Linear networks analysis

- For microwave linear networks analysis is performed in frequency domain.
- The analysis is based on the evaluation of the scattering matrix of the n-port network
- From S matrix all other network functions can be obtained (<u>only ratios</u>, not voltage or current values)
- Using commercial simulators, the network topology is specified via a graphical interface.
- Active components are characterized by means of the measured S parameters with the devices suitably biased. The linearized model is meaningful only for signals with very small amplitude
- In general, a linear device can be characterized either through an analytical model (defining its linear behavior) or using the scattering parameters (derived from simulations or computed analytically)

Format of S parameters data file

Format: text file
Header line: describes the format of the parameters

Header Portion	Description
#	Signifies the beginning of the header.
HZ | KHZ | MHZ | GHZ | THZ	Specifies the frequency units of the data file (choose one).
G | H | S | Y | Z	Specifies the parameter type of the data file (choose one).
MA | DB | RI	Specifies how the complex data are presented (choose one).
[R x]	x is a real number that specifies the reference impedance (optional).

- Following lines: freq, Sa_{ij},Sb_{ij} (use row major order, except for 2-port matrices which are in colum major order)
- Each line may contain a maximum of four network parameters (8 real numbers). If the matrix contains more than four network parameters per row (it is larger than a four-port), the remaining network parameters are continued on the following line.
- The "!" character is used for comments, which may be inserted anywhere in the data file. Comments persist until the end of the line.

Example of data file (ext. S2p)

```
! Vce=8V, Ic=25 mA
# MHZ S MA R
!   FREQ       mag(S11)  phase(S11)  mag(S21)  phase(S21)  mag(S12)  phase(S12)  mag(S22)  phase(S22)
!----------------------------------------------------------------------------------------------------
 100.0        0.630     -50.000      39.080    146.000      0.010     83.000      0.840    -18.000
 200.0        0.558     -74.924      31.740    132.543      0.015     75.553      0.738    -20.497
 300.0        0.491     -98.579      24.825    119.768      0.019     68.784      0.644    -22.796
 400.0        0.433    -119.694      18.760    108.360      0.023     63.374      0.562    -24.696
 500.0        0.390    -137.000      13.970     99.000      0.027     60.000      0.500    -26.000
 600.0        0.364    -149.620      10.747     92.157      0.030     59.099      0.462    -26.583
 700.0        0.353    -158.245       8.845     87.441      0.034     60.131      0.445    -26.623
 800.0        0.351    -163.960       7.886     84.247      0.037     62.313      0.441    -26.371
 900.0        0.355    -167.851       7.490     81.968      0.040     64.864      0.445    -26.079
 1.000E+03       0.360    -171.000       7.280     80.000      0.044     67.000      0.450    -26.000
 1.100E+03       0.362    -174.296       6.950     77.853      0.048     68.114      0.451    -26.325
 1.200E+03       0.362    -177.840       6.488     75.495      0.053     68.301      0.448    -27.000
 1.300E+03       0.361     178.464       5.957     73.011      0.058     67.831      0.443    -27.914
 1.400E+03       0.360     174.712       5.421     70.485      0.063     66.974      0.436    -28.951
 1.500E+03       0.360     171.000       4.940     68.000      0.067     66.000      0.430    -30.000
 1.600E+03       0.362     167.421       4.564     65.632      0.071     65.132      0.425    -30.967
 1.700E+03       0.365     164.055       4.282     63.419      0.074     64.408      0.420    -31.840
 1.800E+03       0.370     160.978       4.070     61.390      0.077     63.817      0.417    -32.631
 1.900E+03       0.375     158.268       3.904     59.574      0.080     63.351      0.413    -33.347
 2.000E+03       0.380     156.000       3.760     58.000      0.083     63.000      0.410    -34.000

! Noise Parameters
1000.0 1.3 .05 28 .17
2000.0 1.7 .3 -154 .16
```

Additional information

Methods for analyzing non linear networks

- Time domain solution (*Transient* e *Convolution*). Noticeable computation power is requested; it is rarely employed for RF circuits (oscillators start-up process, very fast digital circuits, pulse excitations)
- Harmonic Balance (*Harmonic Balance).* It is suitable when the circuit is excited with a combination of not harmonically related sinusoids (tones), each with a specified number of harmonics. Typically the number of tones is limited (<3).
- Envelope method (*Circuit Envelope).* It is convenient with the excitations are constituted by RF modulated signals with a non periodic envelope. (typically digital modulations)

Note that Harmonic Balance is a frequency domain solver, which determines the regime solution (i.e. when the transient is finished); the Circuit Envelope is a mixed method: the solution concerning the carrier discard the transient, which is taken into account for the envelope (having a bandwidth much smaller than the carrier)

Time domain analysis

The system of differential equations characterizing the network are integrated in the time domain.It is then necessary that all the components parameters are independent on frequency.

Problematic when applied to microwave circuits:

- Losses in distributed components are frequency dependent
- Very often must be considered devices characterized by the measured S parameters vs. frequency

Solution adopted in most sophisticated commercial simulators (ADS):
For the components with parameters depending on frequency, the impulse response is first numerically evaluated separately; the convolution is then employed for combining the component with the rest of the network

Harmonic Balance

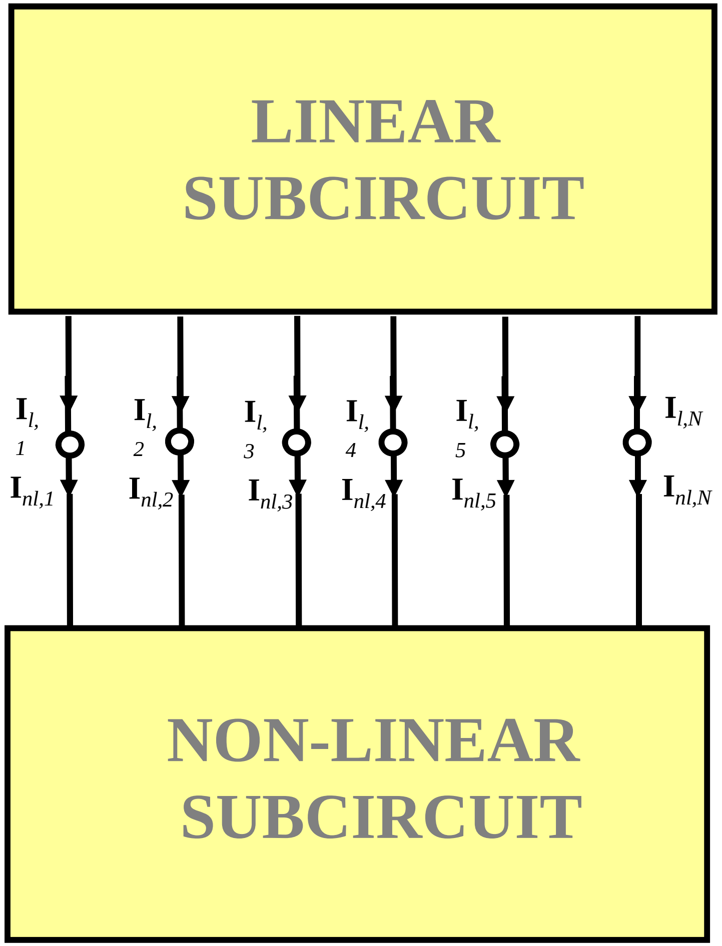
- It allows to solve circuits with non linear components under multi-tone sinusoidal excitation. The solution discards the transient (regime solution)
- Excitation is constituted by periodic sinusoidal signals at arbitrary frequency (tones) not harmonically related, each with a specified number of harmonics
- Modulated signals with a periodic envelope (QPSK, BPSK, GSM, CDMA, ecc) can be approximated with a suitable number of tones and harmonics
- The solution is computationally more expensive of linear analysis but much less than time domain

Frequencies of analysis

- The basic units are the ***tones***, *i.e* sinusoids with specified frequency, amplitude and phase
- *MWOffice* allows up to 8 tones with arbitrary frequency.
- To each tone is associated a specified number of harmonics. The higher is the harmonics number:
  - The better is the modeling of non linearity
  - The higher is the computation time

- When more than 1 tone is used, analysis is performed at all the specified harmonics (nf_1, mf_2,…) and at all the intermodulation frequencies: $\pm mf_1 \pm nf_2 \pm gf_3 \pm ....$ Once the maximum number of harmonics for each tone (*M, N, G* ...) is assigned, the overall number of frequency analysis may reach a very large value. It is however possible to limit the max intermodulation order

Evaluation of the solution (1)



The overall circuit is divided into two sub-network:

The linear sub-circuit includes all the linear components

The non-linear sub-circuit includes all the non-linear elements (also the sources)

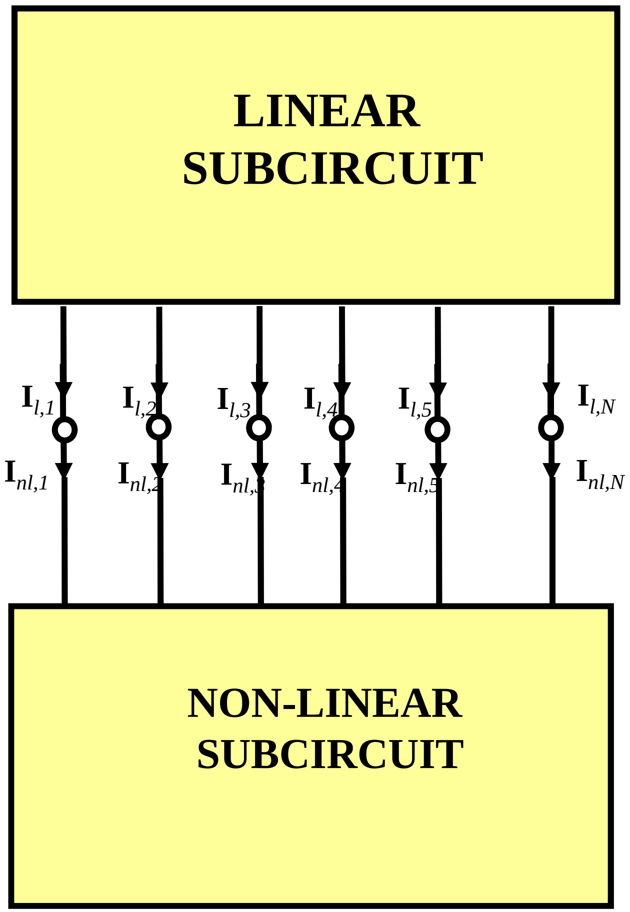
At each common node there are N_{tot} voltage and current phasors

N_{tot} is the overall number of sinusoidal frequencies considered in the analysis

Evaluation of the solution (2)

If all the voltage phasors at each node and analysis frequency would be known at the interface of the two sub-circuits:

- The currents $I_{l,k}$ from the linear sub-circuit can be computed through the admittance matrix **Y**.
- The currents $I_{nl,k}$ from the non linear sub-circuit can be computed in the time domain using the time varying voltages at each node obtained through FFT (tones & harmonics)
- If the voltage phasors at each node is correct, the difference $|I_{l,k} - I_{nl,k}|$ must vanish
- The amplitude and phase of each phasor is then obtained through numerical optimization, by imposing the previous condition



Parameters affecting the solution

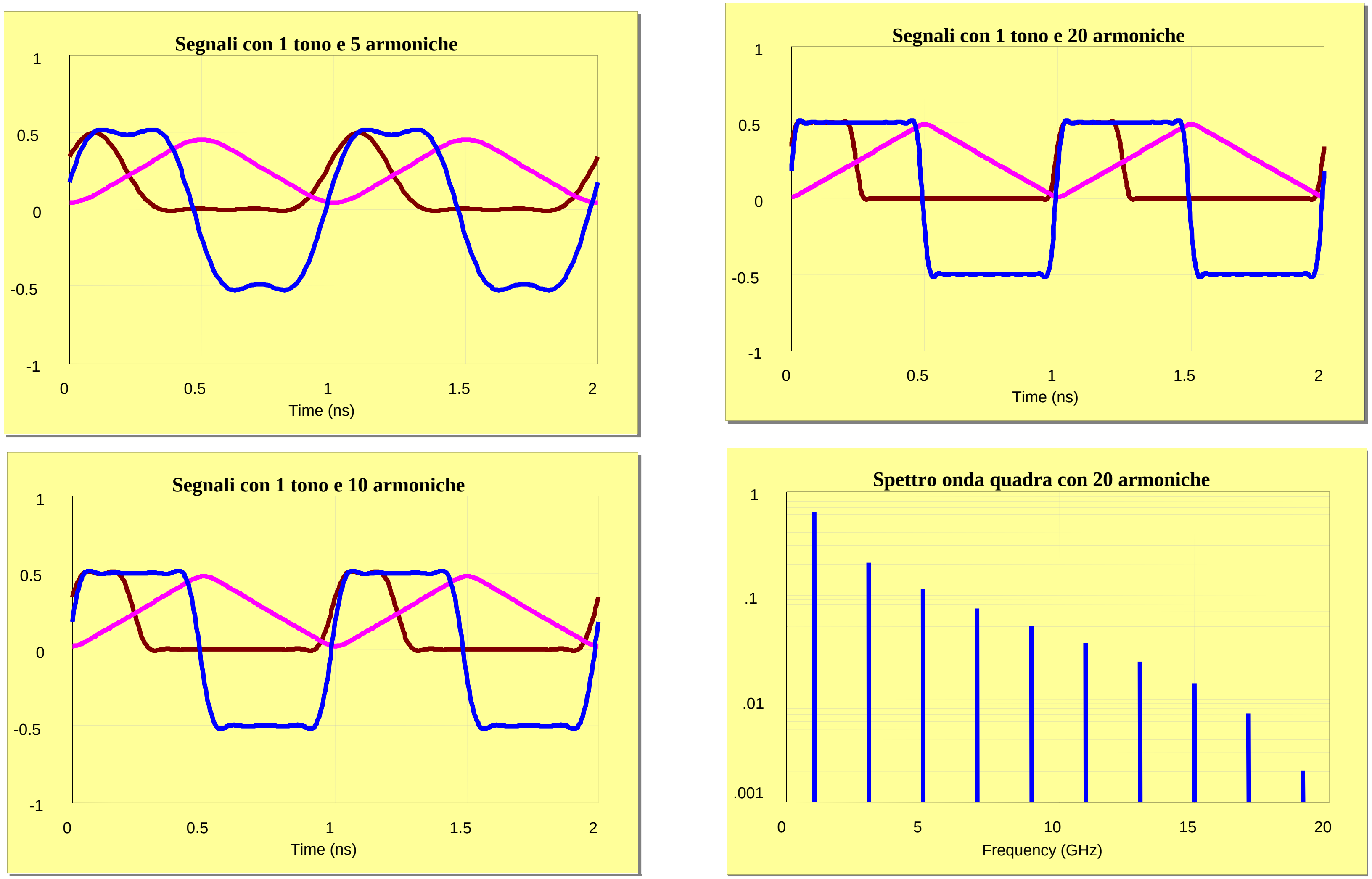
- Number of harmonics for each tone
- Order of intermodulation terms
- Parameters controlling the numerical optimization
- Amplitude of sources (power excitation)
- *Source Stepping*: the solution is found in subsequent steps, by increasing at each step the amplitude of exciting sources (the non linearities are little involved at the start of the solution search)

Signal representation (1)

Single tone source

- Sinusoid with given amplitude and phase. The number of harmonics affect the accuracy of the circuit response in presence of non linerities
- Periodic signal of defined shape (square wave, triangular wave, etc.); the amplitude and phase of the harmonics is defined by the Fourier serie coefficients (the finite number of harmonics limits the accuracy).
- Periodic signal arbitrarily defined (amplitude and phase specified through a data file)

Examples of 1 tone signals

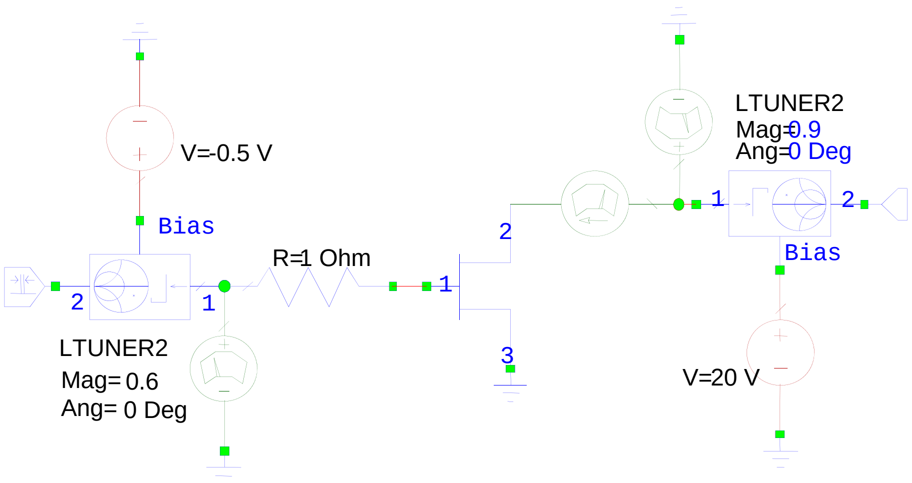


Signal representation (2)

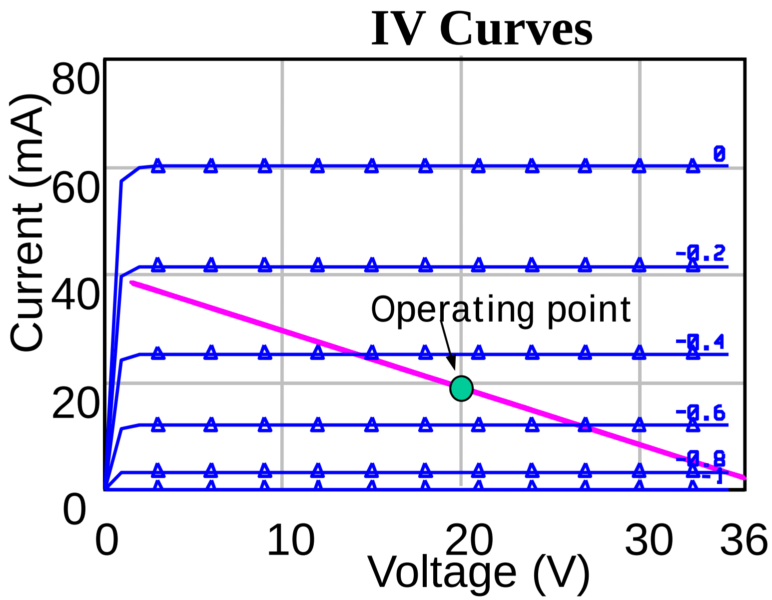
2-tone signals

- Amplitude and phase arbitrarily defined. In addition to the number of harmonics of each tone, also the max order of intermodulation terms must be specified
- When the two tones have the same amplitude, the simplest RF signal is generated: carrier at the mean frequency and variable envelope (3 dB peak factor). It represents a test signal for evaluating the non lineaar behavior of amplifiers.

Example of use of a 2-tone signal



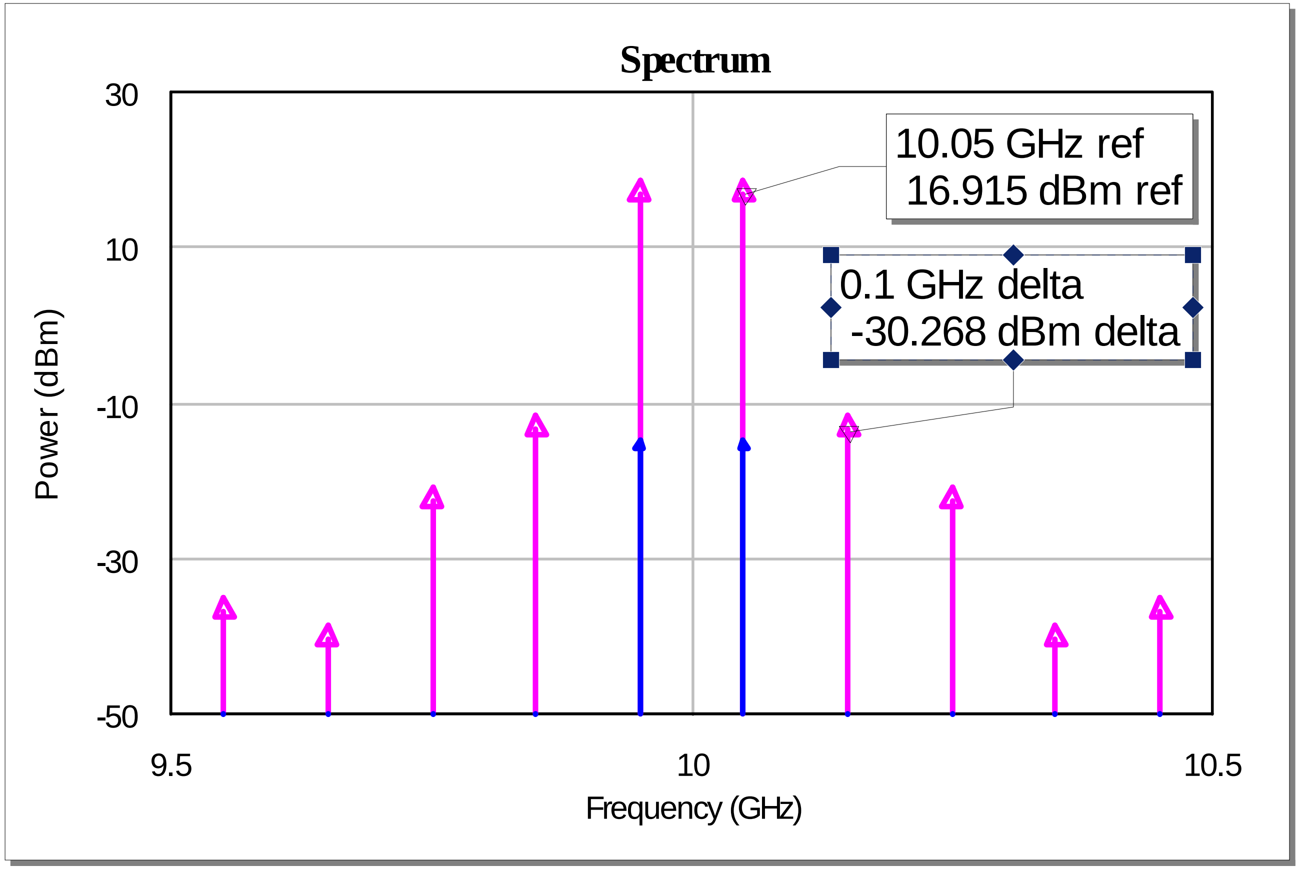
PA scheme



Dynamic load line

Bias: V_{ds}=20V, I_d=19 mA (P_{DC}=380 mW)
Pin=-17.8 dBm (per tono), Pout=16.9 dBm (per tone)
PAE=25.6%

Spectrum of input and output signals



GT=34.7 dB

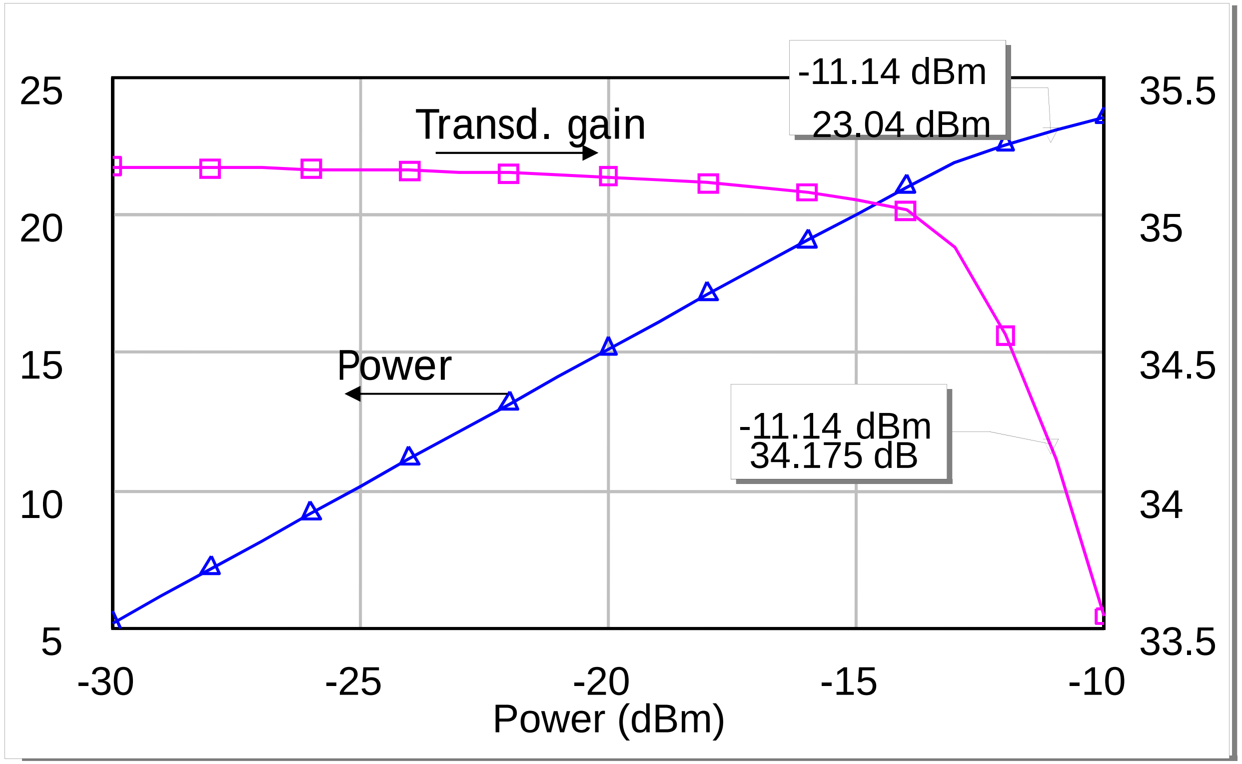
CI=30.3 dB

IP_3=32 dBm

Numbebr of harmonics per tone: 5

Max order of intermodulation products: 9

Evaluation of P1dB (1 tone)



From the graph: P_{1dB}=23.04 dBm.

Note that Δ_p=32-23 ≈ 9 dB. The amplifier works with BO≈3 dB.

Representation of modulated signals

Analytical representation of a RF signal phase and amplitude modulated (radian frequency ω_o)

$$V_{RF} = V_M(t)\cos(\omega_0 t + \Phi(t))$$

Phase notation:

$$V_{RF} = V_M(t)e^{i(\omega_0 t + \Phi(t))} = V_M(t)e^{i(\Phi(t))}e^{i(\omega_0 t)} = \bar{V}_M e^{i(\omega_0 t)}$$

V_M rapresents the complex base band equivalent of the modulating signal. If its spectrum is much smaller than the carrier frequency ($B_W \ll f_0$), it can be approximated with a periodic signal defined by N harmonics of $\Delta f = B_W / N$.

In Harmonics Balance an RF signal can be represented with a 2-tone signal:

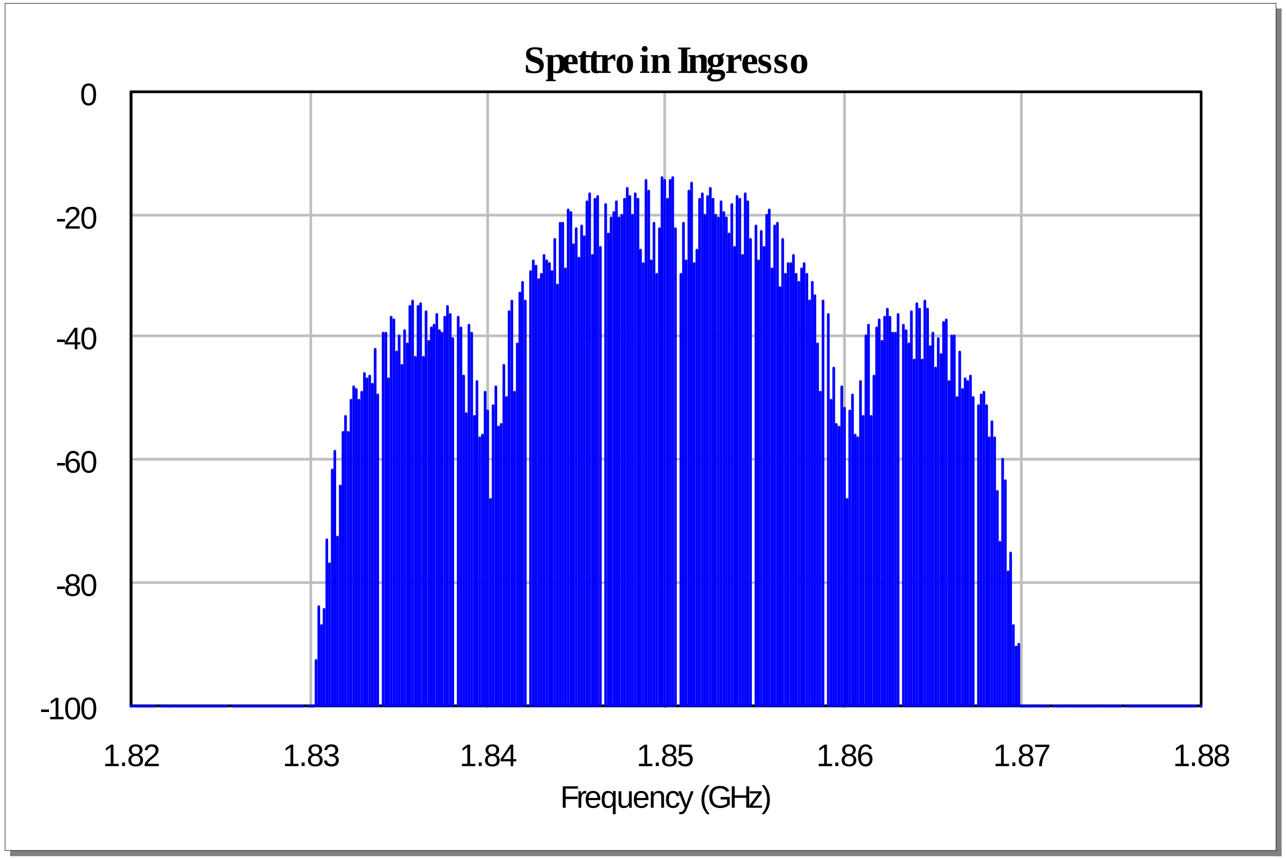
- The first tone is associated to the carrier (with few harmonics, 1-2 are enough)
- The second tone, equal to Δf, needs all the N harmonics with phase and amplitude requested by representing the complex base band equivalent V_M (are generally specified in a data file)

Example of a modulated RF signal

<u>BPSK signal:</u>

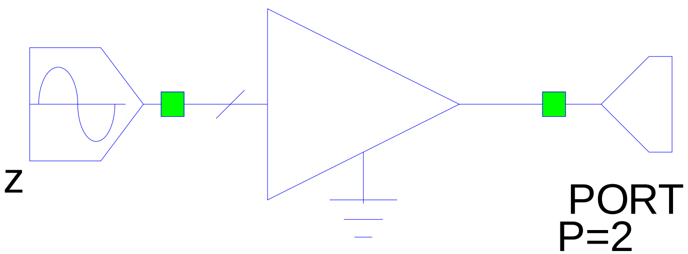
Bitrate=10MBit/sec (256 harmonics) Carrier at 1.85 GHz, P_{av} = 0 dBm

(Δf=156.25 KHz)



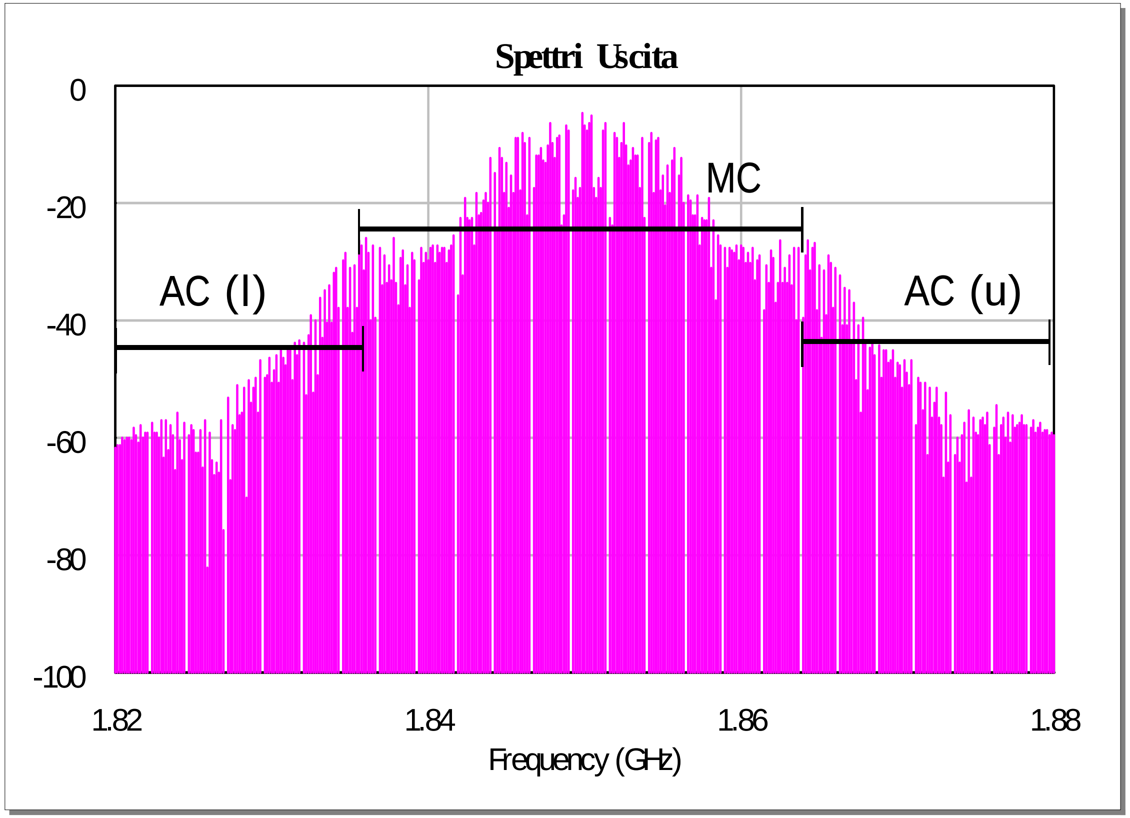
Amplified RF signal

Signal represented in HB:
Tone 1: f_0=1.85 GH,2 harmonics
Tone 2: Δf=156.25 KHz, 256 harm.



Amplifier: G=10 dB, P_{1dB}=14.5 dBm

Output spectrum



Main Channel =30 MHz
Adjacent Channels = 15 MHz

Total Power: 8.4 dBm
Power in MC: 8.4 dBm
Power in ACu: -21.2 dBm
Power in ACl: -21.4 dBm

ACPR(u): 29.7 dBm
ACPR(l): 29.8 dBm