The Radio Receiver
Part 2

What we at the last lecture

- we looked at the various different kinds of signals that impinge on a receiver

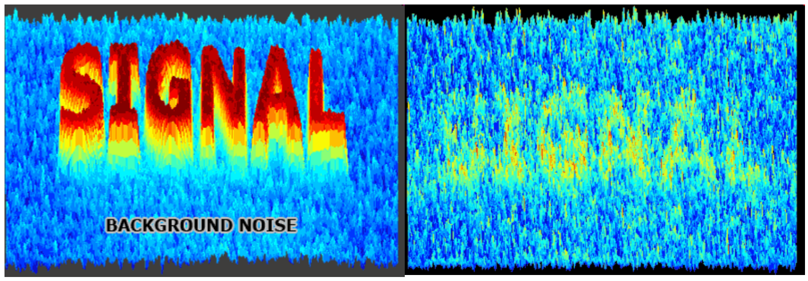
- we studied a particular receiver architecture known as the superheterodyne receiver

characterising behaviour

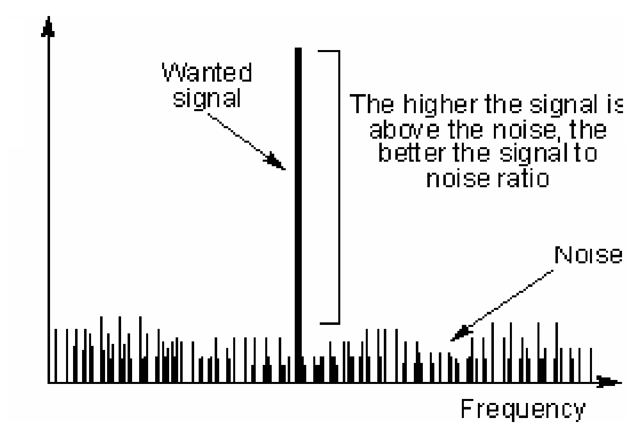
- any receiver, superhet or other, has a number of metrics which can be used to define its performance
- we are now going to look at some of the metrics

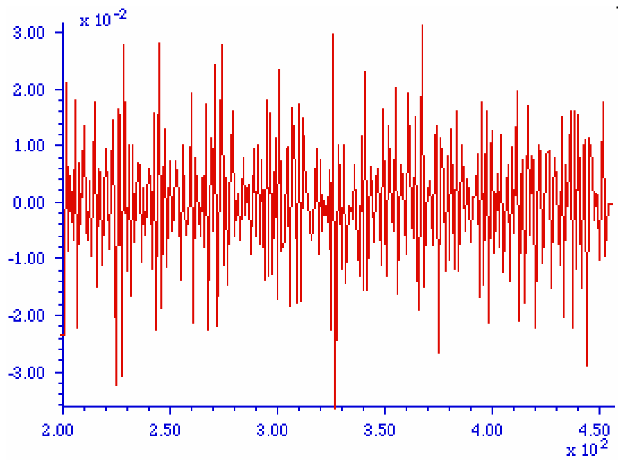
signal-to-noise ratio

- throughout the course we have been talking about different signal-to-noise ratios
- e.g. stronger coding or lower order modulation schemes needed at low SNR



sensitivity





cannot pick out the signal here

where does noise come from?

- In any receiving system the limiting factor is noise - weak signals are not limited by the actual signal level, but by the noise masks them out.
- This noise can come from a variety of sources.
- It can be picked up by the antenna or it can be generated within the receiver

.

- At HF and frequencies below this the combination of galactic, atmospheric and man-made noise is relatively high and this means that there is little point in making a receiver superbly sensitive. Normally receivers are designed such that the internally generated noise is much lower than any received noise, even for the quietest locations.

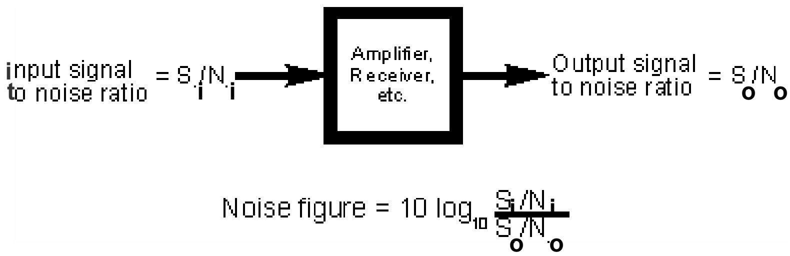
- At frequencies above 30 MHz the levels of noise start to reach a point where the receiver noise becomes far more important. By improving the noise performance of the receiver, it becomes possible to hear much weaker signals.

noise factor

- It is important to be able to specify the amount of noise added by a receiver.
- If the receiver were perfect then no noise would be added to the signal when it passed through the system and the signal to noise ratio would be the same at the output as at the input.
- A figure known as the **noise factor** can be derived simply by taking the signal to noise ratio at the input and dividing it by the signal to noise ratio at the output:
- As the signal to noise ratio at the output will always be worse, this means that the noise factor is always greater than one.

noise figure

The noise factor is rarely seen in specifications. Instead the **noise figure** is always seen. This is simply the noise factor expressed in decibels.

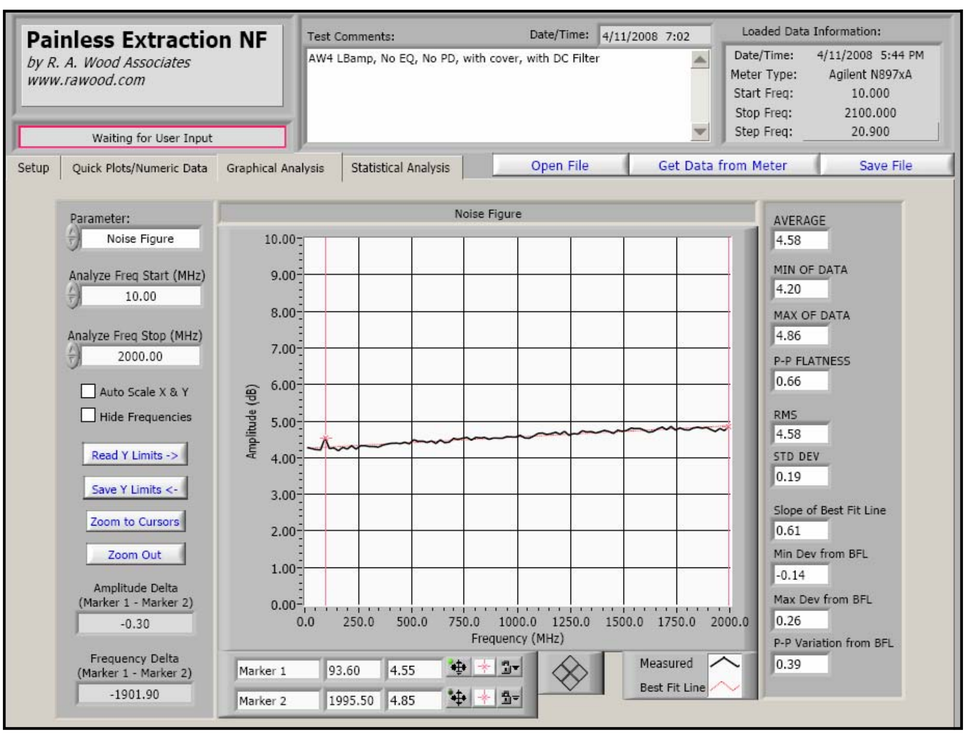


some examples

- As an example if the signal to noise ratio at the input was 4:1, and it was 3:1 at the output then this would give a noise factor of 4/3 and a noise figure of 10 log (4/3) or 1.25 dB.
- Alternatively if the signal to noise ratios are expressed in decibels then it is quite easy to calculate the noise figure simply by subtracting one from another because two numbers are divided by subtracting their logarithms.
- In other words if the signal to noise ratio was 13 dB at the input and only 11 dB at the output then the circuit would have a noise figure of 13 - 11 or 2 dB.

where noise is important

- **In terms of the receiver noise performance it is always the first stages or front end that is most crucial.**
- At the front end the signal levels are at their lowest and even very small amounts of noise can be comparable with the incoming signal.
- At later stages in the set the signal will have been amplified and will be much larger. The same levels of noise as are present at the front end will be a much smaller proportion of the signal and will not have the same effect.
- Accordingly it is important that the noise performance of the font end is optimized for its noise performance.



LNA

the low noise amplifier we spoke about in the superhet structure has a very low noise figure

adaptiveRF
expertise in wireless design

Module Specifications

Single Stage LNAs

Product Code	Fo (MHz)	BW (MHz)	F1 (MHz)	F2 (MHz)	P.Gain (dB)	Flatness (+/-dB)	N.F (dB)	P_1dB (dBm)	OIP3 (dBm)	S_{11} (dB)	S_{22} (dB)	Vd (V)	Id (mA)	Pd (mW)	RF IN PWR (Max dBm)
LNA1-859-70-19	859	70	824	894	19	0.5	0.5	14	27	-18	-10	6	65	390	25
LNA1-925-70-18	925	70	890	960	18	0.5	0.5	14	27	-18	-10	6	65	390	25
LNA1-859-70-20.5	859	70	824	894	20.5	0.5	0.7	20	31	-17	-8.5	6	100	600	25
LNA1-925-70-20	925	70	890	960	20	0.5	0.7	20	31	17	-8.5	6	100	600	25
LNA1-1500-200-16	1500	200	1400	1600	16	0.5	0.7	15	27	-18	-10	6	45	270	25
LNA1-1500-200-17	1500	200	1400	1600	17	0.5	0.6	21	33	-17	-10	6	90	540	25
LNA1-1810-120-15.5	1810	120	1750	1870	15.5	0.5	0.6	16	27	-18	-10	6	45	270	25
LNA1-1810-120-16	1810	120	1750	1870	16	0.5	0.6	21	33	-18	-10	6	100	600	25
LNA1-2045-250-14	2045	250	1920	2170	14	1.0	0.7	16	27	-18	-10	6	45	270	25
LNA1-2045-250-15	2045	250	1920	2170	15	1.0	0.6	20	33	-18	-10	6	100	600	25
LNA1-2500-400-12	2500	400	2300	2700	12	1.5	0.9	16	28	-18	-10	6	45	270	25
LNA1-2500-400-12.5	2500	400	2300	2700	12.5	1.5	0.8	20	33	-18	-10	6	100	600	25
LNA1-3500-200-10	3500	200	3400	3600	10	1.0	0.9	15	32	-16	-12	6	45	270	25
LNA1-3450-300-10.5	3450	300	3300	3600	10.5	1.0	1	21	36	-16	-12	6	100	600	25

other noise issues

- Specifying the noise figure alone is not enough.
- Other factors are important in terms of noise.
- One such factor bandwidth of the receiver. As the noise spreads out over all frequencies it is found that the wider the bandwidth of the receiver, the greater the level of the noise.
- Accordingly the receiver bandwidth needs to be stated to get a sense of the noise issues – as we see next the bandwidth has an effect on the sensitivity of the system

sensitivity

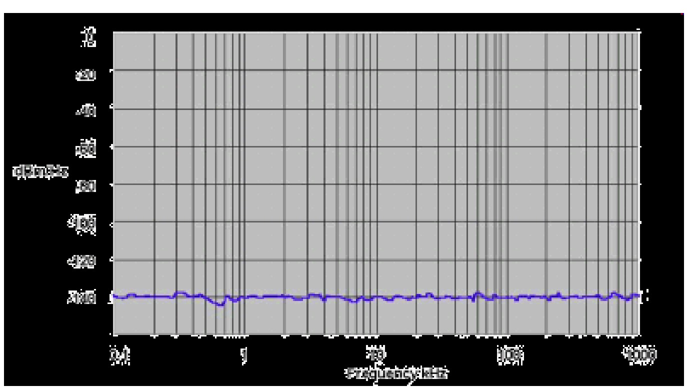
- **Sensitivity**: The ability of a receiver to pick up weak signals close to the noise floor
- Assume for the moment that the only signal present in the spectrum is the "small target signal." The minimum detectable signal, or *sensitivity*, will be determined by the signal bandwidth (B), the receiver's detection threshold, (SNR_{MIN}), the receiver's noise figure, (N_F), and inherent thermal noise limitations (kTB).
- At a temperature of 290 K, the sensitivity can be estimated with the following equation:

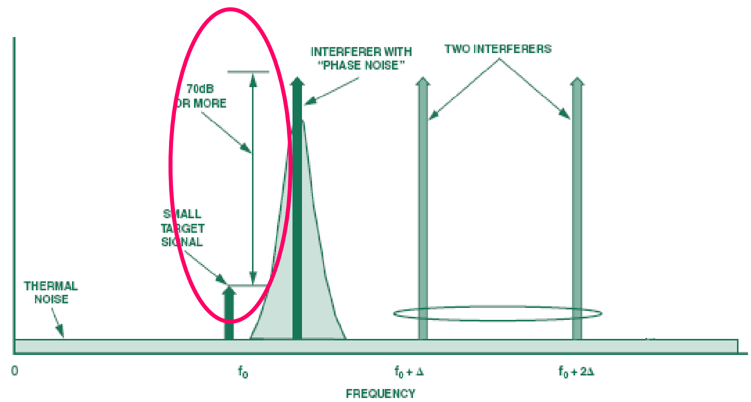
  $sensitivity = SNR_{MIN} + 10\log(B) + N_F + (-174 \text{ dBm/Hz})$

dynamic range

- to a certain extent this is another kind of way of expressing how sensitive a receiver is – though rather than think in absolute terms we think in difference between different signals
- **dynamic range** specifies the ability to be able to discriminate between different signal levels.

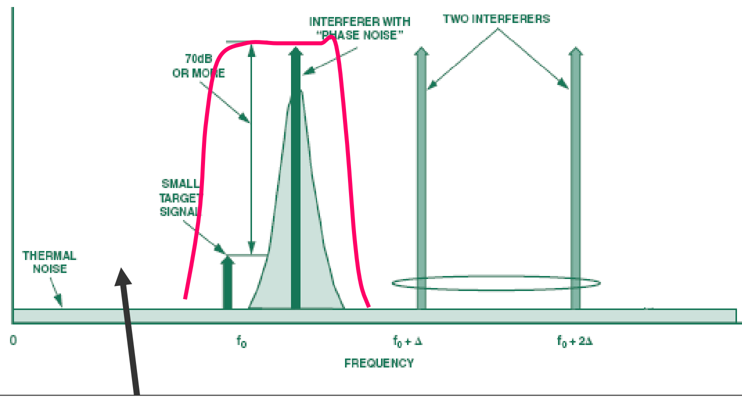
noise floor of a typical high quality receiver





selectivity

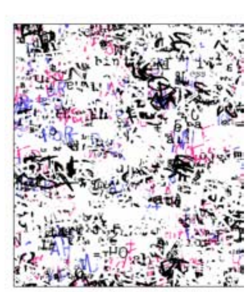
- The ability of receiver to **reject** unwanted signals either in band (co-channel interference), close to the wanted band (adjacent channel interference) or well away from the wanted band (will talk about a selectivity measure later)



the filters on the frontend will not tend to be so perfect that they can block out everything.

typically all of this will be received at the front end

non-linear behaviour of receivers



non-linear behaviour

- a receiver can exhibit what is termed non-linear behaviour
- we need to understand the non-linear behaviour as we need to know how to keep the system operating in the linear zone
- typically the focus of the non-linear analysis is based around the amplifiers

model of non-linear behaviour

$v_o(v_i) = V_{dco} + av_i - bv_i^2 - cv_i^3$ **– higher order terms**

- V_{dco} is a constant offset voltage and can be ignored
- a,b and c are model parameters and are constants
- the desired term is the linear gain times the input
- all other terms distort the output

suppose the input = $A \cos(\omega_1 t) + A \cos(\omega_2 t)$

$$\text{output} = aA(\cos(\omega_1 t) + \cos(\omega_2 t)) - bA^2(\cos(\omega_1 t) + \cos(\omega_2 t))^2 - cA^3(\cos(\omega_1 t) + \cos(\omega_2 t))^3.$$

$$v_0 = aA(\cos(\omega_1 t) + \cos(\omega_2 t)) -$$
$$bA^2 + b\frac{A^2}{2}(\cos(2\omega_1 t) + \cos(2\omega_2 t)) -$$
$$bA^2(\cos(\omega_1 t + \omega_2 t) + \cos(\omega_1 t - \omega_2 t)) -$$
$$c\frac{9}{4}A^3(\cos(\omega_1 t) + \cos(\omega_2 t)) -$$
$$c\frac{1}{4}A^3(\cos(3\omega_1 t) + \cos(3\omega_2 t)) -$$
$$c\frac{3}{4}A^3(\cos(2\omega_1 t + \omega_2 t) + \cos(2\omega_2 t + \omega_1 t)) -$$
$$c\frac{3}{4}A^3(\cos(2\omega_1 t - \omega_2 t) + \cos(2\omega_2 t - \omega_1 t))$$

so what is happening?

- the nonlinear behaviour of the amplifier is generating signals at new frequencies
- harmonics are generated
- we talk about **intermodulation products** coming into being
- we already looked briefly at the idea of intermodulation in the first set of lectures

how is this triggered

- as we saw from two signals entering ther receiver …..
- Interference between closely spaced transmitters
- Interference in receivers caused by powerful signals outside the receiving frequency
- Interference generated in antennas, masts, connectors and filters

intermodulation products

- we talk of second and third order intermodulation products

$$v_0 = aA(\cos(\omega_1 t) + \cos(\omega_2 t)) -$$

$$bA^2 + b\frac{A^2}{2}(\cos(2\omega_1 t) + \cos(2\omega_2 t)) -$$

$$bA^2(\cos(\omega_1 t + \omega_2 t) + \cos(\omega_1 t - \omega_2 t)) -$$

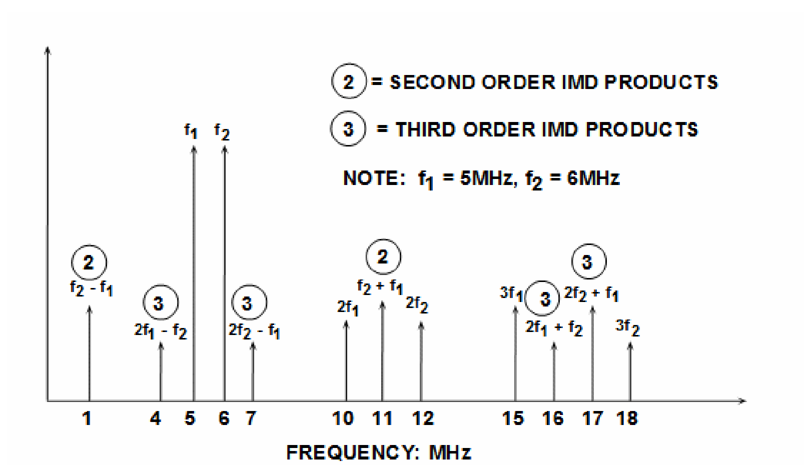
$$c\frac{9}{4}A^3(\cos(\omega_1 t) + \cos(\omega_2 t)) -$$

$$c\frac{1}{4}A^3(\cos(3\omega_1 t) + \cos(3\omega_2 t)) -$$

$$c\frac{3}{4}A^3(\cos(2\omega_1 t + \omega_2 t) + \cos(2\omega_2 t + \omega_1 t)) -$$

$$c\frac{3}{4}A^3(\cos(2\omega_1 t - \omega_2 t) + \cos(2\omega_2 t - \omega_1 t))$$

IMD products



example calculations

FIGURE 1
3RD ORDER INTERMODULATION PRODUCTS

f1 = 100.3 MHz.   f2 = 101.1 MHz.

2f1-f2 = [2(100.3)-(101.1)] = [200.6-101.1] = 99.5 MHz.

2f2-f1 = [2(101.1)-(100.3)] = [202.2-100.3] = 101.9 MHz.

OR

[f1-(f2-f1)] = [100.3-(101.1-100.3)] = [100.3-0.8] = 99.5 MHz.

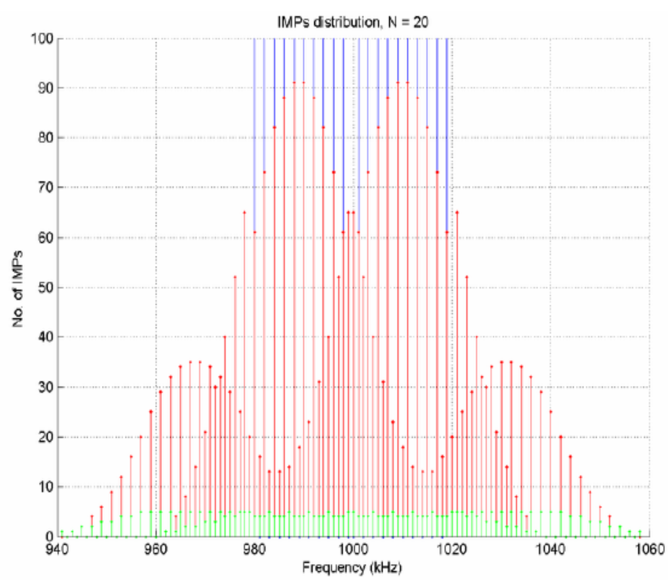
[f2+(f2-f1)] = [101.1+(101.1-100.3)] = [101.1+0.8] = 101.9 MHz.

distortion

- the intermodulation products, especially the third order can really impede the receive process
- second order are more easily filtered out.

result of intermodulation products

- **Thus the signal nearby the signal we want to hear has caused our receiver to saturate or block preventing us from receiving the signal we want to hear.**
- **This saturation or blocking is actually caused by the intermodulation products between the two nearby signals and not directly from either signal being too high in amplitude.**
- **On a practical basis before complete blocking occurs we will notice distortion in the received signal. We may also hear additional sounds that are shrill.**



that third order intercept point

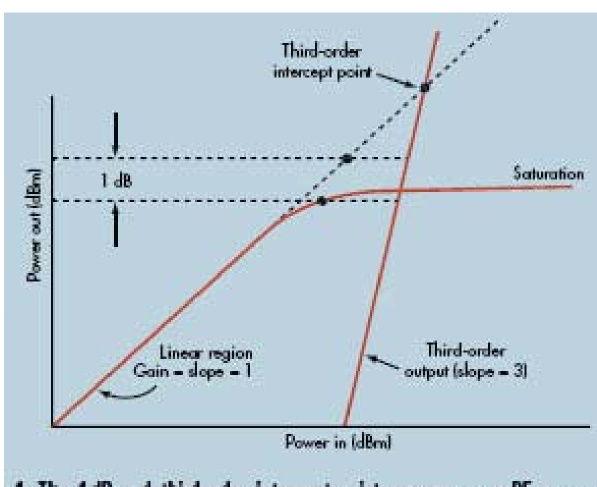
- Third order intercept point is just one of several specifications that can be used to judge the quality of a receiver.
- Some of the other specifications such as signal to noise ratio and selectivity are relatively easy to understand and interpret.
- The term is somewhat involved and many people don't actually know what it really means. Most who us it do know that the higher the number the better the receiver. Numbers may range from something like –10db to something in the range of +30 to 40 db.
- **In very simple terms IP3 is a way of expressing how well a receiver separates two closely spaced signals.**

IIP3

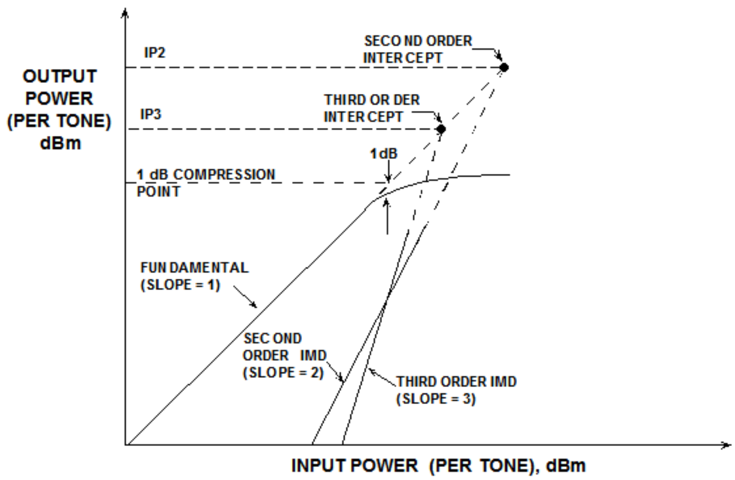
The IIP3 is a theoretical point that is calculated and is not measured as is specifications such as selectivity.

so what is it

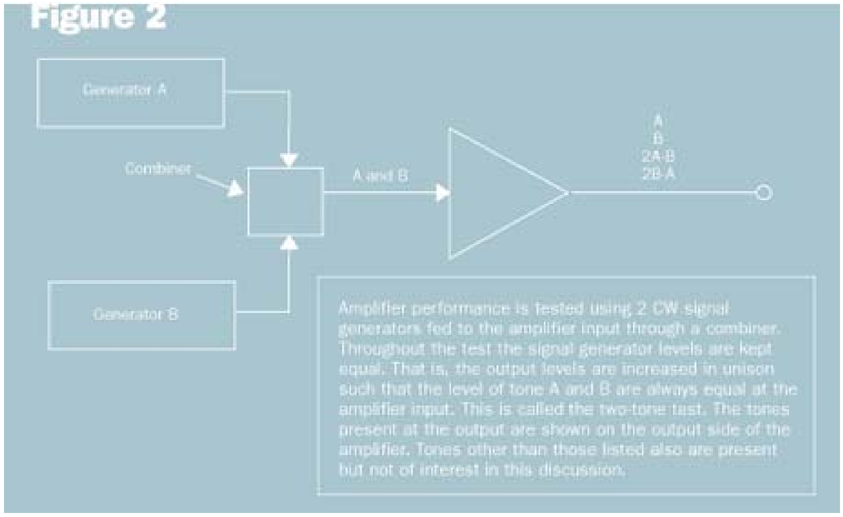
- **As signal strength is increased by 1 db the intermodulation products increase by 3 db.**
- **The IP3 point is the hypothetical output signal level at which the third-order tones would reach the same amplitude level as the desired input tones.**
- **When this point is reached the mixer theoretically becomes saturated and a further increase in input signal will not cause a further increase in output volume.**



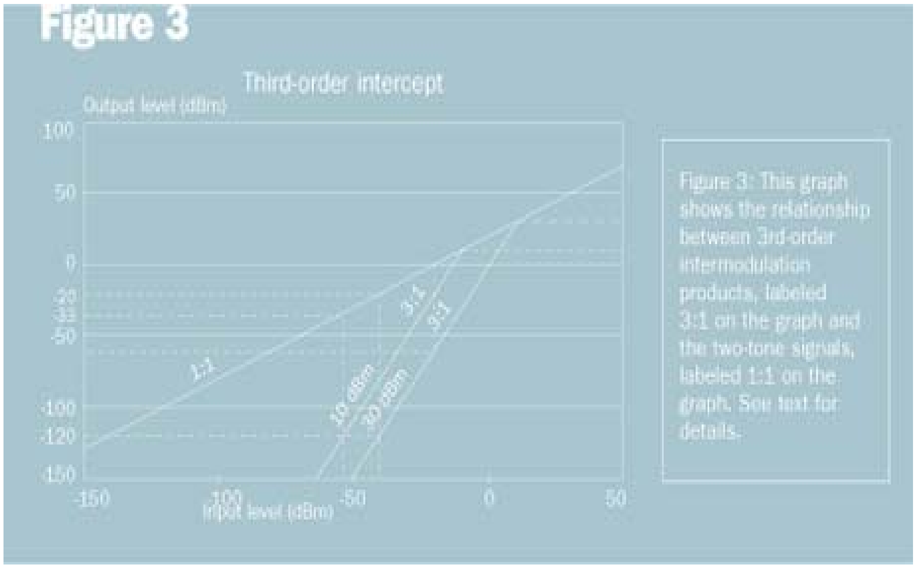
1. The 1-dB and third-order intercept points are common RF power-amplifier measurements.



: Figure 2 shows an RF amplifier where two signals (A and B) are applied to the input port. As long as the RF amplifier is perfectly linear, the only two signals appearing at the output will be A and B. Of course, no amplifier is perfectly linear, so other mixing products will appear in the output — although they may be at a very low level, assuming low signal levels at the input.



With higher signal levels applied to the input, the distortion products at the output can increase rapidly. To better illustrate the importance of the third-order intercept specification, the graph shows the third-order intercept point (IP3) for two amplifiers. Both amplifiers have a gain of 20 dB. The IP3 points of each amplifier are +10 dBm, while the other is +30 dBm respectively.



Suppose that a receiver has a sensitivity of -110 dBm (0.7 μV).

Further suppose that a third-order intermodulation signal formed by the equation 2A - B falls on the frequency of the desired receive signal.

In order to prevent the third-order intermodulation signal from degrading the reception of a -110 dBm signal, the intermodulation signal should be suppressed by at least 10 dB below the level of the desired signal.

In this case, the level of the third-order intermodulation signal should be no greater than -120 dBm in order to cause no harm to the desired signal.

In order to determine the maximum input/output level that the two tones can have, a line is drawn from the -120 dBm point on the vertical scale to intersect the third-order intermod slopes.

Then, vertical lines are drawn up to the 1:1 slope and down to the horizontal scale.

These are shown as dashed lines in Figure 3. The dashed lines intersect the 1:1 slope at the -20 dBm point for the +30 dBm slope and at -33 dBm for the +10 dBm slope

Similarly, the dashed lines intersect the horizontal scale at -40 dBm for the +30 dBm slope and -53 dBm for the +10 dBm slope. Thus, the output level of tones A and B for the +30dBm slope should be no greater than -20 dBm, and the input level to the amplifier should be no greater then -40 dBm.

For the 10 dBm slope, the output level of tones A and B should be no greater than -33 dBm and the input level should be no greater then -53 dBm. If the input/output levels exceed these limits, the third-order intermod signal will exceed the -120 dBm level and will cause degradation to the desired signal at -110 dBm. It is important to note that the third-order intercept point cannot be reached in actual practice because the amplifier would become practically inoperative before this point is reached. However, the TOIP is very useful in understanding how an amplifier will perform with various input levels and in calculating the actual level of a third-order intermod signal at the amplifier output.

When choosing an amplifier, the required specifications for the amplifier would depend upon the particular application. It must provide sufficient gain and it must operate over the required frequency band with stability. If strong signals are anticipated at the input, the amplifier should have a high TOIP. A graph like the one in Figure 3 can help you determine the third-order intermod level at the amplifier output given the input signal levels, A and B. Keep in mind that the graph in Figure 3 assumes that tones A and B are always of equal amplitude.

The analysis performed here is similar to the analysis you would perform on any non-linear device.

Looking and combinations of nonlinearities or situations in which the input tones are at different levels is beyond the scope of this course.

note: weakly non-linear only

- The concept of intercept point is based on the assumption on a weakly nonlinear system, meaning that higher order nonlinear terms are **small enough to be negligible**.

What IP3 points do we want?

- essentially the higher the value the better
- this means that signals can be quite strong and yet not drive the receiver into non-linear behaviour
- however to get the IP3 really expensive components are needed in the radio
- most specifications of a radio will give an IP3 value.

In Summary

- Radio receivers have to be able to deal with a lot of interference
- They have to be able to operate in as linear fashion as possible
- The superheterodyne receiver is a typical RF frontend
- While we looked at details of this, the main broad parameters describing a radio's performance apply to all radios.

FEATURES & SPECIFICATIONS

Receiver Frequency	156.025-163.275 MHz				26.965 - 27.980 MHz
12dB SINAD sensitivity	0.25 μV (distant) / 2.5 μV (local)				0.5 μV (distant) 12.0 μV (local)
20dB SINAD sensitivity	0.35 μV (distant) 3.5 μV (local)				
Adjacent CH selectivity	More than 70 dB	More than 70 dB		More than 70 dB	-36 dB @ ± 6 kHz; -60 dB @ ± 10 kHz
Spurious response	More than 70 dB	More than 70 dB		More than 70 dB	
Intermodulation Rejection Ratio	More than 68 dB	More than 68 dB		More than 68 dB	60dB, 20 kHz channel specs
Residual Noise Level	More than -40 dB unsquelched				More than 60 dB
Audio output power	2 W (with 8 Ω at 10% distortion) 4 W with 4 Ω external speaker		40 mm speaker - 0.5 W (1 W max.)	2 W (with 8 Ω at 10% distortion) 4 W with 4 Ω external speaker	1 W @ 16 Ω, 4 W @ 4 Ω w/ ext. speaker
Compass safe distance	Speaker: 1.5 ft (0.45 m)				

* *US Model*