S-26.3120 Radio Engineering, laboratory course

Lab 2: GSM Base Station Receiver

Pre-study report

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1 Measurement and setup descriptions

Present all the required measurement setups (draw a figure) and procedures. Take into account the attenuation of the cables. In which range is the attenuation of coaxial cables at 900 MHz? Pick the most suitable measurement equipment if there are several options to choose from.

The figure on page 8 in [1] suggests that for a standard PE coax cables the attenuation ranges between 0.32 . . . 1.36 dB/m at a frequency of 900 MHz. Even lower losses may be achieved with more expensive cables (down to roughly 0.2 dB/m, as suggested on page 29 in [1]). Similarly, some maltreated cables may have an attenuation in excess of 2 dB/m. In addition, one should not overlook the attenuation from connectors and connecting.

When it comes to this lab course and our measurements, an attenuation of roughly 0.5 dB/m would most likely be a realistic estimate.

1.1 1 dB compression point of the RX pre-amplifier block

The compression point is a measure of maximum power at which the input amplifier works in linear mode and sets limit to the received signal power level. The frequency of 900 MHz is conveniently around the center of the RX band.

The measurement setup suitable for this measurement is shown in Fig. 1. A signal generator is used as a signal source, and the generated signal is passed through the DDU module before detection with a (precalibrated) spectrum analyzer. The input and output connections used in the DDU module are ANT and RX_1, respectively. An attenuator is used between the generator and the DDU module, if necessary. While the operator's manual of the R&S SML03 signal generator does not explicitly mention the power range, the testing range defined in the *Performance Tests* suggests a (reliable) minimum output power level of −80 dBm.

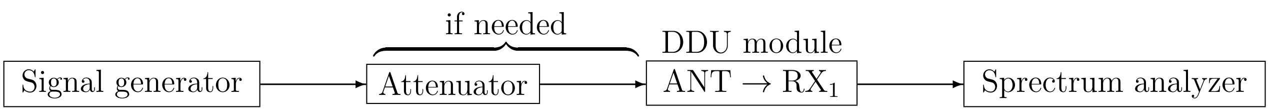

Figure 1: Measurement setup used in the first measurement task.

The measurement itself is basically a power sweep at a constant frequency of $f = 900$ MHz. We start off with a power level well above the receiver sensitivity level ($P_{\text{min, BS}} \approx -112.5$ dBm), say −100 dBm. From there we gradually increase the power in suitable steps of 0.1 . . . 10 dB, depending on the current position on the $P_{\text{out}}(P_{\text{in}})$ transfer curve. That is, we'll start with a big step size and decrease it as we get close to the "sweet spot".

This power sweep is continued until we experience a compression of more than the required 1 dB. While one could just measure the input power required for the output to be 1 dB less than the expected value, this type of "on-the-fly" comparison is prone to error. Thus it's better to measure a full power sweep and leave the comparison to be done after the measurement and against a fitted straight representing ideal behaviour.

Since we are dealing with a GSM receiver, we may use the same settings for the spectrum analyzer as we did in the first labs – except for the averaging factor. They were as follows: an averaging factor of 500, zero span and 30 Hz video and resolution bandwidths. An averaing factor of 500 would make the measurement quite lengthy, especially if dense power "grid" is used. Averaging over 100 measurements will most likely be more than adequate. Depending on the 1 dB compression point, we might need to watch out for compression in the spectrum analyzer. This is taken care of by altering the input attenuation.

The effect of the cables and the attenuator may be measured using a VNA (could be used for the entire measurement aswell), or using the SA by making the whole measurement relative. In a relative measurement, the power is measured again when the DDU module is by-passed to account only for the cables and the possible attenuator. This also required to know the real input power.

1.2 Gain of the RX pre-amplifier block

The bandwidth of the RX block should account for the GSM specification for the RX band limits. Measure the 3 dB bandwidth of the block and determine approximately the equivalent noise bandwidth (graphically using the additional material) and the TX-band (stop band) attenuation.

Wasn't this already covered in the first laboratory assignment as a part of the diplexer characterization? Fig. 2 presents the measurement setup used there. The DDU module is simply connected between the two ports of a precalibrated VNA; ANT and RX_1 connectors of the DDU module are connected to ports 1 and 2 of the VNA, respectively. In the VNA, measurement power shoud be as high as possible due the stop band-attenuation, yet simultaneously small enough not to cause compression in the pass-band (in neither the VNA nor in the pre-amp itself).

DDU module

VNA (Port 1) → ANT → RX_1 → VNA (Port 2)

Figure 2: Measurement setup used when determining the gain of the pre-amplifier block.

The following figure (Fig. 3) shows the results obtained in the first lab works with a transmit power of −20 dBm in the VNA (using the B-half of the BS and connecting the ports vice versa). In the figure, in addition to GSM RX and TX bands (in red), both 3 dB (in blue) and noise (in green) bandwidth of the pre-amp block are visualized. This noise bandwidth visualization is somewhat questionable as it's a purely theoretical concept, but is nevertheless shown for scale. The shown noise bandwidth is found using a numerical approximation with $|S_{12}|$ of the formula given in the lecture supplement handout:

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

The noise bandwidth shown is less than the actual band since we cannot use infinite frequency range. Frequency range of 850 . . . 1000 MHz with $|S_{12}|_\mathrm{max} = 24.4$ dB was used instead.

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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.

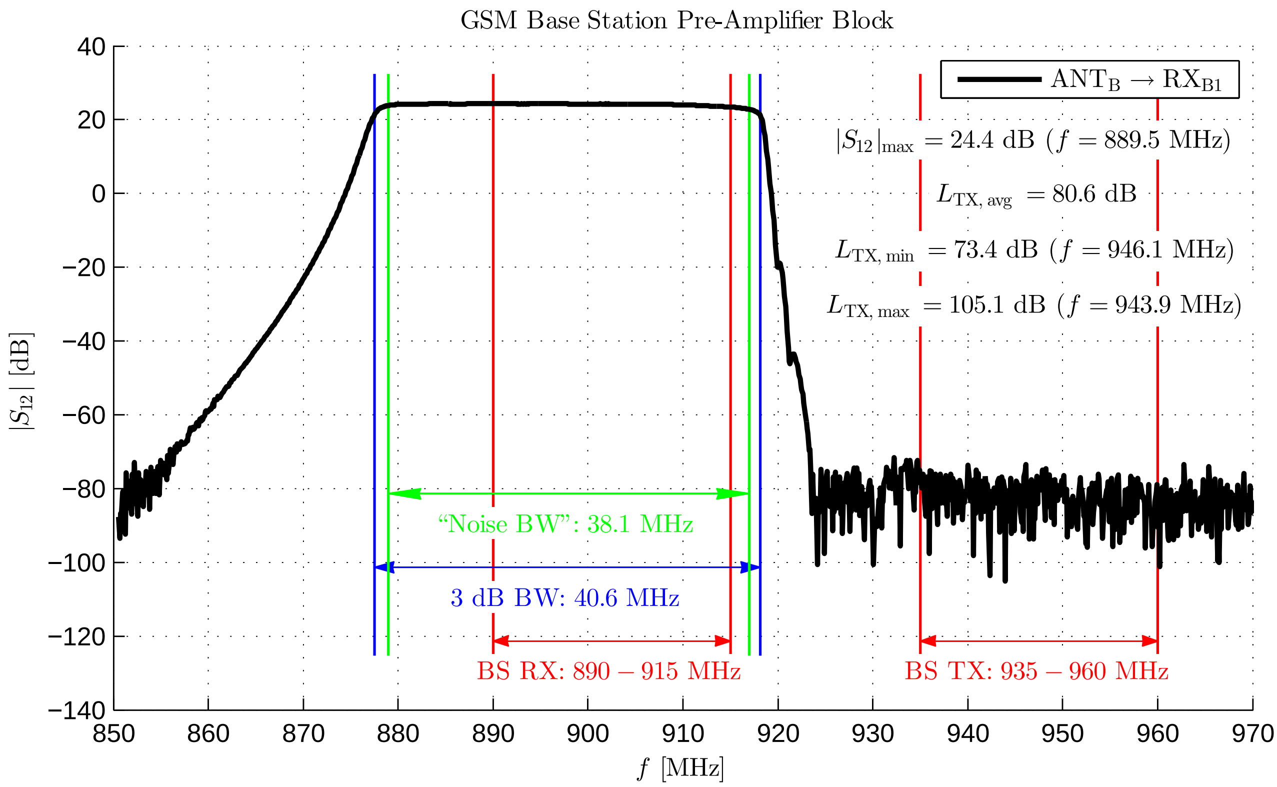

Figure 3: Results from the diplexer characterization.

In the graphical approximation method we need to investigate the effect of frequency roll-off speed. From Fig. 3 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.

If a VNA is not available as the instructions suggest, the task is quite laborious and absurd, just to be honest. Nevertheless, the procedure is listed here for completeness. We would need to simulate the VNA function manually using a signal generator and a power meter or a signal analyzer, leading to a setup like the one shown in Fig. 1. The output power is kept constant while frequency is swept over the range, taking notes on the relative power levels observed in the detector.

1.3 Noise temperature of the RX pre-amplifier block

Determine the noise temperature of the RX block (consisting of bias tee, diplexer and pre-amplifier) with the Y-coefficient method. Use the noise diode as active noise source (and as *passive noise source at room temperature when supply voltage is switched off).*

In the third measurement task, we'll use a setup shown in Fig. 4. A DC-voltage source is connected to a noise diode connected directly to the ANT-input in the pre-amplifier block. This direct connection is desirable as attenuation changes the noise temperature. The signal is led from the RX_1 output to a spectrum analyzer. An LNA may be needed in between the DDU output and the spectrum analyzer, as the spectrum analyzer might not be sensitive enough for the cold noise source. See section 2.2 for details.

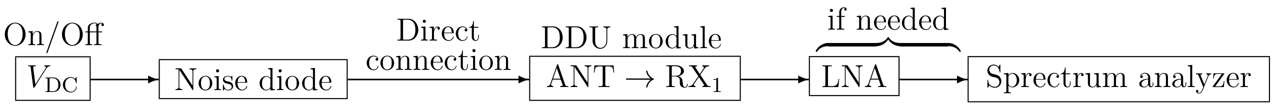

Figure 4: Noise temperature measurement setup

The measurement itself is carried out measuring two power levels required in the Y-parameter; when the DC-voltage is off/shorted ("cold") and on ("hot"). As for the SA settings, we are measuring noise at a single frequency (using zero-span): a very weak, random signal. Thus, input attenuator should be disabled, and minimum resolution bandwith used. A large averaging factor, say a thousand, is also beneficial. The measurement may take a few minutes, and it's OK; there are only two measurements to be made.

1.4 Sensitivity of the RX pre-amplifier block

Measure the sensitivity of the RX block using suitable equipment.

In the sensitivity measurement, we're trying to measure the minimum input power at ANT input that results in a detectable signal above the noise floor in the ouput of the DDU module. For this, a measurement setup identical to the one used in the first task may be used, as is shown in the following figure (Fig 5). This time though it's more than likely that an attenuator is required.

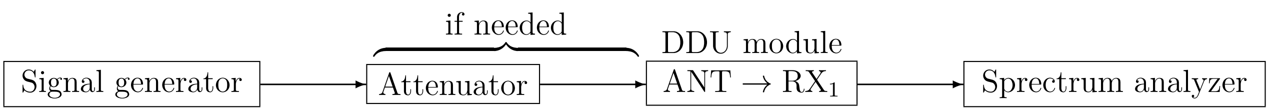

Figure 5: Measurement setup used in the sensitivity measurement.

The measurement starts by measuring the noise floor at 900 MHz without any signal we're hoping to detect. That is, the RF power is switched off at the generator. Then we turn on an input signal that's some dBs sensitivity of −112.5 dBm. We gradually increase the power until the signal-to-noise ratio is no less than the 10 dB required by the standard. One could also measure the power required to beat the noise just barely, and add the SNR later on if $P_{\mathrm{out}}(P_{\mathrm{in}})$ relation is assumed to be ideal.

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Since it's a GSM system, we use the measurement settings as they are defined in the standard. They are as follows: an averaging factor of 500, zero span and 30 Hz video and resolution bandwidths. As the spectrum analyzer input power is expected to be less than −80 dBm ($P_{\mathrm{SA}} \approx P_{\mathrm{DDU,\,min}} + G_{\mathrm{DDU}} = -112.5\ \mathrm{dBm} + 24.4\ \mathrm{dB} = -88.1\ \mathrm{dBm}$), it's best to disable the input attenuator.

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2 Pre-study calculations and related tasks

The following subsections will present answers to pre-study tasks 2.2 – 2.4.

2.1 Mismatch attenuation

A signal generator is connected to the input of the RX pre-amp block. The VSWR (voltage standing wave ratio) of the pre-amp is 2.0 and the VSWR of the output of the signal generator is 1.6.

a) What is the range of additional attenuation due to this mismatch in the measurement of the pre-amp block?

b) In what range is the attenuation due to mismatch, when an ideal 10 dB attenuator is connected between the signal generator and the pre-amp block? What is the benefit/drawback of inserting this attenuator?

Mismatch causes some of the source power to be reflected back from the load, reflecting back again from the source. This way, the power from the source does not transfer fully to the load. The power attenuation η due to mismatch can be calculated using equations

$$\eta_{\mathrm{SL,\ max}} = \frac{(1-|\rho_{\mathrm{S}}|^2)(1+|\rho_{\mathrm{L}}|^2)}{(1-|\rho_{\mathrm{S}}||\rho_{\mathrm{L}}|)^2} \tag{2}$$

and

$$\eta_{\mathrm{SL,\ min}} = \frac{(1-|\rho_{\mathrm{S}}|^2)(1+|\rho_{\mathrm{L}}|^2)}{(1+|\rho_{\mathrm{S}}||\rho_{\mathrm{L}}|)^2}, \tag{3}$$

where ρ_{S} and ρ_{S} are the source and load reflection coefficients, respectively. The equations are special forms of an equation, and are used in the case when the phase relation of the set-up is not known. The reflection coefficients can be calculated from voltage standing wave ratio $VSWR$ by

$$|\rho| = \frac{VSWR-1}{VSWR+1}. \tag{4}$$

Using the equations, the maximum efficiency of power transfer is $\eta_{\mathrm{SL,\ max}} = -0.05$ dB, and the minimum efficiency of power transfer is $\eta_{\mathrm{SL,\ min}} = -1.39$ dB. Therefore, the range of mismatch attenuation is $-1.39\ldots-0.05$ dB.

With the attenuator in between, the reflections are attenuated 20 dB each time the power travels back and forth in between the source and the load. The attenuation for the reflections grows relatively large, and so the maximum efficiency of power may be approximated using an equation that is derived for a set-up where an isolator is placed between the source and the load. The equation is

$$\eta = (1-|\rho_{\mathrm{S}}|^2)(1+|\rho_{\mathrm{L}}|^2), \tag{5}$$

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and it gives a power attenuation of -0.22 dB. The advantage of using a power attenuator in between the source and the load is that the attenuation due to mismatch can be approximated more precisely. Another advantage is that the attenuator protects the signal generator from reflected power. On the other hand, the total attenuation grows to -10.2 dB, which could be a disadvantageous in some situations.

2.2 Noise temperature

The noise temperature of the pre-amp block is determined using the Y-coefficient method. The noise level of the spectrum analyzer HP8596E is $P_{\mathrm{SA}} < -125$ dBm when the input is matched and the resolution bandwidth is 30 Hz.

a) How much gain is required from the LNA in order to measure the noise temperature with the HP8596E? The noise figure of the amplifier is 2.8 dB and the attenuation of the bias tee and the diplexer is 0.7 dB and 0.4 dB, respectively.

b) Does the order (i.e. which is first in the chain) of the amplifier, bias tee and the diplexer in the pre-amp block have any influence on the result of Y-coefficient measurement? If yes, say why.

The receiver path of the DDU module, also referred to as the pre-amp block, consists of a bias tee, diplexer, LNA and a four-way power-divider (in this order). Assuming the physical operating temperature of the pre-amp block to be $T_0 = 290$ K, we have the attenuations and noise factors/figures listed in the following table (Table 1).

Table 1: Given parameters for this problem.

Block	**Subscript**	**Attenuation L**	**Noise figure F**
Bias tee	BT	0.7 dB $\approx$ 1.175	0.7 dB $\approx$ 1.175
Diplexer	DPX	0.4 dB $\approx$ 1.096	0.4 dB $\approx$ 1.096
Low-noise amplifier	LNA	???	2.8 dB $\approx$ 1.905
4-way power divider	DIV	6.0 dB $\approx$ 3.981	6.0 dB $\approx$ 3.981

The total noise figure of a cascaded system F_{T} is given by the Friis noise equation (linear quantities)

$$F_{\mathrm{T}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots, \tag{6}$$

or equivalently using noise powers

$$F_{\mathrm{T}} = \frac{SNR_{\mathrm{in}}}{SNR_{\mathrm{out}}} = \frac{S_{\mathrm{in}}}{N_{\mathrm{in}}} \frac{N_{\mathrm{out}}}{S_{\mathrm{out}}} = \frac{N_{\mathrm{out}}}{G_{\mathrm{T}} N_{\mathrm{in}}} = \frac{N_{\mathrm{out}}}{G_{\mathrm{T}}\, k T_0 B_{\mathrm{N}}}. \tag{7}$$

Solving for N_{out} yields

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$$N_{\text{out}} = F_{\text{T}}\, G_{\text{T}}\, kT_0 B_{\text{N}} = F_{\text{T}} \frac{G_{\text{LNA}}}{L_{\text{BT}} L_{\text{DPX}} L_{\text{DIV}}}\, kT_0 B_{\text{N}} \tag{8}$$

which can in turn be solved for required gain G_{LNA} when we set $N_{\text{out}} > P_{\text{SA, min}}$. Thus we obtain

$$G_{\text{LNA}} > \frac{P_{\text{SA, min}}\, L_{\text{BT}}\, L_{\text{DPX}}\, L_{\text{DIV}}}{F_{\text{T}}\, kT_0 B_{\text{N}}}. \tag{9}$$

a) First we need to find the total noise figure of our four-stage cascaded system. Using Eq. 6, it is found to be

$$F_{\text{T}} = 2.533 + \frac{3.840}{G_{\text{LNA}}}. \tag{10}$$

Using this in Eq. 9 yields

$$G_{\text{LNA}} > 5624.69\ldots = 37.500\ldots \text{ dB} \approx 37.5 \text{ dB}. \tag{11}$$

This assumes the output of the DDU module (RX_1) to be perfectly matched to the spectrum analyzer. If we were to neglect the power divider ($L_{\text{DIV}} = F_{\text{DIV}} = 1 = 0$ dB), a gain of 31.5 dB would be required from the LNA.

b) From Eq. 6 it can be observed that the noise figure of a system is dominated by the noise figure of the first stage since the effect of the following stages are reduced by several gains. That is, if the first stage has a significant gain, the overall system noise figure more or less depends on the noise characteristics of the stage in question. Thus, if the order in the pre-amp block changes, it will definitely have influence on the noise temperature of the block.

2.3 Requirements with evolving standards

Discuss briefly the major changes in the requirements for the RF performance of the blocks in the RX chain when we move from 2G to 3G to 4G systems.

Following table (Table 2) lists some of the major differences between digital cellular commucation standards. The table in question has been simplified; an interested reader is adviced to take a look at the actual specifications [2–4]. In addition, some of the information shown, may be considered “misleading” to an untrained eye, as the information shown is based on the specifications. They are known not to address real-life outcomes as much as possibilities.

For example, there are actually 14 GSM bands defined in the standard, yet only four of those (850/900/1800/1900) are “widely recognized” as there’s overlapping for instances. One should also note that the newer standards have been written on “top of” the existing older standards for backward/co-existence compatibilty. For instance, 3G includes/supports 2G functionality to some extent.

A clear trend toward more users and higher datarates is evident; all the parameters shown point to that fact. More and more frequency bands are allocated as channel bandwidths increse

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Table 2: A simplified list of some of the significant changes in evolving communication systems.

Parameter	**2G** [2]	**3G** [3]	**4G** [4]
System frequency [MHz]	380 . . . 1990	700 . . . 3590	700 . . . 3800
Number of system bands	14	30	38
System bandwidth [MHz]	7 . . . 75	10 . . . 80	10 . . . 200
Channel bandwidth [MHz]	0.2	1.3 . . . 7.7	1.4 . . . 20
Duplexing mode	TDD	TDD / FDD	TDD / FDD
Multi-access method	TDMA	CDMA	FDMA
Modulation schemes	GSMK, 8PSK, 16QAM, 32QAM, AQPSK	QPSK, 8PSK, 16QAM, 64QAM	BPSK, QPSK, 16QAM, 64QAM

at the same time. More complex multi-level modulation schemes with full-duplex all-time transmission has become more and more common. Also multiple input – multiple output (MIMO) and carrier aggregation (CA) techniques are emerging to serve customers with the appetite for even larger data rates, achieved in multi-band and/or multi-antenna configurations.

When it comes to the radio receivers, it's all about flexibility. Software-defined radio (SDR) principles come in real handy when the alternative is to replicate a front-end for each band. Naturally some replication of the RX-chain is required for both MIMO and CA. In addition to being required to work on a larger band using wider channel, the linearity requirements have gone up as. In the last two generations, there have been no groundbreaking changes in the power requirements, such as minimum/maximum levels for (un)wanted signals, inside or outside the band of interest. Of course there are some changes mostly explainable due to increased bandwidth.

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[2] 3GPP Technical Specification, Series 45: Radio aspects – GSM only (Rel-4 and later)

[3] 3GPP Technical Specification, Series 25: Radio aspects – 3G and beyond / GSM (R99 and later)

[4] 3GPP Technical Specification, Series 36: LTE (Evolved UTRA) and LTE-Advanced radio technology