Paul's RF Engineering Notes

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Chapter 1

Noise and Distortion

1.1 Noise in RF Systems

Thermal noise floor is kT_0B, which is the noise power produced by a matched resistor at the IEEE reference temperature $T_0 = 290K$ over a bandwidth of B. If the bandwidth is 1Hz, then the thermal noise floor is -174dBm/Hz.

IEEE definition of noise figures (NF) or noise factor (F) are as follows:

$$\mathrm{F} = \frac{\mathrm{SNR}_{in}}{\mathrm{SNR}_{out}} \tag{1.1}$$

$$\mathrm{NF} = 10\log_{10}(\mathrm{F}) \tag{1.2}$$

where SNR_{in} is the signal-to-noise ratio at the device input, when the input noise is thermal-limited. In other words, the input noise power is equal to the noise power produced by a matched resistor at a physical temperature of $T_0 = 290K$.

Example: Measurement of Amplifier Noise Figure Using Cold Source

In this section, we discuss the noise figure measurement of an RF low-noise amplifier using the cold source method. We will use the TinySA spectrum analyzer and the NanaVNA vector network analyzer. The device under test is the Nooelec LaNA HF, which is an LNA covering the 50kHz to 150MHz band.

With the cold source method, we first measure the gain of the amplifier using the VNA.

...

Next, we measure the noise power generated by the amplifier. We first put a 50Ω termination directly at the input port of the TinySA. We measure a noise floor of -169.3dBm/Hz. Since the thermal noise floor is $10\log_{10}(1.38 \times 10^{-23} \times 10^3 \times 290) = -173.9$dBm/Hz, we conclude that the noise generated by the internal circuitry of the TinySA increased the total noise power by approximately 4.6dBm/Hz. This means the noise figure of TinySA is about 4.6dB. Alternatively, we can say it has an effective noise temperature of approximately $290\left(10^{4.6/10}-1\right)=546.4$K, referred to the inputs.

Having characterize the noise properties of the TinySA, we can now measure the DUT cascaded with its internal receiver. We will then remove the added noise of the TinySA from the overall measurements, to obtain the noise figure of the DUT itself.

1.1.1 Noise Cascade

When multiple noisy stages are cascaded, the total effective noise temperature referred to the input of the first stage is given by:

$$T_{sys} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots , \tag{1.3}$$

here T_n is the effective noise temperature of the n^{th} stage, *referred to its own input*. Moving the reference location of an effective noise temperature value can be done by simply multiplying/dividing the gains of the appropriate stages. In [1.2], it can be seen that the noise temperature of the very first stage dominates the total temperature, if there is large gain afterwards. Hence in a receiver it is desirable to put an LNA as close to the antenna as possible, to reduce the impact of noise in the later stages.

We can also calculate the noise figure of the entire system. Each stage of the system will have its own specified noise figure. Remember that the noise figure [1.2] is defined for when the input noise power is equal to exactly kT_0B. So we cannot simply cascade the noise figures of the individual components together, because the input to the latter stages are no longer a matched resistor. Instead, it is safer to calculate the effective noise temperature of each stage using its specified noise figure, cascade the temperatures together using [1.3], then convert the total temperature back to a total noise figure:

$$F_{sys} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots \tag{1.4}$$

1.2 Signal Distortion

Sources of nonlinear signal distortion:

- Gain compression
- Intermodulation

Chapter 2

Microwave Networks

2.1 Smitch Chart

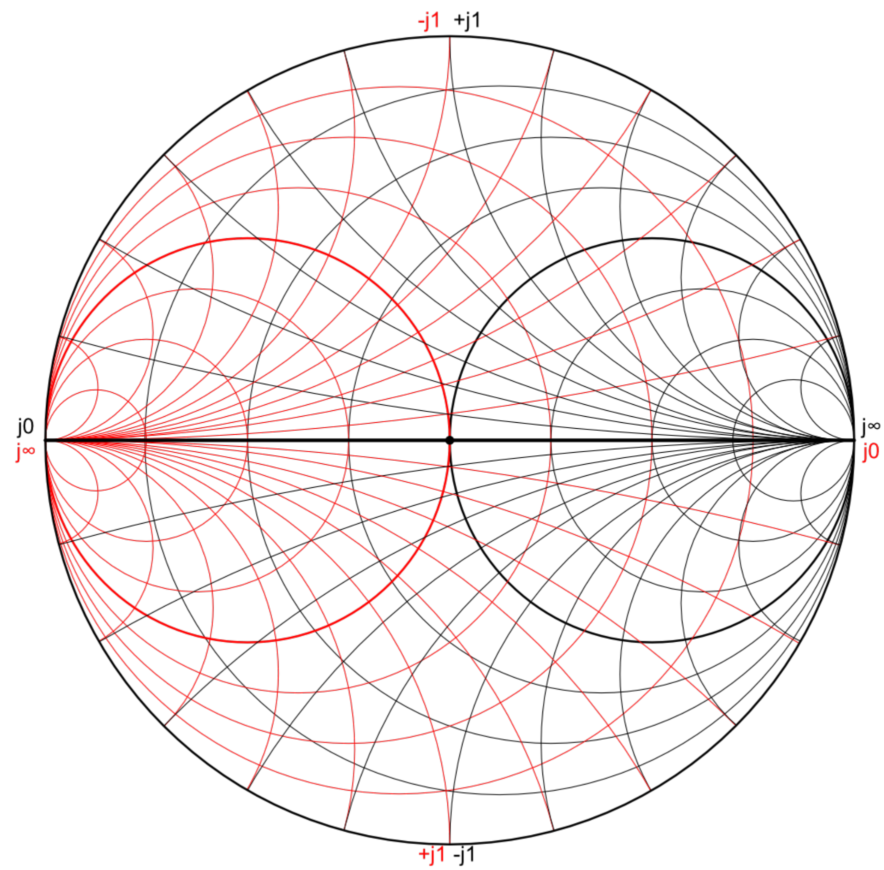

Figure 2.1: Overlaid impedance and admittance Smith chart.

The S_{11} curves will rotate clockwise on the smitch chart as frequency increases. This is related to the Foster Reactance Theorem, which states that the reactance of passive lossless one-port network must increase monotonically with frequency. In the presence of loss or mismatch, the reactance may decrease with increasing frequency, inside a limited range. Correspondingly, within that frequency range, the S_{11} curve will rotate counter clockwise on the smith chart. As a side note, we can use this technique to mimic negative capacitors or negative inductors over a finite bandwidth, achieving broadband impedance matching.

2.1.1 Different Loads on the Smith Chart

Series Capacitance

Series Inductance

Shunt Capacitance

Shunt Capacitance

2.2 Broadband Impedance Matching

Chapter 3

Passive Components

3.1 Filters

3.1.1 Microstrip Filters

3.1.2 Waveguide Filters

3.2 Multiplexers

3.3 Orthomode Transducers

Chapter 4

Amplifiers

4.1 Performance Specifications

4.1.1 Efficiency

4.1.2 Linearity

4.1.3 Temperature

4.1.4 Biasing

4.1.5 Matching

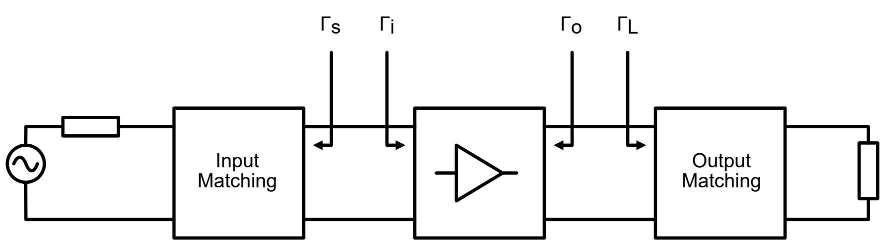

Figure 4.1: Matching networks at the input and output of an amplifier.

4.1.6 Stability

Unstable amplifiers will oscillate: they will output spurious signals even when there is no input. This is because noise in the amplifier circuit can be amplified through positive feedback at the oscillation frequencies. The spurs can be problematic even if they do not fall inside the frequency band of operation because:

- They can mix with other signals, generating in-band noise/distortion
- If they are very high in amplitude, they can saturate the amplifier, reducing the gain of the desired in-band signal

An amplifier circuit is **unconditionally stable** if:

- The reflection coefficient seen into the input (Γ_i) is smaller than 1 for ANY passive load.
- The reflection coefficient seen into the output (Γ_o) is smaller than 1 for ANY passive source impedance.

4.1.7 Gain Flatness

Digital communication systems utilizing OFDM has the ability to compensate for ripples through equalization with the help of **preambles**. These are short bursts of signals with known amplitudes which are inserted in each OFDM frame, before the the actual data payload. Since the receiver has *a priori* knowledge the expected amplitude of the preamble, it can digitally scale the received symbol to the correct amplitude and demodulate it properly.

Thus, even if there are large amplitude variations between different subcarriers, the modem will be able to equalize them. This also helps us combat frequency selective fading, which could produce gain ripples larger than 10dB in some communication systems such as WiFi.

The problem arises when the ripples are so large, we run out of **dynamic range** at the analog-to-digital converter (ADC).

4.1.8 Amplifier Classes

Class A Amplifier

Class B Amplifier

Chapter 5

Mixers

5.1 IQ Mixers

5.1.1 Sideband Reject Mixer

The following diagram depicts an IQ mixer used as a single-sideband (SSB) receiver, with upper sideband (USB) selection. Selecting the other output of the 90° hybrid would give us the lower sideband (LSB).

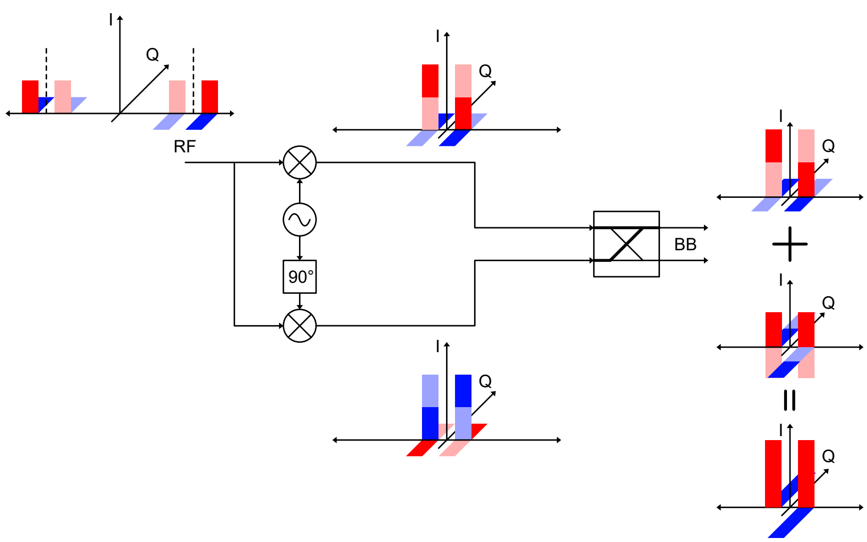

Figure 5.1: Working principles of a sideband rejection IQ mixer

Recall that 90° phase shift of a signal corresponds multiplying all of the positive frequency components by $-j$ and all of the negative frequency components by j. Think about adding 90° to $\cos(\omega t)$, turning it into $\sin(\omega t)$. Now repeat for all values of ω.

In this particular example, the signal in the lower sideband destructively interferes at the output of the hybrid, leaving us with just the upper sideband.

Phase or amplitude mismatch along the signal chain will result in incomplete cancellation of the lower sideband, and attenuation of the summed upper sideband. This is degrades the EVM of the output, since the lower sideband is folded on top of the upper sideband, effectively acting as noise.

Note that noise in the lower sideband behaves the same as signal, in that they add destructively at the output of the hybrid coupler. This means that the SSB IQ mixer has the same noise figure as a conventional double-sideband mixer. It does not suffer the 3dB increase in NF experienced by SSB mixers implemented using bandpass filters.

Chapter 6

Oscillators

6.1 Phase Noise

6.1.1 Model of Noisy Oscillators

We can model the output voltage of a noisy oscillator as:

$$v(t) = A(t)\cos\left[\omega_c t + \phi_n(t)\right] \tag{6.1}$$

where $A(t)$ captures amplitude noise, and $\phi_n(t)$ captures the phase noise.

We can interpret phase noise as phase modulation of the desired ideal oscillator output signal $\cos(\omega_c t)$, except that the modulation signal is pure noise. For simplicity, let us first consider the case when the phase modulation is a single-tone sinusoid. This is a helpful example, since we can interpret a noisy signal as the summation of infinitely many sinusoids all with random amplitudes and phases.

6.1.2 Effect of Phase Noise on EVM in OFDM Systems

The effect of phase noise on the EVM of an OFDM signal can be interpreted as follows.

Instead of getting a clean copy of the down-converted (or up-converted signal), we a bunch of shifted copies of the signal added on top of the desired signal, caused by the side bands of the noisy oscillator. Since each subcarrier is uncorrelated with the others, these additional copies of the signal act as noise.

The total effective ”noise” power added on top of each subcarrier can be determined by the total integrated phase noise. For example, if the single-sideband integrated phase noise is -40dBc, then the total EVM contribution of the noisy oscillator is -37dBc (+3dB since there are two sidebands).

Impact on adjacent channel leakage: as can be seen by the picture above, phase noise causes power to be spilled over to adjacent channels. Unlike spectral regrowth caused

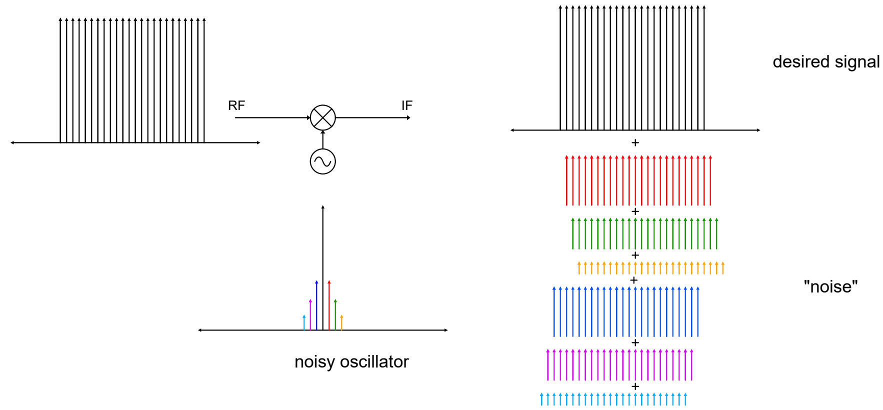

Figure 6.1: Effect of LO phase noise on OFDM signals

by nonlinearity, the adjacent channel leakage ratio will NOT improve as we scale down the channel power. It also cannot be corrected digitally (e.g. using digital predistortion).

6.1.3 White Phase Noise

Consider the case where $\phi_n(t)$ is Gaussian distributed with zero mean and standard deviation σ_{rms}. This means the probability density function of $\phi_n(t)$ is given by

$$f(\phi) = \frac{1}{\sqrt{2\pi\sigma_{rms}}} e^{-\frac{\phi^2}{2\sigma_{rms}^2}} \tag{6.2}$$

6.1.4 Oscillator Pulling

Oscillator pulling happens when a strong (undesired) signal couples to a resonator, causing its resonance frequency to change. It is also called **injection locking** or **injection pulling**.

Chapter 7

Mixed Signal Systems

7.1 Analog-to-Digital

7.2 Digital-to-Analog

Chapter 8

Modulation and Coding

8.1 Modulation and Coding Schemes (MCS)

Different modulation formats and code rates will require different SINAD (signal-to-noise and distortion).