After the discussion of issues of current dynamics of the receivers,

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presents:

“ Measurement of all products intermodulation on HF receivers, with 24000 telegraph channels

Introduction

- The title, although it may seem, it is no exaggeration. Certainly not have used more than two tens of thousands of generators and 24 thousand input ports combiner, but the results are the same as if they were present, at the receiver under test, 24088 telegraph signals, independent, modulated with a speed of word to fill, each, a band of 500 Hz.
- This method has used since sixty years in all the wide-band telecommunications applications with a single carrier and multi telephone channels FDM or in TDM single or multi-carrier (k-QAM modulation), on broadband analog/digital converter, where the distortions and spurious free, introduced under real operating conditions, are not values reflected in the traditional two tone test.

- The method is known by the term "Noise Power Ratio Testing" or simply: NPR testing. A single value, expressed in dB, replacing dozens of measures (IP2, IP3 ... IPn - IMD2, IMD3 ... IMDn - DR2, DR3 ... DRn)

- To make known to as many ham as possible the simplicity and precision of such a method, I would like to take this opportunity to point out, based on my experience, the fundamental concepts of the effects of "nonlinear" distortion.

Any electric “Two-port network” can introduce on the signal only two types of distortion:

- **Linear**
  - **The linear distortions are independent of signal amplitude** can be either amplitude and / or phase (e.g., Response amplitude and phase vs frequency that modify the spectrum of the received signal).

- **Nonlinear**
  - **The nonlinear distortion depends on the size of the signals** and are also amplitude and / or phase. The so-called **AM / AM** and **AM / PM.** In the TV industry uses terms “**differential gain and phase** “. Different way to express the same things.

Effects of distortion

- **The “linear “ distortions change the spectrum of the signal without adding anything.**

  From the two-port network coming out the same signals that are incoming (Different forms in frequency and time if is present linear distorsion).

- **The "nonlinear" distortions gives rise to many spurious signals at different frequencies and amplitudes**.

  The signals coming out of the two-port network are more numerous than those who entered.

Transmitters and receivers

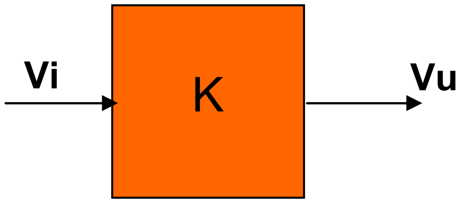
We will treat only the effects of nonlinear distortion, AM/AM, of receiver. However, keep in mind that the same concepts also apply to the power amplifiers of the transmitter .

- Just remember the substantial difference of the different effects due to nonlinear distortion.
  - **In a receiver are distorsion products of signals of the adjacent channels that cause interference in band.**
  - **In a transmitter is distorsion of the main signal that cause interference in adjacent channels** (Or, in the band just wide spectra, scrambled or multicarrier OFDM signal. This anomaly is known as "Spectral Regrowth").

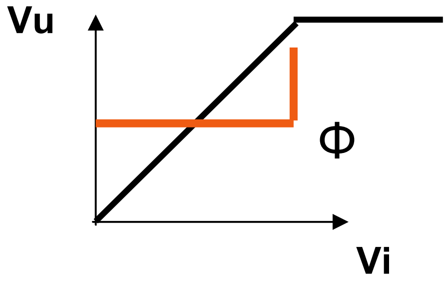
Linearity

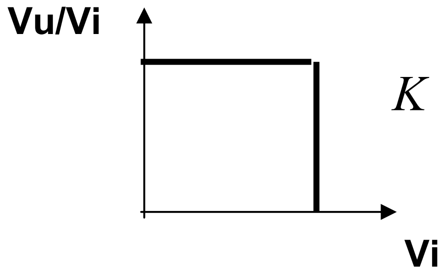
- If an amplifier had the ratio output voltage, **Vu**, and the input voltage, **Vi**, always equal to a constant K (gain or loss) and constant phase, until the saturation ...

Ideal limiter



$$V_u = K \cdot V_i$$





$$K = \frac{V_u}{V_i}$$

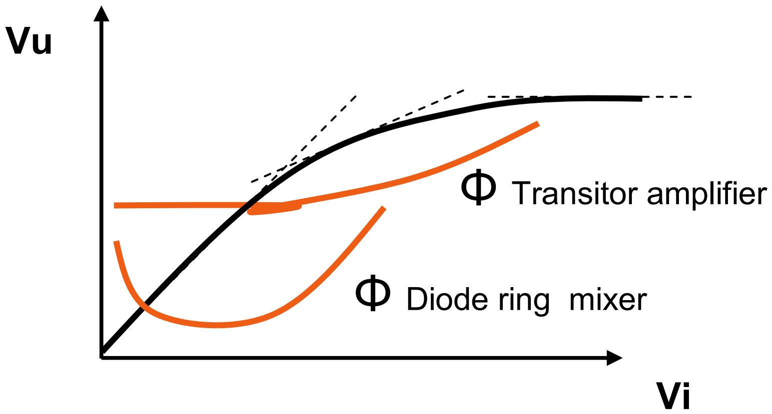
- ....never would introduce any "nonlinear" distortion on the input signals.

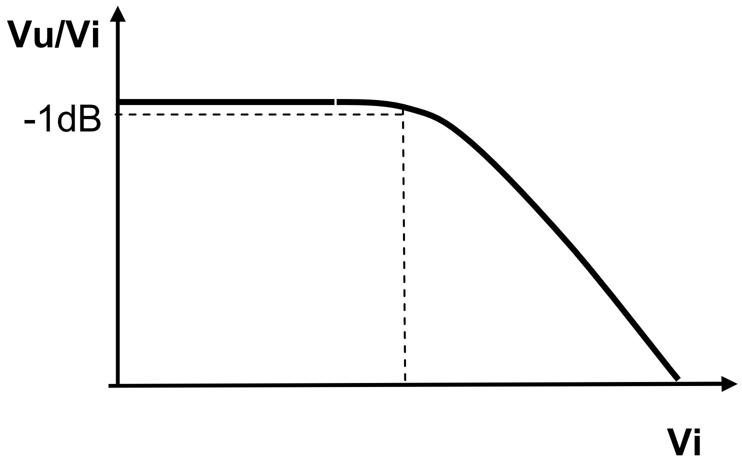
This means both the AM/AM and AM/PM would remain constant regardless of the amplitude of the input signals (up to saturation).

A good performance analog–digital converter has a behavior very similar to an ideal limiter

Nonlinearity

- The reality, especially for analog circuits, is very different, widely known….





1 dB Compression

- The relation from output voltage to input voltage is no simple first order equation (a straight line), but it approximates a line with a component quadratic, cubic …. functions

$$V_u = K_1 V_i + K_2 V_i^2 + K_3 V_i^3 + K_4 V_i^4 \ldots\ldots K_n V_i^n$$

Simplifying example

- Consider, for simplicity of calculation, a quadripole whose output voltage, Vu, has the follow relation with input voltage:

$$V_u = K_1 V_i + K_2 V_i^2$$

- Applied to the quadripole two sinusoidal signals with equal amplitudes and different frequencies, the total signal will be:

$$V_i = V \cos \omega_1 t + V \cos \omega_2 t$$

- At the output of the quadripole we get more signals of those present to the input:

$$V_u = K_1 (V \cos \omega_1 t + V \cos \omega_2 t) + K_2 (V \cos \omega_1 t + V \cos \omega_2 t)^2$$

Second order IMD

- with trigonometric substitutions, we obtain the output signals, Vu :

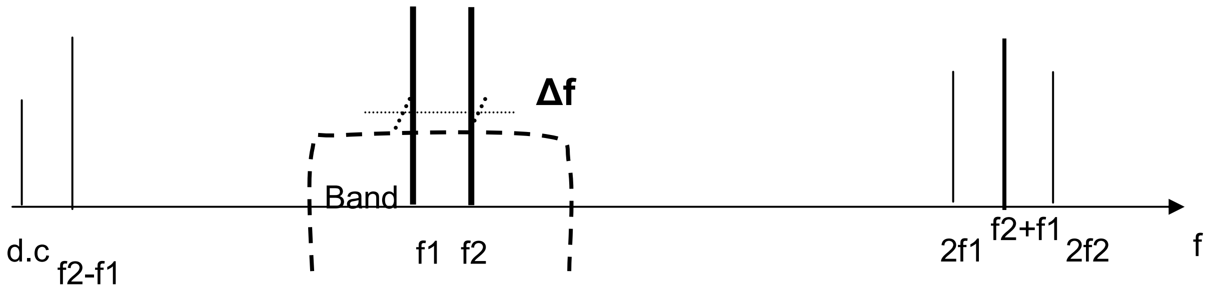
$$V_u = \underbrace{K_1(V\cos\omega_1 t + V\cos\omega_2 t)}_{\text{Input f1 and f2 signals}} + \underbrace{K_2 V^2}_{\text{d.c}} + \underbrace{\frac{1}{2}V^2\cos 2\omega_1 t + \frac{1}{2}V^2\cos 2\omega_2 t + ..}_{\text{Two harmonics 2f1 and 2 f2}}$$

$$\underbrace{+ K_2(V^2\cos(\omega_1 + \omega_2)t + K_2 V^2\cos(\omega_2 - \omega_1)t}_{\text{Second order products f2+f1 and f2-f1}}$$

- At the output beyond the two incoming signals, we have several signals generated in the quadrupole: a d.c. component, two second harmonic of the signals f1 and f2, two components with frequencies respectively the sum and difference frequencies of the two signal applied.
- The sum and difference of the two tones are called products intermodulation of the second order, **IMD2.**

Considerations on even order IMDn

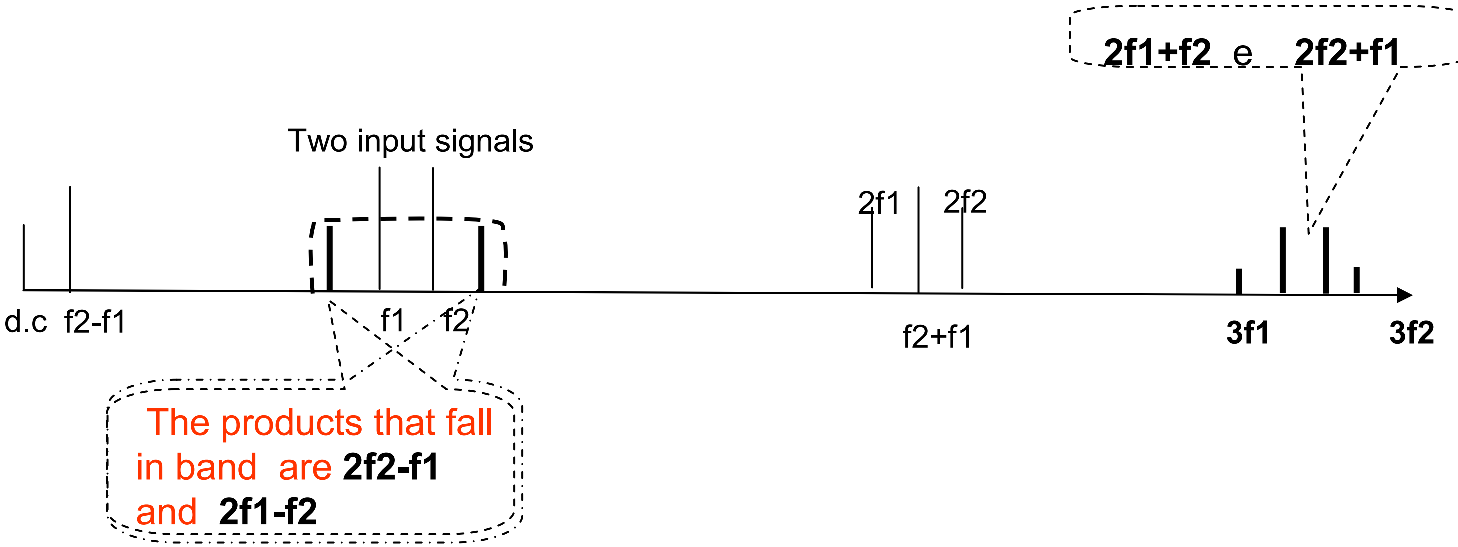
- ..in the frequency domain we get..



- The signals generated by the even orders of IMD (2-4-6 etc.) tend to be out-of-band for most RF applications and easily removed by filters. This is true for all the quadripole RF inputs that have a narrow band as professional receivers up to the 80s, thanks to sophisticated preselectors (e.g., R-390 Collins), the second-order intermodulation was never a problem.
- Today, with irreversible evolution to design multi–octave (broadband) amplifier, mixer, etc you should be careful before say that the receiver under test introduce only distortion of odd-order.
- The easiest way to lessen second order IMD is to use a push-pull configuration

Third order IMD

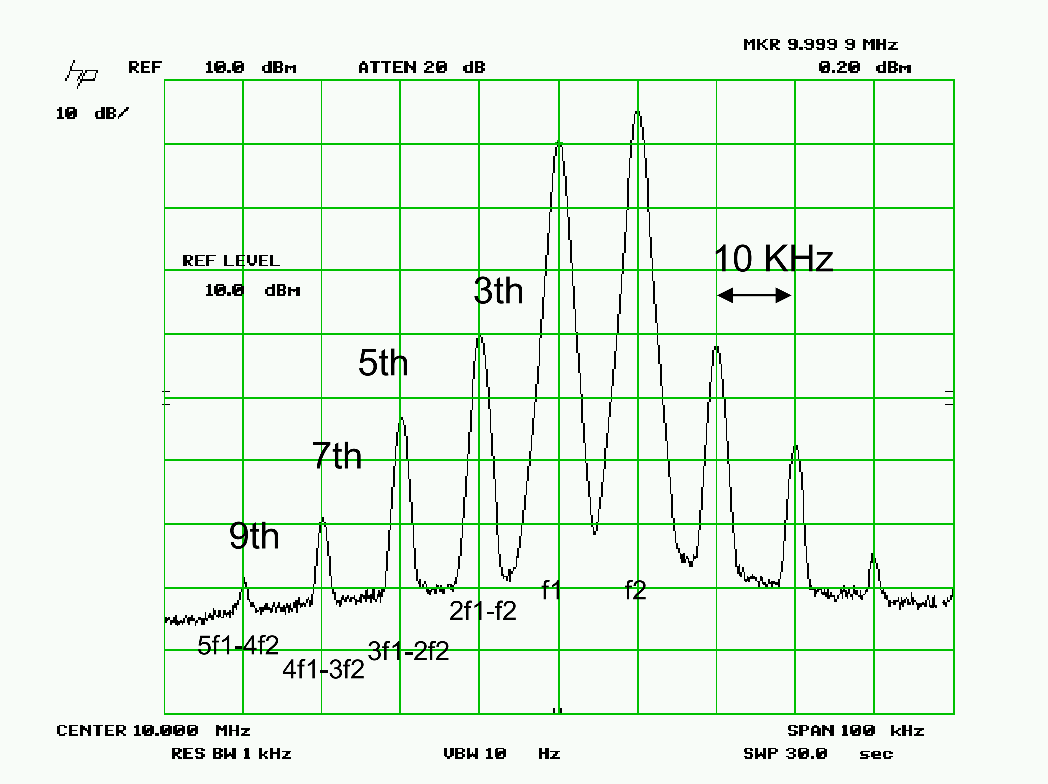
- If now we consider also the cubic component of the non-linearity we get, in addition to the spurious second-order, six more signals



- Only two signals entering and coming out eleven . You imagine how many signals coming out of a non-linear receiver when entering tens of strong signals with all the different frequency spacing (e.g., during a contest). If, then, we consider also the all products IMD of nth-order, the number of all unwanted signals tend to be noise.

nth-orders over

- All products generated by odd order IMD (3th, 5th, 7th, 9 th etc..) tend to be in -band, around the wanted signals (f1 and f2).
- There is not countermeasure to eliminate these unwanted signals, but only try to design, systems more linear as possible.



Two tone test

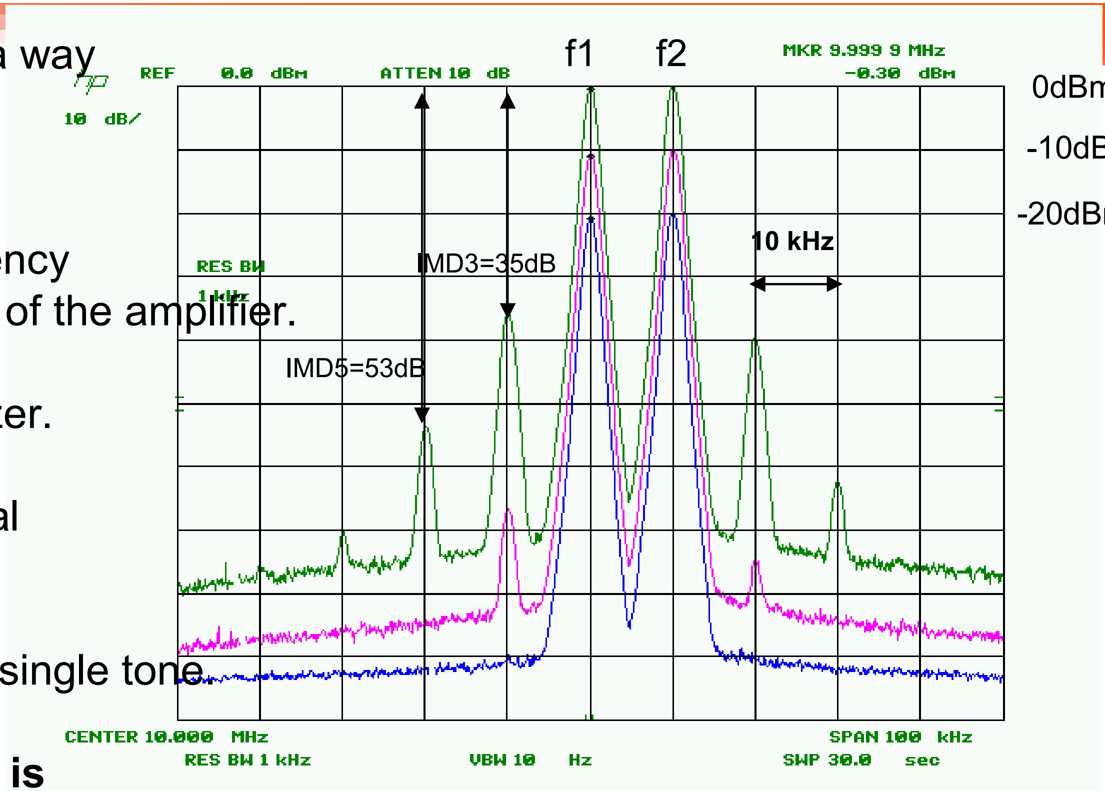
Avantek introduced this measure in 1963 as a way
to specify the non linearity of RF amplifiers,
crossed by a single modulated carrier.

The amplifier is loaded by two tones at frequency
f1 and f2 of equal width, within the bandwidth of the amplifier.

The output is connected to a spectrum analyzer.

The input power is the power sum of individual
tones (+3 dB).

The PEP is 6dB higher than the power of the single tone.



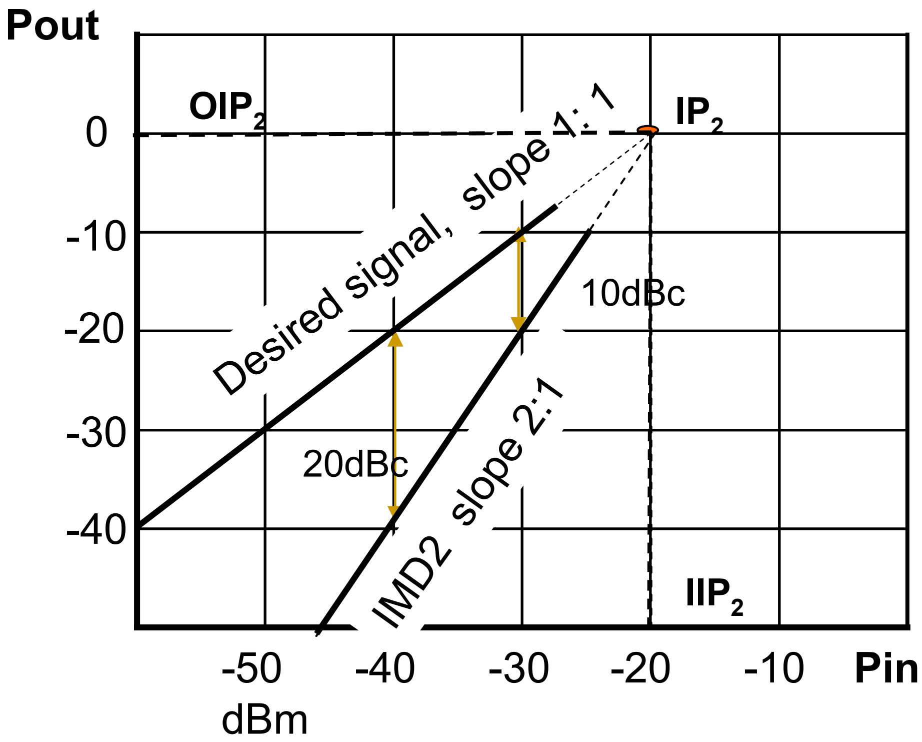
If there is no linear distortion and AM / PM is negligible in the whole dynamic of the input power the spurious are symmetrical around f1 and f2.

For each one dB of increase of the input signal the IMD of order n increases n dB

In this case it is sufficient to know only the value
of IMD in an order n, corresponding to a power input,
to extrapolate the value of IP of n order.

Intercept Point, IP2

- The second-order IMD increases with the square of input voltage
- The hypothetical point where it would meet the curve of the desired signal and the unwanted signal IMD2 is called second-order Intercept Point, **IP2**.
- **In point IP2 by definition IMD2 = 0 dBc**
- The IPn in amplifiers can be referred either to the input power, **IIPn**, or output power,**OIPn**.
- **In radio receivers (RF enters and exits BF) of course always refers to the input power and is simply called "IPn"**
- **If IP2 is known we can calcolate the IM2 values vs input power..**



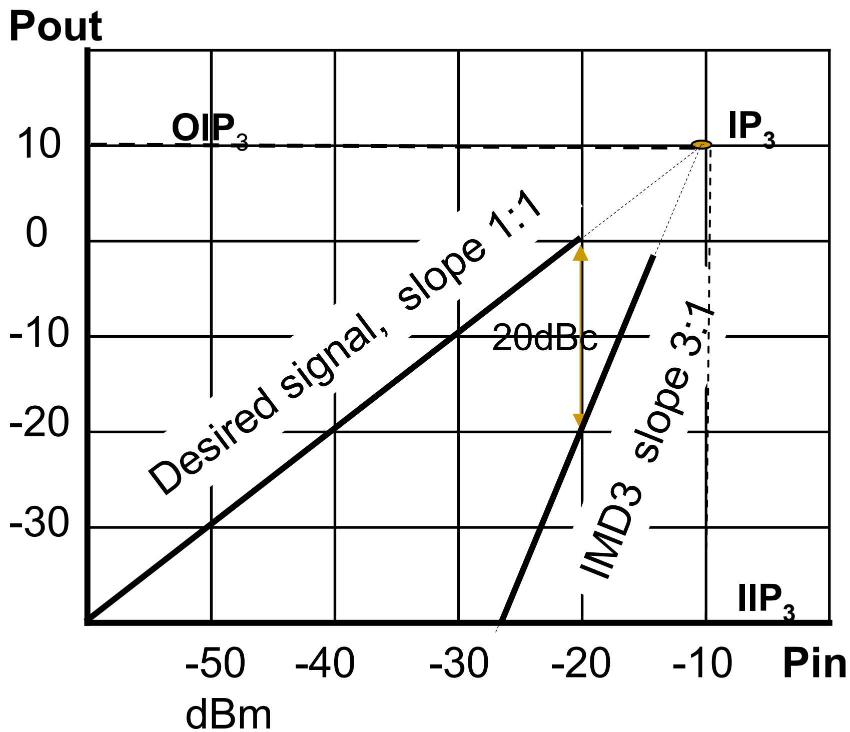
In logarithmic unit , we have :

IMD2 (dBc) = IP2 (dBm) – Pin (dbm)

Intercept Point, IP3

- The third order IMD increases with the cube of input voltage
- The hypothetical point where it would meet the curve of the desired signal and the unwanted signal IMD3 is called third order Intercept Point, **IP3.**
- **In point IP3 by definition IMD3 = 0 dBc**
- **If IP3 is known we can calcolate the IMD3 values vs input power..**
  In logarithmic unit , we have :

IMD3 (dBc) = 2 (IP (dBm) – Pin (dBm))



To continue should be measured IMD5, IMD7, IMD9 and so on, obtaining IP5, IP7, IP9 .... IPn.

Dynamics of receivers, DR

- From the seventies and widespread method of measuring the dynamic range, DR, receivers with single (BDR) and two tones (IPn- DRn)
- The DRn is the difference (in log unit) between the max level and at the mininum level (MDS)
- The max level is determined of the interfering power in the incoming Rx (at different offset frequency (f2-f1)) that increases the output, the MDS value of 3 db on the desired channel,
- In two tone test signal f1 and f2 are considered interfering, and the receiver is tuned, in the case of DR3, on the frequency 2f2-f1 or 2f1-f2.
- In recent years I have seen, on OM magazine, to use frequency spacing (offset) of 100-50-25-20-10 -7-5-3 -2 kHz up to 2.4 kHz SSB channels that 500 Hz CW channel.

Test in field

- Then for each value of frequency offset, we have a huge values family IPn and DRn (for n = 2.3,4 and 5) multiplied by every amateur band into the two classic conditions: high to low sensitivity (Pre on or off).
- A considerable amount of data to interpret and difficult to compare. But what is surprising is that with dozens and dozens of "numbers", yet we do not get a full assessment for confirmation of the true loss of sensitivity, caused by a high number of signals at the input receiver.
- The effective loss of comprehensibility of a weak signal , due to noise generated by adding random in amplitude and phase of dozens of signals with different frequency spacing in entering the front-end receiver, may be different than two tone test (e.g. the distorsion product amplitude may be dependent on the determinated offset frequency) .
- One can understand how, sometimes, when comparing two receivers stressed by so many strong signals, switching in real time the same antenna, you can hear a low signal to the receiver less powerful (as values of two tone test) while the another, the weak desired signal is not decipherable.

Multi tone test

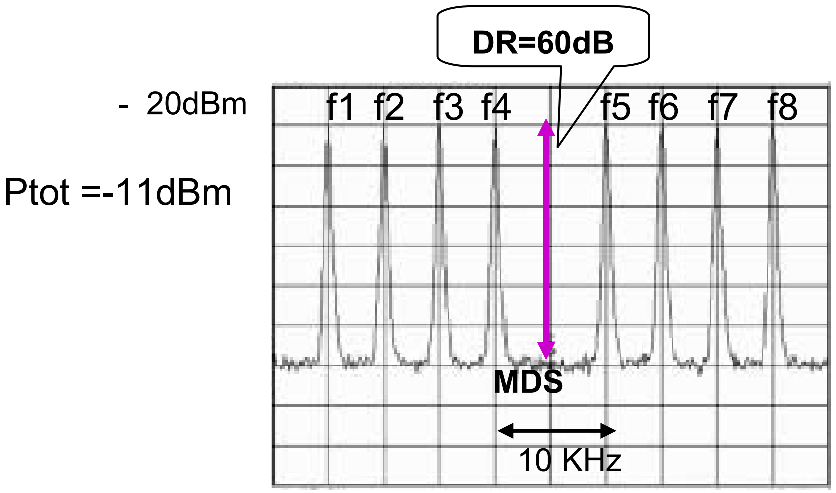
- We have seen that the classical two-tone test does not provide an assessment that matches the real conditions when the system is crossed by many signals. The two tone test has many shortcoming for broadband receiver loaded with many signal.

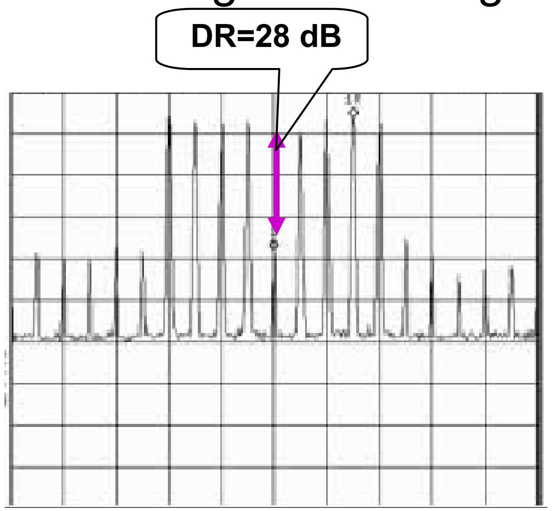
- Even on the transmitters is understood, in the eighties, that microwave amplifiers for scramblered (broad-spectrum) single carrier in ultra linear modulation (n-QAM) or multi-carrier (OFDM), introduce distortions on the spectrum (spectral regrows) not justified by the good values of IP3, measured with the classic two tone test. Everything was clarified with measurements at least eight, also modulated, tones test (Patend in Telettra, 1984- now Alcatel-Lucent)

- A eight uncorrelated tones (four above and four below the desired channel give results more reality over two tone est.

Test with 4 + 4 tones

- Loading the receiver, through a complicated bank with eight generators, leaving an empty space on the desired receive channel, we observe:
- **Increasing the total input power, you see grow, in the clean desired channel, all possible products of nth -order IMD of all possible freguency spacing.** $\mathbf{nf_m - (n-1)f_{m-1}}$ e $\mathbf{(n-1)f_{m-1} - nf_m}$ Where m is equal to the number of tones .
- Becomes meaningless the concept of IP as it becomes immediately the actual value of the quadrupole's dynamic in the presence of the eight interfering





Input Powers of receiver

- The total power of uncorrelated tones of the same amplitude is given by the power of the single tone multiplied by the number of tones, m:

Ptot = m P In logarithmic unit , we have :

$$Ptot_{(dBm)} = 10\log(m) + P_{dBm}$$

- The peak to RMS voltage , increases by “ Crest factor “ :

$$Crest\ factor_{(dB)} = 10\log(2m)$$

- (e.g., Two uncorrelated tones may, at times, add in - phase, create the maximum instantaneos peak voltage of 6dB higher than RMS voltage.

100 - 1.000 -10.000 tones

- If we analyze a large number of uncorrelated tones , a function of time, we get a certain kind of randomness of the amplitude. They follow a regular pattern called a distribution function.
- The most important functions of distributions are: binomial, Poisson, normal or Gaussian and Rayleigh.
- A sufficiently large number of indipendent random variables, each with finite mean and variance, will be approximately a normal or Gaussian (central limit theorem)
- The distribution of the instantaneous voltage resulting from the summation of many independent amplitude and phase signals , follows the law of Gauss. **Exactly the same distribution of the stochastic process thermal agitation of electrons in a conductor (thermal noise).**

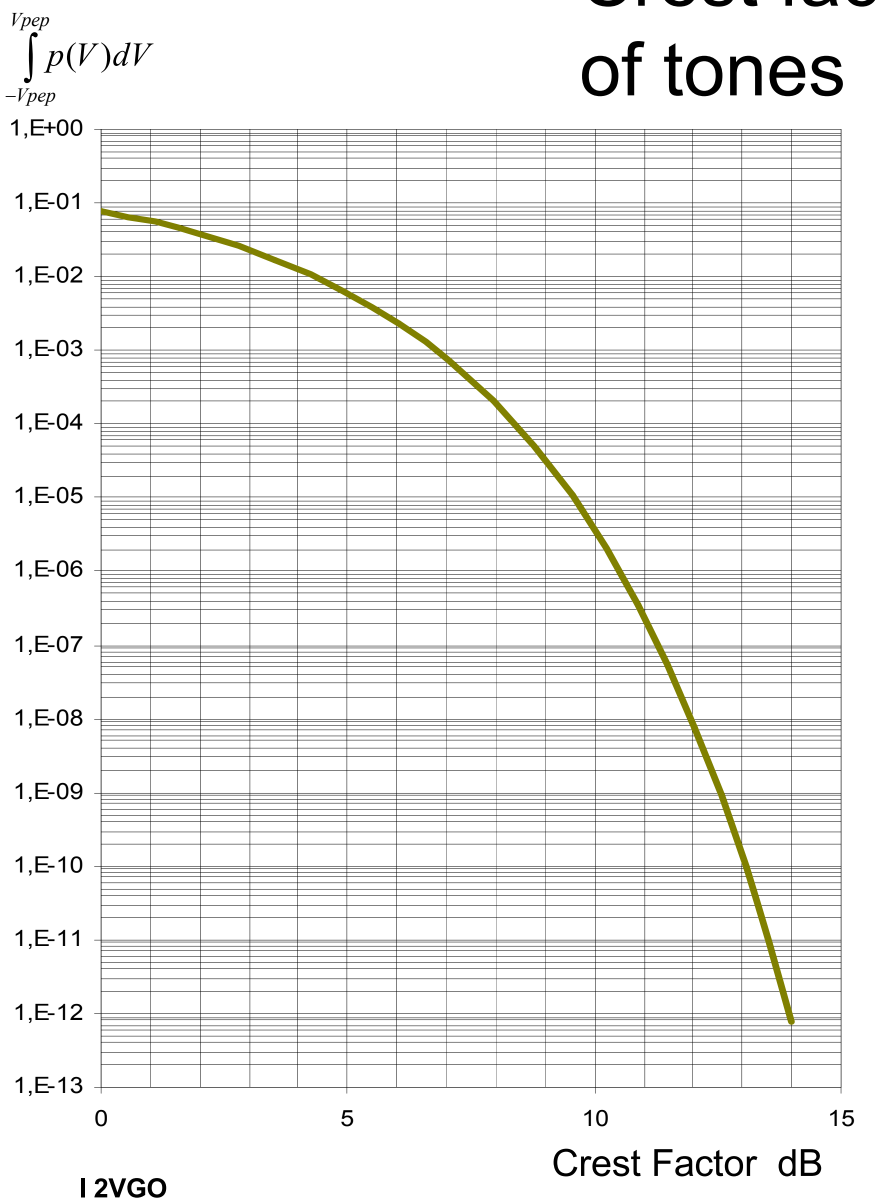
NPR, Noise Power Ratio

- Therefore, if the result of a sum of multi signals produce the same pattern of the thermal noise ....

......then we can use a single white Gaussian noise generator, to simulate a large number of uncorrelated tones.

- This is the basic concept of measuring noise power ratio, NPR.
- The NPR method emulates many signal by loading the receveirs with white noise. In this way, all combinations of carrier frequency spacing are taken into account, and a true worst-case measurement is made.

Crest factor of thousands and thousands of tones



I 2VGO

- The value of the instantaneous power of the N modulated channels is determined by adding to the average power, the crest factor.
- The crest factor is the ratio of the instantaneous power and average power of noise.
- Crest Factor In dB = $10\log\left(\frac{Ppeak}{Paverage}\right)$
- By excel I put in a graphic the probability that the noise power (y-axes) exceeds the crest factor indicated on the x-axes

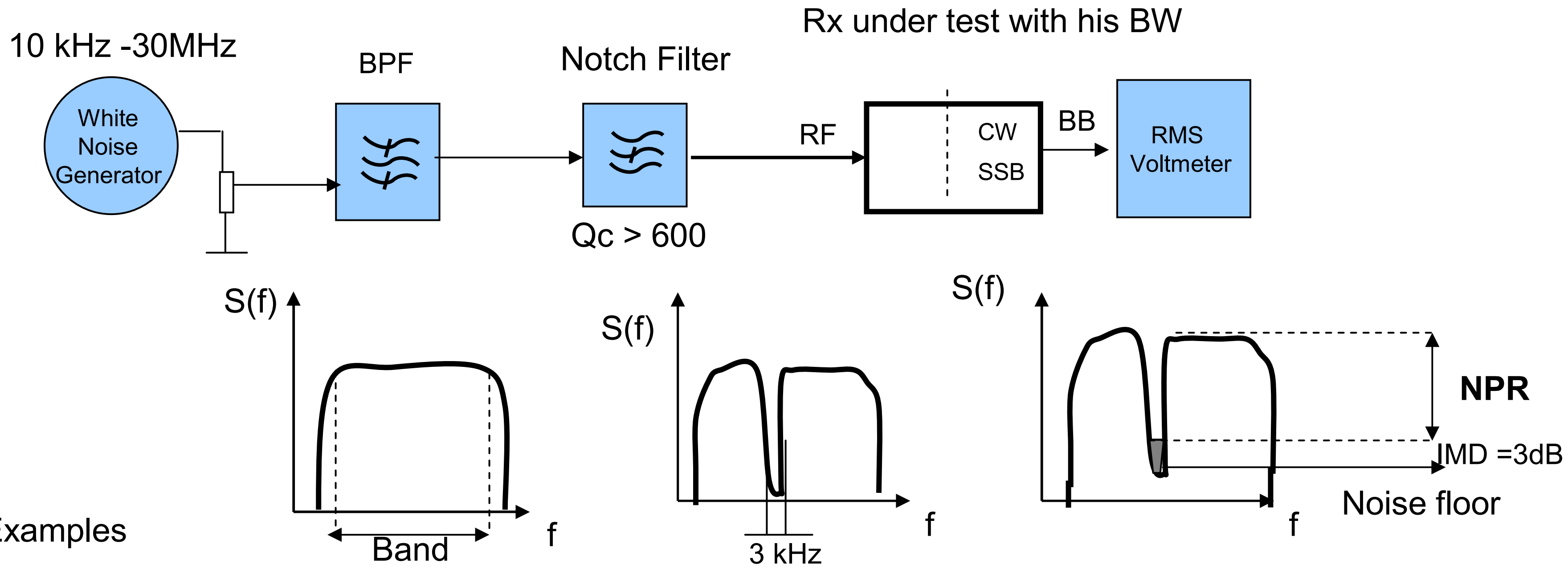
A generic NPR station test is shown in next slide:

- A white noise generator with adjustable output level and shows the power output (like W&G RS-5, RS-50 , Marconi TF 2080B (only generator) or similar or you can use thermocouple a power meter for measure your home-made noise generator.
- A band-pass filter, BPF, which determines the band in which you want to emulate the numbers of the interfering channels that load the receiver (e.g., from 7 to 7.3 MHz)
- A band-stop (notch) filter is inserted to create a silent channel. The desired channel that you are listening.

- The bandstop filter must be a bit larger than of the larger bandwidh, BW, of equivalent channel (SSB, CW or RTTY) of the receiver under test. The filter must have a total Q circuit > 600.

- More spectrum is spread (large number channels) lower will be dynamic receiver (NPR) and less deep notch is tolerated. The depth of the notch must be at least 10 dB greater than the highest value of NPR being measured.

How to set up an NPR testing

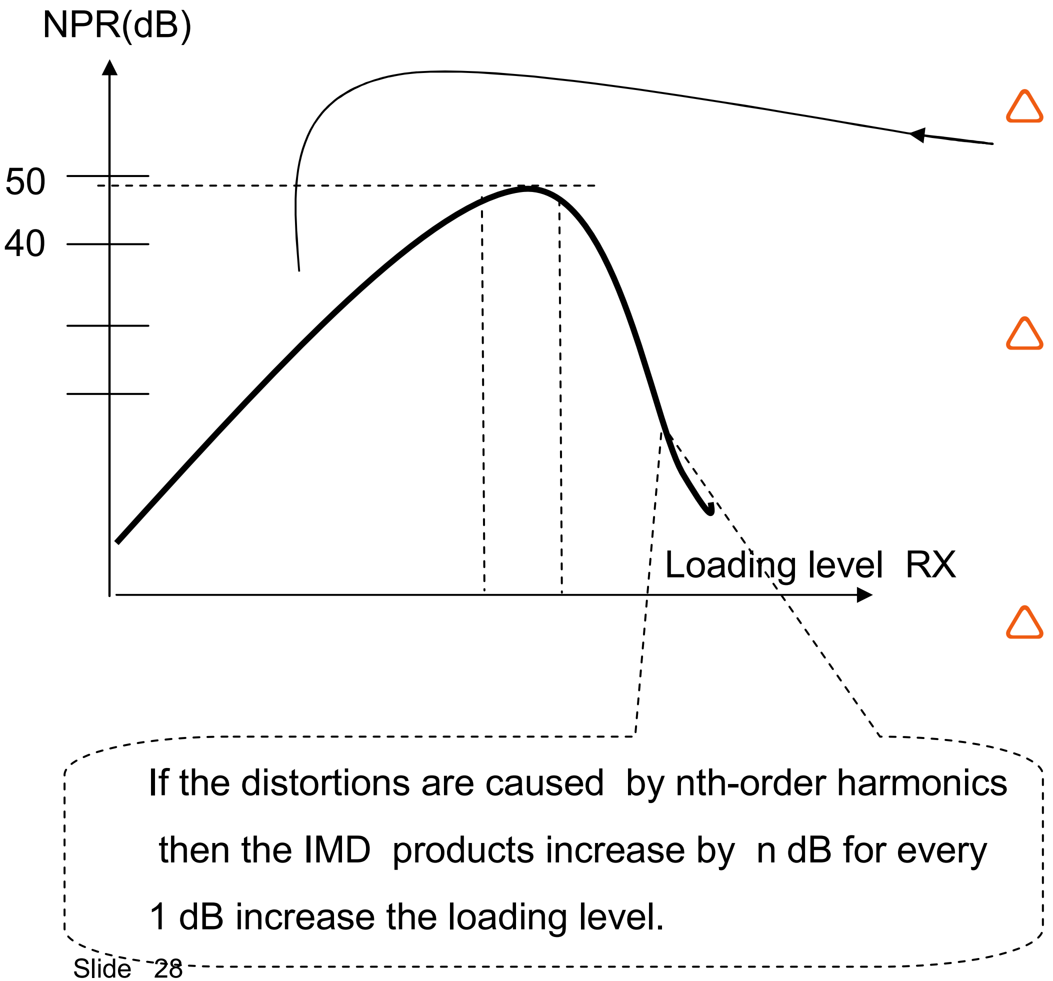


Examples

BPF MHz	Band kHz	Equivalent SSB channels number BW =2,4Khz	Equivalent CW channels number BW = 500Hz	BWR SSB 10log (Band/BW) = 10log (Ptot / PBw)	BWR CW 10log (Band/BW) = 10log (Ptot/PBw)
7-7,3	300	300/2,4= **125**	300/0,5= **600**	21dB	28 dB
14-14,350	350	350/2,4= **146**	350/0,5 = **700**	21,6dB	28.5dB
4-6	2000	2000/2,4= **834**	2000/0,5= **4000**	29 dB	36 dB

- **The procedure is simple. Make it easier to write**
  You tune the receiver to the frequency of the notch filter. It regulates the level of the noise generator to a minimum (low loading) In this way you are sure that the rms voltmeter (I used Hp 3400A) connected to the output of the receiver measures only the noise floor.
- **<u>By increasing the levels of the generator, all IMD products of all orders identified in the non-linear distortion amplitude and phase) and /or spurious free, tend to fill the notch's hole.</u>** Take note the value when the total input power increases the noise floor (observed by the rms voltmeter or even a spectrum if you have SDR receiver) , of 3dB.

NPR vs loading condition to determine the optimum dynamic



- The NPR is poor at low loading levels because the receiver is being operated near its own noise floor.
- Increasing the loading the NPR will improve 1dB for every 1dB of the loading level
- The maximum input power, Ptot, which corresponds the optimum NPR, <u>I have determined when the rms power noise floor into the slot, increase of 3dB.</u>
- The NPR is also poor at very high loading level. But the slope on this side of the curve is steeper since the distortion products are dominant in this case.

NPR

- The NPR (for a given number of equivalent modulated channels) is the ratio between the power of adjacent channel and power of desired channel (in a BW corresponding of type of channel (SSB. CW, RTTY) under test. In practice the noise floor plus 3dB of IMD and/or spurious free. With this trick the value of this power is exactly equal to the value that would determine the MDS with a single tone (S+ N). This is a great convenience and simplification
- By definition, we have for a determined number of equivalent channels :

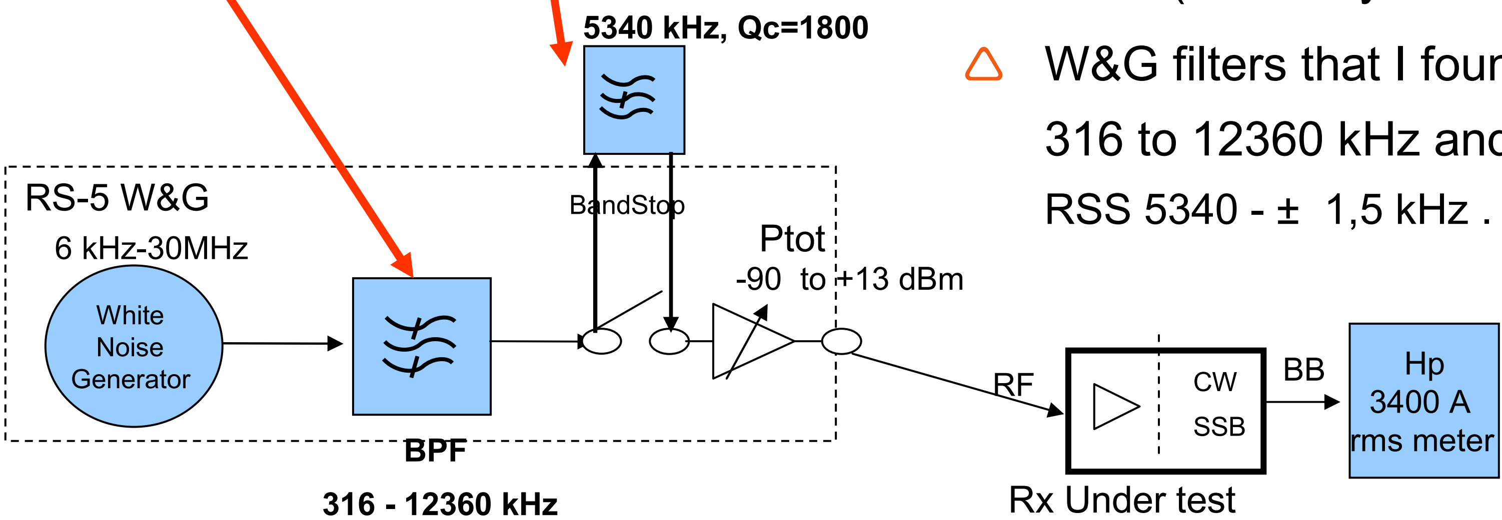
$$NPR_{dB} = (Ptot_{dBm} - BWR_{dB}) - MDS_{dBm}$$

We can also say that the Ptot, measured in the whole band, is the same power that would be concentrated in a single tone and that under this condition emerges a true BDR, equal:

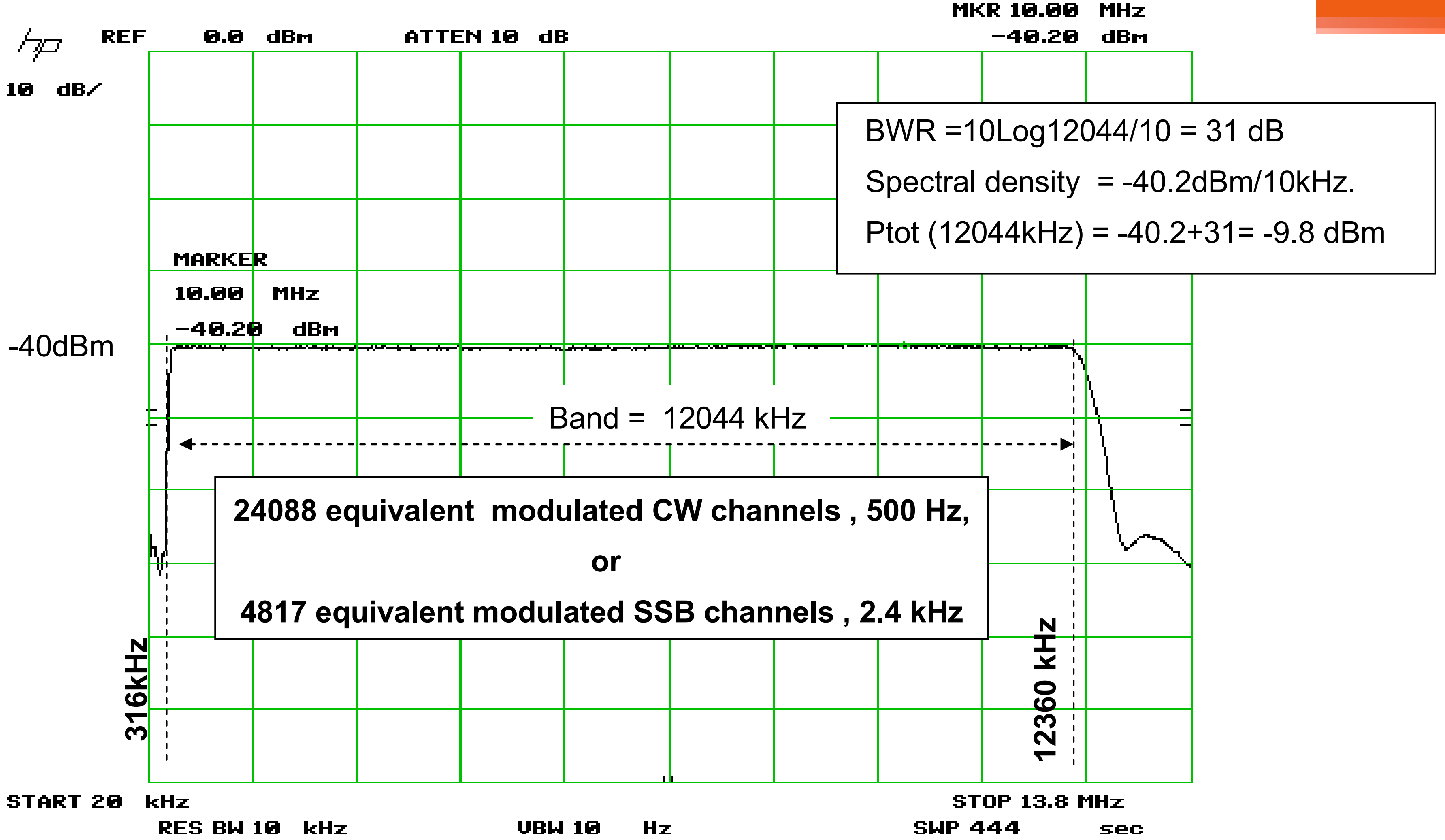
$$BDR_{dB} = Ptot_{dBm} - MDS_{dBm}$$

I used what I found

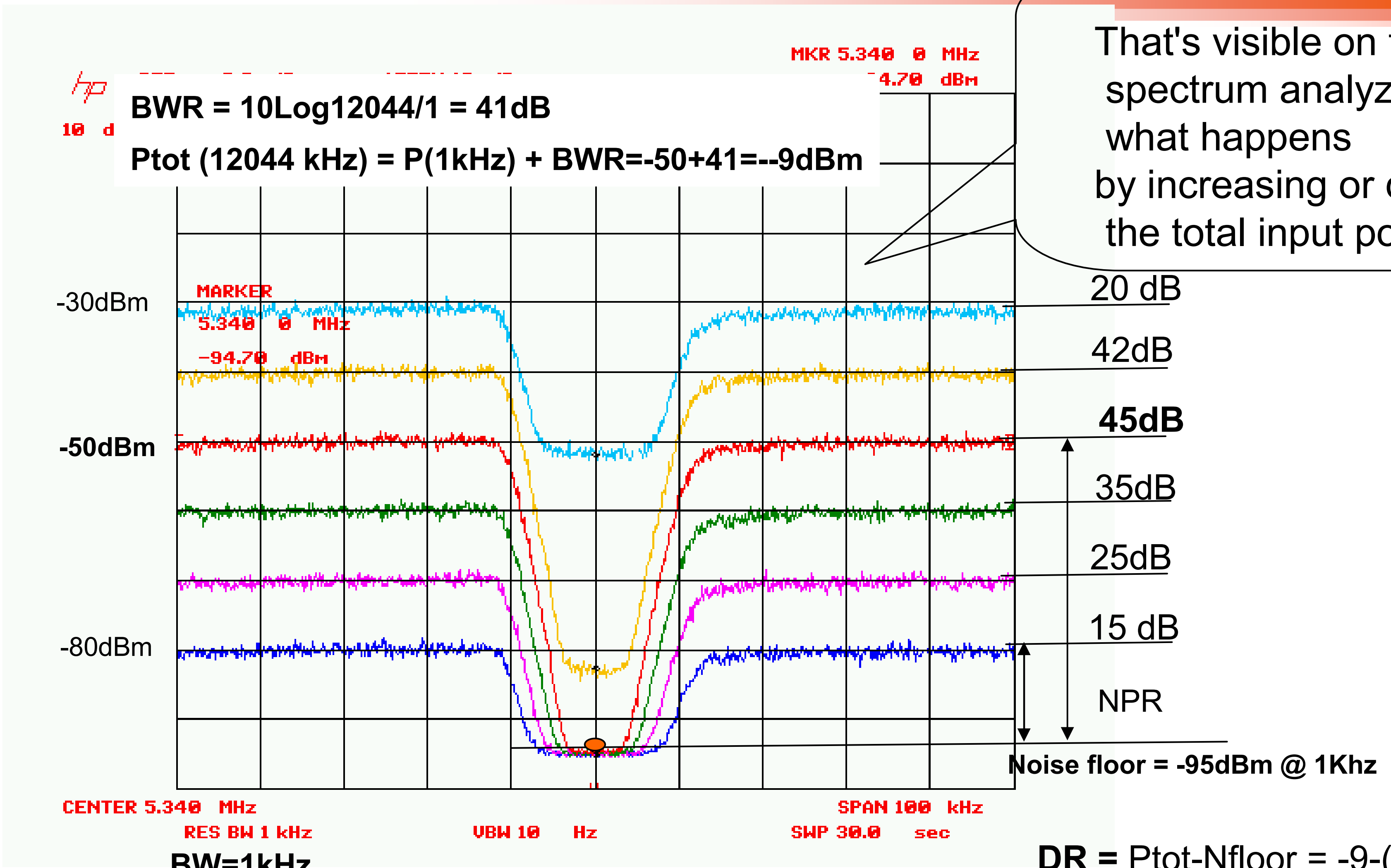
- Years ago, in flea markets, was sold off one of the best generators of noise, the SR-5 from W & G.
- Power density, perfectly flat (within tenths of dB, from 6 kHz to 30 MHz
- Output level adjustable from -90 to +13 dBm. (Accuracy < ± 0,1 dB).
- W&G filters that I found : Band Pass from 316 to 12360 kHz and BandStop model RSS 5340 - ± 1,5 kHz . Depth Notch > 90 dB.



Power spectral density of the signal used



I measure my HP 8566B



That's visible on the spectrum analyzer what happens by increasing or decreasing the total input power

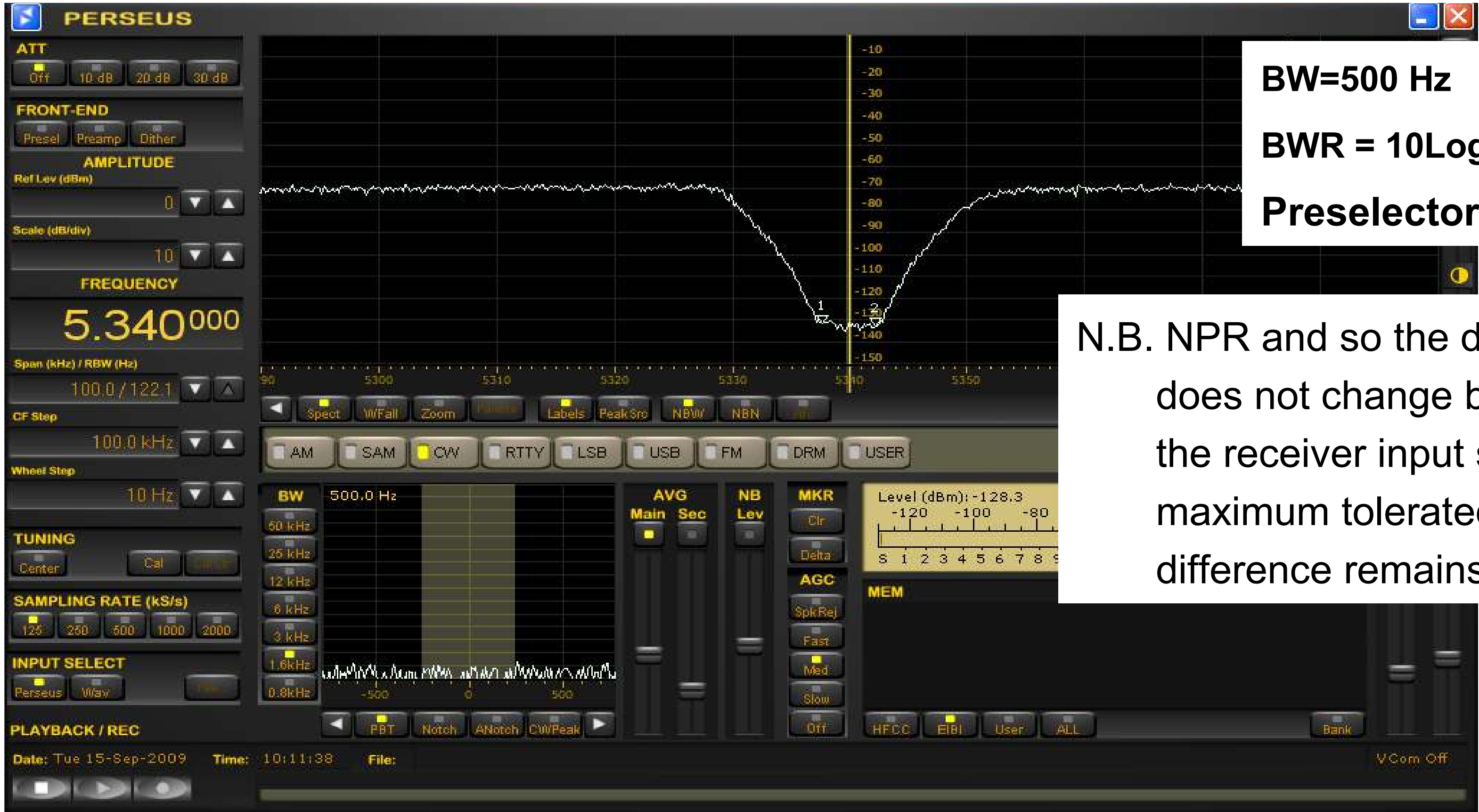
BW=1kHz

5340 kHz

DR = Ptot-Nfloor = -9-(-95) **= 86dB**

Visualization, in real time, behavior NPR vs loading SDR receiver.

Using the utility of Perseus, we project now the recording video (file: *nprSdr.wav*) and see how it is easy to assess the maximum value of the NPR.



BW=500 Hz

BWR = 10Log (12044/0,5) = 43.8 dB

Preselector OFF .

N.B. NPR and so the dynamics of a receiver, does not change by adding attenuation at the receiver input since Increases both the maximum tolerated level that MDS. The difference remains the same.

It's incredible to see such as an overload in a SDR direct sampling that the MDS not change until the peak noise signal don't enter in zone clipper.

Measurement results

- They made the tests on the following receivers: Perseus, 775DSP, AOR 7030, FT1000 Mark IV, SDR14 and QS1R. All predisposed to greater sensitivity in CW and BW = 500 Hz. Except for the AOR 7030 where the minimum BW is 2 kHz
- They measured the MDS @ 500Hz, at 5340 kHz with the standard method and then calculated NF = -147 dBm/500Hz - MDS (500Hz)
- I measured the input level, Ptot, (in the band occupied by the noise 316-12360 kHz) that causes an increase in the noise floor by 3dB (at 5340 kHz) and calculated the value of NPR for CW 24088 channels, as definition

$$NPR_{dB} = (Ptot_{dBm} - BWR_{dB}) - MDS_{dBm}$$

- Where BWR = 10 Log (12044/ 0.5) = 43.8 dB

	MDS @ 500 Hz BW At 5340 kHz dBm on 50 Ohm	**NF** dB	**Total power input, Ptot (dBm)** in the 12044 kHz.	**NPR (24K equiv. Cw channel @** 5340 kHz dB **BWR= 43.8 dB**	SW	Delay Propagation
Perseus Presel Off= **WB** Presel. On =. RF filter = 4.2 - 6 MHz	-129,5 Pre on- Pres off -128,5 Pre on -Pres on -128 Pre 0ff -Pres off- -127 Pre off- Pres on	17.5 18.5 19 20	-18 **-10.6 *** -14.4 **-6.7 ***	**67,7** **74,1** **69,8** **76,4**	Perseus V2.1F	260 – 365 mS (1)
775 DSP RF filter = 4-6MHz	-134 Pre off -138 Pre on	12 9	**-17.8** **-22.6**	**72** **71,6**		6 -9 mS
AOR 7030 I don't Know the Band Pass of the preselector	-119 0 dB -127 +10dB (2 kHz BW)	22 14	**- 4.2** **-23.2**	**71** **60**		0,58 mS @(2Khz BW) 0,29 mS @(10Khz BW)
FT1000 mark IV RF filter = 4-6,6 MHz (5)	-124 Ipo On -131 ipo off.	23 16	**-13.8 *** **-24.2 ***	**66,4** **63**		8-12 ms
SDR14 **WB**	-130,5 Max gain 24 dB	16,5	-23.7	**63**	Win Rad v 1.32	380 mS (2)
QS1R **WB**	-110 -125 With a home made preamplifier. (4) 20dB gain	37 22	-10.2 - 29.2	**56** **52**	QS1R Server V 1.0.039- SDRMAXII. v 1.0.1.4 client.	62 mS (3)

Notes on low NPR of QS1R

- **As you can see from the table, i would have expected on the QS1R of i2ILS, an NPR about only 6 dB worse than Perseus, not 14 dB as I tested** (69,8 - 56 dB). **Perseus has a MDS better 18 dB than to QS1R** (37-19 dB, NF difference), **but Perseus is 12/13 dB worse than input level clipping** (-3.5 , +9 dBm) (1). **So the difference on NPR should be 6 dB** (18-12 dB) **and also I had to get a total of power Input, Ptot, at least about 0 dBm and not -10.2 dBm** (2)
- **I have seen that the low value of the NPR is not due to IMD. When increased input power, from - 7 dBm to over 0 dBm the NPR not to decreased cause distortion products. I saw that inside the slot the noise continued to increased 1dB for every 1dB the power loading** (thousands of tones let see things that often do not emerge with only two tones with a fixed frequency offset).

- (1) If you put a 18 dB attenuator to the input of Perseus, MDS becomes equal to QS1R and improving of 18 dB the maximum level clipping (From about -3,5 to +15 dBm).
- (2) It is the PEP entering the area clipping not the average power. I tested with the same probability of time (10 sec).

Notes

- It clear that the receivers with preselector filter, the input noise power was attenuated in dB of 10Log 12044 / BW (kHz) of the preselector filter. (Considering only the bandwidth at 3dB and not the shape of the filter, in practice I do not know the exact equivalent noise bandwidth).
- I have not found the block diagram of AOR 7030 or the information that what kind RF filter uses.
- Only on QS1R, SDR14 and Perseus (with preselector Off) were loaded with all 24088 equivalent channels telegraph. So the true BDR (see slide 29) is : 99.8 dB for QS1R, 106.8 dB for SDR14 and 113.6dB for Perseus.
- I took the opportunity of the presence of the receivers, to measure also the propagation delay from the RF receiver input to the audio speaker.
- All SDR were used at the minimum sampling rate, 125 kS / s

Continue notes

- Notes
- 1) The 260 mS were obtained with PC Pentium IV, 1.8 GHz, Sound Blaster AWE 64. The 365 mS were measured with PC, Amilo, Centrino 1.7 GHz, integrated AC97 16 bit audio.
- 2) PC ACER Aspire 1654 Wimi – Centrino 2 GHz, integrated audio
- 3) PC like note 2 . The difference is that you do not use the PC sound card.
- 4) A number of users QS1R add an external preamplifier. I2ILS wanted to try a draft of a Ukrainian OM
- 5) The narrow preselector (Qc= 7,) is present only in the amateur radio bands. A 5340 kHz is the classic band-pass filter from 4 to 6.6 MHz

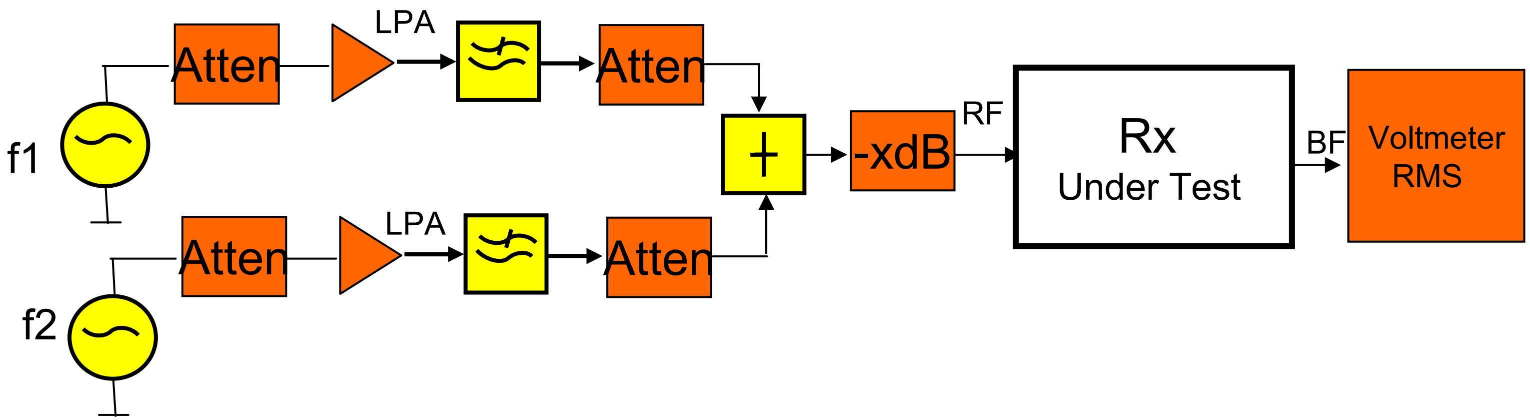
- Easy and accurate to determine NPR for a given load's band. Have you seen, all in just seconds, acting only te knob of the generator's output level The two tone test is more complicated and very critical when it comes to measuring receivers at high IP and low MDS (e.g., when the dynamics is> 95 dB)

- For high-DR, without specific knowledge, proper equipment, a strict procedure and approved, each laboratory and the operator could give (as often happens) discordant measures for the same apparatus.

- It is not enough to have old generators with low phase noise, it is necessary to isolate them as much as possible, have high and constant power to the receiver and lots of experience.

Test bench for two tones

- It needed excellent wideband amplifiers, low-pass filters to eliminate harmonic distortion, wide-band adder for measures of DR2 (preferably resistive). Perfect shielding when measuring IMD> 80 dBc in presence of high levels.
- In figure a bank of a two-tone test to measure high values of DR



Acronyms used

ADC	Analog to Digital Converter
ASP	Analog Signal Processing
BB	BaseBand
BDR	Blocking Dynamic Range
BPF	Band Pass Filter
BWR	Band Width Ratio
dB	Decibel
dBm	Indicates the power in log unit on 50 ohm refered 1 mW.
DRn	Dynamic Range nth- order
DSP	Digital Signal Processing
DUT	Device Under Test
LO	Local Oscillator
IMDn	Intermodulation n order
IPn	Intercept point nth- order
MDS	Minimum Discernible Signal
NPR	Noise Power Ratio
PC	Personal Computer
PEP	Peak Envelope Power.
RF	Radio Frequenza
RMS	Root Mean Square
SDR	Software Dedicated Radio
SNR	Signal Noise Ratio

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