RF Architectural tools for the modern system designer

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Abstract

Current RF architectural tools available for system designers consist of a mixture of budget simulators, spur searching utilities and frequency planning tools. Often these tools or utilities are based on spreadsheets, or perhaps are hard coded algorithms with some user interface. The home brew utilities have a reputation of being poorly supported. The current drive for reducing time to market and efficient design flow means that engineers are no longer encouraged to build their own design utilities. Engineering managers prefer engineers to be designing products, not tools. This presentation aims to outline the types of utilities needed for RF architectural decision making and the benefits of having an integrated approach.

We will show some good reasons why spread sheets have their limitations!

Introduction

Systems fall into two major classes, transmitters and receivers. For both classes, a properly designed system transports the input signal from the input port or source block to the output port through control blocks, frequency translation and signal conditioning. Signal conditioning includes gain, gain control, and filtering. Most often for a transmitter the source is at some low frequency and information will be added by the use of standard modulation techniques. For a receiver, the input or source will be an antenna. Vector Signal Analyzers, Spectrum analyzers derive their signals at the input connector. Likewise, the output port of signal generators is generally a font panel connector.

For communication systems, ECM applications and Radar a transceiver employs both transmitter and receiver functions in the same hardware. Having both classes of system sharing the same physical space can lead to integration problems.

1. System Architecture.

The challenges that face an RF/Microwave system designer can be stated as follows … transport a signal from one location in a system at some power/frequency combination to another location in a system at some other power/frequency combination without distorting any potential modulation present on the signal, without adding additional signals in the form of spurs and at minimum cost. The cost can be reliability, mass, volume or manufacturing cost.

At worst the failure to meet these aims can result in a poorly-working system; that is a system that has marginal performance or one that requires special attention when being used. There are apocryphal stories of fire control radars being switched off whilst missiles are being launched, or command and control links to satellites affecting the payload systems (command and control at L Band, payload at K Band). More mundane evidence can be found in R&D laboratories. Try this simple experiment; connect a 50 ohm load to the input connector of a spectrum analyzer to ensure that there is no input signal, increase the sensitivity and view the signals present on the display. With a few simple tests an experienced receiver designer can establish quite a lot of information about the system architecture … without reference to a datasheet!

Signal distortion can manifest itself through spectral widening, either around the carrier frequency or by harmonic generation. Both these mechanisms provide threats to adjacent channels known as Adjacent Channel Power Ratio (ACPR) or adjacent systems. In the case of communications channels both these forms of spectral widening are regulated by groups such as the Federal Communications Commission (FCC) etc. Whilst these defects affect only other channels sharing the air interface (used in its most general sense to encompass Radar systems as well as communication systems) for the channel in question the distortion limits the system dynamic range. Two figures of merit are employed to define this distortion, Error Vector Magnitude (EVM) and Bit Error Rate (BER).

Normally only a few major building blocks found within a system affect the EVM and related distortion figures of merit; for example, with a power transmitter the PA and the PA driver, or with a receiver the first mixer or any pre-amplification. When a system is poorly designed the degradation in performance maybe due to an unlikely component that at first sight appears to be well specified but actually determines the overall system performance. This can occur when signal levels within a system have not been fully defined. For example a system with an inadequate distribution of power saturation specifications can start to exhibit compression at signals levels that are below the expected powers. In affect the linearity requirements of the final stages are over specified leading to unnecessary cost and wasted R&D resource.

Signal management (constraining wanted and unwanted signals to specific locations within a system) balances filter complexity, module screening technology and block to block interconnection solutions. Leakage control is of paramount importance in complex systems and with systems that house both transmitters and receivers given the disparate signal levels these engineering decisions are critical.

Module screening ranges from simple screwed lids, with or without RF gaskets, through to double screen lids with perhaps a welded lid being used for the ultimate in isolation provision. The more exotic solutions whilst delivering excellent isolation come at a high price … manufacturing costs and repair costs. Welded lids need to be removed using machining and then re-welded. The same issues are found when lids are fixed with conductive glues. With tight weight and volume specifications these more advanced solutions are not always attractive. Piping signals between the functional blocks can be accomplished by using simple flexible coaxial cables, double screened cables and for superior isolation semi-ridged cables. The latter solution poses it own assembly difficulties when space is at a premium and tend to be more expensive than the flexible cables.

With the trend towards the hybrid circuit realization being replaced with integrated semiconductor circuits (GaAs MMIC and SiGe and Si RFIC) the real-estate required to perform a particular circuit function reduces but the packaging and isolation problems still persists! Ironically, with shrinking circuit sizes comes the demand for more functionality … a simple example is the modern mobile phone that can posses up to six radios … Edge/GSM, Bluetooth, GPRS, FM radio, UMTS, LAN. Of course not all six radios need to operate at the same time. A possible two radio operating mode could be with the Bluetooth radio providing phone to Laptop connection and the UMTS radio operating as a Modem. This combination would be used to provide internet access whilst the laptop is away from a WiFi access point.

With non-military applications, signals are generally classified as wanted or unwanted. For military applications the signals can be divided into wanted signals and threats. The threats are subdivided into friendly and unfriendly threats. A friendly threat is the Radar channel being used by a friendly aircraft sharing the same radar band (whose channel allocation is synchronized in some fashion … a topic beyond the scope of this paper), an unfriendly threat not unexpectedly is the term reserved for the enemy aircraft. Warships tend to have the greatest number of friendly threats which navigation radars, search and tracking radars, communications systems, missile and fire control radars, with some very challenging signal power ratios.

Several complimentary approaches to system design have been employed by designers in the past with the design tools implemented using Spreadsheets and spur calculation programs. Whilst these tools have served the designers well in the past they have suffered from some several problems … the severity of these problems depending upon the stand point of the reviewer. This will become clear as the discussion on system architectural tools widens.

The tools most commonly used are Budget Analysis, Spur searching and Frequency Planning; each providing an insight into the system performance and system design.

2. Frequency Planning.

The task of frequency planning takes as the initial system definition the input signal frequency/power specification and the output frequency/power specification. The goal of the systems engineer is to design a system that transports the wanted signal from the input port to the output port using the minimum number of frequency translations (along with the simplest synthesizer architecture) and using the lowest cost filter technology. The phrase lowest cost filter technology means using filters that have realistic circuit Q, a reasonable number of resonators and most importantly filters that meet the environmental specification of the equipment. More filters, more complex synthesizers translate directly into cost, volume, and weight.

There are two aspects of frequency planning. The first to be considered is more of a design tool, which commonly uses so-called spur charts and related algorithms. The second which is closer to a verification process is commonly known as spur searching. Spur searching accounts not only for the mixer generated spurs but also spurs generated by any of the nonlinear building blocks used in the system, not necessarily found in the main signal path but also in any of the mixer synthesizer subsystems. In this section we will first focus on the use of spur charts and describe the general process of spur searching more fully in the third part of this article.

In equation (1) we have the classic mixer equation

$$\omega_{mix} = \pm n * \omega_{lo} \pm m * \omega_{rf} \qquad (1)$$

This equation defines mixing products both wanted and unwanted generated by the process of frequency translation using a mixer driven by a local oscillator. This seemingly innocuous equation understates the complex picture of unwanted signal growth or generation. Remember; this equation describes the signal growth of a single frequency translation block. With complex systems containing multiple frequency translations, the potential for unwanted signal creation grows alarmingly. A typical spur chart (Fig. 1) displays the output signals as a function of input frequency for n and m values. The n and m values have bee constrained to a maximum magnitude of n-Max and m-Max respectively. In this specific chart it will be seen that the input and output frequencies have been normalized to the LO frequency.

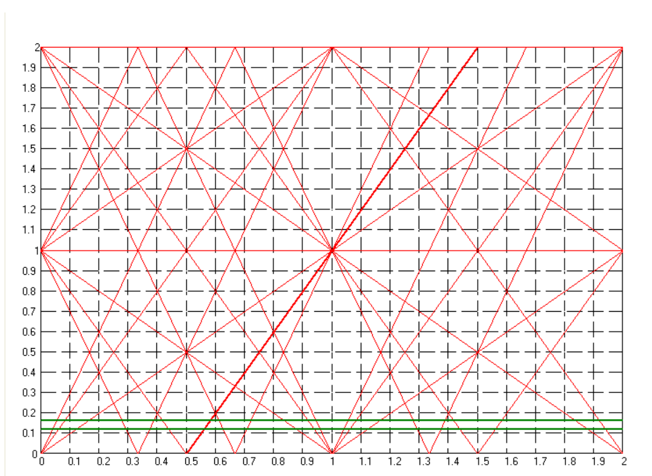
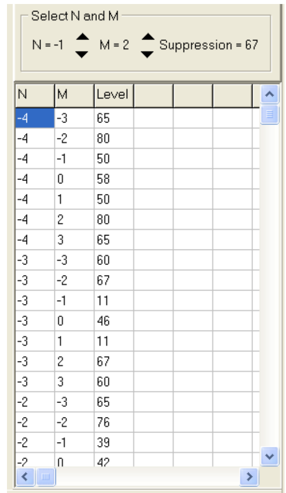


Figure 1: Spur Chart

Normally accompanying such plots would tables that define the relative magnitudes of the mixing products using mixer spur tables derived from mixer manufacturer's data sheets, measurements or simulation.



Select N and M
N = -1 M = 2 Suppression = 67

N	M	Level
-4	-3	65
-4	-2	80
-4	-1	50
-4	0	58
-4	1	50
-4	2	80
-4	3	65
-3	-3	60
-3	-2	67
-3	-1	11
-3	0	46
-3	1	11
-3	2	67
-3	3	60
-2	-3	65
-2	-2	76
-2	-1	39
-2	0	42

Figure 2: Spur Chart Suppression Table

The mixer model employed for spur table generation could either be the classical equations used by mixer manufacturing companies or these could be derived from a complete circuit based model.

Whilst spur charts of the form described above demonstrate the existence of spurs some designers prefer to display the results using a spectral plot. Here the spur equations are enhanced to add the loss and filtering action of the input and output filters. In Fig. 1 the two horizontal lines represent the output filter characteristics. In this example the filter has infinite order; that is the low and high frequency band transition between stop band and pass band are infinitely steep. Obviously a more useful plot would recognize a finite filter skirt slope.

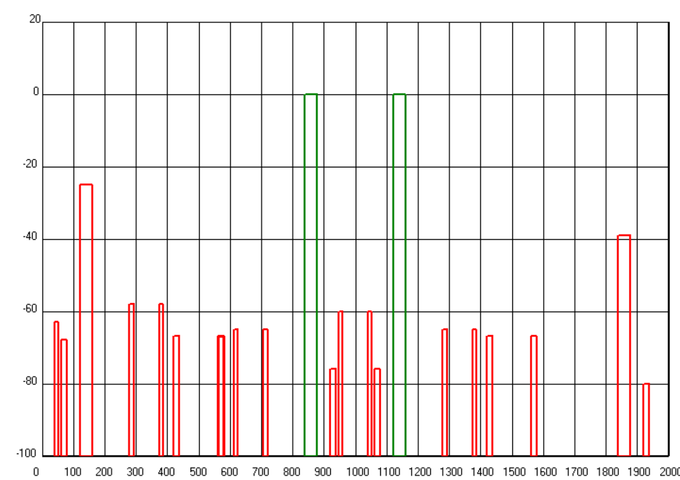


Figure 3: Spur spectral plot

The green rectangles visible in Fig.3 are the Lower Side Band (LSB) and Upper Side Band (USB) conversion products, in other words for this plot the input filter is open to all signals. Note; the spectral plot is input signal referenced, the LO frequency has been set to 1000 MHz for simplicity.

Spur charts enable system designers to make judgments about the allocation of LO frequencies, the filter orders at different points in the system and the number of conversions required. Signal loss is introduced with each frequency conversion (frequency translation) and the application of filters to constrain signals. Of course if the frequencies are low enough for the application of active devices in the mixer design, then some gain maybe possible. To overcome the loss extra gain stages are required which in turn increases the possibility of generation distortion products.

Having defined the mixer architecture, the number of mixing stages and the amplification required to bring the input power to the required output power range one can then sensibly carry out a general spur search procedure. The chief algorithm employed for spur searching tracks signals though the system blocks and at each birth of a new spur or signal setting up the parent child relationship. This child's heritage in then stored in memory. In the following example using Visual System Simulator (VSS) one of a suite of design tools available from AWR a set of spurs is clearly visible (Fig. 4).

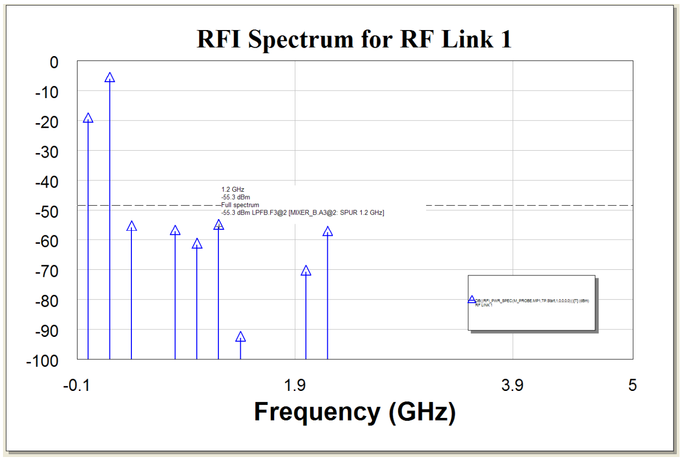


Figure 4: Spur search results

The annotation associated with one of the spurs can be seen in the spectral plot (Fig. 4) describes the spur frequency, power and parent. This information can be expanded to show a comprehensive description of the heritage of a particular spur. To avoid excessive memory requirements a user defined threshold can be set, below this power level new spurs are ignored. A practical approach would be to ignore spurs that fall below the system noise floor.

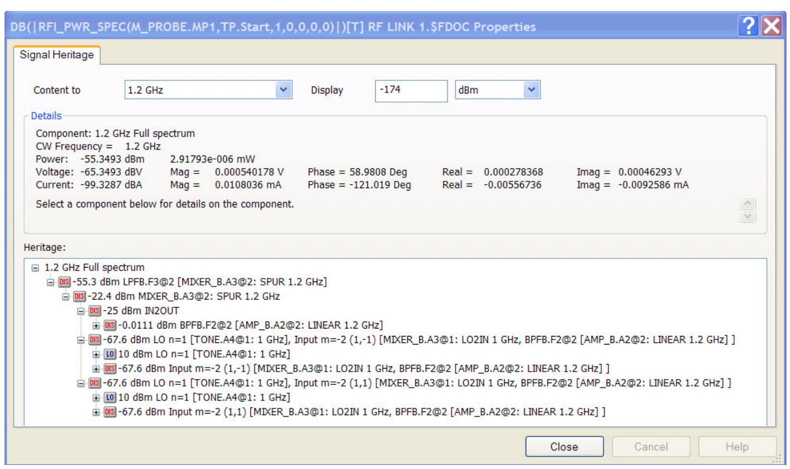


Figure 5: Heritage information of the spur search results

Above we see the comprehensive data displayed after selecting a specific spur in the plot seen in Fig. 4. Here we see the partial heritage of the wanted signal. Alongside this information is the data associated with the unwanted tones.

3. Budget Analysis.

Spreadsheets have traditionally been the favorite approach to budget analysis. The primary advantage of using spreadsheets is the simplicity of capturing the effects of channel defects such a noise and two tone intermodulation as well as defining the system block properties; structuring the information in a linear fashion. Another compelling reason why spreadsheets have been popular is their ubiquitous nature … they come virtually free with the PC! Spreadsheets also support relatively advanced graphical and graph plotting capabilities, meaning that information sharing can be both textual and graphical. With this simplicity come several disadvantages. The first and most obvious is the difficulty of making topology changes. Another difficulty is the lack of linkage between the frequency planning and spur searching tools that should accompany the budget analysis. These three views of the system architecture need to be synchronized by the designer. A process that is nearly impossible with a spreadsheet approach to system design. A schematic diagram is the preferred way to capture system topology and system block properties, a working method that has long been the first choice of circuit designers.

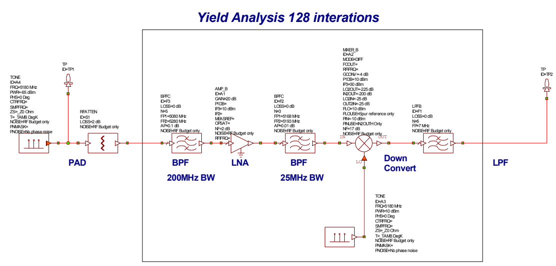


Figure 6: System Diagram

Whilst a schematic or diagram captures the intent of the system designer in a fashion that appeals to many system engineers nevertheless spreadsheets are an excellent way to convey meaning necessary for peer reviews, a fact recognized by AWR who have added a spreadsheet views to complement the budget tools found in VSS.

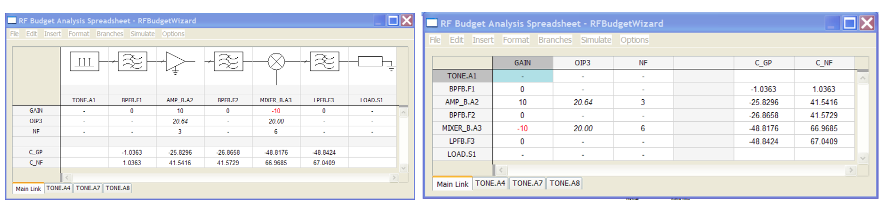


Figure 7: Spreadsheet display of budget information

One objective of the budget tool is to define the location of the gain control blocks, either the static beginning of life (BOL) adjustments made in the factory, or AGC blocks to account for variations in signal magnitude (target range, distance from antenna etc). For the BOL gain adjustments, knowledge of the spread in system gain is necessary, a measurement that is non-trivial when using spread sheets. With a circuit based approach Monte Carlo

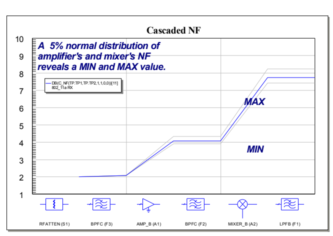


Figure 8: Budget analysis with statistical variation and its effect on system NF

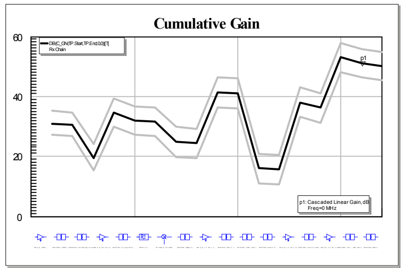


Figure 9: Budget analysis with statistical variation and its effect on system gain.

For these types of simulation the VSWR interactions between the blocks is accounted for, along with first order parameter changes. Unlike the spreadsheet approach, a true parameter sensitivity analysis can be conducted.

Another important consideration when designing systems is accounting for image noise. This is most often overlooked with the spreadsheet approach to system design. The system algorithm within VSS accounts for image noise allowing the designer to make rational judgments as to the filter order and BW of the pre-mixer filter to minimise NF degradations. Of course for some applications image noise cannot be suppressed; regardless the system designer needs to account for all noise sources in these calculations.

For a versatile approach to system design it is important that the figures of merit that define each block are eventually substituted with simulation data derived from circuit tools, and when available measured data. By doing so the system simulation becomes more accurate as the calculations are based on real system block data (circuit data) and not figures of merit. VSS has links to Microwave Office whereby the circuit simulation of amplifiers, oscillators and mixers can be linked into the system simulation in an automated fashion. Replacing block descriptions such as gain and NF can be down as circuit data becomes available.

This link between circuit and system tools has implications in the way circuit designers and systems designers interact and share design ideas. The aim of having a system tool that is integrated with a circuit toll is to promote a more healthy discussion between circuit and system design groups. The chief benefits of this approach are the creation of more optimum systems and improved communication. There are systems in manufacture that have been over engineered, a process that leads to excessive R&D effort and overly complex and expensive solutions. Under engineered systems have their own problems.

In the next figure (Fig 10.) the combination of system and circuit tools is illustrated. Here a simple test of a PA is being conducted.

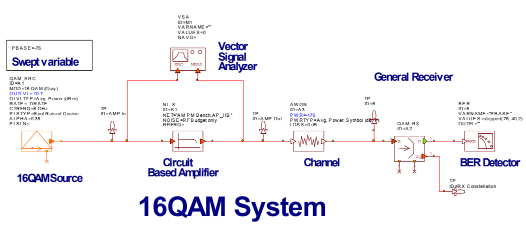


Figure 10: Amplifier test with 16-QAM modulation.

The amplifier is actually defined using measured data; in this example, as can be seen by the close examination of the schematic the measured data is being used in the Cardiff model. The nonlinear data could have equally been S-functions or X-parameters.

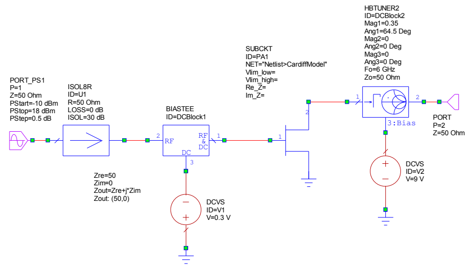


Figure 11: Amplifier circuit simulation

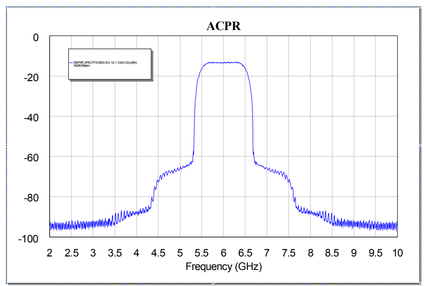


Figure 12: Spectrum showing the PA nonlinearity

The spreadsheet approach works well for spot frequencies, or narrow band systems whereby the system block parameters are constant over frequency, but does not provide a simple interface when a wideband system is being considered. The budget tools in modern system simulators do support the simulation of wideband systems … indeed, if required for ECM applications, over multiple octaves. The example below (Fig. 13) shows the NF simulation over a finite bandwidth. The system block data is provided by data files that capture NF, Gain two tone third order intercept point data etc over a user specified frequency range. This data can be provided either by simulation or from measurements.

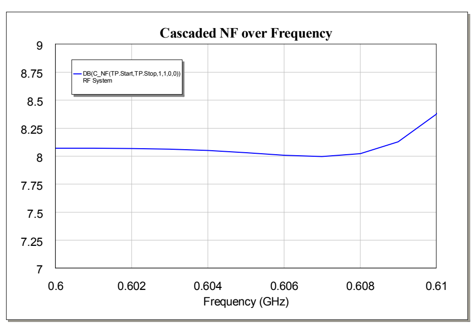


Figure 13: Swept frequency budget analysis

Conclusions

The art of system design entails budget planning, frequency planning and spur searching. The use of a single system diagram to capture the system topology and system block parameters leads to a more productive and problem free design flow. To complement the system tools, its integration into a circuit design tool provides the system and circuit designers a robust method of sharing information at all stages of the system design, from the initial architectural decisions through to the prototype phase.