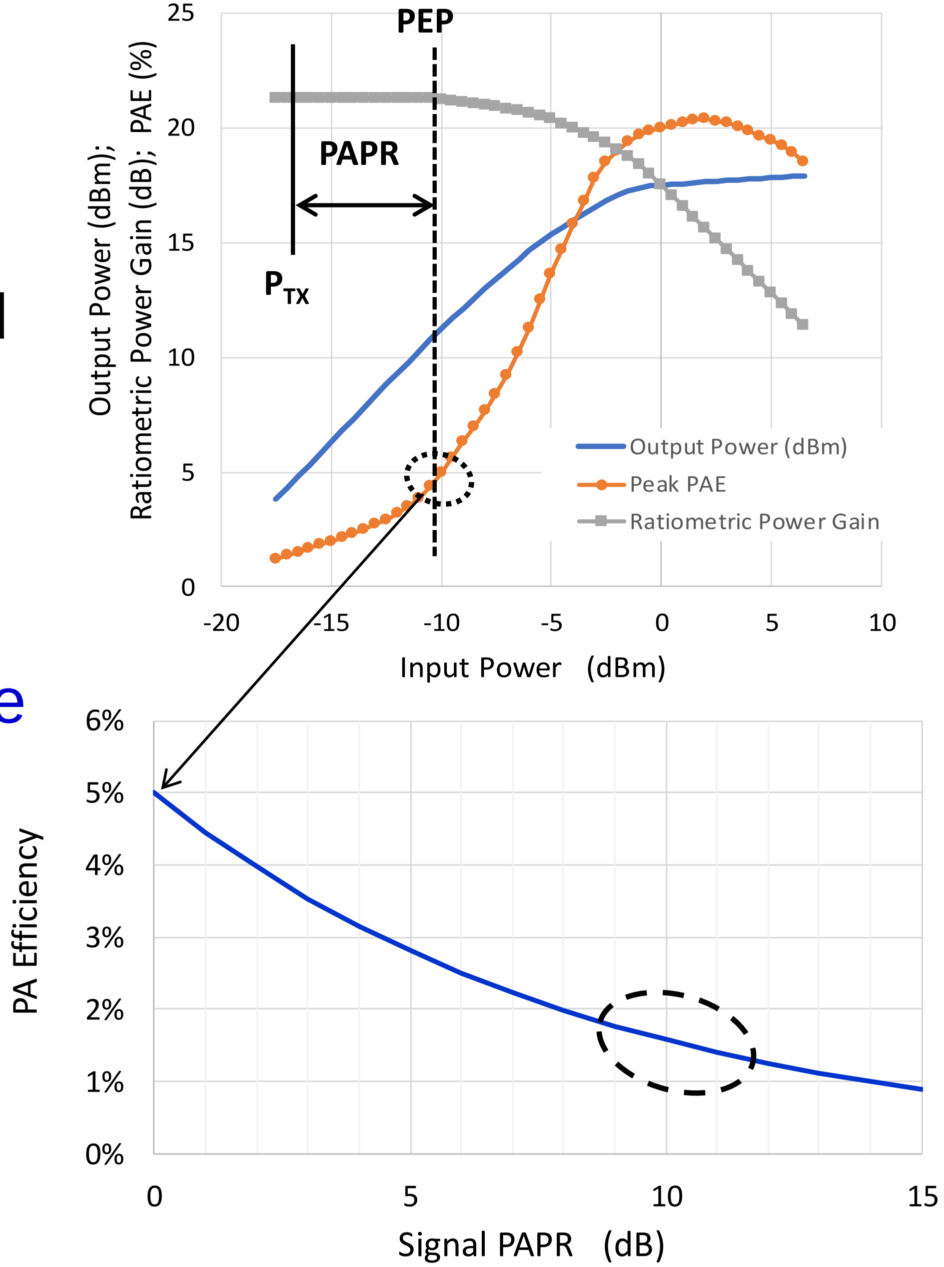





12

# Add Modulation

- The linearity upper limit applies to the modulated signal upper limit: Peak Envelope Power (PEP)
- Signal average power is lower than PEP by the modulation PAPR
- Efficiency drops further
- Signal envelope statistics have a ***major*** influence on the final result
- The efficiency upper bound is known



# Why are we bothering with mmWaves?

Following the mantra

‘*data rates **must** go higher*’

Shannon showed that bandwidth efficiency is constrained by link SNR

$$\frac{R}{B} = \frac{C \cdot U}{B} < \log_2\left(1 + \frac{P_S}{P_N}\right); \qquad 0 < U < 1$$

With a maximum link SNR

bps/Hz is upper bounded

<u>More bps then requires more Hz bandwidth</u>: **mmW**

# Path Loss Issues

Actual LOS path loss is *independent* of frequency

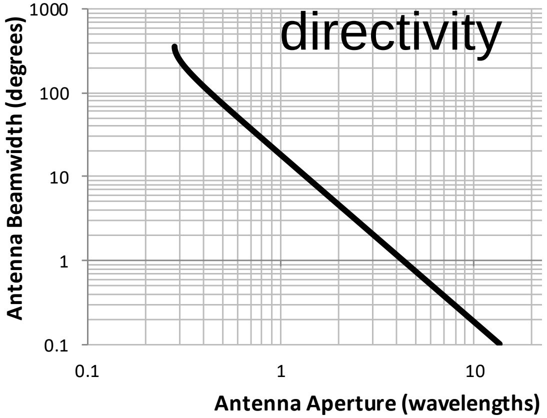
TX forms a EM field density (μW/m²)

What changes with frequency is the RX antenna behavior

Scales with wavelength

mmW wavelength $\lambda$ is much shorter

Larger area antennas ***must*** be directive:




$$$

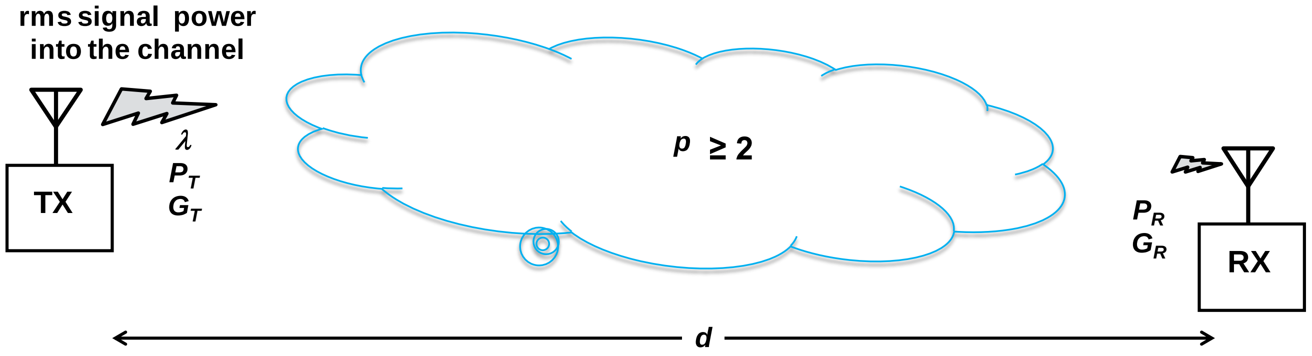
$$P_T = \frac{PEP}{PAPR}$$

LOS path-loss

RX Antenna

$$P_R(d,\lambda,P_T) = \left[ P_T G_T \left( \frac{1}{4\pi d^p} \right) \right] \left[ G_R \left( \frac{\lambda^2}{4\pi} \right) \right]$$

TX Antenna





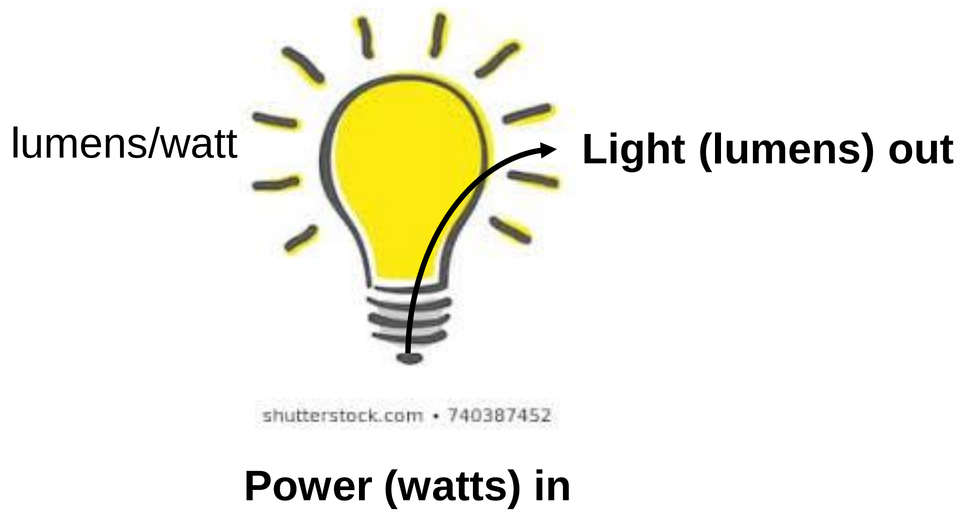



ERIDAN

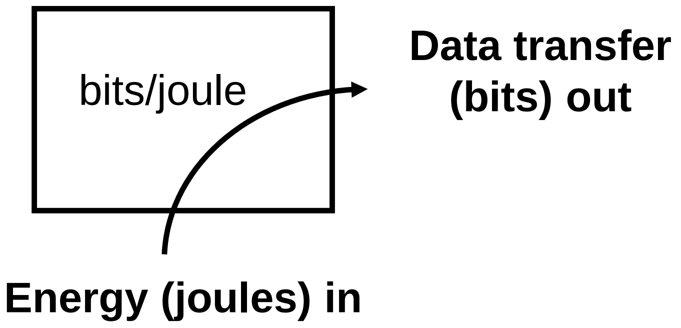
# Efficacy

- ***Has units*** (e.g. lumens/watt for lighting, bits per joule for digital communication)
- Determines how *effective* a process is when using one resource to provide another: **result/resource**

**Electric lighting**




**Digital Communication**








ERIDAN

# Link Efficacy

$$\frac{b}{J} \equiv \eta_{EE} = \frac{b/\sec}{J/\sec} = \frac{b/sym \cdot sym/\sec}{Watts}$$

$$\eta_{EE} = \left( \frac{\eta_0 10^{-\left(\frac{PAPR_{dB}}{20}\right)}}{(kTB) \cdot 10^{\frac{NF_{dB}}{10}} \cdot 10^{\frac{SNR_{d,dB}}{10}}} \right) N \log_2(M) \cdot f_{sym} \cdot G_T G_R \left(\frac{\lambda}{4\pi}\right)^2 d^{-p}$$

$$G_R(\theta) = \sqrt{\frac{2}{1 - \cos\left(\frac{\pi}{360}\theta\right)}}$$

- Unit arithmetic relates the desired efficacy to its comprising link parameters
  - These parameters are *NOT* independent from each other
- Complete efficacy model includes all link parameters: signal, hardware, environment, and physics

# Link Efficacy

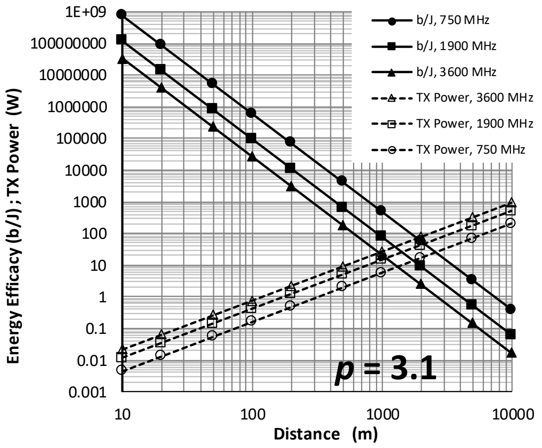
$$\frac{b}{sym} = N \cdot \log_2 M; \quad M = 2^{b/sym}$$

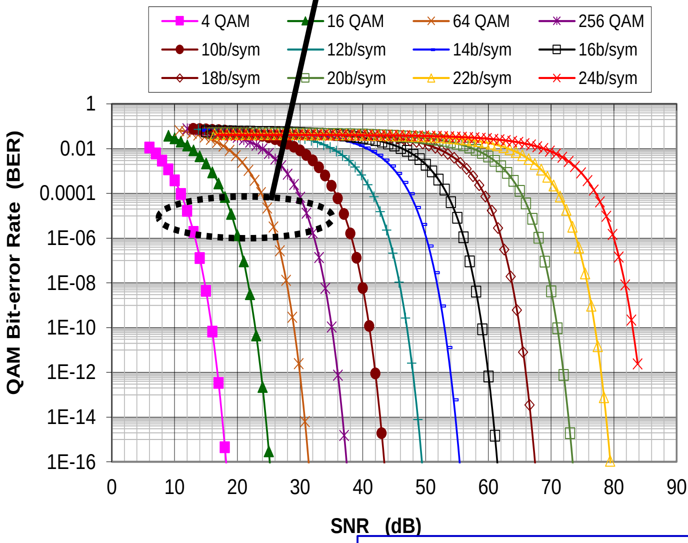
$$f_{sym}$$

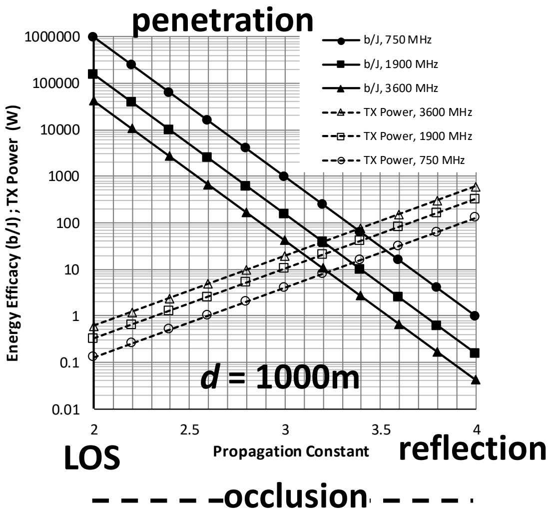
$$\frac{b}{J} \equiv \eta_{EE} = \frac{b/\sec}{J/\sec} = \frac{b/sym \cdot sym/\sec}{Watts}$$

$$P_{DC} = \frac{P_{OUT}}{\eta}$$

$$\eta_{EE} = \left( \frac{\eta_0 10^{-\left(\frac{PAPR_{dB}}{20}\right)}}{(kTB) \cdot 10^{\frac{NF_{dB}}{10}} \cdot 10^{\frac{SNR_{d,dB}}{10}}} \right) N \log_2(M) \cdot f_{sym} \cdot G_T G_R \left(\frac{\lambda}{4\pi}\right)^2 d^{-p}$$




- Unit arithmetic relates the desired efficacy to its comprising link parameters
  - These parameters are *NOT* independent from each other
- Complete efficacy model includes all link parameters: signal, hardware, environment, and physics

$$snr_d = \frac{P_S}{P_N} = \frac{E_b}{N_0}\frac{f_b}{B} = \frac{E_b}{N_0}\eta_{BW}$$

# Antenna Gain and Directivity

$$G_T(\theta), G_R(\theta) = \sqrt{\frac{2}{1 - \cos\left(\frac{\pi}{360}\theta\right)}}$$

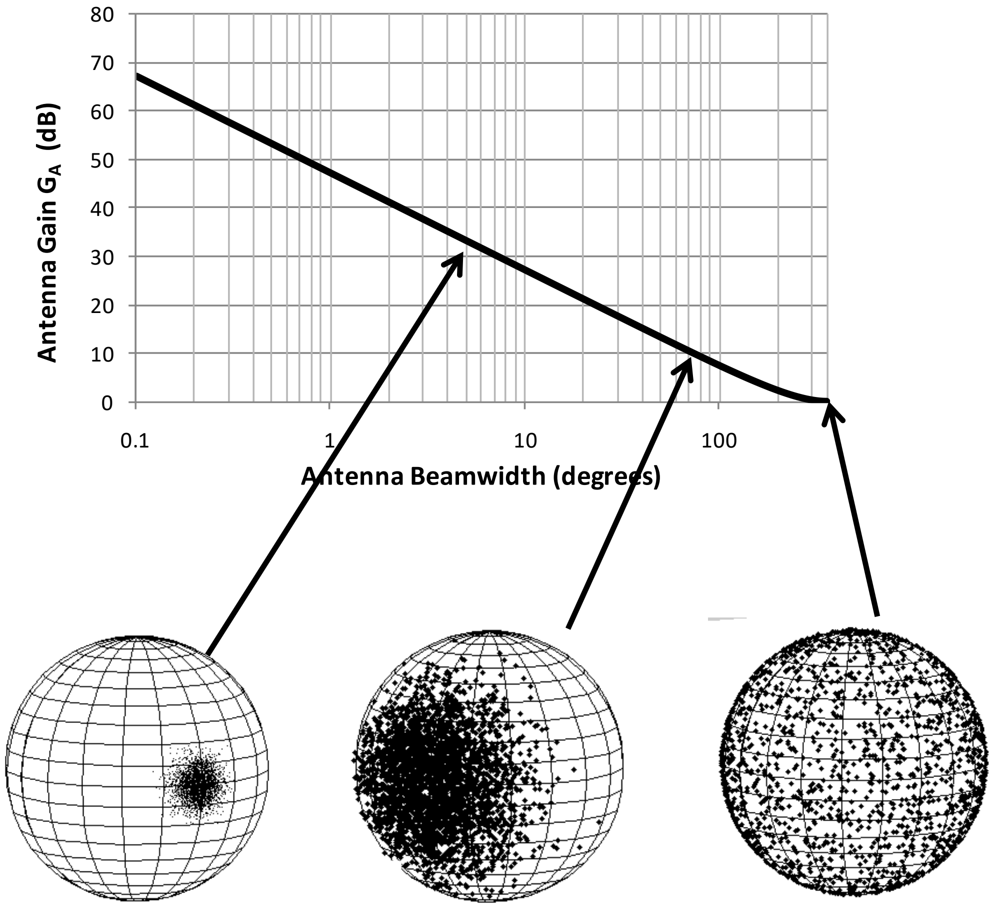
Signal power density: $\mu$W/cm$^2$

More $\mu$W into the RX *requires* more antenna area (cm$^2$)
- *Independent of frequency*!

Directivity (beamwidth) narrows as antenna size increases
- Measured in wavelengths
- Corresponds to antenna "gain"
- Antenna must be aimed

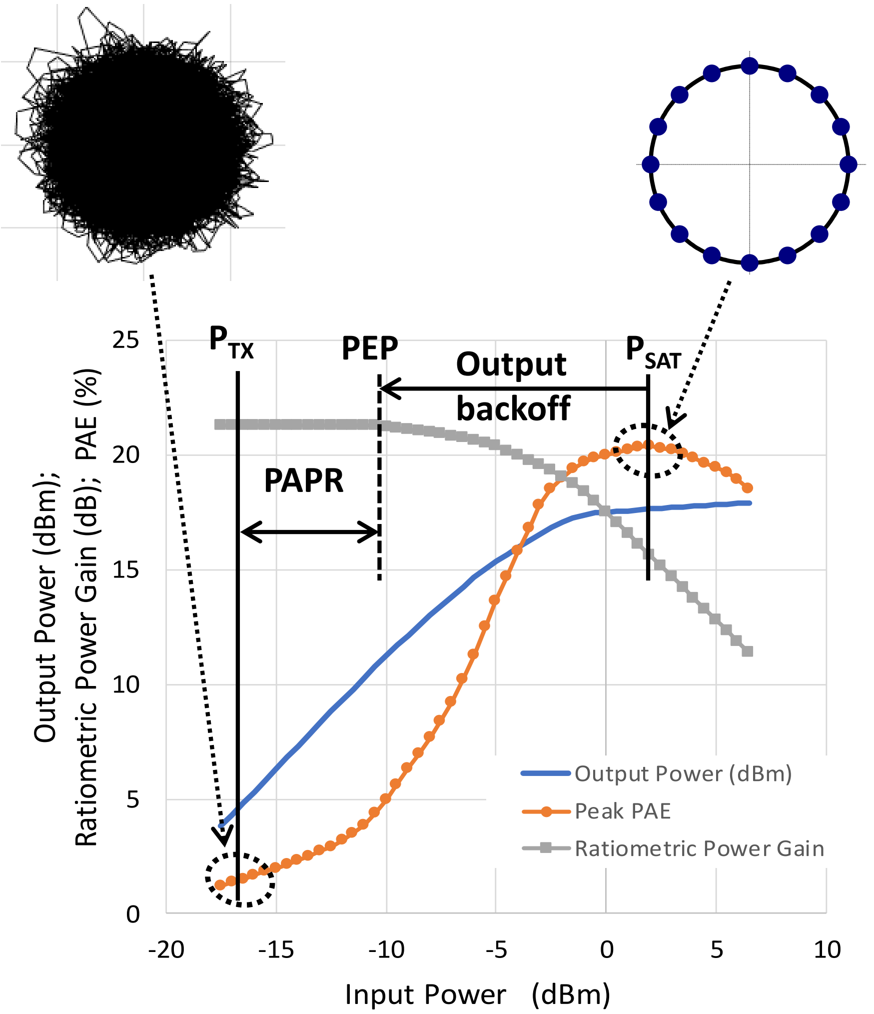
Related by the Fourier Transform
- "Time domain" – Antenna aperture in wavelengths
- "Frequency domain" – Antenna directivity in radians

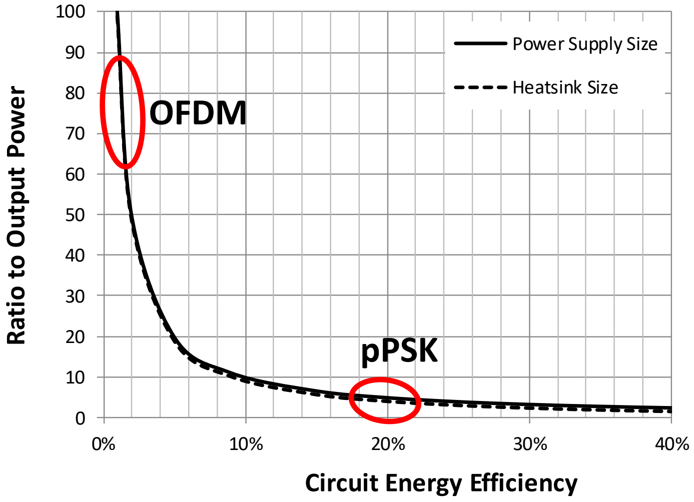
**Directivity (gain) and coverage are in opposition**



# Align Modulation to mmW Circuit Capabilities

- OFDM (3GPP 5G-NR)
  - requires circuit linearity (output backoff)
  - and has a large PAPR (~7-10 dB)
- pPSK
  - PAPR = 0dB
  - No linearity required
- Output power increases
- PA efficiency increases 10-fold (or more)
- OpEx decreases by 10x
- Large decrease in power supply and heatsink sizes








ERIDAN

# mmW Safety – Human RF Exposure

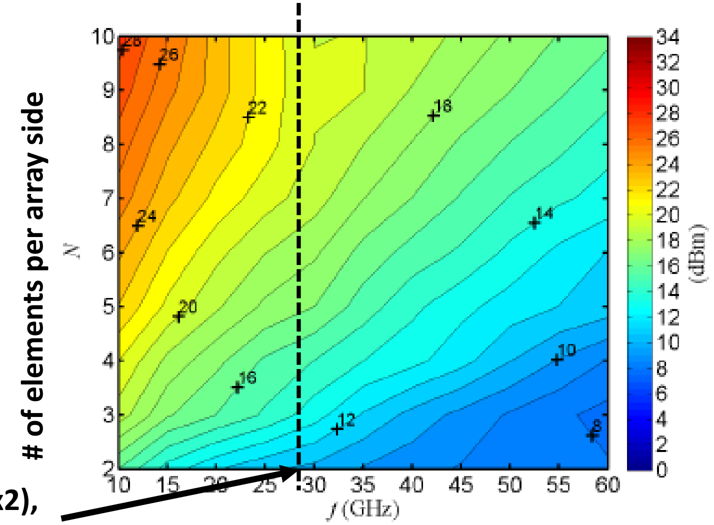
IEEE-C95.1 calls for power density of 1 mW/cm$^2$ as an upper limit when there is unrestricted antenna access (e.g. a mobile device)

Published unit is often EIRP

Beamwidth contributions, more involved calculation

… are *any* present mmW handset products safe??

**Total TX Power**




4 antennas (2x2), 4 dBm each

**FIGURE 6. Maximum transmitted power to be compliant with the IEEE RF EMF exposure limit [10], [11] for $d = 0.5$ cm.**

**Total TX EIRP (far field)**

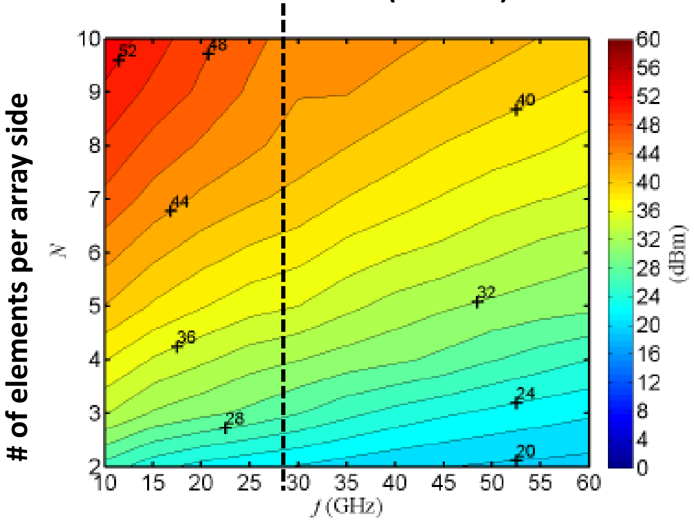



**FIGURE 14. Maximum EIRP to be compliant with the IEEE RF EMF exposure limit [10], [11] for $d = 0.5$ cm.**

# Conclusions

- Dominant contributors to extremely low mmW efficiency
  - Requirement for circuit linearity
  - Signal PAPR greatly exceeding 3 dB
- mmW transistor operation is never as good as at sub-6 frequencies
  - Transistor improvements will likely take a decade
- High efficiency modes familiar at sub-6 are not available (yet)
- Fast improvements require changing the mmW signal modulation
  - One option is to adopt circular constellations
  - Increases the useful output power from any existing PA
  - Circuit linearity is not needed (recover the backoff)
  - PAPR is 0 dB (recover PAPR power loss)
  - **Efficiency improves by at least 15x**
- Network coverage improves dramatically
- **No compromise on baseline bandwidth efficiency**

# Summary

**There is hope!**

But…

- Transistors today are not fast enough to access traditional high-efficiency behaviors at mmWave frequencies
- Adopting a constant envelope signal with good bandwidth efficiency (e.g. 16-pPSK) is doable *now*
  - Will recover most of the efficiency loss
  - Will greatly expand network coverage
  - Requires action from 3GPP
- Operators can demand the performance they really need from their suppliers – and from 3GPP





ERIDAN