ECE 413/513 –RADIO FREQUENCY IC DESIGN

RECEIVER SENSITIVITY, DR, SFDR, PHASE NOISE, EVM, LINK BUDGET

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RECEIVER NOISE FLOOR AND SENSITIVITY

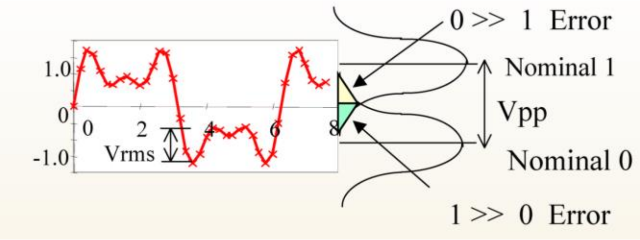
- Noise floor defined at the output of the receiver, before the decision circuit or demodulator
  - Noise *floor* $= \mathrm{kT\Delta fGF}$
  - G= overall gain of the receiver gain
  - F = receiver noise factor
- Receiver *sensitivity*, S_i,
  - Specified for a certain bit error rate
  - Depends on the receiver $F(T_e)$ and required SNR_{RX} of the detector

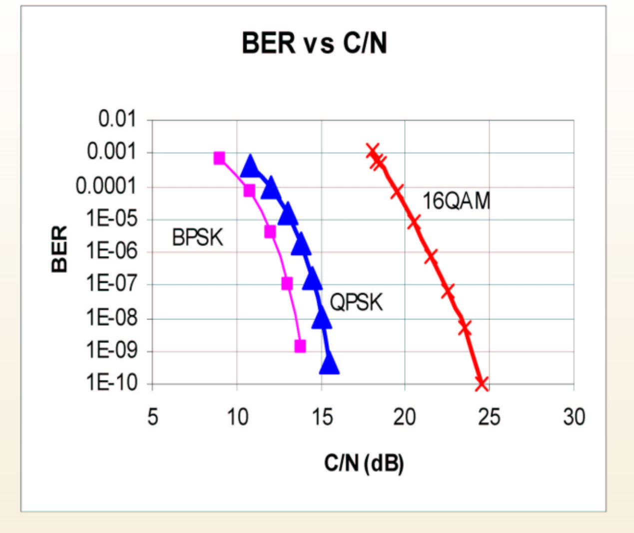
$$\mathrm{S_i = F \cdot SNR_{RX} \cdot k \cdot T \cdot \Delta f = \left(1 + \frac{T_e}{T}\right) SNR_{RX} \cdot k \cdot T \cdot \Delta f}$$

LINK BETWEEN BER AND SNR

For ASK

$$BER = \frac{1}{\sqrt{2\pi}} \frac{e^{-\left(\frac{E_b}{N_0}\right)^2/2}}{\frac{E_b}{N_0}} \qquad \frac{E_b}{N_0} = SNR\frac{B_n}{R_b}$$





- E_b is the bit energy
- N_0 is the one-sided noise power density
- B_n is the noise bandwidth: $\pi\Delta f/2$
- R_b is the data rate
- Refer to a Digital Communication book (Proakis, Goldsmith) for details

SNR VS. MODULATION SCHEME

Modulation	Spectral Efficiency*	SNR@BER=10^{-6}
OOK-NRZ	1.0 (1) bits	13 dB
4L FSK	1.5 (2) bits	17 dB
QPSK	1.6 (2) bits	14 dB
8PSK	2.5 (3) bits	19 dB
16QAM	3.2 (4) bits	21 dB
64QAM	5.0 (6) bits	27 dB

*Bandwidth efficiency = data rate/bandwidth = $\frac{R_b}{\Delta f}$

RECEIVER SENSITIVITY EXAMPLES

- 5-GHz Wireless LAN System
  - NF = 6 dB, B=20 MHz, QPSK => SNR =14 dB

$$S_i(BER = 10^{-6}) = -174dBm + 6 + 10log\frac{20MHz}{1Hz} + 14 = -174 + 6 + 73 + 14 = -81dBm$$

- 60-GHz, 1.5-Gb/s Wireless LAN System
  - NF = 9 dB, B = 1 GHz, QPSK => SNR =14 dB

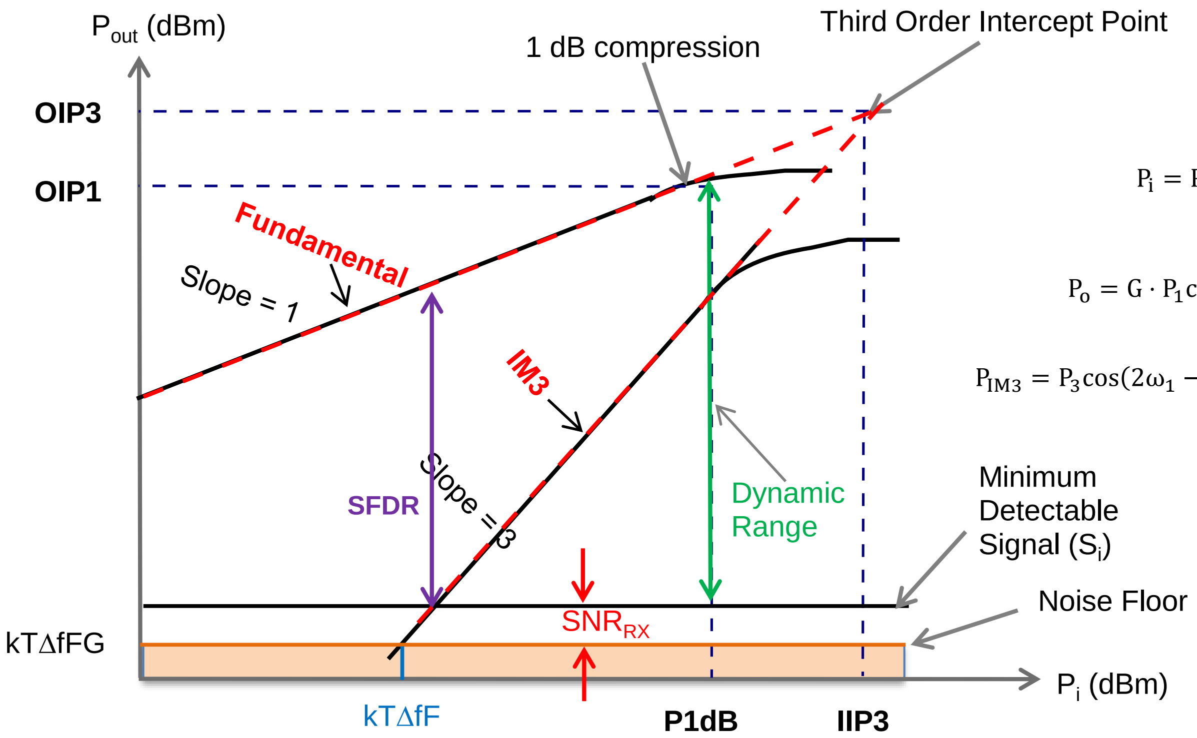
$$S_i(BER = 10^{-6}) = -174dBm + 9 + 10log\frac{1GHz}{1Hz} + 14 = -174 + 9 + 90 + 14 = -61dBm$$

RECEIVER SENSITIVITY EXAMPLES

- 12-GHz, HDTV satellite receiver
  - T=30°K, NF=1dB, B=6MHz, 64QAM=>SNR=27dB

$$S_i(BER = 10^{-6}) = -184dBm + 3.5 + 10log\frac{6MHz}{1Hz} + 27 = -184 + 3.5 + 68 + 27 = -85.5dBm$$

LINEARITY FIGURES OF MERIT



$$P_i = P_1\cos(\omega_1 t) + P_1\cos(\omega_2 t)$$

$$P_o = G \cdot P_1\cos(\omega_1 t) + G \cdot P_1\cos(\omega_2 t)$$

$$P_{IM3} = P_3\cos(2\omega_1 - \omega_2)t + P_3\cos(2\omega_2 - \omega_1)t$$

LINEARITY AND DISTORTION

- The 1-dB compression point: P_{1dB}
- Third-order intercept point: IIP_3, OIP_3
- Second-order intercept point IIP_2 (critical in Zero-IF receivers)
- Broadband measures of linearity
  - Total Harmonic Distortion (THD) = the sum of the powers of all the harmonics, except the fundamental

EQUATIONS FOR IIP_N

- IIP_n can be obtained graphically using dB scales

$$IIP_n = \frac{nP_i - IM_n}{n-1}$$

- Spurious signals due to an interferer *I*, must be *C* dB below the sensitivity level (*C* = margin)

$$IM_n = S_i - C$$

which provides the desired IIP_n

$$IIP_n = \frac{nI - (S_i - C)}{n-1}$$

- Note that IM_n is the input referred n^{th} order harmonic.

DYNAMIC RANGE AND SFDR

- Two definitions are used:
  - **Dynamic Range** (DR) is the difference (in dB) between the 1dB output compression point (P1dB) and the minimum detectable signal level

$$DR = P_{1dB} - S_i$$

  - **Spur-Free Dynamic Range** (SFDR) is the difference (in dB) between the fundamental signal and that of the intermodulation product (IM_n), when IM_n crosses the minimum detectable signal level, i.e. the sensitivity, S_i (Note that C=0dB in this calculation)
    - SFDR can be calculated as

$$SFDR_n = \left(1 - \frac{1}{n}\right)(IIP_n - IM_n) = \left(1 - \frac{1}{n}\right)(IIP_n - S_i)$$

EXAMPLE OF IIP3 SPEC DERIVATION

- $I_1 = I_2 = -38$ dBm, $S_i = -60$ dBm, C = 14 dB, $f_1 = 64$ GHz, $f_2 = 62$GHz => IM3 at 60GHz

$$IIP_3 \geq \frac{3 \times (-38) - (-60 - 14)}{2} = \frac{-114 + 74}{2} = -20\text{dBm}$$

- The most relaxed IIP3 requirement is in the absence of an interferer. Eg. in OFDM systems, the sub-carriers can interfere with each other:
- $I_1 = I_2 = -60$ dBm, $S_i = -60$dBm, C = 40dB, $f_1 = 60.005$GHz, $f_2 = 60.01$GHz => IM3 at 60GHz

$$IIP_3 \geq \frac{3 \times (-60) - (-60 - 40)}{2} = -60 + \frac{40}{2} = -40\text{dBm}$$

LINK BUDGET (*LB*)

- Describes the combined transmitter, antenna, and receiver performance

$$LB = P_{RX} - S_i \qquad\qquad P_{RX}(d) = P_{TX} G_{TX} G_{RX} \left(\frac{\lambda}{4\pi d}\right)^2$$

- λ is the wavelength
- *d* is the distance between the TX and RX >>λ
- P_{RX} is the power at the receiver input
- P_{TX} is the power at the transmitter output
- G_{TX} is the gain of the TX antenna (dBi)
- G_{RX} is the gain of the RX antenna (dBi)
- *EIRP* = $P_{TX}G_{TX}$ effective isotropic radiated power (*dBmi*)

EXAMPLE: 60-GHZ LINK BUDGET

- 2-m 60-GHz link at 4 Gb/s with Df of 2 GHz
- QPSK modulation, SNR = 14 dB, NF = 7 dB

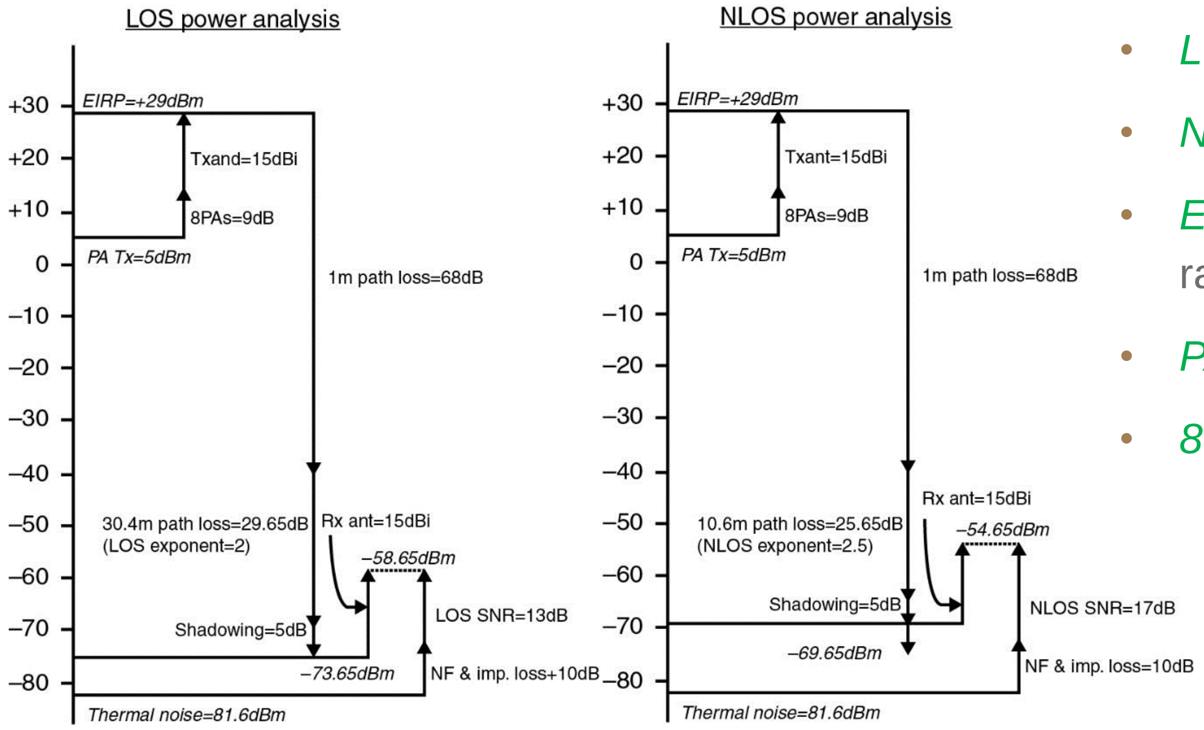
$$\mathrm{S_i} = -174\mathrm{dBm} + 10\log_{10}(2 \times 10^9) + 7\mathrm{dB} + 14\mathrm{dB} = -174 + 93 + 7 + 14 = -60\mathrm{dBm}$$

- P_{TX} = 10 dBm, G_{TX}= G_{RX}= 8 dBi, λ = 5 mm

$$LFS = 20 \cdot \log_{10}\left(\frac{\lambda}{4\pi d}\right) = 74dB$$

- P_{RX} = P_{TX} + G_{TX} - LFS + G_{RX} = 10 + 8 – 74 + 8 = -48dBm
- LB = P_{RX} – S_i = -48 dBm + 60 dBm = 12 dB

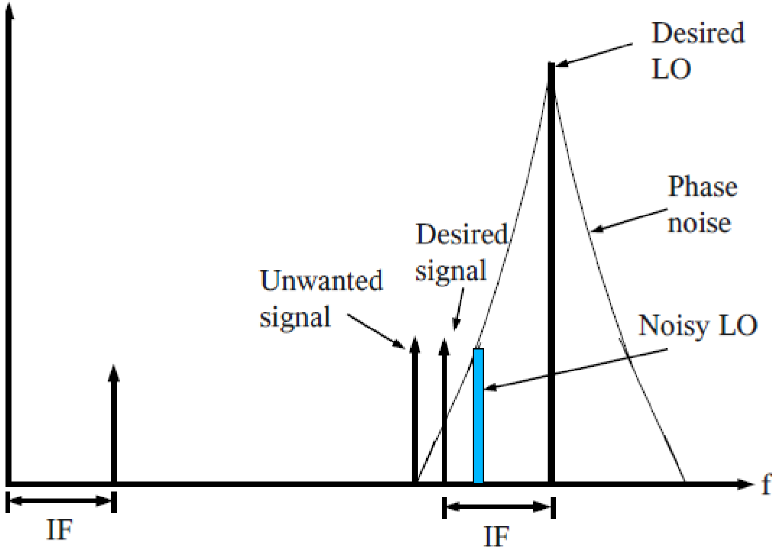
EXAMPLE: 60-GHZ LINK BUDGET DIAGRAM



- *LOS* = line of sight
- *NLOS* = non line of sight
- *EIRP* = $P_{TX}G_{TX}$ effective isotropic radiated power (*dBmi*)
- *PA* = Power amplifiers
- *8PAs* = 8 PAs in a phased array

PLL PHASE NOISE: *L*

- *L* = *a* broadening of the oscillator spectrum
- Measured as noise power in dBc/Hz in a 1-Hz band at an offset frequency f_m relative to the carrier power and frequency f_{OSC}
- Degrades the receiver sensitivity by raising the noise floor and adding *rms* phase error
- Degrades transmitter *EVM*
- Affects velocity resolution in automotive cruise control radar



EXAMPLE OF PLL PHASE NOISE IMPACT

- A phase noise of -100dBc/Hz over a bandwidth of 5 MHz results in a rms phase error

$$\theta_{rms} \approx \sqrt{2L\Delta f} = 0.0316\text{rads} = 1.81^{o}$$

- Oscillator phase noise mixes with an undesired signal and is downconverted to the IF/baseband raising the noise floor and dictating how closely adjacent channels may be spaced
- Formula that gives maximum allowed phase noise to achieve adjacent channel rejection of *C* dB for an interference power *I*

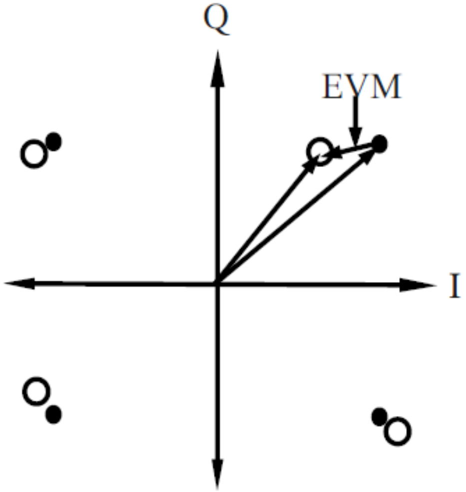
$$L(f_m) = P(dBm) - C(dB) - I(dBm) - 10\log(\Delta f), (dBc/Hz)$$

- In a 60-GHz radio with P=-60 dBm, C=14 dB, I=-38dBm, Df=2.1GHz, f_m = 2.1 GHz
  - L(2.1GHz) =<-128.5 dBc/Hz

TRANSMITTER SPECIFICATION

- *Output power* in dBm
- *EVM* = distortion in the transmitted signal constellation
  - measured with an ideal IQ receiver

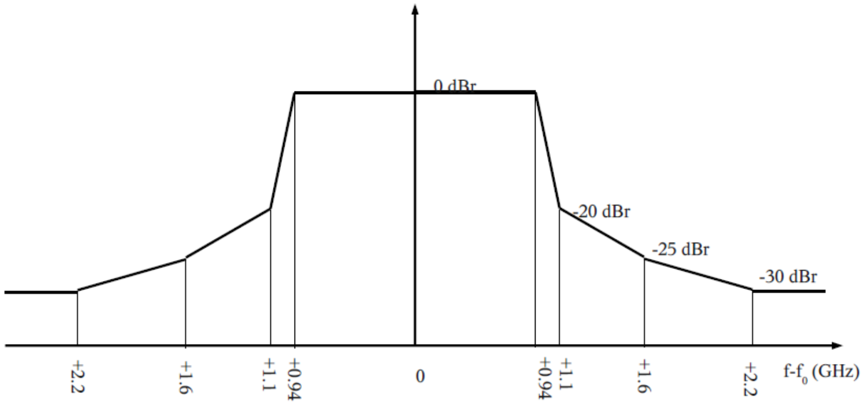
$$EVM = \sqrt{\left(\frac{1}{N \cdot P_{avg}} \Sigma_{i=1}^{N} [(I_i - I_i^*)^2 + (Q_i - Q_i^*)^2]\right)}$$



- P_{avg} = average power of the constellation
- (I_i*,Q_i*) are the complex coordinates of the i^{th} measured symbol
- (I_i,Q_i) are the complex coordinates of the nearest constellation point.

POWER SPECTRAL DENSITY MASK, ACPR

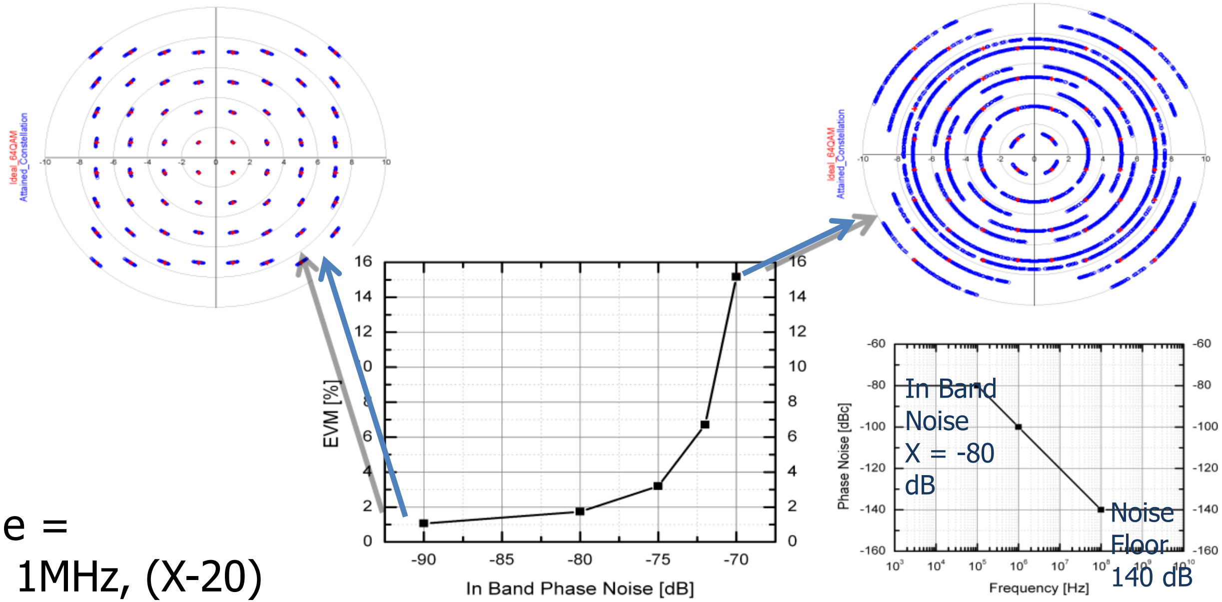
- *PSD* is specified in dB relative to the signal power in the center of the channel to prevent unwanted emissions into adjacent channels



- Adjacent Channel Power Ratio (ACPR) is another parameter specified in dB: 10log10.
  - Ex: <-20 dBc for 16 QAM, <-43 dB for 64 QAM

TRANSMITTER NOISE

- *Transmitter noise (jitter),* mostly from PLL, degrades EVM.



Phase Noise Profile =
list(100kHz, X dB, 1MHz, (X-20) dB, 100MHz, -140 dB)