Radio Design 401, Episode 4 – Intermodulation in Real-World Circuits and Systems

Slides downloaded from: https://ecefiles.org/
Companion videos at: https://www.youtube.com/playlist?list=PL9Ox3wpnB0krNexW2k5JMCaewXN7LoRXd

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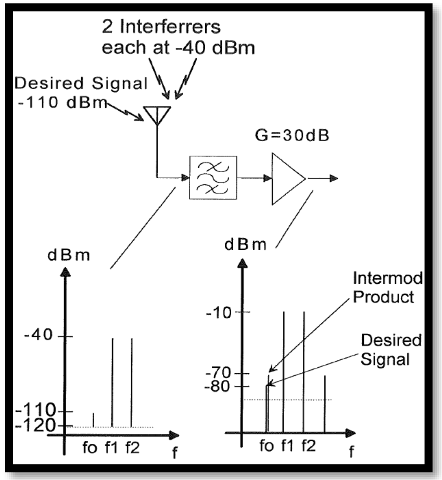
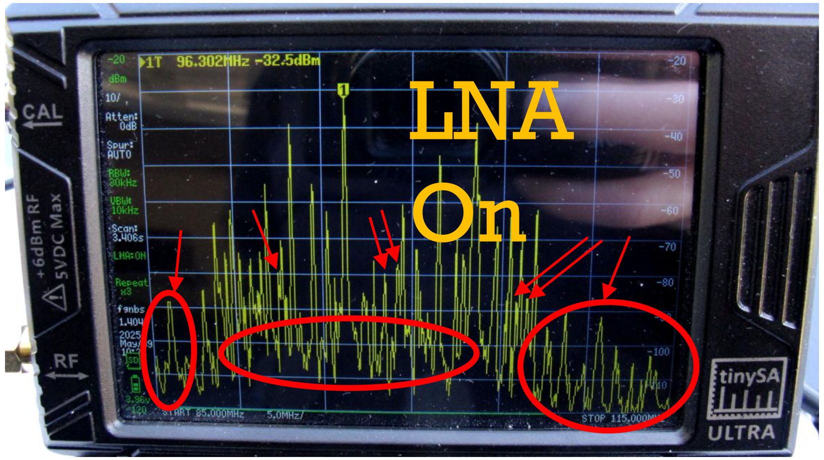
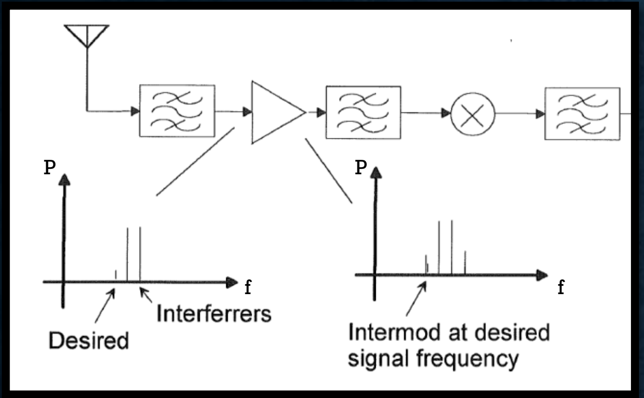
This episode covers essential aspects of Intermodulation distortion in radio receivers but goes beyond the traditional treatment by concentrating on real world circuits and systems. In addition to looking at the mathematics, we examine the circuit-level origins and show the practical effects of intermods on limiting radio receiver sensitivity. Compression and Intercept Point (third order intercept or TOI) are examined and Spurious Free Dynamic Range (SFDR) is discussed. Extensive examples of problems and solutions to the intermod problem in receivers are given.

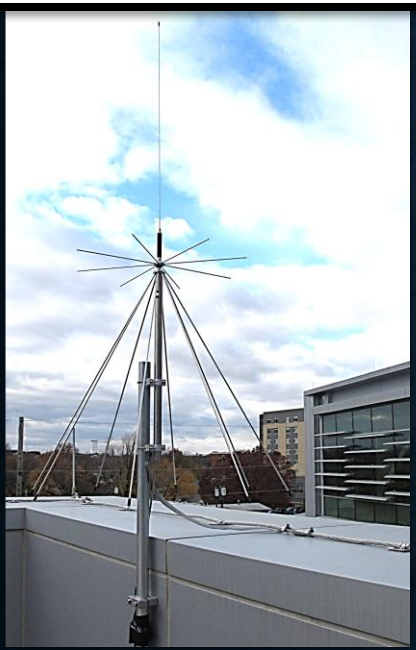


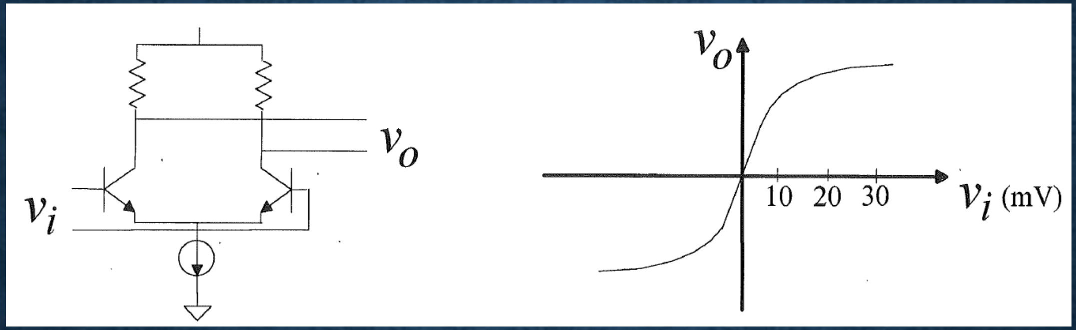


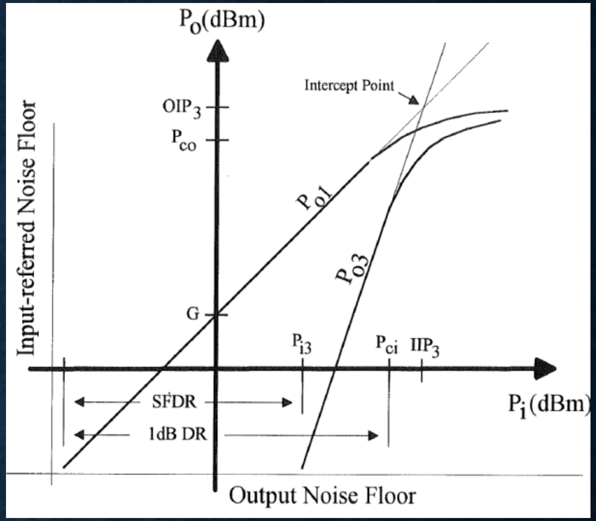


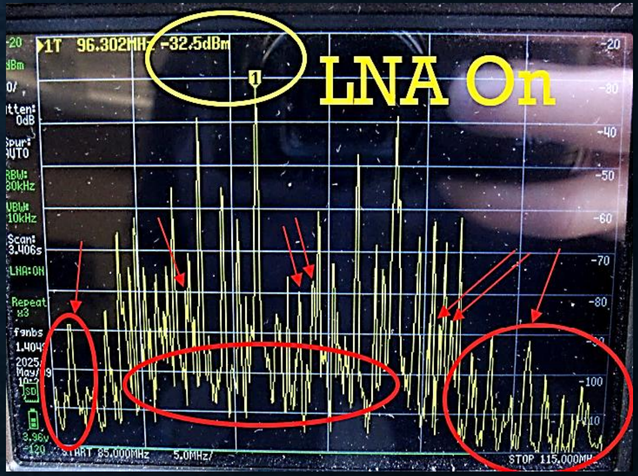
Radio Design 401

Episode 4









$$v_o = A_1 v_i + A_2 v_i^2 + A_3 v_i^3 + \dots$$

Intermodulation

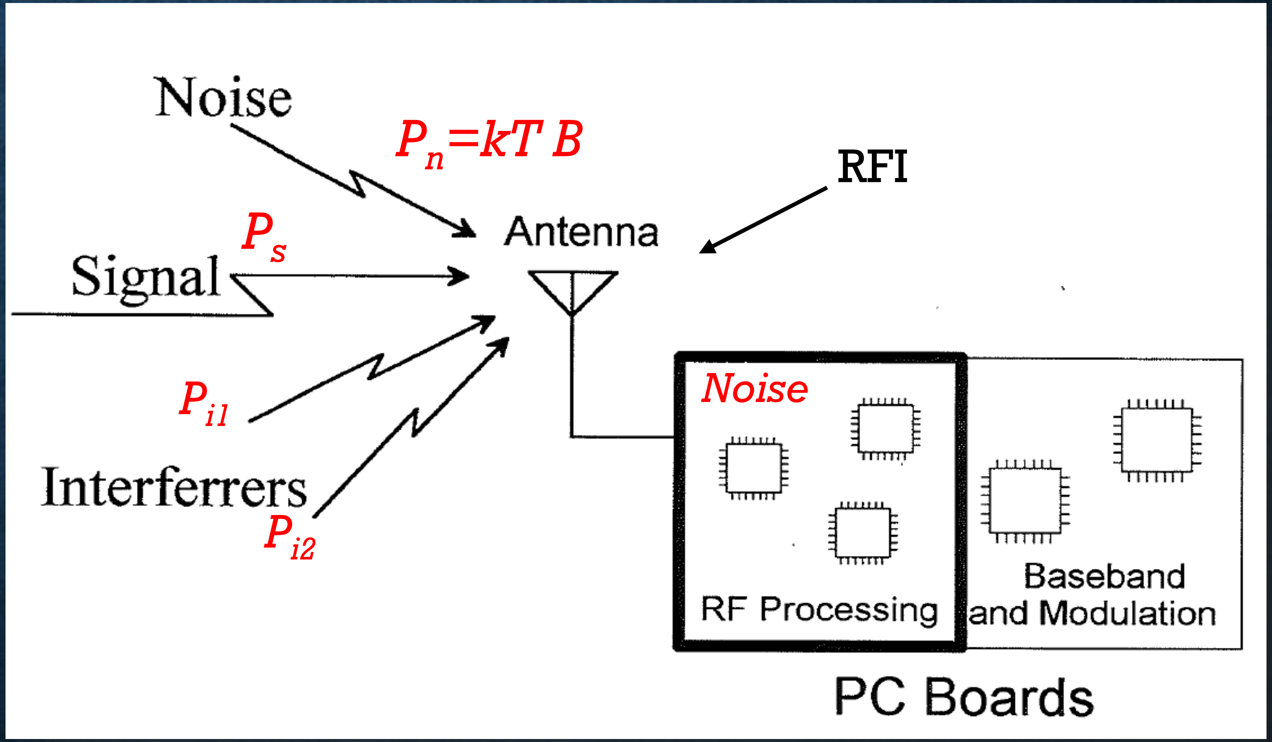
In Real-World Circuits and Systems

MegawattKS - YouTube

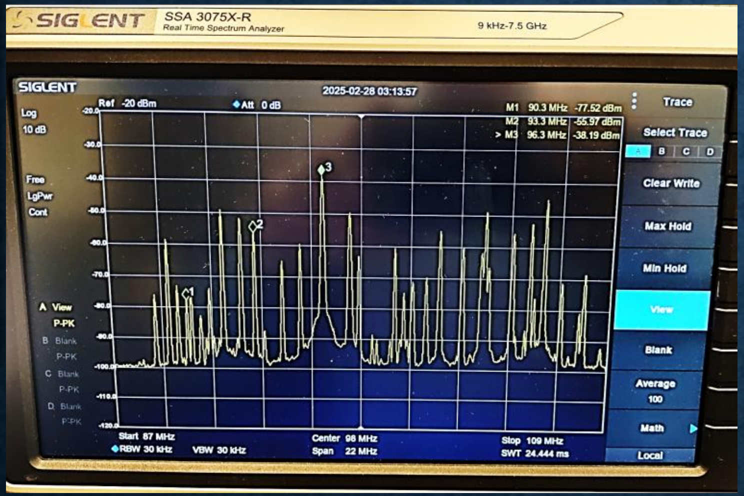
ecefiles.org

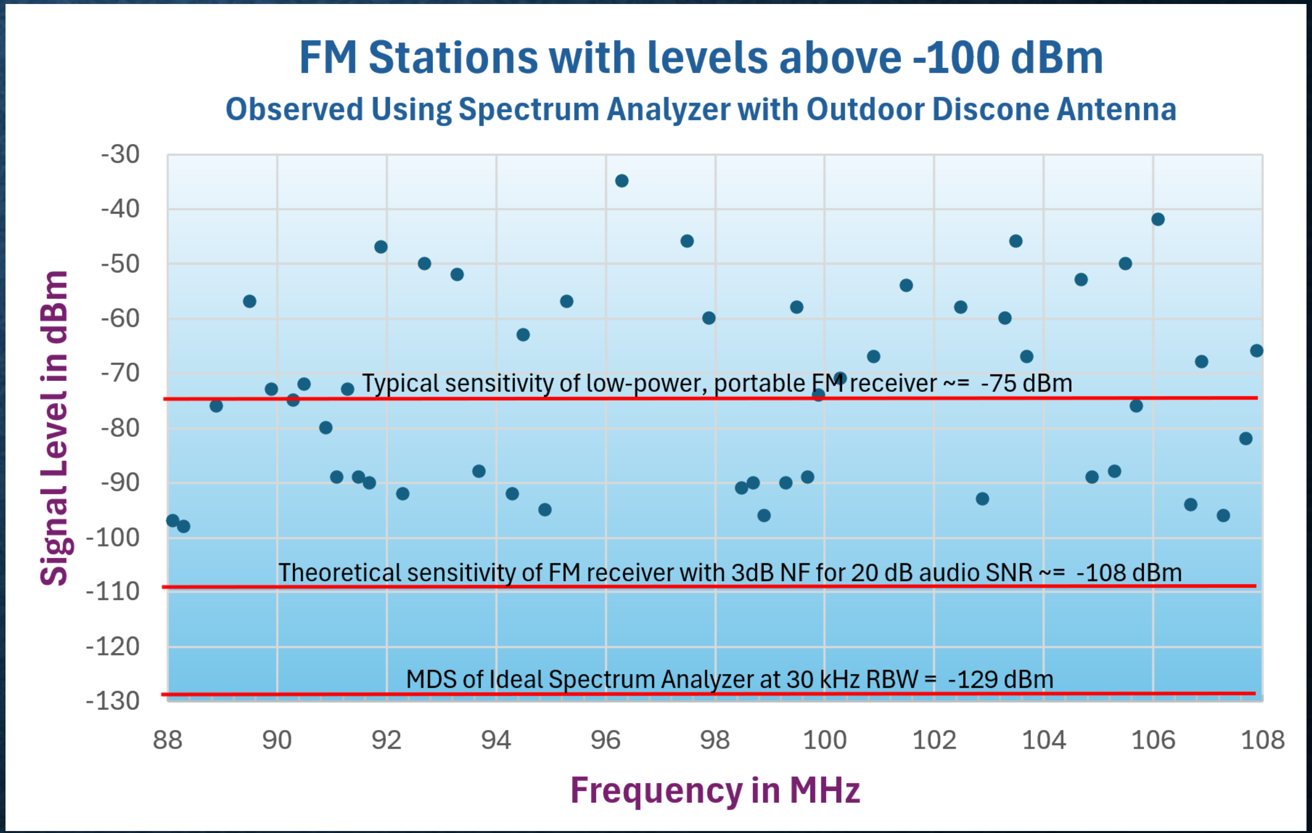
Limits to Receiver Sensitivity

From Episodes 1 through 3



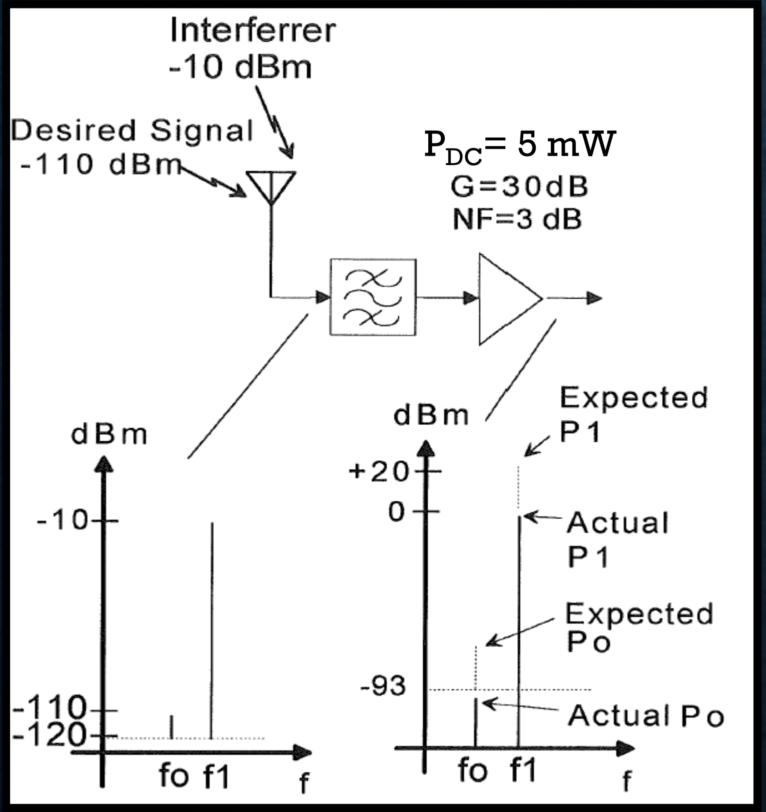
Typical vs Ideal Receiver Sensitivity

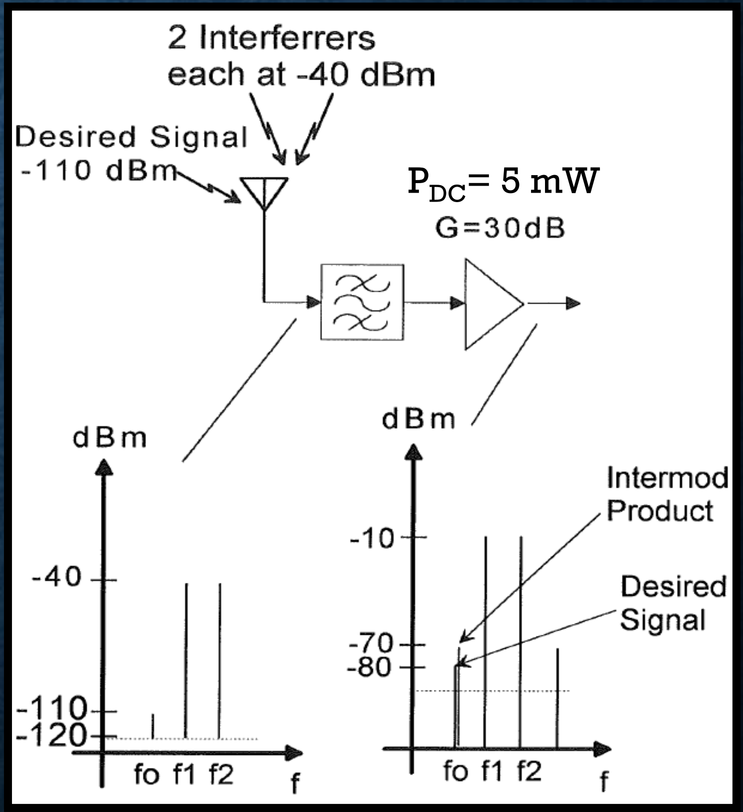




Compression and Intermodulation

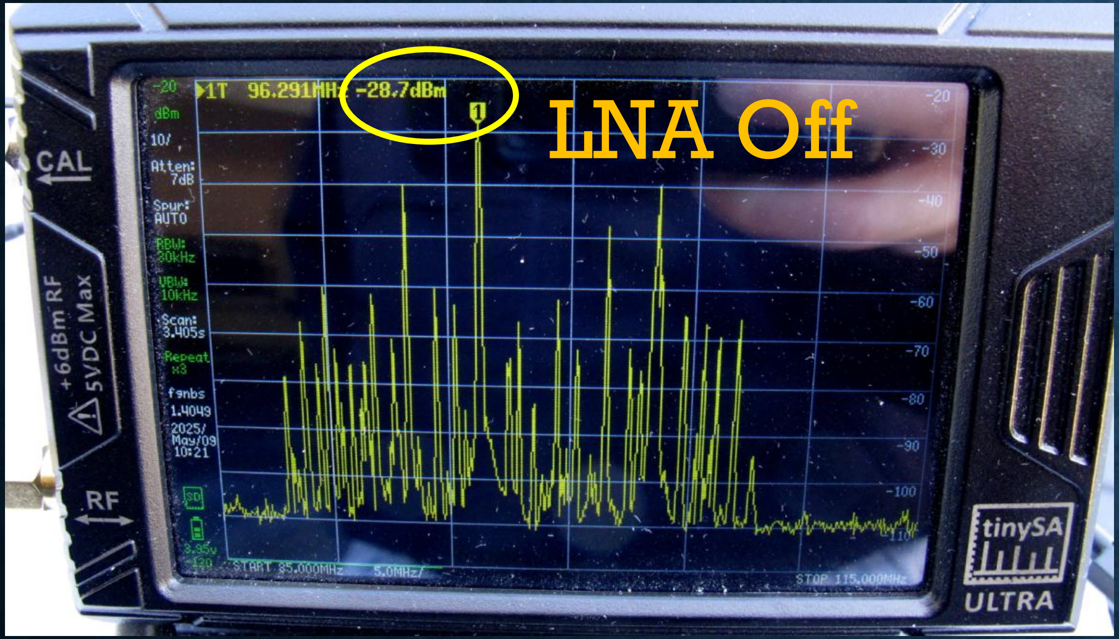
Recall from Episode 1, Part 2: ***Strong signals inside preselect filter passband can overwhelm weak ones !***

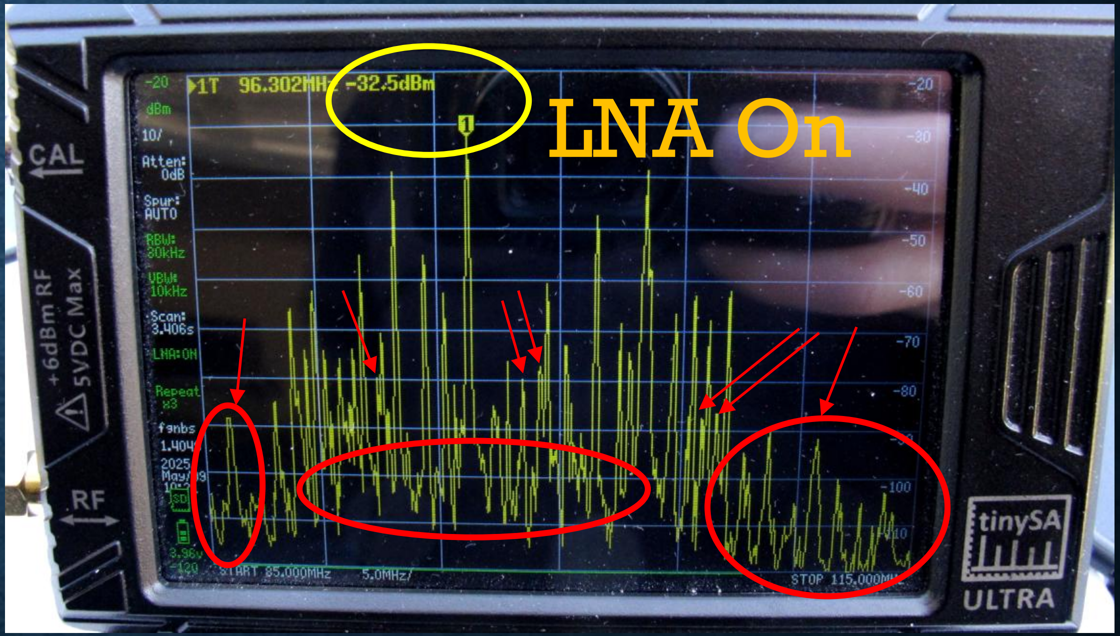




Real-World Example

FM Broadcast Band in Residential Environment

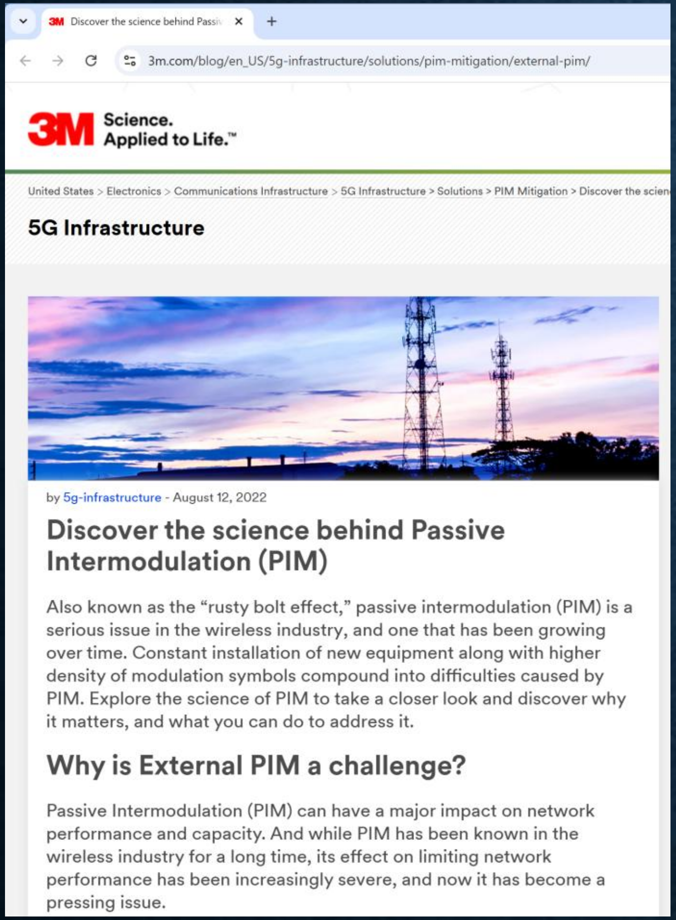




- Analyzer noise figure = 20 dB
- Turning on LNA *should* lower noise floor…

- Strong signal at 96.3 MHz now compressed ?
- Many "signals" seen below -75 dBm are now actually intermods !

Passive Intermodulation



Discover the science behind Passi... ×

3m.com/blog/en_US/5g-infrastructure/solutions/pim-mitigation/external-pim/

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United States > Electronics > Communications Infrastructure > 5G Infrastructure > Solutions > PIM Mitigation > Discover the scien

5G Infrastructure

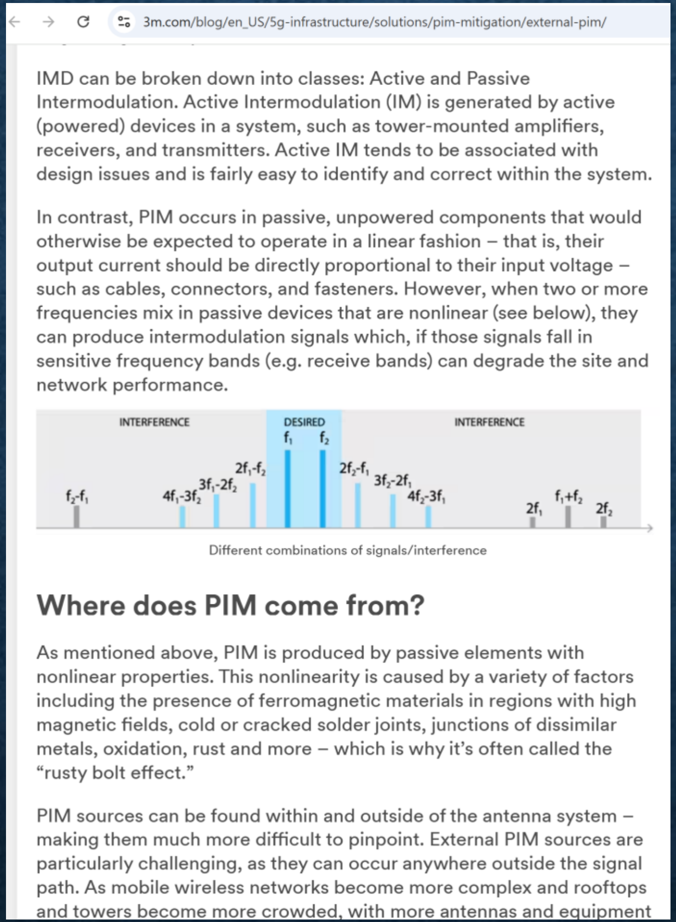
by 5g-infrastructure - August 12, 2022

Discover the science behind Passive Intermodulation (PIM)

Also known as the "rusty bolt effect," passive intermodulation (PIM) is a serious issue in the wireless industry, and one that has been growing over time. Constant installation of new equipment along with higher density of modulation symbols compound into difficulties caused by PIM. Explore the science of PIM to take a closer look and discover why it matters, and what you can do to address it.

Why is External PIM a challenge?

Passive Intermodulation (PIM) can have a major impact on network performance and capacity. And while PIM has been known in the wireless industry for a long time, its effect on limiting network performance has been increasingly severe, and now it has become a pressing issue.



3m.com/blog/en_US/5g-infrastructure/solutions/pim-mitigation/external-pim/

IMD can be broken down into classes: Active and Passive Intermodulation. Active Intermodulation (IM) is generated by active (powered) devices in a system, such as tower-mounted amplifiers, receivers, and transmitters. Active IM tends to be associated with design issues and is fairly easy to identify and correct within the system.

In contrast, PIM occurs in passive, unpowered components that would otherwise be expected to operate in a linear fashion – that is, their output current should be directly proportional to their input voltage – such as cables, connectors, and fasteners. However, when two or more frequencies mix in passive devices that are nonlinear (see below), they can produce intermodulation signals which, if those signals fall in sensitive frequency bands (e.g. receive bands) can degrade the site and network performance.

INTERFERENCE | DESIRED f_1 f_2 | INTERFERENCE

f_2-f_1, $4f_1$-$3f_2$, $3f_1$-$2f_2$, $2f_1$-f_2, $2f_2$-f_1, $3f_2$-$2f_1$, $4f_2$-$3f_1$, $2f_1$, f_1+f_2, $2f_2$

Different combinations of signals/interference

Where does PIM come from?

As mentioned above, PIM is produced by passive elements with nonlinear properties. This nonlinearity is caused by a variety of factors including the presence of ferromagnetic materials in regions with high magnetic fields, cold or cracked solder joints, junctions of dissimilar metals, oxidation, rust and more – which is why it's often called the "rusty bolt effect."

PIM sources can be found within and outside of the antenna system – making them much more difficult to pinpoint. External PIM sources are particularly challenging, as they can occur anywhere outside the signal path. As mobile wireless networks become more complex and rooftops and towers become more crowded, with more antennas and equipment

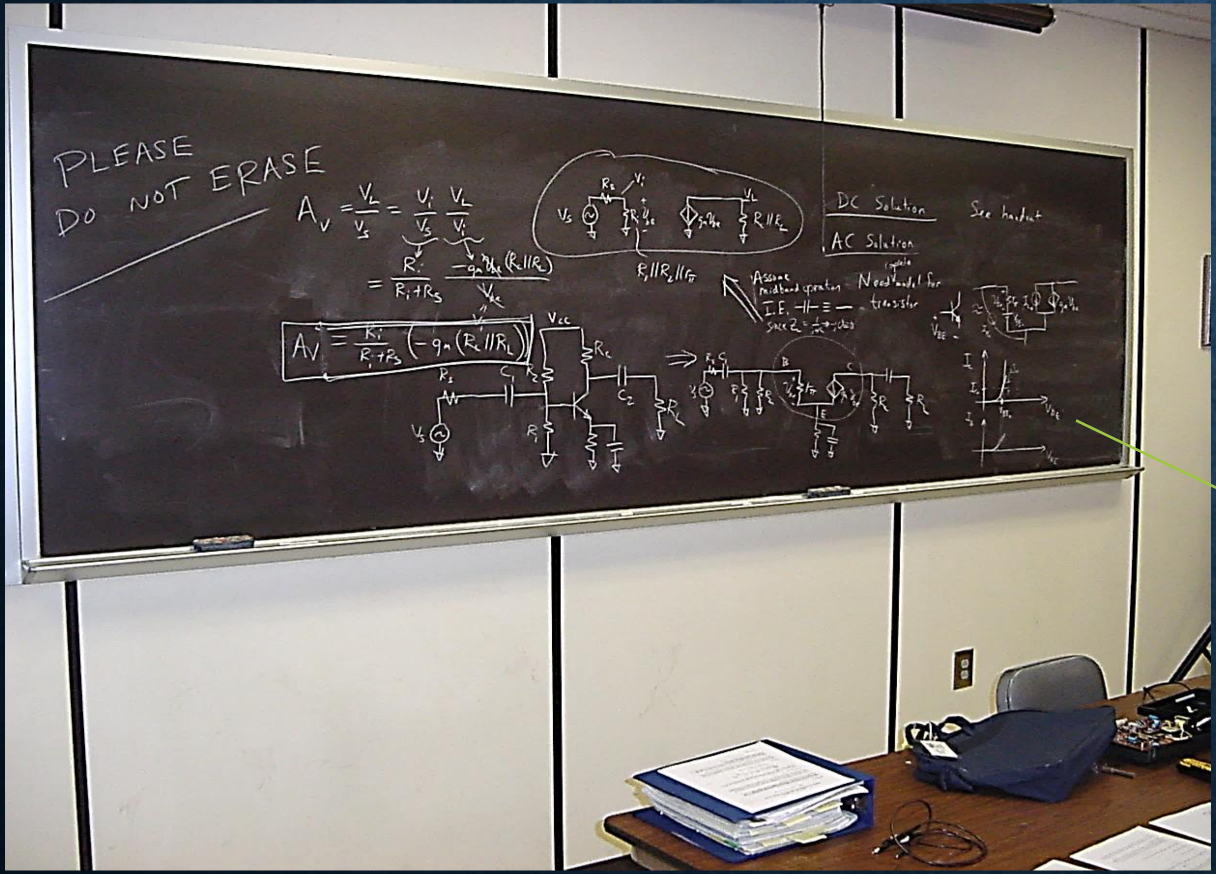
https://www.3m.com/blog/en_US/5g-infrastructure/solutions/pim-mitigation/external-pim/

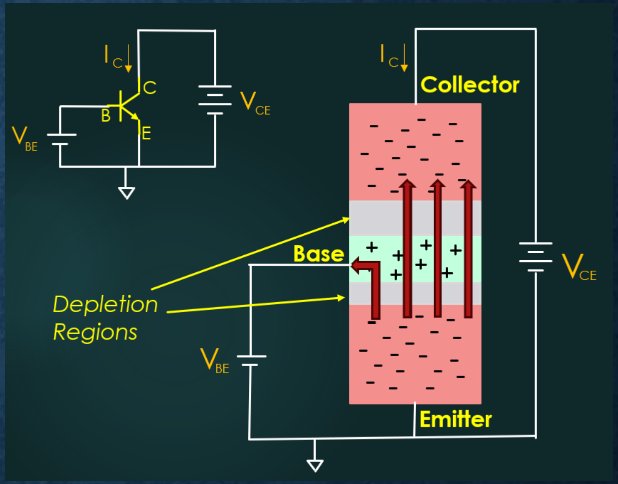
Today's Topics

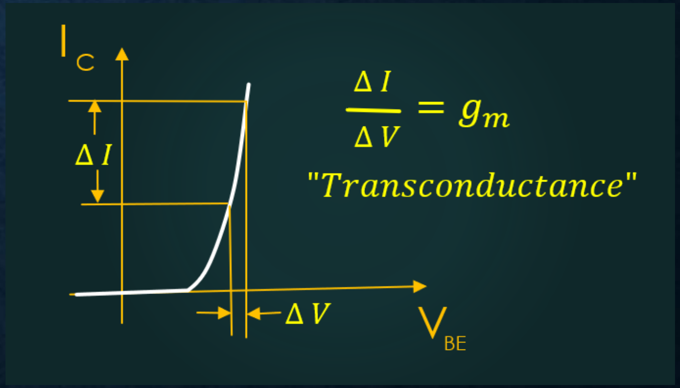
- *The Math*
  - *Circuit Non-Linearities (e.g. V_o vs V_i or I_c vs V_{be})*
  - *Taylor / Maclaurin Series for V_o vs V_i*
  - *Single & Two-Tone Inputs*
- *Performance Characteristics*
  - *IIP3 and Relationship to P1dB*
  - *Multi-Tone Inputs (Crowded Spectrum Case)*
  - *SFDR and Max Signal Levels vs P_{DC}*
  - *Antenna Input Referred Values*
- *Solutions*

Recall Basic Small-Signal Amplifier

From: Radio Design 101 Video Series

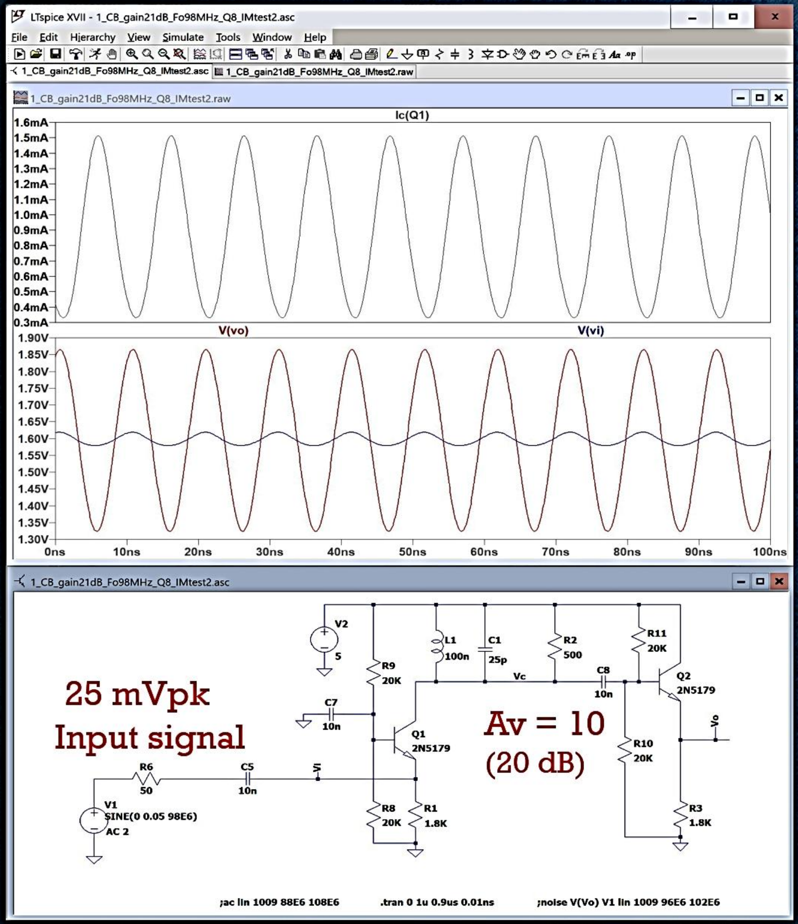


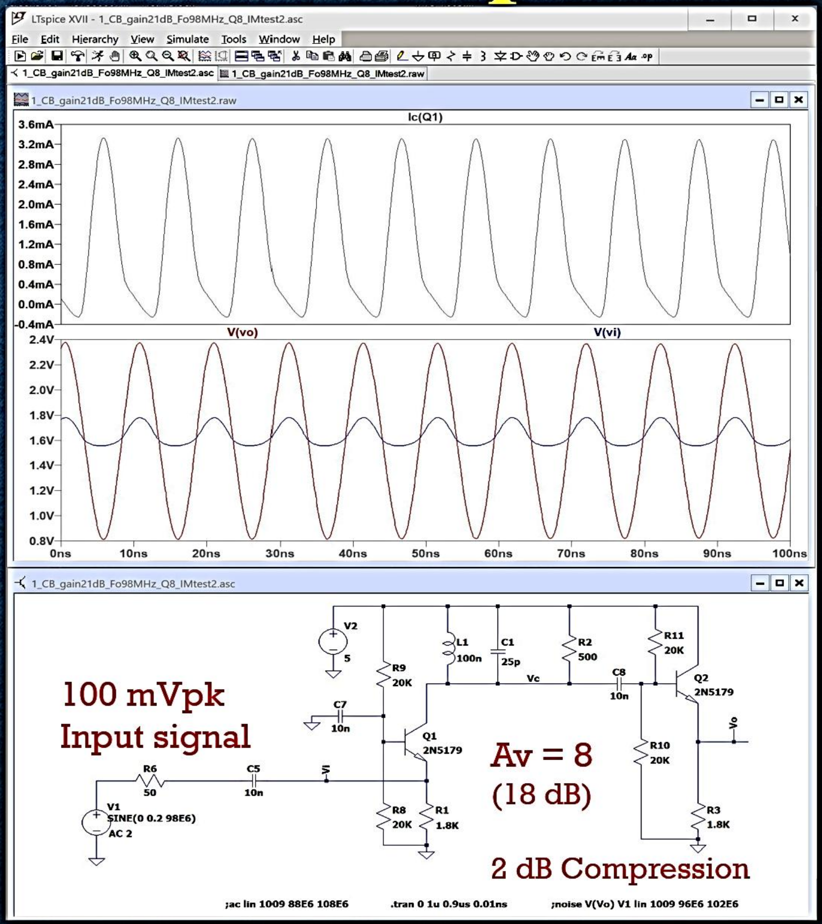




Large-Signal Non-Linear Operation

From: Radio Design 401 Episode 1





Large-Signal Non-Linear Operation

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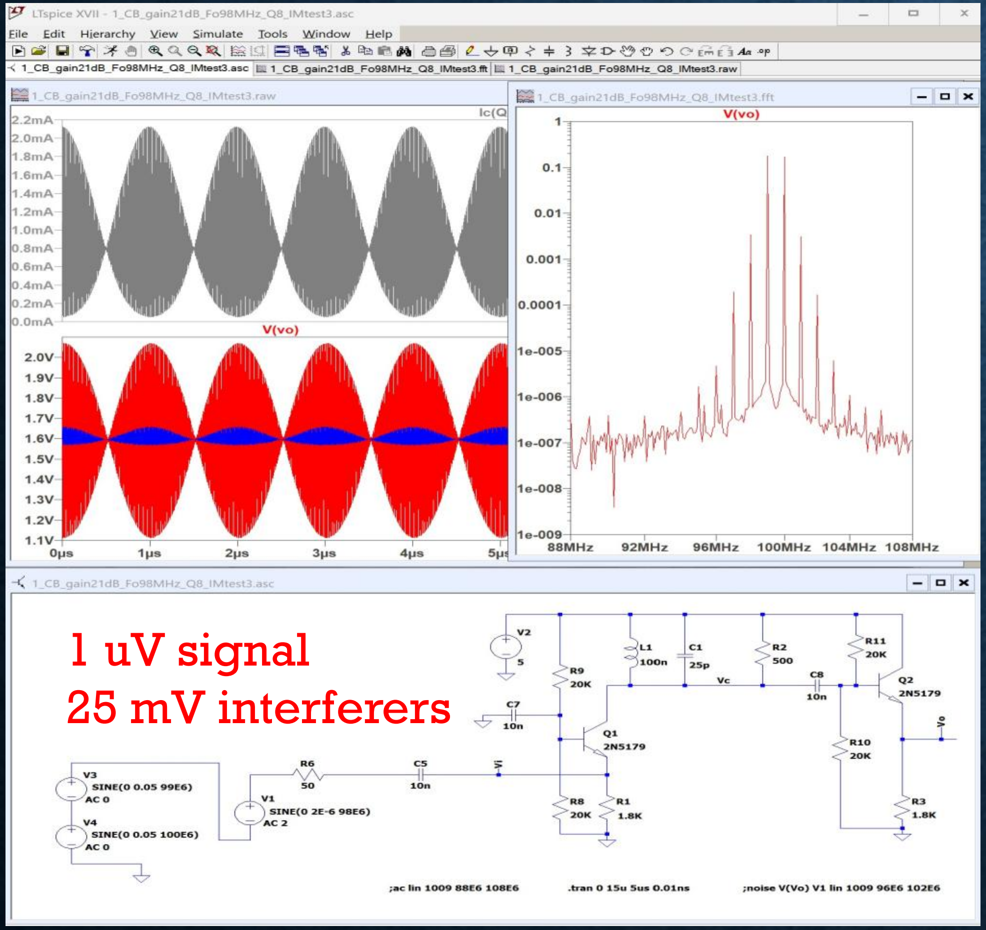
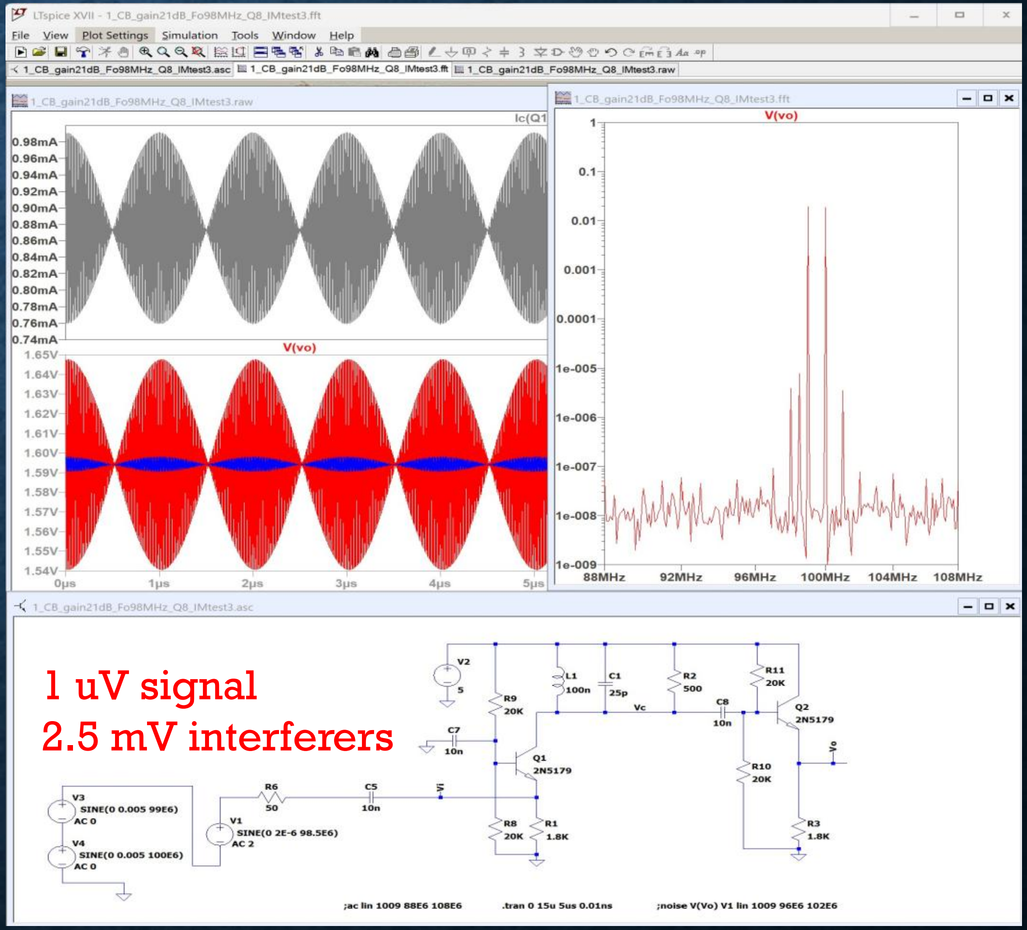
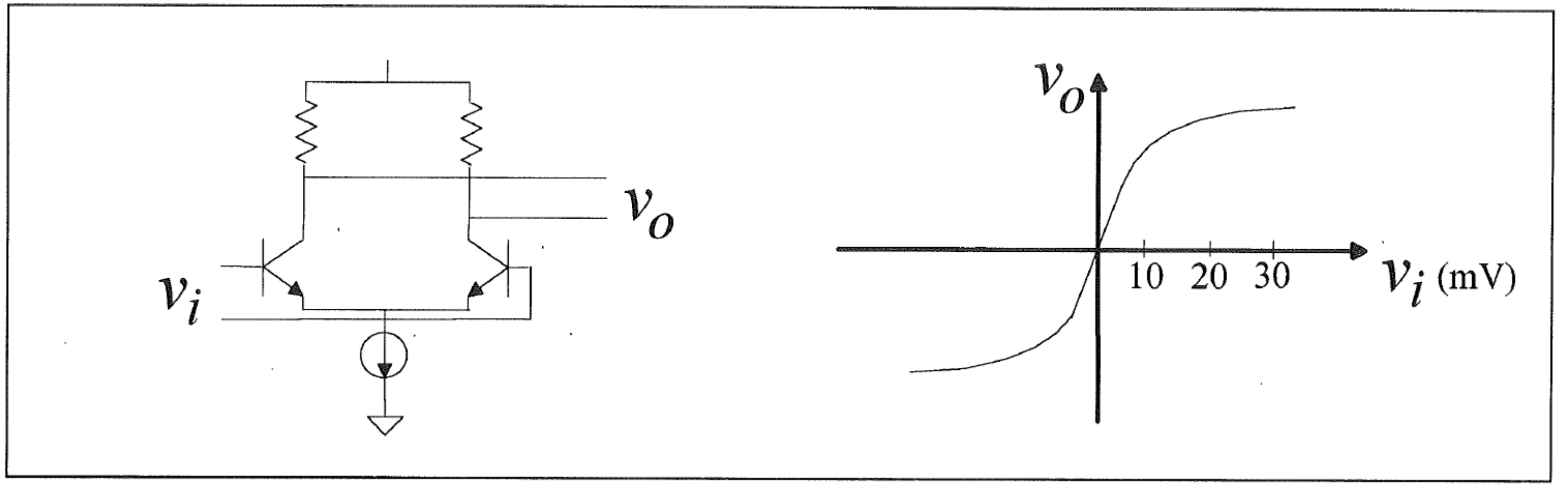




The Math: For *Quantifying* the Problem



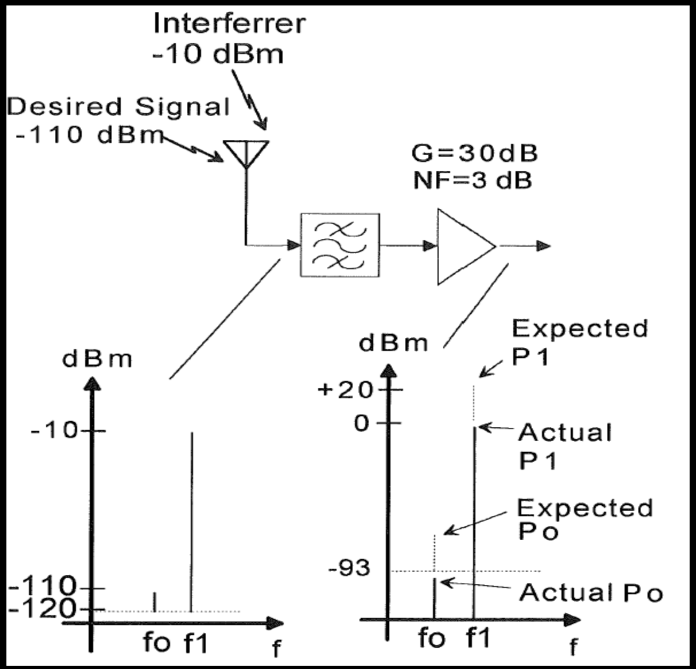
Expand v_o vs v_i in a Maclaurin series:

$$v_o = A_1 v_i + A_2 v_i^2 + A_3 v_i^3 + \ldots$$

Small Signal Output — Non-Linear Distortion Terms

"Single Tone" Input

We're ignoring the "desired signal" here since its 100 dB weaker…



Let $v_i = V\cos(\omega_o t)$

Then:

$$v_o = A_1 v_i + A_2 v_i^2 + A_3 v_i^3 + \ldots$$

$= A_1 V\cos(\omega_o t) +$ — Expected small signal output +

$\frac{A_2}{2}V^2[1+\cos(2\omega_o t)] +$ — Rectification + 2nd harmonic +

$\frac{A_3}{4}V^3[3\cos(\omega_o t)+\cos(3\omega_o t)] +$ — Gain compression* + 3rd harm +

… — Additional harmonics, etc.

*Assuming $A_3 < 0$

1dB Compression Point

Let $v_i = V\cos(\omega_o t)$

Then:

$$v_o = A_1 v_i + A_2 v_i^2 + A_3 v_i^3 + \ldots$$

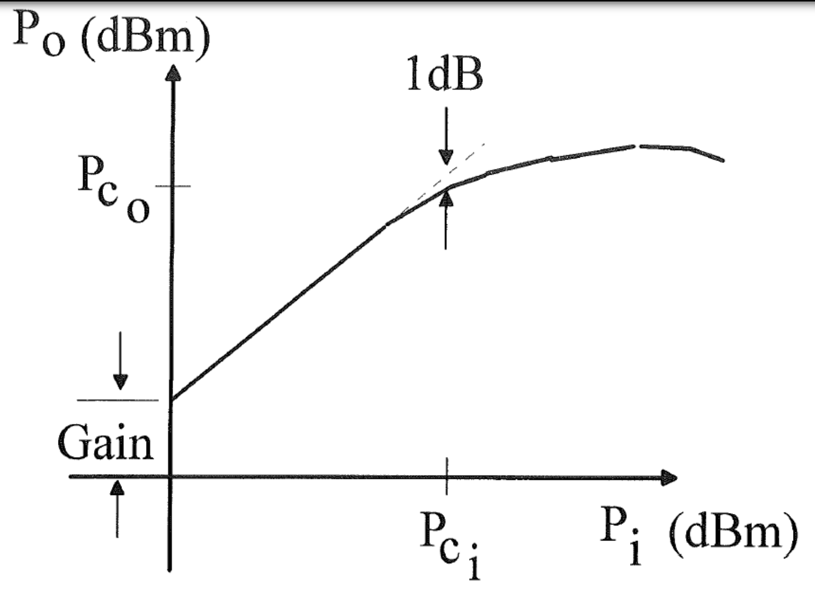
$= A_1 V\cos(\omega_o t) +$	Expected small signal output	+
$\frac{A_2}{2} V^2[1+\cos(2\omega_o t)] +$	Rectification + 2nd harmonic	+
$\frac{A_3}{4} V^3[3\cos(\omega_o t)+\cos(3\omega_o t)] +$	Gain compression* + 3rd harm	+
…	Additional harmonics, etc.	

*Assuming $A_3 < 0$

$$P_i = \frac{v_i^2}{R_i} \qquad P_i(dBm) = 10\log(P_i) + 30$$

$$P_o = \frac{v_o^2}{R_L} \qquad P_o(dBm) = 10\log(P_o) + 30$$

$$Gain(dB) = P_o(dBm) - P_i(dBm) = 10\log\left(\frac{P_o}{P_i}\right)$$



Plot of fundamental frequency output power vs input tone power

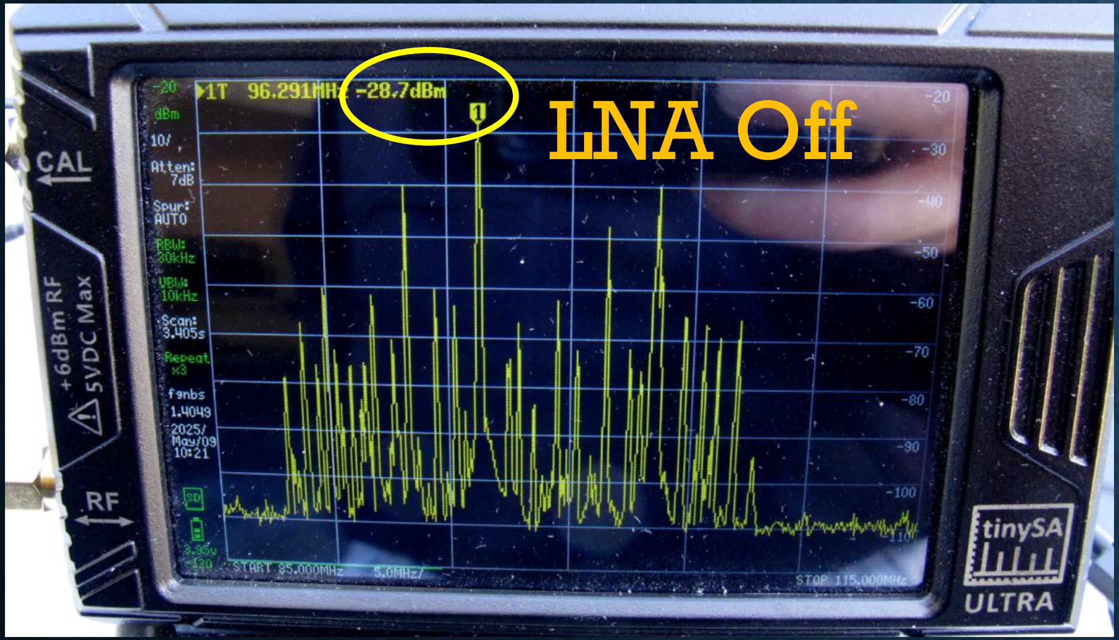
NOTE

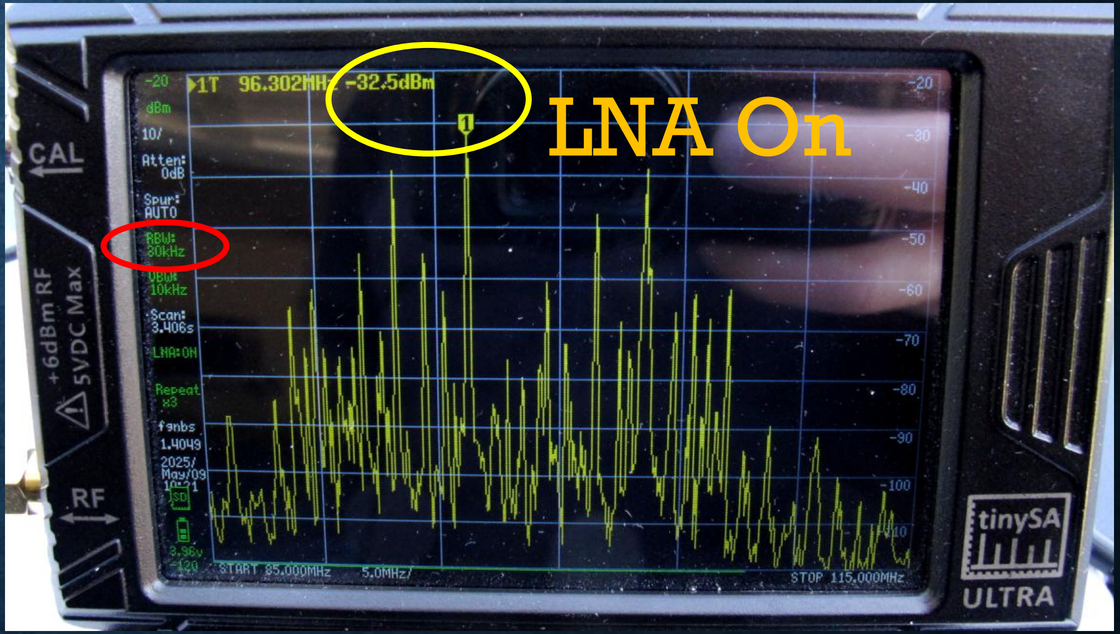
P_{c_o} is typically 0.1 to 0.5 of DC power consumption

$P_{c_i} = P_{c_o}$ - Gain (in dB, dBm units)

Real-World Spectrums

FM Broadcast Band in Residential Environment





- Strong signal at 96.3 MHz now compressed ?

Real-World Amplifier Specs

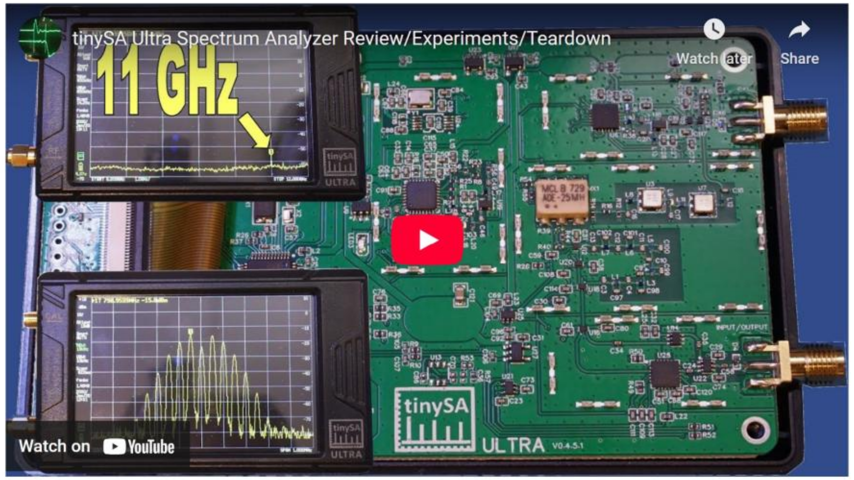
LNA used in TinySA-Ultra Spectrum Analyzer

tinySA Ultra Teardown Pictures – K

Not secure kerrywong.com/2023/06/16/tinysa-ultra-teardown-pictures/

tinySA Ultra is an affordable spectrum analyzer geared towards HAM radio operators, RF enthusiasts and electronic hobbyists. With the Ultra mode enabled, it boasts a calibrated frequency range up to 6 GHz and can observe signals up to 12 GHz. Besides the spectrum analyzer capability, it also has a built-in RF synthesizer that can output frequencies up to 5.4 GHz with the ability to apply AM/FM modulation and do sweep.

I did a detailed review of the tinySA Ultra and compared the captured spectrum with my HP8566B as a reference. You can check out the review below:



In this blog post, let's take a look at some of the teardown pictures.

http://www.kerrywong.com/2023/06/16/tinysa-ultra-teardown-pictures/

BGA2817

MMIC wideband amplifier

Rev. 7 — 30 March 2017 Product data sheet

1. Product profile

1.1 General description

Silicon Monolithic Microwave Integrated Circuit (MMIC) wideband amplifier with internal matching circuit in a 6-pin SOT363 plastic SMD package.

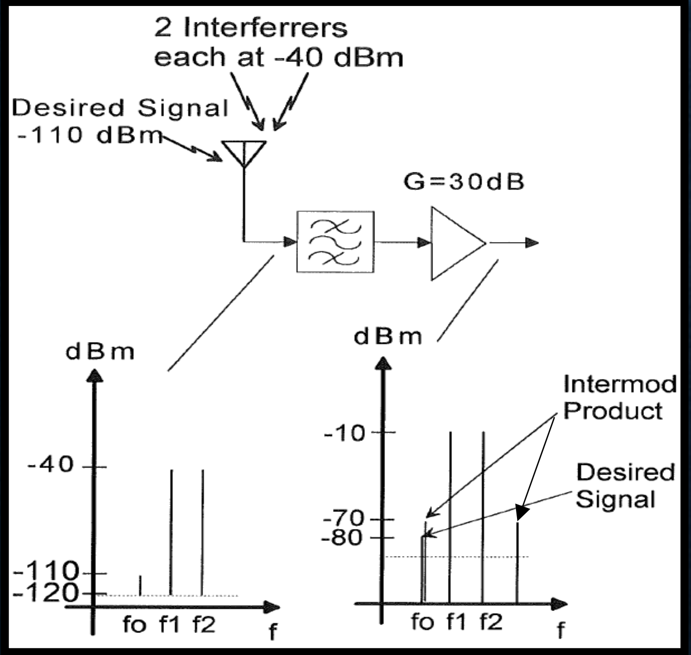
1.2 Features and benefits

- Internally matched to 50 Ω
- A gain of 24.4 dB at 2150 MHz
- Output power at 1 dB gain compression = 5 dBm at 2150 MHz
- Supply current = 20.0 mA at a supply voltage of 3.3 V
- Reverse isolation > 39 dB up to 2150 MHz
- Good linearity with low second order and third order products
- Noise figure = 3.9 dB at 950 MHz
- Unconditionally stable (K > 1)
- No output inductor required

https://www.nxp.com/docs/en/data-sheet/BGA2817.pdf

"Two Tone" Input

We're ignoring the "desired signal" here since its 70 dB weaker…



Let $v_i = V\cos(\omega_1 t) + V\cos(\omega_2 t)$

Then:

$$v_o = A_1 v_i + A_2 v_i^2 + A_3 v_i^3 + \ldots$$

$= A_1[V\cos(\omega_1 t) + V\cos(\omega_2 t)] +$

DC offset and harmonic terms +

$(const)(V^3)[\cos((2\omega_1 - \omega_2)t) + \cos((2\omega_2 - \omega_1)t)] +$

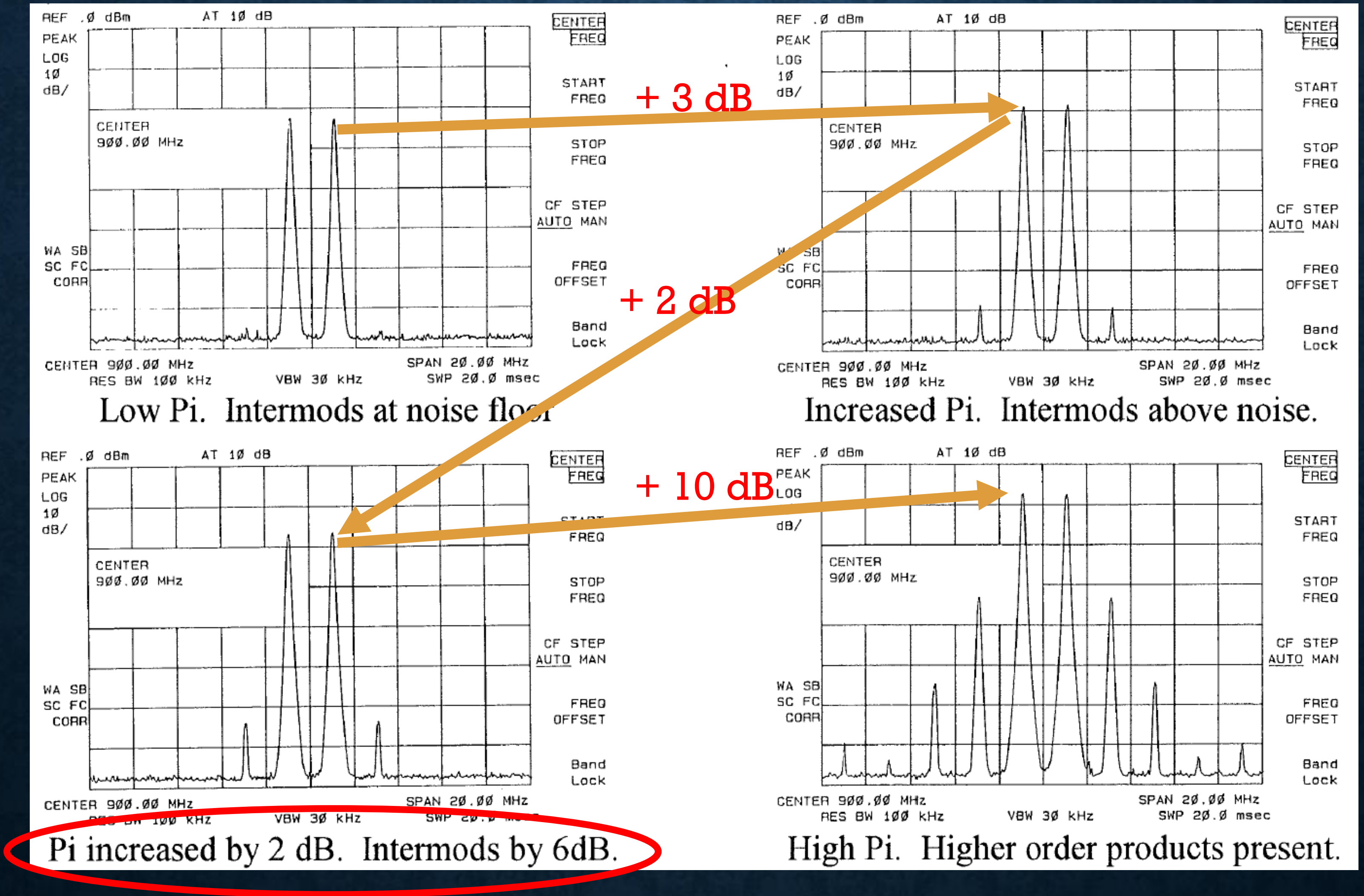
higher order terms

Single vs Two-Tone Inputs

Component of Output	*Voltage at Output*	*Power at Output* (dBm)
"Desired" Signals	$V_{o1} = A_1 V$	$P_{o1} = P_i + const$
Intermods	$V_{o3} = (const)V^3$	$P_{o3} = 3P_i + const$

NOTE: P_{o3} (power in third-order products) increases 3 times faster than P_{o1} (power in input signals).

Example Spectrums at Different Levels



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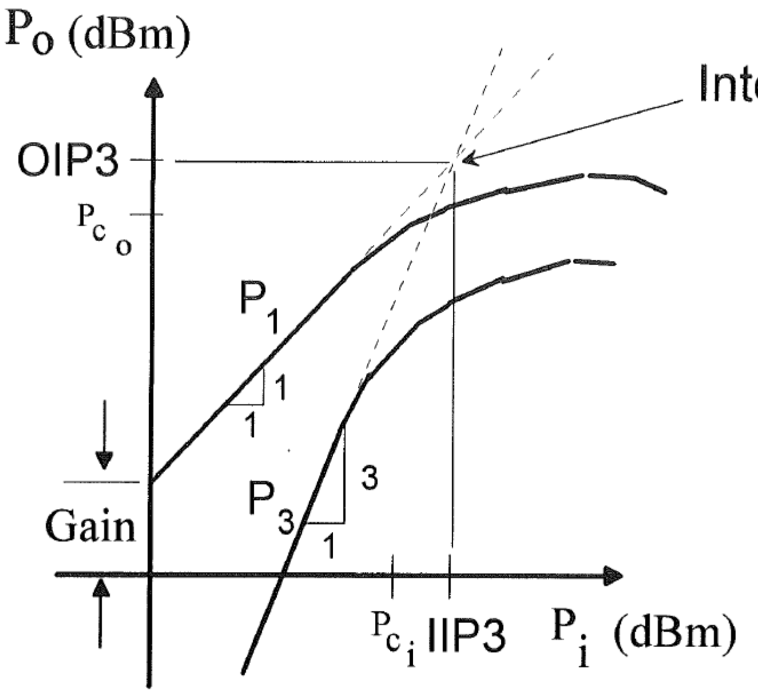
Third Order Intercept Point (TOI, IP3)



Plot P1 and P3 versus Pi at low Pi

Extrapolate to find intercept

Note that
IIP3 = OIP3 - Gain

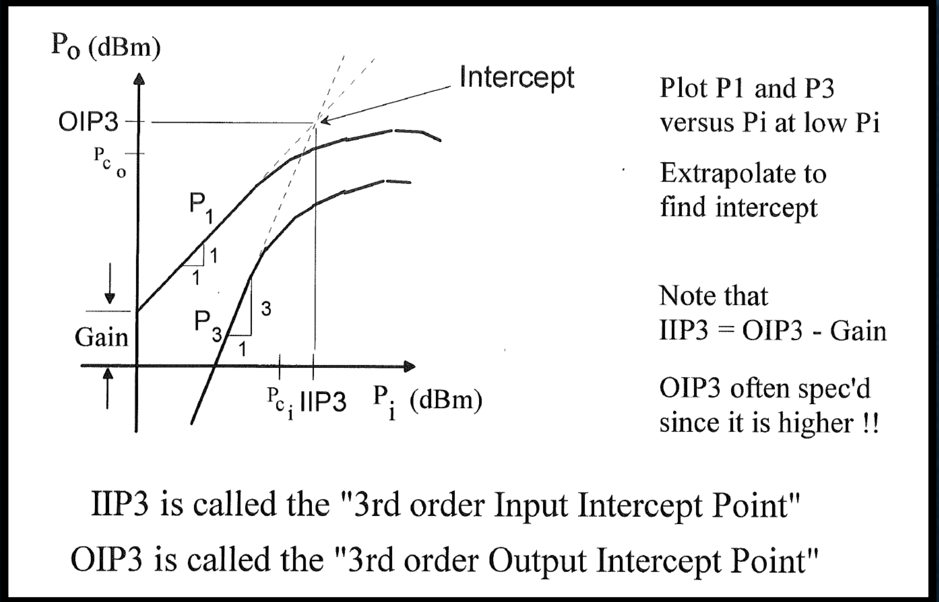
OIP3 often spec'd since it is higher !!

IIP3 is called the "3rd order Input Intercept Point"

OIP3 is called the "3rd order Output Intercept Point"

Real-World IIP3 Example

LNA used in TinySA-Ultra Spectrum Analyzer



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- Output power at 1 dB gain compression = 5 dBm at 2150 MHz
- Su
- Re
- Gc
- Nc
- Ur
- Nc

		f = 2150 MHz	1.5	2.7	-	
$P_{L(sat)}$	saturated output power	f = 250 MHz	8	8	-	dBm
		f = 950 MHz	5	7	-	dBm
		f = 2150 MHz	5	6	-	dBm
$P_{L(1dB)}$	output power at 1 dB gain compression	f = 250 MHz	6	6	-	dBm
		f = 950 MHz	5	6	-	dBm
		f = 2150 MHz	4	5	-	dBm
$IP3_I$	input third-order intercept point	P_{drive} = −40 dBm (for each tone)				
		f_1 = 250 MHz; f_2 = 251 MHz	−9	−7	-	dBm
		f_1 = 950 MHz; f_2 = 951 MHz	−9	−7	-	dBm
		f_1 = 2150 MHz; f_2 = 2151 MHz	−13	−10	-	dBm
$IP3_O$	output third-order intercept point	P_{drive} = −40 dBm (for each tone)				
		f_1 = 250 MHz; f_2 = 251 MHz	16	18	-	dBm
		f_1 = 950 MHz; f_2 = 951 MHz	16	18	-	dBm
		f_1 = 2150 MHz; f_2 = 2151 MHz	12.5	15.5	-	dBm

NOTE: IP3 is typically 5 to 15 dB higher than P1dB

Multi-Tone Inputs and CTB

LETTER

Simple method for intermodulation products counting in multicarrier systems

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Faculty of Electrical Engineering and Computing, Department of Wireless Communications, University of Zagreb, Unska 3, 10000 Zagreb, Croatia

Received 20 February 2006; accepted 16 February 2007

T. Kos et al. / Int. J. Electron. Commun. (AEÜ) 62 (2008) 148 – 154

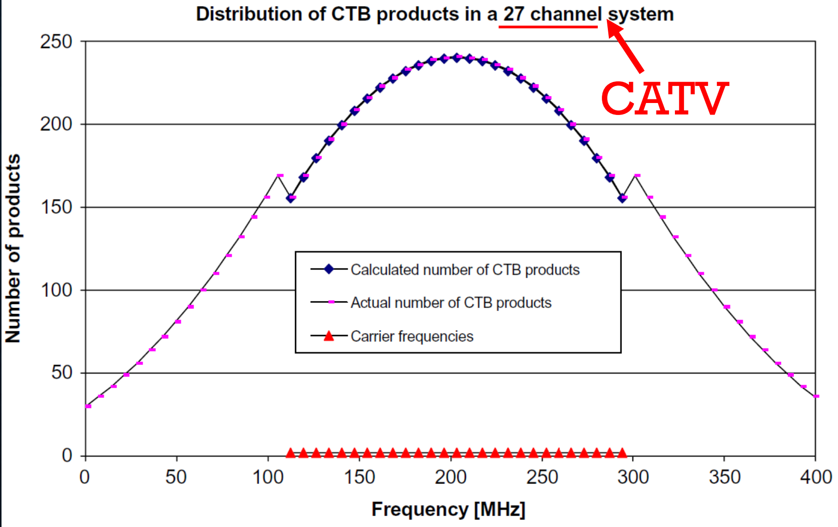


Fig. 4. Comparison of actual number of CTB products with the calculation.

1. Introduction

When several carriers are transmitted through a system with nonlinear characteristic, a large number of unwanted intermodulation products (IM) is generated [1–3]. Distortion products can include second- and third-order harmonics and intermodulation products, as well as double and triple beat products [4]. Frequency products due to second-order nonlinearity are $A \pm B$ and $2A$. Grouped together, $A \pm B$ products form composite second-order beats (CSO). Frequency components due to third-order nonlinearity at $A \pm B \pm C$, $3A$ and $2A - B$ form third-order products. Composite triple beat (CTB) distortion is formed from $A \pm B \pm C$ components. There are several algorithms for sorting and counting third-order IM products generated by a large number of carriers in multicarrier systems [5–8]. Knowledge of the number of

https://www.sciencedirect.com/science/article/abs/pii/S1434841107000829

Early Paper on CTB Calculation

ieeexplore.ieee.org/document/4065046/authors#authors

Third Order Intermodulation Products In A CATV System

Publisher: IEEE Cite This PDF

Bert Arnold **All Authors**

Abstract

Authors

References

Citations

Keywords

Metrics

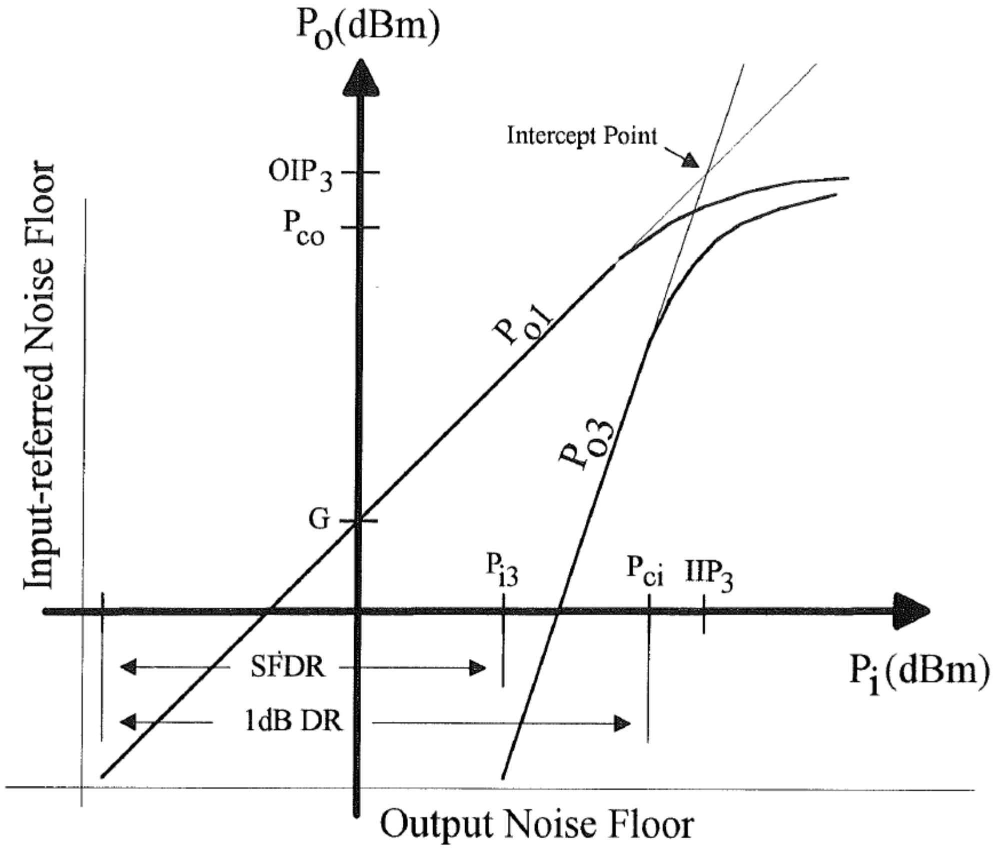
Abstract:
This paper discusses the build-up of third order intermodulation in a CATV system and presents a curve showing the required third order intermodulation (composite triple beat) level for high quality performance. A set of curves which show the relative readings between a power meter, signal level meter and spectrum analyzer, when measuring the third order intermodulation is also given.

Published in: IEEE Transactions on Cable Television (Volume: CATV-2 , Issue: 2, April 1977)

Page(s): 67 - 80 **DOI:** 10.1109/TCATV.1977.285708

Spurious-Free Dynamic Range (SFDR)

(For Classic Two-Tone Case)



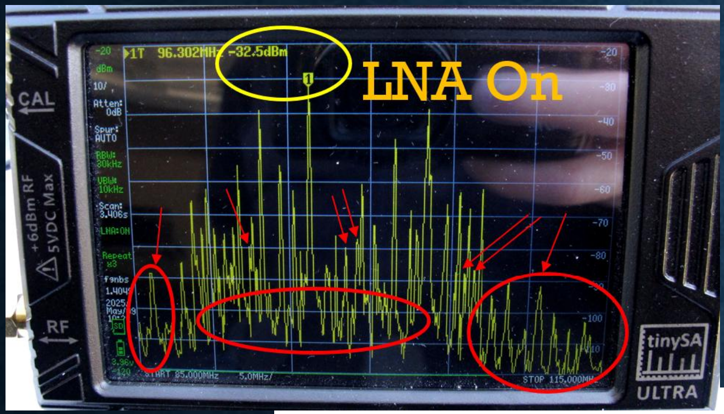
At input power P_{i3} , 3rd order products fall below noise floor. Difference of this and receiver sensitivity is "Spurious Free Dynamic Range" (SFDR)

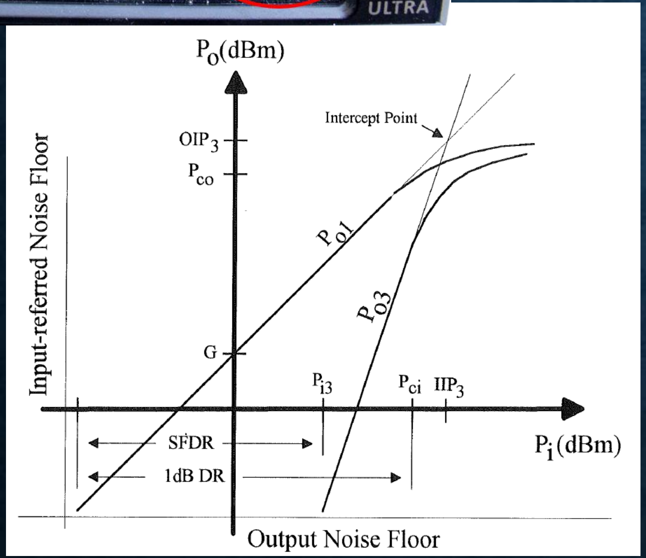
1dB compression dynamic range uses compression point (Pc) as maximum level and is higher than SFDR.

Total dynamic range (using maximum acceptable input signal) may be significantly higher than both, since compression is acceptable in FM/FSK systems.

Two-Tone SFDR and $P_{i\,max}$ Estimates

A work in progress… Doesn't consider CTB and unequal levels, etc…





Consider TinySA-Ultra Spectrum Analyzer with BGA2817 LNA as limiting factor

$P_{co} \approx P_{DC}(0.1) = 6\,mW = 7.8\,dBm \;\; (datasheet\ says\ 6\,dBm)$

$P_{ci} \approx P_{co}$ - Gain = 7.8 – 24 = -16 dBm

$IIP3 \approx P_{ci}$+10dB = - 6 dBm $(datasheet\ says\ -7\,dBm)$

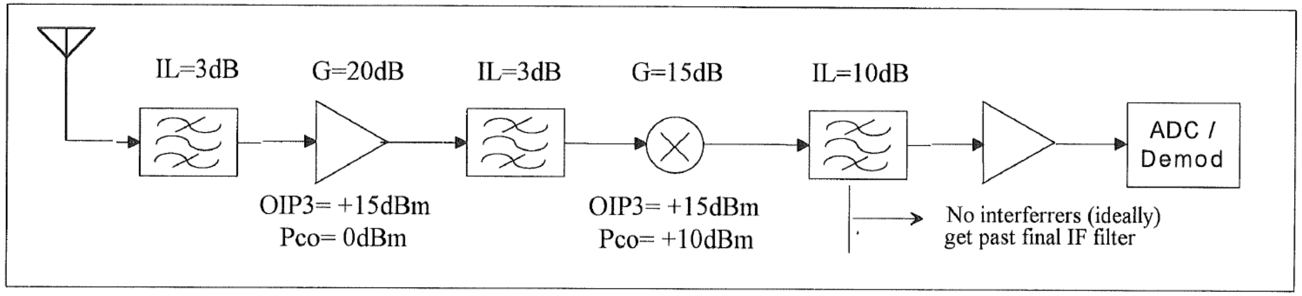
$MDS \approx -174\,dBm + 10log(30kHz) + (NF, RFI) \approx$ - 120 dBm

SFDR = 2/3 (IIP3 – MDS) = 76 dB *

$P_{i\,max} = P_{i3} = MDS + SFDR \approx$ - 44 dBm

*See: https://www.everythingrf.com/rf-calculators/spurious-free-dynamic-range

Overall Receiver *Input-Referred* P1dB and IP3 Example*



Component	Pco	OIP3	Cumulative Gain (Gc)	Pci = Pco - Gc	IIP3 = OIP3 - Gc
Preselect Filter	-	-	-3	-	-
LNA	0	15	17	-17	-2
Image Filter	-	-	14	-	-
Mixer	10	15	29	-19	-14

Overall receiver Pci ≈ -19 dBm (limited by mixer)
Overall receiver IIP3 ≈ -14 dBm (limited by mixer)

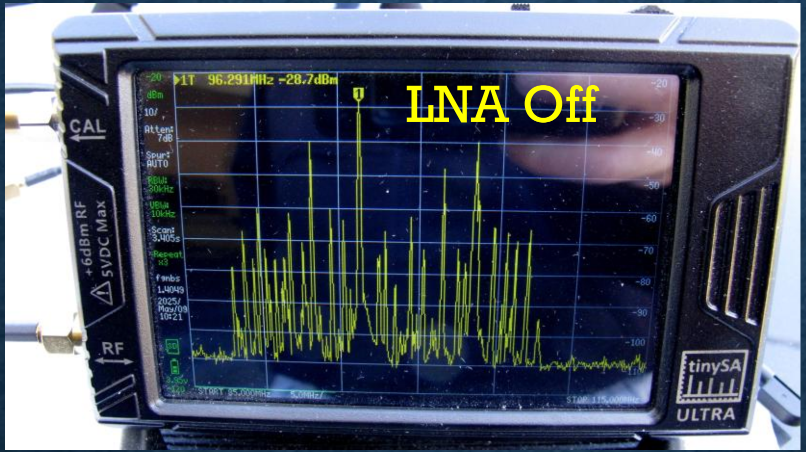
* NOTE: These are _***not***_ the values for the TinySA-Ultra amp and mixer

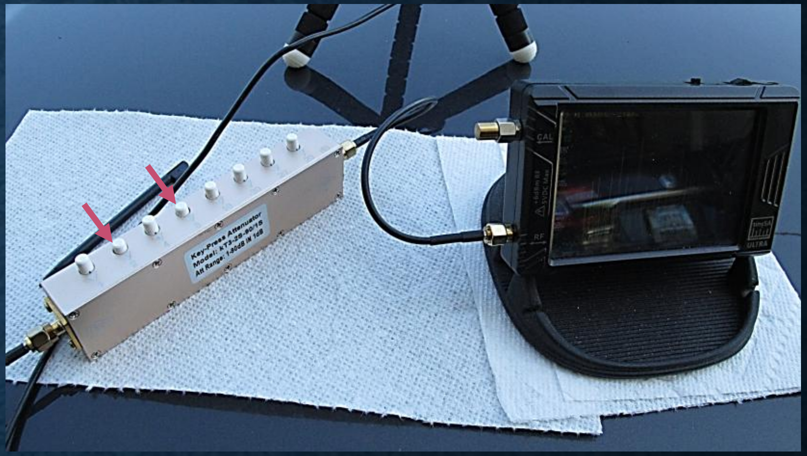
Today's Topics

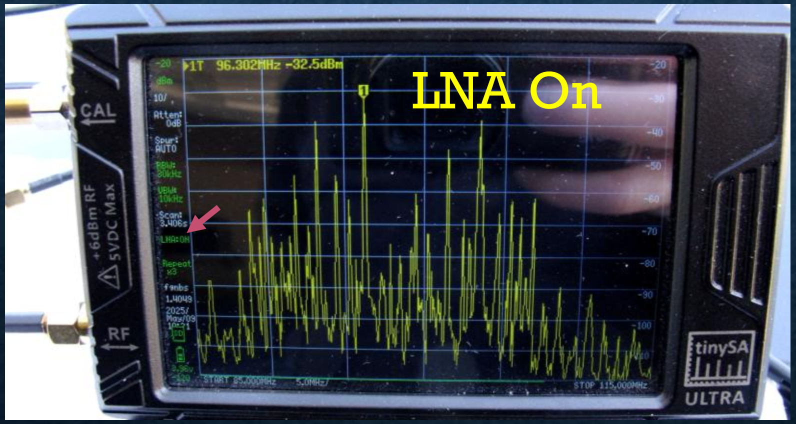
- ***The Math***
  - *Circuit Non-Linearities (e.g. V_o vs V_i or I_c vs V_{be})*
  - *Taylor / Maclaurin Series for V_o vs V_i*
  - *Single & Two-Tone Inputs*
- ***Performance Characteristics***
  - *IIP3 and Relationship to P1dB*
  - *Multi-Tone Inputs (Crowded Spectrum Case)*
  - *SFDR and Max Signal Levels vs P_{DC}*
  - *Antenna Input Referred Values*
- ➡ ***Solutions***

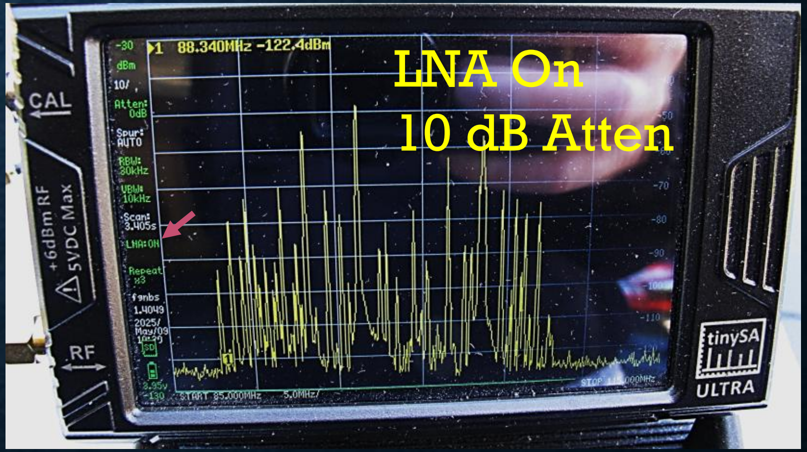
Easy/Partial Solutions

Use Attenuator or AGC (or shorten/<u>move</u> antenna !)



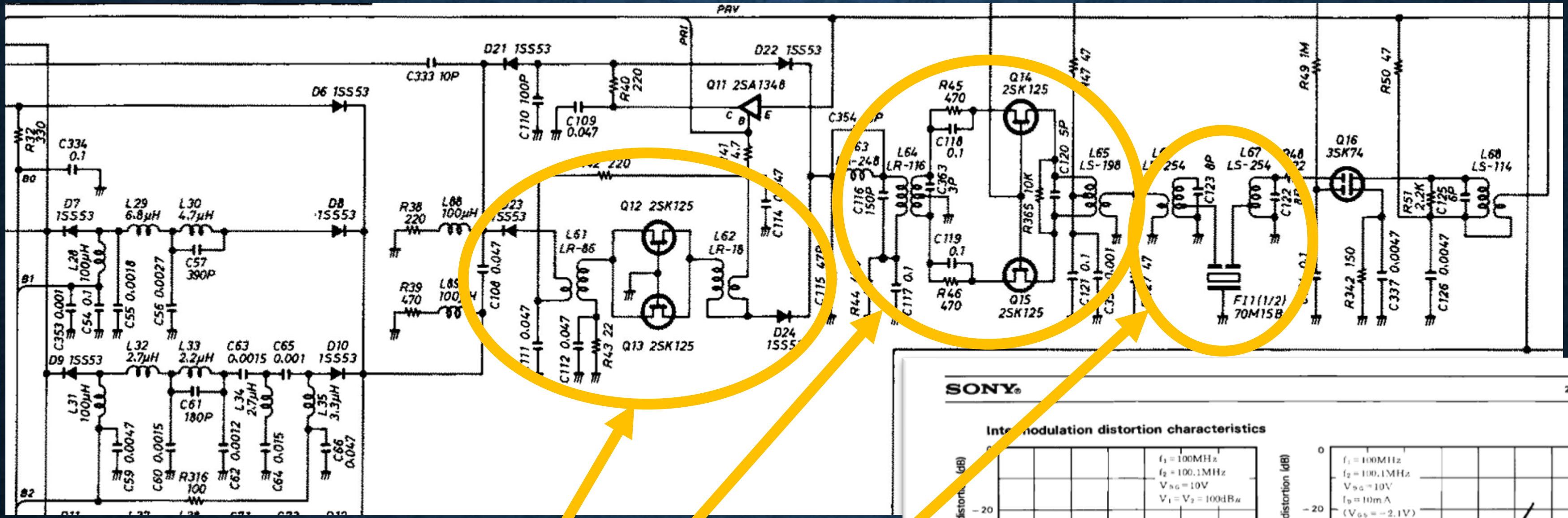


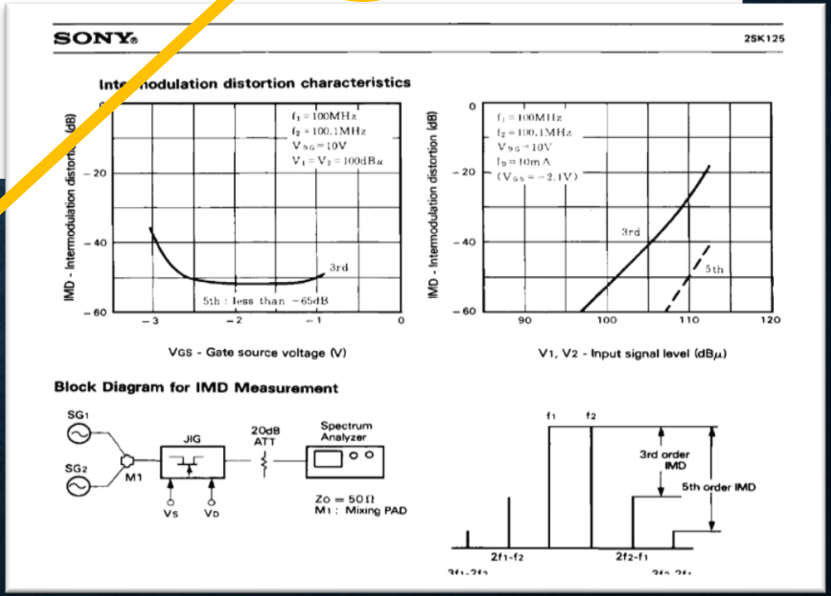




High-Power Solution

Used in ICOM 735 HF Transceiver.   See Episode 1





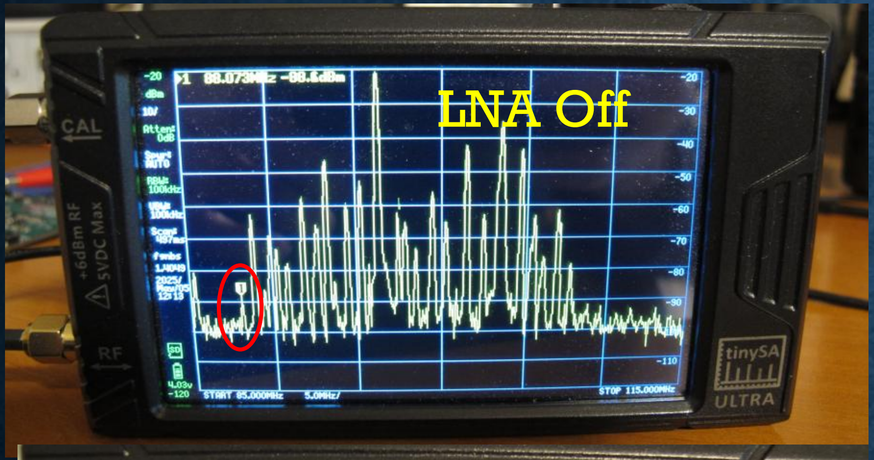
High Power (1/2 Watt) LNA

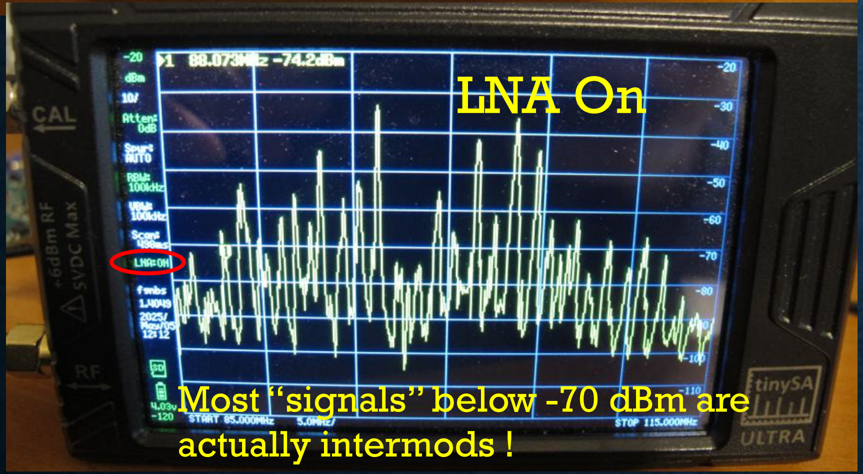
High Power (1/2 Watt) Mixer (upconversion to 70 MHz)

15 kHz BW Crystal Filter with Multi-pole input/output matching

Proposed Low-Power Solution

Q-enhanced Front-End - See Episode 1 White Paper





Comments / Conclusions

- ***The Math***
  - *Circuit Non-Linearities (e.g. V_o vs V_i or I_c vs V_{be})*
  - *Taylor / Maclaurin Series for V_o vs V_i*
  - *Single & Two-Tone Inputs*

- ***Performance Characteristics***
  - *IIP3 and Relationship to P1dB*
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  - *SFDR and Max Signal Levels vs P_{DC}*
  - *Antenna Input Referred Values*

- ***Solutions***

Possible Future Videos

- ***Receiver Performance*** ***(Including the math)***
  - *Noise analysis and simulation in circuits*
  - *Noise Figure Tradeoffs with Intermod Performance* (including CTB ?)

- ***Design of Q-enhanced Front-ends*** ***(Follow-up to Episode 1)***
  - *Effects of positive feedback on gain, selectivity, input Z, ...*
  - *Core CB amplifier design* *(Q_o of inductors, feedback topology, biasing for desired gain…)*
  - *Self-tuning hardware and software ?*

Thanks For Watching !