Noise Figure Performance of an Active 3G Gilbert Cell Mixer: Design & Measurement

This presentation shows why the noise figure of 3G Gilbert Cell and other monolithic active mixers can vary so much from simulated results, depending upon their measurement setup and usage parameters. It explains how mixer simulations can now be iterated faster than ever in the Agilent Technologies Mixer DesignGuide for the Advanced Design System (ADS) and compares actual measurement results to simulations. It will also show the new ease of making noise figure measurements faster and more accurately than ever before, quantify sources of errors in the measurement of active mixers, and address ways to improve the noise performance of active mixers.

Agilent’s new Mixer DesignGuide for the Advanced Design System (ADS) enables designers to iterate mixer simulations faster than ever before, simplifying the usability of the powerful ADS product. Agilent’s new series of Noise Figure Analyzers (NFA) and Smart Noise Sources (SNS) enable the most demanding noise-figure measurements with an entirely new generation of accurate, fast and easy-to-use instruments.

This presentation was developed in conjunction with Besser Associates of Mountain View, California, a training and education company for RF and wireless topics.
These are some typical steps that a designer might follow when designing a mixer. This section of the paper shows how ADS can be used efficiently to simulate key mixer specifications, rather than address the details of mixer design.

Details of mixer design are covered in other sources, three of which are given in the handout.
Typical Mixer Specifications

- Conversion Gain or Loss
- Noise Figure
- Port-to-Port Isolation
- Intermodulation Distortion
- Gain Compression
- Port Impedances
- All of the Above versus LO Power
- All of the Above versus Input Frequency

These are typical specifications that a mixer designer would be interested in simulating. Because of the variety of different measurements here, and because mixers are used for frequency translation, these simulation setups can be somewhat complicated. ADS has example files that show most of these simulations. However, the ADS add-on product, Mixer DesignGuide, makes it much easier and faster to set up and run these simulations and resimulations.
Mixer DesignGuide Tests All of These

Both single-ended and differential-mode topologies are handled. Access in moments what currently takes weeks for an expert!

The Mixer DesignGuide has setups for simulating all of the major characteristics of mixers that designers need to know. They are organized in an intuitive easy-to-use structure so that even relatively novice users of ADS can quickly get up to speed and characterize their mixer designs without having to become expert users. A simulation that currently can take an expert user weeks to create is now accessible in moments!
The Mixer DesignGuide includes several sample mixers that designers can use as starting points. Various common topologies are included.
How Do You Use the Mixer DesignGuide?

- Choose a characteristic to simulate
- Copy simulation setup with sample mixer into your ADS project
- A data display appears
- Replace the sample mixer with your schematic
- Set parameter values for the simulation
- Data display is updated with simulation results of your mixer
- Simulate other characteristics - but you don’t have to re-enter your mixer schematic

Here is the sequence of steps a designer would use when simulating a mixer, using the Mixer DesignGuide. We’ll look at each step in this sequence in the next slides.

Usually you’re interested in simulating multiple performance characteristics. These often require different simulation setups within ADS. When using the Mixer DesignGuide, you only have to enter the mixer schematic into the sample mixer subcircuit once; all other simulation setups will use this updated subcircuit. However, the simulation parameters, such as frequency and power ranges, do have to be set on each simulation setup. After setting these simulation parameters, you do have to run a simulation for the data displays to be updated.

The following slides illustrate the steps shown here.
Choose a Characteristic to Simulate

Example: Noise Figure versus LO Power

Here we choose a characteristic to simulate using a hierarchical menu pick. We’ll simulate the single-sideband noise figure and conversion gain of a single-ended mixer versus LO power.
After you have selected the menu pick shown in the previous slide, the schematic is copied into your ADS project. There are notes in several places on the schematic indicating what to do next, there are red frames around parameters that users should set. There should not be a need to change other parameters on the schematic, outside the red frames, except for the order of the LO tone, which is the number of harmonics simulated.
A Data Display Appears

These are previously simulated results of the sample mixer.

Here is the default data display that is copied into your ADS project and opened. It shows previously simulated results of the sample mixer, in this case an Agilent IAM-81008. You can see now whether or not the simulation setup will give you the information you want to predict.
Next you “push” into the sample mixer subcircuit and replace the sample mixer schematic with your schematic. You do need to keep the input, LO, and output ports, however.
Now you can set the exact parameter values for the simulation. These are the same parameters we saw in the red frames a few slides back. The names of the variables have been defined so that it should be obvious what they are. The LO power is in units of dBm.
Finally you run the simulation and your results will automatically be updated on the data display. These are the simulation results that we’ll compare to measurements in succeeding slides.
Double Sideband (or All Sideband) Noise Figure and Conversion Gain (from a Menu Pick)

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After completing the single-sideband noise-figure simulation, we ran the analogous double-sideband simulation. We selected the menu pick for double-sideband noise-figure simulation, set the LO power range and input frequency range, and ran the simulation. The results are shown here.

The setup for this double sideband (DSB) simulation took literally about one minute once the previous single sideband (SSB) simulation had completed, which itself took only minutes. Without the Mixer DesignGuide, the DSB simulation setup would have easily taken hours to do after the SSB simulation, which would’ve taken days or more.

Note that the DSB noise figure and conversion gain are about 3 dB lower than for the SSB simulation, which is to be expected. The SSB measurement has only half the “ON” noise power versus the DSB measurement, but they both have the same “OFF” noise power, so the difference between their “ON” to “OFF” ratios is close to 2, or 3 dB. We’ll see later that the exact difference depends on the ratio of gains between the two side bands.
Mixer DesignGuide...

- Gives you all the common data mixer designers need to know
- Lets you focus on your mixer design rather than ADS syntax
- Gives you results in minutes that would otherwise take days of simulation and data-display setup

Using the ADS Mixer DesignGuide can greatly increase your design productivity by enabling you to get results in minutes that would have otherwise taken days or even weeks for an expert ADS user. The functions of setup, simulation and data display are automated based on key physical and performance specifications. Circuit design is easier, faster, and more consistent through the use of wizards, templates, examples, and step-by-step instructions.

DesignGuides apply the powerful simulation technologies in ADS to specific design applications such as microstrip circuits, power amplifiers, filters and oscillators, and now, new for 2001, to mixers.
Now let’s turn our attention to measurement topics for active mixers. We’ll look at some of the factors that affect their noise performance, and compare some measurements to the simulations we just saw.
Noise Figure Measurement of 3G and Other Broadband Monolithic Front Ends is Very Susceptible to Error.

- Noise figure analyzers are more accurate than ever
- Measurement uncertainty calculator on the web

But ...

- Mixer architecture and application affect noise figure. Single sideband readings can be typically 1 dB optimistic to 10-15 dB pessimistic

Today's noise figure analyzers are more accurate than ever due to improvements such as lower instrument noise figure, frequency dependant loss compensation, automated correction for noise-source temperature, and more. Unavoidable measurement errors are quantifiable in a measurement uncertainty calculator that we’ll see later.

However, in a broadband environment the most accurate analyzer can give readings that are optimistic by 1 dB, and pessimistic by 10 or 15 dB due to the architecture of the mixer and its application parameters. Results can be even worse in some circumstances, such as when a high level of broadband LO noise mixes with broadband RF noise.

The following slides will discuss and quantify these sources of error, then apply this knowledge to the design of improved monolithic and discrete front ends.
The Problem

“Gilbert Cell” mixers and most monolithic mixers have little filtering on-chip.
- The LO buffer directly drives the mixer cell
- The LNA directly drives the mixer cell

The LNA and LO buffer are broadband amplifiers often with as much as 6 dB per octave gain slope. The following problems arise from the lack of LO and RF filtering:
- Broadband LO noise can appear at the IF output by conversion or intrusion
- Broadband RF noise converted from the image and other sensitive frequencies can appear at the IF output

Unlike printed circuit board design, where bandpass filtering can be accomplished with a few traces and perhaps a chip capacitor, filtering on the integrated circuit chip can be difficult and often requires a large amount of chip area. On-chip filtering is generally minimized for this reason. This lack of filtering can cause unexpected degradation of the noise performance of a monolithic active mixer.
The Gilbert Cell mixer is a compact, efficient approach to combining a differential amplifier with a phase-reversing switch mixer. Often the differential amplifier provides unbalanced to balanced transformation. The switching transistors also can operate with an unbalanced input. The best even-order distortion performance and LO-to-IF isolation is obtained with balanced input. The same circuit topology works well with FET devices also.

The progression of the slide shows how the switching cell operates as a phase reversing switch.

The main point is that with no filter between the differential amplifier and the switching cell, the gain of the mixer has the 1/F slope of the amplifier. Shunt resistors across the RF input will improve the flatness, provide an input match, and add noise.
The limited LO to RF isolation of the mixer results in some LO signal leaking to the RF port. Any noise in the LO signal that is at a frequency where the mixer has conversion ability will be converted to the IF output along with the desired signal. Mismatch at the RF port exacerbates this effect by reflecting additional LO leakage into the mixer to be converted to the IF.

Secondly, the LO buffer amplifier often has appreciable gain at the IF. Noise in the LO buffer output at the intermediate frequency can appear at the IF port of the mixer due to imperfect rejection of the LO signal. This noise will add to the converted RF noise from the LO, further degrading the signal to noise ratio at the mixer output.

Any broadband LO noise also mixes with any broadband RF noise, such as the noise pollution received from the power amplifiers of a base station. The resulting mixed product in the IF can be far greater than would be intuitive. To minimize the noise that reaches the IF via conversion or leakage it is necessary to filter the LO signal.
Measurement of a monolithic GaAs balanced mixer shows a noise figure of about 5 dB with numerous spikes due to the spurious output from the synthesizer that was used as an LO (no, not an Agilent synthesizer in this case!). 40 MHz reference “spurs” are clearly seen. Some off-air signals are also very clearly interfering with the measurement. However, at the frequency of interest, 2430 MHz, the noise figure of 5.45 dB is easily measured. The gain is also shown, 3.78 dB.

Note that a swept noise figure measurement was necessary to enable visibility of the spur in the display. Imagine measuring noise figure only at a spot frequency that happened to be at one of the spur; you couldn’t tell the true performance of the device.

The uncertainty of measurements will be addressed later in the presentation.

In an effort to reduce the spurious responses, an Agilent sweep generator was used as an LO instead of the synthesizer. The next figure shows the results.
Using the signal generator as an LO is indeed much cleaner, with only a few off-air spurs visible in the noise measurement. However, note that the measured noise figure of the mixer has increased to 12.85 dB, while the measured gain appears the same as before. A filter between the signal generator and the mixer LO port is needed to allow an accurate noise figure measurement to be made. No calibration of the system will reduce this inaccuracy.
Here is a direct comparison of two noise figure measurements of a mixer, one with no LO filter and one with a filter; otherwise they are the same measurement. The dramatic difference in performance is over 10 dB! A filter on the LO makes this much difference!

The extensive modulation capabilities of the LO are effective for testing contemporary communications formats. However, the circuitry that enables such capabilities in a source typically raises the broadband noise floor above that of a more simple source with less modulation available. Keep this in mind when choosing a LO source for noise-figure testing.
Here are the results of noise figure measurements on an Agilent mixer at 1.9 GHz with varying LO power and with a filtered LO. This graph compares the measurements to the simulation we saw earlier in the presentation. Note that the difference between the simulation and measurements varies from 1-2 dB depending on LO power.

This difference could be due to a number of reasons, including the packaging of the mixer, which was not considered in the simulation. The models were extracted several years ago, while the devices were built just months ago using current processing. Another reason is the uncertainty in the measurement, which we will look at briefly next.

The formal published specification for the SSB noise figure for this mixer/IF amp is 17 dB for similar test conditions (2 GHz RF, 1.75 GHz LO), so it performs slightly better here than its published spec, by about 1 dB.
Like any electronic measurement, noise figure is subject to uncertainties due to mismatch and other sources, regardless of the application parameters of the DUT. Fortunately these uncertainties can be mathematically estimated using methods such as RSS (Root Sum of Squares) or TAG4. These methods are thoroughly explained in Agilent Technologies Application Note 57-2: Noise Figure Measurement Accuracy - The Y-Factor Method.

The spreadsheet you see here performs these uncertainty calculations after you have entered the application parameters of the device. The uncertainty for the measurement of the Agilent mixer we saw a few slides back is shown here to be 0.14 dB.
This Noise Figure Measurement Uncertainty Calculator is available to use directly on the web and it can also be downloaded for use in a local computer. The URL is in your handouts. The version on the web has the additional capability to display how the measurement uncertainty varies with a parameter that sweeps between limits specified by the user.

The RSS and TAG4 methods are both implemented in the calculator, as you can see from the tabs at the bottom of the spreadsheet.
We have seen that an untuned buffer amplifier can create problems due to broadband LO noise leaking into the RF or IF ports. Next we will look at untuned RF amplifiers and their impact on the noise performance of active mixers.
Here you can see how an active mixer with a low-side LO can have more noise in the IF due to the image band than from the desired RF band. Again, the amplifier has 6 dB per octave typical rolloff, but now the amplifier is in the RF path. The noise from this amplifier at the desired signal frequency is at one level, and the noise at the image frequency is clearly at a higher level due to the gain response in the RF path.

This also shows why the commonly assumed 3 dB difference between a DSB and SSB noise figure measurement cannot be valid when the conversion gain of the mixer is not flat. The 3 dB factor is only accurate for devices with equal gains in the two converted sidebands. We’ll see this more clearly in the next few slides.

One way to minimize this effect is to use a high-side LO, which reverses the desired and image frequencies shown here. The risk of doing this, however, is that a high-side LO would likely have phase noise that is at a higher level, broader, and more expensive to produce.
The Impact of Sloping Gain on Mixer Image Noise in a Monolithic Mixer

In an unfiltered active mixer there is little discrimination between the signal and the image bands. Practically always, only one band’s conversion is desired. However noise from the RF amplifier is present at both of these bands. Noise from both the signal and image bands gets converted to the IF, resulting in a degraded noise figure.

In this example, noise contributed from the desired signal band is less than that from the image band, so the 3 dB difference applied by a noise figure analyzer is insufficient. Note that if the image and desired bands were reversed, such that the LO seen here would be on the high side of the desired band, the 3 dB difference would excessive by the same degree as it was insufficient in the low-side LO case.
Quantifying the Effect of Image Noise

Degradation in S/N as a ratio is:
\[ \Delta(S/N) = (S/n_s)/(S/n_2) = (n_s+n_i)/n_s = 1 + n_i/n_s \]
Where \( n_s \) = noise in desired sideband, \( n_i \) = noise in image sideband, and \( n_2 \) = noise in both sidebands (\( n_2 = n_s + n_i \)).

If the input noise is the same at the signal and image freqs:
\[ \Delta(S/N)dB = 10\times\log(1+ n_i/n_s) \equiv 10\times\log(1+ G_i/G_S) \]

If the gain is flat (so image and RF gain are equal; \( G_i = G_S \)):
\[ \Delta(S/N)dB = 10\times\log(1+ 1) = 3dB \]

In a typical amplifier with -6 dB/octave gain slope (i.e., 1/F) and \( F_S = 1.1\times F_{LO} \), then \( F_S/F_i = 1.1/0.9 = 1.22 \), and the gain falls as 1/F**2, so \( G_i/G_S = (1.22)^{**2} = 1.49 \)
\[ \Delta(S/N)dB = 10\times\log(1+ 1.49) = 4dB \]
The noise figure is degraded by 4dB due to image noise.

What would a noise figure analyzer display?

Here are the mathematics to calculate the SSB noise figure from the measured DSB, given an RF to LO ratio and a gain rolloff rate. We assume a low-side LO for this example, as in previous slides. In the first formula we see that the difference between the noise in the desired sideband and in both sidebands is one plus the ratio of noise in the image sideband \( (N_i) \) to that in the desired sideband \( (N_s) \). The second formula shows this in dB, and shows that the ratio of the noise between the sidebands is very close to the ratio of the gains between the sidebands.

The third formula shows how the previous formula deduces the 3dB factor for the difference between DSB and SSB noise when the gain is equal between them. When \( G_i / G_S = 1 \), then \( \Delta S/N = 10\times\log(1+1) = 10\times\log(2) = 3dB \). Finally, for the example where the desired signal band is centered 10% in frequency above the LO, and the gain rolloff is 6 dB per octave, we see that the difference between measured DSB noise figure and SSB noise figure at the desired signal band is 4 dB.

A noise figure analyzer, however, assumes a 3 dB difference, so in this example it displays 3 dB higher than its DSB measurement, not 4 dB. It displays the SSB noise figure 1 dB better (i.e., lower) than it really is.
**Signal vs. Broadband Noise Source**

“Real world” with no filter between amplifier and mixer

Mixer converts amplified signal and broadband floor noise

\[ S_n \]

\[ \text{LO} \]

\[ \text{IF} \]

At RF

At IF

Image noise (Im) degrades mixer signal to noise ratio

\[ \Delta F = \frac{S_n + n_I}{n_S} \]

NF analyzer measurement

Mixer converts both sidebands of the broadband noise source and floor noise

\[ N_n \]

\[ \text{LO} \]

\[ \text{IF} \]

At RF

Noise source “on” “off”

At IF

\[ N_I + N_S \]

Signal and image add at IF

\[ \text{IF} \]

At IF

Noise floor

\[ F \]

So when an active mixer is tested using a broadband noise source, the image noise from the noise source always gets converted to the IF output, in addition to the noise from the desired signal band. This gives an accurate measurement of double sideband noise factor but not of single sideband. While this presentation is not intended to address details of the Y-factor method of measuring noise figure, the ratio of the Y-factors used to calculate DSB noise figure and SSB noise factor is:

\[ Y_{DSB} = \frac{N_I + N_S}{n_I + n_S} \quad \text{and} \quad Y_{USB} = \frac{N_S}{n_I + n_S} \]

so their difference is:

\[ \frac{N_S + N_I}{N_S} = 1 + \frac{N_I}{N_S} \cong 1 + \frac{G_I}{G_S} \]

And the actual, single sideband noise factor is:

\[ F_{DSB} = F_{meas} \times (1 + \frac{G_I}{G_S}) \]

The corresponding noise figure is:

\[ NF_{dB} = 10 \log_{10} NF_{SSB} = NF_{dB_{meas}} + 10 \log_{10}(1 + \frac{G_I}{G_S}) \]

Details of the Y-factor method are explained in the application notes referenced in the handout.
The Effect of Image Frequency Response on the Measurement of Mixer Noise Figure

The contribution caused by higher order LO products can usually be ignored.

Thus, the measurement error is the same as when neglecting the image noise degradation:

$$\text{NF}_{\text{SSB}}(\text{dB}) \cong \text{NF}_{\text{DSB}}(\text{dB}) + 10 \times \log(1 + G_1/G_S)$$

Mixer noise-figure measurements with a wideband noise source are also subject to errors caused by conversion at other mixer responses ($3F_{\text{LO}} \pm F_{\text{IF}}$, $5F_{\text{LO}} \pm F_{\text{IF}}$, etc.)

Note that the mathematics we saw earlier apply regardless of whether the difference in gains is due to typical rolloff or to any other reason. If the ratio of the gains is known, the correct SSB noise figures can be calculated from the measured DSB noise figure.
Conclusions

- **Active mixers with RF and LO gain are vulnerable to noise degradation from out-of-band sources.**

- **The measurement of these mixers must emulate the environment that they will be operating in, or proper allowance should be made in the results.**

- **The measurement of single-sideband noise figure of an active mixer can be optimistic or pessimistic, depending on the ratio of the gains of the two converted sidebands.**

- **Gilbert Cell mixers are very simple, but are not well suited to low noise and image reject mixer applications due to their sensitivity to down-converted image frequency noise.**

We have seen that active mixers with built-in untuned amplifiers can have degraded noise performance due to the variable gain response of those amplifiers. Proper noise-figure measurement of such mixers must emulate their intended operating environment, and correction must be made to measurements, if necessary, to emulate that operating environment.

Actual measurement results can be off in either direction, high or low, but can be corrected if the gain characterization of the mixer is known. These criteria apply to Gilbert Cell mixers and, in general, active mixers with no filtering.
Agilent Products Used

ADS DesignGuides:
E5615A    Mixers

N8970 Series Noise Figure Analyzers

N8972A    10 - 1500 MHz
N8973A    10 - 3000 MHz
N8974A    10 - 6700 MHz
N8975A    10 - 26500 MHz

N897x Series was introduced in Spring of 2000 with the 2.5 and 3 GHz models. The 6.7 and 26.5 GHz models are new for 2001. The improved accuracy, repeatability and speed over the previous generation is due to their lower instrument noise figure, frequency-dependant loss compensation, automated noise-source-temperature monitoring, and an entirely new user interface. The N897x Series Noise Figure Analyzers are available from the ADS website listed in your handout.

N4000 Series Noise Sources

N4000A    10 - 18000 MHz      6 dB ENR
N4001A    10 - 18000 MHz    15 dB ENR
N4002A    10 - 26500 MHz    15 dB ENR

An N8973A noise figure analyzer was used for the measurements in the presentation. The N897x Series was introduced in Spring of 2000 with the 2.5 and 3 GHz models. The 6.7 and 26.5 GHz models are new for 2001. The improved accuracy, repeatability and speed over the previous generation is due to their lower instrument noise figure, frequency-dependant loss compensation, automated noise-source-temperature monitoring, and an entirely new user interface. The N400x Series Noise Sources are also new for 2001 and feature automatic uploading of ENR values to the NFA Series for faster setups, and automated temperature monitoring just mentioned, for improved measurement accuracy. Product and application details are available from the noise-figure website in your handout.
References

- References on mixer design:
  "Fundamentals of Mixer Design" Agilent EEsof Design Seminar
  "RFIC MOS Gilbert Cell Mixer Design" Agilent EEsof Design Seminar
  "Analysis and Design of Analog Integrated Circuits" by Gray and Meyer (covers Gilbert cell mixers in some detail.)
  "Practical Design of Discrete and Integrated Wireless Circuits" Sections 3 and 9, Besser Associates course

- References on mixer simulation using ADS:
  Application notes, etc.
  http://contact.tm.agilent.com/tmo/hpeesof/apps/ads/index.htm

- References on noise-figure measurement:
  Application notes, product information, uncertainty calculator, etc:
  www.agilent.com/find/nf
For more information about Agilent EEs of EDA, visit:

www.agilent.com/find/eesof

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<td>39 02 92 60 8484</td>
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<tr>
<td>Netherlands</td>
<td>31 (0) 20 547 2111</td>
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<td>Spain</td>
<td>34 (91) 631 3300</td>
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<td>Sweden</td>
<td>0200-88 22 55</td>
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<td>Switzerland</td>
<td>0800 80 53 53</td>
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<td>United Kingdom</td>
<td>44 (0) 118 9276201</td>
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Other European Countries:

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