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Indo-French Workshop on
Microwave and Photonic Technologies (IWMP)

RF Telecommunication Systems Characterization and Optimization

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Cefipra Workshop: Indo-French Workshop on Microwave and Photonic Technologies (IWMP)

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Outline of presentation

- **Introduction, Future Needs of Low Energy Consumption for Transmission Links**
- Non-Linear Characterization
- System Link Budget
- Optimization of RF Nominal Power
- Optimization of Consumed Power, and Consumed Energy per Transmitted Bit
- System Simulation, Characterization, and Optimization

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Future needs of low energy consumption for transmission links

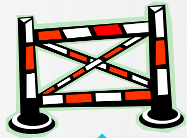
- Channel capacity increases (video)
  - +24 % per year in 2020
  - + 60 % per year for mobile communications in France
- Frequency bands are limited

⇒ Increase spectral efficiency (Bits/second/Hz)

  ⇒ More and more complex signals (64-256-1024 QAM)

- Shannon limit: maximum spectral depends on total signal-to-noise ratio C/N or C/(N+I), SNR or SNIR

⇒ Increase RF power to increase C/N



- Power Amplifier is non-linear
- Intermodulation noise in bandwidth added to thermal noise
- Signal-to-intermodulation ratio: C/I or NPR or EVM

⇒ Increase linearity to increase C/(N+I)

- Catastrophic effect on energy consumption

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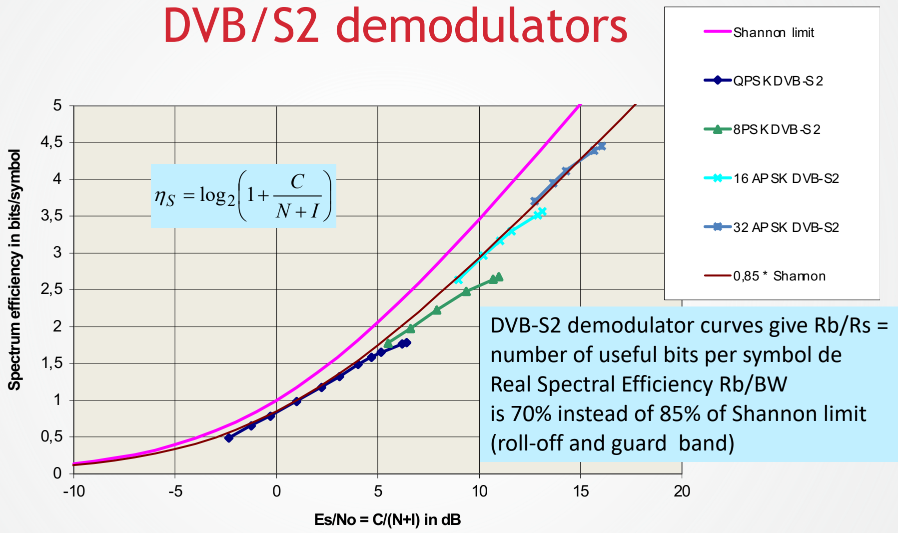
Shannon limit and performances of DVB/S2 demodulators



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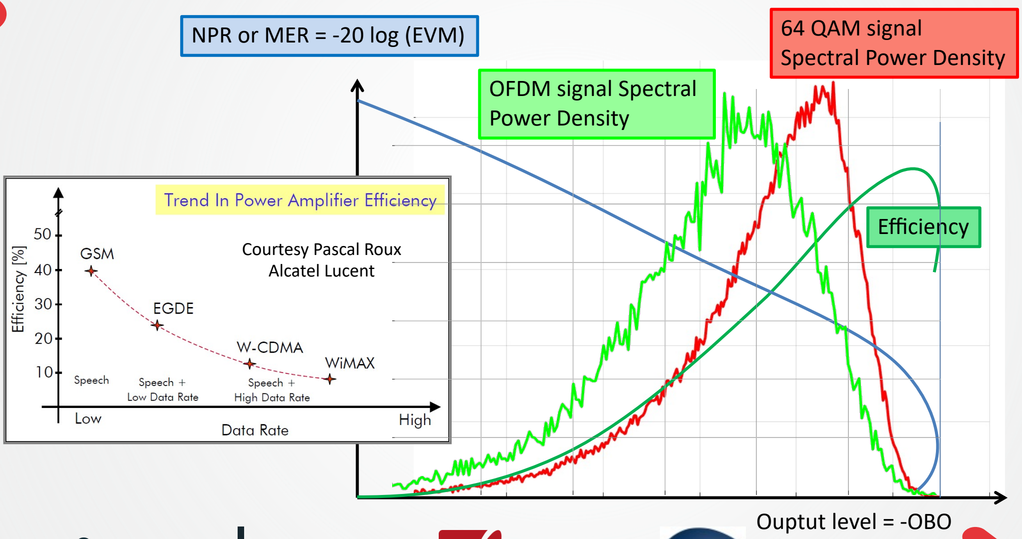
Efficiency and linearity curves of an amplifier



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Long Term Trend is not sustainable

- In 2012, telecoms consumption was 2% of the world's total produced energy (with Internet and data farms but 70% of this was used for radio access)
- Same level as air transport

OK for the short term BUT

- The Telecoms sector increases faster than all other sectors
- Even higher increase for mobile comms
- In France in 2018: 5% (with cooling and data farms)
- Problems were (and are) foreseen in the future
- Even stronger now with energy price increases

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Convergence between satellite and ground telecoms

- Technical
  - A common standard is better than options to include satellites in a ground standard
  - 5G and 6G standards consider non-terrestrial networks (NTN)
- Design and optimization
  - Previous Satellite: best compromise between channel capacity and consumption (satellite equipment cost is small compared to launch and ground segment)
  - Previous Ground Telecoms: best compromise between channel capacity and equipment cost (energy cost is small compared to other costs)
  - Now: consumption, thermal dissipation, and forced air cooling are problems
  - It is necessary to optimize capacity, consumption and cost in both cases
- Cell phones now have direct access to satellites today only for emergency communications

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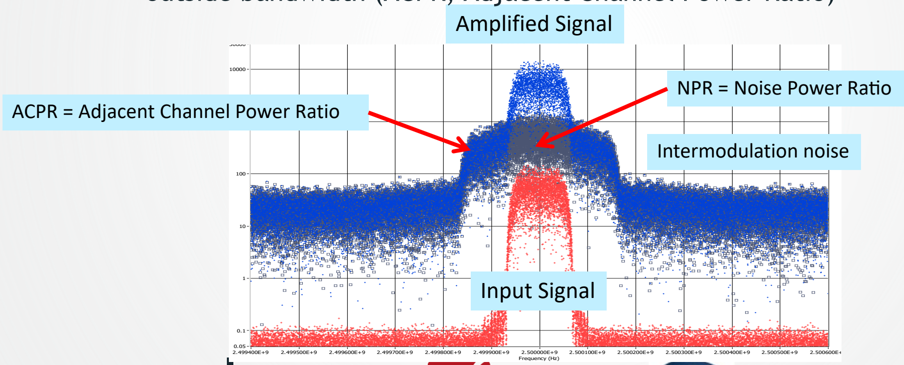
Intermodulation noise: NPR, ACPR

- Modulation 16 APSK (Amplitude Phase Shift Keying)
- with 0,35 roll-off SRC (square root raised cosine) filter
- Solid State Power Amplifier (SSPA)
- Intermodulation noise in useful bandwidth (NPR, Noise Power Ratio) or outside bandwidth (ACPR, Adjacent Channel Power Ratio)



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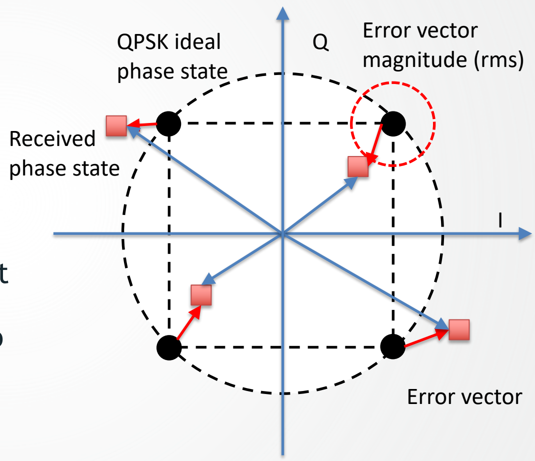
EVM : Error Vector Magnitude

- EVM: voltage ratio of noise over signal in %
- MER: Magnitude Error Ratio = -20*log(EVM)
  Signal over Noise ratio in dB
- Same as average value of NPR in useful bandwidth in the same conditions of signal
- Commercial measurement equipment are available
- Standard measurement used by telco operators
- Precise definition for calibration of equipment in IEEE P1765 standard



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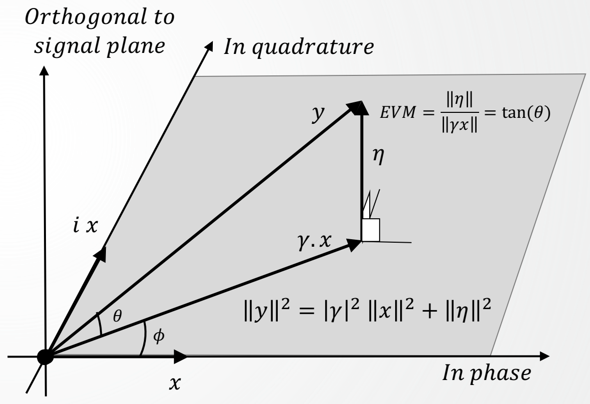
Mathematical identity of EVM and NPR, (strict for OFDM signals) (Orthogonal Frequency Division Multiplex)

- In both measurements, the noise is identified as the part of the noisy and distorted received signal that is nor correlated with the ideal transmitted signal
- An orthogonal projection of the received signal y on the ideal signal x complex plane gives the equivalent complex gain γ and the orthogonal noise vector η

$$y = \gamma x + \eta \qquad \gamma = \frac{y.x}{\|x\|^2}$$

$$\cos(\theta) = \frac{\|y.x\|}{\|y\|\|x\|}$$



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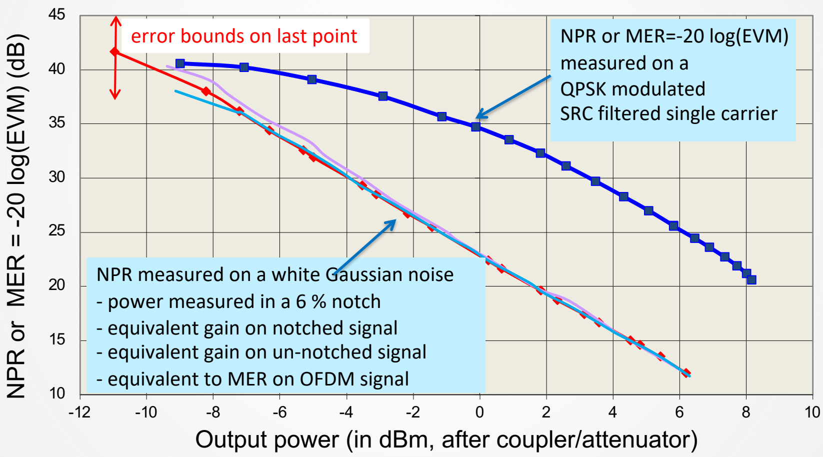
Measured results for NPR and EVM on two different signals for a 500 MHz linearized TWTA



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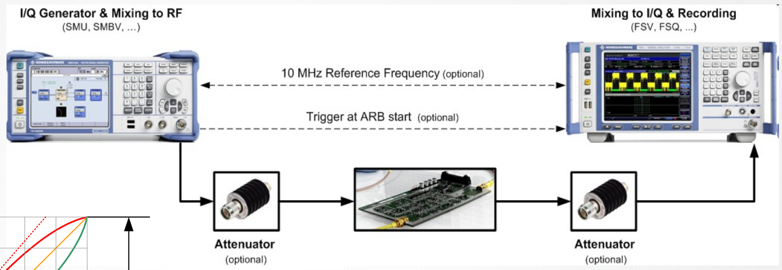
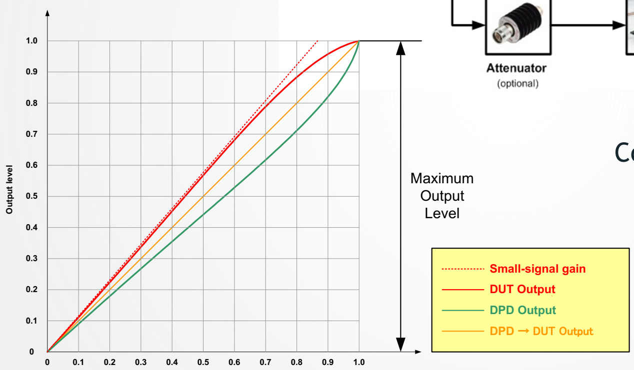
Modelization et linearization





Courtesy Martin Weiss

Rohde & Schwarz

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Optimization of non-linear amplifiers

- Best linearity in back-off
- Needs to use a more powerful amplifier

⇒ Best compromise between nominal power and linearity

- Problem with consumption because efficiency decreases when operating in the linear zone of amplifiers
- Best compromise between consumption and linearity

- More recently, a problem with the dissipation and cooling of amplifiers
- Cooling is always critical on satellites
- Now it is also a problem on phone base stations because the consumption of the cooling is no longer negligible and decreases the total efficiency
- Best compromise between dissipation and linearity

- You may have the 3 constraints together

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Reason to Optimize Power and Consumption to 0.1 dB

- **Absolute RF power precision: 0.25 dB**
- On a telecom or radar satellite payload consumption is 80% of the solar panel and battery available power. It is a large part of the launch mass and the cost.
- A gain of 0.1 dB on consumption allows us to increase the RF power by 0.1 dB or 2%.
- Satellite capacity may increase by 2% for the same cost
- This increases the revenue of the operator by 2% and also benefit
- If the envisioned benefit is around 20% of revenue, it will go to 22% or a relative increase of 10%.
- Essential parameter for investors and deciders
- **Consumption is now also an important criterion for ground telephony**

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Characterization curves and optimization

- We want to compare two amplifiers and choose the best one for a transmission
- We want also to compare the same amplifier with different tunings to choose the best tuning for nominal RF power, the OBO, matching circuits, …
- We must choose the characteristic to optimize and the constraints to be respected:
  - Capacity, C/(N+I), spectral efficiency
  - Nominal RF power
  - Level of RF power used or output back-off (OBO)
  - Consumed power
  - Efficiency
  - Dissipated power
  - …

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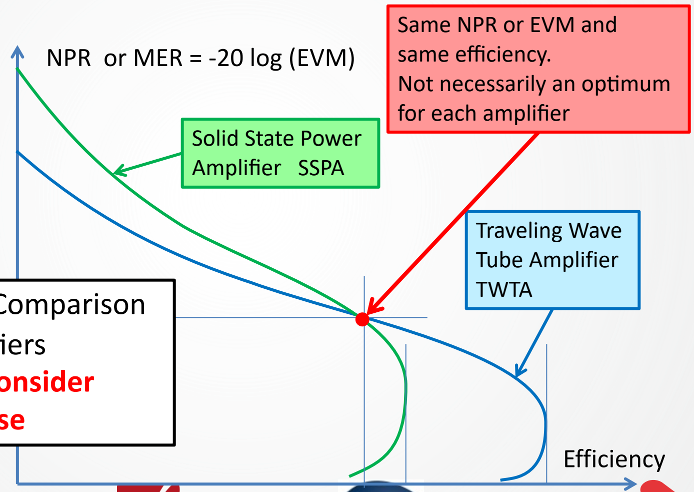
Merit curves for non-linear amplifiers



Seems OK for direct Comparison of two amplifiers
But it does not consider the link noise

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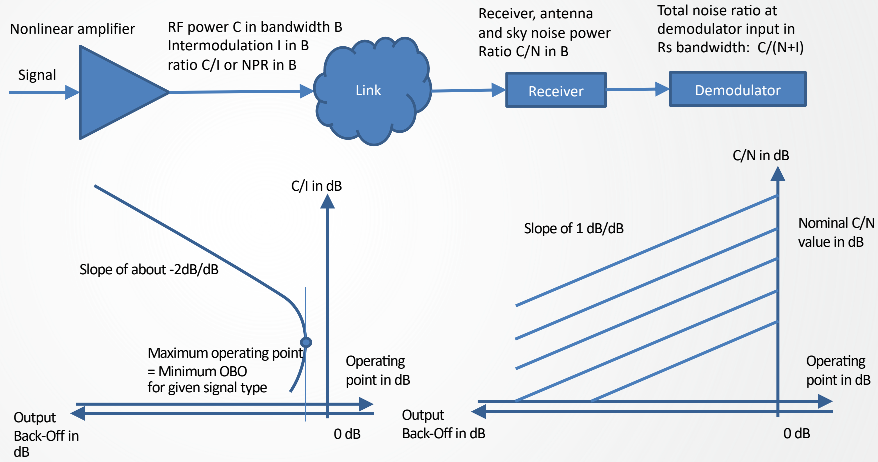
Simplified non-linear link budget

C/N: Carrier-over-Noise

C/I: Carrier-over-Intermodulation

Nominal C/N can be changed by changing the nominal power C or by changing the noise power density No or bandwidth B

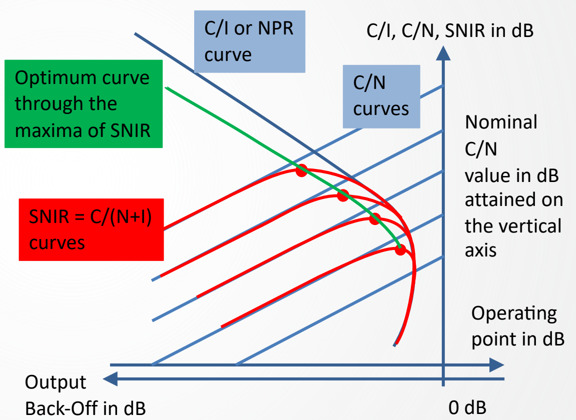


Geometric combination of C/I and C/N

$$\left(\frac{C}{N+I}\right)^{-1} = \left(\frac{C}{I}\right)^{-1} + \left(\frac{C}{N}\right)^{-1}$$

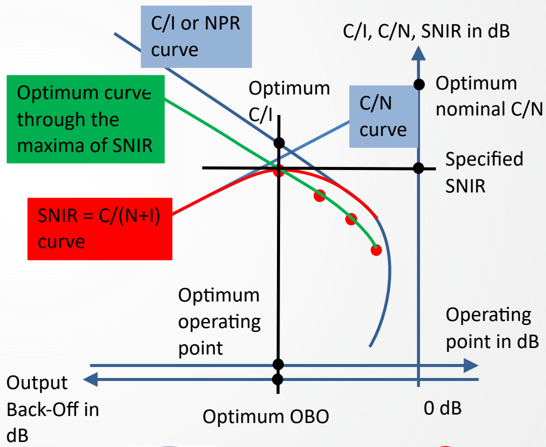
The optimum curve goes through the maxima of SNIR (Signal to Noise plus Intermodulation Ratio) or C/(N+I) curves

It gives the best operating point for a given C/(N+I) in the demodulator



Use of the optimum curve to minimize the nominal RF power

- Specified signal-to-noise-plus intermodulation (SNIR) at the demodulator input:
  → a point on the optimal curve
  → optimum OBO
  → corresponding SNIR curve
  → corresponding C/N curve
  → optimum nominal C/N
- Minimization of nominal RF power necessary to obtain this SNIR at demodulator input



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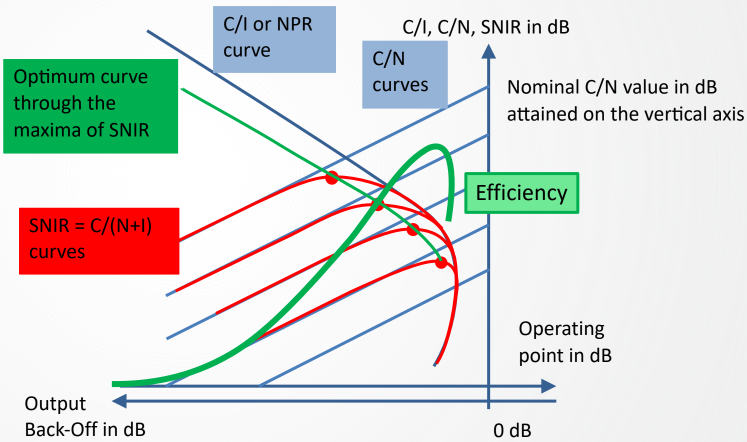
Combination of C/(N+I) curves and efficiency

- We use the efficiency curve versus operating point or OBO



Effect of efficiency

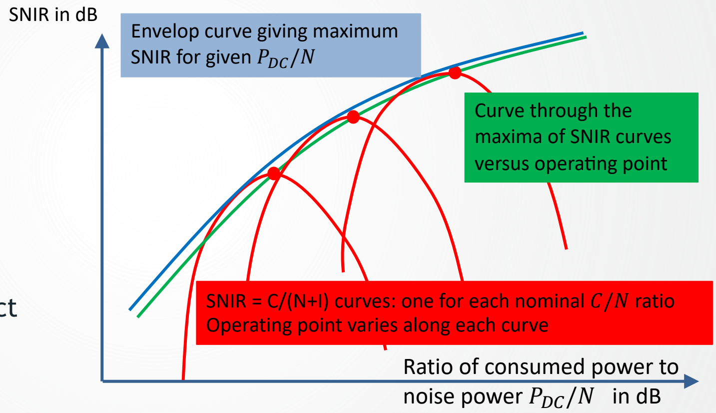
- We will now use the curve giving the amplifier efficiency versus operating point or OBO
- We combine the value of efficiency at a given operating point with the value of the C/N of the curve and the OBO to get the consumed power:

$$\frac{P_{DC}}{N} = \frac{C}{N} \frac{10^{-OBO/10}}{\eta(OBO)}$$

- C/(N+I) curves versus OBO are replaced by C/(N+I) curves versus consumed power

Envelope of C/(N+I) curves versus consumed power

- We get one curve for each value of C/N
- OBO varies along each curve
- Same curves as in the previous picture
- Same curve through all maxima
- The envelope is above the maxima of all curves
- Small improvement on consumed power with respect to previous optimum of nominal RF power



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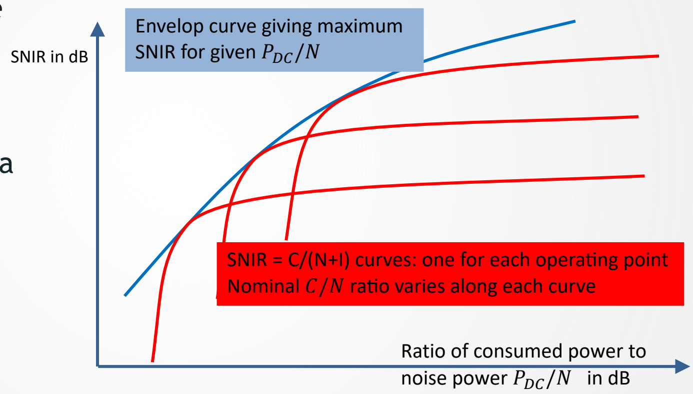
Alternate presentation of the same set of points

- We can also draw one curve for each value of OBO (and thus of efficiency)
- C/N varies along each curve
- There are no maxima on the curves
- They have asymptotes
- We obtain the same envelope



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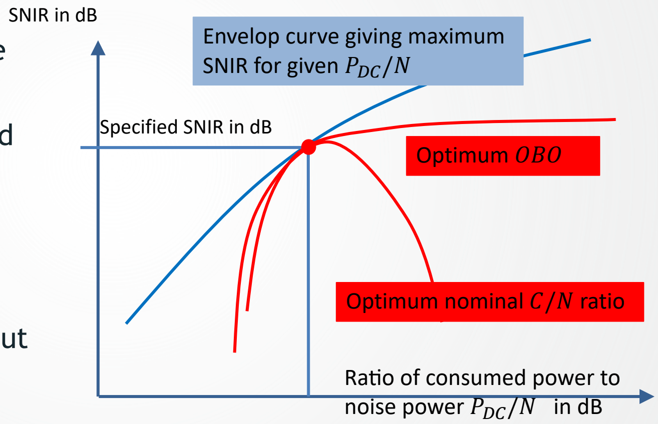
Use of the envelope

- For the SNIR specified at the input of the demodulator:
  → point on the optimum envelope gives the consumed power
  → optimum OBO
  → optimum nominal C/N
- Minimization of the power consumed by the amplifier that provides the specified SNIR at the demodulator input
- Also fixes nominal C/N and OBO



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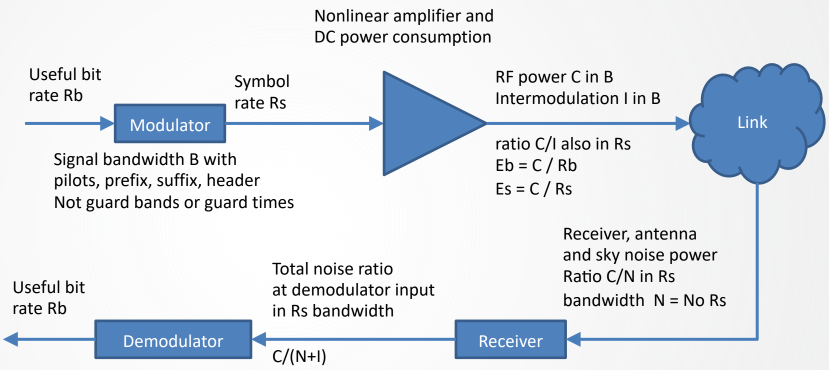
System link budget and capacity

We will now consider the Shannon limit (or the performances of the demodulator) to compute the energy consumed for the transmission of each useful bit



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Transformation of curves

- The performan ce curve of the demodulator gives us the numlber of useful bits that can be received for a specified value of C/(N+I)
- The consumed power per symbol can be transformed in energy consumed per translmitted bit/

$$\frac{P_{DC}}{N} = \frac{E_{DC}}{No}\ \frac{R_b}{R_s}$$

- On vertical axis, we use spectral efficiency Rb/B given in bit/s/Hz
- The channel bandwidth B is larger than the symbol rate Rs (roll-off = 10 to 30% and guard band around 10%)

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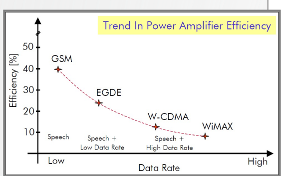
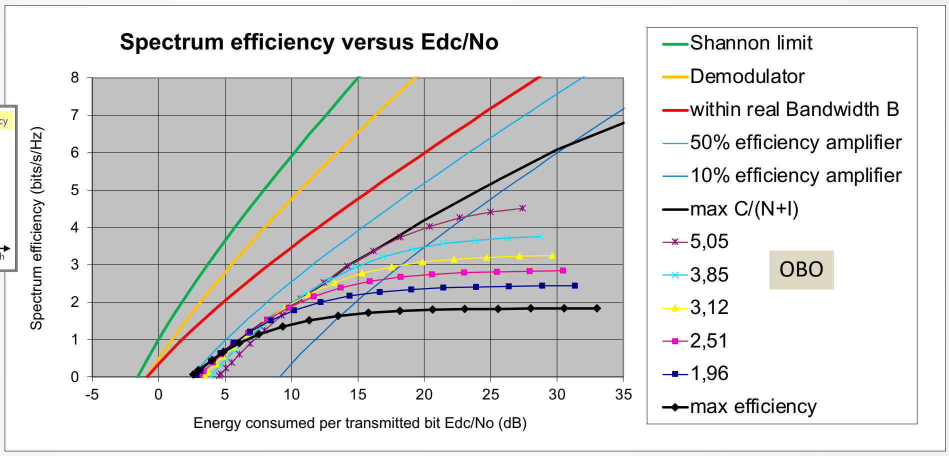
Spectral efficiency curves versus consumed energy per bit





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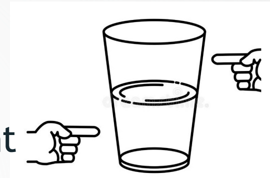
Synthesis on merit curves

1. The curves are far from Shannon limit
2. There is a large margin for improvement



- Efficiency will not be improved significantly by working only on amplifier technology or only on linearizers or only on signals or only on equalizers
- The complete transmission chain must be globally improved with the objective to decrease energy connsumption

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New signals, DVB-SX

- Present signals have been optimized for transmission on an Additive White Gaussian noisy linear channel with no inter-symbol interference (ISI)
- Optimum result is matched filter and Nyquist filter
- These signals are not optimum in a non-linear transmission or a transmission with interference
- New signal have been proposed: “Time packing”, “frequency packing”, “faster than Nyquist”, SC-OFDM, …
- Receiver equalization is necessary with sometimes also pre-distortion at transmission
- Is it possible to get a better practical result by eliminating the constraint of null ISI in a linear additive white gaussian noise channel?

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Possible solutions: Multiplication of the number of links

- Increase the bandwidth
- Use identical links in parallel
- Re-use the same bandwidth on many links in parallel and master interference
  - Increase the number of beams or cells and increase the coverage
  - Increase the number of beams or cells in the same coverage
  - Increase the antenna gain and decrease the RF power for each link keeping the same capacity

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Link budget for broadcasting

The reception coverage area is specified

$S_c = Surface\ of\ the\ coverage\ area$

The equivalent area of the receiving antenna is limited by the physical dimensions and efficiency

$S_r = Equivalent\ Surface\ of\ the\ Receiving\ Antenna$

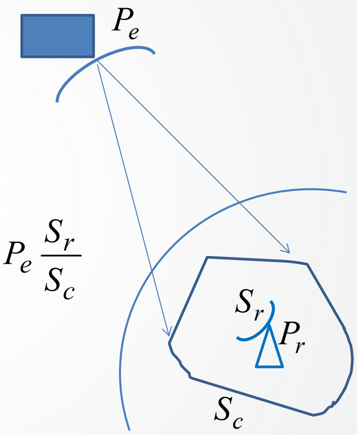
Received power, in first approximation :

$$P_r \approx P_e \frac{S_r}{S_c}$$

Independent of frequency and distance

In addition, consider:

- Losses of equipment (depending on frequency)
- Atmospheric losses(depending on frequency)
- Out of coverage losses (Spill over)
- Gain ripple in the coverage



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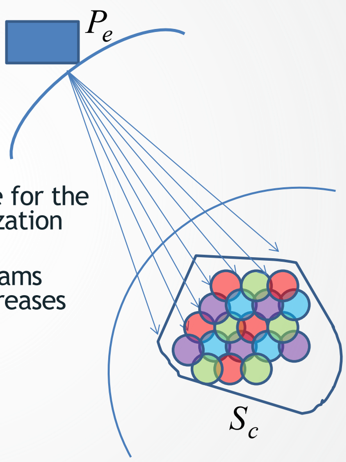
Multibeam link budget

- If the same coverage is divided in cells
- And if it is possible to build a multibeam antenna with one beam for each cell
- **Same total transmit power is needed**

But

- On-board antenna diameter is larger
- Over-spill losses for each beam are interference for the adjacent beam with same frequency and polarization
- Spectrum is divided b y 3 or 4 to minimize interference by increasing distance between beams with same frequency and polarization (also decreases power)
- Number of beams must be high enough > 20
- More complex payload, hundreds of links with frequency mixer, filters, amplifiers, routing of hundreds of waveguides
- In some cases, 3 or 4 antennas



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Higher frequency and bandwidth

- Interesting technical solution
- Capacity increase is proportional to bandwidth increase with a proportional power increase
- Whereas increase of complexity of signals at fixed bandwidth needs much lore power for the same capacity increase
- At higher frequency antennas are smaller for the same gain and it is possible to transmit many beams with a given antenna size and low power per beam
- Beamforming with active antennas is more interesting than MIMO at higher frequency
- However, the cost of microwave devices and antennas is higher, particularly for active antennas
- Part of the gain must be used to decrease interference and self-interference

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Conclusion

- Optimizing the energy consumed per transmitted bit goes in the right direction
- Amplifiers non-linearity and linearizers must be mastered
- The operating point of the linearized amplifier must be optimized for the lowest nominal RF power or the lowest energy per transmitted bit for a given spectral efficiency
- Optimum curves show the limit of increasing spectral efficiency if only the amplifier and its operating point are optimized
- In addition, it is necessary to increase the number of links in parallel:
  - Increase the number of beams for a given coverage for a satellite
  - Increase the number of cells and decrease heir area for ground cell telephony
- Limited by the complexity and cost of the system
- But this limit varies due to the recent increase of the cost of energy
- Hybridization of satellites and ground networks can be used to decreases the costs by using the best suited technology for each case (urban, suburban, rural)

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Thank you for you attention

Questions?

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