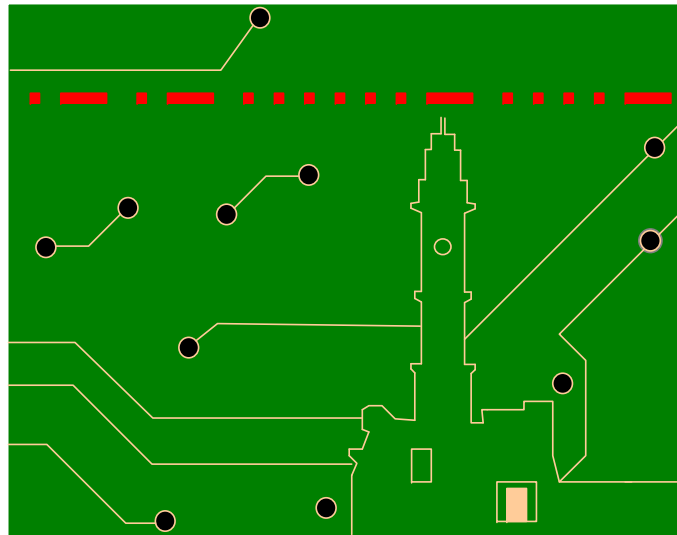# ΤΗΛ412 Ανάλυση & Σχεδίαση (Σύνθεση) Τηλεπικοινωνιακών Διατάξεων
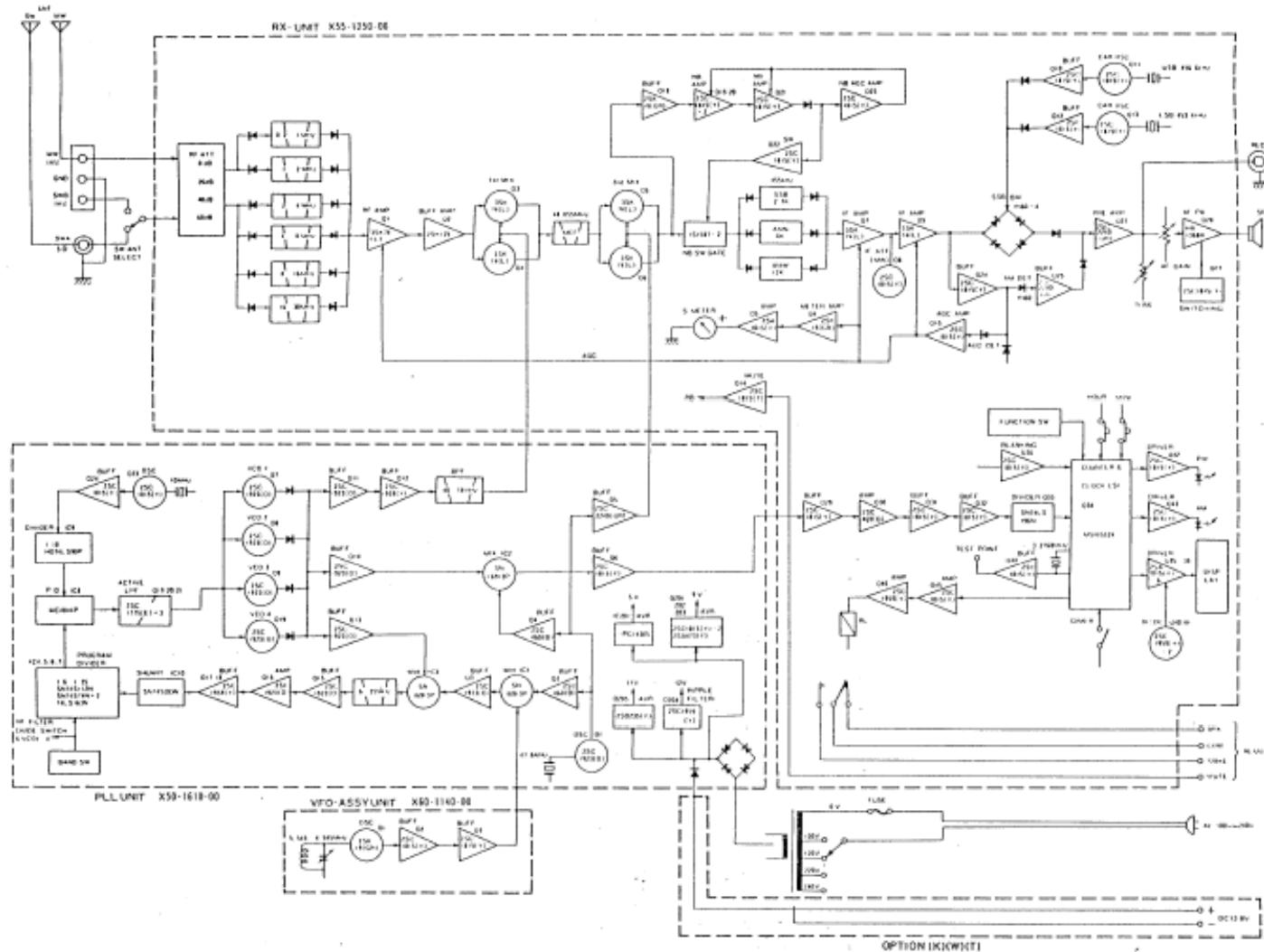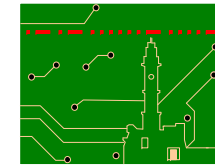
# Διάλεξη 2

Άγγελος Μπλέτσας

ΗΜΜΥ Πολυτεχνείου Κρήτης, Φθινόπωρο 2014
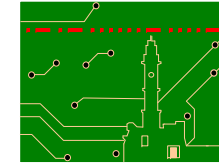
# Διάλεξη 2

Most Figures for today's lecture come from:
B. Razavi, RF Microelectronics, Prentice Hall
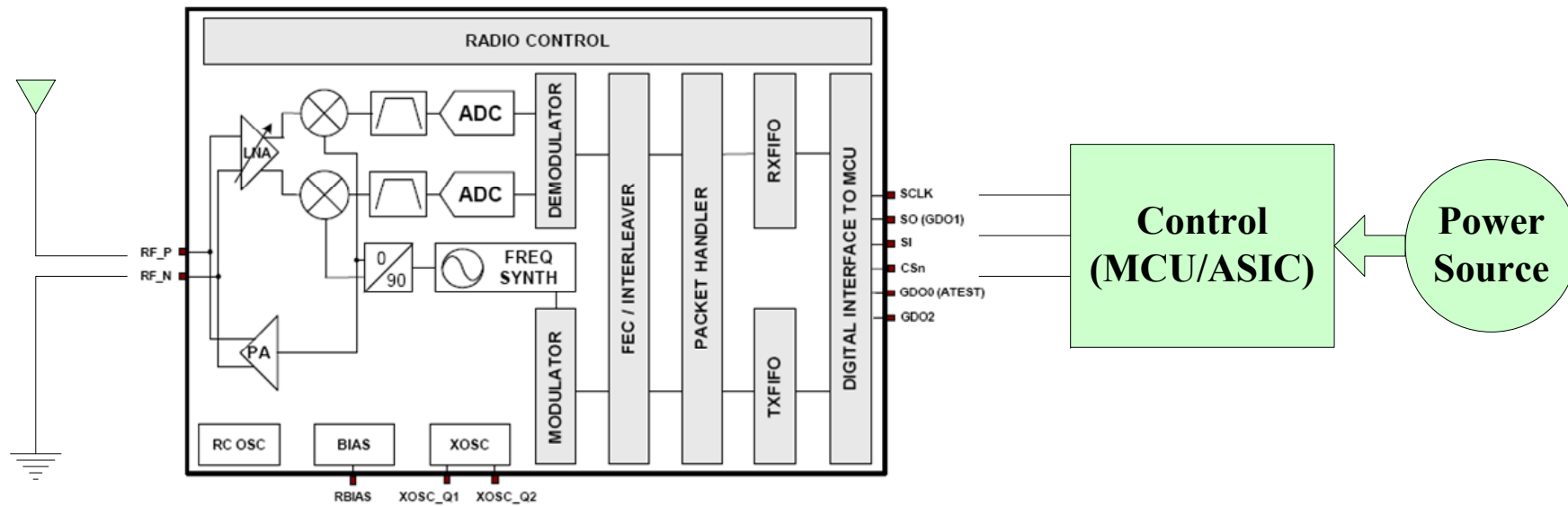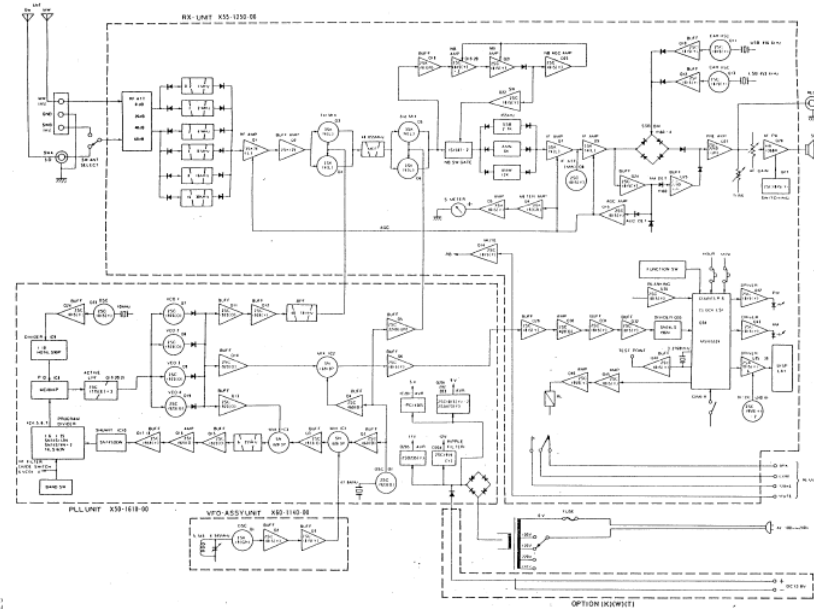1998.

# Intro: 90's Radio Receiver!
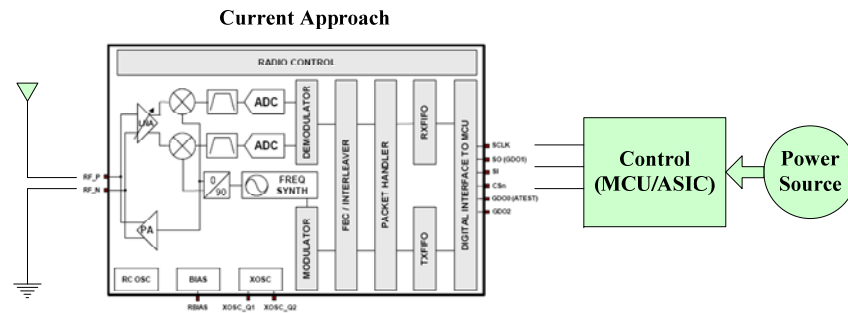
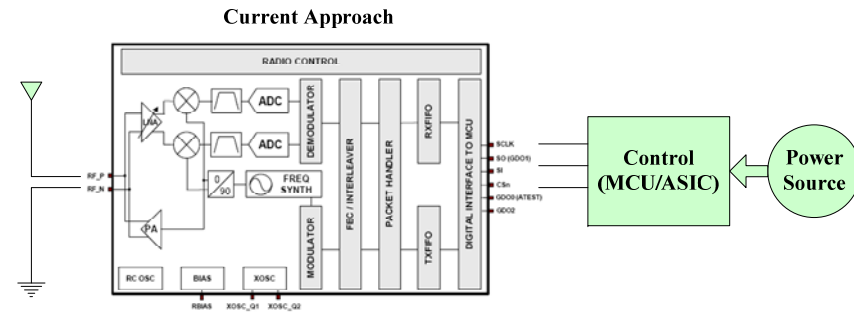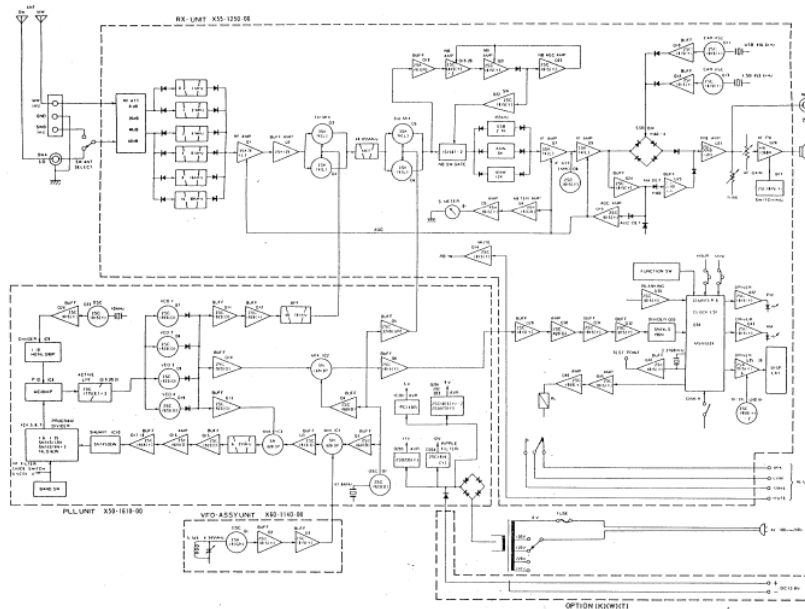# Intro: Radio Transceiver TODAY!

**Current Approach**
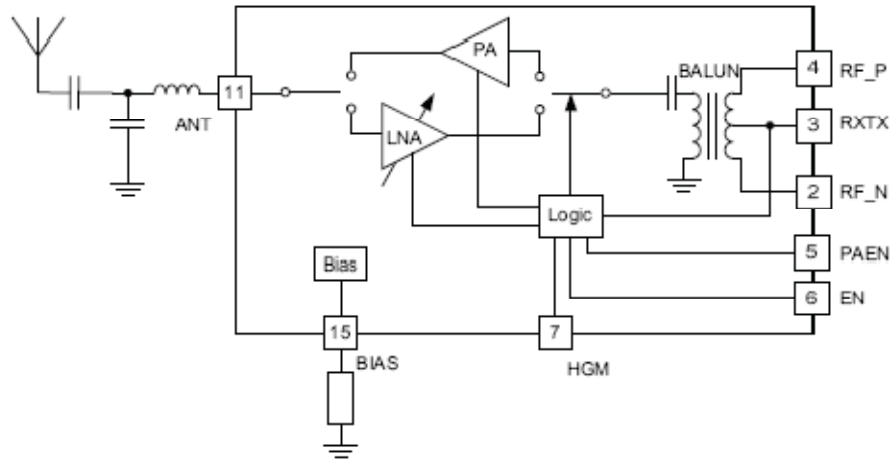
# Real systems = non-ideal!



- Real systems, no matter what generation, exhibit non-idealities.
- Such non-idealities are (should be) well documented!

# Real transceivers = non-ideal!



Current Approach

- Real systems, no matter what generation, exhibit non-idealities.
- Such non-idealities are (should be) well documented!

# Example



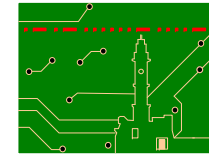| PARAMETER | TEST CONDITIONS | MIN | TYP | MAX | UNIT |
|---|---|---|---|---|---|
| Input IP3, High Gain Mode | HGM = 1 | | −9 | | dBm |
| Input reflection coefficient, S11 | HGM = 1, measured at antenna port | | −19 | | dB |
| RF Transmit | | | | | |
| Gain | | | 14.1 | | dB |
| Output power, P_OUT | P_IN = 4.5 dBm | | 13.8 | | dBm |
| | P_IN = 0.5 dBm | | 12.2 | | dBm |
| | P_IN = -3.5 dBm | | 10.0 | | dBm |
| Power Added Efficiency, PAE | P_IN = 0.5 dBm | | 23.5 | | % |
| Output 1 dB compression | | | 10.4 | | dBm |
| Output IP3 | | | 23 | | dBm |
| Output power variation over frequency | 2400 – 2483.5 MHz, P_IN = 0.5 dBm | | 0.3 | | dB |
| Output power variation over power supply | 2.0V – 3.6V , P_IN = 0.5 dBm | | 3.2 | | dB |
| Output power variation over temperature | -40°C – 85°C, P_IN = 0.5 dBm | | 1.1 | | dB |
| 2nd harmonic power | The 2nd harmonic can be reduced to below regulatory limits by using an external LC filter and antenna. See application note AN032 for regulatory requirements. | | −14 | | dBm |
| 3rd harmonic power | The 3rd harmonic can be reduced to below regulatory limits by using an external LC filter and antenna. See application note AN032 for regulatory requirements. | | −28 | | dBm |

# Περιεχόμενα Διάλεξης 2

Basic Unknown Concepts:

- Spectral Growth from LINEAR systems

- Gain Compression

- Desensitization

- Intermodulation Products and IP3

- Intro to Noise Figure (NF) – calculation of NF in next

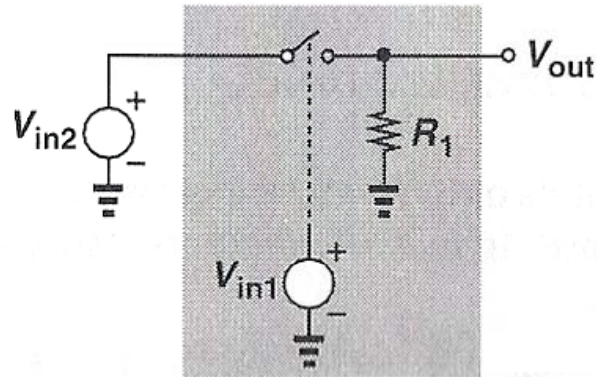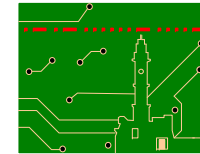lecture.

- Tradeoff between IP3 and NF
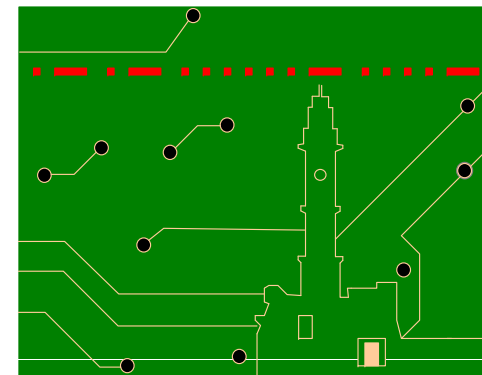
# Can a LINEAR system produce new freqs?
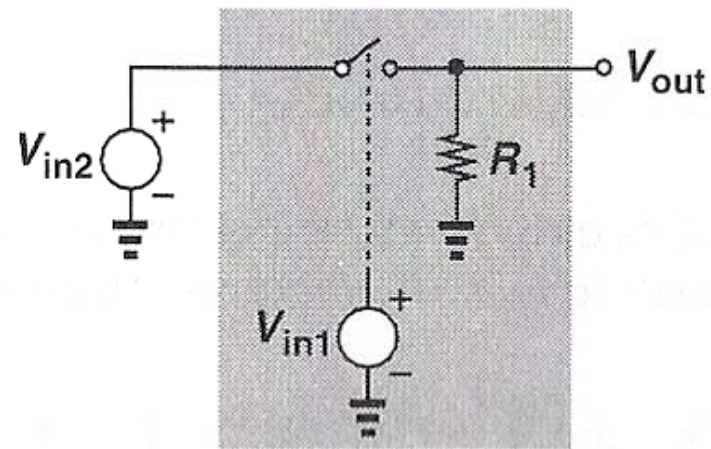


▪ Answer: YES, linear TIME-VARIANT systems, as the (sampling circuit) above!
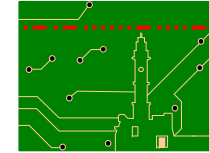
# Proof



$$V_{out}(f) = V_{in2}(f) * \sum_{n=-\infty}^{+\infty} \frac{\sin(n\pi/2)}{n\pi} \delta\left(f - \frac{n}{T_1}\right)$$

$$= \sum_{n=-\infty}^{+\infty} \frac{\sin(n\pi/2)}{n\pi} V_{in2}\left(f - \frac{n}{T_1}\right).$$
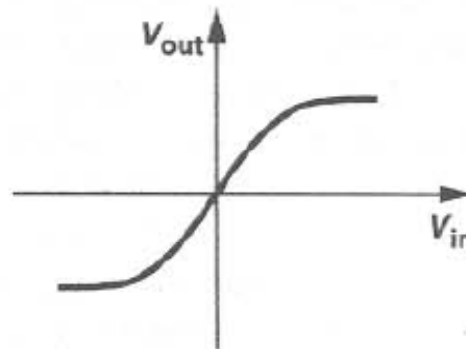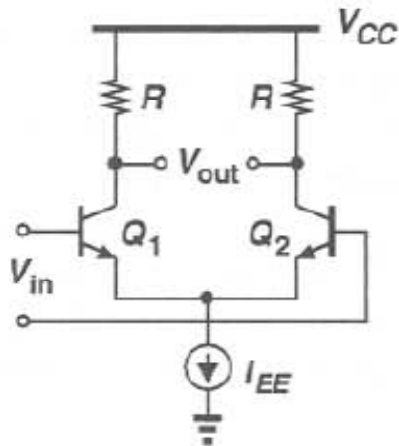
- Linear TIME-VARIANT systems: spectral growth.

- In this lecture, we focus on time <u>invariant</u> non-linearities.

10

# Today: non-linearity, its impact and quantification in time-INVARIANT systems

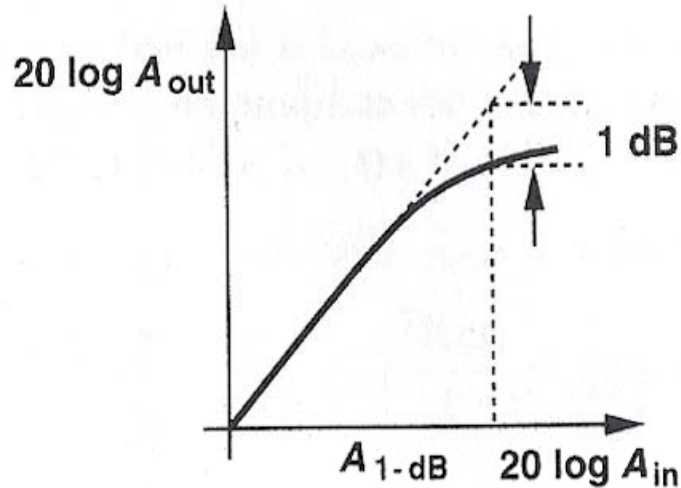$$y(t) = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) + \cdots,$$
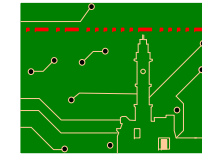
- assume $\{a_i\}$ time invariant (otherwise, system is time-variant)

- Special case: balanced systems.


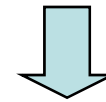
Balanced system = odd symmetry
⇔ $\alpha_j = 0$ for j even

$$v_{\text{out}} = R I_{EE} \tanh \frac{v_{\text{in}}}{2V_T}$$
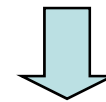
11

# Effects of non-linearity: Gain Compression

$$y(t) \approx \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$
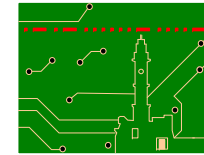
$$x(t) = A\cos\omega t.$$

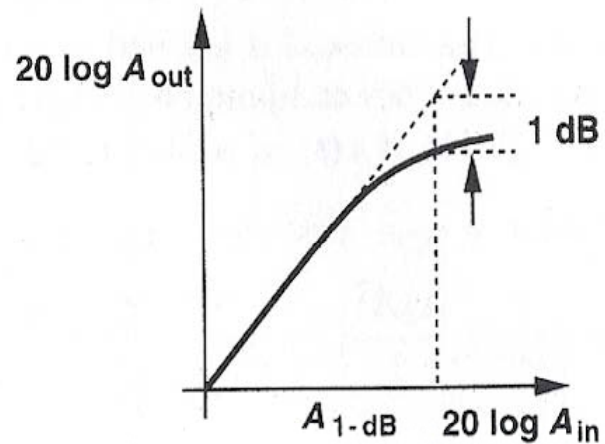$$y(t) = a_1 A\cos(\omega t) + a_2 A^2 \cos^2(\omega t) + a_3 A^3 \cos^3(\omega t)$$

$$= \frac{\alpha_2 A^2}{2} + \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right)\cos\omega t + \frac{\alpha_2 A^2}{2}\cos 2\omega t + \frac{\alpha_3 A^3}{4}\cos 3\omega t$$

- For A small (small signal model), term $\alpha_3 A^3$ negligible…

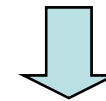- For A not small however and $\alpha_3$ negative, gain is compressed!

# Gain Compression

**Definition:** *Level of INPUT signal where the following holds:*
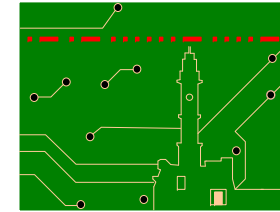


$$20 \log \left| \alpha_1 + \frac{3}{4} \alpha_3 A^2_{1\text{-dB}} \right| = 20 \log |\alpha_1| - 1 \text{ dB}$$

$$A_{1\text{-dB}} = \sqrt{0.145 \left| \frac{\alpha_1}{\alpha_3} \right|}.$$

- Measure of the maximum range of INPUT signal.

# Effects of non-linearity: Desensitization

▪ Desensitization: a strong <u>unwanted</u> signal at the input

decreases the desired signal output! [compare it with gain

compression]
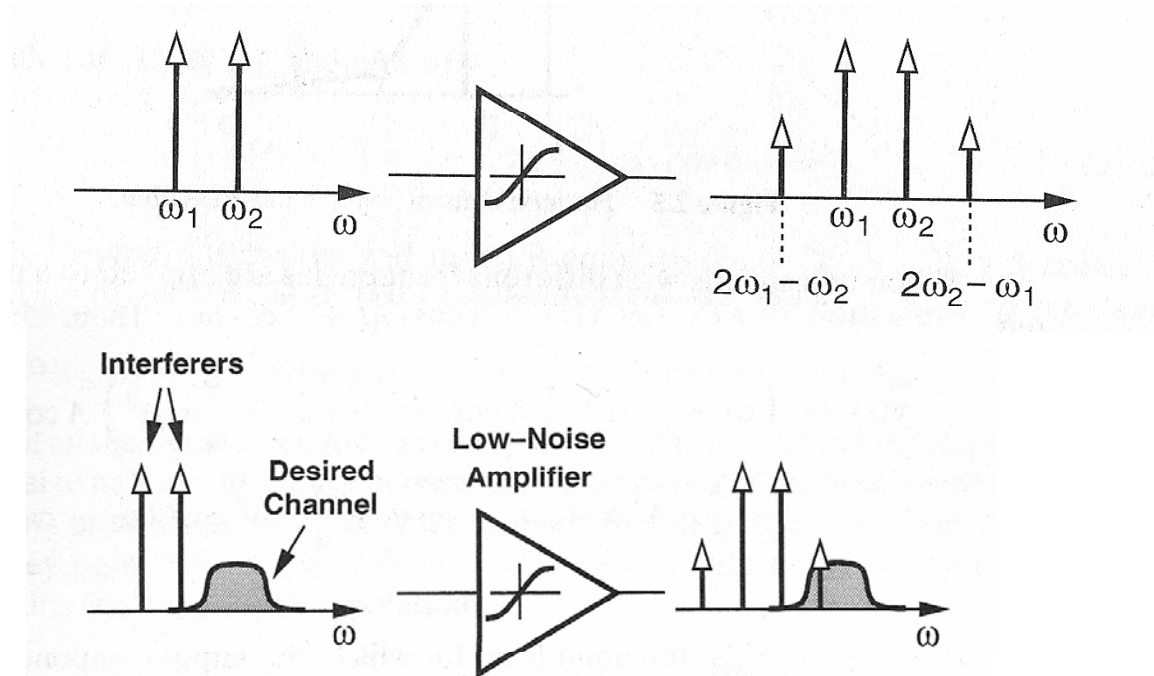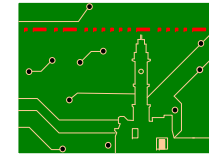
$$x(t) = A_1 \cos \omega_1 t + A_2 \cos \omega_2 t$$

$$y(t) = \left( \alpha_1 A_1 + \frac{3}{4} \alpha_3 A_1^3 + \frac{3}{2} \alpha_3 A_1 A_2^2 \right) \cos \omega_1 t + \cdots$$
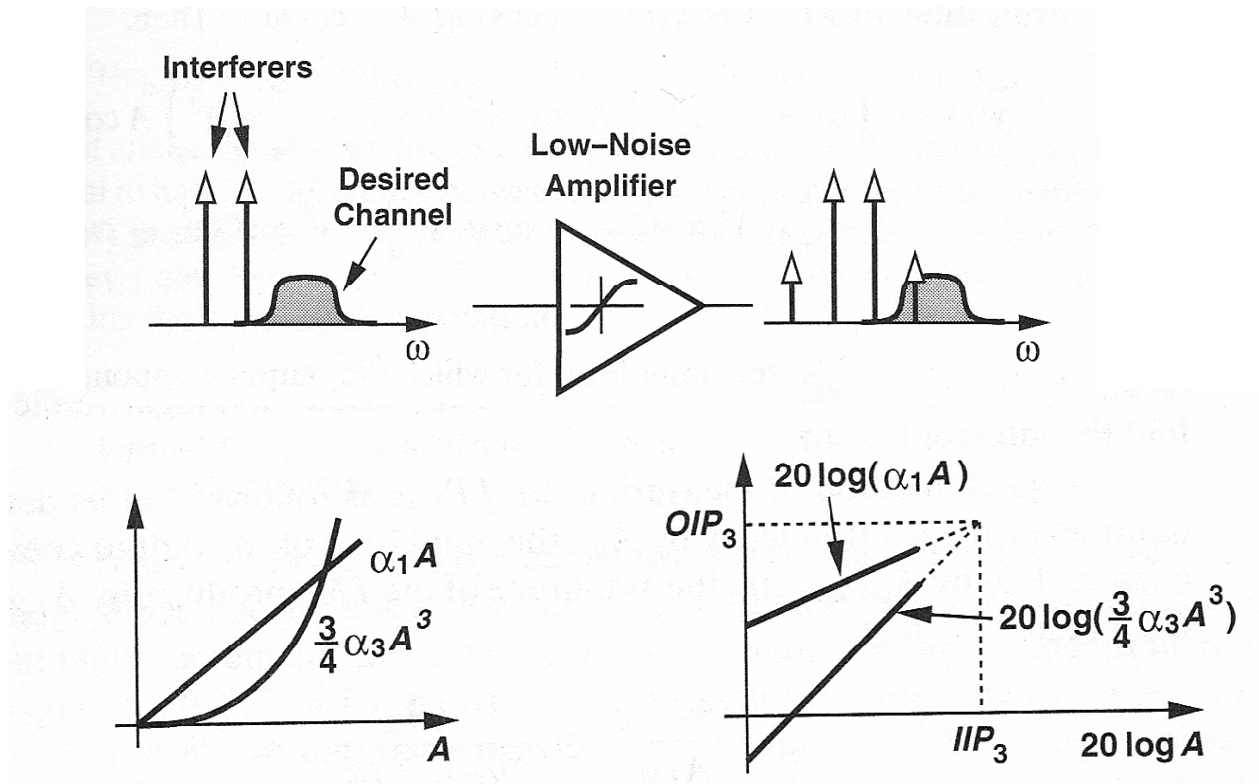
$$a_1 >> \frac{9}{4} a_3 A^2$$

$$y(t) = \left( \alpha_1 + \frac{3}{2} \alpha_3 A_2^2 \right) A_1 \cos \omega_1 t + \cdots$$

# Non-linearity: Intermodulation



- 3rd power term: if $\omega_1$-$\omega_2$ small, then intermodulation products in the vicinity of $\omega_1$ and $\omega_2$.

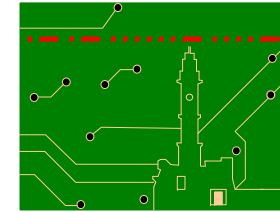- Odd power terms: exist in "balanced" systems (no even terms)!

# Non-linearity: Intermodulation
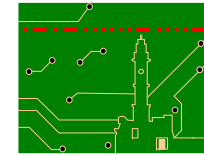


- Input and output 3rd intercept point (IIP3 and OIP3) quantify the nonlinearity due to 3rd power term.

# IP3 vs NF Tradeoff Preview
## (will be analyzed at the end of the lecture)

▪ IP3 of each stage is effectively scaled down by total gain preceding that stage => latter stages become more critical…

▪ NF: Friss equation indicates that the noise contributed by each stage decreases as the gain preceding the stage increases => first stages are the most critical…

▪ NF: if a stage exhibits attenuation, then the noise figure of the following circuit is amplified!

# IP3 vs NF Tradeoff Preview
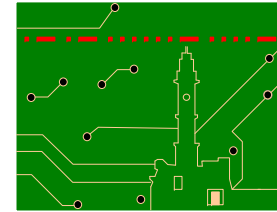
- roughly, greater gain =>smaller NF but also smaller IP3!

# Non-linearity: Intermodulation (1ˢᵗ calc. way)
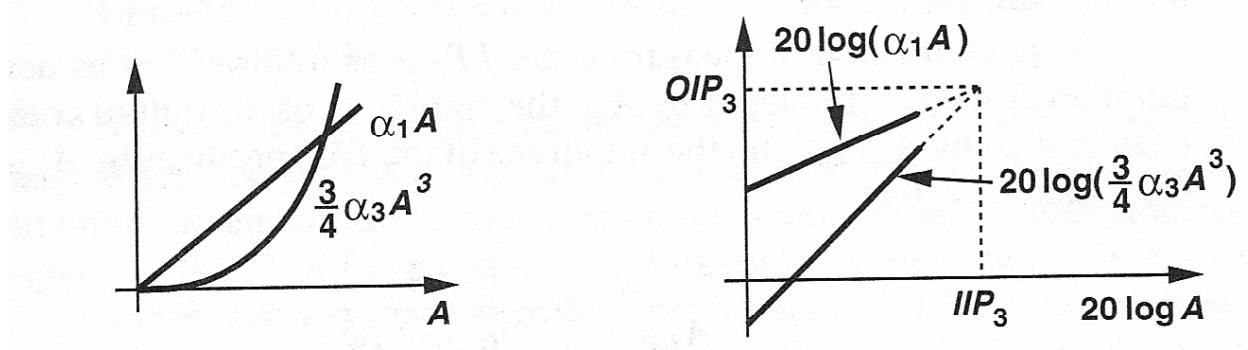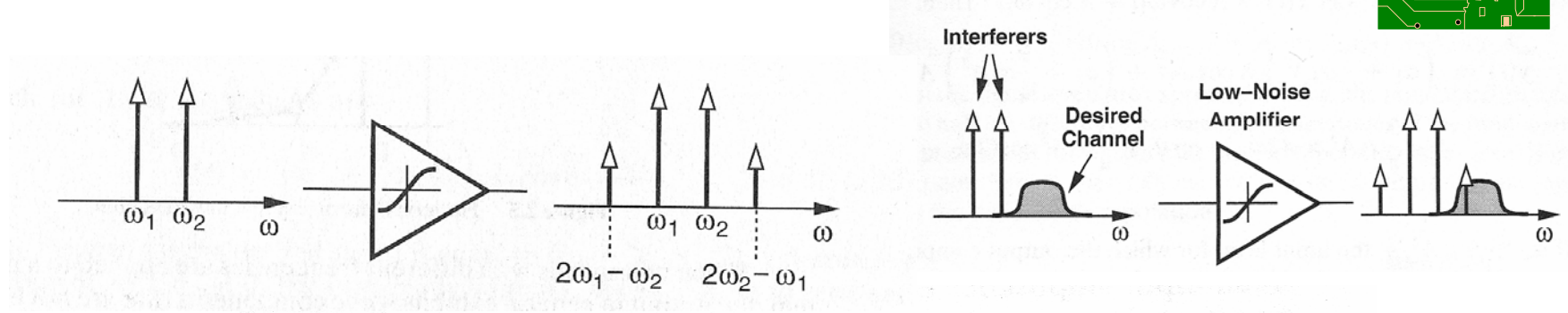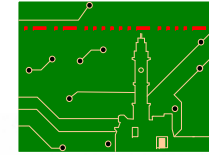


- Input and output 3ʳᵈ intercept point (IIP3 and OIP3) quantify the nonlinearity due to 3ʳᵈ power term.

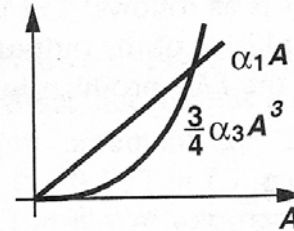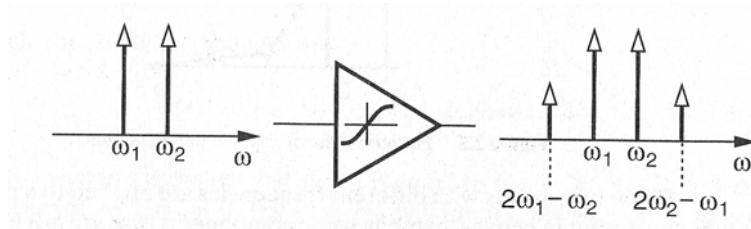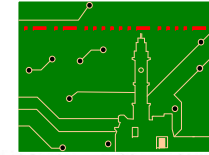- 3rd power term: if $\omega_1 - \omega_2$ small, then intermodulation products in the vicinity of $\omega_1$ and $\omega_2$.

- Odd power terms: exist in "balanced" systems (no even terms)!

# Non-linearity: Intermodulation (1ˢᵗ calc. way)
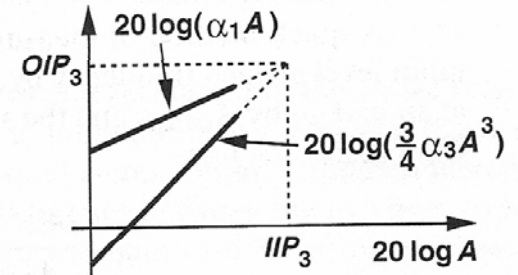
$$x(t) = A\cos(\omega_1 t) + A\cos(\omega_2 t) \Rightarrow$$

$$y(t) = a_1 x(t) + a_2 x^2(t) + a_3 x^3(t) =$$

$$= \left(a_1 + \frac{9}{4}a_3 A^2\right)A\cos(\omega_1 t) + \left(a_1 + \frac{9}{4}a_3 A^2\right)A\cos(\omega_2 t) +$$

$$+ \frac{3}{4}a_3 A^3 \cos((2\omega_1 - \omega_2)t) + \frac{3}{4}a_3 A^3 \cos((2\omega_2 - \omega_1)t) + ...$$

$$a_1 \gg \frac{9}{4}a_3 A^2 \Rightarrow |a_1| A_{IP3} = \frac{3}{4}|a_3| A_{IP3}^3 \Rightarrow A_{IP3} = \sqrt{\frac{4}{3}\frac{|a_1|}{|a_3|}}$$

# Non-linearity: Intermodulation (1ˢᵗ calc. way)
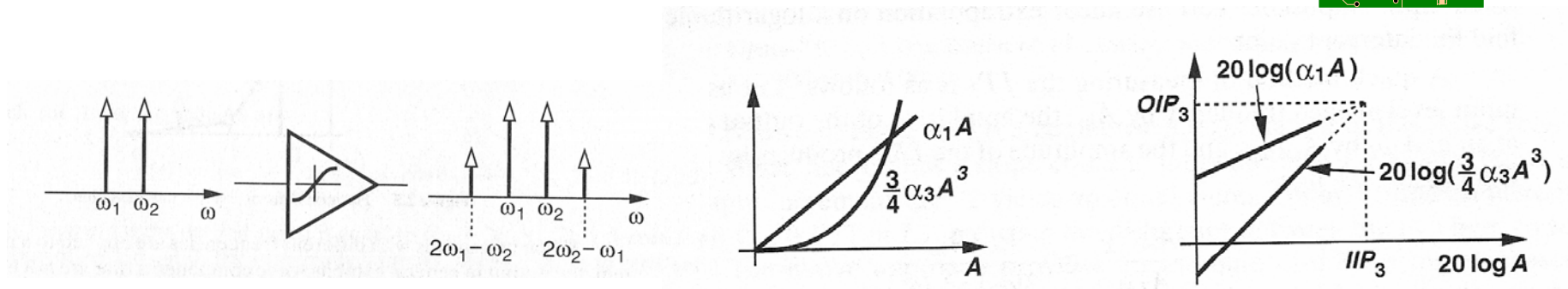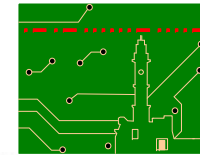


$$|a_1| >> \frac{9}{4}|a_3|A^2 \Rightarrow |a_1|A_{IP3} = \frac{3}{4}|a_3|A_{IP3}^3 \Rightarrow A_{IP3} = \sqrt{\frac{4}{3}\frac{|a_1|}{|a_3|}}$$

- Calculated at the input of the system (e.g. LNA): input IP3…

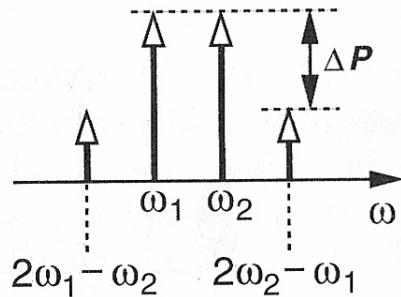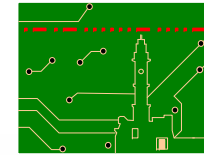- Calculated at the output of the system (e.g. PA): output IP3…

- Drawback of this method: IP3 is well beyond allowable input (e.g. supply voltage)

- Solution: extrapolation (2ⁿᵈ calc. way)

# Non-linearity: Intermodulation (2<sup>nd</sup> calc. way)

$$IIP_3\Big|_{dBm} = \frac{\Delta P\big|_{dB}}{2} + P_{in}\big|_{dBm}$$

$$\frac{A_{\omega1,\omega2}}{A_{IM3}} \approx \frac{|a_1|A_{in}}{3|a_3|A_{in}^3/4} = \frac{A_{IP3}^2}{A_{in}^2} \quad \Longleftrightarrow$$

$$20\log A_{IP3} = \frac{1}{2}(20\log A_{\omega1,\omega2} - 20\log A_{IM3}) + 20\log A_{in}$$
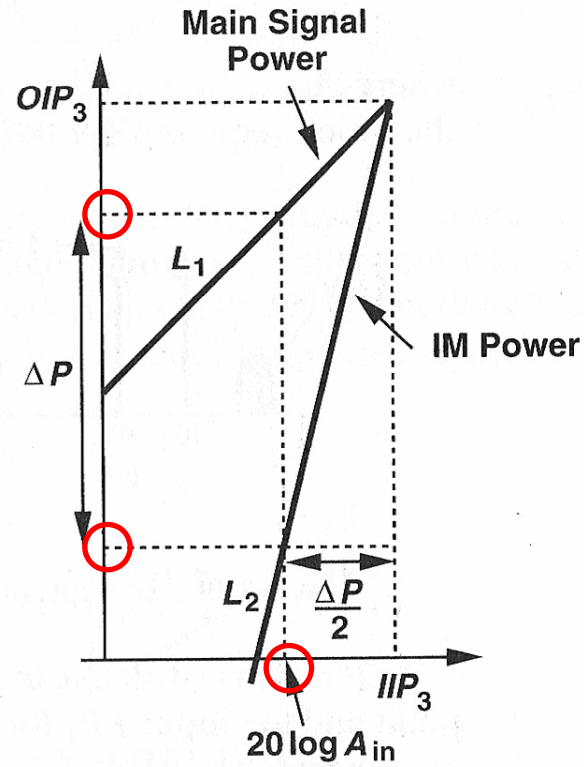
# Intermodulation of Cascaded Systems
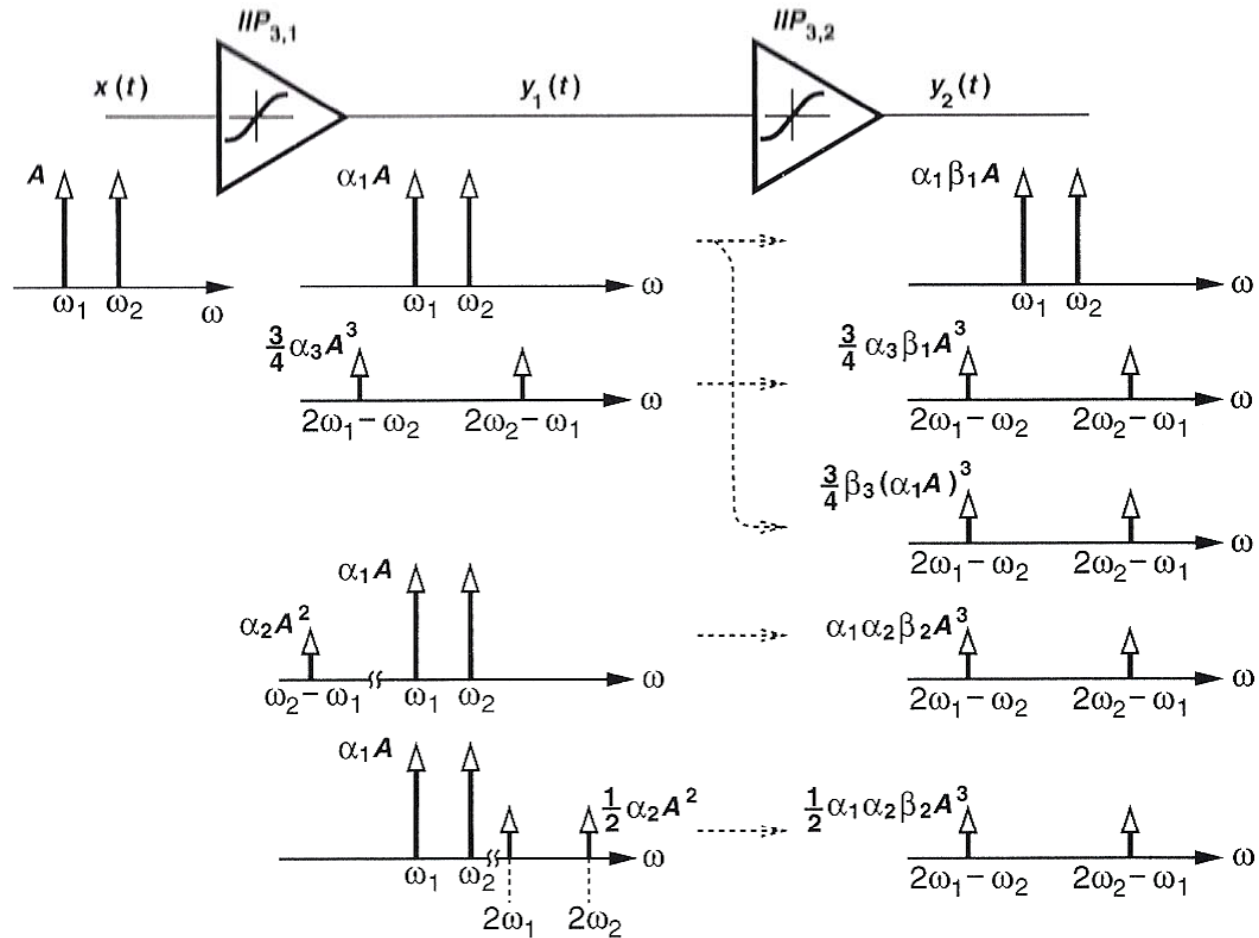


- IP3 calculation for multiple stages (cascade).

- Last products can be omitted in narrowband systems.

# Intermodulation: Cascaded Systems?

$$y_1(t) = \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

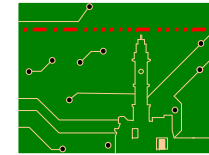$$y_2(t) = \beta_1 y_1(t) + \beta_2 y_1^2(t) + \beta_3 y_1^3(t),$$

$$y_2(t) = \beta_1[\alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)]$$
$$+ \beta_2[\alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)]^2$$
$$+ \beta_3[\alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)]^3$$

$$y_2(t) = \alpha_1 \beta_1 x(t) + (\alpha_3 \beta_1 + 2\alpha_1 \alpha_2 \beta_2 + \alpha_1^3 \beta_3)x^3(t) + \cdots.$$

$$A_{IP3} = \sqrt{\frac{4}{3} \left| \frac{\alpha_1 \beta_1}{\alpha_3 \beta_1 + 2\alpha_1 \alpha_2 \beta_2 + \alpha_1^3 \beta_3} \right|}$$

- IP3 calculation for multiple stages (cascade).

# Intermodulation: Cascaded Systems?

$$A_{IP3} = \sqrt{\frac{4}{3} \left| \frac{\alpha_1 \beta_1}{\alpha_3 \beta_1 + 2\alpha_1 \alpha_2 \beta_2 + \alpha_1^3 \beta_3} \right|}$$
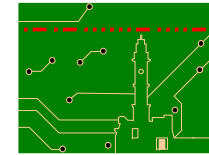
$$\frac{1}{A_{IP3}^2} = \frac{3}{4} \frac{|\alpha_3 \beta_1| + |2\alpha_1 \alpha_2 \beta_2| + |\alpha_1^3 \beta_3|}{|\alpha_1 \beta_1|}$$

$$= \frac{1}{A_{IP3,1}^2} + \frac{3\alpha_2 \beta_2}{2\beta_1} + \frac{\alpha_1^2}{A_{IP3,2}^2},$$

$$\frac{1}{A_{IP3}^2} \approx \frac{1}{A_{IP3,1}^2} + \frac{\alpha_1^2}{A_{IP3,2}^2}$$
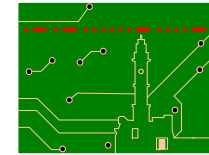
# Intermodulation: Cascaded Systems?

$$\frac{1}{A_{IP3}^2} \approx \frac{1}{A_{IP3,1}^2} + \frac{\alpha_1^2}{A_{IP3,2}^2} + \frac{\alpha_1^2 \beta_1^2}{A_{IP3,3}^2} + \cdots,$$

- Approximate IP3 calculation for multiple stages (cascade).

-  Gain higher than unity scales down IP3 of later stage =>

- …scales down overall IP3 =>

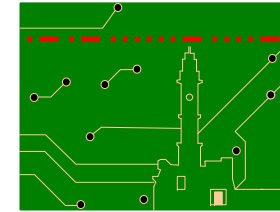- …later stages must have higher IP3 => they become increasingly important!

# Noise Figure

$$\text{noise figure} = \frac{SNR_{\text{in}}}{SNR_{\text{out}}}$$

- Noiseless system (ideal) => NF = 1 (0 dB).

- Noise Figure of Cascaded Systems (Friis eq.):

$$NF_{\text{tot}} = 1 + (NF_1 - 1) + \frac{NF_2 - 1}{A_{p1}} + \cdots + \frac{NF_m - 1}{A_{p1} \cdots A_{p(m-1)}}$$

- NF of a stage decreases with gain of preceding stage =>

- …initial stages are the most (NF)-critical!

# Summary

- IP3 of each stage is effectively scaled down by total gain preceding that stage => latter stages become more critical…


- NF: Friss equation indicates that the noise contributed by each stage decreases as the gain preceding the stage increases => first stages are the most critical…

- NF: if a stage exhibits attenuation, then the noise figure of the following circuit is amplified!

# IP3 vs NF tradeoff!
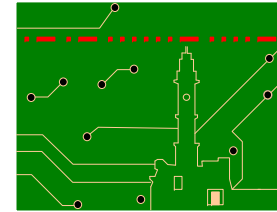
- roughly, greater gain =>smaller NF but also smaller IP3!

# Ερωτήσεις?