S-26.3120 Radio Engineering, laboratory course

Lab 2: GSM Base Station Receiver

Final report

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Group 3:

Sampo Salo	79543L
Tuomas Leinonen	84695P
Huy Nguyen	411330

Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330

1 Introduction

TODO: Huy and Sampo (1st paragraph: general intro, 2nd: the measuremets, 3rd: structure of this report)

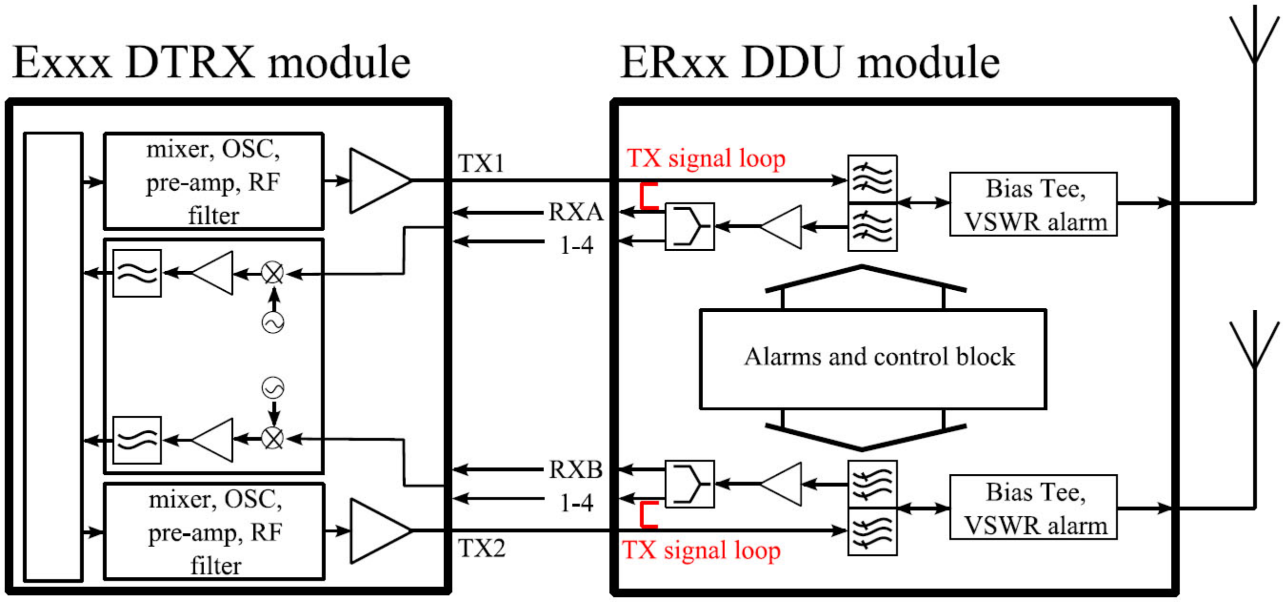


Figure 1: Receiver under study.

Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330

2 Measurement steps

In this section, used measurement configurations are presented for each measurement task. Measurements in question may be divided into two distinct categories: power measurements with a spectrum analyzer (SA) and two-port transmission measurements (S_{21}) with a vector network analyzer (VNA). There were no significant differences between the planned setups and those used in the actual measurements. The following measuremeent specific subsections will elaborate.

2.1 1 dB compression point

To measure 1 dB compression point of a device, one needs a (manually) sweepable signal source and power detector. These may come separately or be incorporated in a single device. In both cases, the DDU module is connected the in between the source and the detector. We used both approaches, and made two measurements with equal power levels.

For separate signal generation and detection, we used *Rohde & Schwarz SML03* signal generator (SG) and *HP 8596E* spectrum analyzer.The measurement setup is shown in Figures 2 and 3. The setup employing *Rohde & Schwarz ZVL* VNA is shown in Figures 4 and 5. All equipment came precalibrated. In both measurements, the A-half of the base station was used.

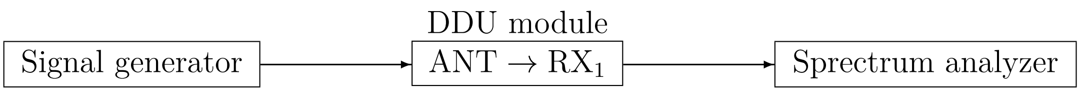


Figure 2: Measurement setup used in the first measurement task.

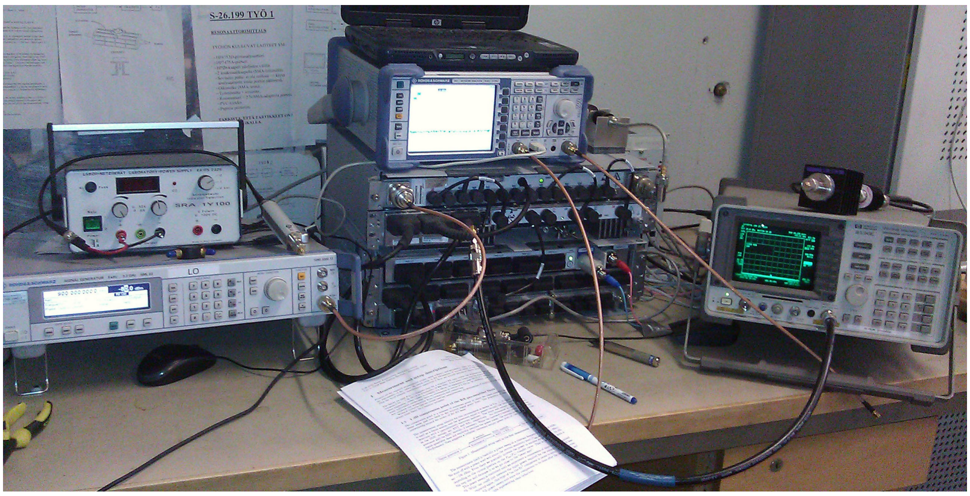


Figure 3: Using a signal generator and spectrum analyzer to characterize the DDU module.

Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330

VNA (Port 1) → [DDU module: ANT $\rightarrow$ RX$_1$] → [$L = 20$ dB: Attenuator] → VNA (Port 2)

Figure 4: VNA measurements connections

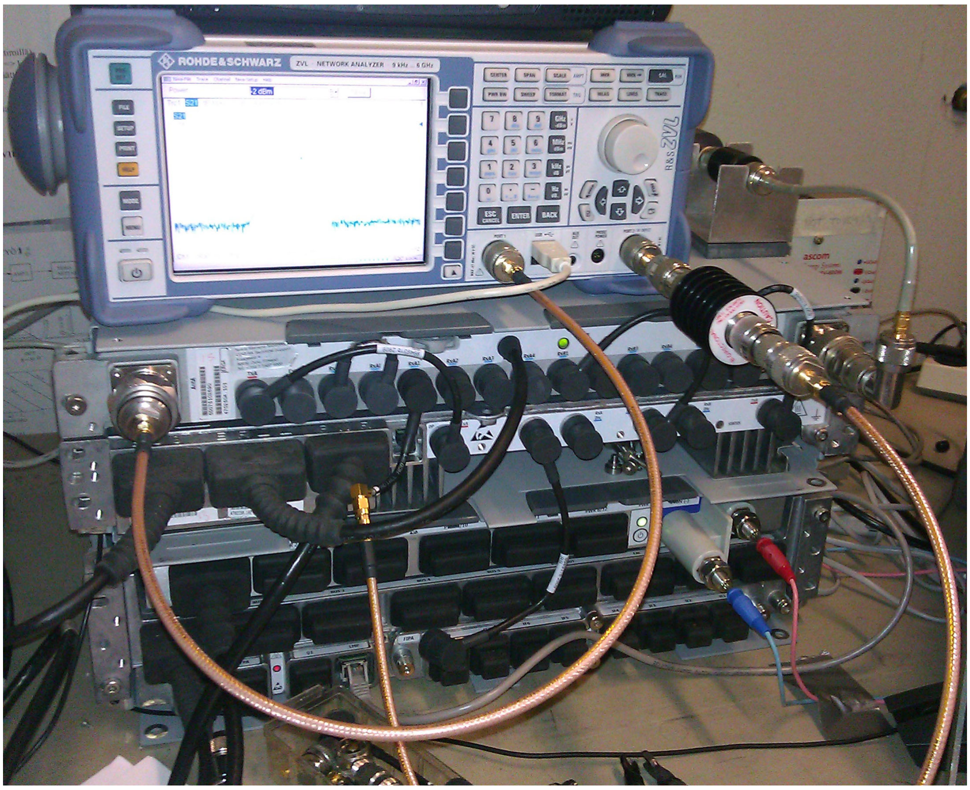


Figure 5: Measuring the DDU module with the VNA.

In essence, the measurement was a power sweep at a constant frequency of $f = 900$ MHz; mapping detected power or gain against used input power. This raw data was later postprocessed using Matlab.

We started with a source power of -40 dBm; a power level well below the 1 dB compression point. The power was gradually used in steps of first 10 dB, then 5 dB and finally 1 dB, until clear compression was observed. Compression may be seen in the lower than expected values of detected power (SG & SA), or equivalently as lower gain (VNA).

Since we were measuring a GSM receiver, we used settings found in the GSM specification for the spectrum analyzer with the expeception of smaller averaging factor. They settings were as follows: an averaging factor of 100, zero span and 30 kHz video and resolution bandwidths. Input attenuation of the spectrum analyzer was increased from 10 dB all the way to 30 dB as we moved onto higher powers.

The two cables and attenuators were measured separately using a VNA. For the VNA, the measurement settings throughout this lab were as follows: 1601 points over a frequency range

Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330

of 800 . . . 1000 MHz, a measurement bandwidth of 10 kHz and averaging over 200 samples with a transmit power of −20 dBm.

For more accurate and/or reliable SA measurements, even a larger attenuation factor could have been used to avoid the small, yet possible, compression in the SA. One chould have also not trusted the quality of the SG as much than we did. The whole power sweep should have also been recorded without the DDU-module in between. Also, there was some oversigth in making the connections as can be seen in Fig. 5. As its only an attenuator in a transmission measurement, there is most likely no great an impact on the results as such. Nevertheless, it begs to question connector repeatability.

2.2 Frequency response

The frequency response was already measured in the first labs using a VNA. Thus we didn't need to measure the gain in these labs, as we used the results from the first labs. While the measurement procedure was given in the final report of the first labs, it is repeated here for completeness.

The measurement was carried out using a *Rohde & Schwarz ZVL* VNA, calibrated by the assistant prior to our arrival. The calibration settings were as follows: full two-port calibration with 1577 points within the 850 . . . 1000 MHz band, −20 dBm reference power, and an averaging factor of 100. The reference plane was located at the non-VNA end of the used cables.

The actual measurement included connecting the VNA to the B-half of the DDU module in order to obtain the values of $|S_{12}|$ over a set frequency range. In terms of physical connections, this would mean the following: VNA (Port 2) → DDU module (in: $\mathrm{ANT_B}$, out: $\mathrm{RX_{B1}}$) → VNA (Port 1). The raw data was stored onto a USB-memory as `*.s1p` files for post processing using Matlab.

The theoretical noise bandwidth B_n for a device may be found as using the following formula

$$B_\mathrm{n} = \frac{1}{G_\mathrm{T,\,max}} \int_0^\infty G_\mathrm{T}(f)\,df, \tag{1}$$

where $G_\mathrm{T}(f)$ is the transducer gain at frequency f. In practice, one may only approximate this using numerical integration over the finite measurement bandwidth. Such approximation is bound to yield slightly optimistic values. Another possibility is to approximate the noise bandwidth as the 3 dB bandwidth, and applying a compensation factor based on the transition bands. Results obtained using both methods are shown and compared later in the text.

2.3 Noise temperature

In the noise measurement task, we used the Y-coefficient method. The setup is shown in Figures 6 and 7. A DC-voltage source is connected to a noise diode which is in turn connected by an SMA-cable to the $\mathrm{ANT_A}$-input in the pre-amplifier block (A-half). It would have been better to use desired direct connection, but that was not possible due to missing adapters.

The signal is led then from the $\mathrm{RX_{A1}}$ output to the spectrum analyzer. We made another measurement where an amplifier was placed in between, as the noise power from the cold noise source might've been masked by the SA noise. The parameters of the amplifier, made by Minicircuits, were as follows: $B = 15 \ldots 3000$ MHz, $G = 19$ dB, $T = 463$ K, $F = 4.1$ dB and $V_{\mathrm{CC}} = +15$ V.

$$\underset{V_{\mathrm{DC}}}{\overset{0/28\text{ V}}{\boxed{V_{\mathrm{DC}}}}} \longrightarrow \boxed{\text{Noise diode}} \longrightarrow \overset{\text{DDU module}}{\boxed{\text{ANT} \to \text{RX}_1}} \longrightarrow \overbrace{\boxed{\text{LNA}} \longrightarrow}^{\text{with and without}} \boxed{\text{Sprectrum analyzer}}$$

Figure 6: Noise temperature measurement setup

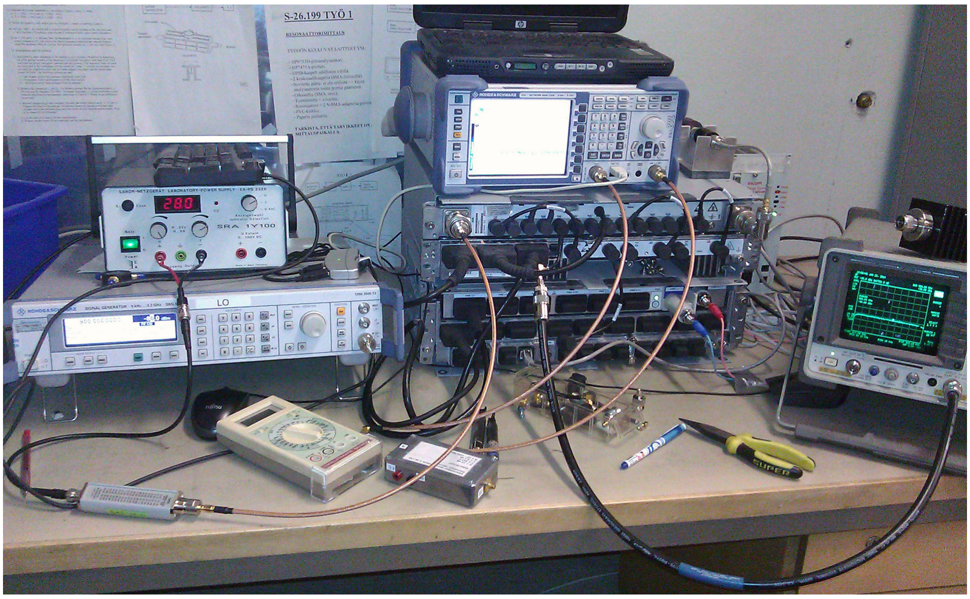


Figure 7: Noise temperature measurement setup without the additional amplifier.

The measurements themselves were carried out measuring two power levels required in the Y-parameter; when the DC-voltage is off/shorted ("cold") and on ("hot"). We used *HP 346B* noise diode ($ENR = 21.48$ dB when $f = 1.00$ GHz) with a control voltage of 28 $\mathrm{V_{DC}}$ taken from a laboratory-grade voltage source.

As for the SA settings, the settings we as follows: 0 dB input attenuation, zero span, 10 kHz resolution and video bandwidths and an averaging over 100 sweeps. For more accurate results, more time should have spent on this measurement. This would have allowed us to use smaller bandwidths and larger averaging factor.

The noise temperature, or equivalently noise factor/figure, may be found using the following formulae. Y-coefficient is given as

$$Y = \frac{P_{\mathrm{H}}}{P_{\mathrm{C}}} = \frac{T_{\mathrm{H}} + T_{\mathrm{e}}}{T_{\mathrm{C}} + T_{\mathrm{e}}} \quad \Rightarrow \quad T_{\mathrm{e}} = \frac{T_{\mathrm{H}} + YT_{\mathrm{C}}}{Y - 1}, \tag{2}$$

where $P_{\mathrm{H/C}}$ is the measured power for hot and cold loads at equivalent noise temperatures $T_{\mathrm{H/C}}$, and T_{e} is the noise temperature of the measured device. $T_{\mathrm{C}} = 295$ K is the physical temperature of the noise diode, and T_{H} may be solved from the definition of *ENR*:

$$ENR = 10\lg\left(\frac{T_{\mathrm{H}}}{T_{\mathrm{C}}} - 1\right) \quad \Rightarrow \quad T_{\mathrm{H}} = T_{\mathrm{C}}\left(10^{\frac{ENR}{10}} + 1\right). \tag{3}$$

Obtained noise temperature T_{e} may be converted to noise factor F or figure F_{dB} using the following relationship:

$$F_{\mathrm{dB}} = 10\lg\left(F\right)\ \mathrm{dB} = 10\lg\left(1 + \frac{T_{\mathrm{e}}}{T_0}\right)\ \mathrm{dB}. \tag{4}$$

One should notice that the T_{e} given by Eq. 2 is actually the noise temperature of the whole chain. This chain is a cascaded system, consisting of a SMA-cable, the DDU module, the optional amplifier, another SMA-cable and the spectrum analyzer, in this order. The contribution of the DDU module may be determined by reverse calculating Friis' noise equation:

$$F_{\mathrm{total}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots \quad \Leftrightarrow \quad T_{\mathrm{total}} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots, \tag{5}$$

where G_i is the available power gain of the ith stage. Similar indexing is also used for both of the noise quantities F and T. This simplified formula assumes equal noise bandwidths between the stages.

The parameters required by the formula may be obtained through calculation, or are provided by the manufacturer. For example the noise contribution of the cables can be obtained from their attenuation L and physical temperature T_{phys} through formula $F = (L-1)T_{\mathrm{phys}}$. The amplifier specifications were given already in the text. For the spectrum analyzer, $F =?$ dB.

2.4 Sensitivity

In the sensitivity measurement, we're measured the minimum input power at the $\mathrm{ANT_A}$-input that results in a reliably detectable signal above the noise floor in the ouput of the DDU module. In GSM-systems, a signal with $SNR > 10$ dB is detected with an acceptable *BER*. For this, a measurement setup identical to the one used in the first task may be used. The setup used there is shown in Figures 2 and 3. An attenuator may be used between the signal generator and the DDU module.

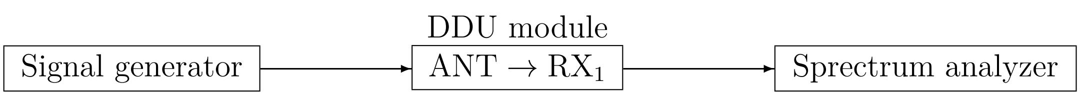


Figure 8: Measurement setup used in the sensitivity measurement.

The first step was to measure the noise floor at 900 MHz without any signal we're hoping to detect. That is, the RF power was switched off at the generator. Then we turned on an input signal that's some dBs below the reported sensitivity level of −112.5 dBm. We gradually

Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330

increased the power until the signal-to-noise ratio was no less than the 10 dB required by the standard. The corresponding power level was recorded.

One could have also measure the power required to beat the noise just barely, and add the SNR later on. This approach is, however, less accurate and more painful. It also assumes $P_{\text{out}}(P_{\text{in}})$ relationship to be ideal in the range.

Since it's a GSM system, we use the measurement settings as they are defined in the standard with the exception of averaging. The standard 500-sweep averaging was used in when measuring the noise floow, but 100 was used when RF power was enabled. The final settings were as follows: an averaging factor of 500/100, zero span and 30 kHz video and resolution bandwidths. The input attenuator was disabled in the SA settings.

Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330

3 Results

TODO: Huy and Sampo (general results and intro to more specific results)

3.1 1 dB compression point

1 dB compression point arises from the nonlinearities of the receiver LNA. At high enough powers, the gain of the LNA for a certain frequency starts to drop with increasing power. The input power at which the LNA gain is compressed by 1 dB was measured using two different measurement setups.

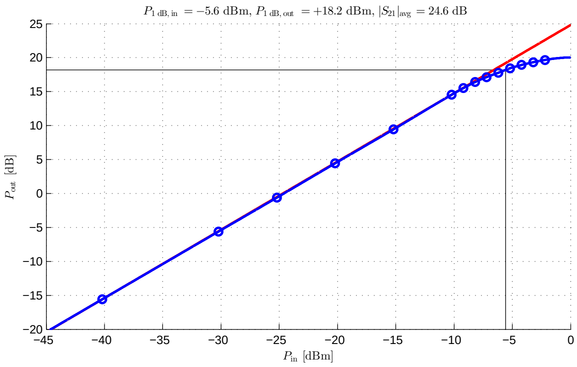
The first measurement setup consisted of a signal generator and a spectrum analyser. With this setup, a single frequency of 900 MHz sent from the signal generator was measured with the spectrum analyser. The signal generator power was increased gradually, until a -1 dB drop in the gain was achieved. The measurement results for the first setup are presented in figures 9 a (original data), c, and e, for which the attenuations of the cables are taken into account.

The second measurement setup consisted of a vector network analyser. The VNA was measuring the S21 –parameter as the input power was increased gradually, until a -1 dB drop was visible in the S21 -parameter. An attenuator was required in between the base station and VNA port 2 to protect the device from the amplified signal. The measurement results for the second setup are presented in figures 9 b, d (original data), and f. The vector network analyser was calibrated before use.

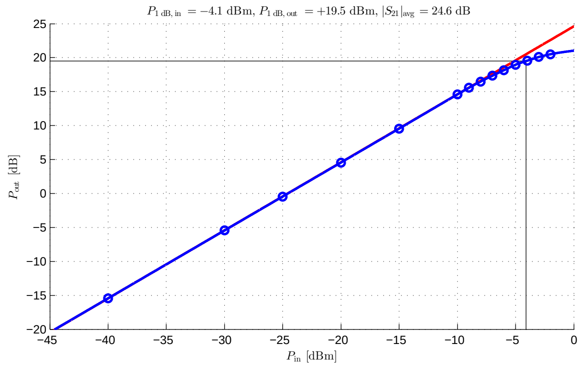
All the subfigures are plotted from one data set for spectrum analyser setup and VNA setup each. The data sets are post processed using Matlab. Both data sets are visualised with three different figures, so that it is easier to compare the two measurements. The extrapolated sections are plotted only for eye candy, and they should not be taken into account when analysing the RX block performance.

The compression point derived from the spectrum analyser measurement is $CP_a = -5.6$ dBm. Figure 9 c shows how the measured gain fluctuates around the average gain of 24.6 dB, however, with a small amplitude. The compression point derived from the VNA measurement is $CP_b = -4.1$ dBm without gain fluctuation.

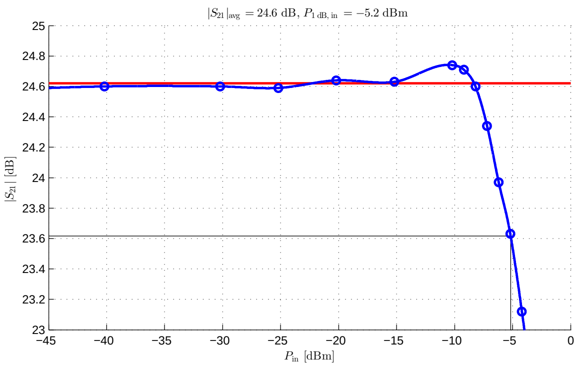
Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330



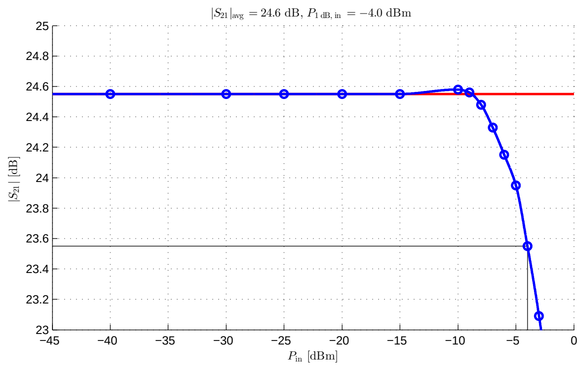
(a) $P_{\mathrm{out}}(P_{\mathrm{in}})$ using SG & SA



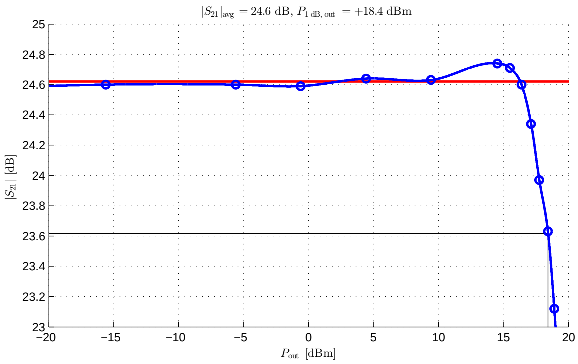
(b) $P_{\mathrm{out}}(P_{\mathrm{in}})$ using VNA



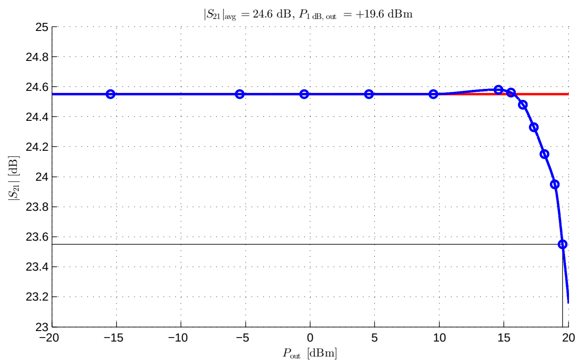
(c) $G(P_{\mathrm{in}})$ using SG & SA



(d) $G(P_{\mathrm{in}})$ using VNA



(e) $G(P_{\mathrm{out}})$ using SG & SA



(f) $G(P_{\mathrm{out}})$ using VNA

Figure 9: Results from the 1 dB compression point measurements. Ideal behaviour is shown with red straights, measuremets with blue markers and Matlab `'pchip'` interpolant in blue.

Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330

3.2 Frequency response

The $|S_{12}|$ response of the DDU module (B-half) within the 850 . . . 1000 MHz band is shown in the following figure (Fig. 10). In the figure, in addition to the actual response (in black), additional information is shown. GSM RX and TX band limits (in red), both 3 dB (in blue) and noise (in green) bandwidth of the pre-amp block are also visualized. Visualization of the noise bandwidth is somewhat questionable as it's a purely theoretical concept, but is nevertheless shown for scale.

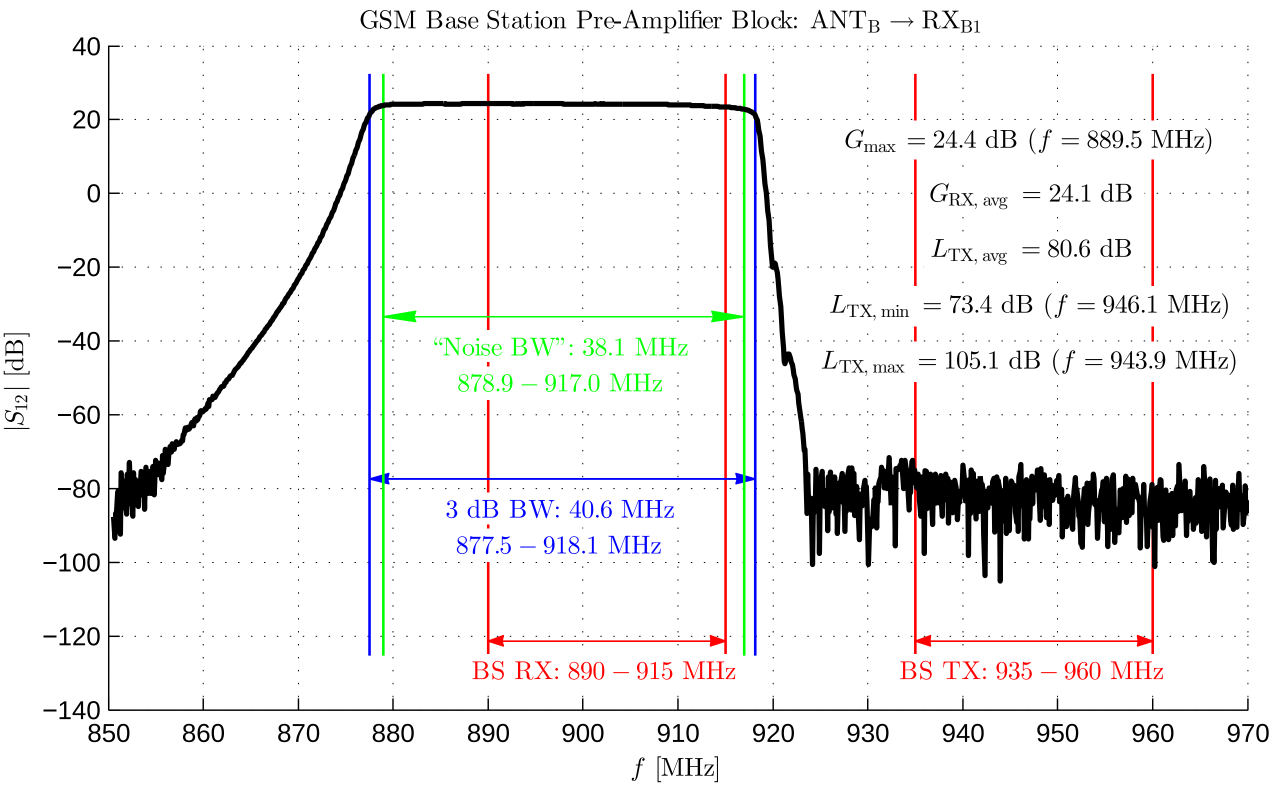


Figure 10: S_{12} of the DDU module as was measured in the first labs.

The noise bandwidth shown, obtained from Eq. 1 is less than the actual band since we cannot use infinite frequency range. Frequency range of 850 . . . 1000 MHz with $G_{T,\,max} = |S_{12}|_{max} =$ 24.4 dB was used instead. The obtained value (38.1 MHz) is roughly 6 % shy of the 3 dB bandwidth (40.6 MHz), as one might expect. The 3 dB bandwidth may thus be used to avoid being overly optimistic.

In the graphical approximation method we need to investigate the effect of frequency roll-off speed. From Fig. 10 the transition bands are approx. 30 MHz (3.4 %) and 5 MHz (0.55 %) for lower and upper bands, respectively. During this transition, the S_12 drops roughly 100 dB from +20 dB to −80 dB. This corresponds to a slope of 3.3 dB/MHz (29 dB/%) and −20 dB/MHz (−180 dB/%), respectively. The effect of such steep slopes are neglectable, and thus the 3 dB bandwidth may be used as the noise bandwidth.

Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330

3.3 Noise Temperature

The noise of the RX block was measured two times using the Y coefficient method, the noise diode working as a hot load and a short circuit as a cold load in room temperature (295 K). The first measurement was done without an extra LNA in between the spectrum analyser and the RX block, and the second measurement was done with the LNA in between.

The noise temperature of the hot load can be calculated from the ENR using equation (3), which gives $T_H = 41773.4$ K. The equivalent noise temperature of the chain in between the diode and the spectrum analyser can be calculated from this temperature, room temperature and the measured noise powers. This is done using the Y coefficient method, which gives $T_{\text{total,w}} = 164.9$ K and $T_{\text{total,wo}} = 654.9$ K for the setups with and without the LNA, respectively.

The previous noise temperature values still include the noise powers from the other parts of the chain, eg. cables and the LNA. The RX block noise temperature can be obtained from equation 5, which is for example for the LNA setup

$$T_{\text{DDU,w}} = T_{\text{cable1}} + \frac{T_{\text{DDU}}}{L_{\text{cable1}}} + \frac{T_{\text{LNA}}}{L_{\text{cable,1}} G_{\text{DDU}}} + \frac{T_{\text{cable,2}}}{L_{\text{cable}} G_{\text{DDU}} G_{\text{LNA}}}, \tag{6}$$

and yields $T_{\text{DDU,w}} = 142.4$ K and $T_{\text{DDU,wo}} = 612.1$ K for the setups with and without the LNA, respectively.

Table 1: Results from the noise measurement.

LNA?	P_{C} [dBm]	P_{H} [dBm]	T_{total} [K]	T_{DDU} [K]	F_{DDU} [dB]
No	−107.3	−90.8	654.9	612.1	4.9
Yes	−91.3	−71.7	164.3	142.4	1.7

The final results are presented in table (1). The results differ significantly. The noise temperature calculated from the LNA setup is clearly closer to reality, than the result obtained without the LNA. The reason for this is that the noise power is situated lower than the actual noise floor of the spectrum analyser. The LNA is required in the setup to rise the noise level high enough, so that it can be defined more precisely with the spectrum analyser.

3.4 Sensitivity

TODO: Huy and Sampo

3.5 Dynamic range

TODO: Huy and Sampo (refer to 1dB comp and sens.)

Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330

Table 2: Results from the sensitivity measurement. The noise floor was measured to be at −101.98 dBm.

SNR [dB]	P_{transmit} [dBm]
7.5	−118.0
10	−115.6
12.5	−113.0

4 Error estimates

TODO: Huy and Sampo (make additions, corrections, change the style to avoid excess repetition etc.)

In this section, error estimates for the two types of measurements are presented. The values presented here are only rough estimates based on literature (with more or less general cases) and their soundness in this case is somewhat questionable. In this section, we do not take human errors (see previous section) into account. It is just stated that systematic errors arising from the cables and connections are possible in measurement all measurements. Thus they are valid only for "correct" measurements, and are more of the "provided for completeness" nature. Probabilities are not given due to the nature/basis of the estimation.

4.1 Spectrum analyzer

Each of the components inside the spectrum analyzer contributes to the total uncertainty, depending for example on the signal frequencies, amplitudes, and measurement settings. The Agilent (former HP, manufacturer of the used SA) has made available a document that specifies the different error sources, giving also rough estimates for some spectrum analyzers. According to the document [3], the error estimates vary broadly among different analyzer models, giving worst case uncertainties exceeding ±6 dB. On the other hand, the document gives also representative values of amplitude uncertainties, which in our case yields about ±1 dB.

The second error source for the spectrum analyzer is the power marker reading. In each of the tasks, the spectrum analyzer was set to average 500 measurement points, which should average out most of the random errors. However, reading the power marker in the screen, there was a noticeable fluctuation in the shown power value. Based on the experience obtained during the measurements, the power marker error is estimated to be approximately ±0.5 dB.

In conclusion, the error estimates that can be taken into account numerically are the manufacturers representative value of approx. ±1 dB, and the power marker fluctuation of roughly ±0.5 dB. These uncorrelated errors may be summed to achieve the total uncertainty of the SA measurements of approx. ±1.5 dB.

There is also the question of calibrating the spectrum analyzer properly with the time interval defined by the manufacturer. Agilent suggests to have the spectrum analyzer calibrated thoroughly once in a year, and quick-calibrated if there are changes operating environment [4]. If the spectrum analyzer used in the measurements is not calibrated correctly, it is possible that

Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330

the measurements are not reliable. In this case, the calibration is the most important error source, and the device should be calibrated correctly before estimating any other errors.

4.2 Vector network analyzer

For the VNA, different error sources and ways to cope with them are listed in the lecture slides discussing VNA measurements. The different sources are noise, cabling/connector repeatability, directivity, isolation, mismatch and environment induced drift.

Noise and cabling/connector repeatability are random errors, which can be averaged out. In our case, only the noise was averaged, since we did not touch the cabling. Systematic errors arising directivity, isolation, and mismatch in this task were for the most part neglected with a calibration. Before conducting measurements, the VNA is always calibrated using a standard calibration module. The calibration moves the reference planes to the connectors of the test cables, and somewhat cancels the systematic errors from the connectors and cables used in a specific measurement. Finally, the environment induced drift is not relevant, since the measurement was done inside a short time interval.

Rohde & Schwarz provides specifications that describe the measurement uncertainty of the VNA in question in different frequency bands. For transmission measurements in the frequency range of 50 MHz to 3 GHz, accuracy for signal powers of $-50 \ldots 0$ dB is better than 0.2 dB (0.3 dB for powers of $-50 \ldots -70$ dB) with 0 dBm transmit power. [5] The reader should note that these ranges was exceeded from both ends during the measurements (the measurement power range was roughly $-100 \ldots +4$ dBm).

In conclusion, two things are assumed. First, calibration is assumed to cancel the systematic errors arising from cables and connectors. Second, random errors are cancelled with averaging. The manufacturer provides error estimates for the device itself, giving an error estimate of under 0.3 dB that is mostly applicable in our case. The topics discussed in the last paragraph of the last subsection apply here to some extent to here as well.

4.3 Noise diode

See lecture handout supplement.

Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330

5 Conclusions

In this laboratory assignment, the receiver part of a GSM base station was measured. The measurements covered the most important performance parameters of a receiver part, including 1-dB compression point, frequency response, noise temperature, and sensitivity. The most important learning outcome was to understand high and low power measurements, and how a power level affects measurements. Sensitivity and noise measurements require very low power measurements, whereas 1-dB compression point demonstrates the effects of high powers. This report presented the measurement setups and their corresponding results.

The 1-dB compression point was measured with two different measurements. The first was done using a signal generator and a spectrum analyser, and the second was done using only a VNA. In a nutshell, the input power was gradually increased, and the output power measured. In this report, figures were presented from which it was possible to define the 1-dB compression point. The compression point defined with the first setup is $CP_a = -5.6 \pm 1.5$ dBm, and the second setup gave a compression point of $CP_b = -4.1 \pm 0.2$ dBm, with the given error estimations.

The frequency response was already defined in the previous laboratory assignment.

The main measurement instruments included a spectrum analyser, a vector network analyser, and a signal generator, which all were pre calibrated and ready to use. An attenuator and a low noise amplifier were used to transform the measured signals to proper levels. In addition, different connecting cables were used, and their attenuations defined with the VNA.

Sampo Salo, 79543L
Tuomas Leinonen, 84695P
Huy Nguyen, 411330

6 Feedback

TODO: Huy and Sampo (not all devices are listed in the instructions sheet, learning from feedback, sweeptime)

References

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