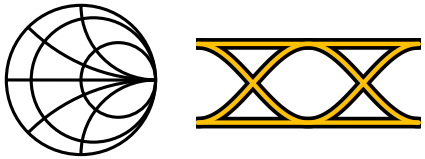
Physical Foundations of Green Communications

Earl McCune

IEEE MTT DML



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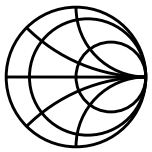
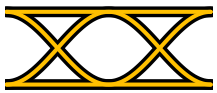
Outline

- **Green Communications corresponds to achieving minimum energy consumption**

Globally and jointly minimize circuit power dissipation across the entire communications subsystem

- PHY Hardware
- Signal Selection
- Protocol

- Design Criteria to maximize total efficiency

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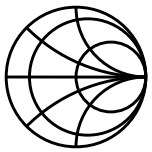
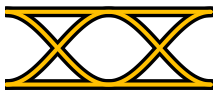
Introduction

- **To date, most energy efficiency optimizations are local only**
  - e.g. optimize only the protocol impact
- **Actual circuit efficiency characteristics are generally not well modeled in COMSOC papers**
- **Circuit optimizations are necessary but not sufficient**
  - Transmitter, receiver, digital and analog basebands
- **Protocol and signal modulation selection are extremely important**

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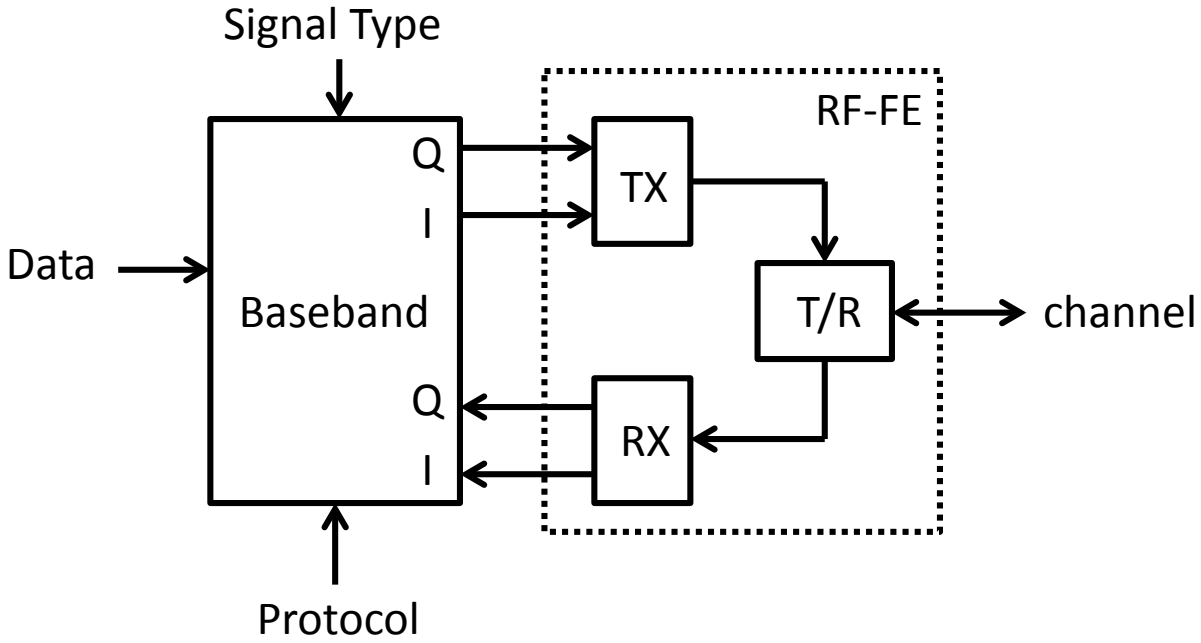
Communications Block Diagram



- **4 hardware blocks**
  - Transmitter, receiver, T/R management, baseband
- **Additional critical information**
  - Communication protocol
  - Signal modulation selection

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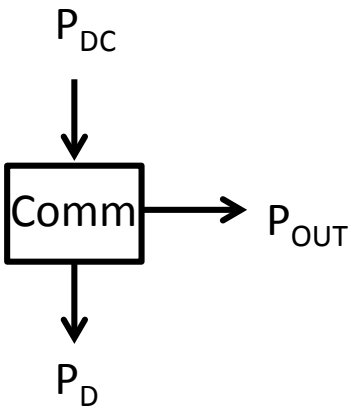
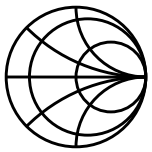
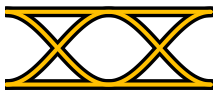
Energy Efficiency



$$P_{DC} = P_{OUT} + P_D$$

$$\eta \equiv \frac{P_{OUT}}{P_{DC}} = 1 - \frac{P_D}{P_{DC}}$$

- **Conservation of Power is used, instead of conservation of energy**
- **Power losses in the conversion process are dissipated as heat**
- **Objective: all input power is converted to the output signal**
- **Effective *design criterion*: minimize total dissipated power**

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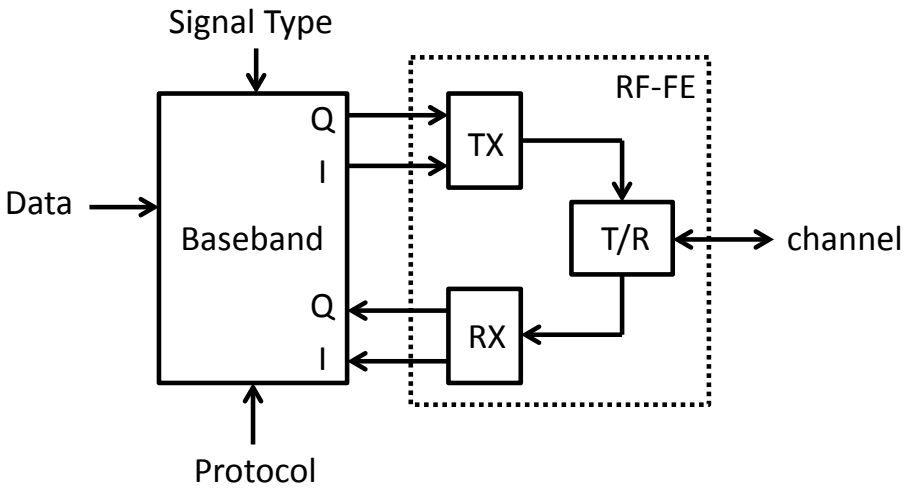
Joint Optimization Procedure



1. **Identify the minimum power dissipation conditions for each circuit block**
2. **Assure that the signal modulation allows these minimum power dissipations to be realized**
3. ***Then* optimize the protocol for minimum total power dissipation**

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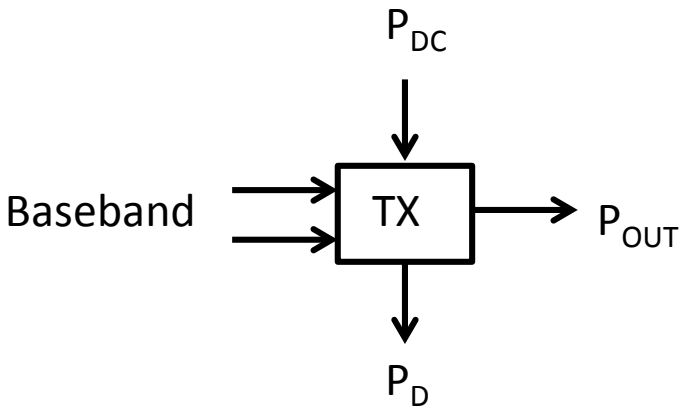
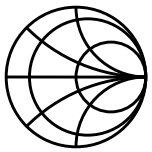
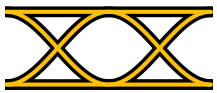
Circuit Blocks: TX



- **Transmitter is traditionally the highest power consumption block**
- **Most modern communication systems require very linear transmitter circuitry**

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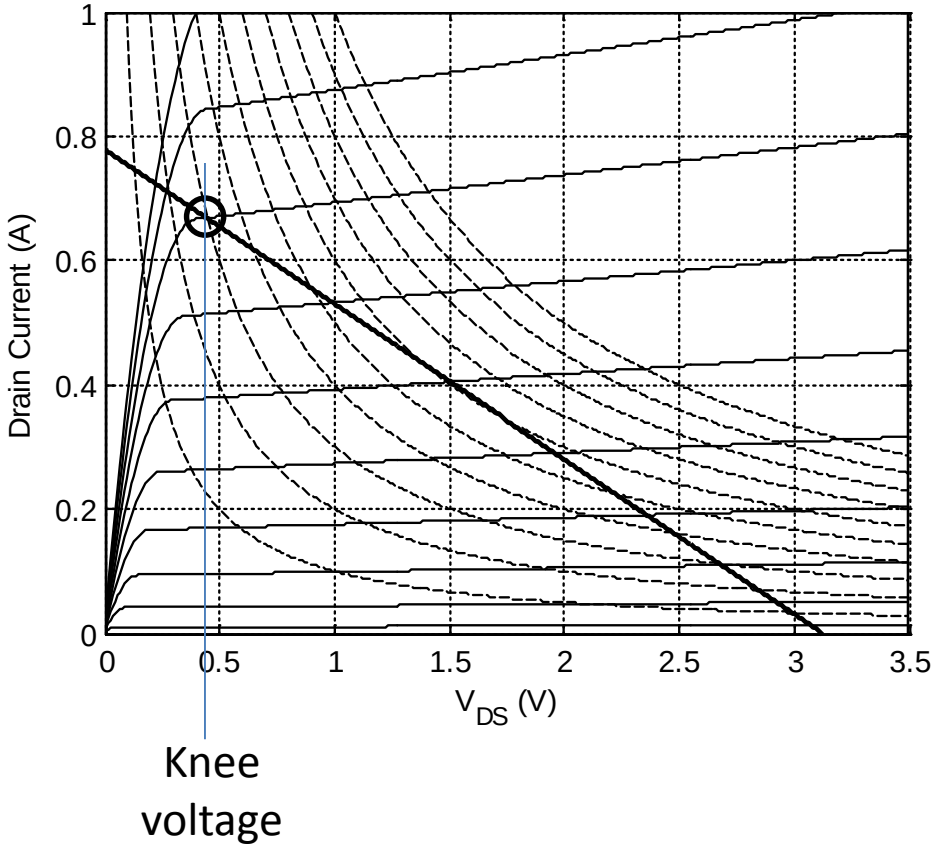
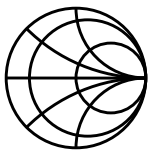
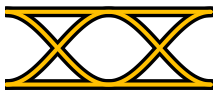
Amplifier Power Dissipation



- **Any transistor has finite resistance**
- **Linear amplifiers require transistor controlled current source (CCS) operation**
  - Output waveform remains above the *knee voltage*
- **Amplifier operation requires knowing the load line**
- **Amplifier power dissipation is evaluated along the load line**
  - intersections with constant power contours
- **Note: loadline mid-point (best linearity) is near the *highest* power dissipation**

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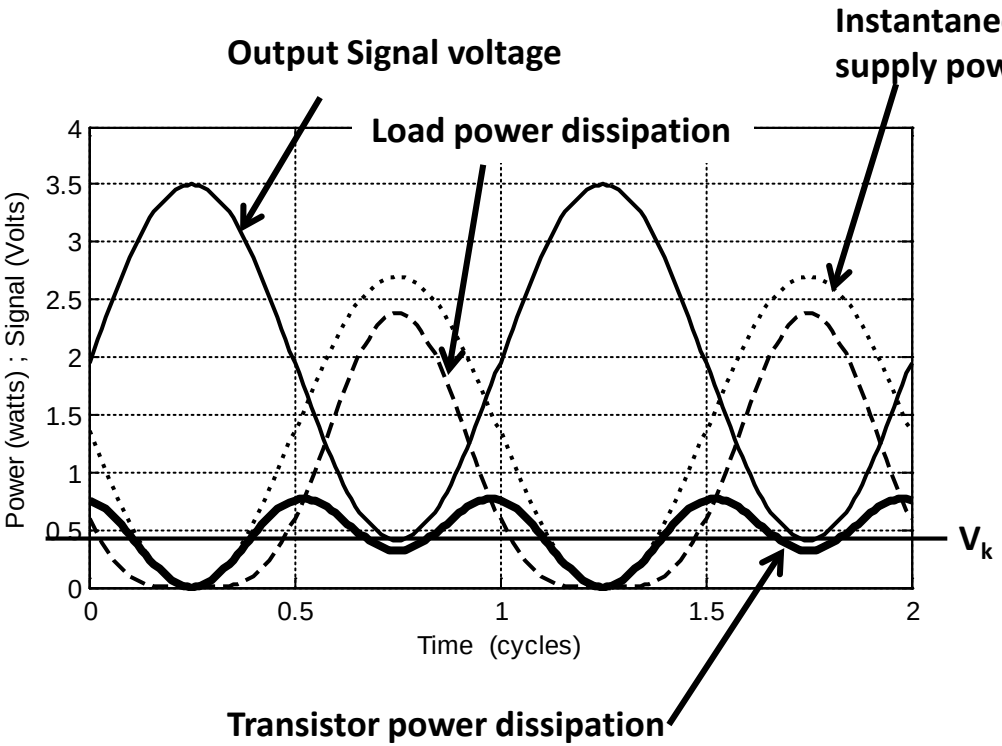
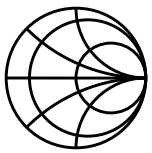
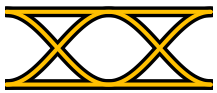
Operating Dissipation



- **As the output signal varies, the power dissipation varies in real-time**
- **Output signal waveform cannot fall below the knee voltage**
  - This elevates the minimum power dissipation when conducting

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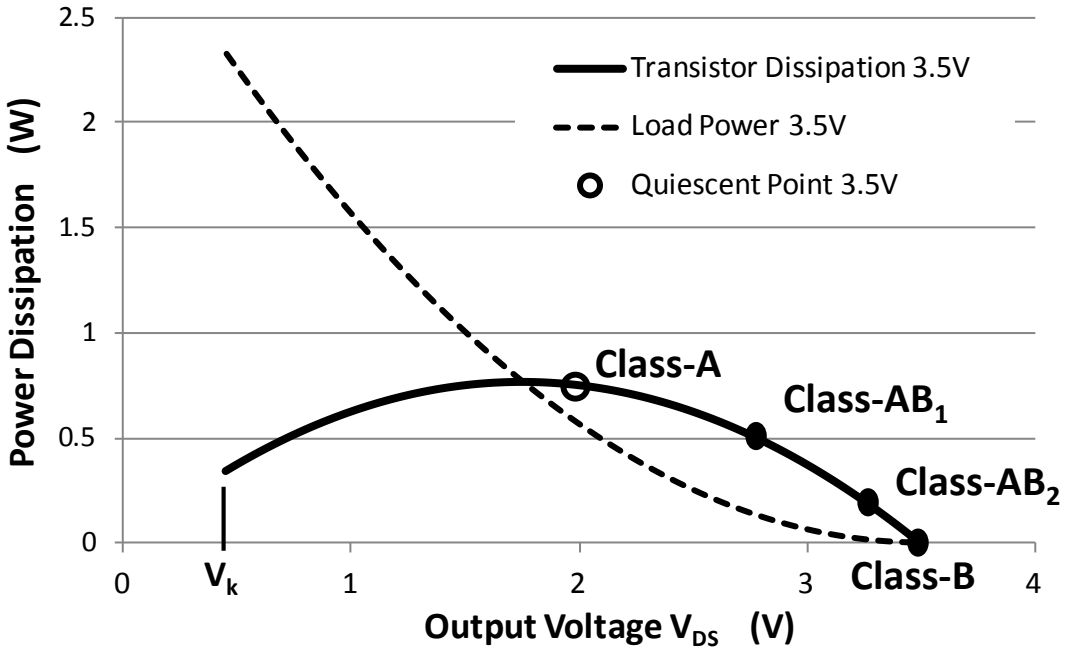
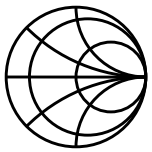
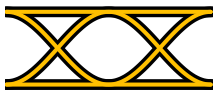
Dissipation and Amplifier Class



- **Class-A (best linearity) is biased near the highest power dissipation: the *lowest efficiency***
- **Class-AB or class-B bias has lower power dissipation**
  - BUT: *requires* transistor nonlinear operation (cut-off)

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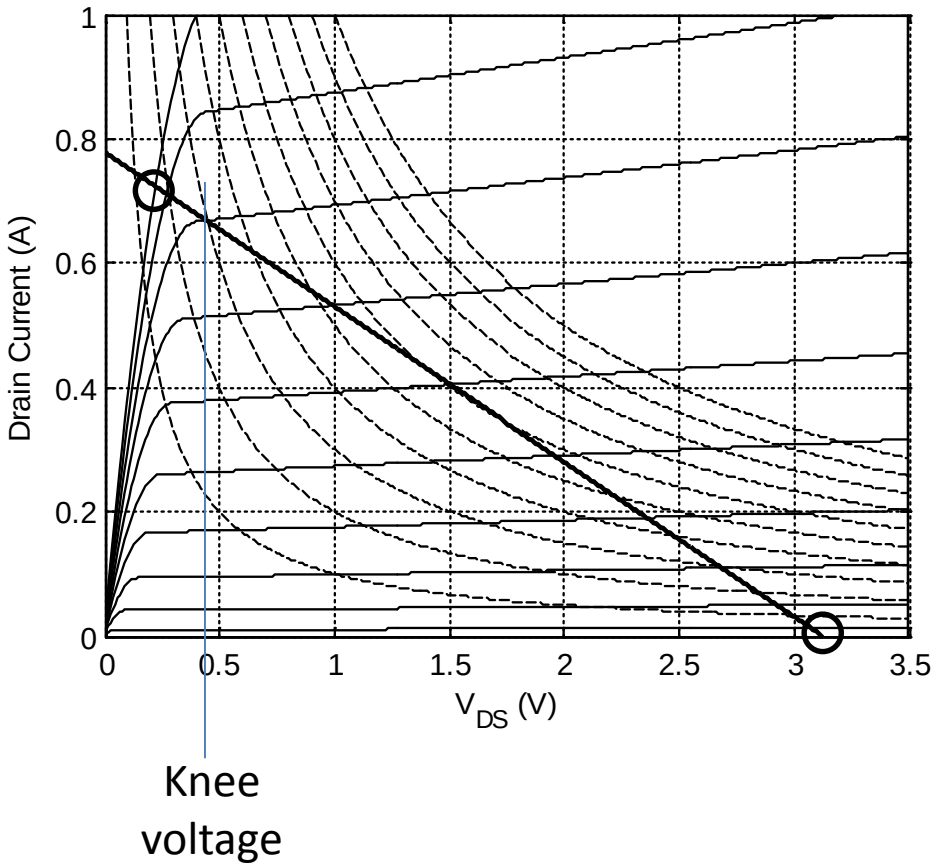
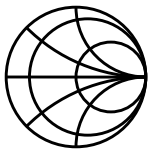
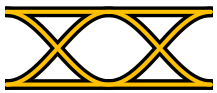
Below the Knee Voltage



- **Power dissipation is minimum at**
  - Cutoff operation
  - Resistive operation
- **Both conditions are outside the CCS linear operating region**
- **Conclusion: efficiency is maximum only when linearity is minimum**
- **Corollary: at the best amplifier linearity, efficiency is *minimum***

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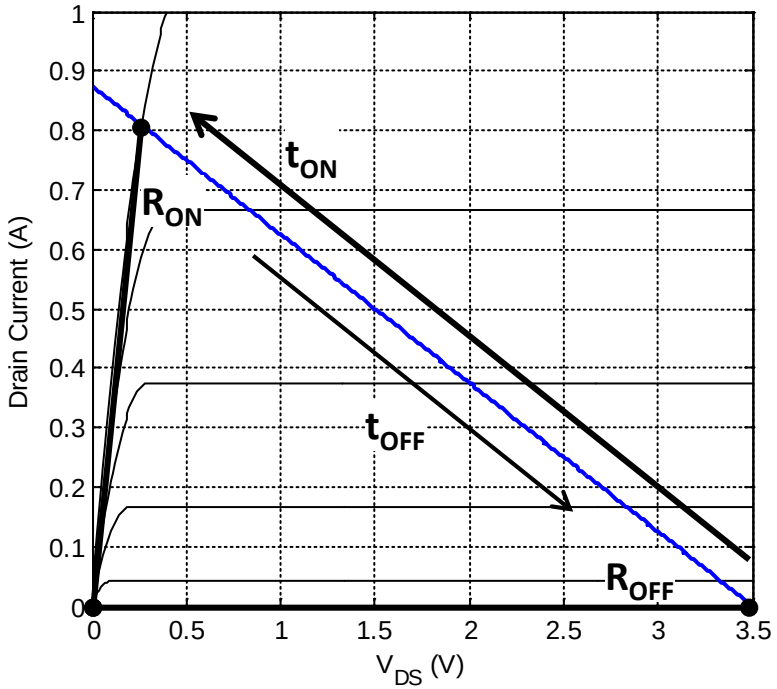
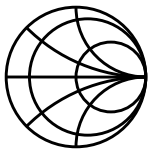
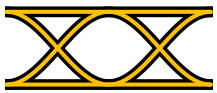
Switching Operation



- **Transition between the minimum power dissipation points in very short time**
  - "short time" here means with respect to the signal carrier period
- **Stay at minimum power dissipation as long as possible**
  - Cut-off operation = OFF state
  - Resistive operation = ON state

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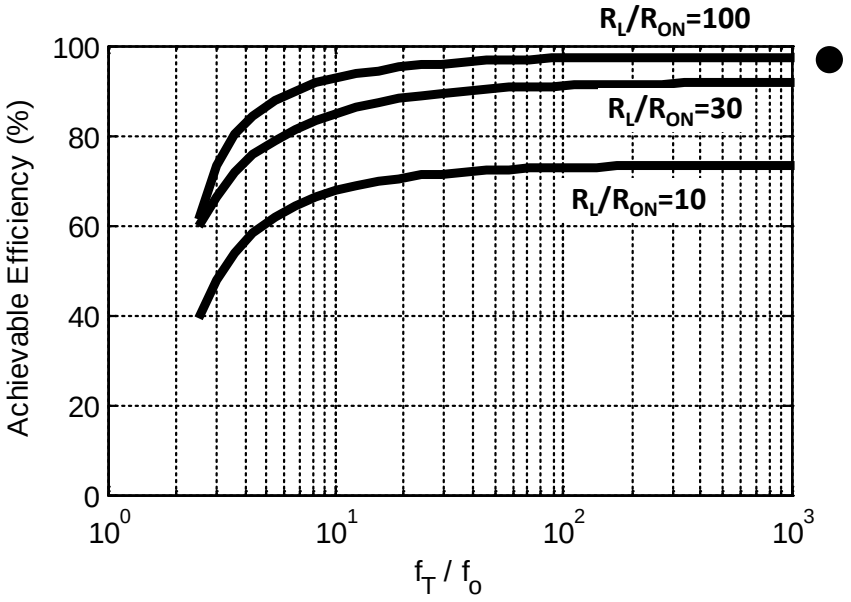
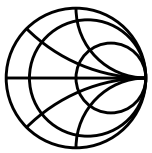
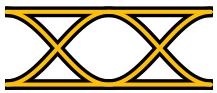
Achieving PA Switching



- **Load resistance must be much greater than the transistor ON resistance**
- **Operating (carrier) frequency must be well below the transistor f_T**
  - Best efficiency is available when the carrier frequency is **below 2%** of f_T
- **With moderate increase in power dissipation the operating frequency can increase to 10% of f_T**
- **Any higher operating frequency has significant penalty in available efficiency**
- **This result is consistent with switch-mode power supply (SMPS) operation**





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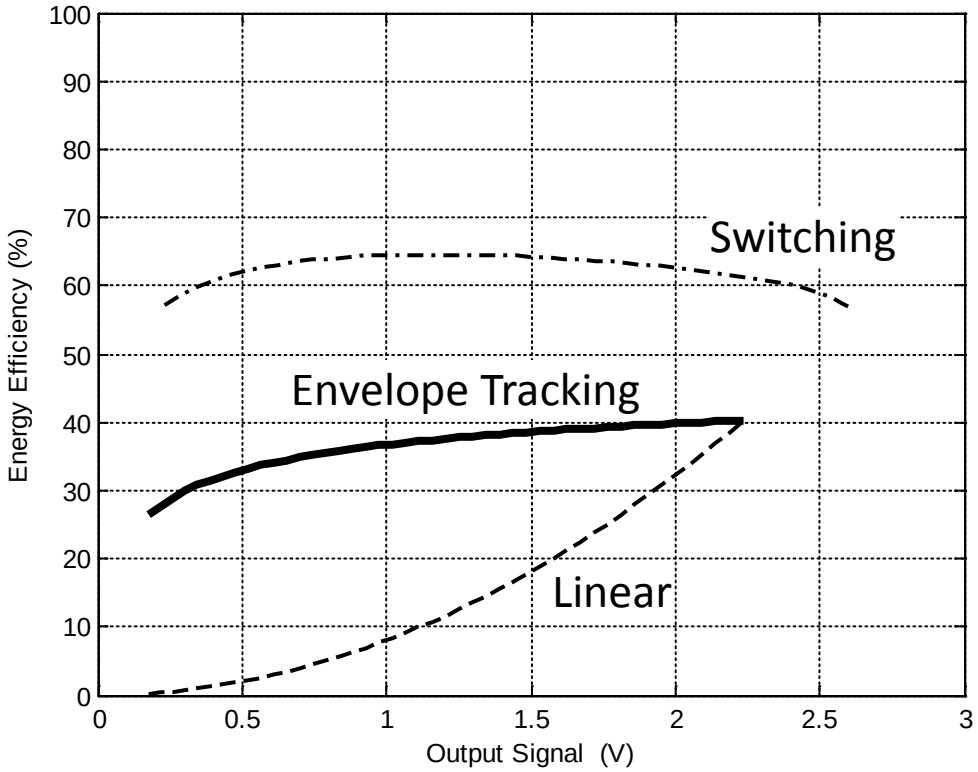
PA Efficiency Comparison



- **Switching operation has dramatically (8x-20x) higher overall efficiency**
- **Switching operation maintains efficiency across output power variations**
- **Requiring circuit linearity is the *antithesis* of Green Communications**

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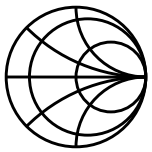
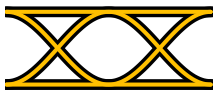
PA Summary for GComm

- **Circuit linearity is inherently bad for PA energy efficiency**
- **Switching operation (no linearity) is best for PA energy efficiency**
- **Circuit linearity requirements *guarantee* poor Green Communications performance**

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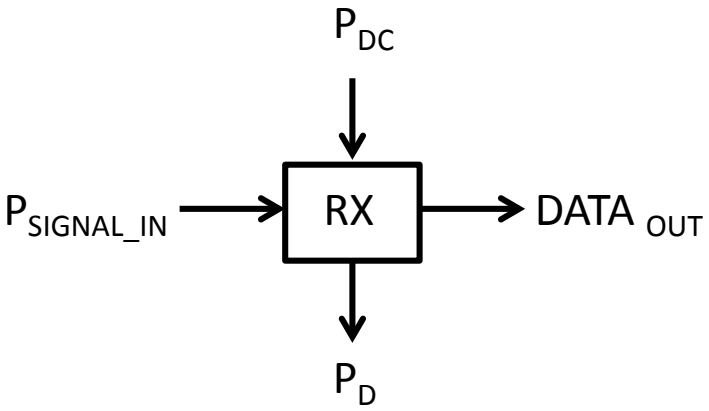
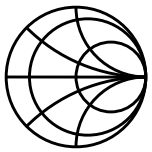
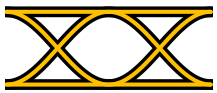
Circuit Blocks: RX



$$P_{DC} + P_{SIGNAL\_IN} = P_D + P_{DATA\_OUT}$$

$$\eta_{RX} \equiv \frac{P_{DATA\_OUT}}{P_{DC}} = 1 - \frac{P_D - P_{SIGNAL\_IN}}{P_{DC}}$$

- **Receiver efficiency is inherently zero because there is no output power**
- **Efficiency for a receiver is measured by the *power efficiency* of the modulation**
  - How much input power is needed to achieve a specified receiver error rate

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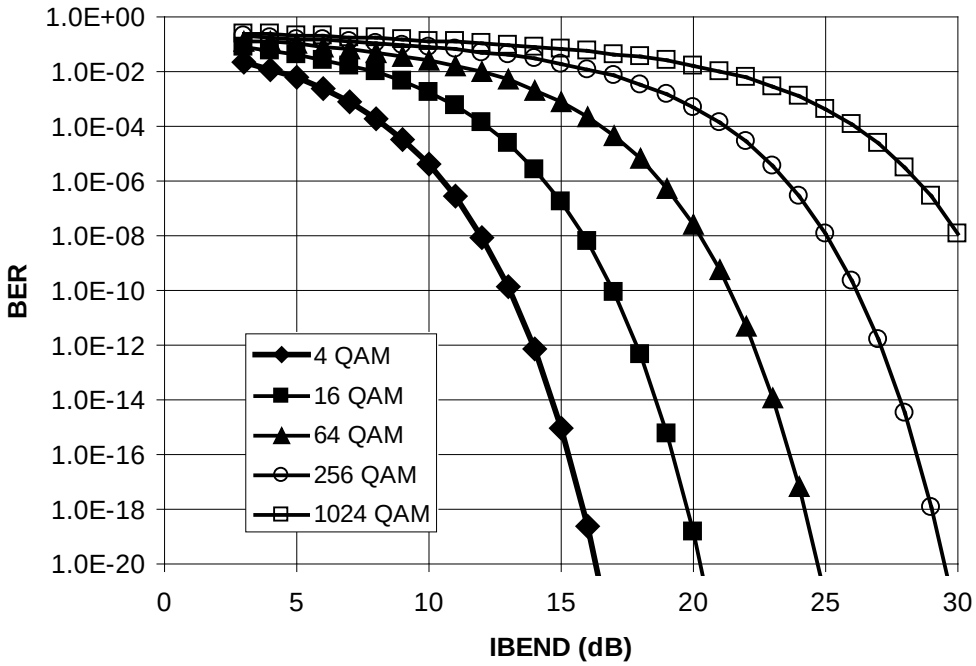
RX Efficiency



- **Digital signal receivers are measured by the individual bit error to noise density (IBEND) ratio**
- **Higher order modulations require higher IBEND for identical error rates**
- **Best performance for Green objectives corresponds to lower signal order values**

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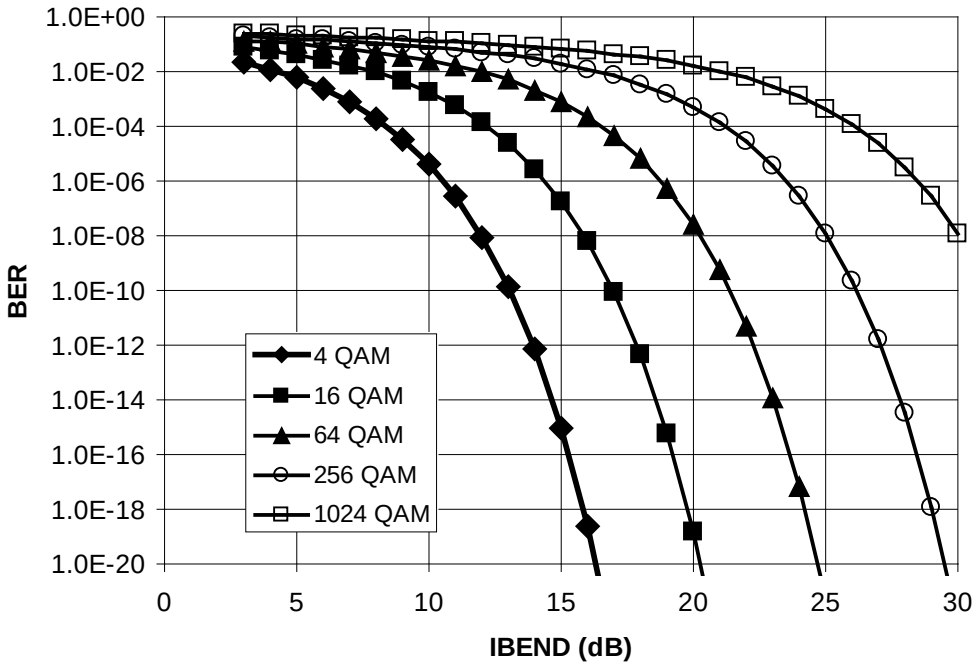
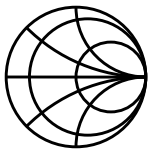
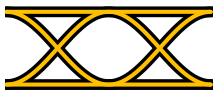
High Power is Useful



- Higher power allows higher signal order
- Higher signal order corresponds to shorter ON time
- All else being equal, shorter ON time corresponds to lower overall power dissipation

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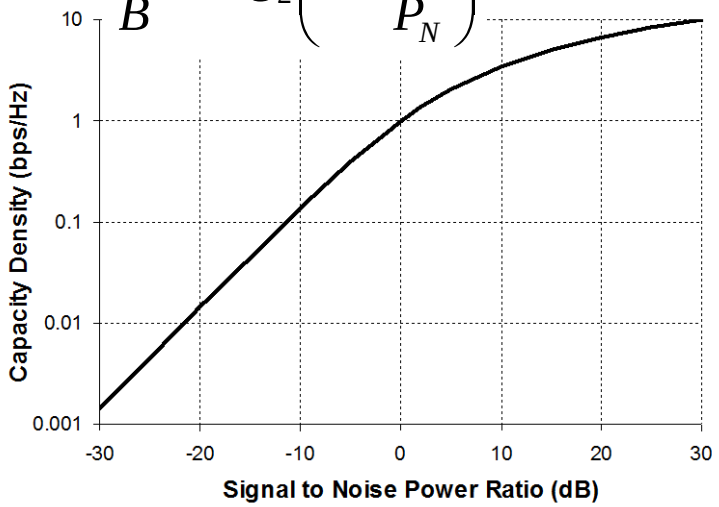
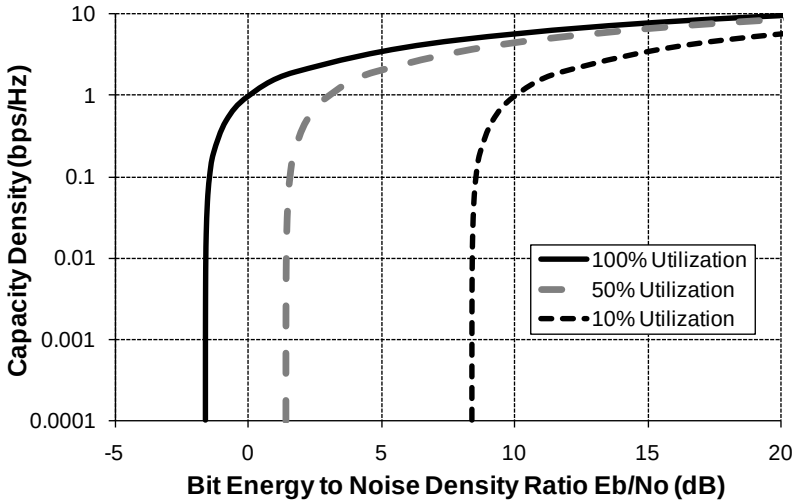
IBEND ≠ SNR

$$\frac{C}{B} = \log_2\left(1 + \frac{P_S}{P_N}\right)$$



$$\frac{E_b}{N_o} = \left(\frac{1}{U}\right)\frac{2^{C/B} - 1}{C/B}$$



- **It is unfortunate that an otherwise excellent reference book states that IBEND = SNR**
  - It is not
- **SNR is *by definition* a power ratio**
  - IBEND is an *energy* ratio
- **Evaluating the Shannon Limit vs. SNR and IBEND provides the *very* different results seen above**

$$\frac{C}{B} = \log_2\left(1 + \frac{E_b R}{N_o B}\right)$$

$$R = U \cdot C \quad ; \quad 1 \geq U \geq 0$$

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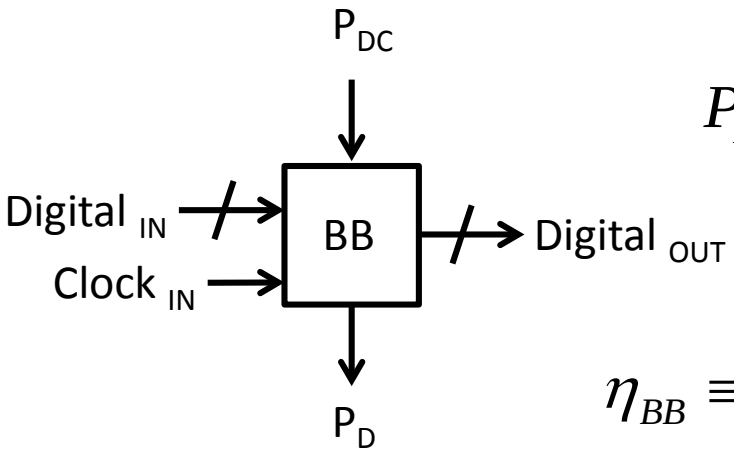
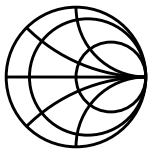
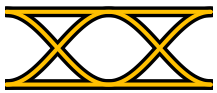
Circuit Blocks: Digital Baseband



$$P_{DC} + P_{DIGITAL\_IN} + P_{Clock} = P_D + P_{DIGITAL\_OUT}$$

$$\eta_{BB} \equiv \frac{P_{DIGITAL\_OUT}}{P_{DC}} = 1 - \frac{P_D - P_{DIGITAL\_IN} - P_{Clock}}{P_{DC}}$$

- **Like the receiver block, the baseband does not have significant output power**
  - Its energy efficiency is therefore inherently zero
- **Design must focus on minimizing the baseband total power dissipation**

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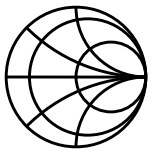
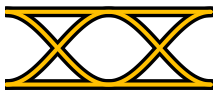
CMOS Power Dissipation

$$P_{D,BB} = \alpha N C V^2 f$$

- **Minimizing CMOS power requires**
  - Operating at the minimum possible voltage (*V*)
  - Having the smallest available CMOS geometry (*C*)
  - Use the *slowest* possible clock frequency (*f*)
  - Have the minimum gate count (*N*)
  - Keep the active gate fraction small (α)
- **For Green system design, the important parameter is *N***
  - Don't require many gates to get the needed job done

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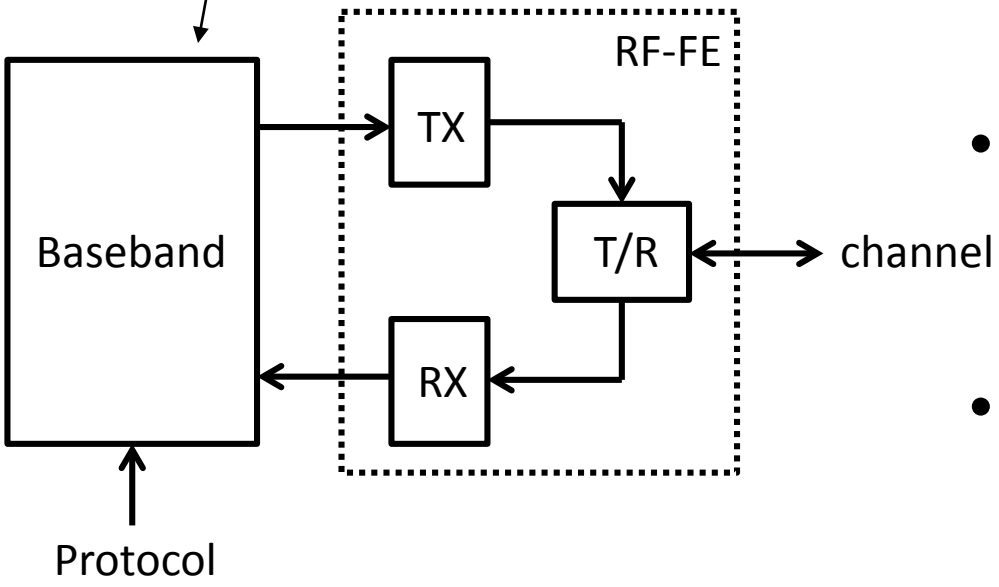
Minimum Baseband Dissipation

$$P_{D,BB} = \alpha NCV^2 f$$



- **Assume that voltage and clock frequency are already minimum**
- **Keep the gate count down**
  - only one signal should be needed when interfacing to the RF-FE
- **This corresponds to one signal modulation dimension**
  - ASK: only using the signal magnitude parameter
  - FSK: only using the frequency parameter
  - pPSK: only using the signal phase-shift parameter

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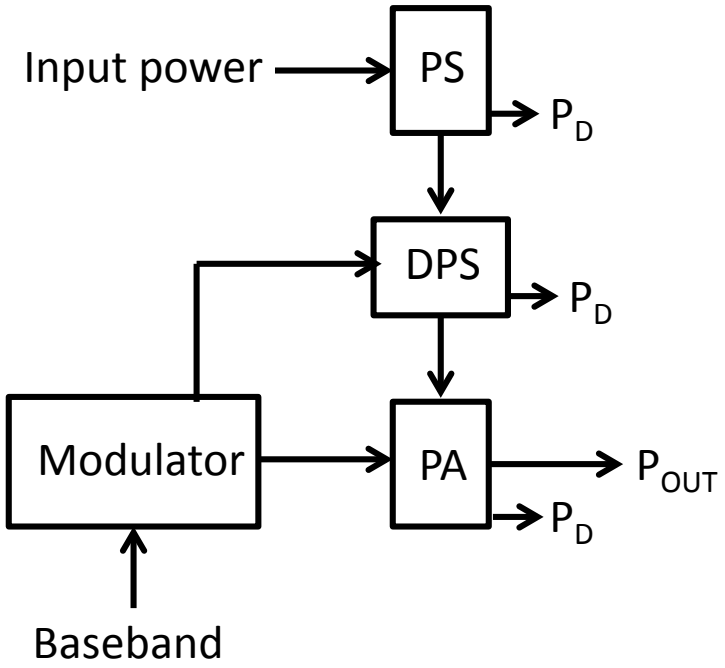
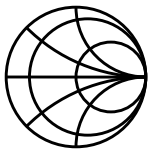
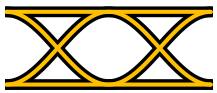
Top Level Efficiency

$$P_{DISS} = P_{OUT}\frac{1}{\eta_{PA}}\left(\frac{1-\eta_{PS}}{\eta_{DPS}\eta_{PS}} + \frac{1-\eta_{DPS}}{\eta_{DPS}} + \left(1-\eta_{PA}\right)\right)$$



- ***Total*** **power dissipation must be minimized for best efficiency**
- **PA efficiency is in each term**
  - Overall efficiency will *never* exceed the PA efficiency
- **Dynamic supply efficiency is a window on the PA efficiency**

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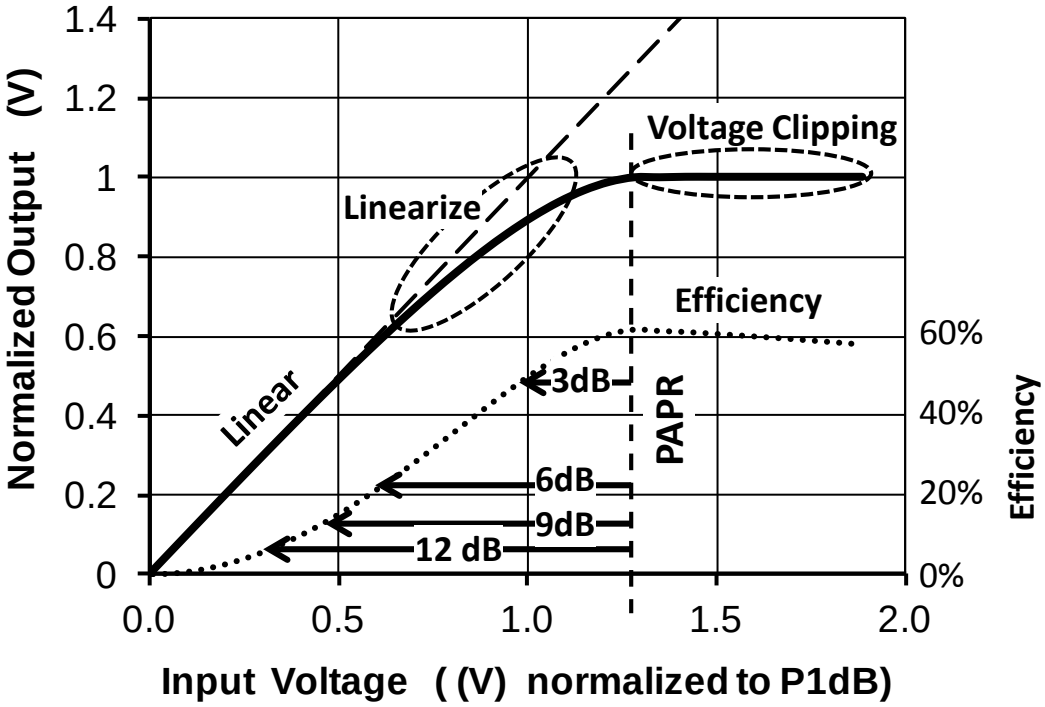
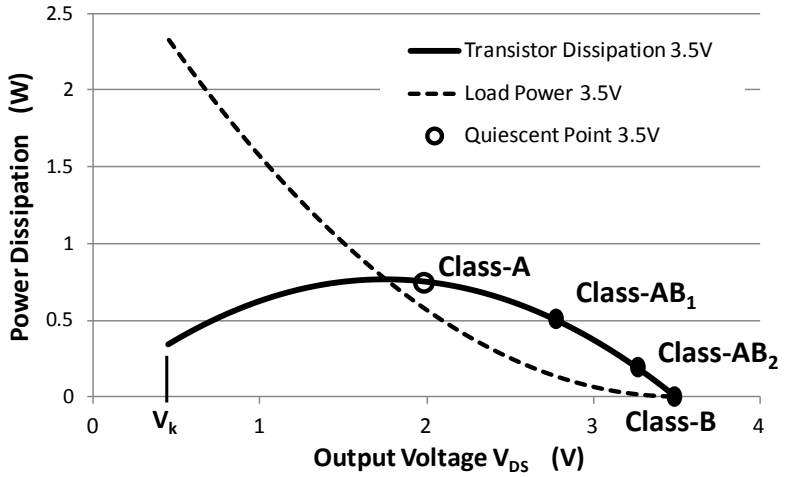
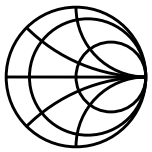
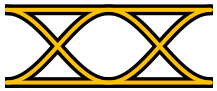
Efficiency vs. Signal PAPR





- ***All* transmitters must be designed for signal peak power**
- **System coverage is designed around signal average power**
- **Signal PAPR forces PA design to have a larger amplifier than the system coverage design would imply**
  - PA efficiency also goes down since the mean output power is close to the transistor power dissipation peak





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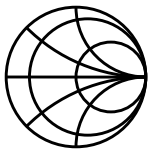
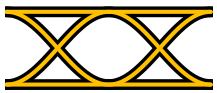
Importance of Signal Selection

- **Hardware power dissipation is governed by Ohm's Law**
  - Linear operation maximizes power dissipation
  - Switching operation minimizes power dissipation
- **Signal selection must align with this physical reality**
  - Requiring circuit linearity actually minimizes achievable transmit efficiency
  - Quadrature modulation increases power dissipation on all circuitry blocks (TX, RX, BB)

- ***Selected modulation sets a floor on achievable energy efficiency***

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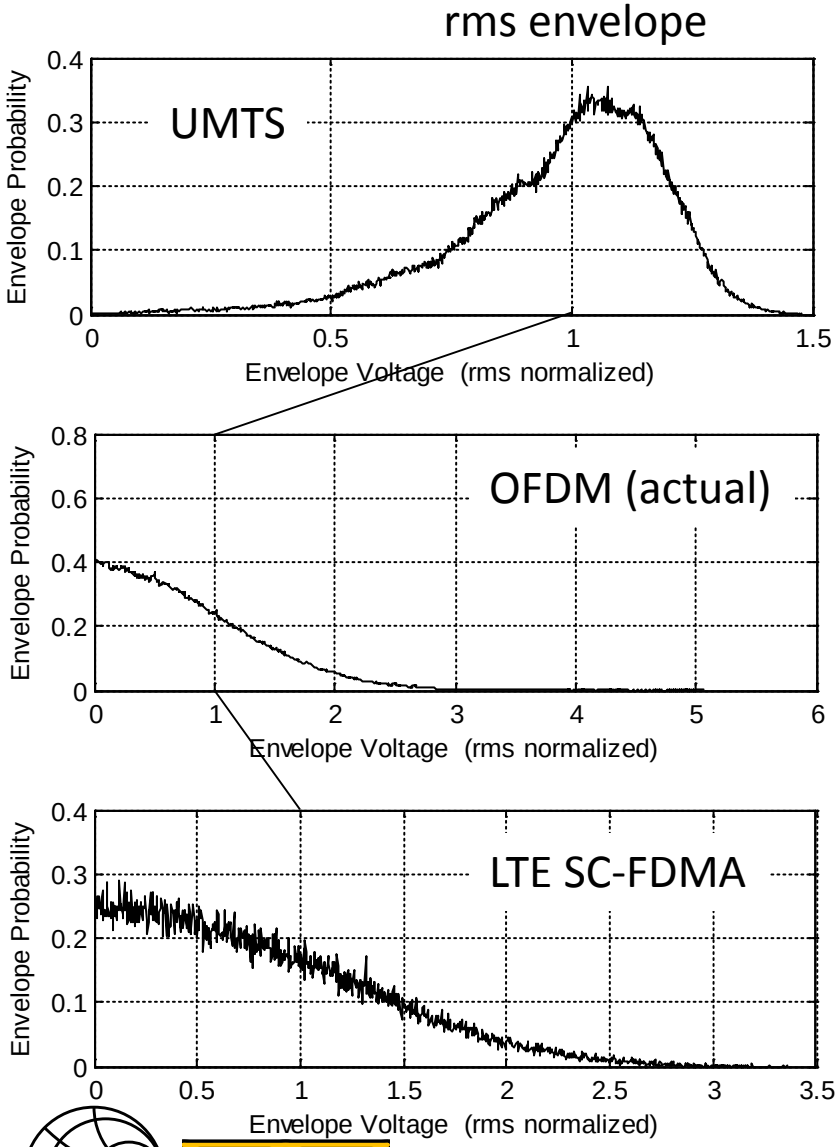
Envelope Property Requirements



Green Communications requires certain properties of the signal envelope:

- **Minimize signal PAPR**
  - Keep the signal power near the best PA efficiency
- **Eliminate signal envelope zero crossings**
  - This is where most linearity requirements are driven from

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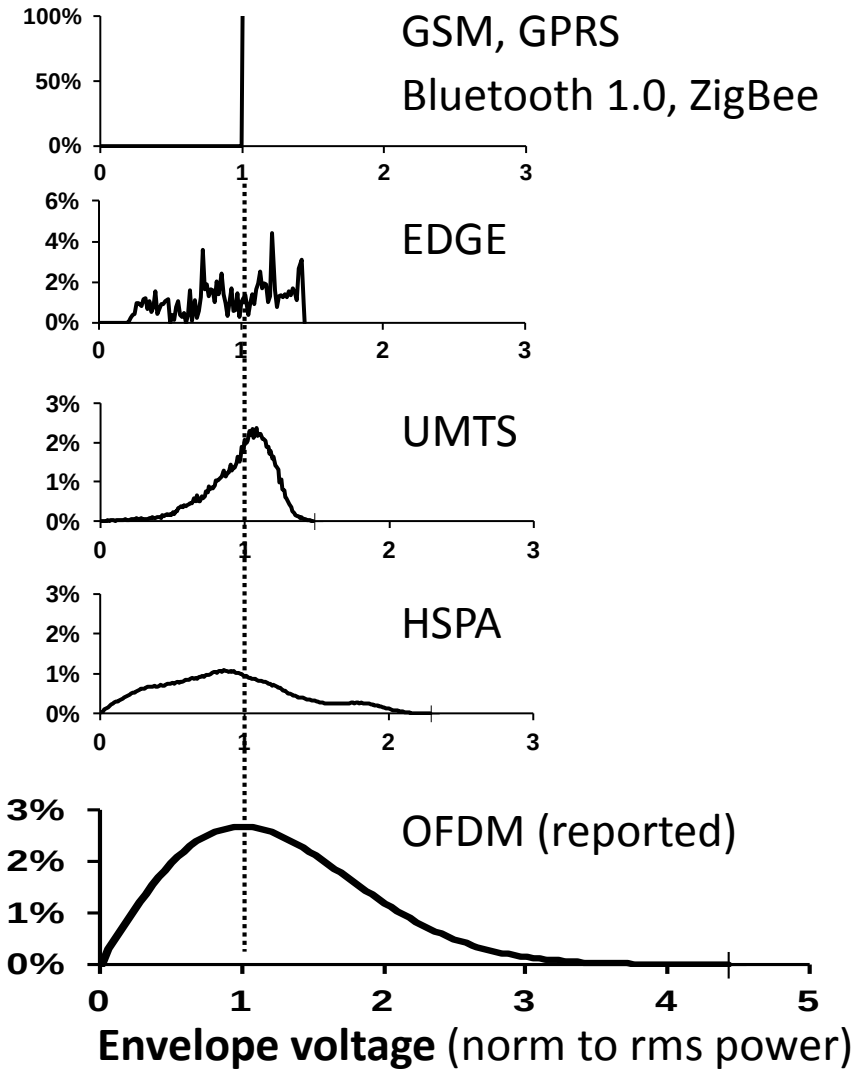
PAPR of Standard Signals



- **PAPR for cellular signals have continuously increased over the past 20 years**
- **Bandwidth efficiency of these signals is not increasing proportionally with the PAPR**
- **Overall energy efficiency is actually *decreasing***

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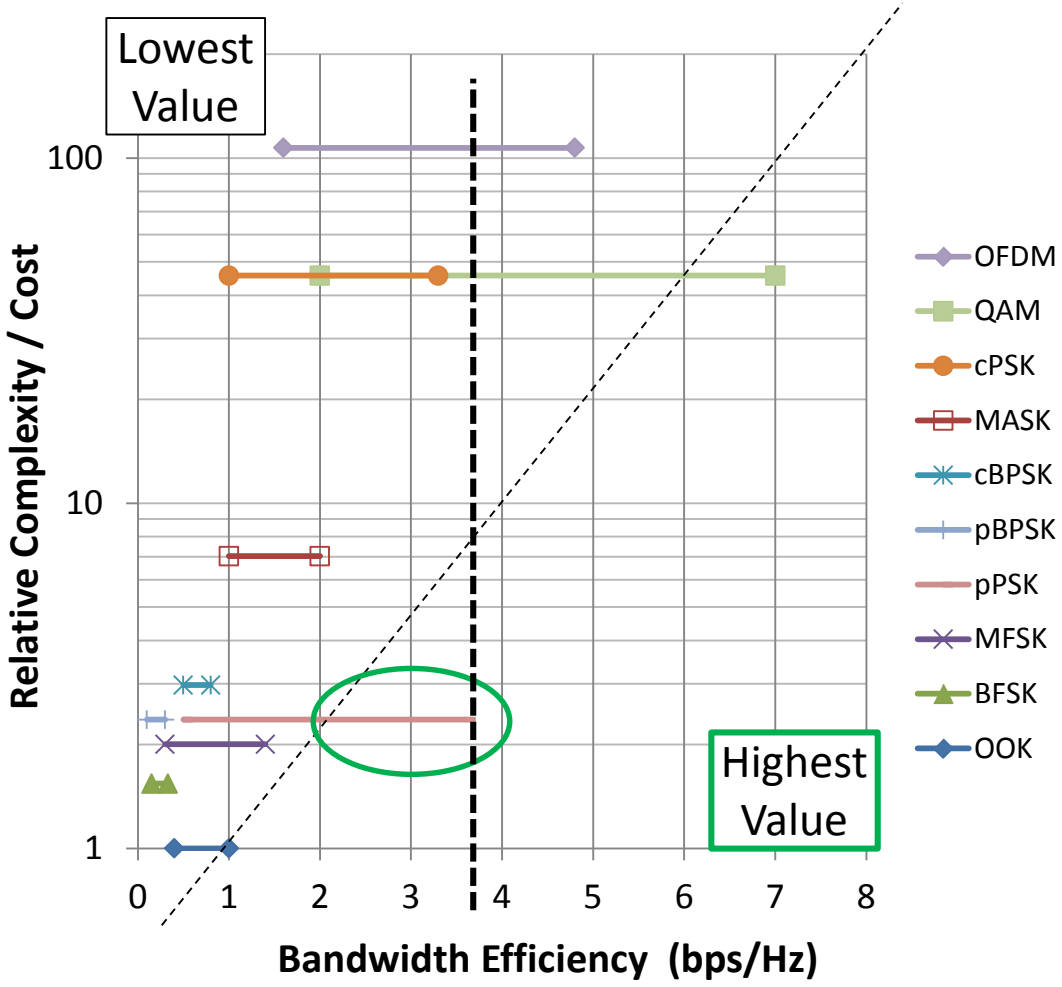
Comparison of Signal Types



- **Increased bandwidth efficiency generally corresponds to**
  - higher signal complexity
  - Lower energy efficiency
- **Simple modulations generally have the poorest bandwidth efficiency but the best energy efficiency**
- **Highest value signal types**
  - QAM provides the best bandwidth efficiency
  - pPSK gets closest to the highest value region

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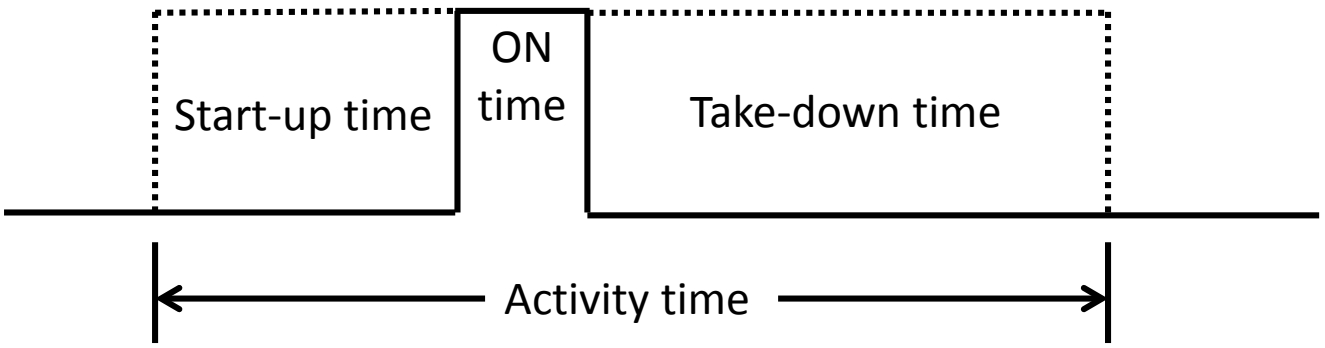
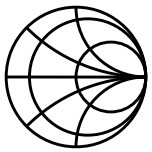
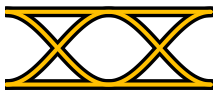
Protocol Impacts



- **Sleep intervals are a very effective technique**
  - As long as power really does go to zero when OFF
- **Keep the system OFF as long as possible**
  - Minimize start-up overhead time
  - Minimize post-communication shut-down time

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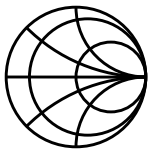
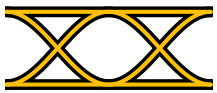
Specs By Circuitry Blocks

- **Transmitter**
  - Minimize transmit energy (high power, shortest time)
  - Frequency <2% of PA transistor f_T
  - Build using switching circuitry
  - Only 1 modulation signal path (ASK, FSK, pPSK)
  - PA at the highest possible voltage
- **Receiver**
  - Operate half-duplex (TDD)
  - Limiter to compress dynamic range, not an AGC
  - Only 1 demodulation signal path
- **Baseband**
  - Use reasonably advanced CMOS process nodes: no static power
  - Use lowest possible voltage and clock frequency
  - Maximize use of digital gates (DSP)
  - Only 1 modulation data path

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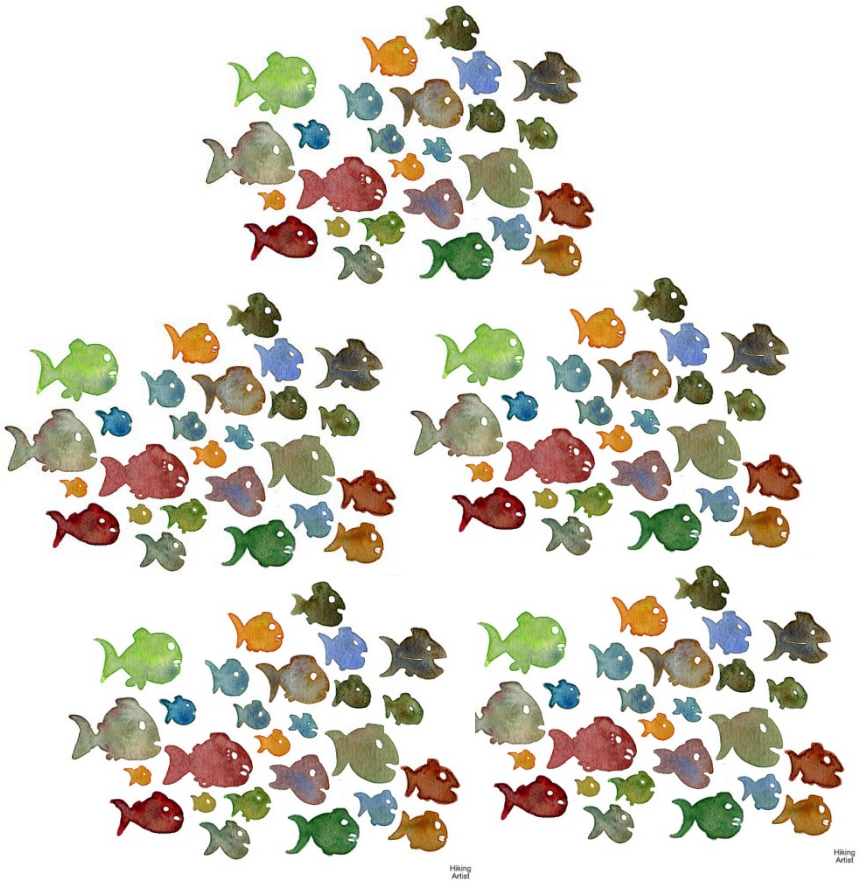
Don’t Forget the Antenna



- **The RF signal going by has fixed power per unit area**
  - *Independent* of frequency
- **Large antenna area intercepts more signal power**
- **Antennas greater than $\lambda/4$ on a side *must* be directional**

- **“You need a big net to catch more fish”**

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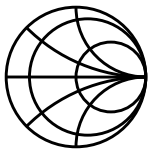
Conclusions

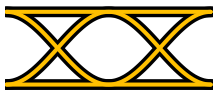
Basic physics is clear on where power dissipation comes from

- **Circuit linearity inherently minimizes available energy efficiency**
- **Quadrature modulation increases power dissipation in all communication circuitry blocks**
- **Long start-up and shut-down times keep the communication circuitry operating beyond communication times**

<u>To maximize Green Communication operation</u>

- **Build the TX using switching circuitry**
- **Adopt signals that can tolerate this switching circuitry**
  - *No envelope zero-crossings*
- **Use 1-dimensional modulations to reduce RX and BB power**
- ***Then* optimize the protocol**





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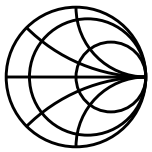

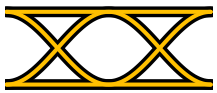

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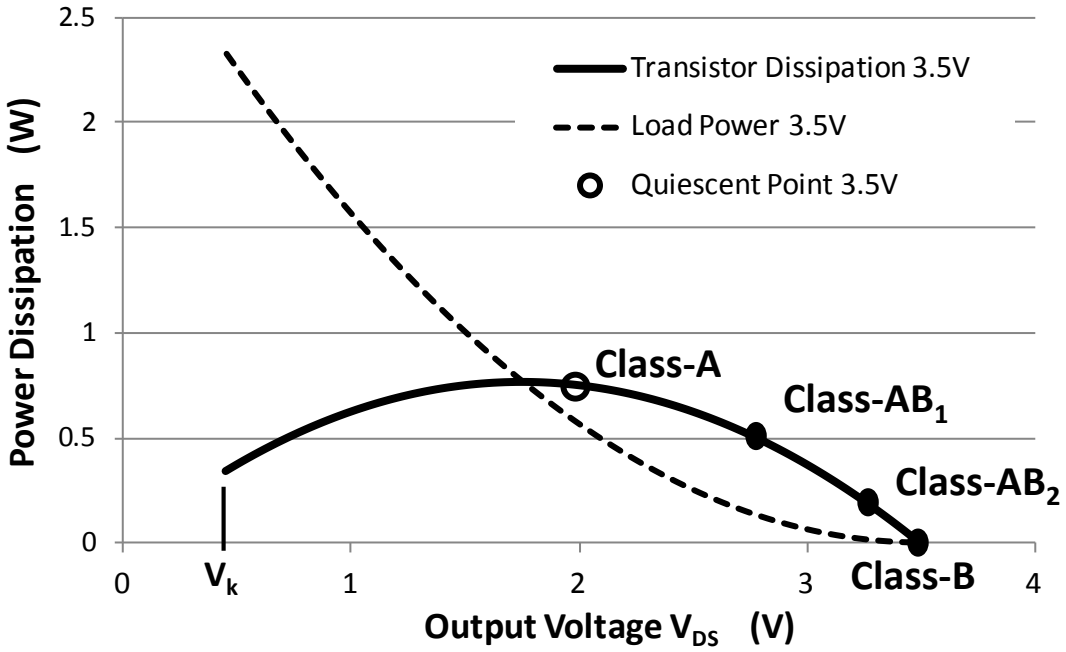
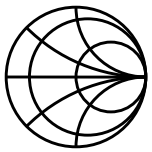
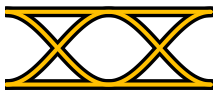
Amplifier Power Transfer



- **Power dissipated in the load is good**
- **Power dissipated in the transistor is bad**
- **This ratio is best at the signal voltage minimum**
  - At the knee voltage (V_k)

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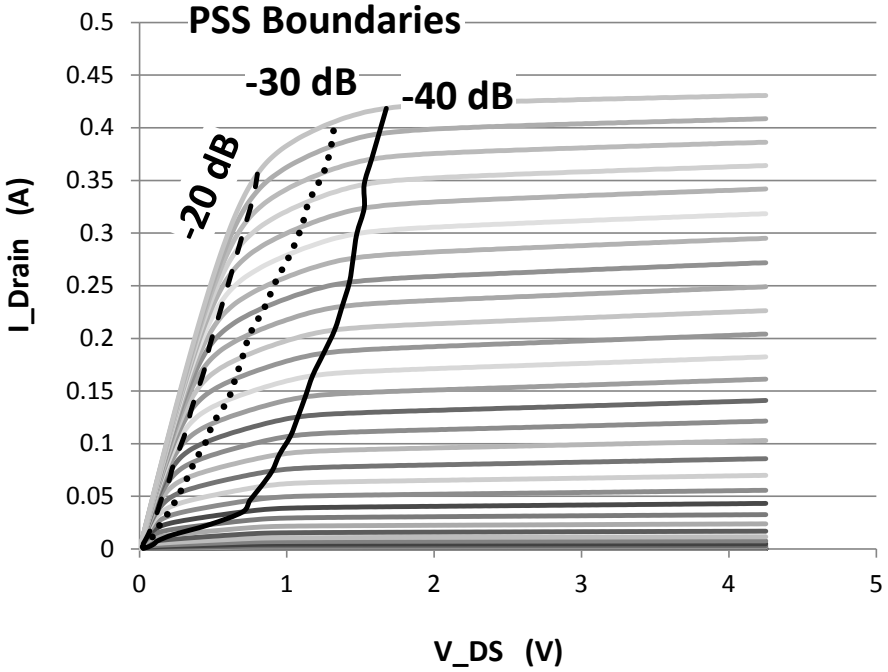
Knee Voltage

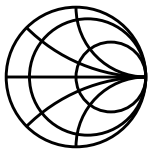
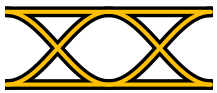


$$V_k\left(V_{GS}\right) = \text{minimum } V_{DS} \text{ satisfying}$$

$$\frac{dI_D\left(V_{DS}, V_{GS}\right)}{dV_{DS}} = k$$

$$PSS = 10\log_{10}\left(k^2\right)$$

- **The boundary between resistive and CCS regions of transistor operation**
- **Easy to see for ideal $r_o = \infty$ devices**
- **Requires a definition (such as this) for general use across all devices**

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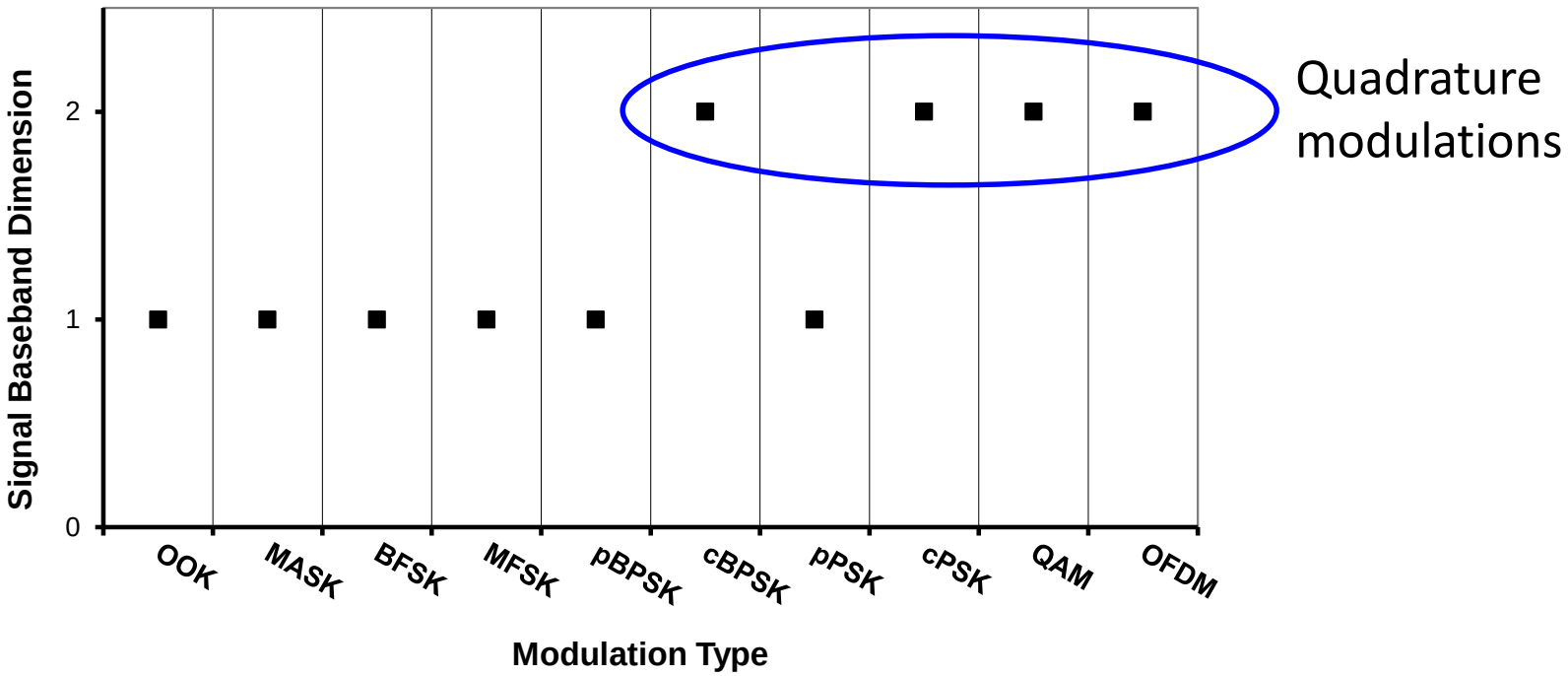
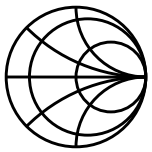
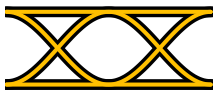
Modulator Dimension



- **Modulations that require more than one signal parameter inherently require more baseband power**
- **All quadrature modulations have this inherent energy efficiency *disadvantage***

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