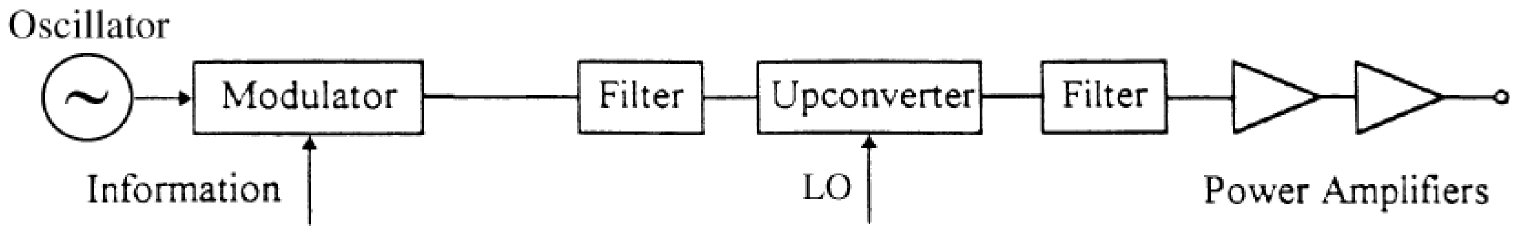
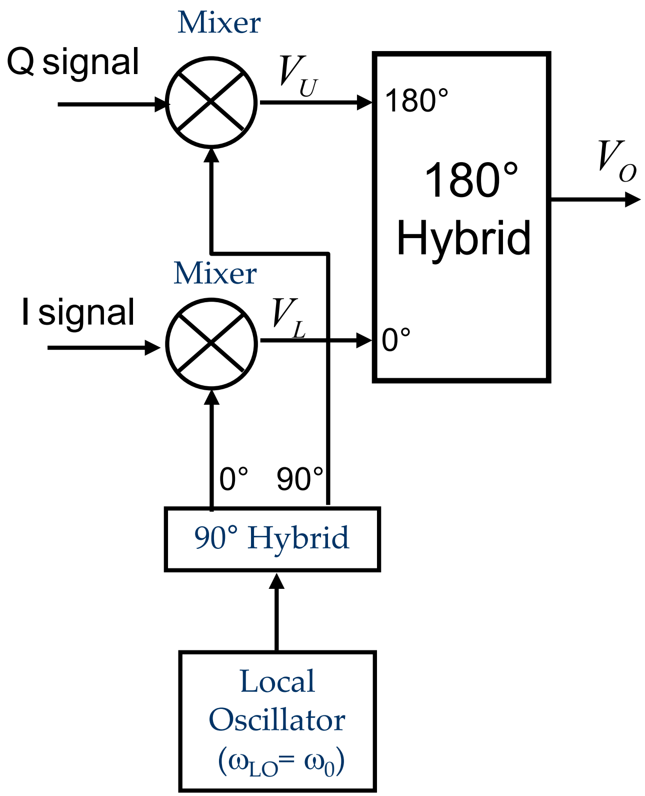
Transmitter

General configuration



- In some cases the modulator operates directly at the transmission frequency (no up conversion required)
- In digital transmitters, the information is represented by the I and Q signals); the modulator combines these baseband signals into a phase and amplitude modulated signal
- Transmitter and receiver in a transceiver share part of the hardware (e.g. local oscillators)

Modulator for digital signals



$$V_U = -kV_{OL}V_Q(t)\sin(\omega_0 t)$$

$$V_L = kV_{OL}V_I(t)\cos(\omega_0 t)$$

$$V_0 = -V_U + V_L =$$

$$= \frac{k}{\sqrt{2}}V_{OL}\left(V_Q(t)\sin(\omega_0 t) + V_I(t)\cos(\omega_0 t)\right) =$$

$$= \frac{k}{\sqrt{2}}V_{OL}V_M(t)\cos(\omega_0 t + \Phi(t))$$

The information is represented by two base-band signals (the I and Q components). These are suitably combined at the transmitter side to modulate both the amplitude and the phase of the carrier

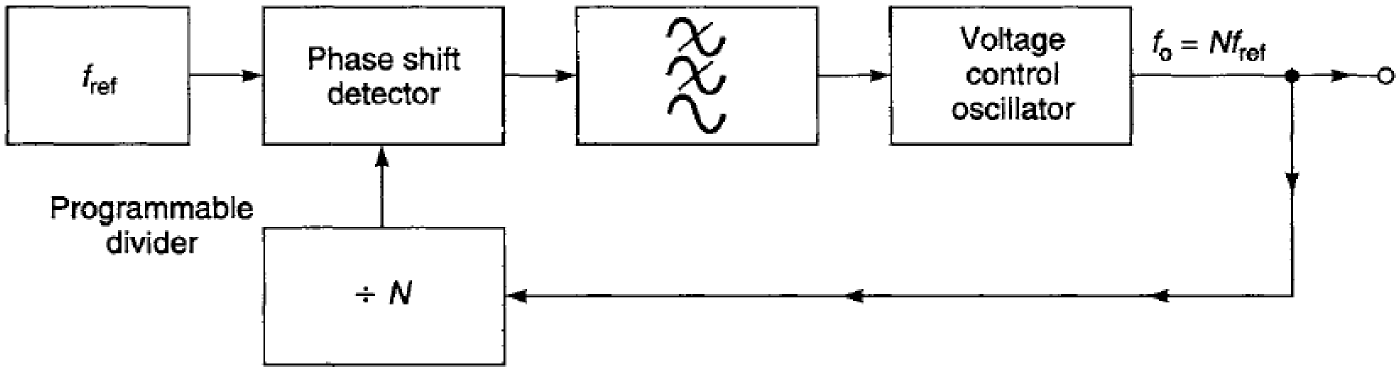
Up converter

- The frequency of the input signal is in this case much lower than the output frequency and the frequency of LO.
- The filter at the output selects the signal with the sum or difference frequencies produced by the mixing. It must also strongly reject LO signal (to avoid it arrives to the antenna)
- The phase noise of LO must be strictly controlled because it is amplified and transmitted with the wanted signal

Local Oscillator requirements

- In transmitting systems local oscillator determines the frequency of the radiated signal
- The quality of the generated oscillation is fundamental for producing RF signals without degraded information
- One of the most important requirement is the frequency stability, because this affects the quality of extracted information at the receiver side (phase noise depends on the stability)
- Another requirement concerns the frequency tunability, requested for changing the transmitted channel.
- Simple oscillators cannot satisfy both these requirements at the same time
- Synthesizers based on Phase Locked Loop (PLL) are generally adopted

PLL Synthesizers



- A fixed frequency (f_{ref}), very stable oscillator is used as a reference.
- The Voltage Controlled Oscillator (VCO) is a high frequency oscillator whose oscillating frequency can be controlled by a voltage signal
- The stability and phase noise of VCO taken alone are poor, while those of the reference oscillator are very high
- When the PLL is locked, the frequency and phase of the signal generated by VCO are strictly related to those of the reference oscillator
- As a consequence, also the stability and phase noise of the output oscillation become the same of the reference oscillator

Transmitter characteristics

- *Power output and operating frequency*: the output RF power level generated by a transmitter at a certain frequency or frequency range.
- *Linearity*: defines the quality of generated signal depending on the deviation from the ideal linear response
- *Efficiency*: the DC-to-RF conversion efficiency of the transmitter.
- *Power output variation*: the output power level variation over the frequency range of operation.
- *Frequency tuning range*: the frequency tuning range due to mechanical or electronic tuning
- *Stability*: the ability of an oscillator/transmitter to return to the original operating point after experiencing a slight thermal, electrical, or mechanical disturbance.

Distortion due to transmitter non-linearity

- We already know that a non-linear characteristic produces two effects:
  - Distortion of the amplified signal (loss of the associated information)
  - Generation of out-of-band spurious components (affecting adjacent channels)
- Linearity requirements impose the maximum power of distortion noise produced in the adjacent channels. The typical reference spec is the ACPR (Adjacent Channel Power Ratio)
- The effects of in-band distortion are in general less important because the level of the signal is much larger. When however the non-linearity becomes relevant (small back-off), also this distortion must be controlled (→ EVM requirement)
- It can be observed that RF signals with constant envelop tolerate higher distortion with respect signals with both amplitude and phase variation. This also means higher efficiency

Envelop of digital modulations

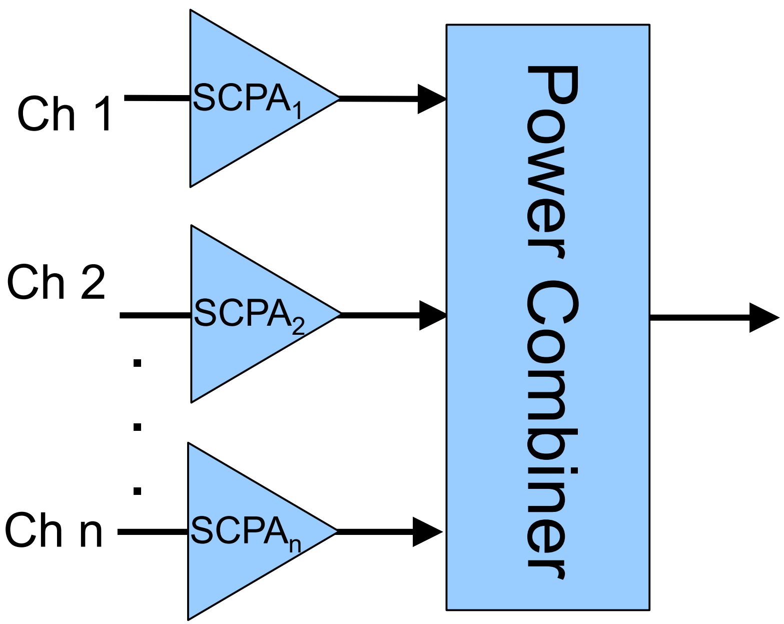
- Digital modulations include both constant and not constant-envelop schemes
- Pure phase modulations like FSK, QPSK, nPSK produce constant-envelop signals
- Phase and amplitude modulations like nQAM produce variable envelop signals, but allow higher date rate for a given bandwidth
- <u>The spectral efficiency</u> is introduced to take into account both the signal bandwidth (B) and the data rate (DR). It is defined as the ratio DR/B (larger for nQAM)
- To increase the spectral efficiency, the signal band must be limited (through a suitable shaping filter)
- This introduces in general an envelop variation also in phase modulated signals.
- The larger is the peak factor of a signal, the larger is the distortion produced by the non-linearity

Envelop variation and efficiency

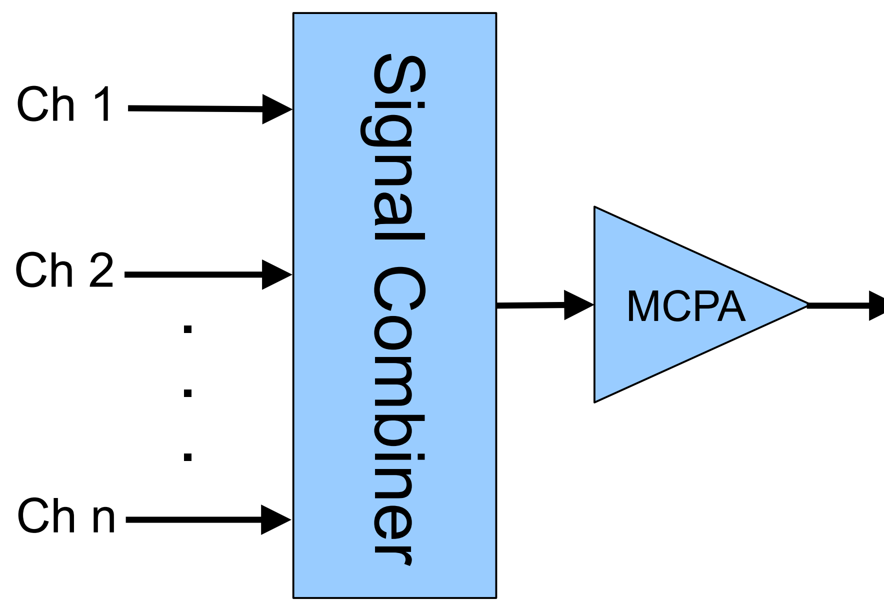
- Constant envelop signals can be amplified with high efficiency amplifiers (poor linearity). Note that the peak factor is 1.
- These amplifiers may operate in class AB, B and even C without significantly affects the quality of the transmitted signals (out-of-band distortion must be however limited)
- Due to poor spectral efficiency, constant envelop modulations tends however to be replaced with more efficient modulation schemes producing RF signals with envelop variation (peak factor >1). Note that the peak factor is defined on a statistical base by the PAPR (Peak-to-Average-Power-Ratio) curve
- High PAPR values call for a linear power amplification in order to limit IM distortion (the degree of linearity depending on the application)
- In many current applications (e.g. mobile communications) it is not easy to find an acceptable trade-off between linearity and efficiency, so suitable solutions have been developed for reducing the distortion in high efficiency amplifiers (<u>linearizing systems</u>)

Multi-channels power amplification

- In many communication systems the signals to be transmitted are constituted by several channels with assigned bandwidth.
- The final power amplification can be approached in two ways:
  a) Amplify each channel with a PA and combine all the PAs output by means of combiner
  b) Combine the channels at signal level (low power) and amplify the combined signal with a single PA (possibly followed by a broadband filter)



a)



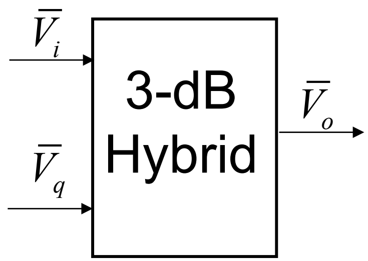
b)

Comments on the two solutions

- The first solution (SCPA: Single Carrier PA) allows the use of less linear amplifiers, with a lower delivered power. The overall efficiency is however low due to the use of many PAs (and for the losses in the power combiner)
- In the second solution (MCPA: Multi Carrier PA) the PA gain must be higher than in the previous case (to recover the losses in the signal combiner). The linearity must also be higher, because the PA amplifies the combined signal to the output power rate Pout (in the previous case each PA operates a Pout/N).
- The necessary linearity of MCPA is typically achieved by introducing suitable linearizing solutions

Implementation of Power Combiner

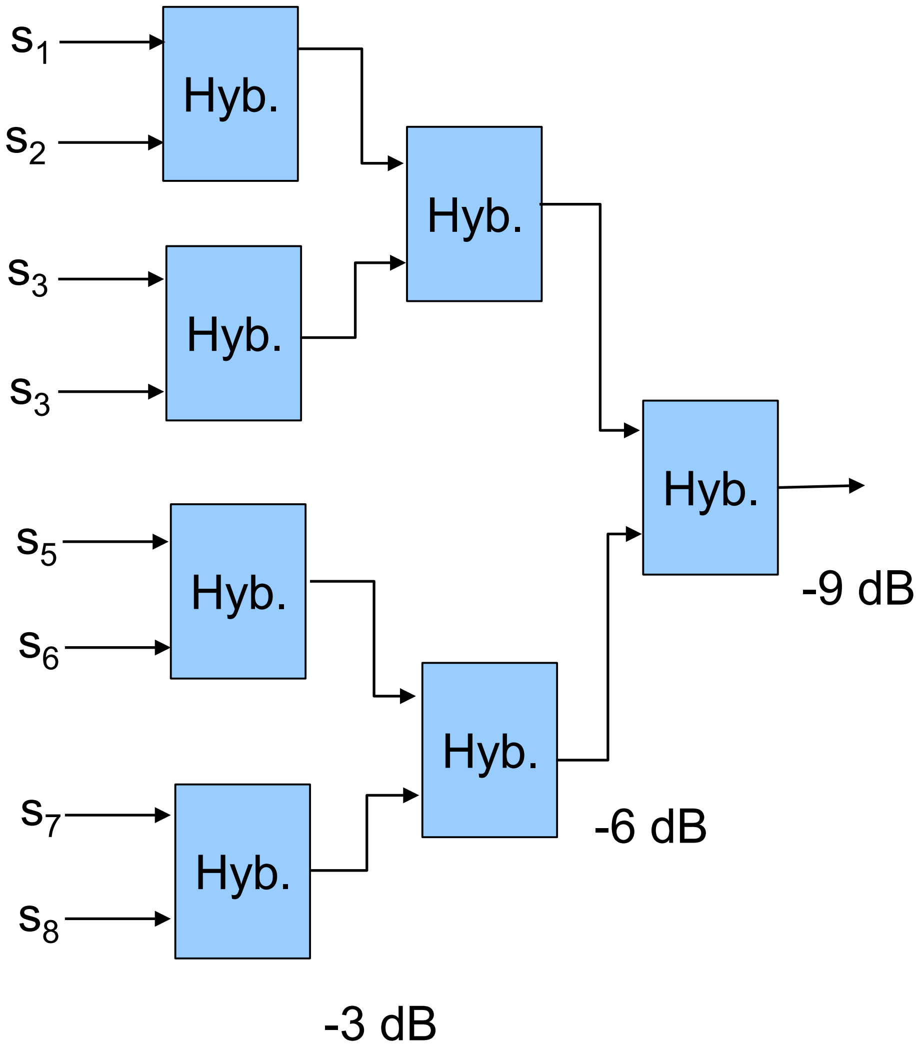
- Combining different signals generally implies loss of power (apart the case of identical signals)
- Adopting a 3-dB 180° hybrid the minimum loss is 3 dB (discarding dissipation). We have in fact seen that the power at the output ports, assuming incorrelation, is given by:



$$\boxed{P_o = \frac{1}{2}\left(P_i + P_q\right)}$$

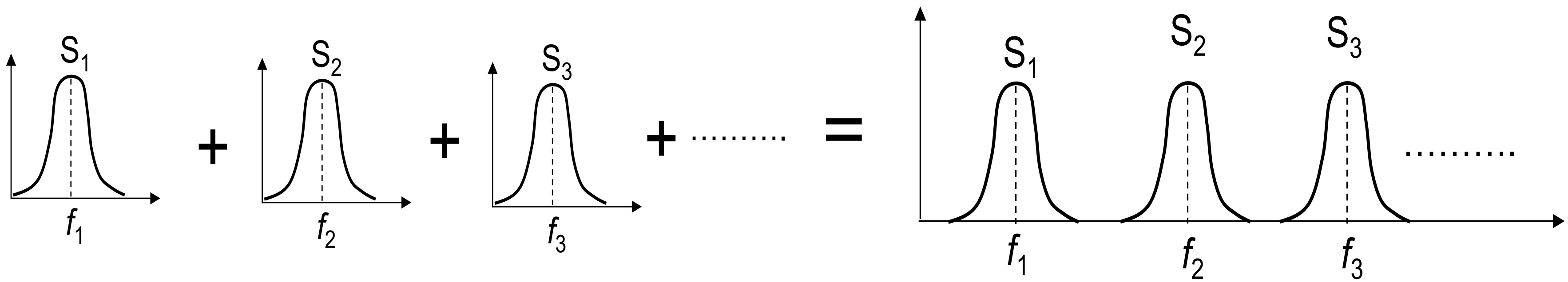
- When N signals must be summed, we have to cascade several hybrids. The overall (minimum) loss is $3 \cdot \log_2(N)$ dB (rounded to the closest largest integer)
- If the signals to be summed are spectrally distinct, a selective power combiner can be used. It allows lower losses with respect the use of hybrids at expense of larger size and cost

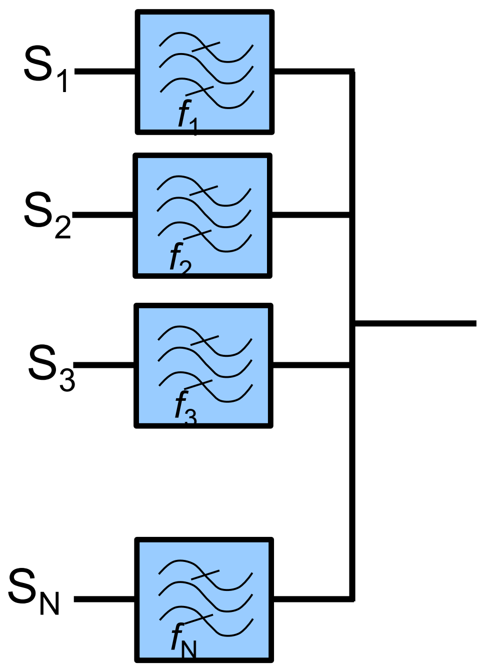
Lossy sum of N signals



- The average output power is 9 dB lower the sum of the average power in each signal.
- Actually the overall attenuation is even higher due to the dissipation in each hybrid

Sum of spectrally distinct signals





$$S_{out} = \sum_{k=1}^{N} S_k$$

Selective Combiner (Multiplexer)

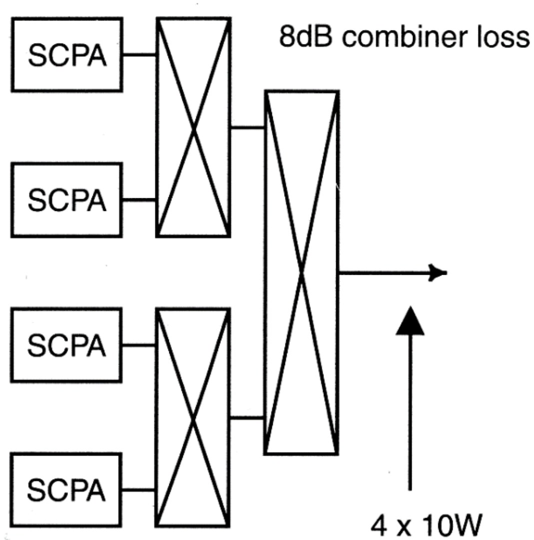
- For ideal filters the average output power is the sum of the average power of the input signal.
- Assuming A_0 the loss in the passband of the filters, the actual average power of S_{out} is the sum of the input powers divided A_0.
- This combiner is much expensive and larger than the lossy combiner realized with hybrids

Example: EDGE Base Station 4x10 W

Peak Factor of EDGE: 3.2 dB

Estimated Peak factor of combined signal: 8 dB

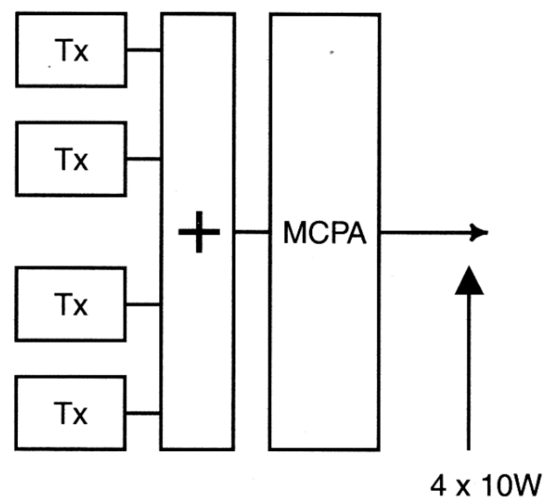
4 x 63 W (mean) SCPA



SCPA power required @ 25% efficiency = 1008 W
EDGE SCPA BTS efficiency = 4 %

Lossy combiner + SCPA

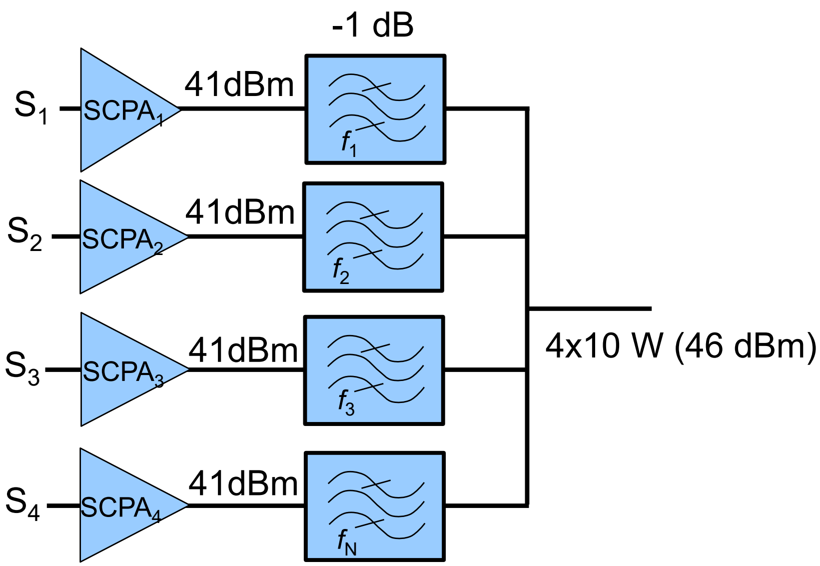
4 x 10 W (mean) MCPA



MCPA power required @ 12% efficiency = 333 W
EDGE MCPA BTS efficiency = 12 %

Combining at low level + MCPA

Use of a selective combiner:



Output power at each SCPA: 12.589 W

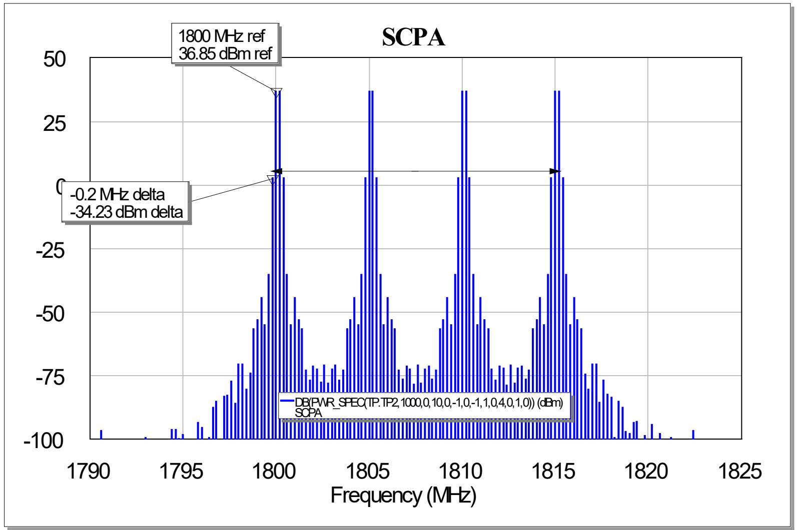
Absorbed DC power (25% efficiency):
4 x 50.356=201.424

Total BTS efficiency: **40/201.424=19.8%**

But:

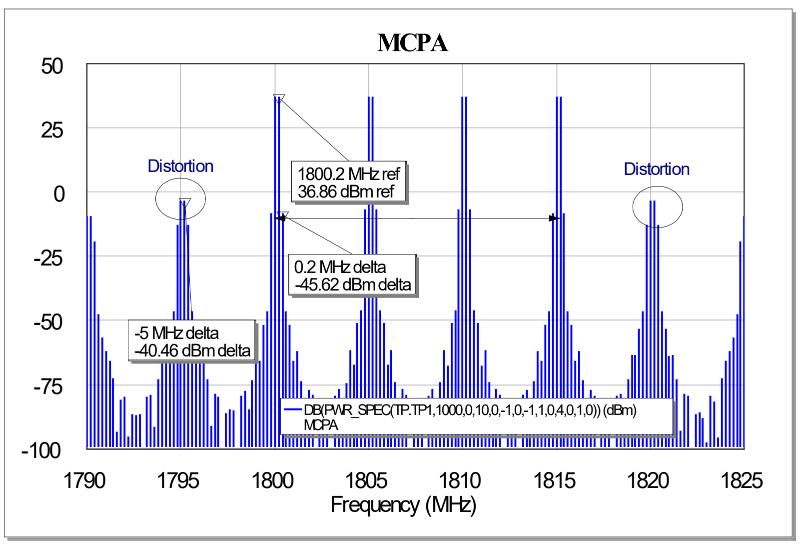
- The combiner is bulky and expensive
- Lack of flexibility (complex to add or remove a channel)
- Filters tuning must be very accurate and stable

2-tone simulation of 4 channels PA Pout=9.66W/channel



4 SCPA + lossless combiner

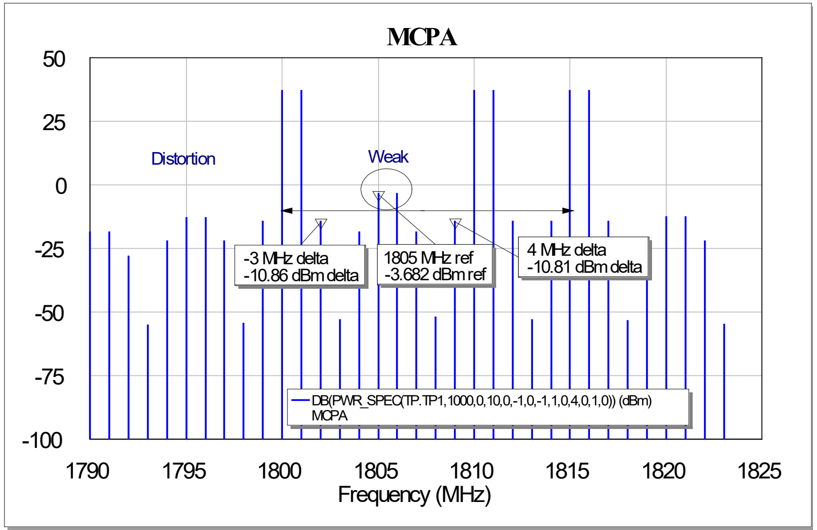
P1dB=44 dBm (BO=4 dB)
CI=34.2 dB (local)
No IM3 from the carriers



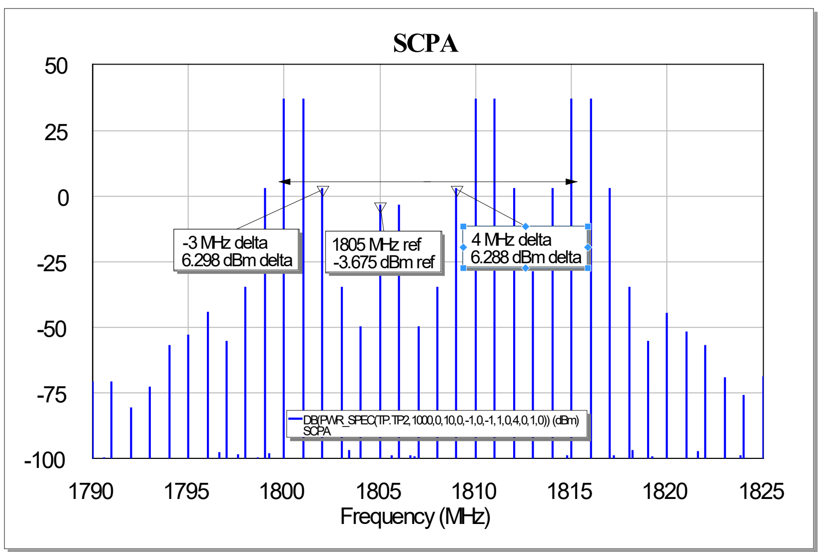
1 MCPA

P1dB=59.2 dBm (BO=13.3 dB)
CI (local)=45.6 dB
CI (from the carriers)=40.5 dB

Power in carrier 2 is 40 dB below the power in the other carriers



<u>MCPA</u>:
The power in car. 2 is still 10 dB above the distortion produced by adjacent carriers



<u>SCPA</u>:
The power in car. 2 is **6.3 dB below** the distortion produced by adjacent carriers

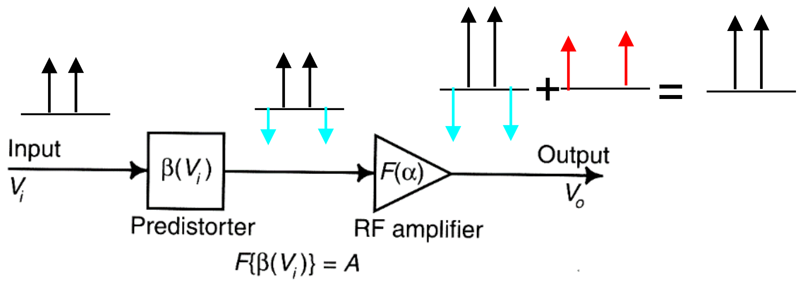
How to get the high linearity in MCPA?

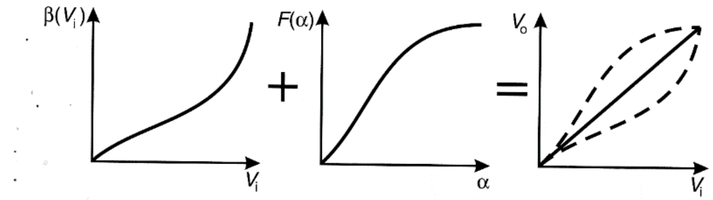
- The simplest way is to increase the back-off until the desired linearity (for the specific RF signal) is obtained
- This method is however extremely expensive in term of efficiency: for example, a backoff of 10 dB means that we need to “consume” 10 times the power of a PA operating with the output mean power equal to P1dB
- In many applications this in unacceptable and other methods must be devised
- The conceptual method most used for increasing linearity without penalizing too much efficiency is the **linearization**

Linearization Techniques

- Pre-distortion (very effective if implemented in baseband)
- Feedback (not easy at RF)
- Envelope Feedback (more easy but not much effective)
- Feedforward (very effective at RF, complex to implement)

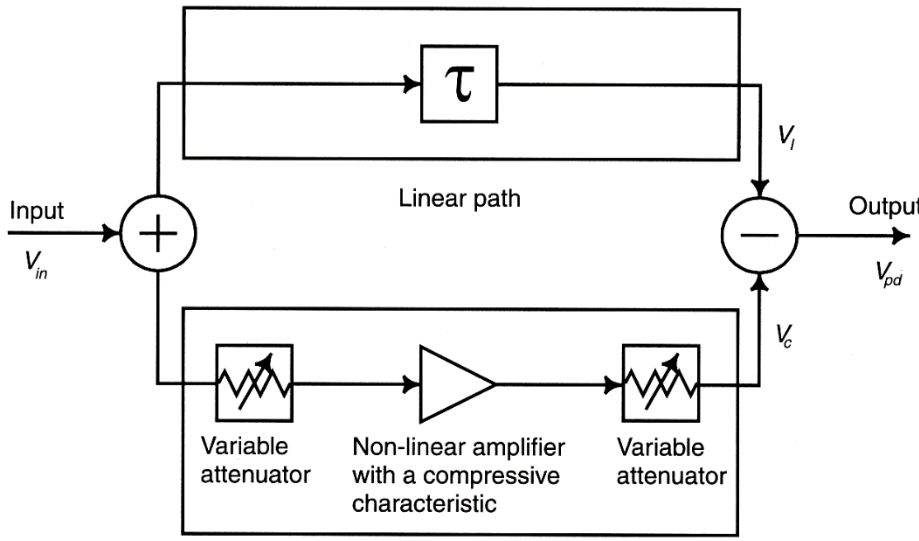
Linearization based on pre-distortion





- This method is based on the block called “Predistorter” which distorts the low-power input signal in a way that the distortion components generated (and amplified by PA) exactly cancel the distortion generated inside PA
- The linearization depends on how accurate is the implementation of inverse non linear characteristic of the PA
- This is a not easy task because, in the real devices, the characteristic is variable dynamically (memory effects, temperature, etc.)
- Linearization can be performed at IF to make easier the creation of the inverse non-linear function
- The most effective implementation of pre-distortion is however done in baseband where the formation of the correcting function is performed through DSP (the dynamic behavior of PA is periodically sampled and stored in a look-up table

Generation of an expansive characteristic



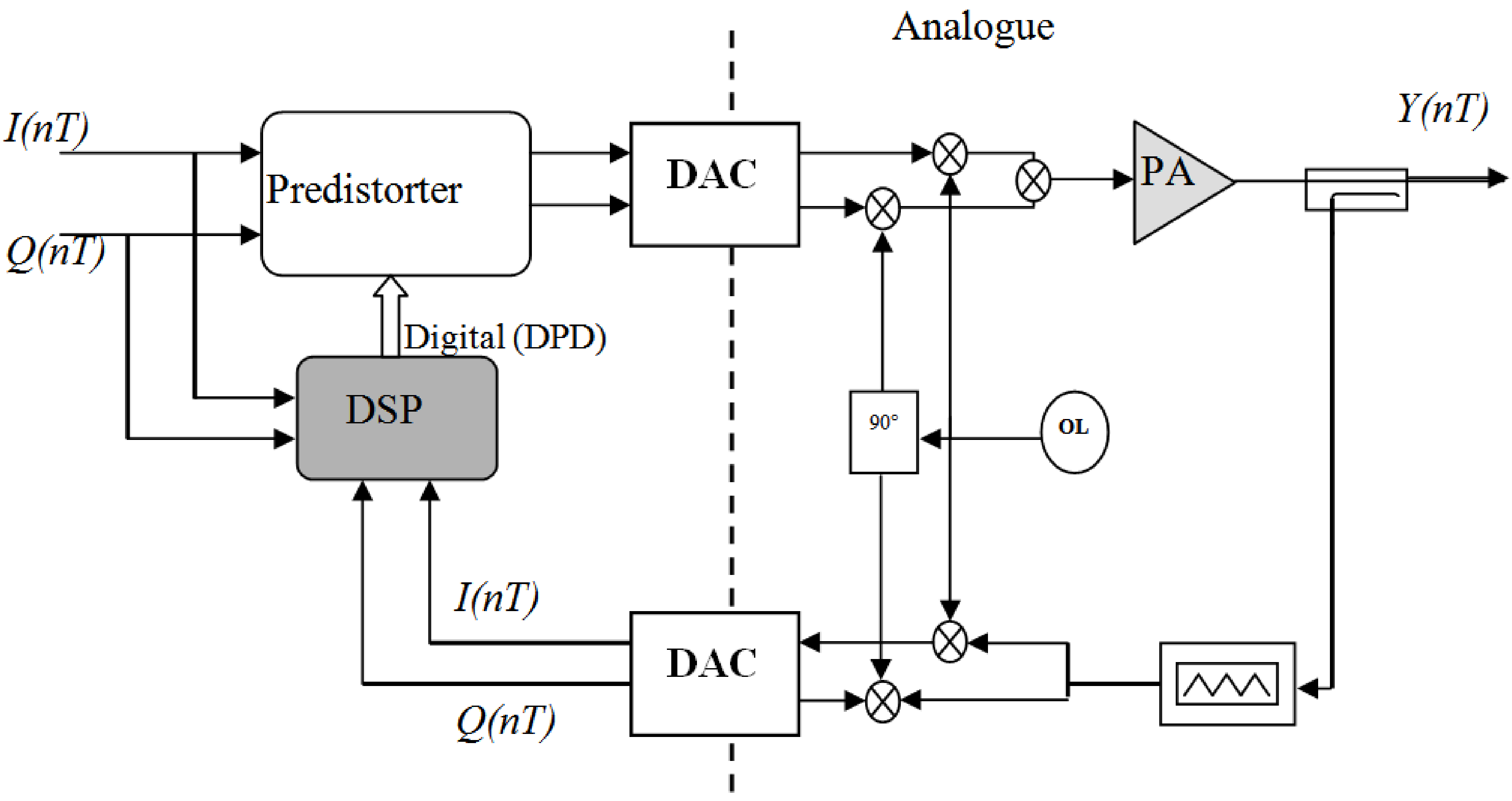
Linear path: $v_l\left(v_{in}\right) = a_1 v_{in}$

Compressive path: $v_c\left(v_{in}\right) = a_2 v_{in} - b v_{in}^3$

Output: $v_c\left(v_{in}\right) = \left(a_1 - a_2\right) v_{in} + b v_{in}^3$

The coefficients a_1, a_2, b are chosen for the best match of the linear and 3th order coefficient of the PA characteristic

Digital predistortion (basband)

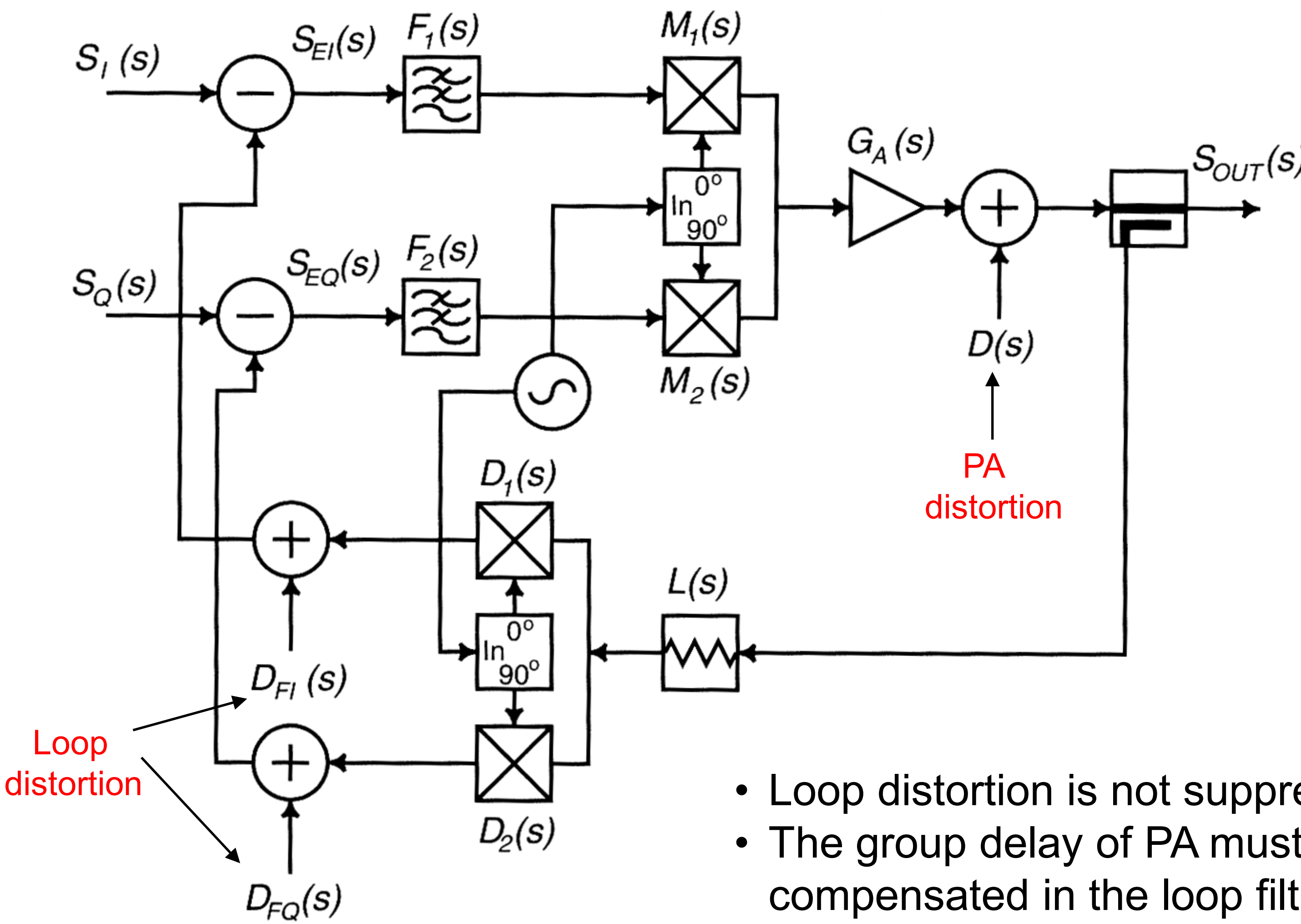


Baseband digital predistorter
(adaptive)

Envelop Feedback

- It is known that feedback improve linearity of amplifiers
- At microwave frequencies it is however difficult to control the signal feed back to input (a very small delay may introduce instability issues)
- A more viable solution is to feedback the envelop of the output signal and use it for controlling the gain of the input modulator:

Practical implementation with IQ mod.-demod-(Cartesian Loop Transmitter)



- Loop distortion is not suppressed
- The group delay of PA must be compensated in the loop filters to avoid instability issues

FeedForward Linearization

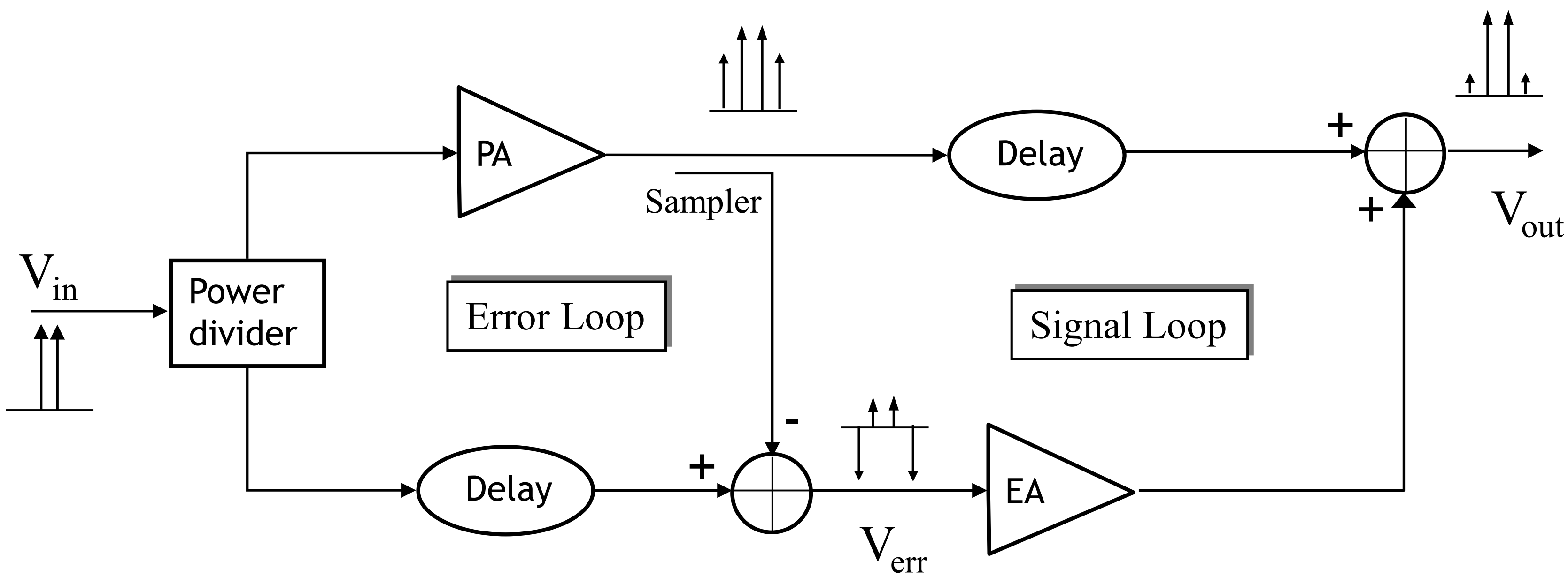
Advantages (Pros)

- Very good performances even on broad band signals (e.g. multicarrier)
- Improve also the PA noise figure
- No instability issues

Disadvantages (Cons)

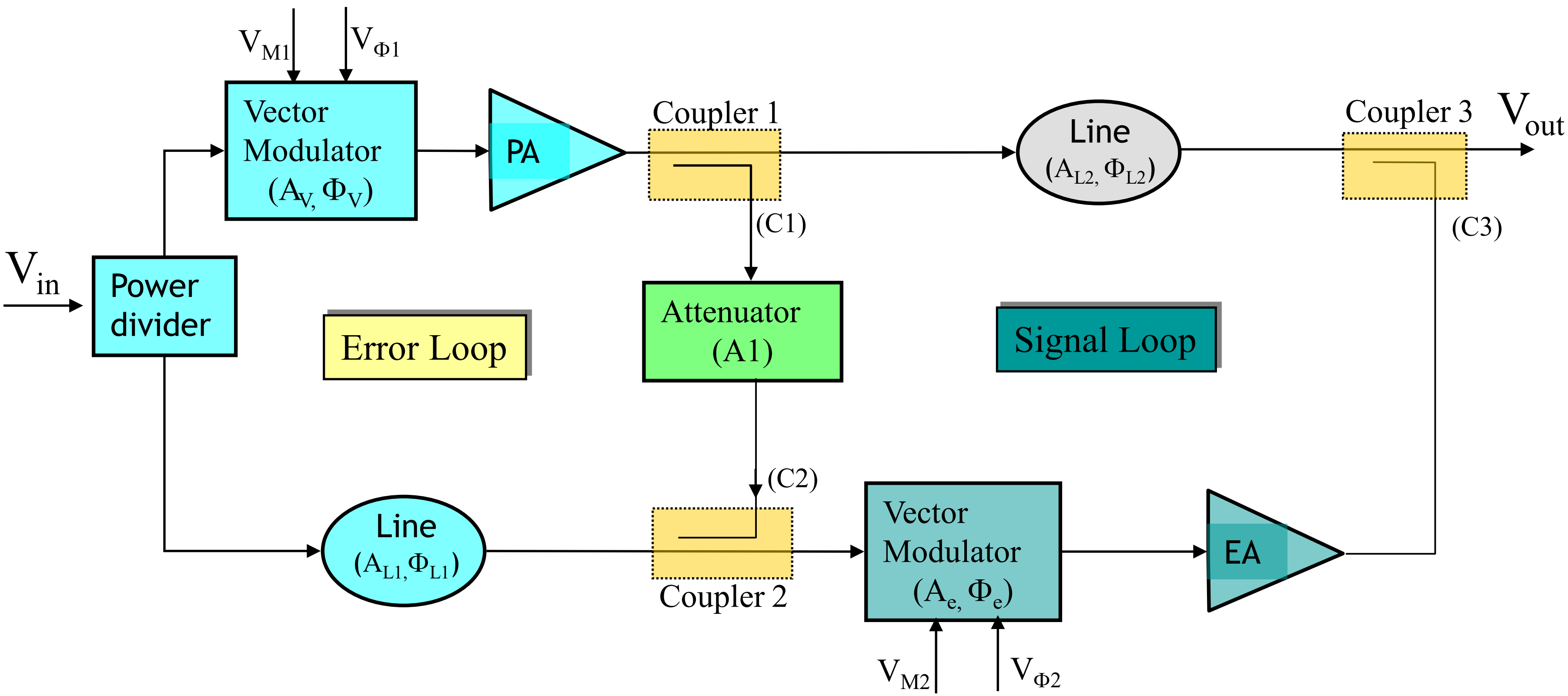
- Complex hardware
- Distortion suppression depending on frequency behavior of the components
- The best performance requires a dynamic control of the drifts of the PA gain and phase shift

Basic Operation



PA: Power Amplifier (to be linearized)
EA: Error Amplifier (linear)
Delay: Delay line

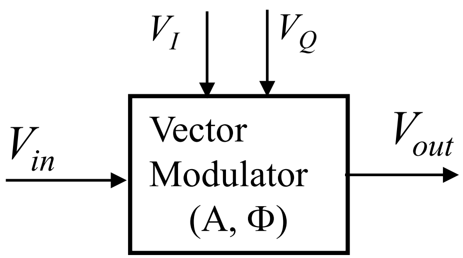
Practical implementation of feedforward



Note: The Vector modulators are needed for the fine tuning of the loops balancing (they also allow a dynamical control of the loops balancing)

Components (1)

Vector modulator

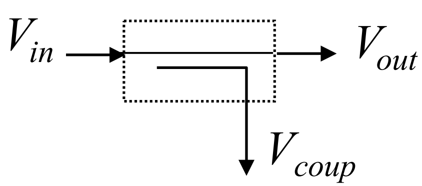


$$V_{out} = K_m\left[\left(V_0 + V_I\right) + j\left(V_0 + V_Q\right)\right]V_{in} = Ae^{j\Phi}V_{in}$$

V_0: reference voltage , K_m: sensitivity factor (1/Volt).

$$A = K_m\left[\left(V_0 + V_I\right)^2 + \left(V_0 + V_Q\right)^2\right]^{\frac{1}{2}} \quad , \quad \Phi = \tan^{-1}\left\{\frac{V_0 + V_Q}{V_0 + V_I}\right\}$$

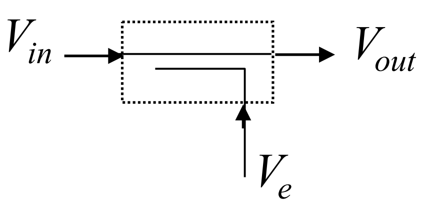
Directional coupler



$$V_{coup} = \gamma V_{in} \quad , \quad V_{out} = -j\beta V_{in}$$

$$B = -20\log_{10}\beta \quad , \quad C = -20\log_{10}\gamma$$

Lossless condition: $\beta^2 = 1 - \gamma^2$



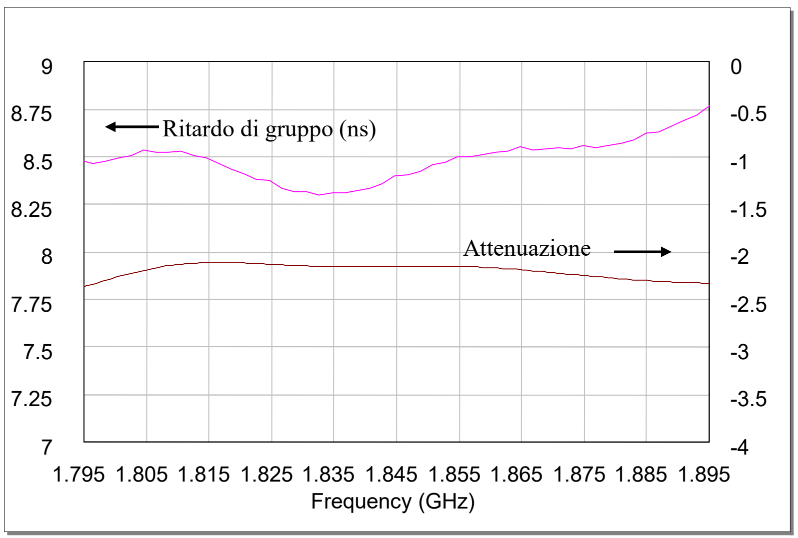
Combining the signal at ports *in* and *coup*:

$$V_{out} = \gamma V_e - j\beta V_{in}$$

Components (2)

Delay lines

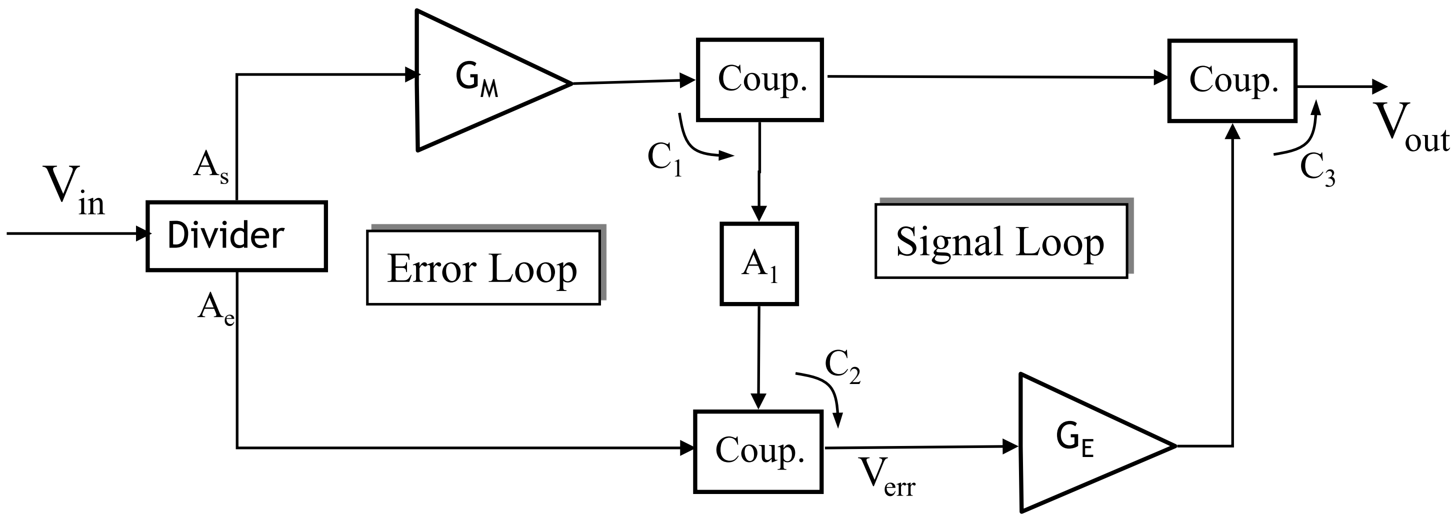
Task: equalize the delay of the two amplifiers.
They are often implemented as passband filter. The maximum group delay fluctuation in the signal band is assigned



Example of the group delay response of a microstrip filter used in the error loop

Analysis of feedforward

The delay lines are assumed to balance the delay of the two amplifiers.
Also the phase rotations in the two loops are assumed matched.
C_1, C_2, C_3 are sufficiently high (so β can be assumes 1 for all of the couplers)



Balance conditions (in dB) :

Error Loop : $G_M - A_s - C_1 - A_1 - C_2 = -A_e \quad \Rightarrow \quad G_M = \left(A_s - A_e\right) + C_1 + A_1 + C_2$

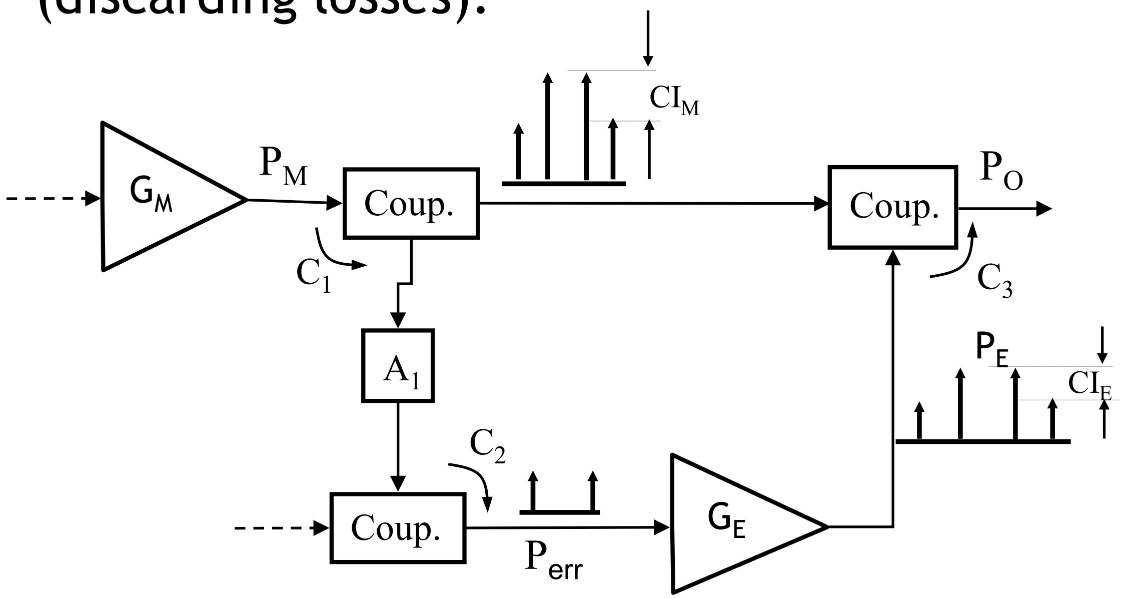
Signal Loop : $-C_1 - A_1 - C_2 + G_E - C_3 = 0 \quad \Rightarrow \quad G_E = C_1 + A_1 + C_2 + C_3$

Overall Gain of Feedforward: $G_{ff} = G_M - A_s = \left(C_1 + A_1 + C_2\right) - A_e$

Improvement of C/I (ideal case)

<u>Balanced loops (2-tone test)</u>

The output distortion is produced only by the error amplifier. It has (discarding losses):



CI_M = Carrier-to-Int of PA = P_M-$P_{M,d}$

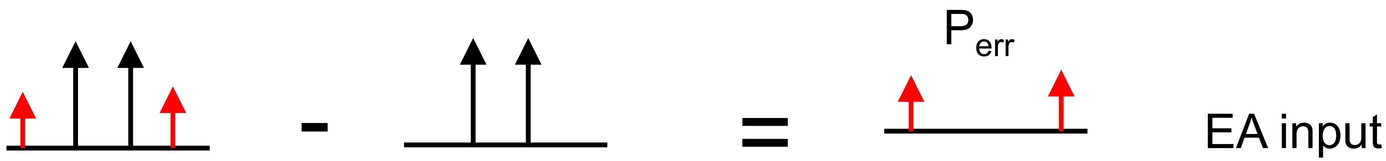
CI_E = Carrier-to-Int of EA = P_E-$P_{E,d}$

$P_{x,d}$ = Distortion power

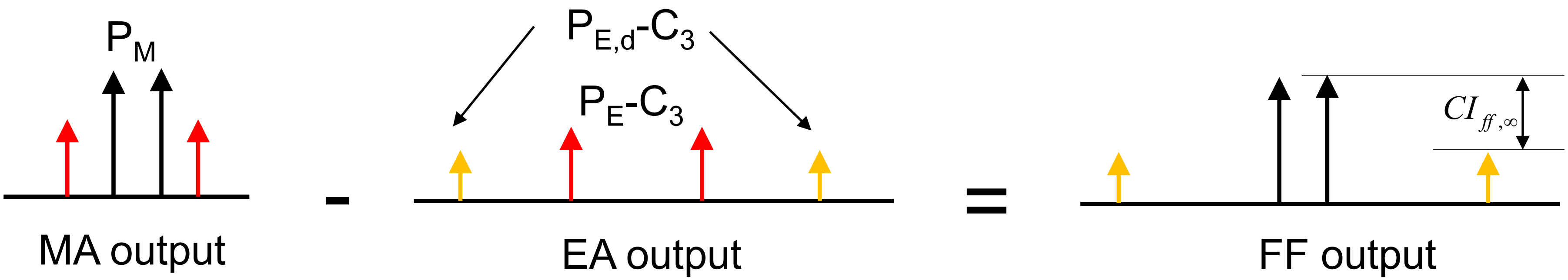
$$P_E - C_3 = P_{M,d}$$ Distortion cancellation condition

$$P_{E,d} = \left(P_E - CI_E\right)$$

Error Loop Output:



Signal Loop Output:



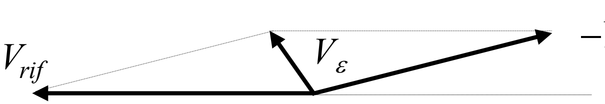
$$CI_{ff,\infty} = P_M - \left(P_{E,d} - C_3\right) = P_M + CI_E - P_E + C_3 = CI_E + \left(P_M - P_{M,d}\right)$$

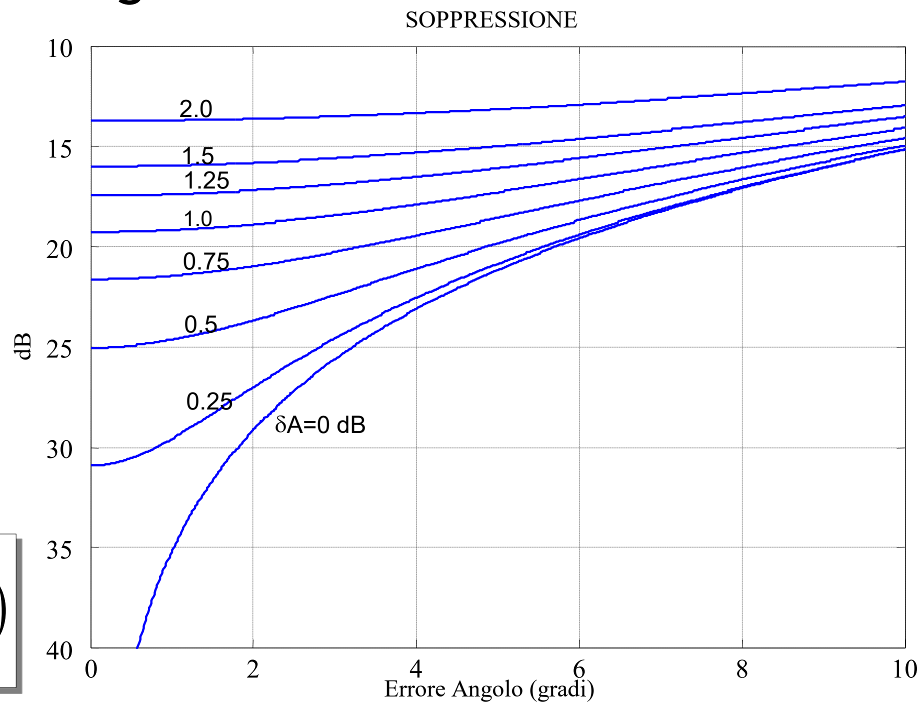
$$\boxed{CI_{ff,\infty} = CI_E + CI_M}$$

In dB

Unbalanced loops

A mismatch error of the loops magnitude (δA) and/or phase (δΦ) determines a reduction of the distortion suppression.
The dependence of the suppression on the mismatch error can be estimated from the following vector diagram:





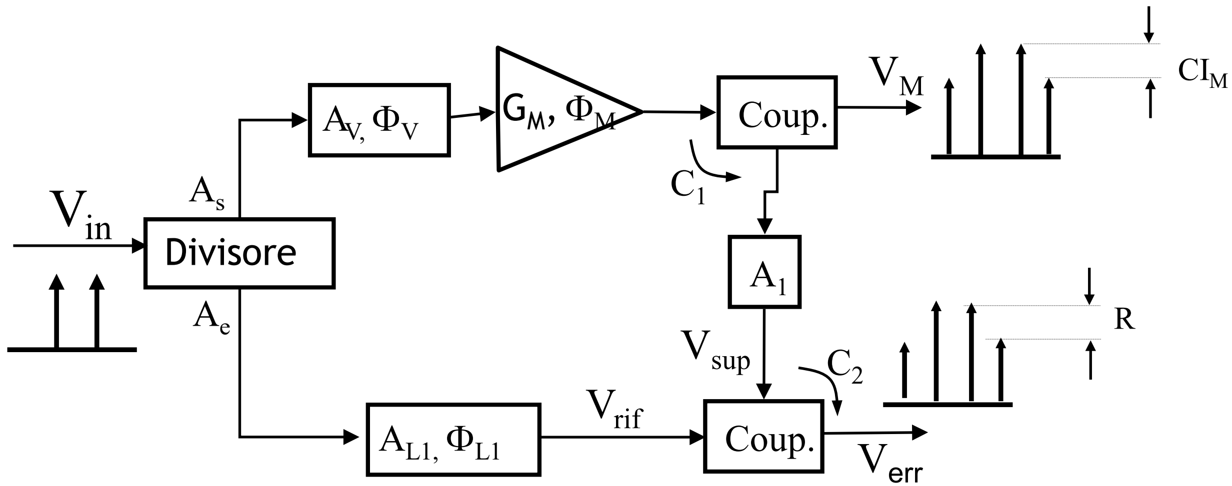
$$B = 10^{-\frac{\delta A}{20}}$$ (δA in dB)

$$S = -20\log\left(\left|\frac{V_\varepsilon}{V_{rif}}\right|\right) = -10\log\left(1 + B^2 - 2B\cos\left(\delta\Phi\right)\right)$$

Note: S represents the ratio between the power in the residual and the reference power

Mismatch in the error loop

A finite suppression (S_1) in the first loop add a fraction of the main signal to the distortion entering the second loop (low branch)

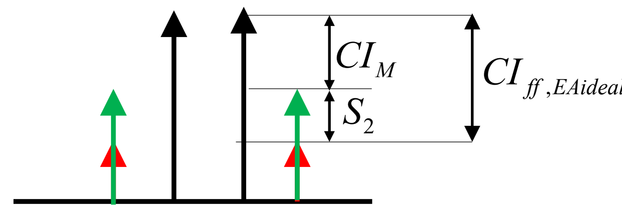


This residual main signal causes an increase of the output power of the EA (increasing also the distortion).
<u>In the practice it is however impossible to have the suppression of V_{rif} better than 30 dB</u> (due to the fluctuation of the phase Φ_{L1}).
Note that the <u>peak factor</u> of the error signal also depends on the main signal suppression

Criteria for the EA selection

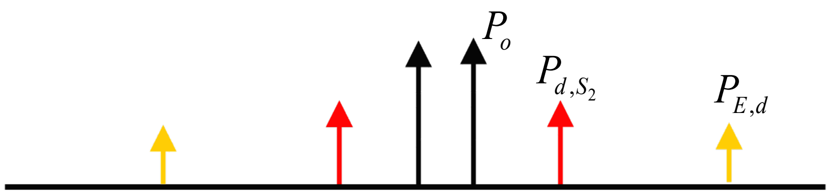
With an ideal EA (no distortion) and unbalanced loop 2 (S_2 is the suppression of distortion signal at output), it has:

$$\boxed{CI_{ff,EAideal} = CI_M + S_2}$$



FF output

A real EA adds its distortion at the FF output:



$$P_{E,d} = P_E - CI_E$$

$$P_{d,S_2} = P_0 - CI_{ff,ideal}$$

In order the EA distortion don't affect much the performances, we impose the $P_{d,S2}$-$P_{E,d}$>10 dB. Then:

$$10 < P_{d,S_2} - P_{E,d} = P_o - CI_M - S_2 - P_E + CI_E = CI_E - S_2 + \left[\left(P_o - CI_M \right) - P_E \right]$$

P_E is the power from the EA at FF output. It is about equal to $P_{d,m'} = P_o - CI_M$.
Then $(P_0 - CI_M) - P_E = 0$ and:

$$\boxed{CI_E > S_2 + 10}$$

Improvement of C/I in the general case

There are not exact expression available in the general case (both loops unbalanced).
However some empirical formulas have been derived which allows a first order evaluation of CI.

Consider first only loop 1 unbalanced (suppression S_1):

$$\boxed{CI_{ff,1} = CI_M + CI_E - 10 \cdot \log\left(1 + 10^{(CI_M - S_1)/10}\right)}$$

If also the second loop is unbalanced (suppression S_2), the overall CI_{ff} is given by:

$$\boxed{CI_{ff} = CI_{ff,1} - 10 \cdot \log\left(1 + 10^{\left(CI_{ff,1} - CI_M - S_2\right)/10}\right)}$$

Evaluation of Feedforward efficiency

- Assigned parameters
  - Main Amplifier: Efficiency (η_M), Output power (P_M), CI ratio (CI_M)
  - Error Amplifier: Efficiency (η_E), Output power (P_E),
  - Output coupler: Coupling (C_3), Through-path coupling (L_3)
- It is assumed that the loops are almost balanced and distortion is suppressed

It has: $f_M = 10^{-CI_M/10}, \quad l_3 = 10^{-L_3/10}, \quad c_3 = 10^{-C_3/10}$

At the output of the coupler, the distortion elimination requires:

$$P_M f_M l_3 = P_E c_3 \Rightarrow P_E = \frac{P_M f_M l_3}{c_3}$$

The overall efficiency of the FF is defined:

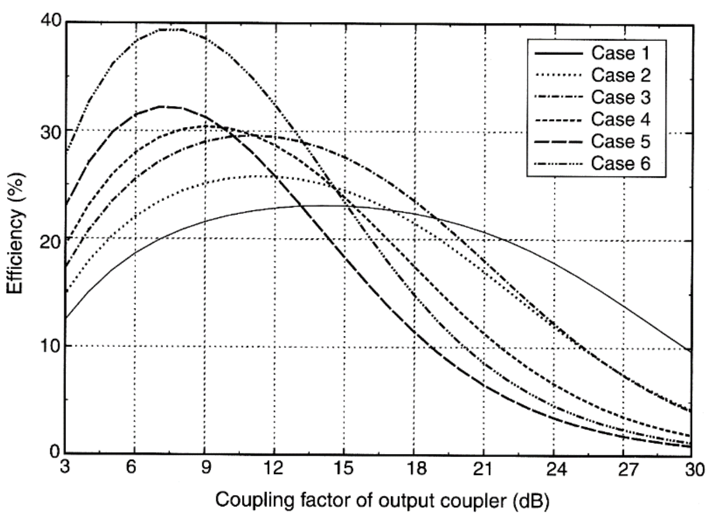
$$\eta_{ff} = \frac{P_{RF,out}}{P_{DC,M} + P_{DC,E}} = \frac{l_3 P_M}{P_M / \eta_M + P_E / \eta_E}$$

Substituting P_E from the derived expression and assuming $l_3=1-c_3$ (lossless condition) it has:

$$\eta_{ff} = \frac{\eta_M \eta_E P_M \left(1-c_3\right)}{\eta_E P_M + \eta_M f_M l_3 P_M / c_3} = \frac{\eta_M \eta_E c_3 \left(1-c_3\right)}{\eta_E c_3 + \eta_M f_M \left(1-c_3\right)}$$

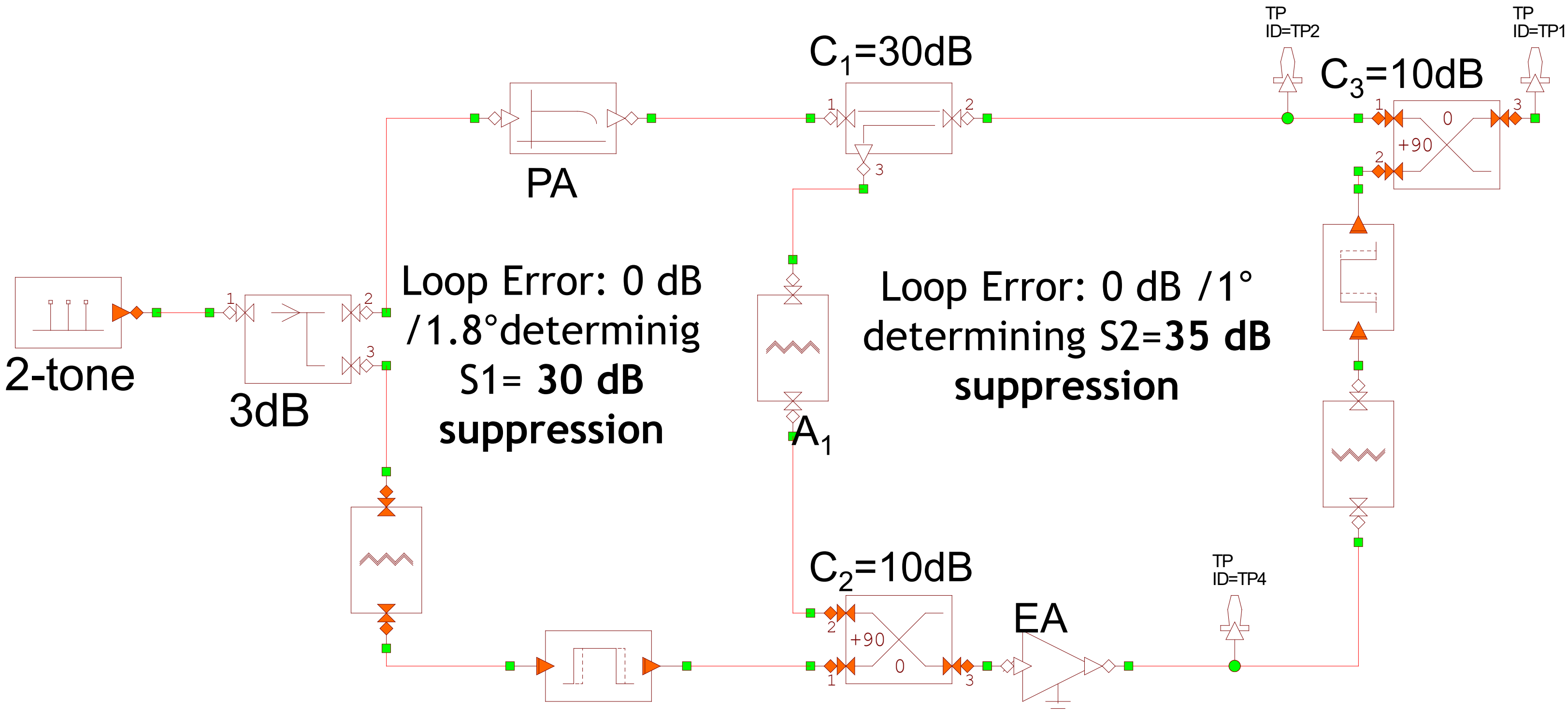
It can be observed that the efficiency depends on the value of c_3. The optimum value is the one maximizing η_{ff}. Taking the derivative of the previous expression with respect c_3 and setting it to zero the optimum c_3 can be found:

$$c_{3,opt} = \frac{2\eta_M f_M \pm \sqrt{4\eta_M \eta_E f_M}}{2\left(\eta_M f_M - \eta_E\right)}$$



Case	Main amplifier IMD level (dBc)	Main amplifier efficiency (%)	Error amplifier efficiency (%)
1	−35	25	5
2	−30	30	5
3	−25	35	15
4	−20	40	20
5	−15	50	30
6	−15	60	40

Example of Feedforward simulation (f_0=1.8 GHz)



G_E=10+G_M=52 dB
CI_E=S2+10=45 dB
A1=G_M-C_1-C_2=2 dB

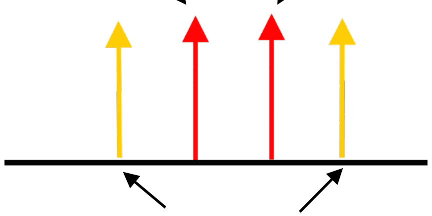
Power Amplifier (2-tone excitation):
P_M=36 dBm (average)
G_M=42 dB
$IP3_M$=49.6dBm
CI_M = 31.4 dB (PEP≅P_{1dB})

$$CI_{ff,1} = CI_M + CI_E - 10 \cdot \log\left(1 + 10^{(CI_M - S_1)/10}\right) = 72.6 \text{ dB}$$

$$CI_{ff} = CI_{ff,1} - 10 \cdot \log\left(1 + 10^{(CI_{ff,1} - CI_M - S_2)/10}\right) = 65.5 \text{ dB}$$

Evaluation of IP3 of Error Amplifier

At the input of EA (output of error loop), the spectrum of error signal is constituted by 4 lines:



The average power in the two pairs of lines is given by:

$$P_{nc} = P_M - G_M - S_1$$

$$P_d = P_{d,M} - C_1 - A_2 - C_2 = P_M - CI_M - G_M$$

The total power of the signal ($P_{nc}+P_d$) is then given by:

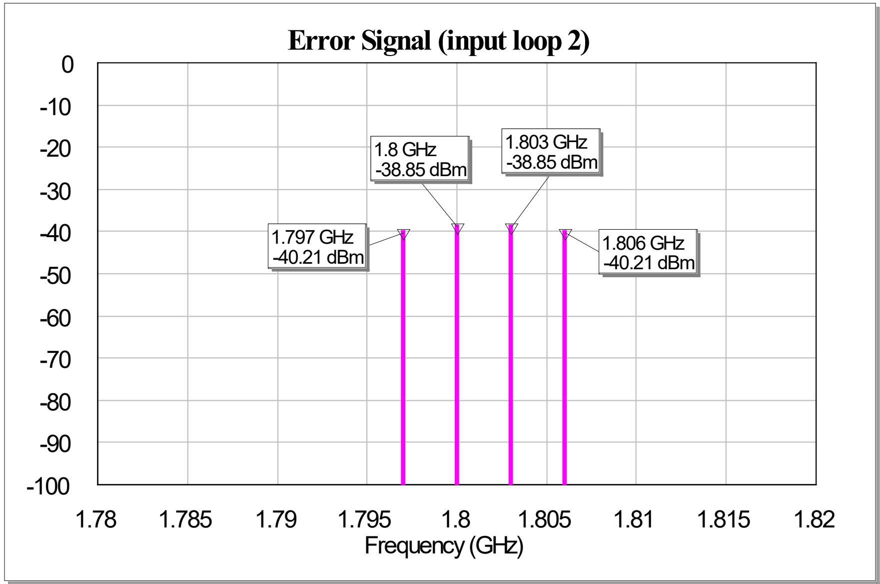
$$P_{e,in} = P_M - CI_M - G_M + 10\log\left(1 + 10^{(CI_M - S1)/10}\right)$$

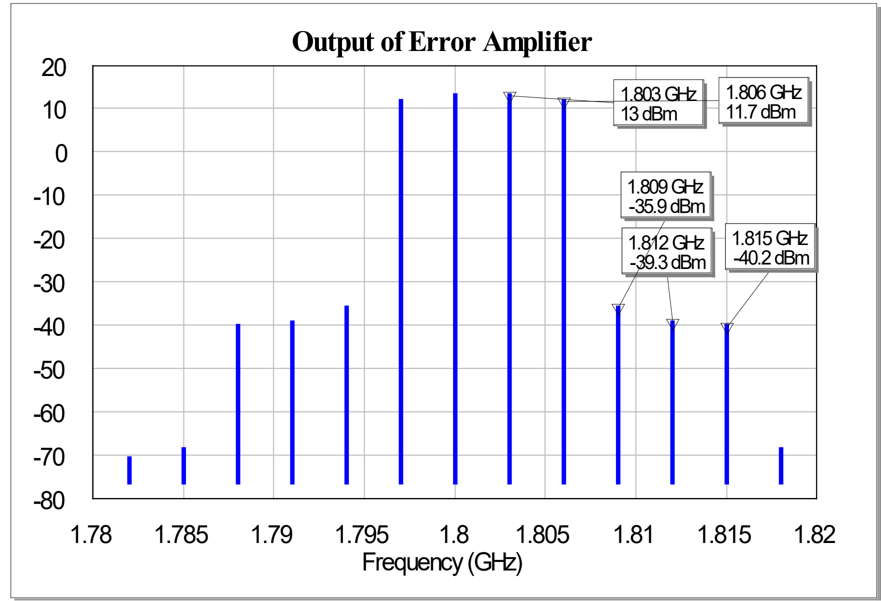
The power at the EA output is then:

$$P_{e,out} = P_M - CI_M - G_M + G_E + 10\log\left(1 + 10^{(CI_M - S1)/10}\right) = P_M + C_3 - CI_M + 10\log\left(1 + 10^{(CI_M - S_1)/10}\right) = 18.4 \text{ dBm}$$

Note that the distortion produced by this signal is quite different with respect the one generated by the EA when there is no signal residue (the distortion spectrum is quite different). For this reason there is no way to compute the required IP3 of the EA, we need to resort to simulations

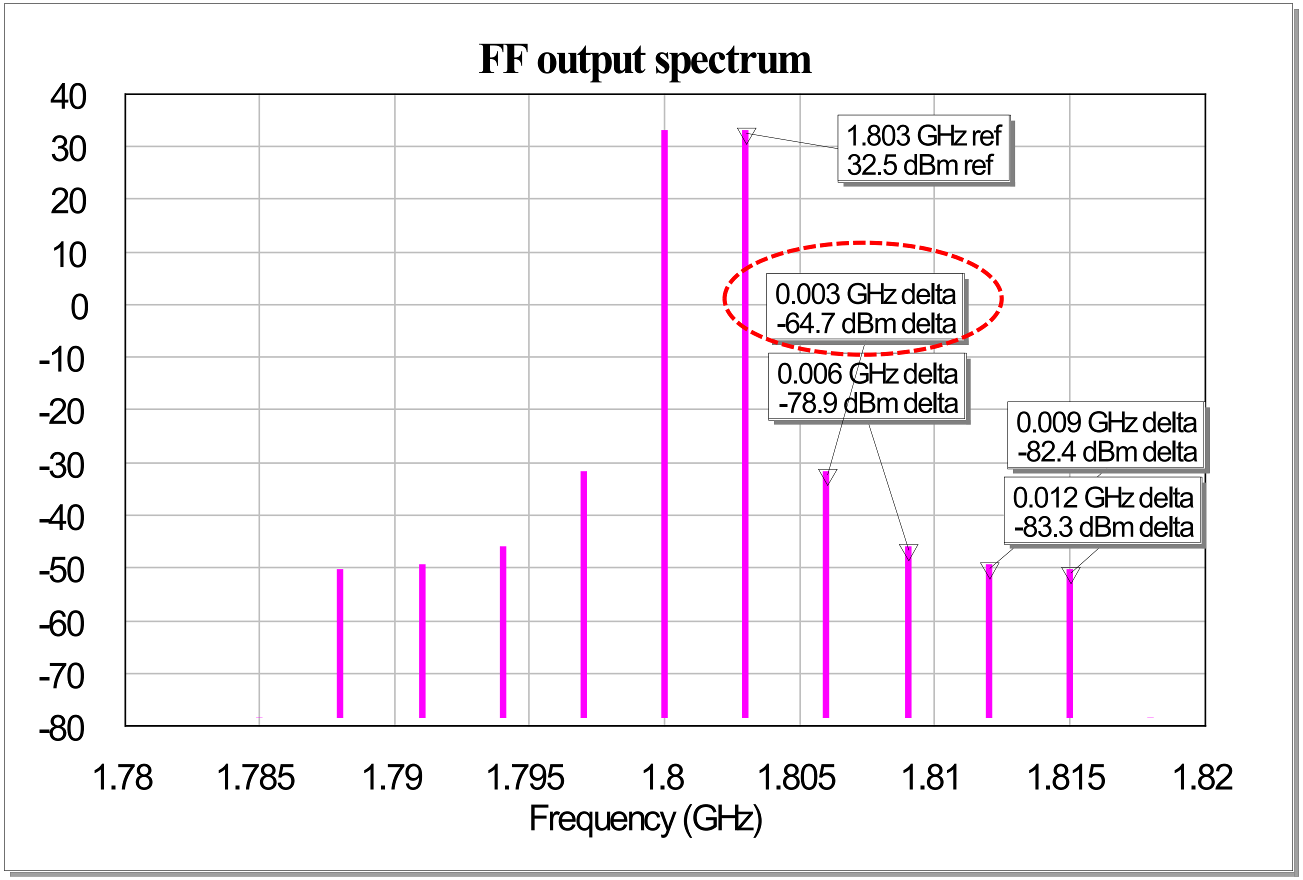
Simulation of Error Amplifier





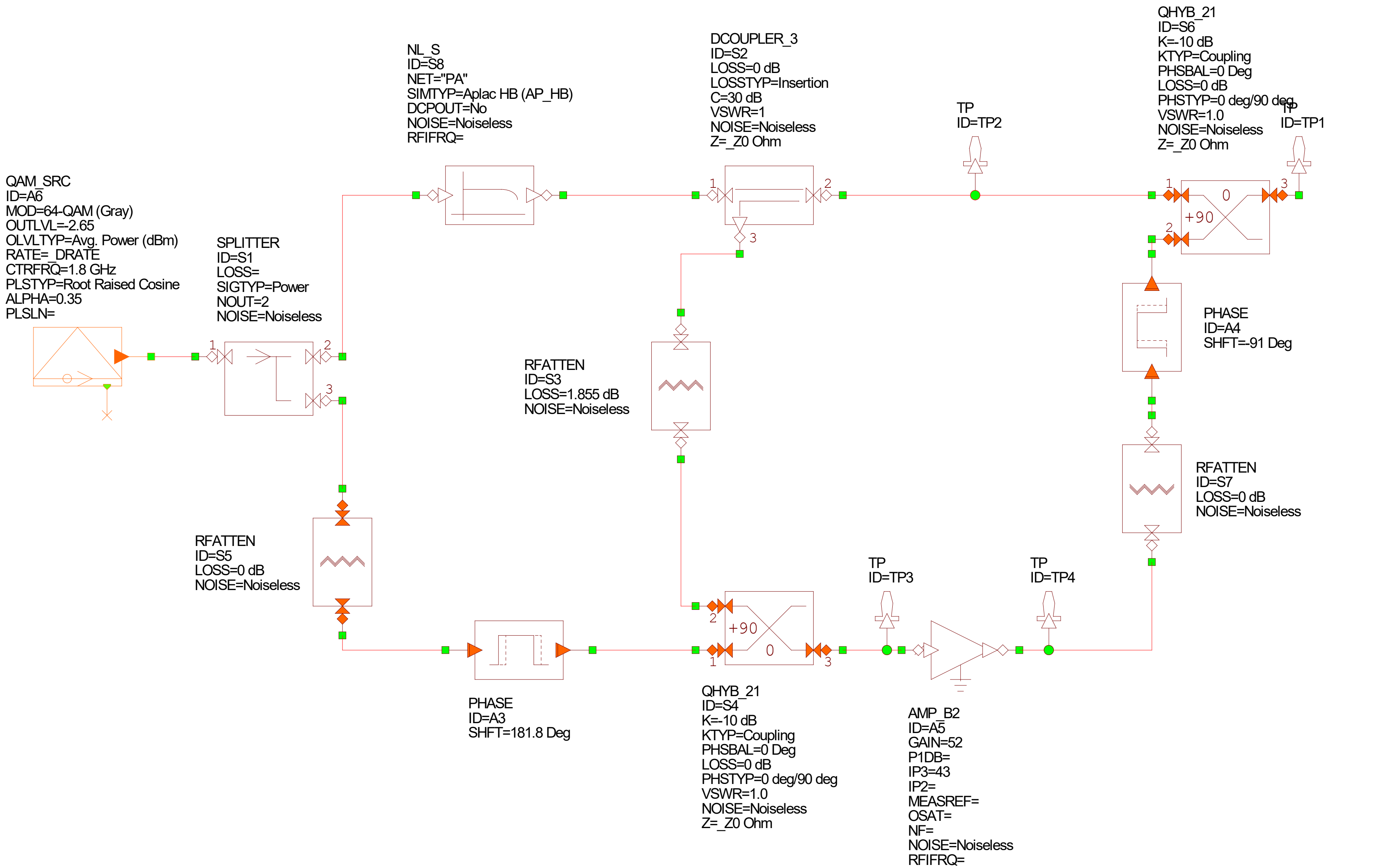
Here it is shown what is obtained by assigning $IP3_{EA}$=38 dBm. At the output of EA we have an overall signal power equal to (about) 18.5 dBm while the overall distortion power is (about) -32 dBm. As a result CI_{EA}=50.5 dB, 5.5 dB larger than required. Nevertheless, the final evaluation should be carried out at the FF output, considering the residual distortion with respect the original 2-tone signal.

Output FF spectrum (simulation)



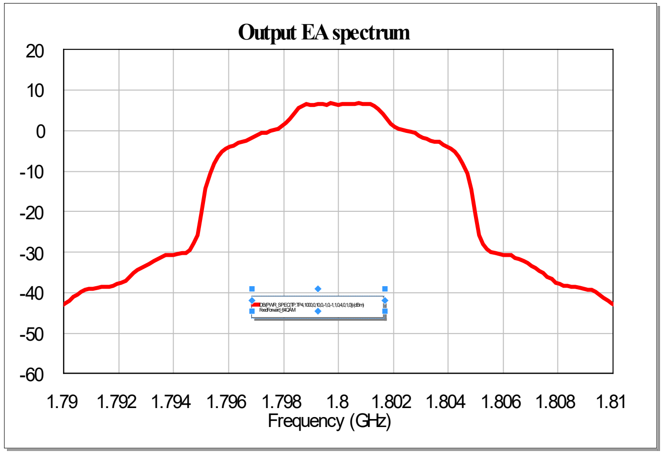
The graph shows that the estimated CI_{ff} (65.5 dB) is in good agreement with the one obtained from simulation (64.7 dB). The distortion of the EA are all below 10 dB the level of the residual PA distortion

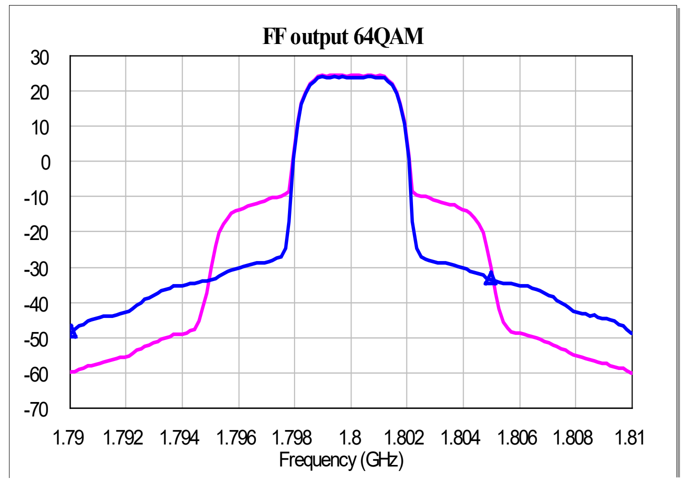
Simulation of FF with 64-QAM



FF with 64-QAM signal

Pm=35 dBm (4 dB back-off)

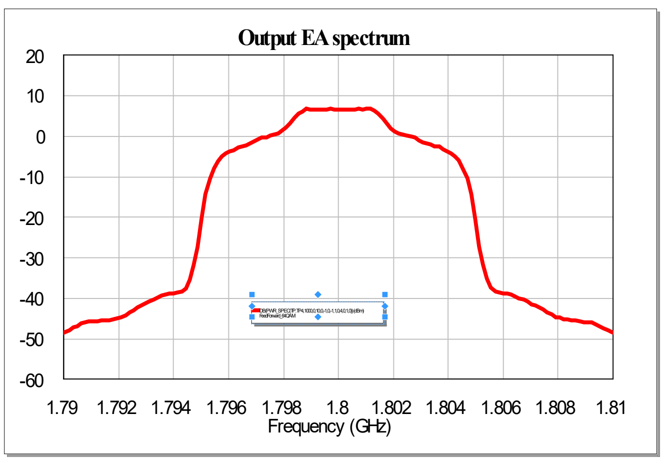


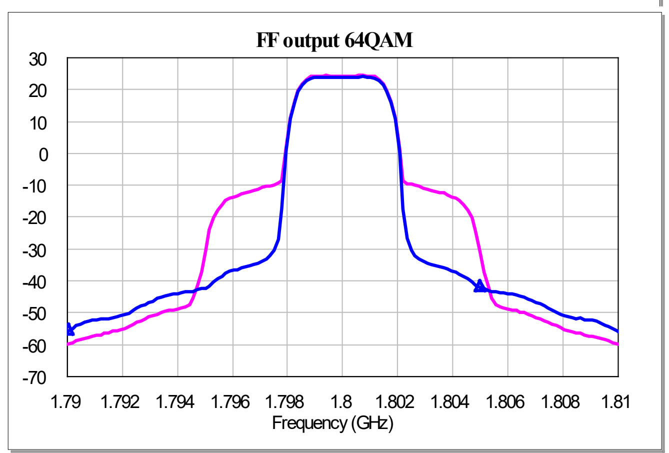


$IP3_{EA}$=37.9

ACPR: -59 dB

EVM: 0.31%





$IP3_{EA}$=43

ACPR: -61.6 dB

EVM: 0.19%

Unlinearized PA (P1dB=39 dBm): ACPR -47 dB, EVM 3%