

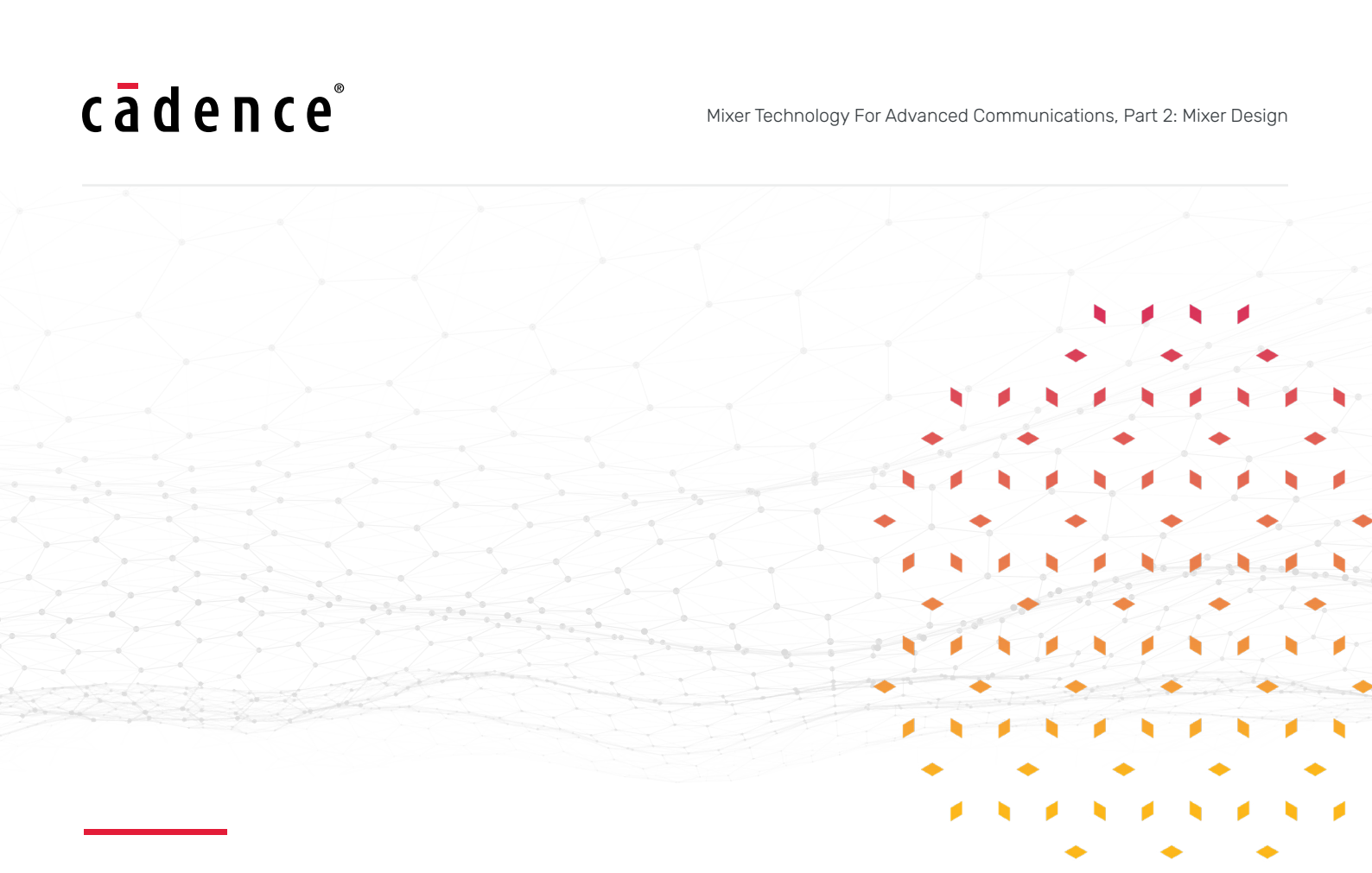


Mixer Technology For Advanced Communications, Part 2: Mixer Design

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Content

Introduction	3
A Quick Review	4
Microwave Office: Mixer Component Design And Simulation	4
Mixer Criteria	4
Spurs And Frequency Planning	5
Mixer Metrics	6
Conversion Loss, NF, and IP3 vs Lo Power	7
IF Output vs RF Power	7
Mixer IF Output Power Spectrum	8
Mixer Test Benches	8
VSS: System-Level Simulation	9
Simulation Models	9
System-Level Analysis Tools	10
Conclusion	11



Mixer Technology For Advanced Communications, Part 2: Mixer Design

Introduction

The implementation of any mixer topology begins with defining key design criteria—including the RF and IF input ranges, LO frequency and drive level, port isolation, and whether a fixed IF or LO is desired. While various mixer configurations, such as single-balanced or double-balanced, can be selected to optimize specific parameters, system frequency planning ultimately remains essential. This involves using the mixer's spur table to adjust factors like LO frequency to shift unwanted intermodulation (IMD) products out of the desired output band. Finally, key mixer metrics can be evaluated through mixer test benches to assess overall performance.

However, this approach optimizes the mixer only at the component level. Modern communication systems face additional challenges due to increasing modulation densities and wider carrier bandwidths. At the system level, parameters like adjacent channel power ratio (ACPR), error vector magnitude (EVM), bit error rate (BER), and complementary cumulative distribution function (CCDF) become critical for evaluating overall radio performance.

This is Part 2 of a two-part series, focusing on mixer design and simulation using Microwave Office software, and demonstrating how the Visual System Simulator (VSS) integrates with Microwave Office software to enable system-level simulations, such as those for receivers and transmitters.

For more information on mixer fundamentals, Part 1 provides an overview of mixer operation and topologies.

A Quick Review

In Part 1 of this series, several fundamental questions about mixers were addressed:

1. What is a mixer?
2. How are mixers fabricated?
3. What are some common mixer topologies?
4. What are SSB, IR, and I/Q mixers?

In essence, mixers perform frequency up- or down-conversion by using nonlinear circuit elements (e.g., diodes or transistors) to generate sum and difference frequencies from the interaction of two input signals. In a receiver, these inputs are typically the radio frequency (RF) and local oscillator (LO), producing an intermediate frequency (IF) according to $IF = RF - LO$. For a transmitter, the inputs are the IF and LO, generating the RF (e.g., $RF = IF + LO$). Mixer design parameters affecting performance metrics such as conversion gain (CG), linearity (P1dB and IIP3), noise figure (NF), isolation, dynamic range, and bandwidth, may be optimized to achieve maximum receiver or transmitter performance.

While addressing questions 1–4 helps establish some mixer fundamentals, this paper focuses on answering how a mixer can be designed and simulated and how its performance can be optimized within an RF system.

Microwave Office: Mixer Component Design and Simulation

Mixer Criteria

The design and simulation of mixers is performed using Microwave Office design, where mixer design criteria are generally organized into five areas:

1. RF/IF input
2. LO input
3. RF/IF output
4. Port isolation
5. Fixed IF or fixed LO

In general, the RF input (receivers) or output (transmitters) frequency range is known. For receivers, the required dynamic range of the signal i.e. the range the mixer can handle without significant distortion, must also be considered. For the mixer component this is defined largely by its NF at the low end and its input P1dB compression point at the high end.

For both receivers and transmitters, selection of the LO frequency is important to prevent spurious frequency products generated within the mixing process from falling into the output frequency band. This will depend on the mixer configuration and type of 'building block' mixer used (e.g. single- or double-balanced).

Finally, the choice between a fixed IF or a fixed LO must be made. In some systems, the RF frequency varies while the LO remains fixed, resulting in a changing IF frequency. In other systems, the IF is kept constant while the LO is

varied to select the RF. For example, maintaining a constant 100 MHz IF while adjusting the LO frequency from 1 GHz to 1.1 GHz requires a corresponding adjustment of the RF frequency. In broadband applications this may require variation of both LO and IF to achieve the required spurious-free bandwidth.

Required LO power, or drive level, is dependent on whether the mixer uses active or passive devices and, in the case of passive mixers, the particular topology (more diodes need more LO power). It is also impacted by the required 1dB compression or IP3 performance. The LO power is typically at least 7 dB higher than the highest anticipated RF input to prevent the mixer from entering compression, and usual ranges between +7 dBm and +18 dBm for most diode mixers.

Port isolation must also be considered: LO signals should not leak back into the RF, and any LO present in the IF can generally be mitigated through filtering. More complex topologies tend to have more inherent isolation properties.

Spurs and Frequency Planning

Since mixers are non-ideal devices, they produce both the desired frequency components and numerous unwanted products resulting from the mixing of all signals within the device. The following equation defines the frequency products that appear at the mixer output:

$$F_{IF} = |n \cdot F_{LO} + m \cdot F_{RF}|$$

*Where n is a positive integer and m is an integer.

In a typical downconverter, the IF frequency (F_{IF}) is the difference between the RF and LO frequencies (F_{RF} and F_{LO}), where $F_{IF} = |n \cdot F_{LO} + m \cdot F_{RF}|$. In other words, the desired F_{IF} occurs when $n=1$ and $m=-1$, but other combinations exist with $n= 0, 2, 3, 4...$ and $m=...-2, 0, 1, 2...$

Thus, when designing a mixer, it is essential to identify spurs of interest, which are those that fall within the usable IF bandwidth and are not filtered out.

Figure 1 shows a spur table, spectrum, and spur chart for a mixer with a fixed F_{LO} of 650 MHz, an F_{RF} of 1000 MHz (BW from 960 to 1010 MHz), and an F_{IF} of 350 MHz, where the desired signal is $F_{IF} = |F_{LO} - F_{RF}|$. It is important to note that this spur table displays only the spectrum around the IF, so high-frequency products are not visible.

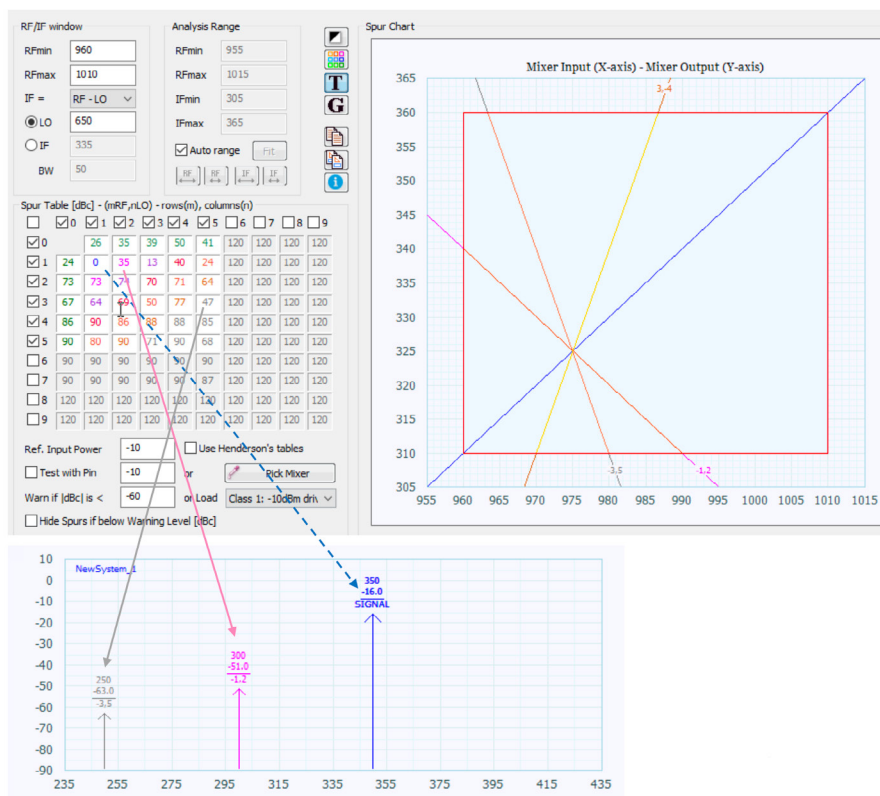


Figure 1: A spur chart (upper right) is a helpful tool to view the intermodulation products that fall into the passband. Parameters like LO drive level and frequency can be modified to push these spurs out. Source: Cadence

The desired signal is indicated by the dashed blue line at Row 1, Column 1, marked with a "0." This denotes that the spur is 0 MHz away from the IF, meaning it corresponds to the desired IF signal. In this case, $F_{IF} = |F_{RF} - F_{LO}| = 350$ MHz, with a strength of -16 dB as shown in the spectrum plot at the bottom of Figure 1.

The pink arrow shows another spur at $F_{IF} = 2F_{LO} - F_{RF}$ (300 MHz), or 35 MHz below the IF (335 MHz), with a strength of -51 dB. The grey arrows represent a spur at $F_{IF} = 5F_{LO} - 3F_{RF}$ (250 MHz), with a strength of -63 dB.

Lastly, the spur table illustrates how these spurs intersect with the passband, which is defined from 960 to 1010 MHz for the RF frequency with a fixed LO of 650 MHz. Some of these spurs fall directly within the band of interest; however, adjusting the LO frequency can shift them out of the passband and eliminate their impact. Careful selection of the LO frequency is therefore crucial. At this stage, the NF can only be controlled through the use of diodes with low series resistance.

Mixer Metrics

After establishing the basic mixer criteria and analyzing spurious activity to fine-tune the design, the next step is to examine key performance measurements. **Figure 2** illustrates several critical mixer metrics for a 90° single-balanced diode mixer. The design incorporates a Lange coupler at the input, followed by capacitor-inductor matching networks. The two diodes are then summed, and the output is passed through an IF filter.

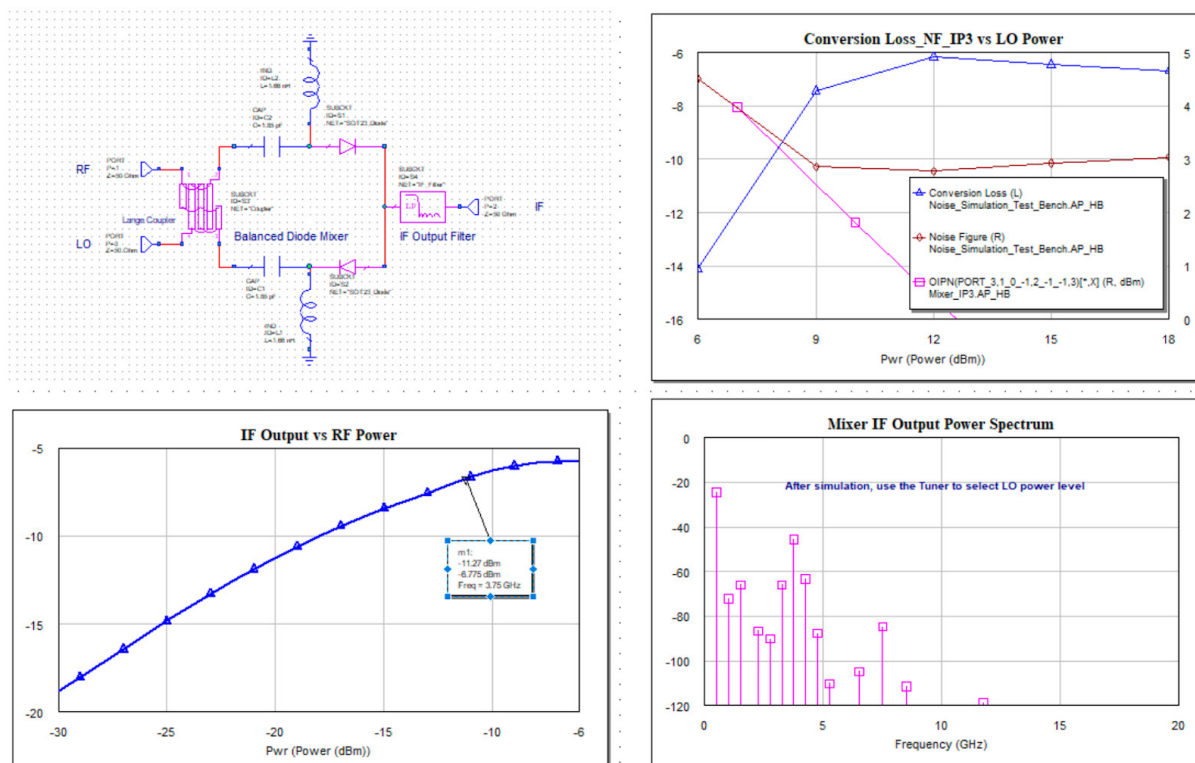


Figure 2: Critical mixer metrics of a 90-degree single-balanced diode mixer. Source: Cadence

Conversion Loss, NF, and IP3 vs LO Power

The top-right plot in Figure 2 shows conversion loss, NF, and the third-order intercept point (IP3) as functions of LO power. The first key metric is the conversion loss of the design (blue line). Because this is a passive mixer, a loss of signal power is inherent. Conversion loss is often considered the most critical mixer measurement, representing the ratio of output power to input power. The mixer in Figure 2 demonstrates a minimum conversion loss of approximately 6 dB with an LO input power of 12 dBm.

The NF is also shown (red line). It remains relatively low, approximately 3 dB in this design, because the simulation uses ideal diodes that do not account for series resistance. Although it might be assumed that the NF equals the conversion loss for dissipative elements such as attenuators, this is not the case for mixers, where the NF can be lower than the conversion loss.

The last parameter shown is the IP3 value as a function of LO power (pink line). This metric characterizes the mixer's ability to convert the input signal without distortion—that is, its linearity. In general, higher linearity is achieved with increased LO power, as the IP3 typically lies several decibels above the LO power level.

IF Output vs RF Power

The bottom-left graph in Figure 2 shows the IF output as a function of RF power. The plot indicates that up to approximately -20 dBm, the output power remains relatively linear with respect to the input power. Beyond this point, the slope begins to decrease, signifying that the mixer is entering compression.

Mixer IF Output Power Spectrum

The bottom-right graph in Figure 2 presents the output power spectrum of the mixer at a single LO power level and RF input frequency. The desired signal is the dominant component, appearing at a power level of approximately -20 dBm. Other spectral components are also visible, generated as a result of nonlinearities within the mixing element. As discussed earlier, these effects can be mitigated during the frequency planning stage of mixer design.

Mixer Test Benches

Microwave Office software includes built-in “Testbench” projects that preconfigure measurement scenarios. **Figure 3** highlights this using the same single-balanced diode mixer with a 90° coupler described earlier. The associated schematic and graph within a “Testbench” can be imported into a project, allowing parameters to be quickly modified through annotated instructions to generate the required measurement. To achieve this, the testbench should be embedded within a higher hierarchy level corresponding to each measurement being configured.

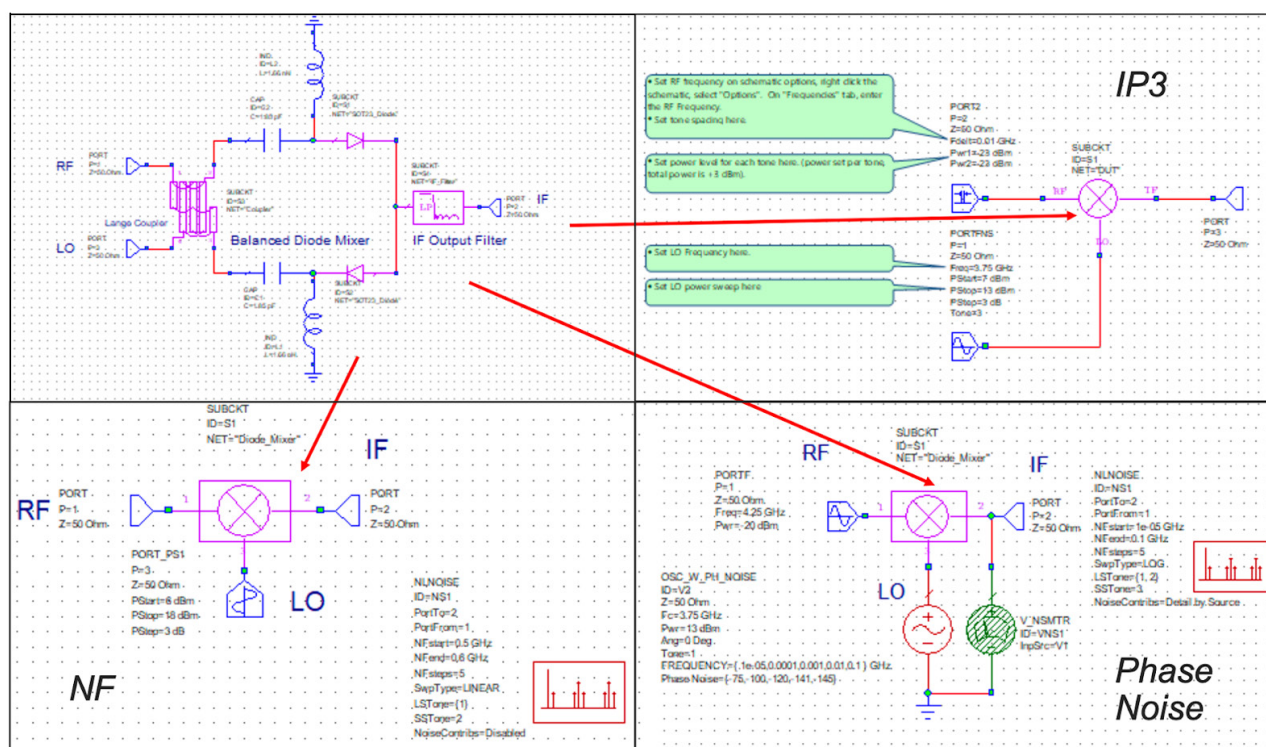


Figure 3: Three different mixer test benches in one simulation of a 90° single-balanced diode mixer, including tests for IP3, NF, and phase noise. Source: Cadence

Figure 3 presents three different testbenches: the two-tone test for IP3 (top right), the NF test (bottom left), and the phase noise test (bottom right).

Test #1 embeds the mixer in a configuration driven by two RF input signals rather than one. This setup enables

a two-tone measurement to determine the mixer's IP3. In Test #2, NF is measured by sweeping the LO power to determine NF as a function of LO power. A small red block at the bottom right, labeled NLNOISE, performs a nonlinear noise analysis on the mixer. Test #3 applies an LO with added phase noise and then measures the resulting phase noise at the circuit output, or at the IF frequency. The NLNOISE block is also included in this test.

Assessing the impact of LO phase noise has become increasingly critical in 5G systems, as it can cause degradation in both millimeter-wave and OFDM systems, resulting in common phase error (CPE) and inter-carrier interference (ICI). Testbenches like these can be configured within a schematic to evaluate such effects early in the design process and optimize performance.

VSS: System-Level Simulation

Simulation Models

The complexity of advanced communication systems demands agile system-level analysis, as traditional circuit simulation methods, such as transient and Harmonic Balance, can be overly detailed and inefficient. VSS addresses this by using one of two models to simulate circuits, ranging from simple conceptual designs to highly complex circuit-based systems. VSS can employ either of these two models for simulation:

- **Behavioral models:** These primarily use complex envelope signal representations, often employing 5th-order polynomial models. Users can input datasheet parameters for components and perform system-level analysis.
- **Co-simulation:** Components already designed in the Microwave Office software can be integrated into VSS. As shown in Figure 4, VSS triggers an initial Microwave Office Harmonic Balance simulation and generates a corresponding 5th-order polynomial, linking the Microwave Office component within the VSS environment. The Microwave Office schematic's frequency and power sweeps must be adjusted to encompass those being used in VSS.

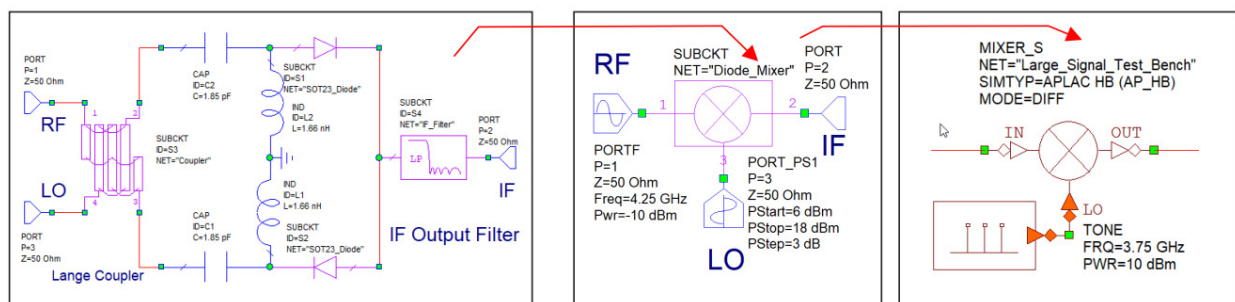


Figure 4: Converting a mixer model from the Microwave Office software environment to the 5th-order polynomial form in the VSS environment. Source: Cadence

From here, several powerful tools in VSS enable designers to perform detailed system-level analysis, including RF Inspector, cascade analysis for RF budget evaluation, and digital modulation metrics.

System-Level Analysis Tools

Figure 5 displays the RF Inspector tool and the Heritage Window, which is primarily used for spur analysis. Clicking and holding on a spur in the spectrum plot shows details of that spur, including the associated mixing product. Double-clicking the spur opens the Heritage Window, providing a detailed view of all components contributing to the spur of interest. The tool traces the origin of the contributing signals, showing the mixer products (m, n mixing).

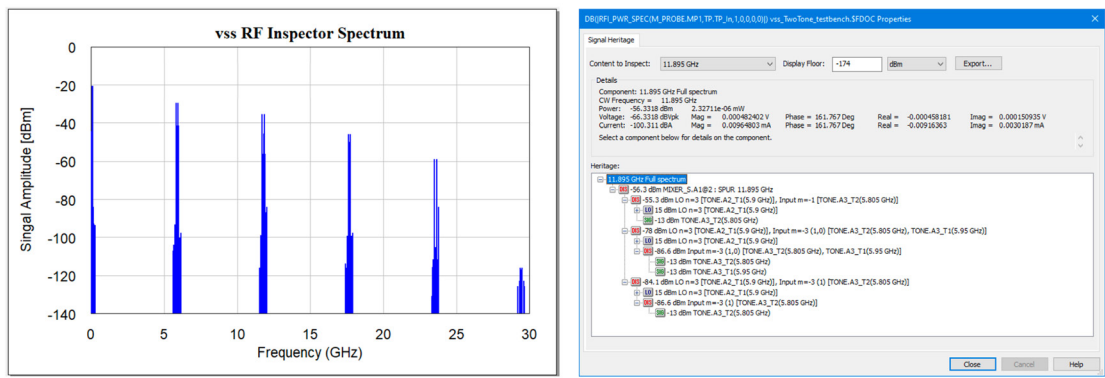


Figure 5: The RF Inspector showing spur analysis visually (left) and the Heritage Window tool, which provides a detailed description of intermodulation components (right). Source: Cadence

The RF budget analysis performs a cascade evaluation of an RF system that can include measurement of gain, noise, distortion, and power at each stage (**Figure 6**). This approach identifies which block contributes most to distortion and enables rapid analysis of trade-offs introduced by filtering.

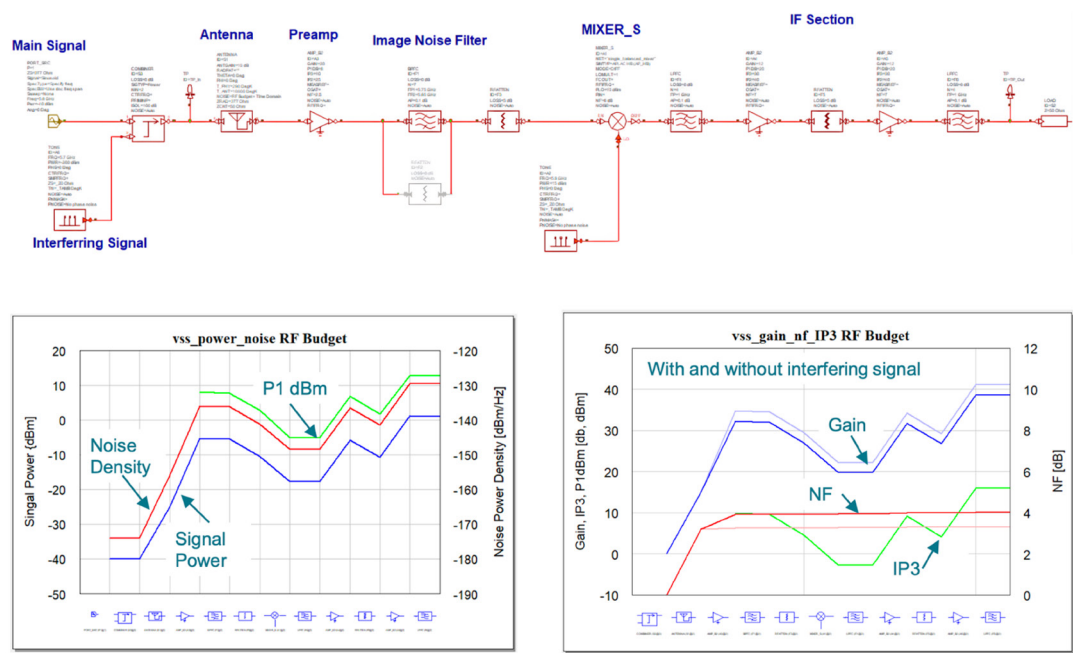


Figure 6: RF budget analysis including measurements like: gain, signal power, noise power density, NF, IP3, IP2, P1dBm, SNR, phase noise, and s-parameters.

The previous analyses were performed in the frequency domain. A time-domain analysis can also be performed to obtain system-oriented metrics such as Adjacent Channel Power (ACPR), EVM, BER, and Complementary Cumulative Distribution Function (CCDF). VSS's ideal modulation receiver blocks are added to the system so that these metrics can be evaluated on the demodulated signal. This approach enables analysis from the mixer component level up to the receiver or transmitter, providing a clear view of how mixer performance directly impacts system-level behavior.

Conclusion

Mixer simulation allows designers to assess critical parameters and fine-tune the mixer for optimal linearity, dynamic range, and minimal distortion within the passband. The Microwave Office software provides a powerful platform for performing nonlinear analysis of mixers, including phase noise evaluation. Its comprehensive toolbench simplifies the design of complex 5G systems, where constraints are often tight. VSS can be used to rapidly verify mixer designs from Microwave Office simulations by implementing behavioral models for the remaining system components. For more information, please visit the [AWR Design Environment Platform page](#).



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