Lab 1 - Receiver Characterization

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***Abstract*—This lab introduce the superheterodyne radio receiver architecture. The components were characterized and compare with the theoretical analysis. We focus on the Wi-Fi band from 2.4GHz to 2.5GHz, mainly at Wi-Fi channel 6 centered at 2.437GHz. The channel bandwidth is 20MHz. The receiver has the cascade gain of 38 dB and estimated noise figure 38dB.**

I. Introduction

IN the lecture, the homodyne and superheterodyne receivers were introduced. The homodyne received radio frequency signal is fed directly into a frequency mixer, using a zero Intermediate Frequency (IF). It has superior performance due to the single conversion stage, and reduced circuit complexity as well as power consumption. However, it has DC offset issue cause by the local oscillator (LO) leakage. Ideally, the mixer would produce an output that is the product of the two signals, the input signal and LO signal. In frequency domain, the output frequency should be at the sum and difference of the input signal frequency and LO frequency, nothing else. In real-world, the LO signal from the mixer input port may leak to the mixer's output port, which produce some energy at the LO frequency. The LO signal can leak through the mixer stage to the antenna input and then reflect back into the mixer stage. The overall effect is that the local oscillator energy will self-mix and create a DC offset signal. The energy at LO frequency can be a problem if it is very close to or within the desired output signal and difficult or impossible to remove by filter, since the filter might also filter the desired signal.

To solve this DC offset issue, one of the solution is using nonzero IF, which is what we called superheterodyne. In this way the LO leakage and the desired signal have a separation of IF in the frequency spectrum. This enables filtering of the undesired image band as well as the LO leakage. Figure 1 [1] shows a good illustration of superheterodyne RF spectrum. Superheterodyne architecture has been commonly used in the radio design such as handheld radio, unmanned aerial vehicle data link, or a signal intelligence receiver. The benefits of this design are clear: proper frequency planning can allow for very low spurious emissions, the channel bandwidth and selectivity can be set by the intermediate frequency (IF) filters, and the gain distribution across the stages allows for a trade-off between optimizing the noise figure and linearity [2].

In this lab, the superheterodyne radio lab kit is provided for receiver characterization and measurement. The pegboard is used for it's flexibility. The system diagram is shown in Figure 2. The signal comes through the antenna, band-select filter (1), low noise amplifier (LNA) (2), RF amplifier (3), image reject filer (4), mixer (5), channel select filter (6) , IF amplifier (7), LO (8), LO amplifier (9), and LO phase reference (10). The complex IF sampler part is ignored in the lab. The connected lab kit is shown in Figure 3. The components number is corresponding with Figure 2. This report include superheterodyne radio lab kit important quantities and theory and measurement comparing.

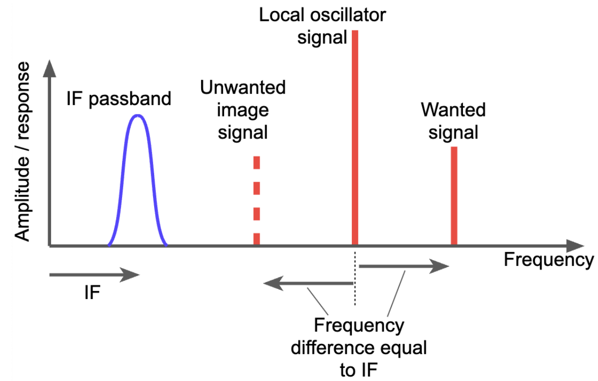

Fig. 1. Superheterodyne receiver image is twice the IF away from the wanted signal [1]

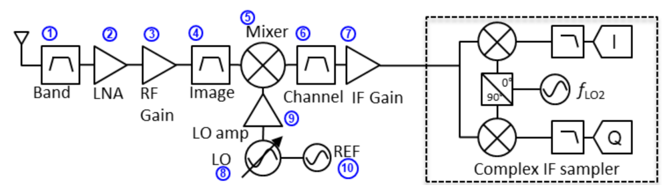

Fig. 2. Superheterodyne receiver structure diagram

II. Background Knowledge And Cascade Analysis

A. Noise Factor and Noise Figure

Noise figure is a parameter the noisiness of the two port network or devices, compared with a reference noise source at the input port. Take amplifier as an example, the noise factor of the amplifier can be express as:

$$F = \frac{SNR_{in}}{SNR_{out}} = \frac{\frac{S_i}{N_i}}{\frac{GS_i}{G(N_i+N_{ai})}} \tag{1}$$

where S_i = signal power at the input port, N_i = noise power at the input port, G = amplifier gain and N_{ai} = amplifier noise referred to the input port. The equation 1 can be further simplify as

$$F = \frac{N_i + N_{ai}}{N_i} = 1 + \frac{N_{ai}}{N_i} \tag{2}$$

The noise figure is

$$NF = 10log_{10}(F) \tag{3}$$

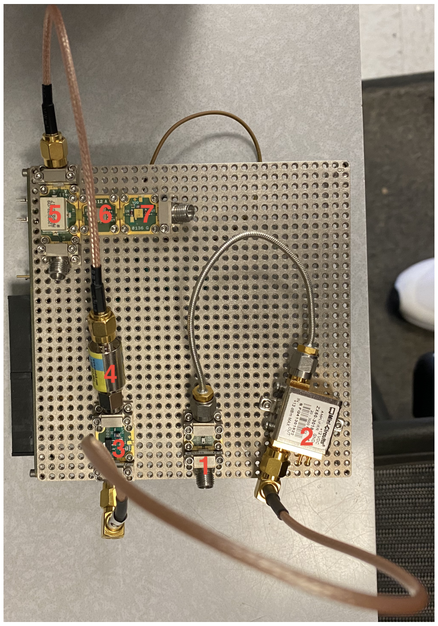

Fig. 3. Fully connected Superheterodyne receiver structure

from the equation 2, we can have $N_{ai} = (F-1)N_i$. Meanwhile, we can replace N_i with kT_sB and N_{ai} with kT_eB. The T_e is named equivalent noise temperature or effective noise temperature. From the derivation above, we can have

$$T_e = (F-1)T_s \tag{4}$$

Or since the T_s usually is $290K$, it can be written as $T_e = (F-1)290K$.

B. Cascade Analysis

When the two networks or two devices are connected together,the composite noise factor can be written as

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} \tag{5}$$

where G_1 is the gain of network 1, $F_1$and F_2 are their noise factor. The multistage noise factor is explained later in the measurement section, Equation 7.

The gain cascade is

$$G_{total} = G_1 G_2 ... G_N \tag{6}$$

The theoretical noise cascade analysis is shown in the Figure 4.

III. Measurements

In the lab, all the components used vector network analyzer (VNA) to do the linear gain (frequency response) measurements. A VNA measures the power of a high-speed signal pass through and reflected from the device or network, and it can be measured accurately at high frequencies. The linear measurement summary is in the Table I, the detail of each components is in the rest of the section.

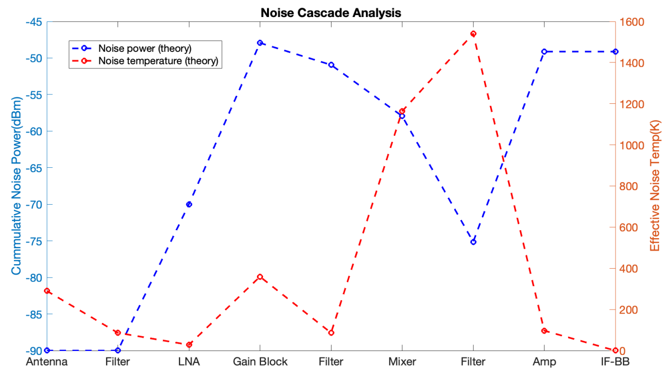

Fig. 4. Noise cascade analysis

TABLE I
LINEAR MEASUREMENT RESULT SUMMARY

component	Theory gain	Measured gain
Band-select filter	-1.13	-1.34
LNA	19.4	18.86
RF Amplifier	22	22
Image-reject filter	-3	-1.88
Channel-select filter	-8	-8.9
IF Gain	26	25.2

The active components require additional nonlinear measurements. We use two tone test to characterize the nonlinearity of the components. When the device's gain is 1dB less than expected value, the input power is IP_{1dB}, and the intercept point of the gain and third-order distortion is third-order intercept point IP3.

TABLE II
NONLINEAR MEASUREMENT RESULT SUMMARY

component	IIP3dB (theory, measured)	OIP3(theory, measured)
LNA	-, 1.97 dBm	23dBm, 18.6dBm
RF Amplifier	12.6dBm, 18.22dBm	34.6dBm, 36.29dBm
IF Gain	-, 9.2dBm	37.4dBm, 34.78dBm

A. Band Select Filter

The band select filter frequency response is shown in Figure 5. The purpose of band select filter is to protect the LNA from other frequency interference and not amplify the frequency that we are not interested. Futhermore, the band select filter can protect the LNA from overload. When the power on other frequency is relatively high, it may reach the IP1dB point cause LNA to operate at non-linear region and adding band select filter can prevent that. The insertion loss 1.34 dB which is close to the datasheet value 1.13 dB, thus its NF is also 1.34 dB. Because it is symmetric, the S_{21} and S_{12} are the same.

B. LNA

When n networks or devices connected in series, the relationship between stages in Equation 5 continues. The

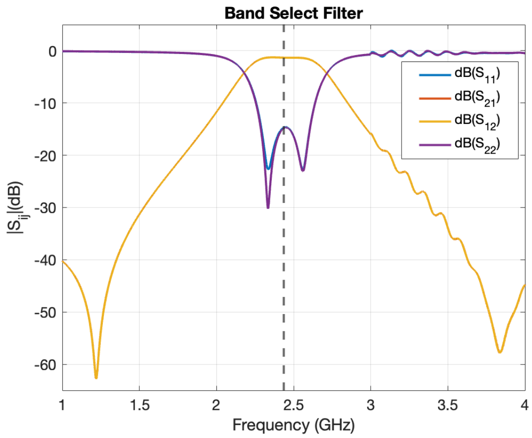

Fig. 5. Frequency response of band select filter

composite noise factor for a sequence can be written as

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + ... + \frac{F_n - 1}{G_1 G_2 ... G_{n-1}} \quad (7)$$

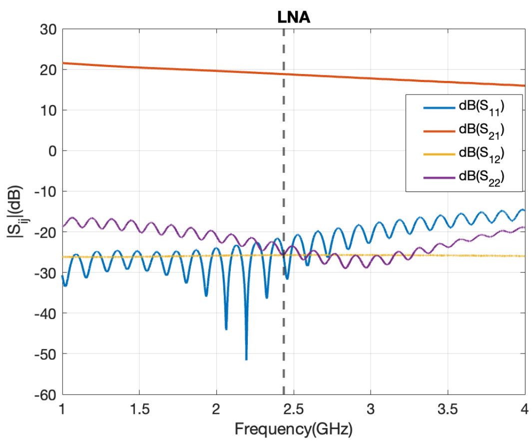

Fig. 6. Frequency response of LNA

According to the Equation 7, at the front end of the receiver, the signal is most easy to be effected by noise. Therefore, the first stage should have as low noise figure as possible and meanwhile get as high gain G_1 as possible because the noise figure of each subsequent stage is reduced by the gains of the prior stages. Ideally, the LNA should be in the first stage for it's high gain and low noise figure. But in order to protect LNA from saturation, we put the Band select filter in front of LNA. The LNA noise figure did not get measure at this lab, but according to the data sheet the noise figure is 2.61 dB. The frequency response is shown in the Figure 6, and the gain is 18.86 dB from our measurement. Thus, using our components, we should not changing the sequence of the components. It will be better if we have a lower NF LNA and changing the sequence, in that case, LNA in front of the band pass filter will get us lower cascade noise figure and lower SFDR.

Based on the linear measurement data we have, and the two tone test data, the calculation can be done and the IIP3 is 1.975 dBm.

C. RF Amplifier

The RF amplifier should get a high gain stage after the LNA to maintain SNR, in other words, keep the signal from the noise floor. Furthermore, it will compensate the insertion loss of the image-reject filter, mixer and channel-select filter. The frequency response is shown in Figure 7, which shows its gain at 2.437 GHz is about 22 dB. Figure 8 shows the nonlinear measurements of the RF amplifier. The IP_{1dB} is -6.97 dBm and the OP_{1dB} is about 10.12 dBm based on the measurements. Using the forecast line, we can find the first order component and the third order component line intercepted, so the IIP_{3dB} is 18.22 dBm and OIP_{3dB} 36.9 dBm. One of the reason that cause the little distortion on the third order component line is because of the fifth order term, which is not shown in the figure. Comparing with the data sheet, the OP_{1dB} is around 16 dBm. The difference might come from the cable or the fieldfox was saturated and did not set it right.

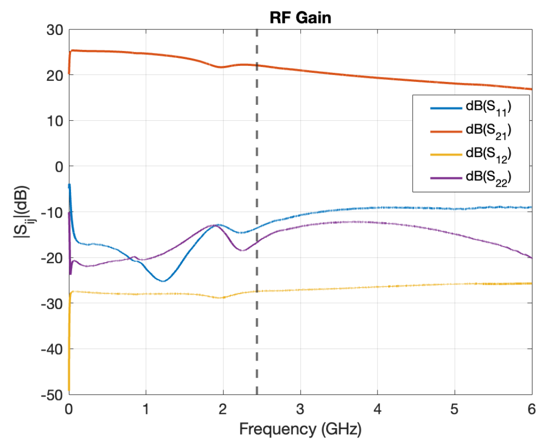

Fig. 7. Frequency response of RF amplifier

D. Image-reject Filter

The image-reject filter is used to solve the image spectrum problem. As shown in the Figure 1, the up converted RF signal will have image spectrum because of the mixer. The filter's response is shown in Figure 9, which transition from low attenuation at the wanted band to high attenuation at the image band. The insertion loss of the image-reject filter at 2.437GHz is 1.88 dB, and the attenuation of the image frequency is 36.94 dBc. After the image-reject filter, ideally only the wanted signal will preserve a good SNR to down-convert and do the I-Q demodulation.

E. Mixer

The mixer will down convert the RF to IF as shown in Figure 10. In our setup, the RF signal has a 20 MHz bandwidth

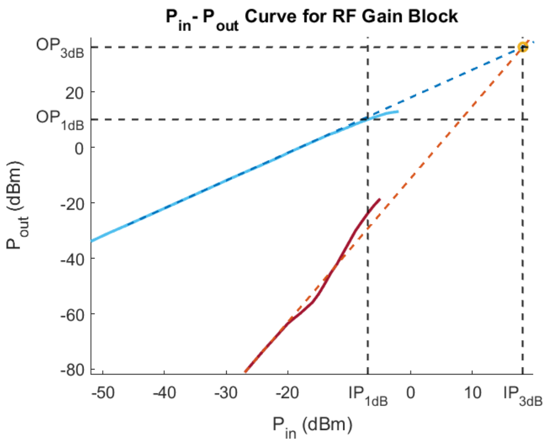

Fig. 8. Nonlinear measurement of RF amplifier

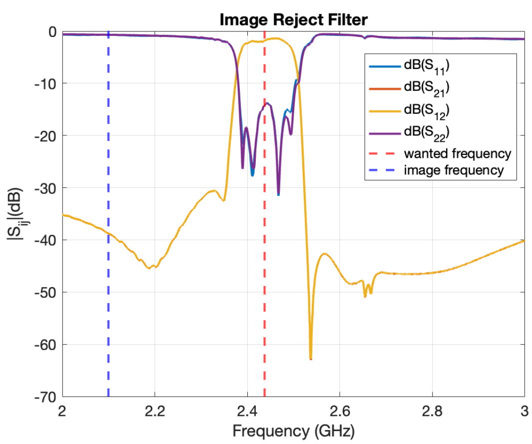

Fig. 9. Frequency response of image-reject filter

centered at 2.437 GHz, and the LO is a pure tone at 2.2685 GHz generated by signal generator.

Ideally, the out put of the mixer should be

$$\begin{aligned} & cos(2\pi\omega_{RF}t)cos(2\pi\omega_{LO}t) \\ & = \frac{1}{2}cos(2\pi(\omega_{RF}-\omega_{LO})) \\ & +\frac{1}{2}cos(2\pi(\omega_{RF}+\omega_{LO})) \end{aligned} \tag{8}$$

However, in the reality, the nonlinear components of the circuits create a series of output signals that contain multiples

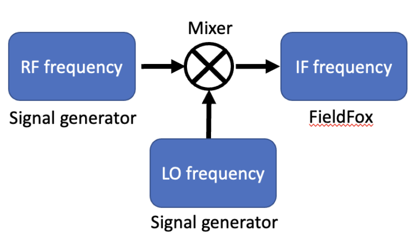

Fig. 10. Mixer convert RF frequency to IF frequency

of the input signals, plus sums and differences of all signals, fundamental and harmonic, as described by: $f_{out} = |nf_{LO} \pm mf_{RF}|$. In Figure 11, we put the input RF frequency at 2.427 GHz and 2.447 GHz to mimic that we have 20 MHz bandwidth input and see the frequency plan.

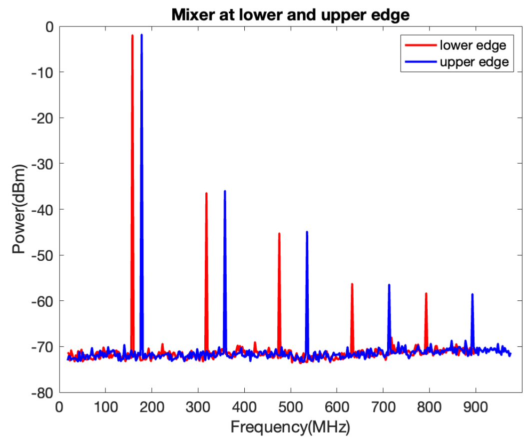

Fig. 11. Mixer convert RF frequency to IF frequency: frequency plan

TABLE III
SPUR SIGNAL SPECTRUM, $P_{in} = -30dBm$

Frequency[MHz]	P_{out}**[dBm]**
168.5	*7.2*
337	*-33*
505.5	*-56.4*
674	*-75*

TABLE IV
FREQUENCIES OF INTERMODULATION BANDS

	M=1, N=1	**M=2, N=2**	**M=3, N=3**	**M=4, N=4**
f_{LOW} **[MHz]**	*158.5*	317	*475.5*	*634*
f_{HIGH}**[MHz]**	*178.5*	358	*535.4*	*713*
P@f_{LOW}**[dBm]**	*-2.065*	-36.53	*-45.18*	*-57.16*
P@f_{HIGH}**[dBm]**	*-1.787*	-35.88	*-44.89*	*-57.33*
Isolation (LOW)[dBc]	*0*	34.465	*43.115*	*55.095*
Isolation (HIGH)[dBc]	*0*	34.093	*43.103*	*55.543*

Table IV shows the measured isolation relative to IF. The power input of the RF signal is 10 dBm, so the conversion loss = $P_{in_{RF}} - P_{out_{IF}}$ can be calculated and it is around 12 dBm. This is more than the data sheet maximum value, one of the reason is because our lossy cable. The isolation value is relatively close to the datasheet value.

F. Channel-select Filter

The channel-select filter or IF-filter is going to filter the output signal of the mixer. As we saw in the frequency plan, the output of the mixer has a lot of harmonics, the channel-select filter we used has 20MHz passband, and will significantly attenuate the out of band signal. However, the channel select filter passband will suffer from the high noise floor due to the high cacade gain of the former steps, we can see this in the Figure 17. According to the Figure 12, the insertion loss of the channel-select filter is 8.9 dB, which is matched with the data sheet.

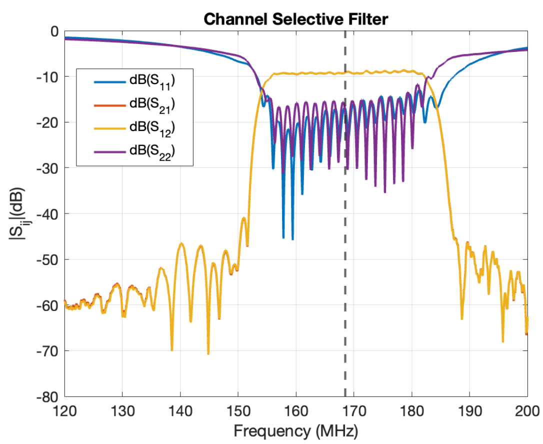

Fig. 12. Mixer convert RF frequency to IF frequency: frequency plan

TABLE V
ATTENUATION OF INTERMODULATION BANDS BY CHANNEL-SELECT FILTER

frequency[MHz]	Attenuation[dB]	Attenuated Distortion[dBc]
158.5	*-9.276*	*9.276*
178.5	*-8.88*	*8.88*
317	*-66.098*	*100.563*
358	*-69.39*	*103.855*
475.5	*-65.9*	*109.015*
535.5	*-70*	*113.115*
633	*-86*	*141.095*
713	*-93*	*148.095*

Base on the table, we can draw the Figure 13.

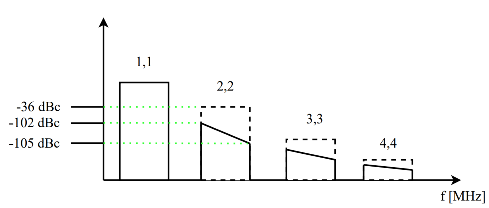

Fig. 13. Intermodulation distortion

Since the signal of the interest is at $-43dBm/Hz$, so the $(2,2)$ term power should be $-43-102.2+10log_{10}40MHz = -69.1794dBm$. Using the same way, the power at $(3,3)$ is $-43-111.1+10log_{10}60MHz = -76.3185dBm$ and $(4,4)$ is $-43-144.595+10log_{10}80MHz = -108.5641dBm$.

G. IF Gain

The IF gain is to provide sufficient SNR to the ADC to demodulate the signal. According to the Figure 14, the IF gain provided 25.2 dB gain.

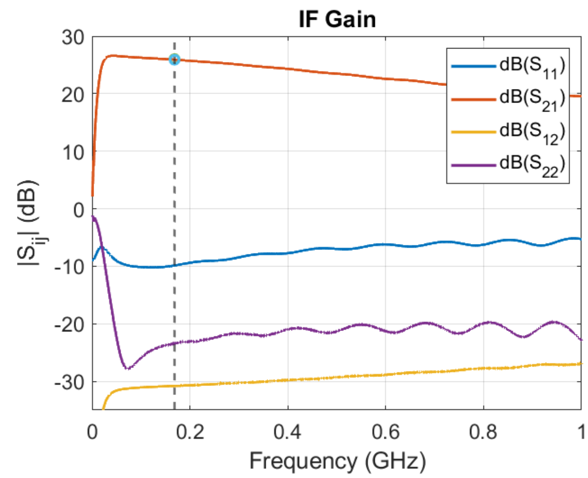

Fig. 14. IF gain

IV. OVERALL PERFORMANCE ANALYSIS

The receiver was connected once all the components measured. From the P_{in}, P_{out} curve of the receiver in Figure 15

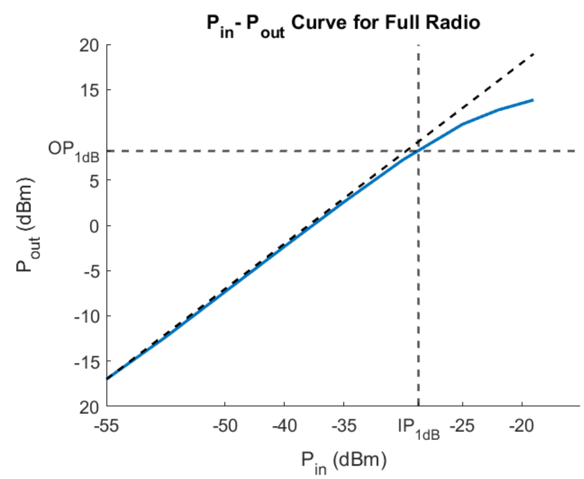

Fig. 15. Nonlinear measurement for the receiver

we can get the $IP_{1dB} = -28.6923dBm, OP_{1db} = 8.25dBm$. The IP_{1dB} is much smaller than the separate components, because overall gain is much large then separate components. And the noise power is shown in the Figure 17. As we can see in the figure, the channel select filter limit the out put band noise floor. The first four stages S-parameters is shown in Figure 16. The gain of the first four stages is around 32 dB. The actual overall cascade gain of the receiver part is around 38 dB. The coarse noise figure can be estimated by the equation:

$$NF = P_{out} - (P_{in} + gain) \tag{9}$$

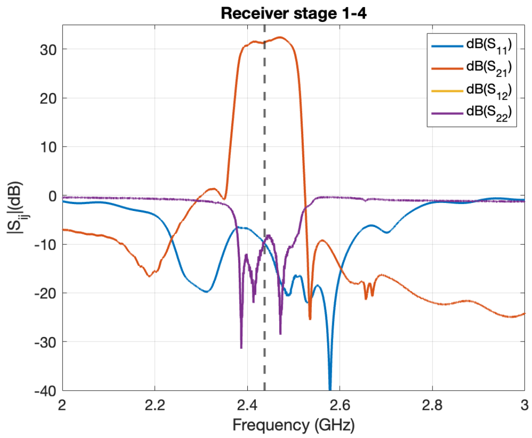

Fig. 16. First four stages s-parameters

Now we have the input power $P_{in} = -174dBm/Hz$,

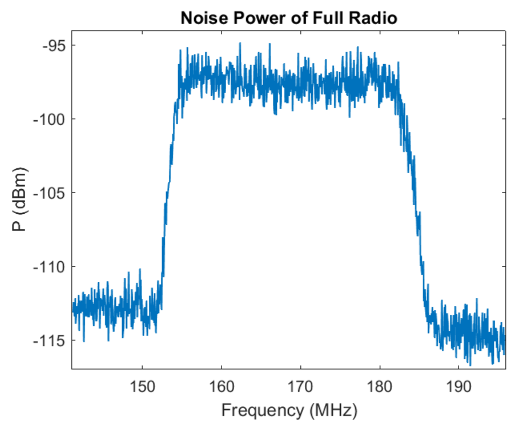

Fig. 17. Noise power

output power $P_{out} = -98dBm/Hz$ so the noise figure is around 38. The image reject table is shown in table VI. The Image rejection ratio is equal to $\frac{G_{RF}}{G_I M} = G_{RF_{dB}} - G_{IM dB}$

TABLE VI
IMAGE-REJECTION RATIO AT f_{IF}

Input Power[dBm]	Image Power[dBm]	Image Gain[dB]	Image Rejection Ratio
0	*-28.33*	*-28.33*	*66.33*

The cascade analysis of the overall gain, linearity and dynamic range are shown in the Figure 18. The dash line represent the theory value and the solid line represent the measured value. According to the cascade gain analysis, the expected gain predicted by each measured component is 47.35dB. However, the system overall, cascade gain we measured is 38 dB. One of the possible reason cause mismatch between the measurement and prediction is the cables loss. In this lab, we went to coaxial cable region twice and have three cables between the components, which will present relatively large loss in the overall cascade gain calculation.

$$SFDR = \frac{2}{3}(OPI3 - N_{output}) - SNR \qquad (10)$$

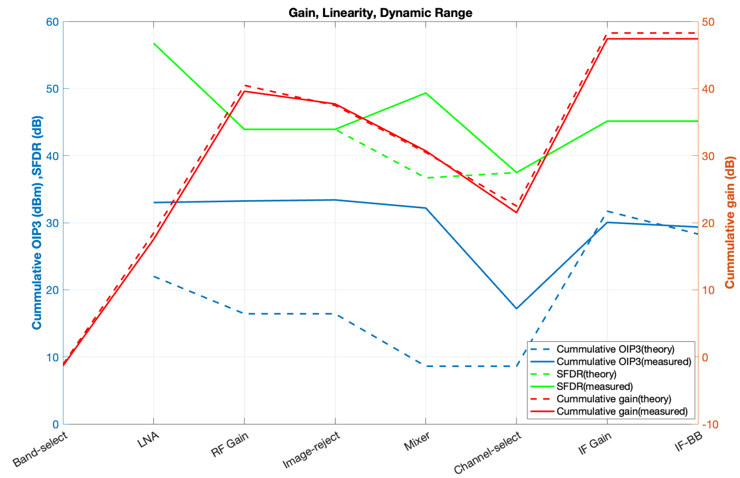

Fig. 18. Gain, linearity and dynamic range theory and measurement comparison

Assume we are to interface this receiver with a baseband analog-to-digital converter with 12- bits of resolution and a maximum voltage range of +/-1V. In this case, the

$$V_{LSB} = \frac{2V_p}{2^{12}} = 0.48828mV \qquad (11)$$

So the minimum detectable signal is

$$P_{LSB} = \frac{(\frac{V_{LSB}}{\sqrt{2}})^2}{50} = 2.4nW = -56.2dBm \qquad (12)$$

If the input power is -100 dBm, then $-100dBm + Gain_{total} = -62$ dBm. Since we want the SNR in the end is 10 dB, the $Gain_{IFBB} = 10 + 62 - 56.2 = 15.8dB$.

V. CONCLUSION

In this lab, we characterized a superheterodyne receiver which operates at 2.4 GHz and receives 20 MHz band WiFi signal. In our case with high NF LNA, the switching sequence will not help the overall performance. The receiver has the cascade gain of 38 dB and estimated noise figure 38dB.

REFERENCES

[1] https://www.electronics-notes.com/articles/radio/radio-receiver-selectivity/image-rejection-response.php

[2] https://www.analog.com/media/en/training-seminars/design-handbooks/Software-Defined-Radio-for-Engineers-2018/SDR4Engineers.pdf

[3] I. S. Jacobs and C. P. Bean, “Fine particles, thin films and exchange anisotropy,” in Magnetism, vol. III, G. T. Rado and H. Suhl, Eds. New York: Academic, 1963, pp. 271–350.