Future test benches

for the optimization of spectrum and energy efficiency in telecom nonlinear RF components and amplifiers

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Outline of talk

- Introduction - Presentation of problem
- Base station solutions and test benches
- Space amplifiers solutions and test benches
- Future problems and future needs
- Merit curves for nonlinear amplifiers
- Future test benches
- Conclusion

Introduction - Presentation of problem

- Compromise between frequency bandwidth and amplifier power (nominal RF, useful RF or consumed DC)
- Higher data rates in same bandwidth: Higher spectrum efficiency
- Higher SNR or energy per bit: Higher RF power
- Lower consumed power

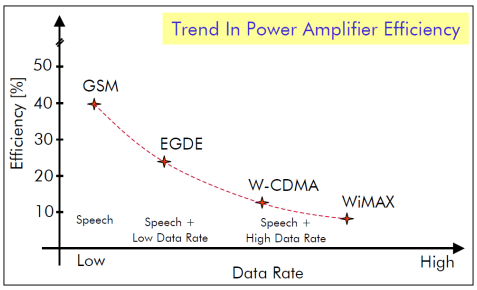
- Higher power efficiency at operating point
  Nonlinear power amplifiers (transistors and tubes)
  But distortion and inter-modulation noise decrease spectrum efficiency

- New technologies or techniques
- Better combined optimization of signals, linearizers and amplifiers

Base station solutions

- Improvement of RF emitters
  - New techniques: linearization, Doherty, LINC, Class-S switching amplifier, …
  - New technologies: GaN
- But new demands on frequency band, number of carriers, RF power, new modulations
- Extrapolation of present curve is not acceptable

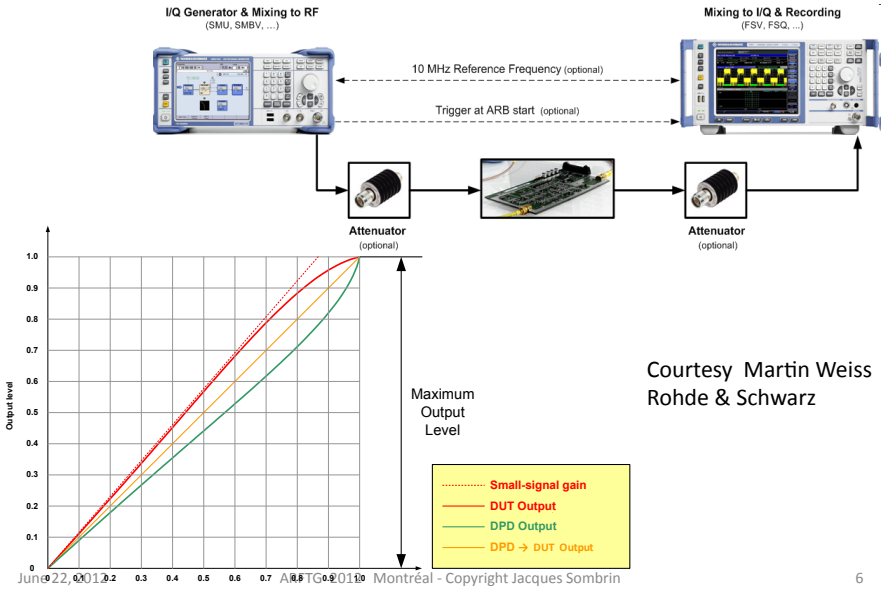
Courtesy Pascal Roux
Alcatel Lucent



Base station test benches

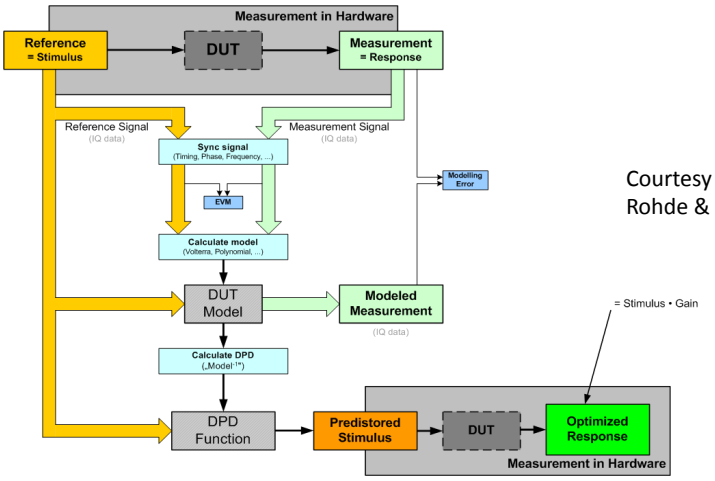
- Measurement of EVM and efficiency in same conditions of operation
- Nobody has been able to write a test specification for a “good nonlinearity” except that it should be easy to linearize and give good inter-modulation and efficiency results when linearized.
  - In the last 2 decades, cellular telephony base station manufacturers have specified that RF nonlinear components should be measured under “best linearization” conditions
    (e.g. Motorola then Freescale optimization of power transistor design)
  - Component level or amplifier test benches can model either a memoryless or a memory nonlinearity
  - Test benches include an adaptive linearizer (a pre-distortion function) for these measurements either in RF or in digital form (on modulation signal)
- The base station or amplifier manufacturer will then build its power amplifier together with a practical linearizer (real time, either analogue or digital) targeting this best linearized performance.

Base station amplifier test bench



Courtesy Martin Weiss
Rohde & Schwarz

Signal processing flow in base station test bench



Courtesy Martin Weiss
Rohde & Schwarz

Space amplifiers solutions

- Optimization of output power and output backoff for:
  - Lowest nominal RF output power for given capacity
  - Or highest capacity for given nominal RF power

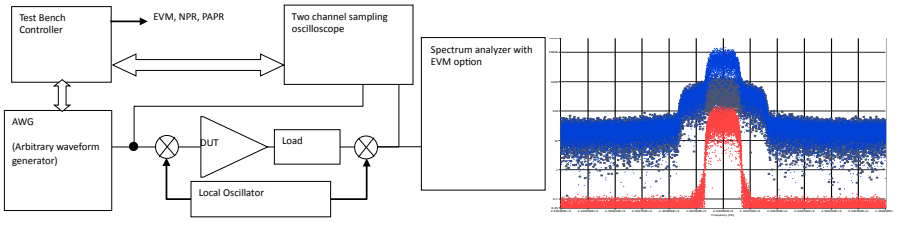
  In a noisy channel given by its SNR = C/N = Es/No

  Use of either SNIR = C/(N+I) or TD = total degradation
- Even better: optimization of consumed power in real working conditions for a given capacity
  - Equivalent to optimization of spectrum efficiency as a function of consumed energy per bit
- Improvement of space traveling wave tube technology to 72% CW efficiency at saturation
  - Efficiency in back-off to be improved
- Linearized amplifier used for multicarrier operations

Space amplifiers test benches

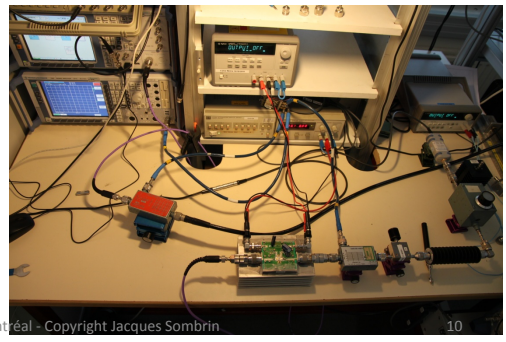
- Custom test benches for space amplifiers
  - Ku or Ka or Q/V band (10 to >50 GHz)
  - 0.5 GHz instantaneous bandwidth, max 900 MHz
  - Short term objective: 1.5 GHz inside a 3 to 5 GHz bandwidth
- Measurement of NPR or EVM and efficiency at tube level
  - Hardware linearizer difficult to include in tube measurement (because of specific tuning)
  - Bandwidth too large for software linearizer
  - Tube is memoryless but a linearized amplifier may have memory because of the solid state linearizer
- Measurement of NPR, EVM, BER, RF power and consumed power at amplifier or linearized amplifier or payload level

Space amplifiers test bench



Test bench used for generation of test signal, measurement of sampled input and output signals and computation of EVM and NPR

Courtesy CNES and XLIM



Equipment used in test benches

- Arbitrary waveform generators (or DAC)
- Digital scopes (or ADC)
- Modulated signal generator and signal analyzer
- Agilent, LeCroy, Tektronix, Rohde & Schwarz

- RF generator, IQ modulator or mixer, filters, couplers
- Active or passive loads or matching circuits for unmatched components,
- DC couplers, power supply, …

- Computer and software

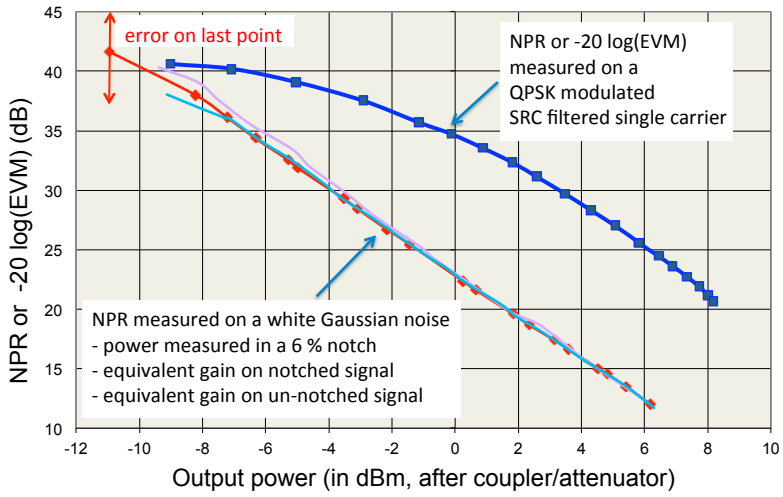
Main limits of present equipment

- 8 bits or ±127 gives around 1% EVM floor or a 40 dB NPR floor (if ADC and DAC used at maximum dynamic)
- Sampling frequency of 1GHz for 2 channels limit bandwidth to less then 1GHz (with IQ mixer)
- Filters and mixers in microwave hardware introduce RF memory at highest bandwidth
- Record length of 20 Mbytes limits signal duration to 10 milliseconds at 1 GS/s

- Newer equipment with bandwidth > 60 GHz, 160 GS/s, 2 Gpts memory, same limits on signal duration, 8 bits, ENOB of 5.5 but would give 0.5% EVM
- Direct test of amplifier possible
- Prices around 300 k€ each AWG and scope

NPR and EVM results for a linearized TWTA with 500 MHz signal bandwidth

with an 8 bits arbitrary wave generator at 1 GS/s, 2 channels IQ



Use of NVNA ?

Replace time domain analysis (AWG and digital scope) with frequency domain analysis (spectrum generator and vector analyzer)

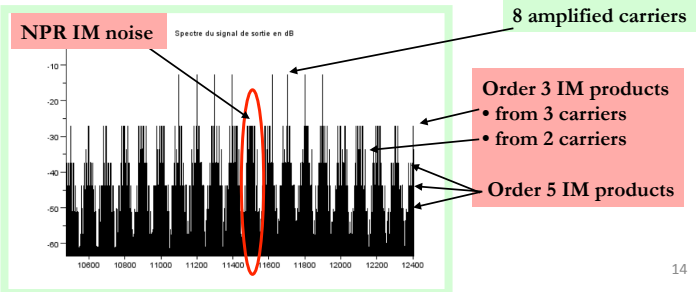
Easier for unmatched component or on-wafer measurement

Frequencies of products well known, small bandwidth, higher dynamic

Possibility to simulate NPR and EVM from one carrier AM/AM and AM/PM measurements (with power sweep)

Possibility to measure C/I with 2 or a limited number of carriers

Possibility to measure wideband NPR with an 8-carrier measurement if wide bandwidth (1 GHz) and high resolution (1 kHz)

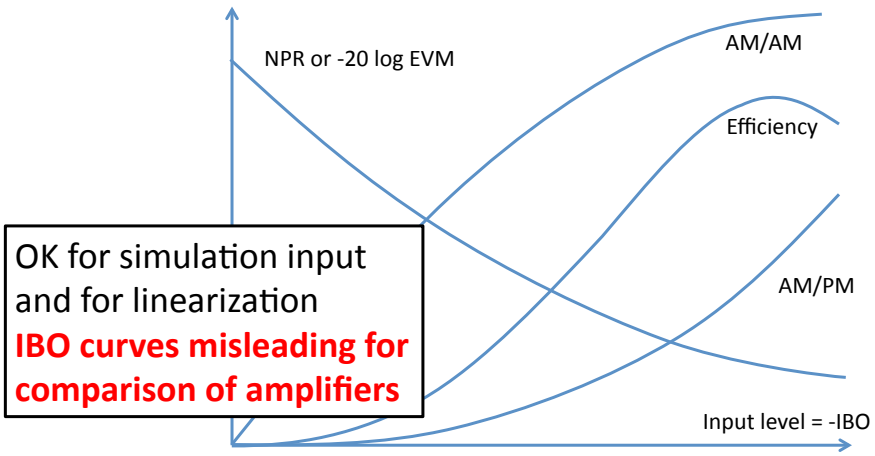


Future problems and future needs

- Higher capacity
- Higher center frequency and instantaneous bandwidth: RF up to 60 GHz LANs, optics
- More complex modulation and coding:
  - SC-OFDM, time and frequency packing or "faster than Nyquist", reduced roll-off and reduced guard bands
- Multicarrier and multi-standard operation
- Higher RF power per carrier
  - More concern of operators, users and public on RF power, consumed power and dissipated power
  - cooling power is no longer negligible in base station

Merit curves for nonlinear amplifiers

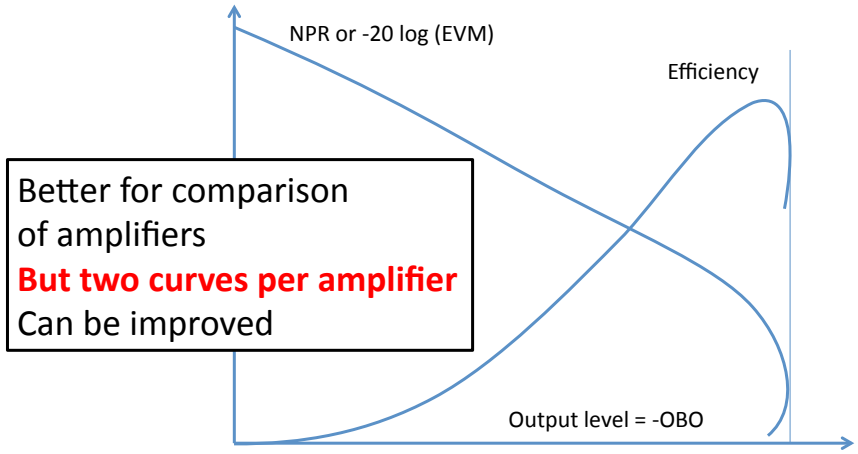
AM/AM, AM/PM, NPR or EVM and efficiency vs. IBO in CW or in same conditions of operation



OK for simulation input and for linearization
IBO curves misleading for comparison of amplifiers

Merit curves for nonlinear amplifiers

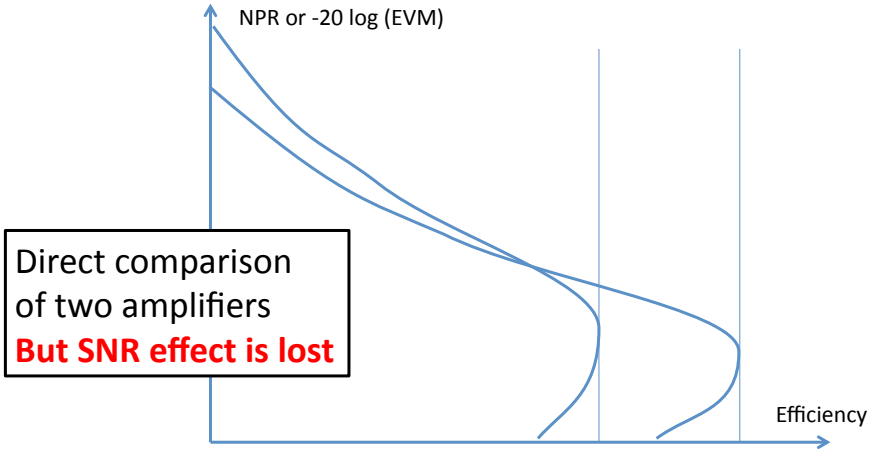
NPR or EVM and efficiency vs. OBO
in same conditions of operation



Better for comparison
of amplifiers
But two curves per amplifier
Can be improved

Merit curves for nonlinear amplifiers

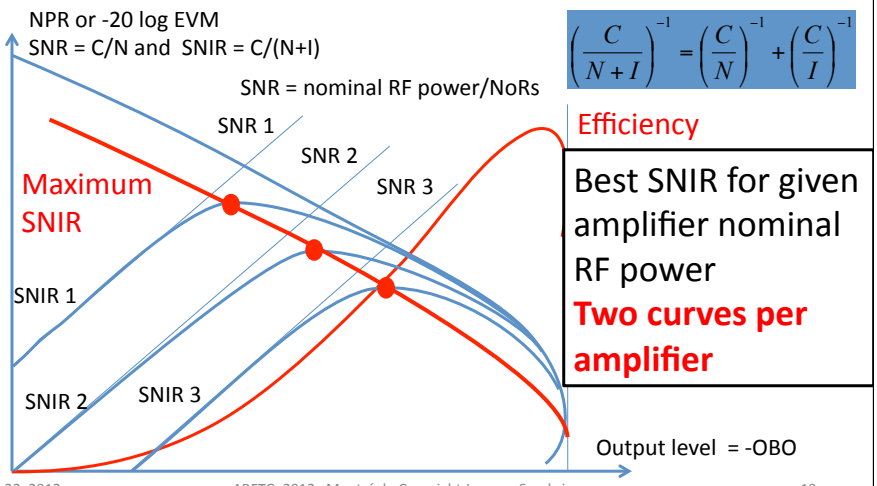
NPR or EVM vs. efficiency in conditions of operation



Direct comparison
of two amplifiers
But SNR effect is lost

Merit curves for nonlinear amplifiers

SNIR and efficiency vs. OBO in conditions of operation for different nominal SNR

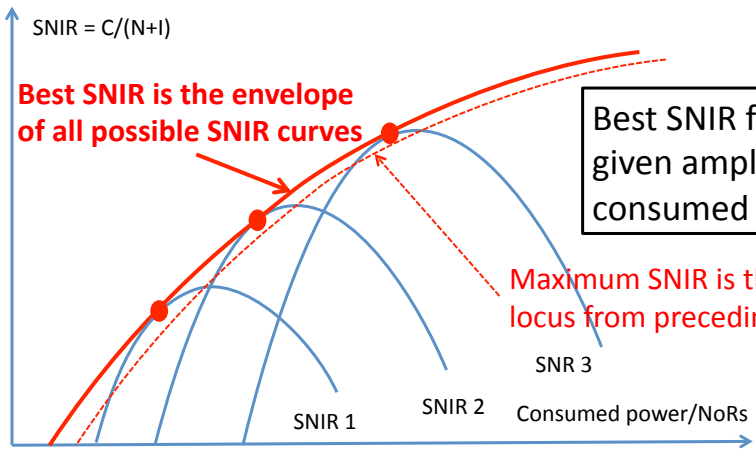


$$\left(\frac{C}{N+I}\right)^{-1} = \left(\frac{C}{N}\right)^{-1} + \left(\frac{C}{I}\right)^{-1}$$

Best SNIR for given amplifier nominal RF power
Two curves per amplifier

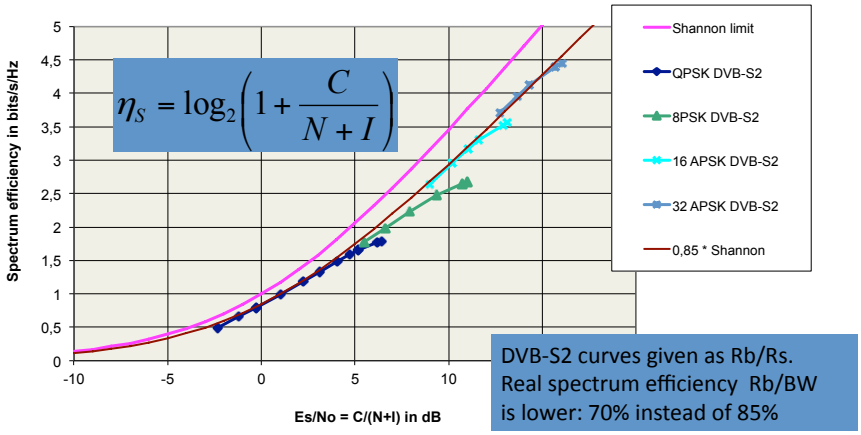
Merit curves for nonlinear amplifiers

SNIR vs. power consumed by amplifier in conditions of operation (relative to channel noise)



Best SNIR for given amplifier consumed power

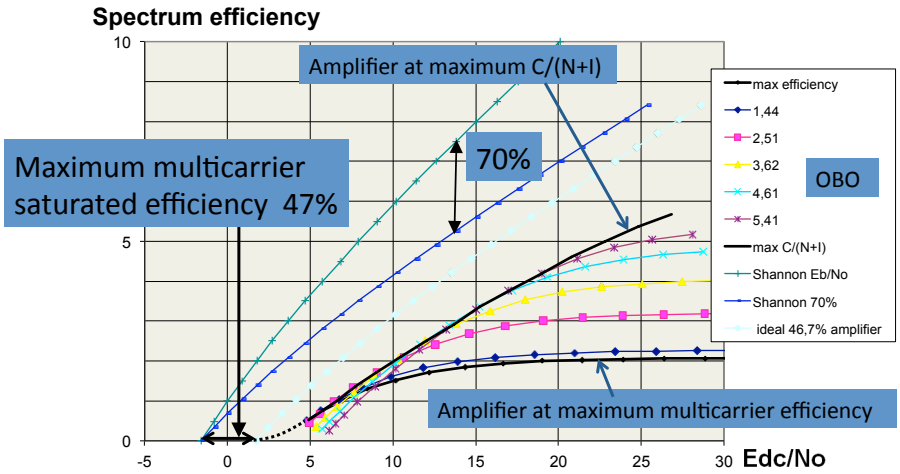
Shannon curve (or spectrum efficiency versus SNIR curves for given coding and modulation)



DVB-S2 curves given as Rb/Rs. Real spectrum efficiency Rb/BW is lower: 70% instead of 85%

Combining both curves

Spectrum efficiency vs. consumed energy per transmitted bit



Merit curves - Synthesis

1. Huge margin for optimization
2. Combined amplifier, linearizer and signal optimization is independent of link budget
   - Depends only on amplifier measurement curves and on demodulator curve (standard or Shannon limit)
   - Can be done on a laboratory test bench
3. Optimize most needed resources:
   - Spectrum efficiency
     (= minimize product of time and bandwidth)
   - Energy consumed for each transmitted bit

Note: A similar merit curve can be obtained with dissipated power for applications where it is the main constraint (space, hand-held, base stations, …)

Future test benches – Wish list

- Combination of base station test bench features and space amplifier frequency and bandwidth (60 GHz for LANs)
- Higher spectrum efficiency signals (time and frequency packing, low roll-off, single carrier, multicarrier or OFDM), SC-OFDM in operation conditions
- Computation and output of best compromise between either RF or consumed energy and spectrum efficiency of linearized amplifier in conditions of operation
  - taking into account nominal RF power and operating point of the device, thermal noise, inter-modulation noise and interference: SNIR or SNIIR.
- Real time to allow combined optimization of amplifier, linearizer and signal

Future test benches – How to

- New front ends (frequency, bandwidth)
- Much higher sample frequency (keeping the same memory length and depth or more): high frequency 10 to 12 bits ADC and DAC and fast memory storage
- Computation of best linearization curves
  - including the case of memory nonlinearity
- Simulation of new test signals
- Propagation conditions, channel simulation, MIMO
- Adaptive equalization of receiver or signal analyzer
  - because pre-distortion of transmitted signal will no longer be sufficient
- Measurement of ACPR, EVM or NPR and BER
- Computation and presentation of optimum operating point performances

Short term roadmap

- Presentation of merit curves for optimization of amplifiers, linearizers and signals
- New signals (faster than Nyquist, reduced roll-off…)
- Using an existing analog or hardware linearizer for high bandwidth measurements is simpler but less flexible:
  - choice of hardware linearizer depends on the customer, more cumbersome tuning compared to computing AM/AM and AM/PM curves and storing them in LUT
- Propagation conditions effect may be simulated after measurement
  - then equalization of receiver may not be real time
- Higher center frequency and wider bandwidth
  - Higher sampling rate, ENOB ≥ 10, longer memory
  - Use RF mixers and filters

Conclusion

- Huge margin for optimization of nonlinear amplifiers and signals in operating conditions
- Most measurements available in present benches
  - Link budget is not needed only standard demodulator curves
  - Improved presentation of optimum results of linearized amplifier
- New hardware for higher frequency and bandwidth
- Wide band propagation and MIMO
- Receiver or signal analyzer equalization

References

Measurement of nonlinearity C/I, NPR, EVM, TD (total degradation)

R. J. Westcott, "Investigation of multiple FM+FDM carriers through satellite TWT operating near to saturation", Proc. IEE, Vol. 114, No. 6, June 1967, pp. 726-740

J. Sombrin, "Non-linéarités des tubes à onde progressive", Note Technique CNES N° 28, janvier 1976

J. Sombrin, "Simulation des non-linéarités", Note Technique CNES N° 74, juillet 1977

M. Begue, "Testing new digital RF communication systems with smart stimulus and analysis", The 1995 advanced test solutions for aerospace and defence seminar, Hewlett-Packard

S. W. Chen, W. Panton, and R. Gilmore: "Effects of nonlinear distortion on CDMA communication systems", IEEE Trans. on Microwave Theory and Techniques, vol. 44, no 12, December 1996, pp 2743-2749

A. Mashhour and A. Borjak: "A method for computing error vector magnitude in GSM EDGE systems-simulation results", IEEE COM Letters, vol. 5, No 3, March 2001, pp. 88-91

Anakabe, A et al.: "Ka-band multi-port amplifier characterisation for space telecommunication operation", in 6th Int. Vacuum Electronics Conf., IVEC 2005), 20–22 April 2005, Nordwijk, The Netherlands.

J. Sombrin ''Conditions d'équivalence des mesures ou simulation de NPR et d'EVM'', JNM 2011, 4D-1

J. Sombrin "On the formal identity of EVM and NPR measurement methods: Conditions for identity of Error Vector Magnitude and Noise Power Ratio " EuMC 2011, Manchester

C/(N+I), TD, Criterion for comparison and optimization of amplifiers

"Definition of C/(N+I)", COMSAT Technical Review, Vol. 2, N° 2, Fall 1972, pp. 454-475

Sombrin, J.: "Critère de comparaison, d'optimisation et d'utilisation optimale des amplificateurs de puissance non-linéaires", NoteTechnique CNES DT-96-16-CT/AE/TTL/HY, 24 mai 1996.

Sombrin, J.: "A new criterion for the comparison of TWT and linearized TWT and for the optimization of linearizers used in transmission systems", ESA-NATO 1997 Workshop on Microwave Tubes for Space, Military and Commercial Applications, 7–10 April 1997, ESTEC, Nordwijk, The Netherlands.

Casini, E.; De Gaudenzi, R.; Ginesi, A.: "A semi-analytical method to assess satellite nonlinear channel performance", Proc. 23rd AIAA ICSSC, 2005, Session ACT3, Paper 1000071

M. Aloisio, E. Casini and A. Ginesi, "Evolution of space travelling wave tubes requirements and specifications for modern communication satellites", IEEE Trans on Electron Devices, Vol. 54, No 7, July 2007, pp. 1587-1596

L. Lapierre, J. Sombrin : "A New Criterion for the comparison of Non-Linear Amplifiers and the Optimization of Linearizers and Amplifiers used in Transmission Systems", workshop EuMW 2010

J. Sombrin: "Optimization criteria for power amplifiers", International Journal of Microwave and Wireless Technologies, Volume 3, issue 1, pp. 35-45, published on line February 3, 2011

J. Sombrin, "Critères d'optimisation des amplificateurs non linéaires", Note Technique CNES 2011

Thank you for your attention

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