Department of Communications and Networking

Spectrum analyzer

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January 19, 2024

1 Introduction

Electrical signals can be represented either in time or frequency domain. Signals analysis, in the frequency domain is called as *spectral analysis*.

This work introduces the basics of spectral analysis and the operation principle of spectrum analyzers. The purpose of this document is to describe spectrum analyzers by their basic features and provide necessary prerequisites to perform experiments using the same.

1.1 Signal Analysis

Sequency of signal samples can be presented as a vector. Vectors can be expressed as sum of weighted orthogonal vectors, components. The set of orthogonal vectors spanning the space is called basis vectors. The singnal vector can be represented by the sum of basis vectors.

There are multiple options for selecting basis vectors. In Fourier transform we are used trigonometric functions or exponential functions as basis vectors.

In order to describe a non periodic signals using periodic functions (like trigonometric functions) we first convert the non perioriodic signal to correspondic periodic signal l $f_{T_0}(t)$ with time period T_0 and then extending the time period to infinity

$$\lim_{T_0 \to \infty} f_{T_0}(t) = f(t). \tag{1}$$

With that conversion the nonperiodic continuous time signals can be presented by its frequency domain components, computed as

$$\vec{X_f}(f) = F\left\{x(t)\right\} = \int_{-\infty}^{\infty} x(t) \cdot \mathrm{e}^{-j2\pi ft}\mathrm{d}t, \tag{2}$$

where $\vec{X_f}$ is the signal in frequency domain, $x(t)$ is the time domain signal and $F\left\{x(t)\right\}$ is Fourier transform of the time domain signal [1, s. 9–10].

In digital spectrum analyzers the continuos time singal $x(t)$ is sampled and its Fourier transform is computed in digital signal processor. For accurately collecting all information about the signal, it should be sampled at twice of its highest frequency components, i.e at Nyquist frequency.

$$\vec{X}(k) = \sum_{n=0}^{N-1} \vec{x}(nT_S) \cdot e^{-j2\pi kn/N}. \tag{3}$$

In this equation the continuos signal $\vec{x}(t)$ is sampled into N discrete components. Hence, the discrete signal is represented by the fundamental frequency or tone $(\Omega) = \frac{2\Pi}{N}$ and it's harmonics. The Fourier transform is computed over N individual samples. The result is discrete spectrum $\vec{X}(k)$ [1, p. 18 to -19].

1.2 Energy and Power of a Signal

Energy of the signal $x(t)$ is the integral of $x^2(t)$. By taking the power we ensure that the positive and negative values of the signal don't cancel out each others.

$$E_x = \int_{-\infty}^{\infty} x^2(t) \cdot \mathrm{d}t. \tag{4}$$

The integral can be interpreted as the amount of energy dissipated, when voltage $x(t)$ is applied across 1 Ω resistor. Notice, the definition of the signal energy depends upon the load (resistor size).

Signal power is time average of the energy of the signal $x(t)$

$$P_x = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} x^2(t) \cdot \mathrm{d}t. \tag{5}$$

1.3 Noise and noise like signals

Electrons are charged particles and their movement creates current. Noise is generated by random movement of electrons. Total current generated by electrons is sum of each electron movement. Sum of randomly moving electrons can be approximated by a normal distribution. Since the noise is independent of the signals it addes to the signal. Such noise model is called additive white Gaussian noise. [1] [2, p. 3].

Power spectrum denisity (PSD) of a white noise is infinity. In practice receivers have input filters that select only part of the spectrum. For ideal brickwall filters the received noise power at the filter output is multiplication of PSD and selected bandwidth. Practical filters have smooth transfer function that shapes the noise spectrum. The noise power has be computed as integral over the filtered noise spectrum. However, by knowing the noise power at the filter output we can define a brickwall filter at the output of which would be the same amount of power. The bandwidth of such filter is called equivalent noise bandwidth (ENBW).

[1] This is result of the central limit theorem in probability theory.

Digital signal is a noise like if its amplitude distribution resembles a normal distribution (this is the case for instance for IS-95 CDMA and LTE OFDM signals). While studying such signals we have to look at their power in spectral domain. Signal power in certain bandwidth can be computed as

$$P_{ch} = \left(\frac{B_s}{B_n}\right)\left(\frac{1}{N}\right)\sum_{i=n_1}^{n_2} 10^{\frac{p_i}{10}}, \tag{6}$$

where P_{ch} is the signal power in the channel (given bandwidth), B_s is the channel bandwidth, B_n is eqvivalent noise bandwidth for given resolution bandwidth and p_i is the sample i power in decibels (or in decibel per milliwatt, dBm) n_1 and n_2 are bandwidth start and endpoints. In given bandwidth we have $N = (n_2 - n_1) + 1$ samples [2, s. 14].

1.4 Spectrum analyzer

Spectrum analyzer is a device that can show the input signal in frequency domain. Spectrum analyzers can be divided into two categories: Fourier transform based analyzers and heterodyne types analyzers [1, p. 17 27].

Fourier transform based analyzers have hardware support for evaluating Fourier transform of the input signal. Usually they use fast Fourier transform (FFT) processors. Since the time to collect the samples is much longer than computing FFT from them in practice the signal can be sampled continuously.

The performance of Fourier transform based analyzers is defined by properties of their analog digital (A/D) converters. A/D converters have limited bandwidth and dynamic range. Moreover, the dynamic range of the samples is usually decreased when the sampling rate is increased [1, p. 18 25 to -26].

Heterodyne type spectrum analyzers examine the spectrum directly. Instead of calculating the conversion they filter certain frequency and show the spectrum as power of that frequency. The input signal is swept over a filter that separates one frequency at a time. Such operation gives a very accurate picture of the spectrum at the expense of processing time. [1, p. 27 29].

A simplified structure of heterodyne type spectrum analyzer is shown in Figure 1. The first component of the Spectrum analyzer is the attenuator. The attenuater allows to study high power signals that otherwise would damade the input amplifiers. After the attenuator is the mixer, whose task is to combine the input signal with local oscillator (LO) frequency and to shift the signal to an intermediate frequency (IF). The mathematical relationship between the intermediate frequency and the input signal is

$$f_{in} = |f_{LO} \pm f_{IF}|, \tag{7}$$

where f_{in} is the input signal, f_{LO} is the oscillator frequency (adjustable) and f_{IF} is the intermediate frequency. The image frequency at the mixer output is removed by the IF filter. The bandwidth of the IF filter is defined as separation or resolution bandwidth (RBW) . It determines how close frequency domain components the analyzer can separate [1, p. 32, 34, 39 to -40].

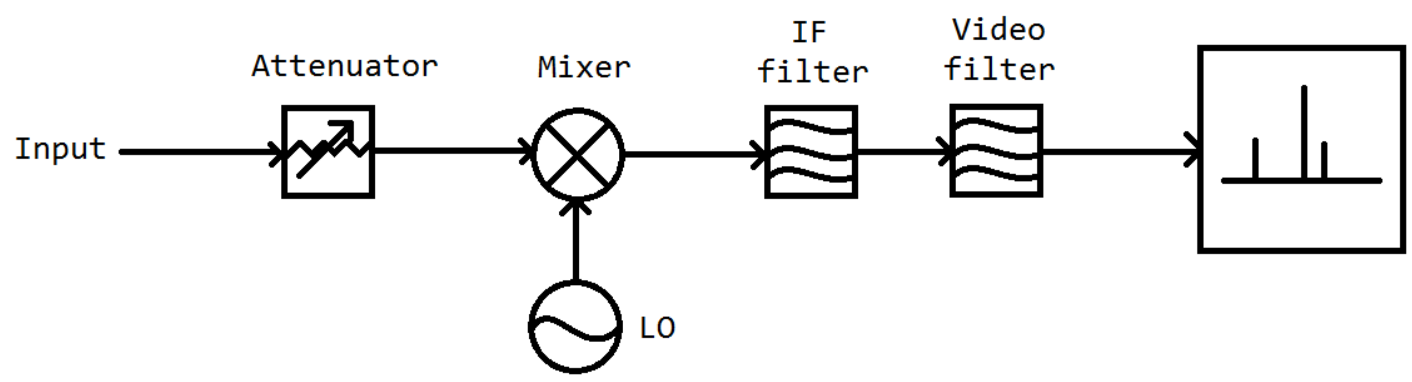

Figure 1. Functional components of a Heterodyne Spectrum analyzer [1, s. 220].

The next component wideband video filter reduces the noise variance. By reducing video filter bandwidth (VBW), we can identify signals that are barely recognised due to the background noise level. [3, p. 18]. Effect of video filter on sinus wave is illustrated in Figure 2.

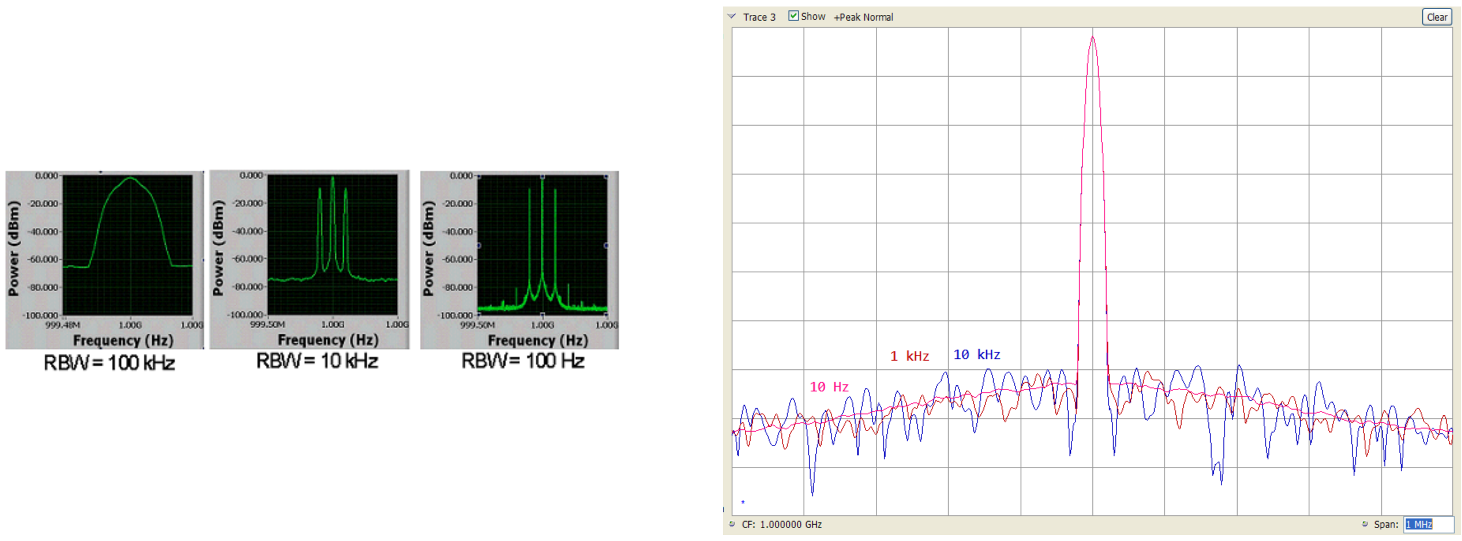

Figure 2. Impact of RBW(Left) and VBW(right) on a signal spectrum.

1.4.1 Spectrum analyzer

In the laboratory, we use spectrum analyzers from Rhode & Schwarz, Tektronix or Siglent. All of them provide basic spectrum analyzer measuremetn features with slightly different user interfaces. An user interface with default setup for Tektronic spectrum analyzer is presented in

Figure 3. In figure, the window displays the frequency spectrum of a 1490 MHz sinusodial signal, input fed from signal generator. Also the window contains various configuration options to tweak relevant parameters of the spectrum. There are parameters for configuring center frequency (CF) and visible bandwidth, known also as *span*. In the bottom of the figure, we can see there is a option for selecting the attenuation value at the input port. This attenuator protects input low noise amplifier from burnout by very large signals. Its default value is 25 dB. If you are interested to measure maximum possible dynamic range, the attenuator has to be set to be as small as possible. However, in order to protect the input amplifier,we should be careful when we use low attenuation.

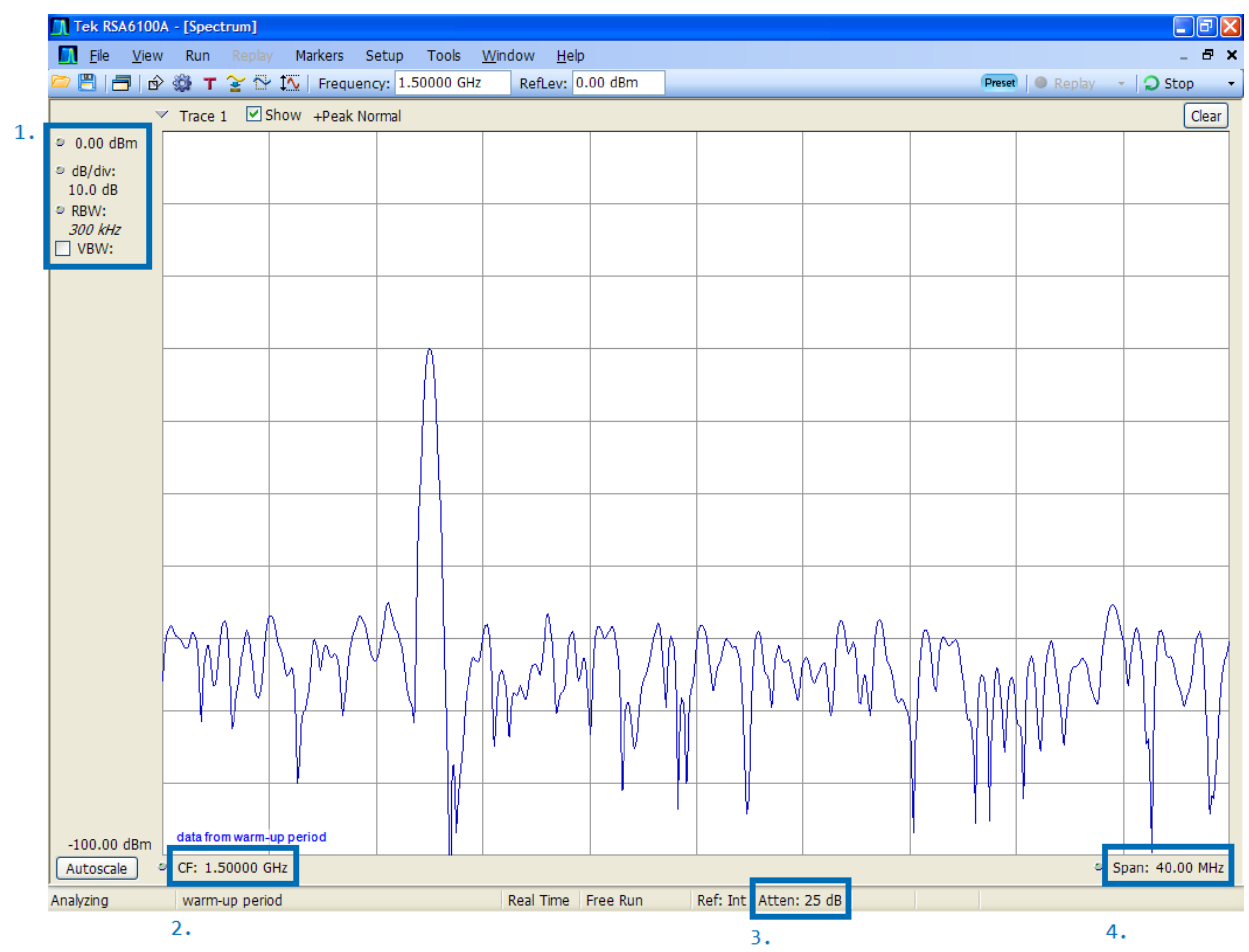

Figure 3. Tektronix RSA 6114A- Typical Spectrum analyzer interface Spectrum analyzer's parameters : 1) The reference level , resolution bandwidth and video bandwidth. 2) Center frequency. 3)Internal attenuation 4)Observed frequency bandwidth or span.

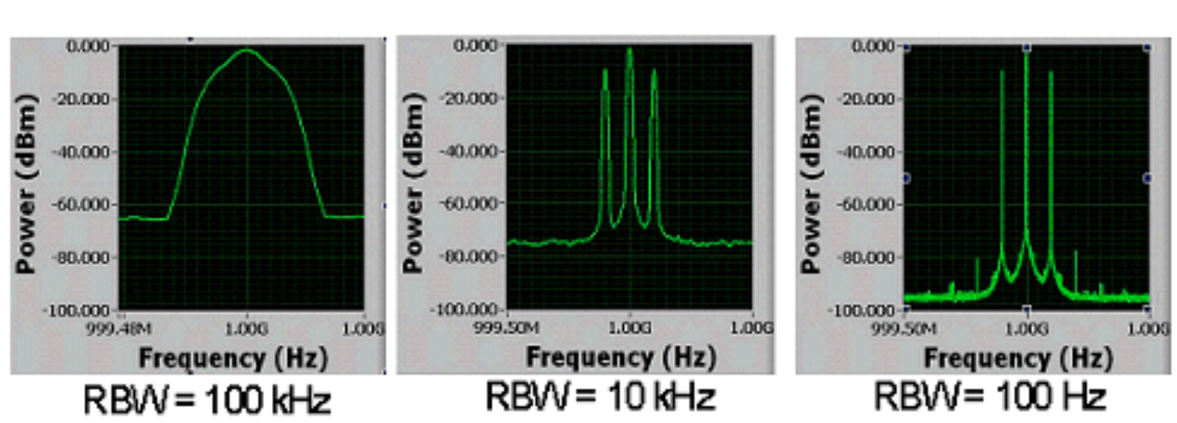

Figure 4. Same Signal at different RBW

The bin size of the Fast Fourier Transform(FFT) or the lowest range of frequency to be sweeped characterizes the frequency resolution of the spectrum analyzer. In different manufacturers this parameter has different name. In Tektronics is defined by RWB (resolution bandwidth) parameter in Siglent and Rhode & Swartz FSV(R&S) is set as RW (resolution bandwidth) and in R&S FSEA as Coupling. In Figure 3 the options, such as eference power levels(in the Figure 0.00 dBm), RBW settings, can be found on the left side of the interface. In other equipments the options can be found under physical buttons. Resolution bandwidth setting have a impact on the spectrum that is displayed on the analyzer. It impacts FFT size, computation time of FFT, Noise floor level. The impact of RBW is illustrated in Figure 4 and 2.

In top side of the figure, you find icons of shortcut menus. Most of these icons can be accessed also through buttons on the device front panel.

Beside spectrum view, the spectrum analyzer can have also other views, such as constellation diagrams, time domain view of the signal etc. Those can be selected from the front panel **Displays** options. Other buttons are **Settings** that opens the option panel of the current selected view, **Markers** that enables setting markers on the display, **Freq**, **Span**, **Ampl** and **BW** are used for spectrum analyzer basic settings.

2 Equipment used in the laboratory work

In this laboratory work we are using following equipments:

- Spectrum analyzers
  - Tektronix RSA 6114A
  - Rohde & Schwarz FSEA 50 Hz - 3.5 GHz
  - Rohde & Schwarz FSV 10 Hz - 13.5 GHz
  - Siglent SSA 3075 YR
- Oscilloscope
  - Rohde & Schwarz RTM 3004
- Vector signal generators
  - Rohde & Schwarz SMBV100A signal generator
  - Rohde & Schwarz SMW 200A signal generator
- R&D Microwaves C1-A29 directional coupler.

We need also suitable cables and adapters to connect the equipment together.

3 Intructions

3.1 Using spectrum analyzer

First, we illustrate how to use a spectrum analyzer. We feed to analyzer a simple signal. The time domain presentation of the signal will be viewed by oscilloscope. The measurement system is shown in Figure 5.

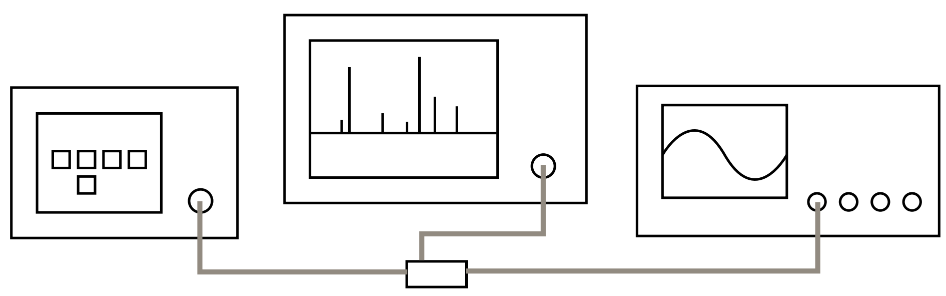

Figure 5. S

1. Start the signal generator, spectrum analyzer and oscilloscope. Do not connect the cables and connectors before the spectrum analyzer has fully started. In this way you do not disturb the automatic calibration that the analyzer makes during the start up phase. Reset all devices Settings by **PRESET** - or **Default Setup** buttons.

2. Make the connections.
   The signal generator is connected by cable to the directional coupler common port. The oscilloscope is connected to the main port of the coupler. The attenuated branch is connected by cable to spectrum analyzer. Depending on the coupler the attunation is 10 or 20 dB. Set the signal generator to generate 900 MHz carrier with power level that matches the maximum spectrum analyzer reference level. (For instance for Tettronix it is 0 dBm.) These levels can be set by **FREQ** and **LEVEL** buttons.
   Switch the generator on from **RF OFF** button. Now it should generate sinusoidal carrier frequency.

900 MHz

(!) 3. Set the oscilloscope input impedance to be 50 Ω. Find the signal with the oscilloscope. The oscilloscope shows the signal voltage. Give the equation that relates this value to the power level set at the signal generator.

69 mV

0 dBm

4. Set the internal attenuation of the spectrum analyzer to zero.
   In Tektronix it is done by selecting from **Setup** menu **Amplitude** and in **Input Attenuation** section tick off field **auto** and set the field value to 0 dB.

900 MHz

R=50Ω

$$P = \frac{U^2}{R} = \frac{0.165^2}{50}$$

	0 dBm	-10dBm	-20dBm	-30dB
(VPP) U	331.73mV/2	108mV/2	33.32mV/2	11mV/2

P

In R&S FSEA **REF** menu **RFAtten manual**.

In R&S FSV **Amplitude** menu **RFAtten manual**.

In Siglent **Amplitude** menu **Attenuator** set to **manual**.

大砖:

-10dB
衰减

Attention! At the analyzer input are very sensitive components that provide high-dynamic range of the equipment. However there components are very fragile and high level signals can damage them. **Never** connect to the analyzer input unknown signals without ensuring that their level does not damage the equipment. For instance use separate attenuators and internal frontend attenuator such that the input signal does not exceed allowable signal at the analyzer input.

center freq
900 MHz
SPAN: 50 MHz

(!) 5. Use spectrum analyzer and find the signal by selecting suitable center frequency and span.
How and why the spectrum analyzer displayed image differs from the oscilloscope image?
What is the maximum power of the signal? -32.59 dBm

(!) 6. Sketch the theoretical spectrum of the sinusoidal input signal.
How the spectrum shown by spectrum analyzer differs from the theoretical spectrum?

(!) 7. Change the resolution bandwidth
10 MHz, 100 KHz, 10 KHz, 1KHz, 100 Hz.
Comment how the resolution bandwidth impacts the spectrum plot?
Give the numerical values of the resolution bandwidth and the observed spectrum change.

3.2 Noise floor and dynamic range

Spectrum Analyzer's ability to distinguish between low amplitude signals is limited by the noise floor. The noise floor is reported with respect to resolution bandwidth. In this way the noise level can be normalized, for instance to one Hz.

Next we study noise floor levels. At the same time we observe how the analyzer high dynamic range allows to study very low power signals.

8. Set the signal generator power level to -30 dBm.
At the spectrum analyzer set a marker at the generated signal.
Set the signal generator power level to -120 dBm.
Try find the signal on the oscilloscope screen.

(!) 9. Connect the signal generator output directly to the spectrum analyzer. Set internal attenuator to 0 dB. Attempt to find the signal. Beside of selecting suitable resolutions bandwidth, you can also use spectrum averaging if it is available in your equipment.
You can also smooth the noise by setting suitable video filter bandwidth.

In Tektronix the spectrum averaging is activated in spectrum view by **Settings** button. In **Traces** tab set **Function** value to averaging *Avg (VRMS)* and by select samples size for instance 100.

Hint: The time required for scanning can be reduced by reducing the monitored bandwith area (span). Measure and record the noise floor level.

(!) 10. The impact of resolution bandwidth on the noise floor level can be removed by normalizing the noise floor value to one Hz. For that you have to remove from the measured noise floor level the resolution bandwith $10log(RBW)$ dB. Use that approach and compute the noise floor per Hertz? Insert it into final report.

dB/Hz

100 Hz
−102.85 dB
(−122.85)

In question 10 calculated noise floor consists of thermal noise and spectrum analyzer components own noise (noise figure). The thermal noise can be calculated as

$$N = kTB, \tag{8}$$

B = 20 MHz

where $k \approx 1.38 \cdot 10^{-23} \frac{\mathrm{J}}{\mathrm{K}}$ is Boltzmann's constant, T is the temperature in Kelvin, and B is bandwidth in Hertz.

(!) 11. Assume the temperature is 290 K. Calculate the spectrum analyzer's noise figure.

100

$1.38 \times 10^{-23} \times \cancel{2\times10^{7}} \times 290 = 8.004 \times 10^{-16}$

$= 8.004 \times 10^{-1?}$

$10 \log(8.004 \times 10^{-1?})$

$= -120.9$

3.3 Power measurements

In this exercise we use signal generator to make QAM signal and study its spectrum and contellation view. The QAM signal is generated from pseudo random sequence and therefore its spectrum resembles noise.

12. In signal generator select from **Baseband config...** menu **Custom Digital Mod ...**. Check that the **Data Source** is set to *PRBS* (the number of bits does not matter) and select from **Modulation Type** menu *16QAM*. Set symbol rate to *500 Ksym/s*. Set shaping fitler **Filter** to *Root Cosine* and set the filter parameter to 0.35. Finally, activate the modulation by switching on the *Custom Digital*

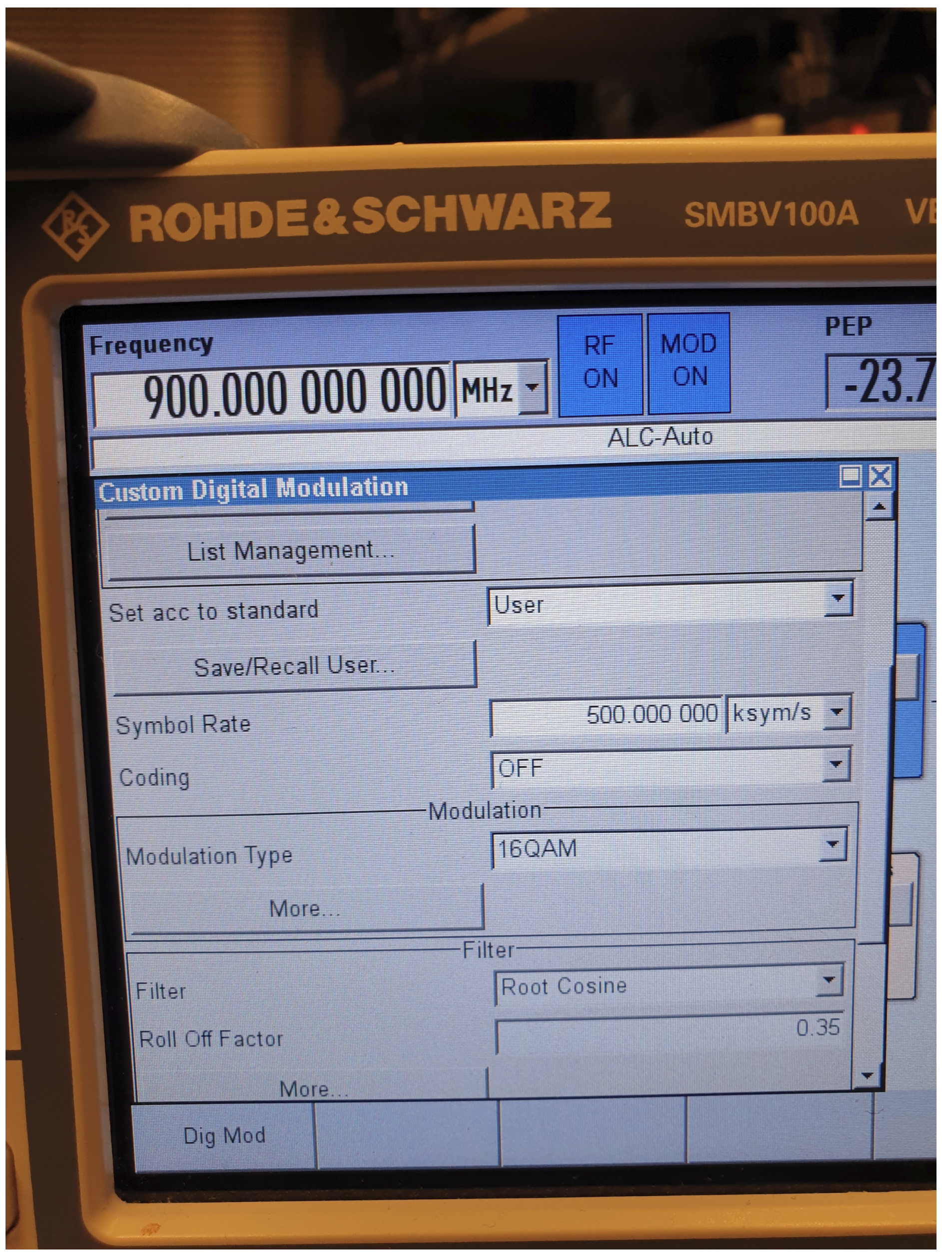

Figure 6. Signal generator settings for QAM-modulation.

Modulation button at the top of the window. The settings are also shown in Figure 6.

13. Set the signal generator frequency to 900 MHz and the power level to -30 dBm. Switch on the signal generator blocks **Baseband**, **I/Q Mod** and **RF/A Mod**. Reset the spectrum analyzer settings and search for QAM signal.

(!) 14. Set the spectrum analyzer internal attenuation to 0 dB and examine QAM signal. What is the signal bandwidth? What signal generator option determines the necessary bandwidth?

0.27x2 MHz
0.54MHz
540 kHz

15. Select from spectrum analyzer constellation view. Set modulation to be 16QAM symbol rate and filter to be same as in genertor. Set trace symbol set to be 1.

(!) 16. Set constellation view such that the constellation points should be clearly visible.

Are the constellation points equally distributed? Why/or why not?

For this exercise you could configure Textronix as follows:
Select **Constellation** view and press the **Settings** button front panel. Select from **Modulation Params** tab modulation type *16QAM* and set symbol rate to be the same as in generator ie. 500 kHz. In the same tab are selections for filters disable them by selecting *None*. In **Trace** tab set **Content** to *Points* and **Points / symbol** set to 1. The settings view is shown in Figure 7. Constellation points should now be clearly visible.

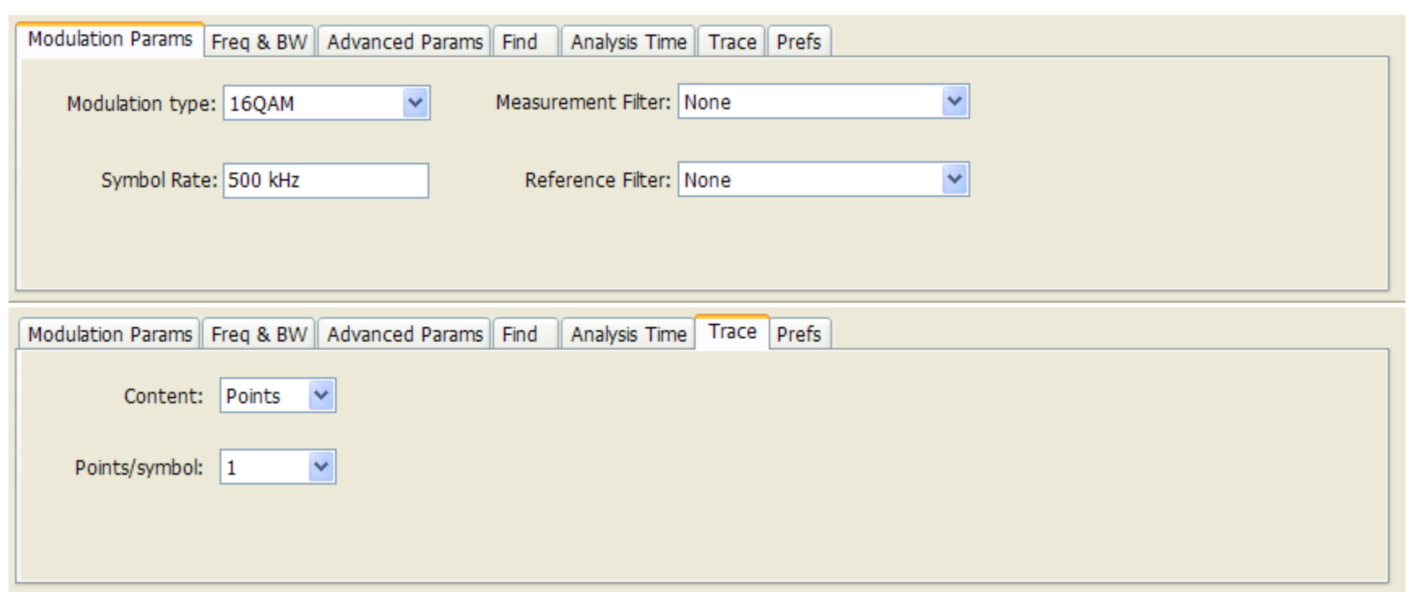

Figure 7. Settings for the constellation plot

17. From the ACPR set the analyzer to measure only one cahnnel. Set the channel bandwidth to the value you estimated for the transmitted signal.

    In the Textronix it can be done by: select **Channel Power and ACPR** view and click on the **Settings** button. In the tab **Channels** set the channels pairs to 0. Now the analyzer measures only one channel. In the same tab, set the channel bandwidth to the value you estimated for the transmitted signal. The **Channel Spacing** value is not relevant for this measurement. The value there does not impact the measurment result.

(!) 18. Measure the channel power by averaging over 100 samples and by disabling "Channel filter". Compare the analyzer measured channel power to the power set in signal generator. How the signal power calculation of power now is different from signal power estimation from the voltage measured by oscilloscope?

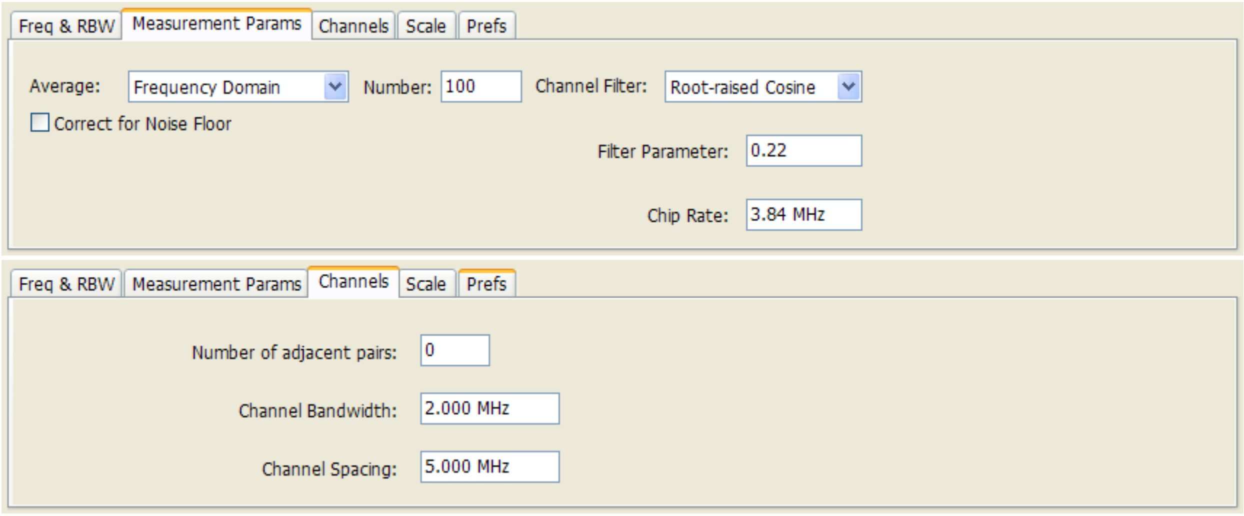

Figure 8. Settings for channel power measurement.

References

[1] C. Rauscher, *Fundamentals of Spectrum Analysis*. Rohde & Schwarz, 2007.

[2] Agilent Technologies, *Spectrum and Signal Analyzer Measurements and Noise*, Application Note, 2012.

[3] ——, (2012). Spectrum Analysis: Back to Basics, [Online]. Available: `http://ewh.ieee.org/r5/denver/sscs/Presentations/2012_10_Agilent1.pdf` (visited on 07/07/2014).

A Questions

1. Why we use sometime wide resolution bandwidth (RBW, RB). At narrow resolution bandwidth the spectrum analyzer can separate more frequencies and noise level is also reduced. Why then sometimes is better to use wide resolution bandwidth, what problems arise when we use too narrow resolution bandwidth?

2. Show by equations what frequencies are generated by multiplication of two frequencies f_{LO} and f_{IF} in equation 7.

3. Why the spectrum analyzer is connected througth directional coupler and not by measurement probe, like it is used in oscilloscope connetion?

B View of the Setup

Figure 9. Tektronixin DPO 3054 oscilloscope , Rohde & Schwarz SMBV100A signal generator and Tektronixin RSA 6114A spectrum analyzer