Design and Analysis of an LTE RF Uplink

ECE 770 (Radio and Wireless Systems) 2023 Final Project

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1. Uplink Transceiver Design

The first part of the project requires us to design a base-station receiver with the specifications listed in Table 1. The workspace that we are required to use consists of a receiver duplexer filter, low noise amplifier (LNA), a mixer, a voltage-controlled oscillator (VCO), and an intermediate frequency (IF) variable gain amplifier (VGA). The receiver duplexer filter is a 5th order Butterworth bandpass filter (BPF) with an insertion loss of 1 dB. For the VGA, the AD8367 device from Analog Devices was used. The task was to determine the noise figure (NF), gain, third order intercept input power (IIP_3) of the LNA and mixer, as was as the phase noise for an output power of -5 dBm and root-mean-square (RMS) error vector magnitude (EVM) of less than 5%. These design variable values are tabulated in Table 2 further in this section.

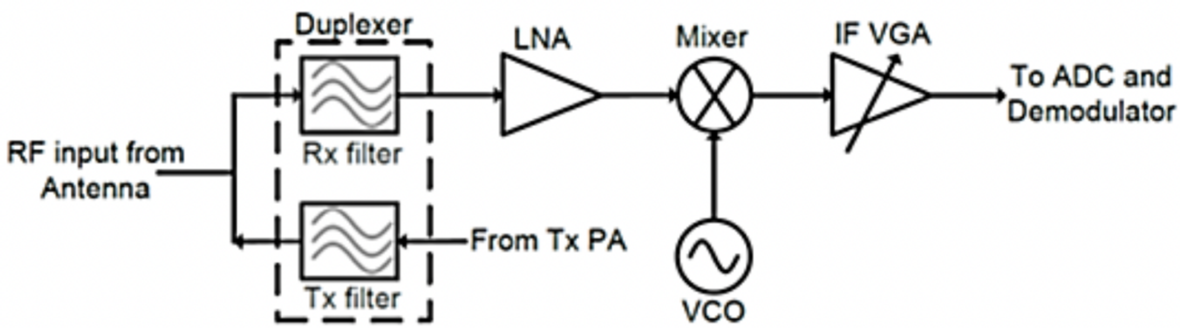

Figure 1: Block diagram of the receiver

Table 1: Base-station receiver specifications

Receiver Frequency	1.95 GHz
IF Frequency	100 MHz
Modulation BW	5 MHz
Modulation Type	64 QAM
Receiver Sensitivity	-70 dBm
EVM	< 5%
Receiver Dynamic Range	> 40 dB
Antenna Noise Temperature	290 K
IF Output Power	-5 dBm

To determine the necessary values in Table 2, the overall gain, NF, and IIP_3 were first found. The overall gain would differ for the maximum and minimum received powers, but the gain of the IF VGA would compensate for it by changing depending on the scenario. From the overall gain, the total NF was determined. Using the peak to average power (PAPR) and the 1 dB compression point of the receiver, the total IIP_3 was found. Afterwards, I did some tuning of the numbers on an Excel spreadsheet to determine the IIP_3 variables. The mixer NF and conversion gain/loss were set to the default values of 10 dB and 0 dB respectively that came with the workspace for simplification.

To determine the overall gain, NF, and IIP_3 of the receiver, I calculated the signal-to-noise ratio at the input of the receiver (SNR_{in}) and at the output of the receiver (SNR_{out}). The former was done by using the spec_power function to calculate the total power over a frequency band that was provided for us in the workspace. The power in our desired signal band and the power in another signal band that consisted of only noise were determined. Using the following equation provided in the pre-lab 3 manual

$$SNR + 1 = \frac{Signal + Noise}{Noise}$$

we can find the total SNR for the maximum input power and minimum input power for our dynamic range. Because the minimum detectable signal is -70 dBm and the receiver has a dynamic range of -40 dB, this would mean that the minimum and maximum input powers would be about -70 dBm and -30 dBm respectively.

$$DR[dB] = P_{in,max}[dBm] - S_{in_{MDS}}[dBm]$$
$$\Rightarrow P_{in,max}[dBm] = -30\ dBm$$

Using the spec_power function gave

$$P_{in,min} = -70.051\ dBm,$$
$$N_{in,min} = -106.812\ dBm$$

and

$$P_{in,max} = -30.051\ dBm,$$
$$N_{in,max} = -106.822\ dBm.$$

Assuming that the noise density is constant in both bands, the input SNR was calculated to be

$$SNR_{in,min} = 36.833,$$
$$SNR_{in,max} = 76.834.$$

To calculate the SNR_{out} value, we can use another equation that was provided in the pre-lab 3 manual

$$EVM[\%] = 10^{-\frac{SNR[dB]+3.7}{20}} \cdot 100.$$

According to the Help Session slide deck, we should design with for a margin of error, and recommended to use the following modified equation and rearranging for SNR, we get

$$EVM[\%] = 10^{-\frac{SNR[dB]}{20}} \cdot 100$$
$$\Rightarrow SNR_{out}[dB] = -20 \log \frac{EVM[\%]}{100}.$$

Thus, for a required EVM of 5%, we would need a SNR_{out} of

$$SNR_{out}[dB] = 26.021\ dB.$$

We can determine the total gain of the receiver for a desired output power of -5 dBm.

$$G_T[dB] = P_{out}[dBm] - P_{in}[dBm] = 65.051 dB$$
$$G_{T,max} = -5 - (-70) = 65\ dB$$
$$G_{T,min} = -5 - (-30) = 25\ dB$$

Calculating the total noise figure from the minimum detectable signal gives us

$$S_{in\_MDS}[dBm] = SNR_{out_{\mathrm{m}}}[dB] + NF[dB] + 10\log(kT_0B) + 30$$
$$NF[dB] = -70 - 26.021 - 10\log(1.3807 \times 10^{-23} \cdot 290 \cdot 5 \times 10^{6}) - 30$$
$$NF[dB] = 10.964\ dB$$

Therefore, we must design a receiver with a maximum gain of 65 dB, a minimum gain of 25 dB, and a maximum noise figure of 10.964 dB before the input signal is indistinguishable.

Adding a Complementary Cumulative Distribution Function (CCDF) sink to the schematic and enabling OutputPeakMean allows us to obtain the PAPR. The sample size was left how at 25,000 samples for a quick initial calculation. The PAPR obtained for the minimum input power was

$$PAPR[dB] = 6.464dB.$$

The PAPR tells us the peak input power. We require the peak power to be less than or equal to the 1 dB compression point to avoid nonlinear distortion. From the Help Session slide deck, we have

$$P_{in}[dBm] = IP_{1dB} - PAPR[dB]$$
$$\Rightarrow IP_{1dB} = -30 + 6.464 = -23.536\ dBm.$$

We know the relation between IIP_3 and IP_{1dB} is

$$IIP_3 = IP_{1dB} + 9.8\ dB$$
$$\Rightarrow IIP_{3,T} = -13.736\ dBm$$

After determining the overall gain, NF, and IIP_3, we can proceed to determine the design variables of the individual parameters. The gain and NF of the VCO can be determined by using the datasheet from Analog Devices and interpolating the data points in MATLAB using the function interp1. The noise figure was read to be about 7.3 dB at a temperature of 25°C, frequency of 100 MHz, and v_{GAIN} of 1V from Figure 6 of the datasheet. Using the interp1 code and the noise figures for the maximum gains listed under specifications, the gain was determined to be 43.4167 dB.

Before tuning the system to optimize its values, I wanted approximate values to work with as a starting point. To simplify the design and the amount of tuning required, I assumed that the conversion gain/loss of the mixer was very small, or approximately zero. Using this, the total gain, and the given attenuation of the Butterworth BPF, we can determine the gain of the LNA.

$$G_T[dB] = G_{1,BPF}[dB] + G_{2,LNA}[dB] + G_{3,Mixer}[dB] + G_{4,VGA}[dB]$$
$$\Rightarrow G_{2,LNA}[dB] = 65.051 - (-1) - 43.4167 = 22.634\ dB$$

All the gains have now been determined. The noise factor can be calculated using Friis' equation

$$F_T = F_{1,BPF} + \frac{F_{2,LNA} - 1}{G_{1,BPF}} + \frac{F_{3,Mixer} - 1}{G_{1,BPF}G_{2,LNA}} + \frac{F_{4,VGA} - 1}{G_{1,BPF}G_{2,LNA}G_{3,VGA}}.$$

The noise factor is high dependent on the order of the stages, as well as the gain of each stage. Since we know that the gain of the LNA is quite high, as it is about 183 (W/W), the numerator of the third and fourth terms will be approximately zero and will not affect the noise factor as much. Therefore, we can approximate the noise figure of the LNA to be

$$F_T = F_{1,BPF} + \frac{F_{2,LNA} - 1}{G_{1,BPF}}$$
$$\Rightarrow F_{2,LNA} = 8.573$$

where

$$F_{1,BPF} = 1\ dB = 1.259,$$
$$G_{1,BPF} = -1\ dB = 0.794.$$

The noise factor of the LNA is then at most

$$NF_{2,LNA} = 10 \log F_{2,LNA} = 10 \log(8.573) = 9.331.$$

Since the noise factor of the third and fourth stages does not contribute much to the total noise factor, I left the noise factor of the mixer to be 10 dB. It is also not needed in the calculations of the other design variables.

Lastly, the IIP_3 of each component was determined iteratively. The equation for the cascaded IIP_3 is

$$\frac{1}{IIP_{3,T}} = \frac{1}{IIP_{3,BPF}} + \frac{G_{1,BPF}}{IIP_{3,LNA}} + \frac{G_{1,BPF}G_{2,LNA}}{IIP_{3,Mixer}} + \frac{G_{1,BPF}G_{2,LNA}G_{3,Mixer}}{IIP_{3,VGA}}.$$

I assumed that the Butterworth BPF was a linear device, so that $IIP_{3,BPF} \to \infty$. From the Help Session slide deck, I learned that the first stage of the cascaded system would have an IIP_3 equal to the total overall IIP_3.

$$IIP_{3,LNA}[dBm] = IIP_{3,T}[dBm] = -13.736\ dBm$$
$$OIP_{3,LNA}[dBm] = IIP_{3,LNA}[dBm] + G_{LNA}[dB]$$
$$\Rightarrow OIP_{3,LNA}[dBm] = 8.898\ dBm$$

The power entering the mixer will be the average input power plus the gain. Adding the PAPR to obtain a backoff so that the peak power is less than or equal to the 1 dB compression point of the mixer and finding the IIP_3 gives

$$IIP_{3,mixer}[dBm] = 8.898\ dBm$$

Here, we assumed that the PAPR does not change throughout the system and remains constant. Recalling that the conversion gain/loss of the mixer is set to 0 dB, the OIP_3 of the mixer is then

$$OIP_{3,mixer}[dBm] = 8.898\ dBm.$$

Again, repeating the same steps as before: finding the average input, obtaining the peak power by adding the PAPR, setting the peak power equal to or less than the 1 dB compression point, and obtaining the IIP_3 gives

$$IIP_{3,VGA}[dBm] = 8.898\ dBm$$
$$OIP_{3,VGA}[dBm] = 52.3147\ dBm$$

Using the above starting values, the receiver workspace was tuned with the help of an Excel Spreadsheet to optimize the design variables to yield an output power of -5 dBm and an EVM of less than 5%. The Excel Spreadsheet and MATLAB code in the workspace were set up to calculate the related OIP_3 values based on the gain of the LNA and to determine the figure of merits (FOM). To determine the noise figure and the OIP_3 of the VGA, a MATLAB code was written to interpolate for a gain of 2.366 dB (the gain required when using the maximum input power and subtracting the starting value of the LNA gain from it).

A phase noise of -94 dBc/Hz was used since the minimum phase noise possible is -95 dBc/Hz.

After tuning, it was determined that the following values in Table 2 optimized the EVM and FOM requirements.

Table 2: Receiver design variables

Component	**Design variable**	**Value**	**Min**	**Max**
LNA	NF	4.45 dB	1 dB	n/a
	Gain	18.634 dB	0 dB	30 dB
	IIP_3	-13.736 dBm	n/a	n/a
Mixer	NF	8.45 dB	n/a	n/a
	Conversion gain/loss	3.9493 dB	n/a	n/a
	IIP_3	4.898 dBm	n/a	n/a
VCO	Phase noise (Δf=100kHz)	-94 dBc/Hz	-95 dBc/Hz	n/a
IF VGA	NF (lower)	7.3 dB	n/a	n/a
	NF (upper)	34.8 dB	n/a	n/a
	Gain (lower)	43.4167 dB	n/a	n/a
	Gain (upper)	4 dB	n/a	n/a
	IIP_3 (lower)	52.3157 dBm	n/a	n/a
	IIP_3 (upper)	34.8 dBm	n/a	n/a

We can confirm the FOMs for the LNA and the mixer blocks in the receiver are satisfied.

$$
\begin{aligned}
FOM_{LNA} &= \frac{G_{LNA}\left[\frac{W}{W}\right]\cdot IIP_{3,LNA}[W]\cdot f_0[GHz]}{F_{LNA}\left[\frac{W}{W}\right]-1} < 0.005\, W\cdot GHz \\
&= \frac{\left(10^{\frac{18.634}{10}}\right)\left(10^{\frac{-13.736-30}{10}}\right)(1.95)}{10^{\frac{4.45}{10}}-1} \\
&= 0.003229\, W\cdot GHz \\
&< 0.05\, W\cdot GHz
\end{aligned}
$$

$$
\begin{aligned}
FOM_{Mixer} &= \frac{G_C\left[\frac{W}{W}\right]\cdot IIP_3[W]\cdot f_0[GHz]}{F_{Mixer}\left[\frac{W}{W}\right]-1} < 0.004\, W\cdot GHz \\
&= \frac{\left(10^{\frac{3.9493}{10}}\right)\left(10^{\frac{4.898-30}{10}}\right)(1.95)}{10^{\frac{8.45}{10}}-1}
\end{aligned}
$$

$$
\begin{aligned}
&= 0.002426\, W \cdot GHz \\
&< 0.004\, W \cdot GHz
\end{aligned}
$$

$$
\begin{aligned}
FOM_{VCO} &= \left(\frac{f_0[Hz]}{\Delta f[Hz]}\right)^2 \frac{1}{L[Hz^{-1}]} < 1.2 \times 10^{18} Hz \\
&= \left(\frac{1.95 \times 10^9}{100 \times 10^3}\right)^2 \frac{1}{10^{-\frac{94}{10}}} \\
&= 9.551 \times 10^{17} Hz \\
&< 1.2 \times 10^{18}\, Hz
\end{aligned}
$$

The spectrum plots of the receiver input and output are shown in Figure 2 and Figure 3. The ACPR values for both the receiver input and output are tabulated in Table 4, while the PAPR values are tabulated in Table 5. For the PAPR table, the sample size of the simulation was increased from 25,000 to 250,000 samples to obtain a better and more consistent PAPR than when doing the initial calculations. The constellation plots of the receiver input and output are shown in Figure 4 and Figure 5.

Table 3: Receiver output EVM

Input Power (dBm)	Output Power (dBm)	EVM (%)
-70.051	-5.037	4.974
-30.051	-4.94	2.788

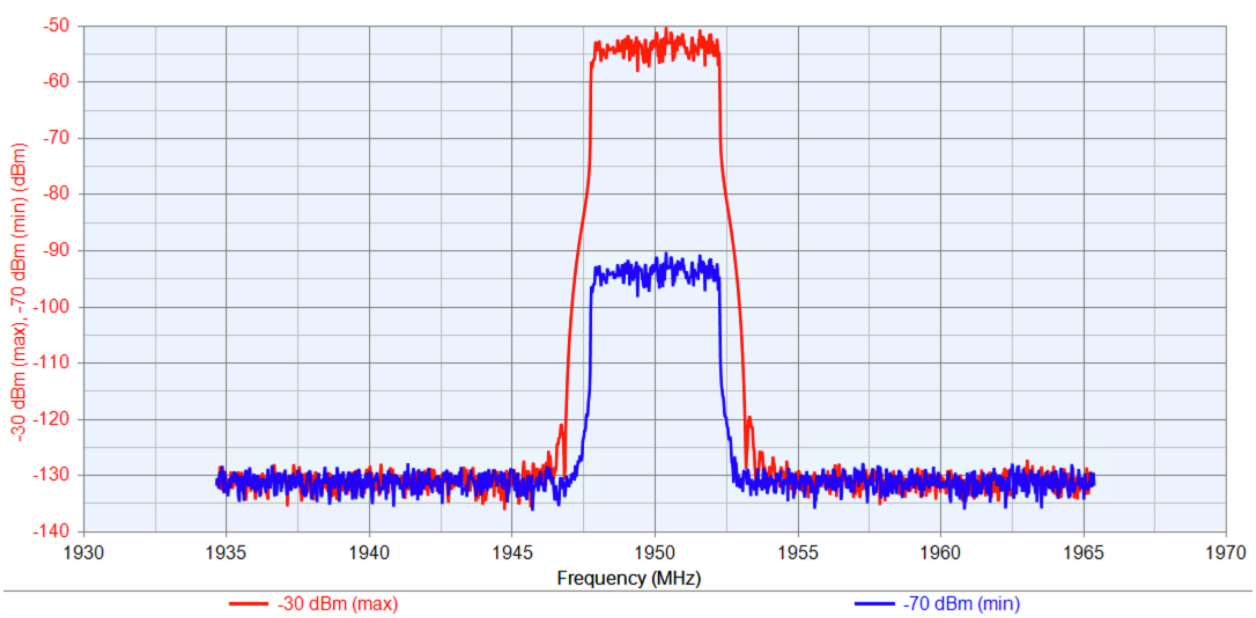

Figure 2: Receiver Input Spectrum Plot

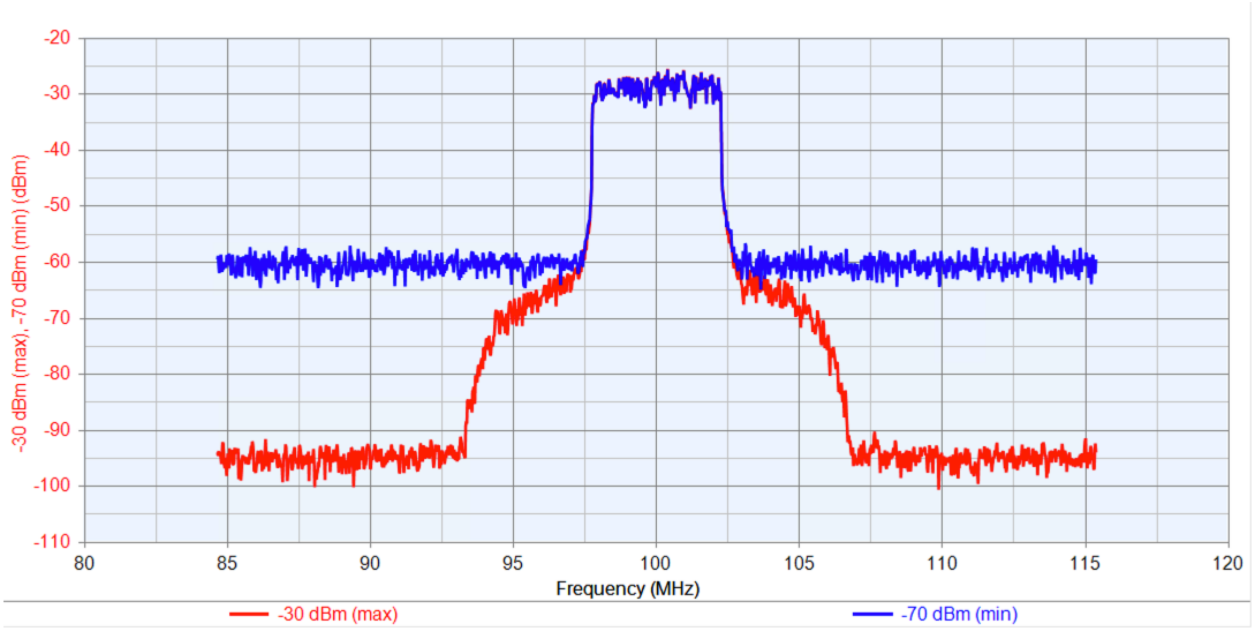

Figure 3: Receiver Output Spectrum Plot

Table 4: Adjacent Channel Power Ratio

Input Power		**Lower Channel (dB)**	**Upper Channel (dB)**	**Lower Channel (W/W)**	**Upper Channel (W/W)**	**ACPR (dB)**
-70 dBm	RxIn	-36.706	-37.002	213.5e-6	199.4e-6	-33.841
	RxOut	-31.296	-31.113	741.9e-9	773.9e-6	-28.194
-30 dBm	RxIn	-69.734	-68.26	106.3e-9	149.3e-9	-65.925
	RxOut	-39.852	-39.284	103.5e-6	117.9e-6	-36.549

Table 5: Peak to Average Power Ratio

Location	**Input Power (dBm)**	**Peak Power (dBm)**	**Mean Power (dBm)**	**PAPR (dB)**
Input	-70	-63.107	-70.004	6.897
	-30	-23.148	-30.009	6.86
Output	-70	2.05	-4.989	7.039
	-30	1.183	-4.911	6.094

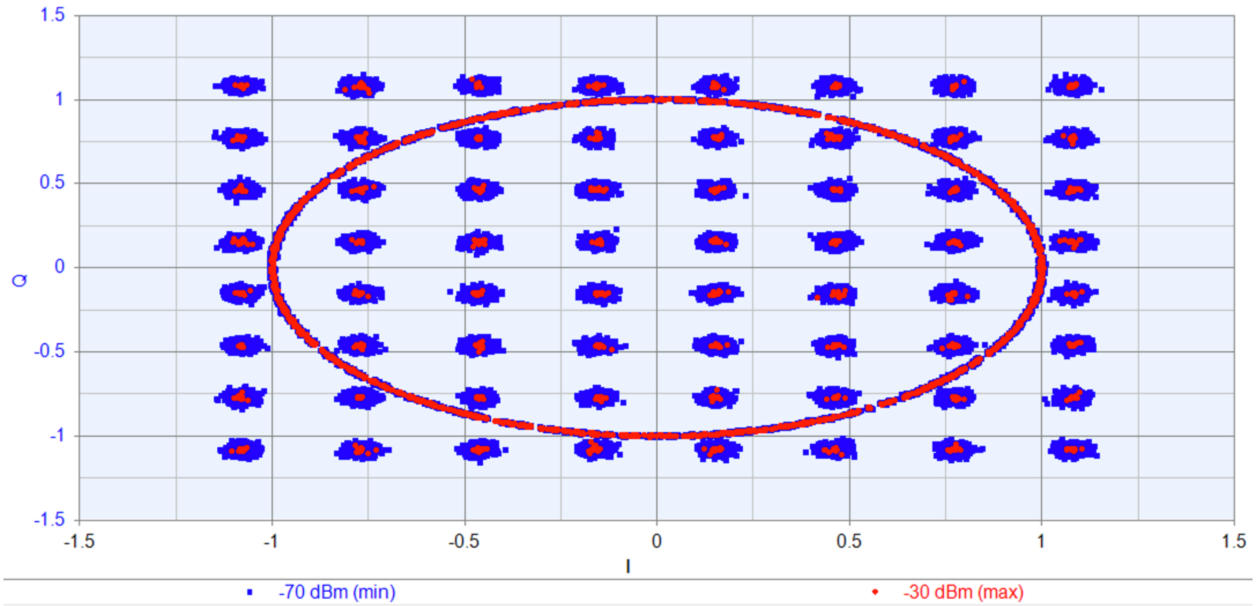

Figure 4: Receiver Input Constellation Plot

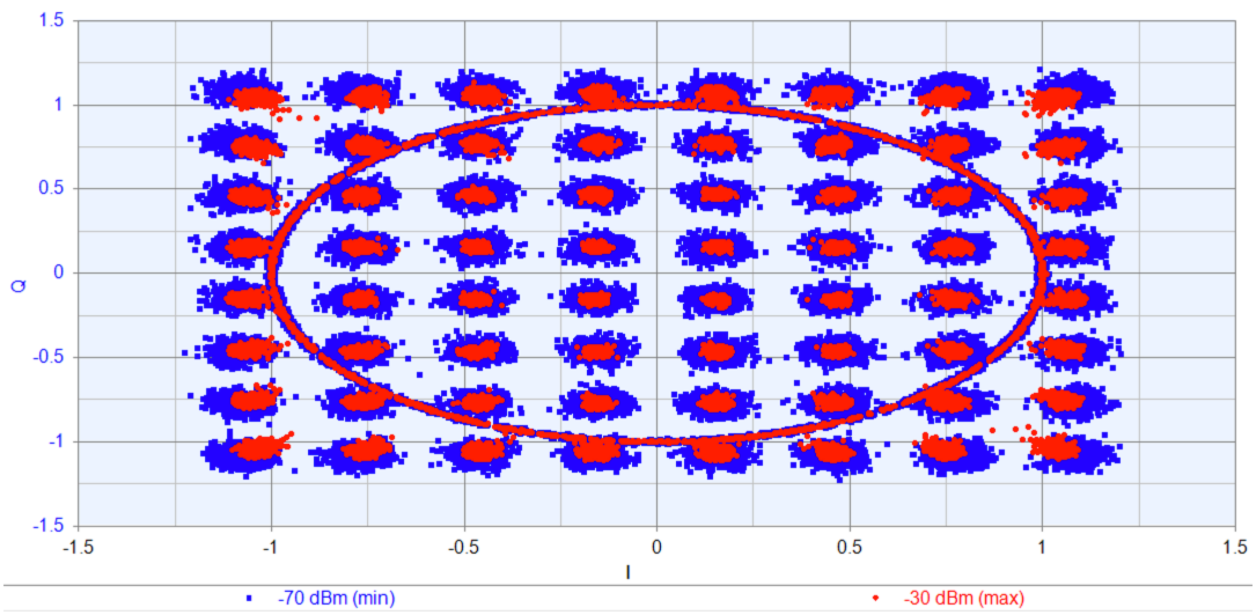

Figure 5: Receiver Output Constellation Plot

From the spectrum plots, we can see that there is out of band distortion occurring outside our band of interest at the receiver output. While from the constellation plots, we can see some in band distortion occurring at the receiver output. We can see the expected constellation plot for a 64-QAM signal, and a circle of points centred at the centre. The plots display this behaviour because we are using a LTE signal, which uses a 64 QAM modulation scheme as well as a reference signal (which is the circle).

From the ACPR table, the magnitude of the ACPR is greater for the -30 dBm signal than the -70 dBm signal, as seen in the ACPR plots. This makes sense because there is large differentiability between the middle band, which is the desired frequency band of interest, and the side bands. This differentiability is larger than the one seen in the -70 dBm signal. As for the PAPR table, the PAPR of the -70 dBm signal about 7 dB while the PAPR of the -30 dBm signal is about 6 dB. The mean power stayed about constant, but the peak power of the -70 dBm signal is a little larger than the peak power of the -30 dBm signal.

When simulating with an input power that is below or above the receiver's dynamic range, the ACPR and PAPR values change. Using a -10 dBm signal, we get an ACPR value of -13.438 dB, which means the middle band and the side band are much less differentiable than before. This may also suggest that more distortions are occurring out of band. The PAPR is much smaller as well, 0.148 dB, which indicates in band distortion. These results can be verified in the spectrum plot and constellation plot in Figure 6 and Figure 7. When simulating with a -90 dBm signal, the ACPR value is -4.046 dB and the PAPR is 8.427 dB. These results can be seen in Figure 8 Figure 9, where the graphs are extremely noisy and distorted in band. In conclusion, the receiver does not work well for input powers outside of its dynamic range and will interpret it as noise.

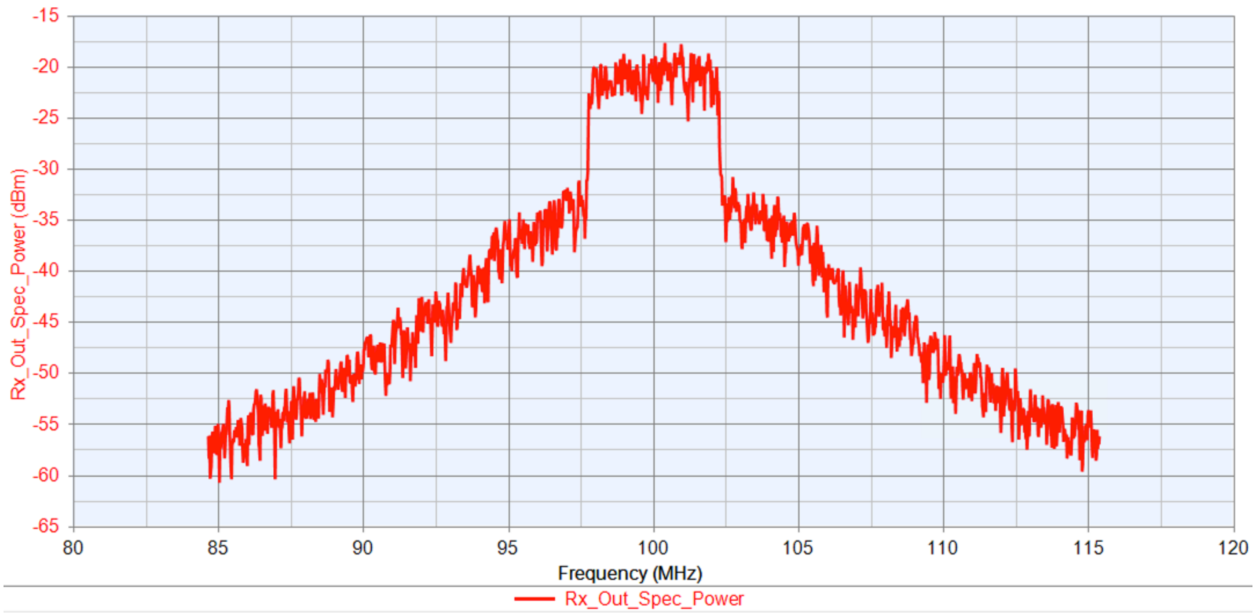

Figure 6: Spectrum plot at receiver output with 0 dBm input power

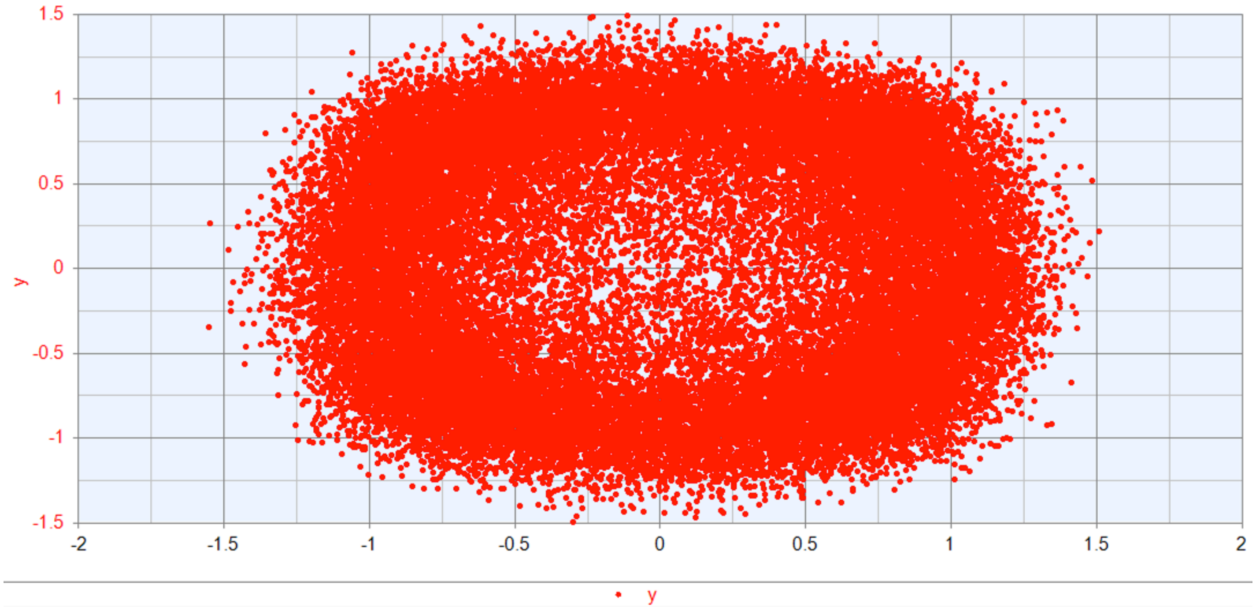

Figure 7: Constellation plot at receiver output with 0 dBm input power

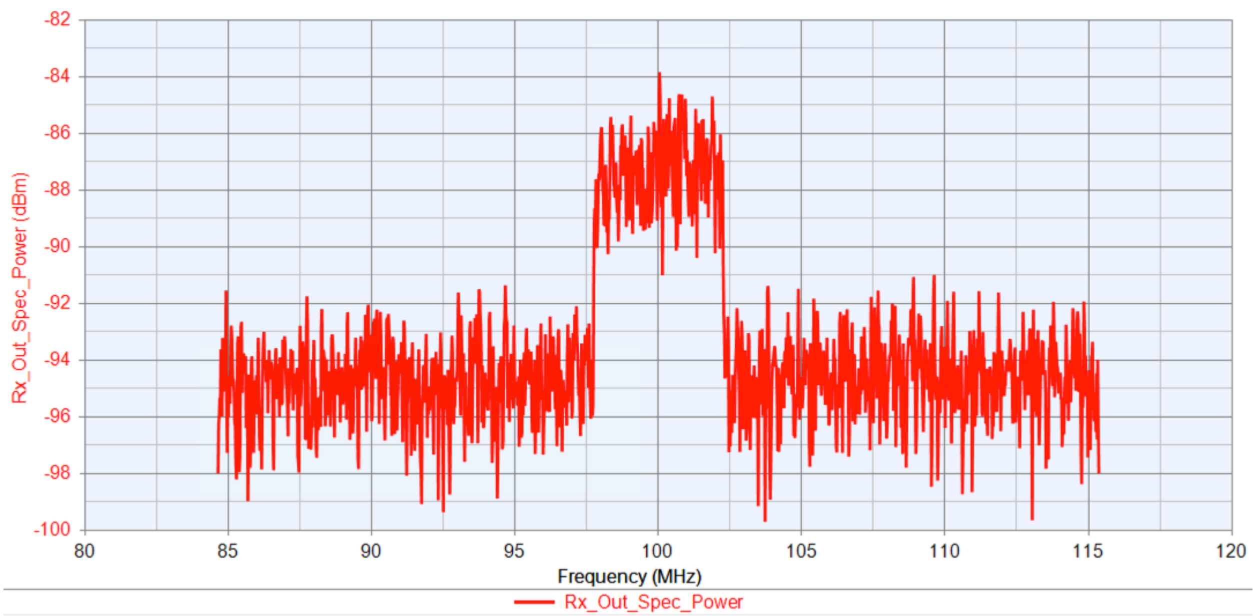

Figure 8: Spectrum plot at receiver output with -90 dBm input power

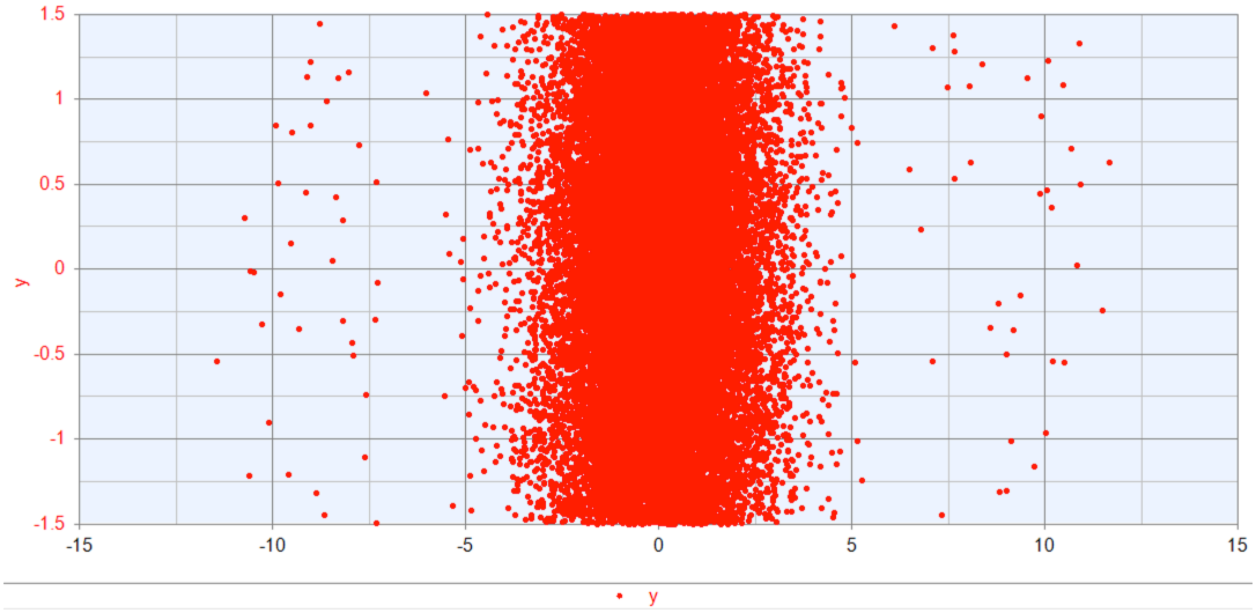

Figure 9: Constellation plot at receiver output with -90 dBm input power

2. Uplink Channel Modelling

This section required us to study the channel path loss across the uplink communication channel. This was done by enabling multipath fading with the following parameters:

Delay = {0 s, 0.11 µs, 0.19 µs, 0.41 µs},
Power = {0 dB, -9.7 dB, -19.2 dB, -22.8 dB},
RiceanFactor = {0}

To calculate the channel path loss, the following equation was used

$$Channel\ Path\ Loss = P_{out,Tx} - P_{in,Rx}$$

where the power outputted by the transmitter is the input of the channel and the power at the input of the receiver is the output of the channel. The results are recorded in Table 6.

Table 6: Uplink channel path loss with and without multipath fading

	No Multipath Fading		**Multipath Fading**	
Channel Path Loss	93.583 dB		91.059 dB	
	Transmitter Output	Receiver Input	Transmitter Output	Receiver Input
Power	-10.05 dBm	-103.633 dBm	-10.05 dBm	-101.109 dBm
EVM	1.629	1.629	1.629	1.649

The following parameters were used for the case without the multipath fading model:

Delay = {0},
Power = {0},
RiceanFactor = {0}.

Comparing the channel path loss with and without the multipath fading, we can see that the loss with the multipath fading enabled is slightly higher. The power at the receiver input with multipath fading is lower than without the fading. Lastly, the EVM stays the same in the case of multipath fading disabled, while the EVM with it on increases.

Multipath fading refers to the fact that the transmitted signals can reach the receiver in two or more paths. This is caused by interferences, reflections, diffraction, and scattering from other objects and could negatively impact the received signal and create ghosts from time delays. Therefore, the data comparing the multipath fading enabled and disabled makes sense, as the signal is degraded in comparison to the more ideal case. Overall, the transmitted power is heavily influenced by its line of sight.

3. Mobile Transmitter Design

This section requires us to design the mobile transmitter shown in Figure 10 with the specifications outlined in Table 7 to be used with the receiver from section 1 and the uplink channel from section 2. Some transmitter design variables such as the noise figure and the gain have already been given, but the OIP_3 of the power amplifier (PA), driver, and the upper and lower gains of the radiofrequency (RF) VGA must be determined. The transmitter duplexer filter is a 5^{th} order Butterworth BPF with a 1.5 dB insertion loss.

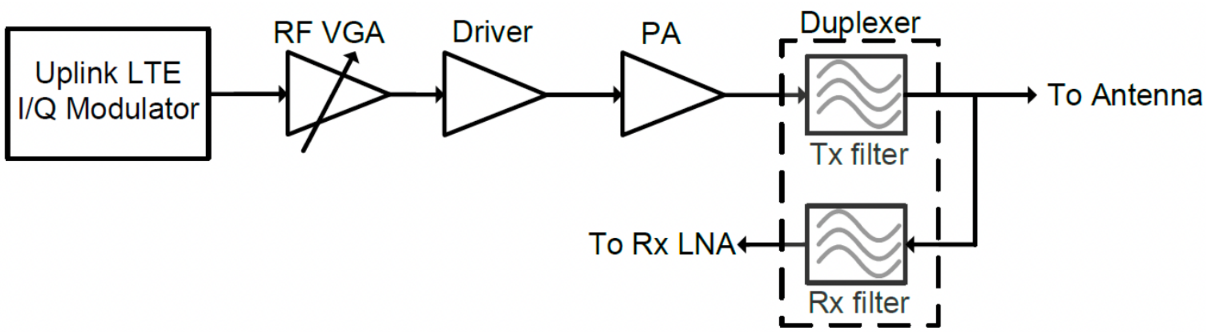

Figure 10: Block diagram of the transmitter

Table 7: Transmitter/channel/receiver link specifications

Transmitter Frequency	1.95 GHz
Modulation BW	5 MHz
Modulation Type	64 QAM
EVM (at receiver output)	<6%
Transmitter Power Control	+10 dB
Modulator Output Power	-10 dBm

According to the list of transmitter/channel/receiver link specifications, the modulator has an output power of -10 dBm. Furthermore, the project manual specifies that the LTE modulator has a 0.2 dB gain imbalance and a 0.5° phase imbalance. For the receiver to pick up the signal, the output power of the transmitter must be at least -70 dBm (the minimum detectable signal) by the time it reaches the input of the receiver. Thus, we can write an equation for the power at the output of the transmitter as

$$P_{out,Tx}[dBm] = CPL[dB] + P_{in\_MDS}[dBm]$$

where CPL is the channel path loss of the uplink channel determined in section 2. We can assume that the CPL of this design does not change to simplify the design and design for the minimum detectable signal. It is also possible to design for the maximum detectable signal to allow the receiver to still detect a signal in the case the channel path loss decreases. For this design, the minimum detectable signal was chosen. Therefore, we would require

$$P_{out,Tx}[dBm] = 91 + (-70) = 21\ dBm.$$

We know that the transmitter has a 10 dB power control, which determines the output range. The minimum power outputted by the transmitter must be 21 dBm, and its maximum power outputted must be 31 dBm. For this design, we are required to design for an EVM of less than 6%.

The total gain required in the system to obtain 21 dBm and 31 dBm at the output of the transmitter can be calculated based on the -10 dBm input signal. The upper and lower gains of the RF VGA can be determined by subtracting the gain of the PA and the driver and adding the insertion loss of the Butterworth BPF, which are both given, from the total gain.

$$G_{T,min} = 21 - (-10) = 31dB$$
$$G_{T,max} = 31 - (-10) = 41\ dB$$

$$G_{VGA,min} = 31 - 10 - 15 - (-1.5) = 7.5\ dB$$
$$G_{VGA,max} = 41 - 10 - 15 - (-1.5) = 17.5\ dB$$

The RF VGA has a gain between 7.5 and 17.5 dB, which we can fine tune in Excel and in SystemVue.

Similarly, to section 1, the strategy to determine the OIP_3 of the PA and the driver would be to determine the input power and add the gain to it, based on the previous stages. If we use the lower bound gain, the power at the input of the driver would be

$$P_{in,Driver}[dBm] = -10 + 7.5 = -2.5\ dBm.$$

Including the PAPR (7 dB from section 1) as back-off to avoid operating in the nonlinear regions and distortions, we'd have

$$P_{in,Driver} = -2.5 + 7 = 4.5\ dBm$$

which we would set to be equal to or less than the 1 dB compression point of the driver. The IIP_3 of the driver is then

$$IIP_{3,Driver}[dBm] = 3.5 + 9.8 = 14.3\ dBm$$
$$OIP_{3,Driver}[dBm] = 29.3\ dBm.$$

Repeating the procedure for the PA gives us

$$OIP_{3,PA}[dBm] = 39.3\ dBm.$$

On the other hand, using the max gain of the RF VGA would give us an OIP_3 of 39.3 dBm and 49.3 dBm for the driver and PA respectively. These values provided us the possible range the OIP_3 of the driver and PA. We can start with the upper bound on the OIP_3 and begin to tune the OIP_3 downwards. We can also keep in mind that to obtain the figure of merit for the PA, the OIP_3 would need to be about 48.1 dBm or less.

Using these values as a starting point, I tuned the system until I obtained the required transmitter output values for maximum power (about 31 dBm). Then I adjusted the IF VGA accordingly (with the interp1 function in MATLAB) for an input power of -60 dBm at the receiver input for a receiver output of -5 dBm. I changed the gain of the RF VGA for the minimum transmitter output power and used the IF VGA values for the minimum detectable signal found in section 1.

I used this strategy because it is better to work with a higher quality signal and scale it downwards rather than to amplify a noisy or distorted signal upwards. The values of the OIP_3 were then tuned downwards to give an EVM of less than 6% at the output of the receiver. The transmitter design variables are recorded in Table 8.

Table 8: Transmitter design variables

Component	Design variable	Value
PA	NF	12 dB
	Gain	10 dB
	OIP_3	48 dBm
Driver	NF	8 dB
	Gain	15 dB
	OIP_3	42 dBm
RF VGA	NF	8 dB
	Gain lower (dB)	7.5 dB
	Gain upper (dB)	17.5 dB
	OIP_3	35 dBm

We can confirm that the FOM of the driver and PA are satisfied with the receiver output power and EVM results recorded in Table 9.

$$FOM_{Amp} = G\left[\frac{W}{W}\right] \cdot OIP_3[W] \cdot f_0[GHz]$$
$$FOM_{PA} = 1548.940 < 1600\ W \cdot GHz$$
$$FOM_{Driver} = 489.818 < 600\ W \cdot GHz$$

Table 9: Transmitter/receiver output EVM

Transmitter Output Power (dBm)	**Receiver Input Power (dBm)**	**Receiver Output Power (dBm)**	**Transmitter Output EVM (dBm)**	**Receiver Input EVM (%)**	**Receiver Output EVM (%)**
20.887	-70.169	-5.173	1.658	3.124	5.439
30.299	-60.757	-5.096	3.718	3.827	4.297

The ACPR values at input and output of the transmitter and receiver are shown in Table 10. Examining the spectrum plots of the transmitter input and output, and receiver input (Figure 11, Figure 14) and output (Figure 12, Figure 15), we can see that the magnitude of the ACPR values correspond to the differentiability between the middle band and the side bands. The receiver output was plotted separately because it was in a different frequency band.

A CCDF sink was added to the input and output of the transmitter and the receiver to determine the mean power, peak power, and PAPR at the inputs and outputs of the transmitter and receiver (Table 11). The constellation plots at all 4 locations are plotted in Figure 13 (for 21 dBm, the minimum transmitter output power) and Figure 16 (for 31 dBm, the maximum transmitter output power.

Table 10: Transmitter/receiver/link ACPR

Transmitter Output Power (dBm)		Lower Channel (dB)	Upper Channel (dB)	Lower Channel (W/W)	Upper Channel (W/W)	ACPR (dB)
20.887	TxIn	-70.615	-68.872	86.79e-9	129.6e-9	-66.647
	TxOut	-56.459	-55.791	2.26e-6	2.63e-6	-53.102
	RxIn	-36.913	-36.571	203.5e-6	220.2e-4	-33.729
	RxOut	-31.156	-30.912	766.3e-6	810.6e-6	-28.022
30.299	TxIn	-70.615	-68.872	86.79e-9	129.6e-9	-66.647
	TxOut	-37.197	-36.604	190.7e-6	218.6e-6	-33.88
	RxIn	-37.843	-36.045	164.3e-6	248.6e-6	-33.841
	RxOut	-36.251	-34.932	237.1e-6	321.2e-6	-32.531

Table 11: Transmitter/receiver/link PAPR

Location	Output Power (dBm)	Peak Power (dBm)	Mean Power (dBm)	PAPR (dB)
Transmitter Input	20.887	-3.471	-10.028	6.557
	30.299	-3.471	-10.028	6.557
Transmitter Output	20.887	27.493	20.905	6.588
	30.299	36.079	30.315	5.764
Receiver Input	20.887	-63.432	-70.16	6.728
	30.299	-55.107	-60.755	5.648
Receiver Output	20.887	1.711	-5.139	6.85
	30.299	0.571	-5.08	5.651

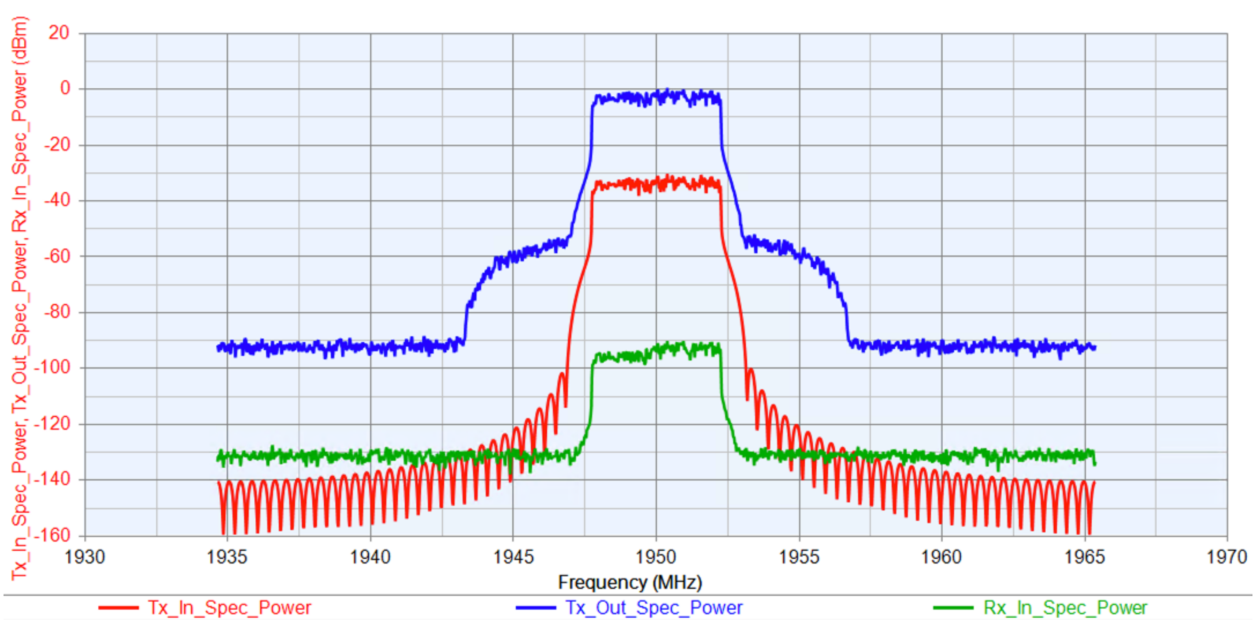

Figure 11: Spectrum plots at transmitter input/output and receiver input for 21 dBm transmitter output power

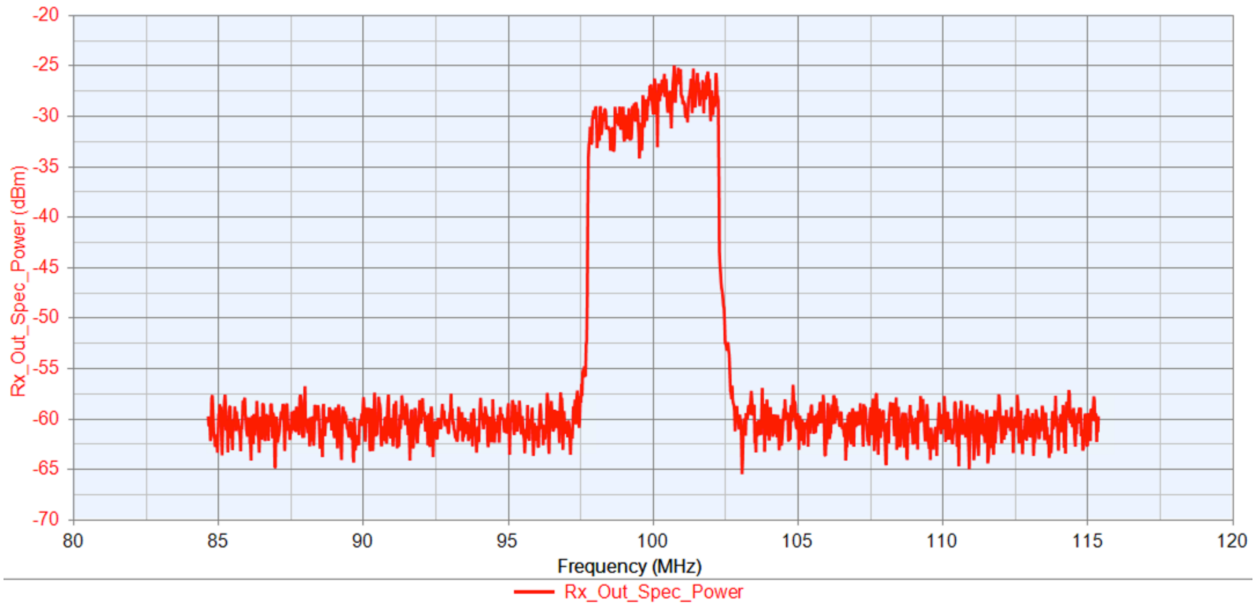

Figure 12: Spectrum plot at receiver output for 21 dBm transmitter output power

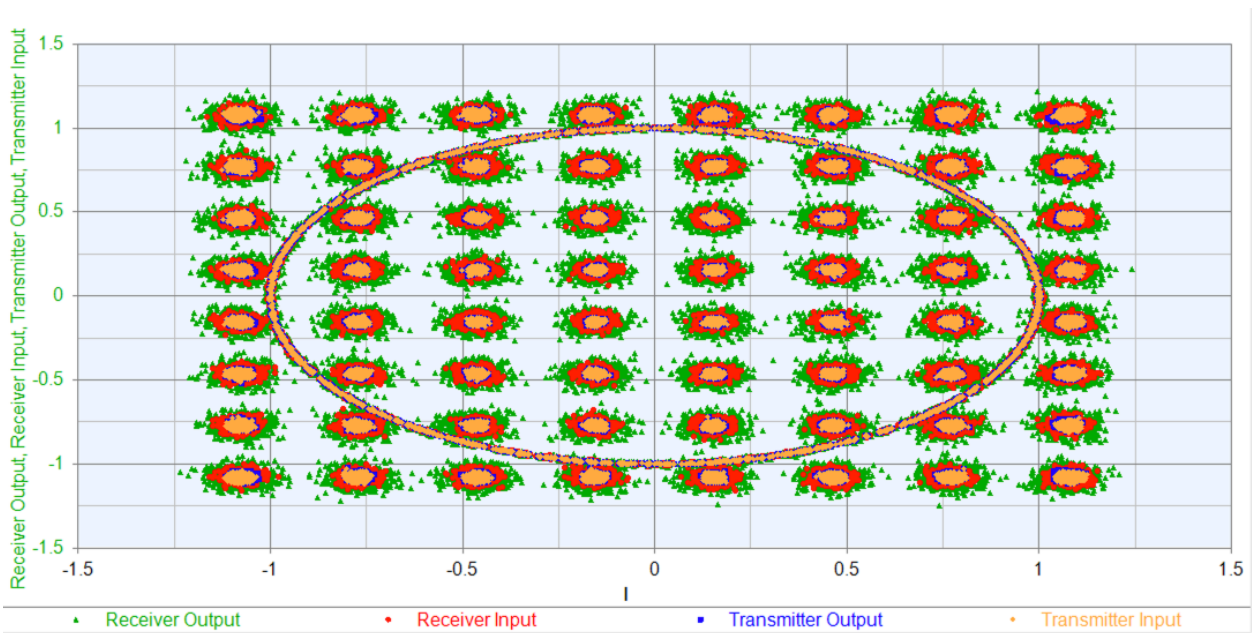

Figure 13: Constellation plots of transmitter/receiver inputs/outputs for 21 dBm transmitter output power

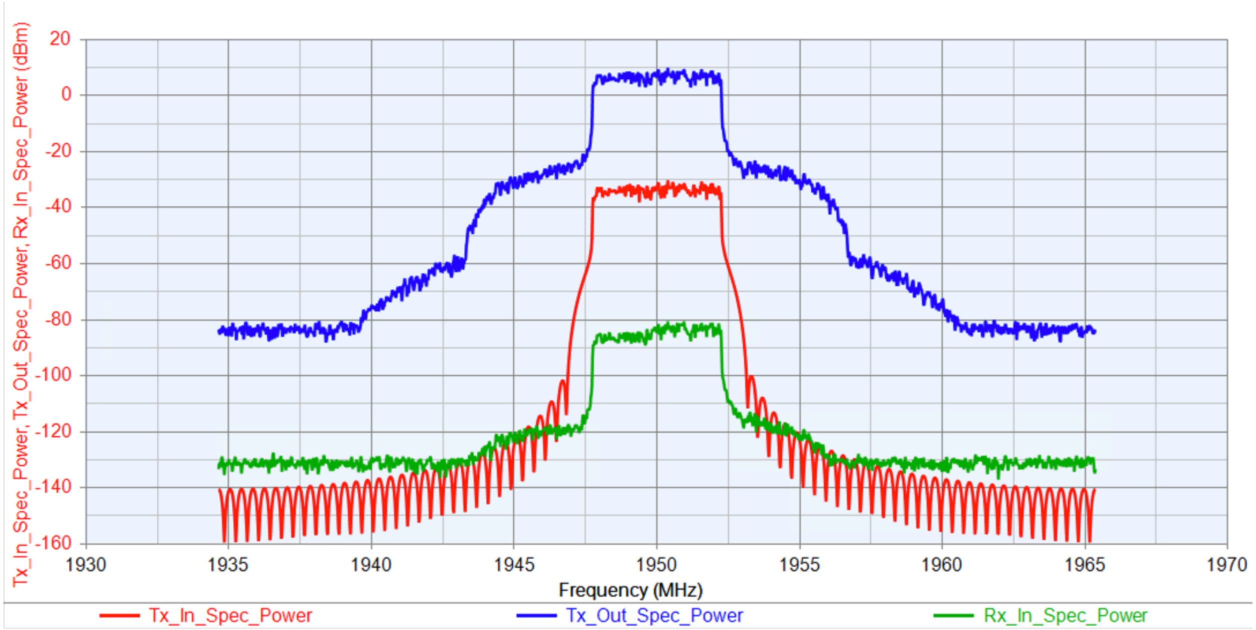

Figure 14: Spectrum plots at transmitter input/output and receiver input for 31 dBm transmitter output power

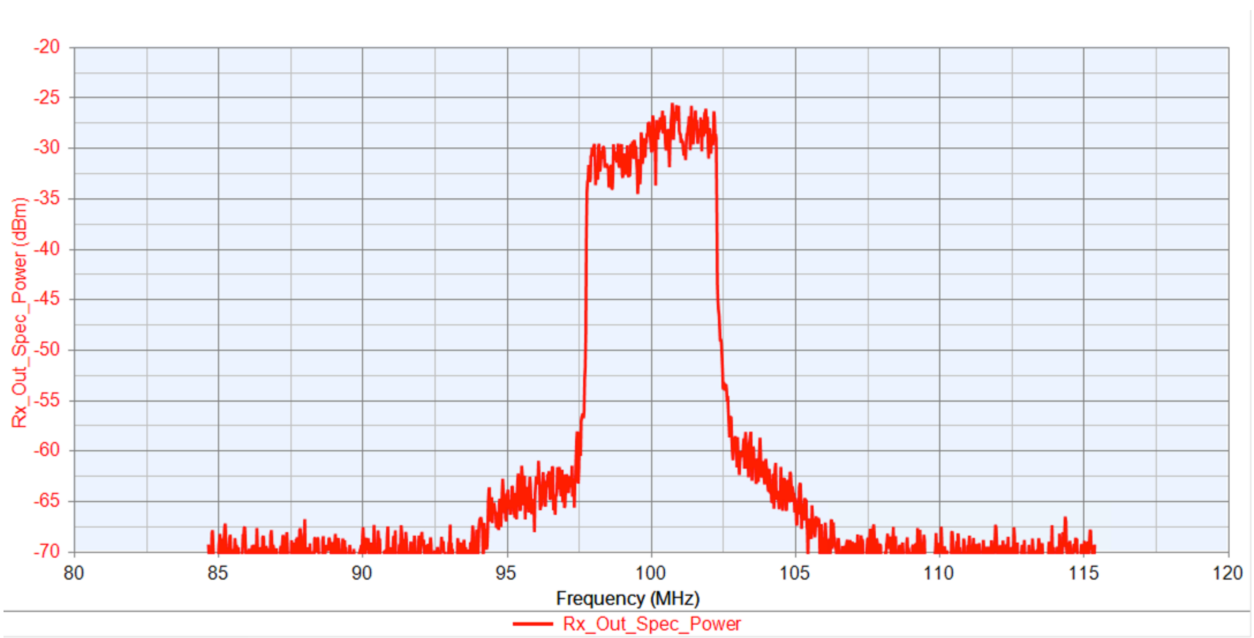

Figure 15: Spectrum plot at receiver output for 31 dBm transmitter output power

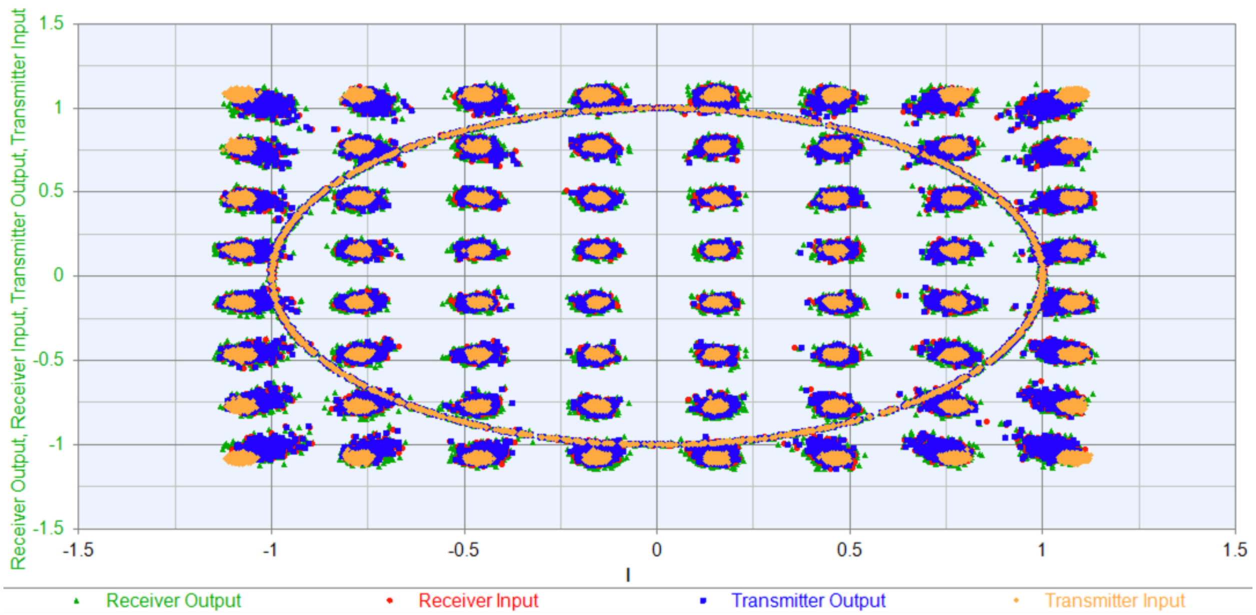

Figure 16: Constellation plots of transmitter/receiver inputs/outputs for 31 dBm transmitter output power

Examining the spectrum plots, we can see the very noticeable higher power at the transmitter output compared to the transmitter input and the receiver input. We also see some distortion occurring out of band due to nonlinearity. The out of band distortion is still visible in the plot of the receiver input and output graphs, particularly in the case of the maximum transmitted output signal. The mean powers are all as expected or similar to what has been calculated by hand. The ACPR values make sense as well because the magnitude of the ACPR is greater for the transmitters than it is for the receivers. However, the ACPR at the transmitter input is greater than the transmitter output, which can be argued due to the nonlinear distortions occurring in the side bands of the transmitter output signal. Examining the constellation plots, we can see that there is higher in band distortion occurring with the higher transmitted power, which is expected because the noise in the modulator is being amplified more than in the minimum transmitted output power. Recall that the modulator has a 0.2 dB gain imbalance and a 0.5° phase imbalance, which we can see more clearly in the constellation plots rather than the spectrum plots as expected from lab 2.

If the channel loss is increased by 20 dB, the transmitter and receiver link will no longer work. This is because the transmitter output power was designed such that the receiver would be able to detect the signal with a 91 dB channel path loss. Increasing the channel path loss would mean there would be a higher requirement on the transmitted output power. Furthermore, the transmitter power control only gives a 10 dBm range, therefore increasing the channel path loss by 20 dB would be greater than this control range. The transmitted output power would then be seen as noise. To simulate the behaviour, the propagation distance was increased from 100 m to 350 m to obtain approximately 111 dBm channel path loss. Examining Figure 17, Figure 18, and Figure 19, we can see there is a lot of in band distortion from the EVM plot and the receiver in and out powers are small and noisy.

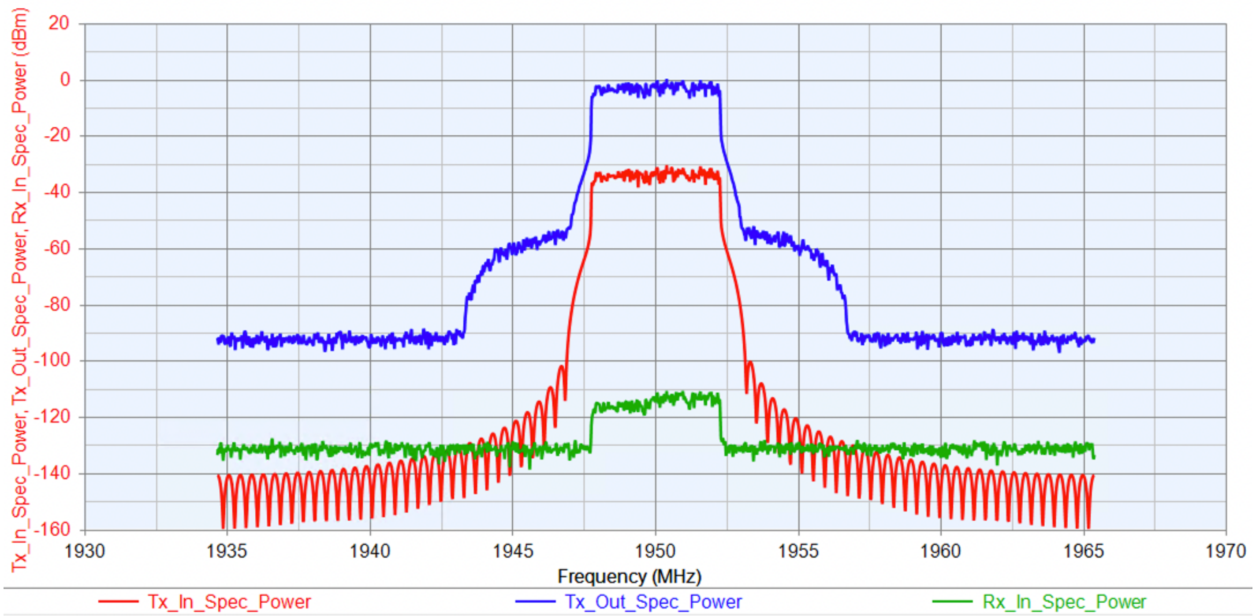

Figure 17: Spectrum plot at transmitter input/output and receiver input at 21 dBm transmitter output power and 111 dBm channel path loss

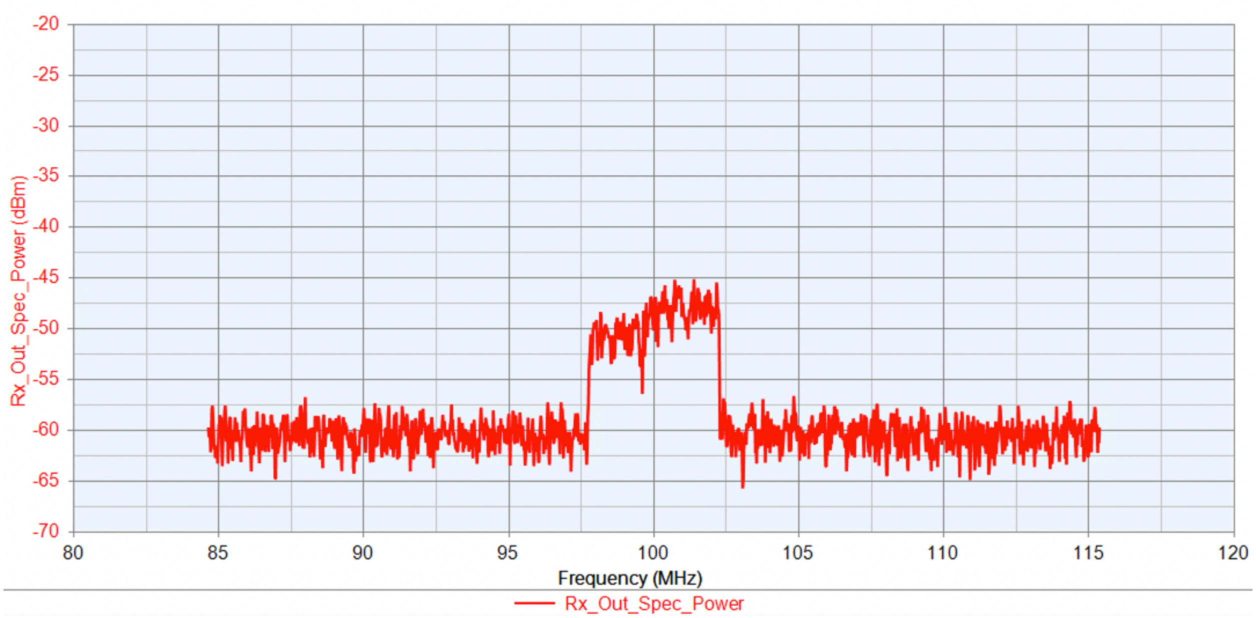

Figure 18: Spectrum plot at receiver output at 21 dBm transmitter output power and 111 dBm channel path loss

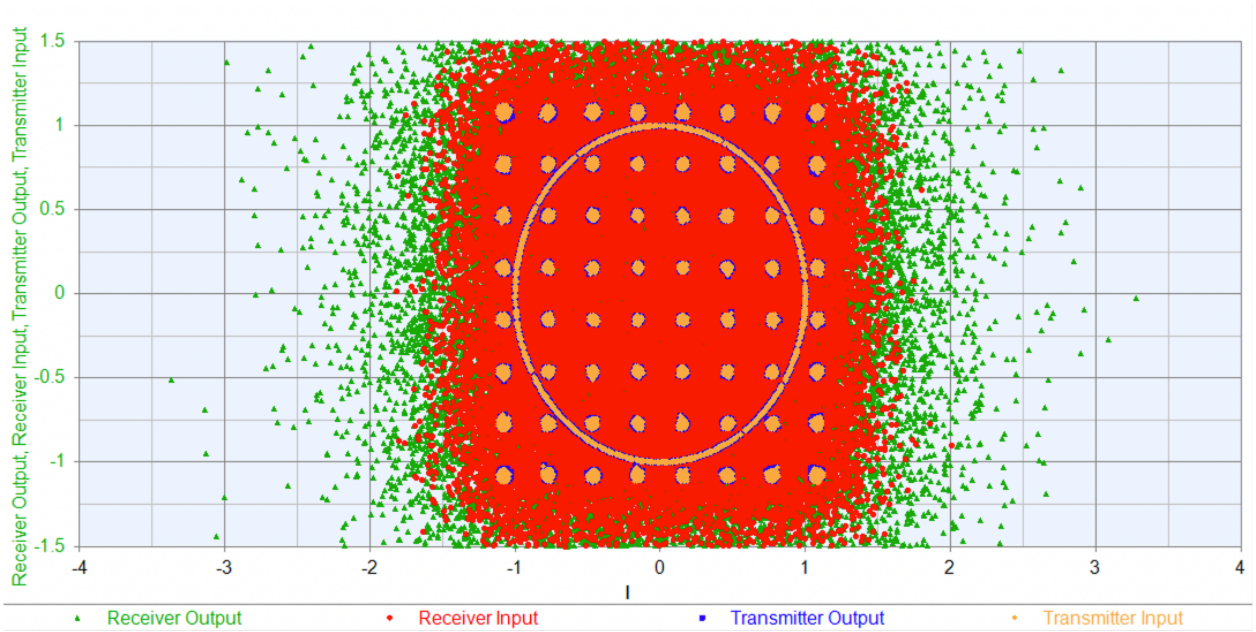

Figure 19: Constellation plots of transmitter and receiver input/output at 21 dBm transmitter output power and 111 dBm channel path loss

4. Summary

Receiver				
Component	Metric	Value	FOM	FOM max
LNA	NF (dB)	4.45	0.003229 W GHz	0.05 W GHz
	Gain (dB)	18.634		
	IIP_3 (dBm)	-13.736		
Mixer	NF (dB)	8.45	0.002426 W GHz	0.004 W GHz
	CG (dB)	3.9493		
	IIP_3 (dBm)	4.898		
VCO	100 kHz PN (dBc/Hz)	-94	9.551×10^{17} Hz	1.2×10^{18} Hz
IF VGA	NF lower (dB)	7.3		
	NF upper (dB)	34.8		
	Gain lower (dB)	43.4167		
	Gain upper (dB)	4		
	IIP_3 lower (dBm)	52.3157		
	IIP_3 upper (dBm)	34.8		
Rx Overall			7.482×10^{12}	
Transmitter				
Component	Metric	Value	FOM	FOM max
PA	NF (dB)	12	1548.940 W GHz	1600 W GHz
	Gain (dB)	10		
	OIP_3 (dBm)	48		
Driver	NF (dB)	8	489.818 W GHz	600 W GHz
	Gain (dB)	15		
	OIP_3 (dBm)	42		
RF VGA	NF (dB)	8		
	Gain lower (dB)	7.5		
	Gain upper (dB)	17.5		
	OIP_3 (dBm)	35		
Tx Overall			758698.693	
Transmitter and receiver Overall			5.676×10^{18}	

References

[1] Analog Devices, "500 MHz, Linear-in-dB VGA with AGC Detector," AD8367 Data Sheet, Sept. 2006.