

# **S-26.3120 Radio Engineering, laboratory course**

## **Lab 2: GSM Base Station Receiver**

### **Final report**

February 3, 2014

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## 1 Introduction

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

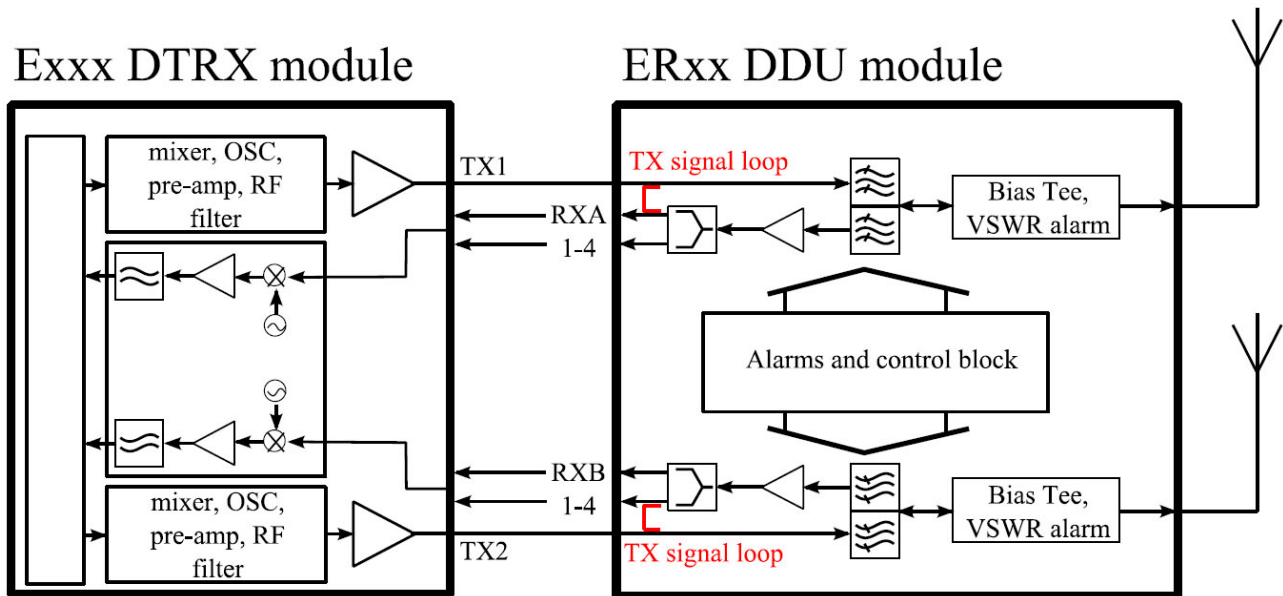


Figure 1: Receiver under study.

## 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 measurement 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 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.

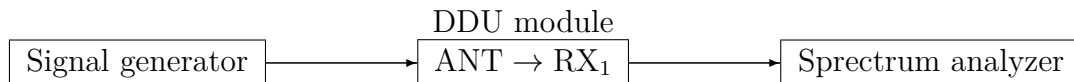


Figure 2: Measurement setup used in the first measurement task.

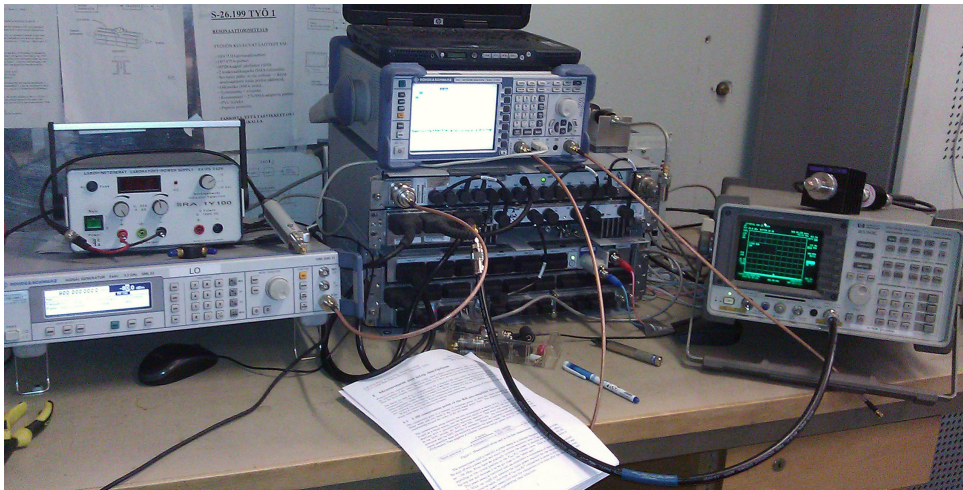


Figure 3: Using a signal generator and spectrum analyzer to characterize the DDU module.

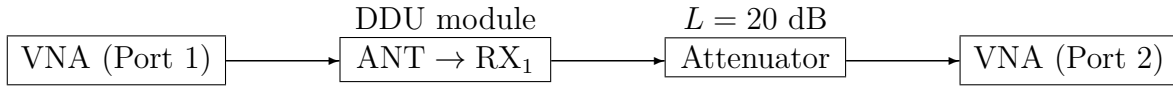


Figure 4: VNA measurements connections

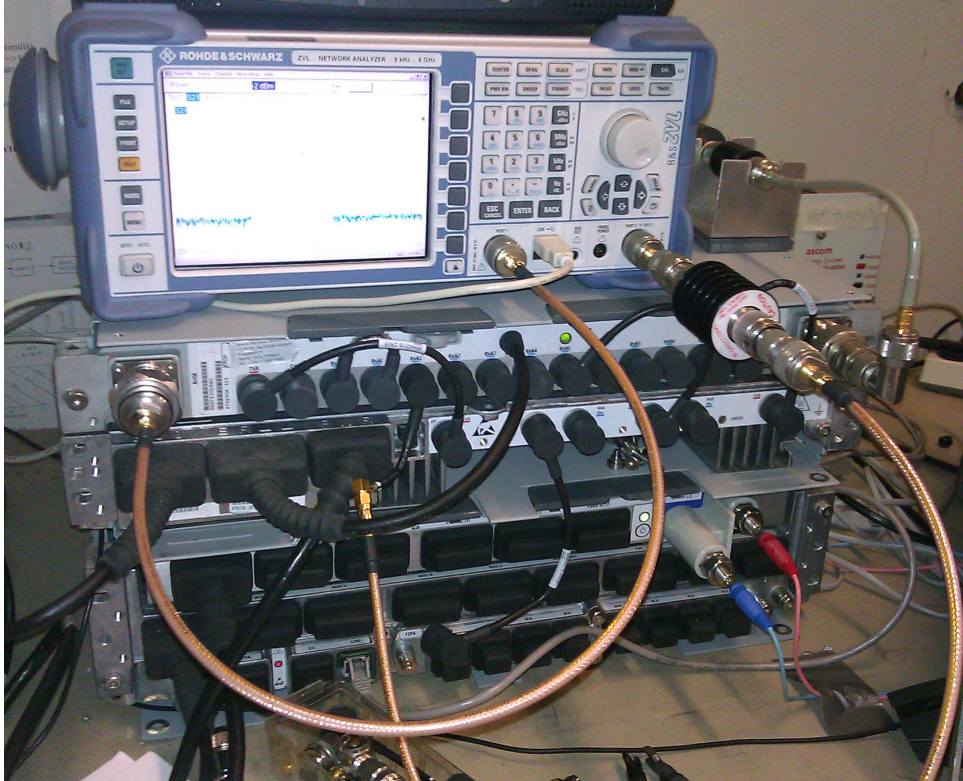


Figure 5: Measuring the DDU module with the VNA.

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 exception 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

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 should 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 oversight 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)  $\rightarrow$  DDU module (in: ANT<sub>B</sub>, out: RX<sub>B1</sub>)  $\rightarrow$  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

$$B_n = \frac{1}{G_{T, \max}} \int_0^\infty G_T(f) df, \quad (1)$$

where  $G_T(f)$  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 ANT<sub>A</sub>-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 RX<sub>A1</sub> 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:  $B = 15 \dots 3000$  MHz,  $G = 19$  dB,  $T = 463$  K,  $F = 4.1$  dB and  $V_{CC} = +15$  V.

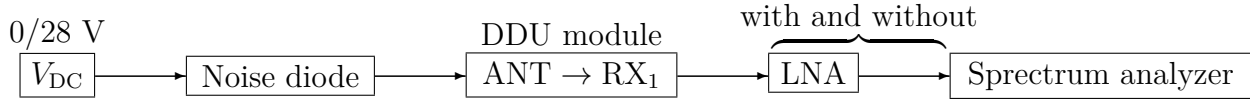


Figure 6: Noise temperature measurement setup

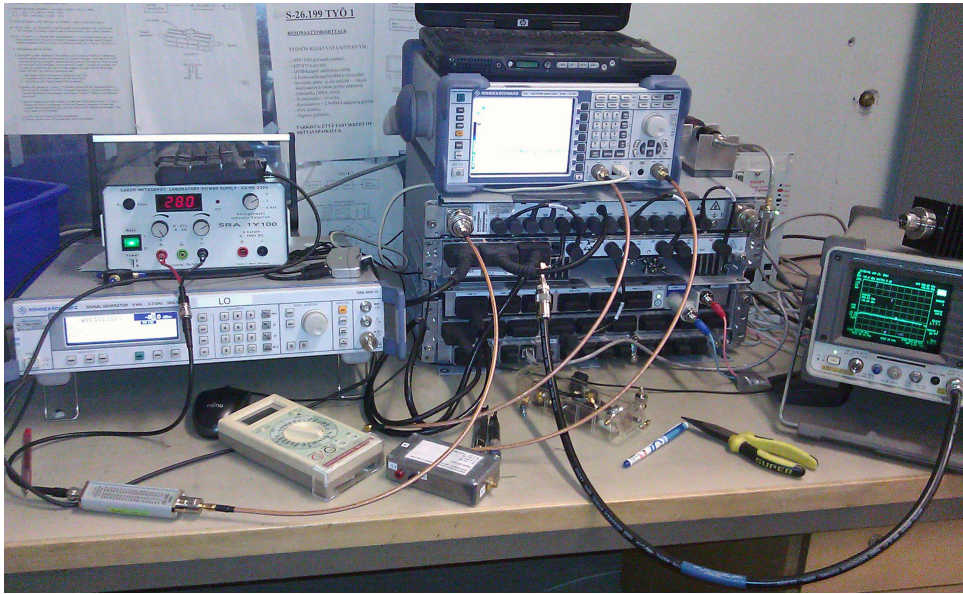


Figure 7: Noise temperature measurement setup without the additional amplifier.

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  $28 V_{DC}$  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

$$Y = \frac{P_H}{P_C} = \frac{T_H + T_e}{T_C + T_e} \Rightarrow T_e = \frac{T_H + YT_C}{Y - 1}, \quad (2)$$

where  $P_{H/C}$  is the measured power for hot and cold loads at equivalent noise temperatures  $T_{H/C}$ , and  $T_e$  is the noise temperature of the measured device.  $T_C = 295$  K is the physical

temperature of the noise diode, and  $T_H$  may be solved from the definition of  $ENR$ :

$$ENR = 10 \lg \left( \frac{T_H}{T_C} - 1 \right) \Rightarrow T_H = T_C \left( 10^{\frac{ENR}{10}} + 1 \right). \quad (3)$$

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

$$F_{dB} = 10 \lg (F) \text{ dB} = 10 \lg \left( 1 + \frac{T_e}{T_0} \right) \text{ dB}. \quad (4)$$

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:

$$F_{\text{total}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots \Leftrightarrow T_{\text{total}} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \dots, \quad (5)$$

where  $G_i$  is the available power gain of the  $i$ th 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  $T_{\text{phys}}$  through formula  $F = (L - 1)T_{\text{phys}}$ . 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  $\text{ANT}_A$ -input that results in a reliably detectable signal above the noise floor in the output 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.

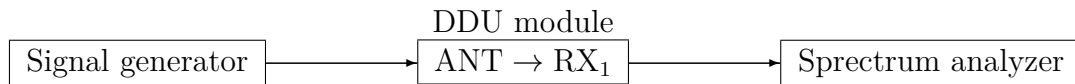


Figure 8: Measurement setup used in the sensitivity measurement.

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

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 floor, 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.

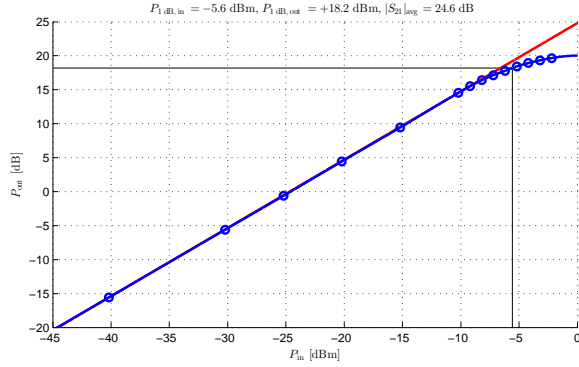


## **3 Results**

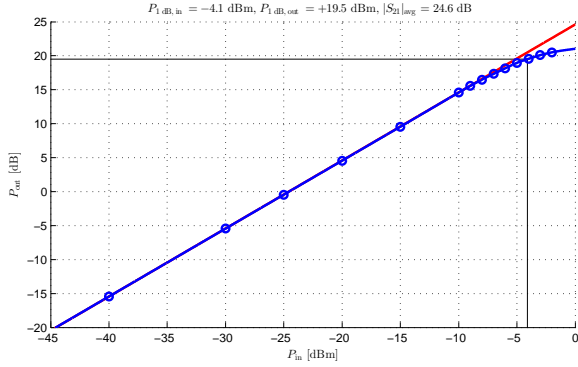
TODO: Huy and Sampo (general results and intro to more specific results)

### **3.1 1 dB compression point**

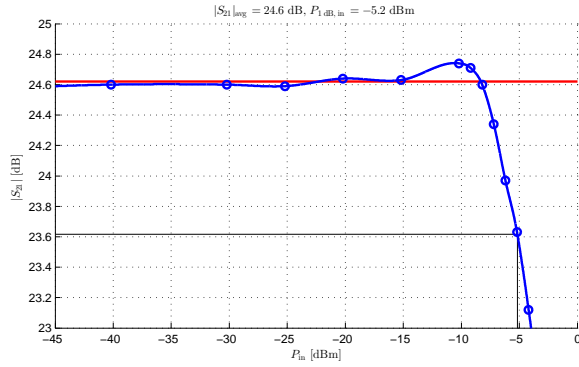
TODO: Huy and Sampo



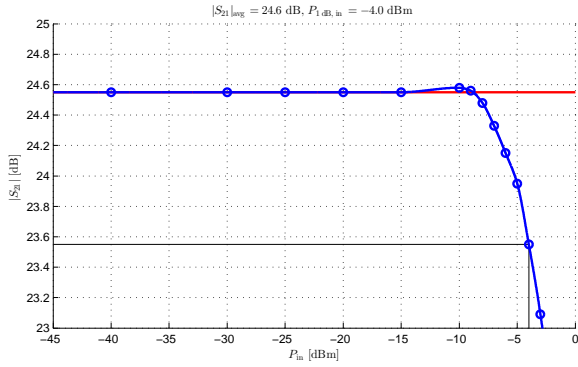
(a)  $P_{\text{out}}(P_{\text{in}})$  using SG & SA



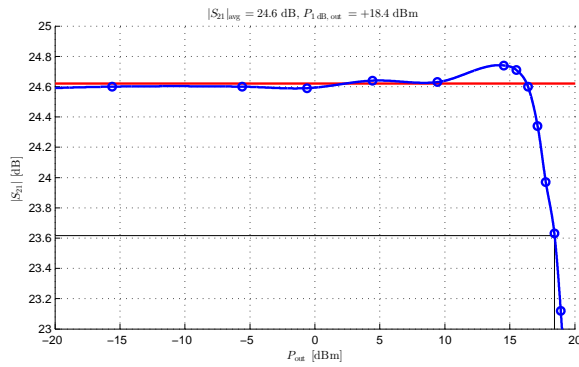
(b)  $P_{\text{out}}(P_{\text{in}})$  using VNA



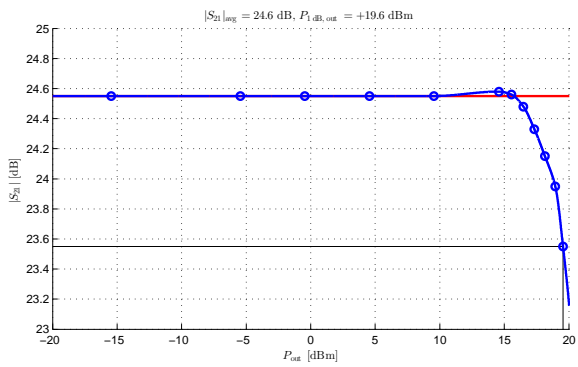
(c)  $G(P_{\text{in}})$  using SG & SA



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



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



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

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

### 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.

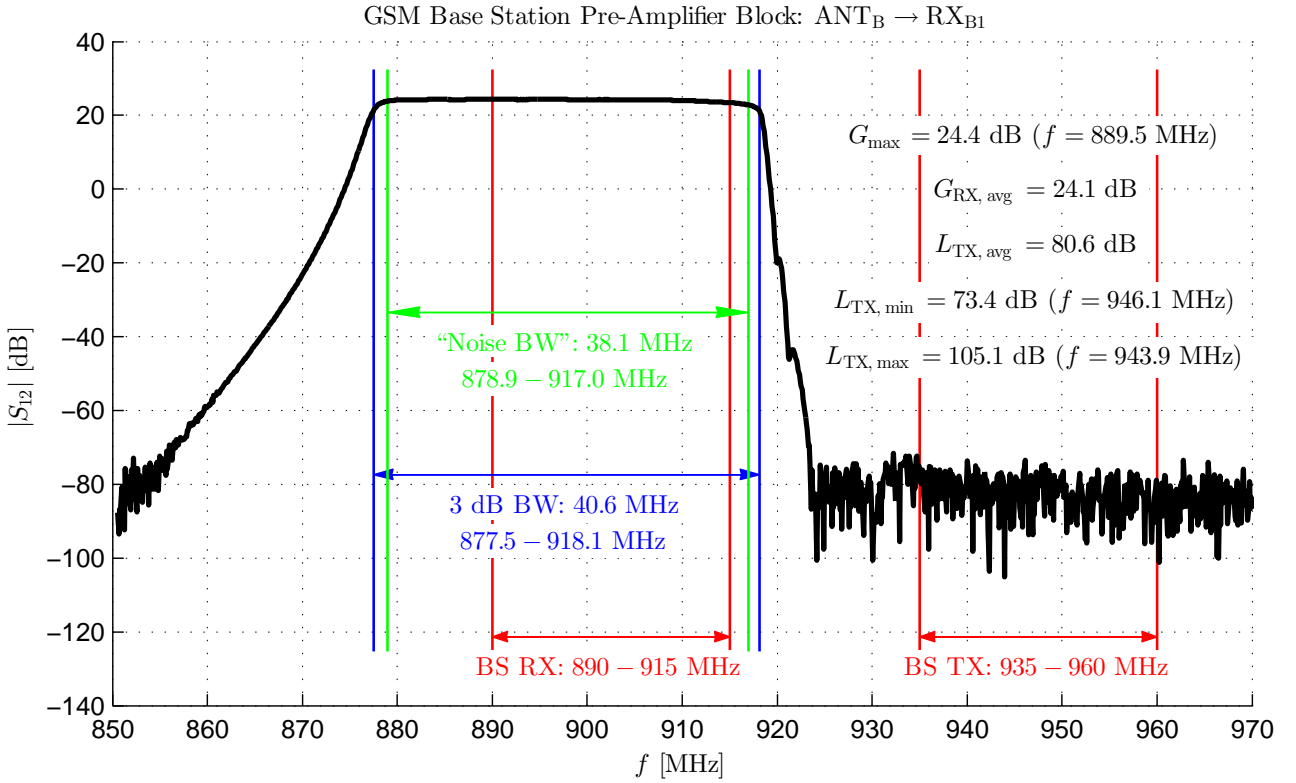


Figure 10:  $S_{12}$  of the DDU module as was measured in the first labs.

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  $G_{\text{T, max}} = |S_{12}|_{\max} = 24.4$  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.

### 3.3 Noise Temperature

TODO: Huy and Sampo

Table 1: Results from the noise measurement.

LNA?	$P_C$ [dBm]	$P_H$ [dBm]	$T_{\text{total}}$ [K]	$T_{\text{DDU}}$ [K]	$F_{\text{DDU}}$ [dB]
No	−107.3	−90.8			
Yes	−91.3	−71.7			

### 3.4 Sensitivity

TODO: Huy and Sampo

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

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

### 3.5 Dynamic range

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

## 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  $\pm 6$  dB. On the other hand, the document gives also representative values of amplitude uncertainties, which in our case yields about  $\pm 1$  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  $\pm 0.5$  dB.

In conclusion, the error estimates that can be taken into account numerically are the manufacturers representative value of approx.  $\pm 1$  dB, and the power marker fluctuation of roughly  $\pm 0.5$  dB. These uncorrelated errors may be summed to achieve the total uncertainty of the SA measurements of approx.  $\pm 1.5$  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 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 from 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  $-50 \dots 0$  dB is better than 0.2 dB (0.3 dB for powers of  $-50 \dots -70$  dB) with 0 dBm transmit power. [5] The reader should note that these ranges were exceeded from both ends during the measurements (the measurement power range was roughly  $-100 \dots +4$  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.



## 5 Conclusions

TODO: Huy and Sampo

## **6 Feedback**

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

## References

- [1] C. Icheln, S. Khanal, *GSM Receiver laboratory assignment instructions*, S-26.3120 Laboratory course in Radio Engineering course material.
- [2] C. Icheln (edited), *Lecture supplement handout*, S-26.3120 Laboratory course in Radio Engineering course material.
- [3] Agilent, Spectrum Analysis Basics, Application Note 150. Available online at <http://cp.literature.agilent.com/litweb/pdf/5952-0292.pdf> [Retrieved: Jan 2nd, 2014].
- [4] Agilent, 8590 Series Analyzers Calibration Guide. Available online at <http://cp.literature.agilent.com/litweb/pdf/08594-90106.pdf> [Retrieved: Jan 2nd, 2014].
- [5] R&S ZVL Vector Network Analyzer Specifications, Version 06.00, Dec 2008. Available online at [http://www.upc.edu/pct/documents\\_equipament/d\\_160\\_id-655-2.pdf](http://www.upc.edu/pct/documents_equipament/d_160_id-655-2.pdf) [Retrieved: Jan 2nd, 2014].