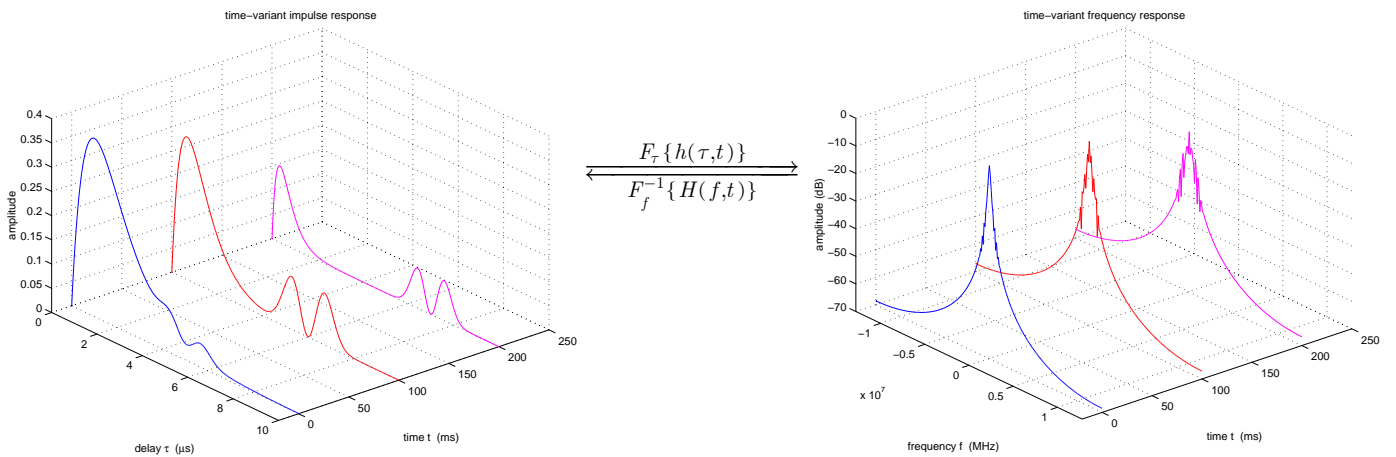


S-72.260

Laboratory Works in Radiocommunications

Laboratory Work #5

LTV CHANNELS



Version 0.21

Version history

Date	Version	Changes
11.4.2001/JSa	0.1	First draft
3.8.2001/JSa	0.2	Preliminary and laboratory exercises changed slightly
26.9.2001/JSa	0.21	Laboratory measurements adapted for PROPSIM+.

Prerequisites: S.72.232 Radio Communication Systems, knowledge of MATLAB.

See the course home page for more information.

Student laboratory is in the room E306.

Good luck!

LINEAR TIME-VARIANT CHANNELS

1 Introduction

This laboratory work is mostly about linear time-variant (LTV) systems. Mobile radio channel is an archetypal example of an LTV system.

The goal of this laboratory work is to gather an understanding of how LTV systems are characterized by their system functions. The effect of time-variant communications channel on BER performance of a GSM receiver is also investigated.

Pointers to literature on LTV systems, mainly from the perspective of radio channels, are listed at the end of this document. Seminal publications include [Kai59] and [Bel63]. [Ken69], [Jak74], and [Par92] contain a lengthier treatment of the subject. Standard textbooks on communications theory, like [Pro95] and [AZ98], might also be useful. A good tutorial can be found in [Sk197]. At HUT the topic is discussed in the course S-72.232, see [Häg00].

The purpose of this document is to present an overview of certain topics covered in the laboratory exercise, not to reproduce material already covered in literature and lecture notes. Section two discusses deterministic and stochastic LTV system functions and section three touches on measurement of impulse response of an LTV system.

2 LTV system functions

The purpose of this section is to define the notation used in this laboratory work. Something about simulation of a Rayleigh fading communications channel is said as well.

2.1 Deterministic LTV system functions

Figure 1 shows an example of a real-valued time-variant impulse response $h(\tau, t)$ at the output of an LTV system at time instants t_1, t_2, t_3 . The response of the first

impulse response is observed to begin at time $t_1 = 0$. It is clearly different from the response observed to begin at time $t_2 = 1$. All time units have been normalized.

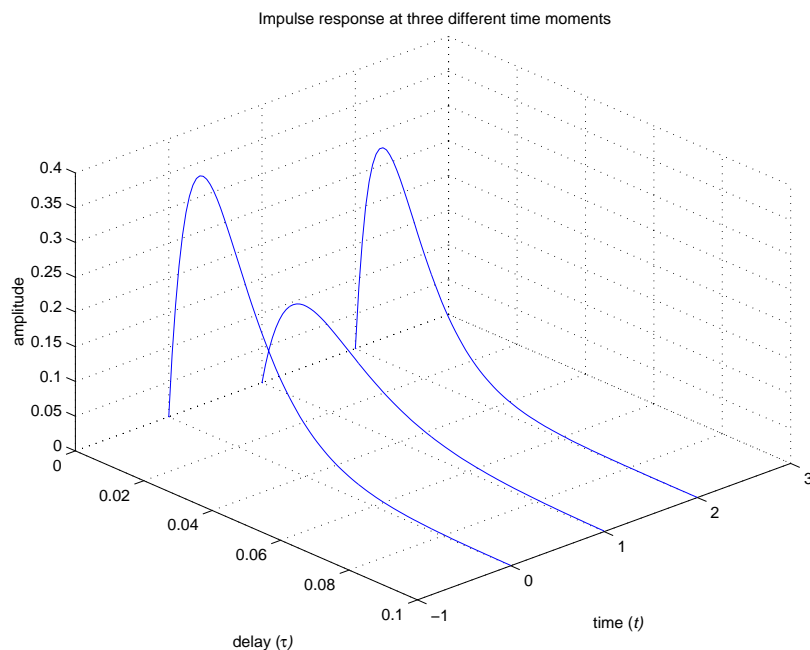


Figure 1. An example of LTV system impulse response at three different time instants.

In the time-invariant case the frequency response $H(f)$ of the channel can be obtained by Fourier transforming the impulse response $h(\tau)$. Generalizing this to the time-variant case, we can obtain the time-variant frequency response $H(f, t)$ by transforming $h(\tau, t)$ with respect to the τ variable. Fourier transforming $h(\tau, t)$ with respect to t produces a function $h(\tau, \phi)$ that depicts the frequency spread of the channel for each delay τ . In context of radio channels ϕ is often called Doppler variable. Variables $\tau \leftrightarrow f$ and $t \leftrightarrow \phi$ are dual variables as shown in Figure 2. Function $h(\tau, \phi)$ is often called Doppler-delay function.

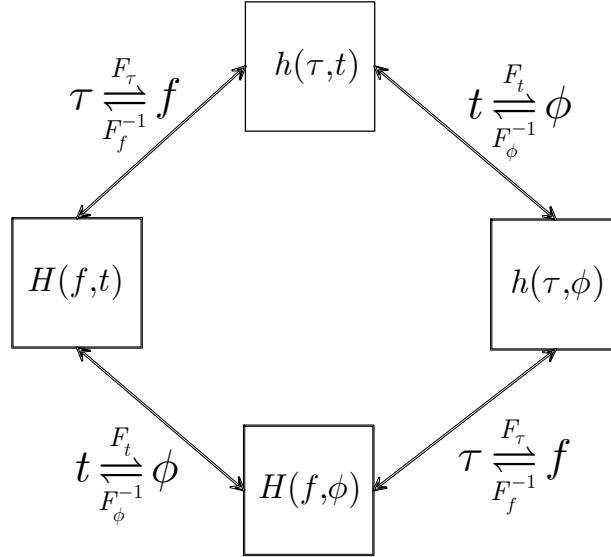


Figure 2. Deterministic LTV system functions and their relationships.

2.2 Statistical LTV system functions (2nd order, WSSUS case)

In the previous section the LTV system functions were assumed to be deterministic. Often the LTV systems encountered in practice can only be modeled by treating the system as a *randomly* time-variant linear system. Mobile radio channel (or a tropo-scatter channel) is the standard example of an LTV system that can only be described statistically.

The autocorrelation function is by far the most widely used statistical description of an LTV system function. For example, the autocorrelation function of the randomly time-variant complex impulse response is defined as

$$\Phi_h(\tau_1, \tau_2, t_1, t_2) = E[h(\tau_1, t_1)h^*(\tau_2, t_2)]. \quad (1)$$

Even this simple 2nd order statistic is often too difficult to handle in practice and simplifications are almost always required.

Assuming that $h(\tau, t)$ is wide-sense stationary in the t (time) variable leads to

$$E[h(\tau_1, t_1)h^*(\tau_2, t_1 + \Delta t)] = \Phi_h(\tau_1, \tau_2, \Delta t).$$

Furthermore, assuming that $h(\tau, t)$ is uncorrelated in the τ (delay) variable results in

$$E[h(\tau_1, t_1)h^*(\tau_2, t_1 + \Delta t)] = \Phi_h(\tau_1, \Delta t)\delta(\tau_2 - \tau_1).$$

The left-hand side is usually denoted $\Phi(\tau, \Delta t)\delta(\tau)$. The delta function states that the values of the impulse response are uncorrelated between any two delay values. Real-world measurements have proven that this assumption cannot be justified for most mobile radio channels¹. Nevertheless, in analysis and simulation the uncorrelatedness assumption is still often made because it simplifies the situation.

A system that is assumed to fulfill both the WSS and US assumption is called a WSSUS system.

The WSSUS system functions and their relationships are shown in Figure 3.

Many quantities describing the channel characteristics can be computed from the statistical LTV functions. These include coherence bandwidth, coherence time, and Doppler power spectrum. See literature for more details.

The statistical LTV functions cannot be determined in practice because the evaluation of the expectation in (1) requires knowledge of the corresponding multi-dimensional probability density function, which in general is unknown. Thus, statistical LTV functions must be *estimated* from a finite data sample.

¹ Practical measurement systems are always band limited so some correlation in τ domain is inevitable even if the channel itself was uncorrelated.

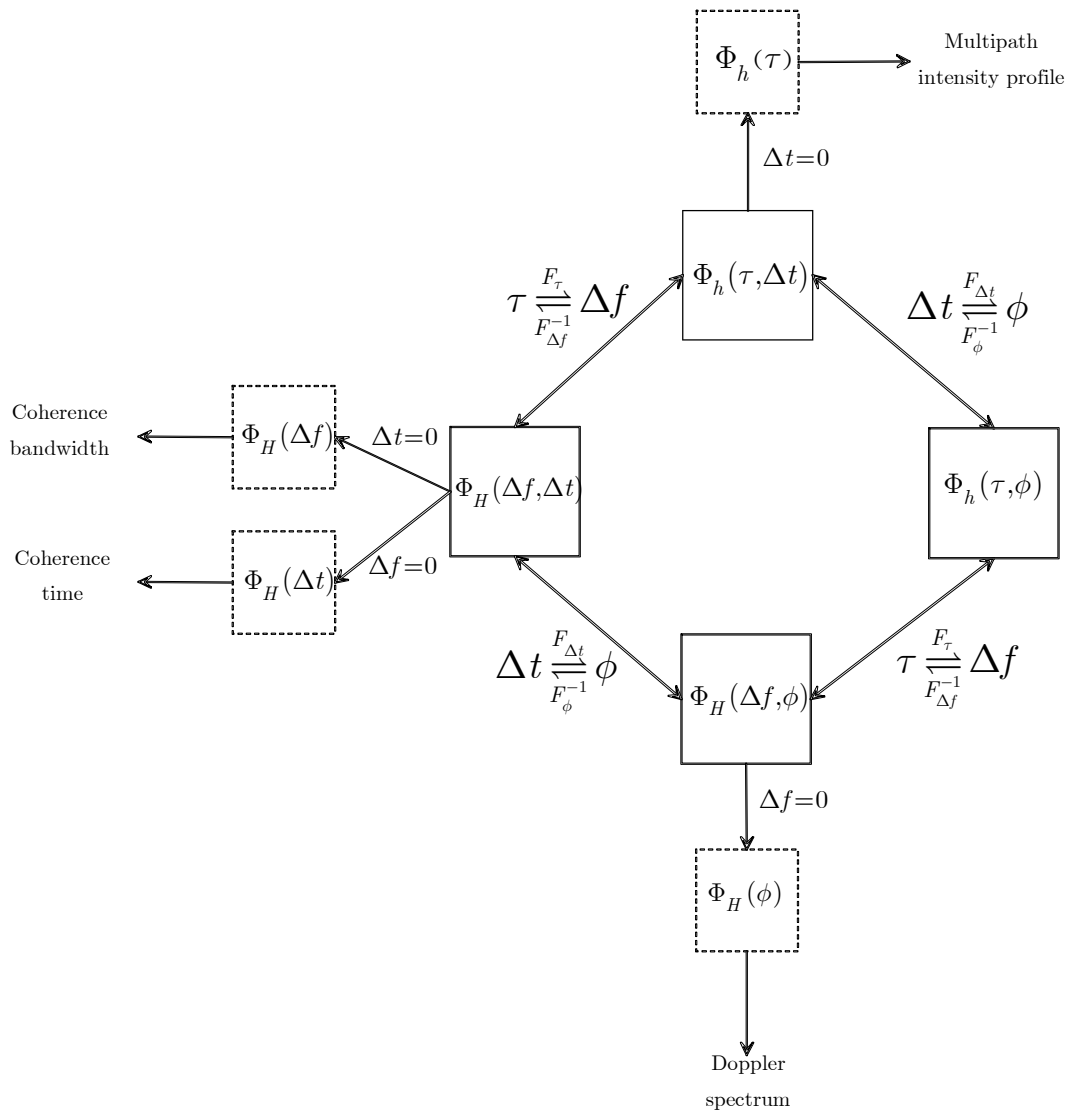


Figure 3. Statistical LTV system functions in the WSSUS case. Adapted from [AZ98].

2.3 Simulation of a fading channel

How to simulate a fading communications channel? There are many approaches. Here we shall briefly discuss how to simulate a Rayleigh fading signal. See [Jak74] and [Par92] for more details.

To obtain a Rayleigh fading envelope and uniformly distributed phase one must generate a zero-mean complex Gaussian signal. The most straightforward way is to low-pass filter two uncorrelated (=independent for Gaussians) Gaussian noise sources and feed them to an IQ modulator. The resulting RF signal will have the complex envelope of a Rayleigh fading signal.

Another approach, also utilized by the PROPSIM radio channel simulator, is based on the bandpass signal²

$$y_{bp}(t) = \text{Re} \left\{ y_{lp} e^{j\omega_c t} \right\},$$

where

$$y_{lp}(t) = A \sum_{n=1}^N e^{j(\omega_n t + \theta_n)} = A \sum_{n=1}^N e^{j[\omega_D t \cos(\alpha_n) + \theta_n]}$$

is the complex envelope of the multipath signal model. $y_{lp}(t)$ is the superposition of N multipath components, each having Doppler shift ω_n and a random phase shift θ_n . All have the same amplitude A . The arrival angle α_n of each multipath component is picked from the uniform distribution. ω_D is the maximum Doppler shift. It follows from the central limit theorem that if the number of multipath components, N , is large enough, $|y_{lp}(t)|$ has a Rayleigh fading amplitude.

Ricean fading signal can be generated by giving one phasor, say A_1 , a bigger amplitude. This can be interpreted as a line-of-sight path.

3 About LTV system measurements and PROPSIM radio channel simulator

3.1 Measurability of LTV system characteristics

In order for an LTV system to be *measurable*³ in the first place the system must not change its characteristics too fast; if the system changes during the observation of an impulse response we cannot expect to measure it accurately even in the absence of noise. It has been shown in [Kai59] that if only maximum⁴ delay spread $T_{m,\max}$ and maximum Doppler spread $B_{d,\max}$ of the system are known, the impulse response is measurable if, and only if, $B_{d,\max} T_{m,\max} \leq 1$. The quantity $S_r = B_{d,\max} T_{m,\max}$ is called the (rectangular) spread factor. If $B_{d,\max} T_{m,\max} > 1$ the system cannot be measured without additional side information.

² This is the response of the channel when a sinusoid with frequency ω_c is applied at the channel input.

³ Impulse response (and other system functions) of a measurable system can be measured as accurately as desired.

⁴ Minimum T_m so that $h(t, \tau) = 0, \tau > T_m$, for all t . Similarly for $h(\tau, \phi)$.

If more information about the channel is known $B_{d,\max}T_{m,\max} \leq 1$ may be too stringent a requirement for measurability of an LTV system. It was shown in [Bel69] that the rectangular spread factor S_r is a special case of a more generalized measurability criterion. If Doppler-delay function $h(\tau, \phi)$ of the LTV system is known the system is measurable iff area spread factor $S_a < 1$. S_a is defined as the area of the region in (τ, ϕ) plane where $h(\tau, \phi)$ is nonzero.

3.2 Measuring impulse response by using a matched filter

Let us first study measurement of a time-invariant system. We then generalize this to the time-variant case simply by repeating the measurement of the quasi-stationary LTV system fast enough.

Theoretically the most obvious way to measure the impulse response of a linear system is to feed an impulse to the input of the system and observe the output. However, this method is susceptible to measurement noise and has also other impracticalities.

Another way to measure impulse response is the matched filter method. Figure 4 portrays a simple block diagram of this method.

A real signal $s(t)$ is sent to the channel with complex impulse response $h(t)$. The received signal is matched-filtered. The output waveform of the matched filter is

$$\begin{aligned} s_{out}(t) &= s(t) \otimes h(t) \otimes s(-t) \\ &= \underbrace{\left(\int_{-\infty}^{\infty} s(\tau) s(\tau - t) d\tau \right)}_{R_{ss}(t)} \otimes h(t) \\ &= R_{ss}(t) \otimes h(t). \end{aligned}$$

We note that the output is a convolution of the autocorrelation function of $s(t)$ and the impulse response $h(t)$. Ideal measurement signal has $R_{ss}(t) = \delta(t)$ since then $\delta(t) \otimes h(t) = h(t)$. In practice the sounding signal $s(t)$ is chosen so that $R_{ss}(t)$ is as close to delta function as possible.

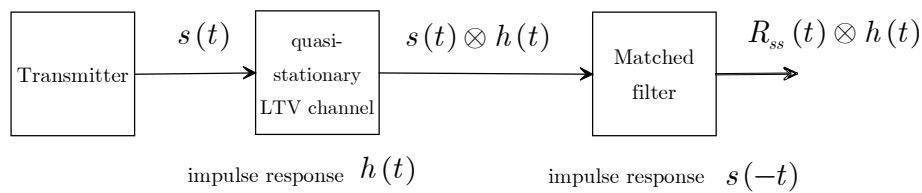


Figure 4. A simplified schematic of impulse response measurement.

A typical choice for $s(t)$ is an m-sequence. Using an m-sequence of length L results in processing gain of $20 \lg(L)$.

When measuring a time-variant system it is assumed that the system does not change during the measurement of one impulse response (quasi-stationary channel). The time-variant impulse response can be constructed by continuously measuring snapshots of the time-varying impulse response. The measurement repetition rate should be significantly higher than the rate of change of system; this is just another manifestation of the sampling theorem. In the case of mobile radio channels the rate of change can be estimated from Doppler spread.

3.3 An overview of PROPSIM radio channel simulator

See Appendices.

Appendices

1. General information on PROPSIM+ radio channel simulator
2. Technical data on PROPSIM+

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Appendix 1: General information on PROPSIM+ radio channel simulator

The following excerpt is from the operation manual of PROPSIM+.

See also www.elektrobit.fi

PROPSIM WIDEBAND RADIO CHANNEL SIMULATOR

PROPSim represents the latest technology in multipath fading simulator systems. With features like 35 MHz bandwidth, 312 fading paths and 2.5 ns delay resolution it has the power to meet the channel simulation requirements of current and future mobile, WLL, and radio LAN systems as well as many other wireless applications.

PROPSim was developed with input from customers at the leading edge of wireless communication technology. This, coupled with high-performance RF/DSP hardware and enhanced channel simulation software, has led to a product of unparalleled performance and versatility. Consequently, PROPSim can be used to simulate a wide range of radio channels including GSM, DCS/PCS/PCN, DECT, IS-54, IS-95, TETRA, ISM-band, UMTS, FPLMTS, B-CDMA, W-CDMA, indoor and user defined / measured channels. PROPSim enables the use of both synthetically generated and real measured impulse responses, including real time changes of delay spread.

PROPSim has many powerful features based on very fast and flexible hardware and software. The incorporated digital signal processing technology enables accurate and reliable channel simulation, with calculations of up to 50 giga operations per second. With the provision of numerous academically proven synthetic channel models and an extendible selection of customisable features, PROPSim provides the user with the ultimate in state of the art radio channel simulation technology.



(Note: Laptop PC is not included in standard PROPSim delivery.)

1. GENERAL

This manual describes the usage of the PROPSim simulator. It contains a general overview of the product and examples concerning its use. In addition to examples, there are detailed descriptions regarding each User Interface item. Figure 1-1 shows the PROPSim, PropSoft and General-IR-Generator windows of the User Interface.

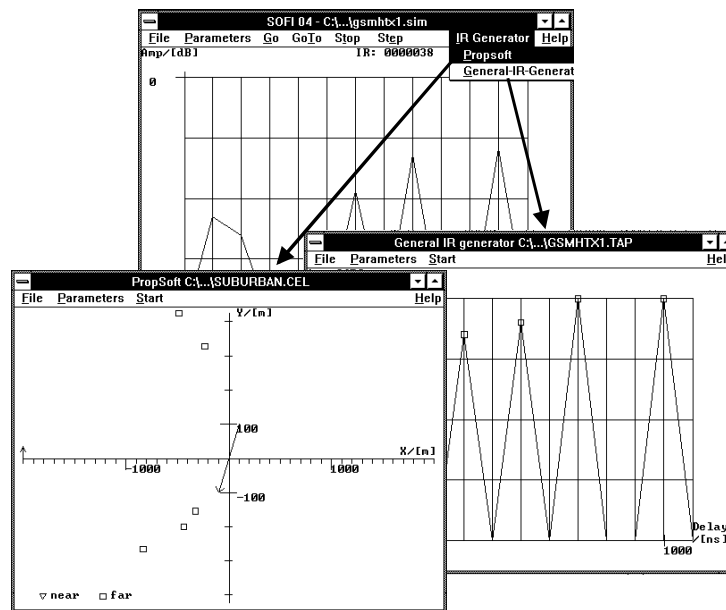


Figure 1-1. PROPSim, PropSoft and General IR generator windows.

The PROPSim system architecture is described in Figure 1-2. The user's RF input signal is down converted into analogue complex base band signals. These signals are filtered and then A/D converted. The multipath fading simulation and summing of taps is carried out in digital parts utilising DSP technology. After fading, the signal is D/A converted and up converted back to the original RF frequency.

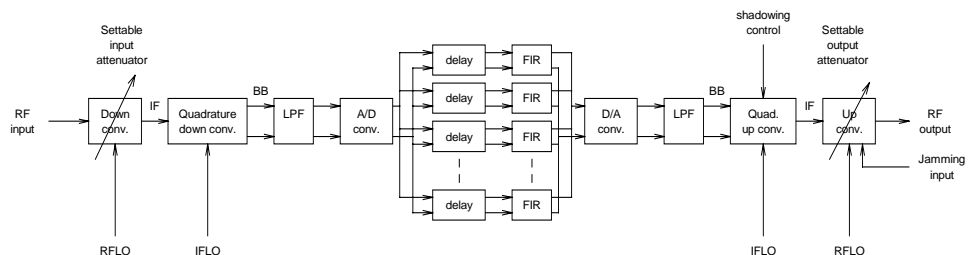


Figure 1-2. General block diagram

1.1 Main functions of external equipment

Note: The external equipment is not included in the standard PROPSim delivery

Host PC

- User interface for setting the operating parameters
- Loading the impulse response files into the PROPSim
- Stores and displays the impulse response files
- Generates the synthetic impulse response files

RF signal generator(s)

Provides the RF local oscillator (RFLO) signals for the LOCLK-unit

Reference source

Reference signal to the LOCLK-unit for phase/frequency locking of the 500 MHz IF local oscillator and the 40 MHz system clock signals. The reference source is usually included in RF signal generators.

NOTE: An alternative reference signal is also provided internally by the LOCLK-unit.

1.2 Configurations

Channels

- One or two channels

Interfaces

- Baseband to baseband
- RF to RF

Note: Independently configurable for each channel.

Fading paths

- 26 paths / taps per fading block
- Min. configuration is 26 paths / taps per channel
- Max. configuration 12*26 paths / taps.

Technical Data

From <http://www.elektrobit.fi/propsim/> [24.1.2001]

Maximum number of channels	2 ¹
Maximum number of fading taps	312
Simulation interfaces	RF, analog baseband
RF frequency range	100...400, 600...2650 MHz
Maximum RF bandwidth	35 MHz
Maximum RF peak input	-15...+10 dBm in 1 dB steps, adjustable
Typical RF output	-40...-15 dBm in 1 dB steps, adjustable
Delay resolution	any
Tap Spacing (TS)	25...3200 ns, adjustable
Tap to tap amplitude and delay error	negligible due to digital tap combining
Maximum propagation delay	100 µs with 25 ns TS 400 µs with 100 ns TS
Maximum Doppler shift	1250 Hz (SD ² =12)
Maximum vehicle speed	613 km/h at 2.2 GHz center frequency (SD=12)
Pre-defined fading distributions	Constant, Classical (Rayleigh), Flat, Pure Doppler, Rice, Gaussian, Nakagami, Log-Normal, Suzuki
Pre-defined channel models	GSM, IS-54, IS-95, ITU 3G, TETRA
Channel modelling software ³	General IR Generator, PropSoft+
Supported Windows versions	95, 98, NT 4.0
Power supply	115/230 V, 50/60 Hz, 800 W
Mechanical dimensions (h x w x d)	400 x 450 x 440 mm

1) Possible to synchronize multiple PROPSim™ units. 2) Sample Density. 3) Also possible to import user defined channel models and measured channel data. 4) Digital Baseband available in PROPSim DBB.

Configurations

- Number of Channels (1 or 2)
- Number of Fading Blocks (1 ... 12)
 - 26 Taps in each Fading Block
 - Maximum Number of Taps 12 x 26 = 312
- Interfaces⁴:
 - RF and Analog Baseband
 - Analog Baseband only

PRELIMINARY EXERCISES

P1

How can you generate the 2-tone signal centered at $f_c = 400$ MHz needed in L1? You have an arbitrary waveform generator and an IQ modulator ($f_c = 400$ MHz) at your disposal. AWG can generate any waveform whose maximum frequency component is less than 100 MHz. How can you generate an M -tone signal? $M = 2, 4, 6, \dots$

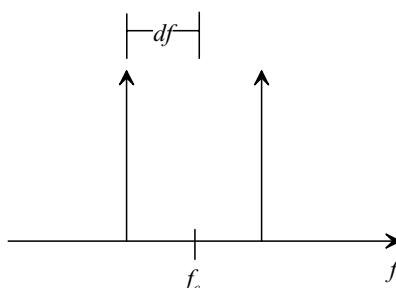


Figure 1. A 2-tone signal on the positive frequency axis.

P2

Rayleigh probability density function is the amplitude distribution of a complex Gaussian signal. Let's derive the Rayleigh pdf

$$f(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} u(r),$$

where $u(r)$ is the unit step function. See e.g. [Pro95, pp. 31-32].

- Present the complex signal $X + jY$ in polar form $re^{-j\theta}$. What is r ? What is θ ?
- The random variables X and Y have zero-mean Gaussian distributions with the same variance σ^2 (this is the "complex Gaussian"). They are also assumed to be independent. What is the joint pdf $f(x, y)$?

- c) Assume that $0 \leq \theta \leq 2\pi$. Find the joint pdf $f(r, \theta)$. This is the joint pdf of the amplitude and phase of a complex Gaussian signal at any given time instant.
- d) Find the Rayleigh pdf $f(r)$ by integrating θ away from $f(r, \theta)$. What is the pdf of the phase, i.e. $f(\theta)$?
- e) How can the assumption that X and Y are Gaussian be justified in a multipath fading scenario?
- f) What would $f(r)$ be if X and Y are not zero-mean (but still independent Gaussians)?

P3

In L1 we shall measure the spaced-frequency correlation function with the so called 2-tone measurement. In this problem we derive the theoretical spaced-frequency function for comparison with the measurement result. The channel model has two independently Rayleigh fading taps with equal average powers. The second tap is delayed 200 ns. Derive the spaced-frequency correlation function $\phi_H(\Delta f, 0)$ for this channel. Plot the absolute value of the function to a graph for frequency separations 0...5MHz.

P4

Level crossing rate (LCR) and average fade duration (AFD) measure how frequently a certain threshold level is crossed and average duration of a fade below certain level, respectively. In this problem we derive AFD and LCR for a Rayleigh fading signal.

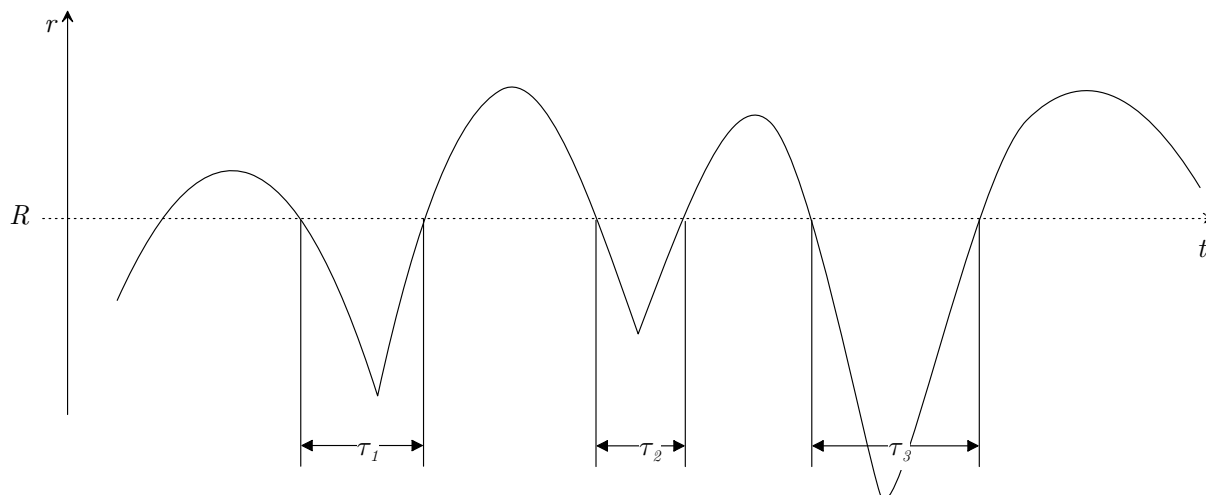


Figure 2. LCR is the average number of positive-going crossings per second. AFD is the average of $\tau_1, \tau_2, \dots, \tau_n$ [Par92].

LCR is defined as the expected rate at which the envelope crosses a specified signal level, R , in the positive-going direction. It can be computed from

$$N(R) = \int_0^{\infty} \dot{r} p(R, \dot{r}) d\dot{r},$$

where $\dot{r} = dr/dt$ and $p(r, \dot{r})$ is the joint probability density function of r and \dot{r} at $r = R$. The problem is now to find $p(r, \dot{r})$. It is known that when $E[r\dot{r}] = 0$, for a complex Gaussian process the joint density in the four random variables $r, \dot{r}, \theta, \dot{\theta}$ is [Jak74]

$$p(r, \dot{r}, \theta, \dot{\theta}) = \frac{r^2}{4\pi^2 \sigma_r^2 \sigma_{\dot{r}}^2} e^{-\frac{1}{2} \left(\frac{r^2}{\sigma_r^2} + \frac{\dot{r}^2}{\sigma_{\dot{r}}^2} + \frac{r^2 \dot{\theta}^2}{\sigma_{\dot{r}}^2} \right)},$$

from which $p(r, \dot{r})$ can be obtained by integrating over θ from 0 to 2π and $\dot{\theta}$ from $-\infty$ to ∞ (why?). θ is the argument ("angle") of the complex signal.

- Find $p(r, \dot{r})$. Then show that $N(R) = \sqrt{\sigma_{\dot{r}}^2 / \pi} \sigma_r^2 R / R_{rms} e^{-R^2 / R_{rms}^2}$, where $R_{rms} = \sqrt{2} \sigma_r$ is the root mean square value of r . Hint: $\int_0^{\infty} e^{-ax^2} dx = \sqrt{\pi / 4a}$.
- What is the level crossing rate for $R = 0.3 R_{rms}$ if the maximum Doppler shift is 0.37 Hz? Hint: From literature¹ we know that $\sigma_{\dot{r}}^2 = 0.5 \sigma_r^2 \omega_d^2$. ω_d is the maximum (angular) Doppler frequency.

¹ See [Jak74], pages 24-26, for details.

- c) The average fade duration of fades can be calculated in the following way. Let τ_i be the duration of the i th fade below $r = R$. Then the probability that $r \leq R$ for a time interval of length T is

$$P(r \leq R) = \frac{1}{T} \sum_i \tau_i.$$

The average fade duration is

$$D(R) = E\{\tau\} = \frac{1}{TN(R)} \sum_i \tau_i = \frac{1}{N(R)} P(r \leq R).$$

Show that the average fade duration for a Rayleigh fading signal is given by

$$D(R) = \sqrt{\frac{\pi\sigma_r^2}{\sigma_i^2}} \frac{R_{rms}}{R} \left(e^{R^2/R_{rms}^2} - 1 \right).$$

- d) What is the average fade duration of a Rayleigh fading signal for $R = 0.3R_{rms}$ and maximum Doppler shift 0.37 Hz?

P5

(Ahlin, Zander: prob 3.1) A linear time-variant (LTV) system is described by its impulse response

$$h(\tau, t) = e^{-\pi \left(\frac{\tau^2}{m^2} + \frac{t^2}{n^2} \right)}, \quad n = 4m.$$

Compute and sketch the following functions:

- The impulse response $h(\tau, t)$.
- The frequency response $H(f, t)$.
- The Doppler-frequency function $D(f, \psi)$.

P6

(Ahlin, Zander: prob 3.4) The statistical properties of the impulse response of a fading channel is characterized by the autocorrelation function

$$\phi_h(\tau, \Delta t) = \begin{cases} (1 - 10^4 |\Delta t|) \cos(1000\pi\tau), & |\tau| < 5 \cdot 10^{-4}, |\Delta t| < 10^{-4} \\ 0 & \text{elsewhere} \end{cases}.$$

- a) Sketch the autocorrelation function $\phi_h(\tau, \Delta t)$.
- b) Compute and sketch the frequency-time correlation function $\phi_H(\Delta f, \Delta t)$.
- c) Compute and sketch the scattering function $S_h(\tau, \psi)$.
- d) Compute and sketch the spectral density $S_H(\Delta f, \psi)$.

P7

(Ahlin, Zander: prob 3.5) For the channel in the previous problem, estimate the following parameters:

- a) The delay spread T_m
- b) The coherence bandwidth B_m
- c) Verify the relation $B_m \approx 1/T_m$.
- d) The coherence time T_d .
- e) The Doppler spread B_d .
- f) Verify the relation $B_d \approx 1/T_d$.

P8

Explain briefly the following concepts:

- a) Flat fading and frequency-selective fading
- b) Slow fading and fast fading
- c) Spread factor.

P9

Examine the laboratory exercises, and make sure that you understand what is being measured in each experiment. Write down any relevant questions that pop into your mind when reading the measurement instructions. You can ask them from the assistant during the laboratory shift and possibly avoid unpredictable troubles in the postprocessing of the measurement results.

LABORATORY MEASUREMENTS

The laboratory part consists of two parts. In part A we study characteristics of time-varying channels directly by using spectrum analyzer, A/D cards and MATLAB. In part B we study the effect of fading on BER performance of a GSM receiver. PROPSIM radio channel simulator is used in both parts for simulating the time-variant communication channel. You should return a report of your measurement results, preferably written with a word processor. Embed graphs, scripts etc to your report.

Part A

DEMO (Flat fading and frequency-selective fading)

Feed an upconverted pseudorandom wideband signal from the AWG to PROPSIM. Observe the channel output with the spectrum analyzer in a flat fading and frequency-selective fading case. Use channel models *1tapray.sim* and *2tapray2.sim*. Use center frequency $f_c = 400$ MHz and RF output level -10 dBm.

How do flat fading or frequency selective fading conditions influence the design of a radio receiver? What are the typical countermeasures used in each case?

L1 (2-tone measurement of spaced-time spaced-frequency correlation)

In this exercise we measure a form¹ of the spaced-time spaced-frequency correlation function $\phi_H(\Delta f, \Delta t)$ by using a spectrum analyzer and the Arbitrary Waveform Generator (AWG).

Load channel model *2tapray2.sim* to PROPSIM. Generate a 2-tone signal by using the AWG and the vector signal generator (as an IQ modulator). Use 400 MHz carrier frequency, resolution bandwidth 30 kHz, frequency span 3 MHz, MS speed 1 km/h.

¹ See question L1b.

Feed the 2-tone signal to PROPSIM and measure amplitude values with five different frequency separations (200 kHz...2.5MHz) using the spectrum analyzer. Marker values from the spectrum analyzer can be read to a file by using the LABVIEW program *read_markers.vi*. Read at least 500 marker values for each frequency separation.

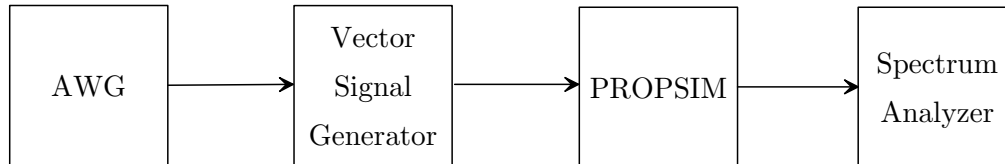


Figure 1. Measurement set-up

- a) Compute the correlation between signal amplitude values for each frequency separation, i.e. $\phi_H(\Delta f, 0)$. Plot the measured correlation into the same graph with the one you computed in P3. Compare and comment on the reason of possible differences.
- b) There is a fundamental difference between this frequency correlation function, and the one computed in P3. What? Hint: What are the estimated expectations in each case?
- c) What is the approximate coherence bandwidth of the fading signal? Assume a correlation of 0.5 or less as the definition of coherence bandwidth. Compare your results with the approximation formulas $B_m \approx 0.276/T_m$ and $B_m \approx 1/5T_m$ given in lecture notes of S-72.232 and [Sk197]. T_m is the delay spread.
- d) Would a GSM receiver need an equalizer in a radio channel having these power-delay properties? Why?
- e) Compute the time correlation function $\phi_H(0, \Delta t)$ for a few delay values. Plot it into a graph. Compare your theoretical result from P3 to the measured result. If they differ, what might be the reason? When plotting time correlation use small delay values, like 10-20 samples. For smoother results compute time correlation for all measurements and average them.
- f) In the GSM system the channel is assumed time-invariant during one burst period. Is this a reasonable assumption in this case? Why?
- g) Suppose that you are a radio network planner and your job is to decide the frequencies used in a GSM frequency hopping sequence. What would be your

choice if the radio channel possessed the frequency correlation properties measured in this experiment? Explain.

L2 (Measurement of LCR and AFD)

In this measurement we investigate the average level crossing rate and the average fade duration of a Rayleigh fading signal. Use 400 MHz carrier frequency.

Set mobile speed to 1 km/h. Use the spectrum analyzer and the LABVIEW program *read_markers2.vi* to measure the power of the fading signal. Measure 1000 values. Use channel models *1tapray.sim* and *5tapray.sim*.

- a) Plot the amplitude of the signal using logarithmic scale for the y axis. What is the dynamic range² of the signal in dB? What is the rms signal level?
- b) Determine the average level crossing rate and the average fade duration of the signal at $R = 0.3R_{rms}$. Compare to theoretical results obtained in the preliminary exercises.
- c) Estimate amplitude probability distribution function using histogram³. Compare with theory, i.e. plot the Rayleigh pdf to the same plot using the same variance as the sample variance of the measured signal.
- d) Repeat part c) for the channel model *5tapray.sim*. How does the result differ from the 1-tap case and why? Compare variances of the 1-tap and the 5-tap signals and explain the difference.

L3 (Measurement and analysis of LTV system functions)

In this exercise we measure the time-variant impulse response and compute other LTV system functions from it. Statistical LTV system functions are also estimated from the measured data sample and important channel parameters are extracted from them.

² Difference between minimum and maximum values of the signal.

³ If you want you may use kernel-based density estimation methods or other fancy stuff.

Use the baseband outputs in the backside of PROPSIM to connect the real and imaginary signals to the A/D cards (see Figure 2). Load channel model *5tap2.sim* to PROPSIM. Set CIR update rate to 120 Hz. Use the 127-chip long pseudorandom code (*pn127*) as the input signal to PROPSIM baseband (real or imaginary part) input. Set triggering signal frequency to 20 Hz. Set the AWG to send three bursts of the pn code for each trigger instant. Set the AWG output filter bandwidth to 100 MHz. Record relevant parameters of the measurement, such as the sampling frequency in both dimensions, for later use.

Measure 1024 snapshots of the channel baseband output using the sampling cards and MATLAB script *cap2.m*. Save the measurement data to a file for post-processing.

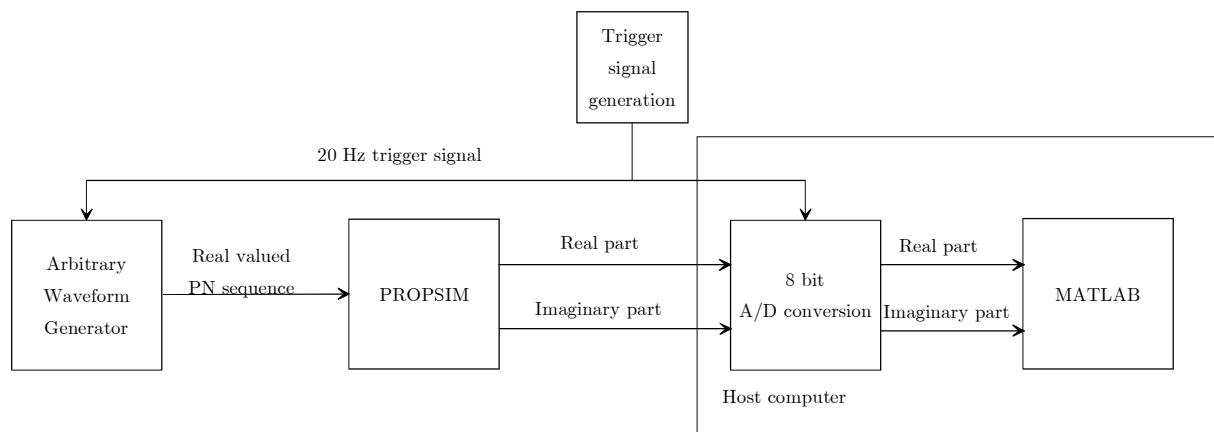


Figure 2. Block diagram of impulse response measurement.

Directly measured LTV system functions

- a) Construct the time-variant impulse response $h(\tau, t)$ by correlating or matched filtering the measured data with the 127-chip long pseudorandom code; the end result should be the same using both methods. Plot a segment of the real part, imaginary part, and the absolute value of the impulse response, for instance the first 25 impulse response snapshots.
 - What is the absolute delay spread (in contrast to rms delay spread) of the impulse response? Give your answer in micro seconds.
 - What are the tap delays in micro seconds? Assume that the first tap has zero-delay.

- What can you say about the amplitude distribution of the channel taps? Any visible differences between the taps?
 - What are the average powers of the channel taps? Normalize the strongest channel tap to 0 dB.
- b) Construct the time-variant channel transfer function $H(f, t) = \mathbb{F}_\tau \{h(\tau, t)\}$ by using `fft`. Plot a segment of the magnitude response $|H(f, t)|$. Use logarithmic scale.
- What is the approximate bandwidth⁴ of the channel during the observation interval⁵?

Construct the delay-Doppler spread function and plot it.

- What seem to be the Doppler distributions of the channel taps?
- What is the Doppler spread during the observation interval?
- Assume that the measurement was done at the mobile station and carrier frequency is 900 MHz. Estimate the speed of the mobile station. Show your calculations.

Statistical LTV system functions (estimated)

- c) Estimate and plot the frequency correlation function $\phi_H(\Delta f, 0)$. What is the coherence bandwidth?
- d) Estimate and plot the time correlation function $\phi_H(0, \Delta t)$. What is the coherence time?
- e) Estimate and plot the Doppler power spectrum $S_H(0, \psi)$. Compare to the classical Jakes' (U-shaped) Doppler spectrum.
- f) Estimate the spread factor.

⁴ When talking about bandwidth, one should always declare which definition is being used, e.g. null-to-null bandwidth, -3dB bandwidth,...

⁵ This is evaluated for the observed data sample. If we wish to know what is the bandwidth of the channel *on average* we must use the statistical LTV system functions.

Part B

In this part we investigate the BER performance of a GSM receiver in different fading scenarios. Use the same GSM1800 phone in all measurements. You can read BER values from the GSM tester by using the program *cts_ber2.exe*. Set the simulator average output level to -20 dBm and use the tunable attenuator to control the MS received level. Use GSM1800 channel number 516. This corresponds to downlink center frequency of 1806 MHz, and uplink center frequency of 1711 MHz.

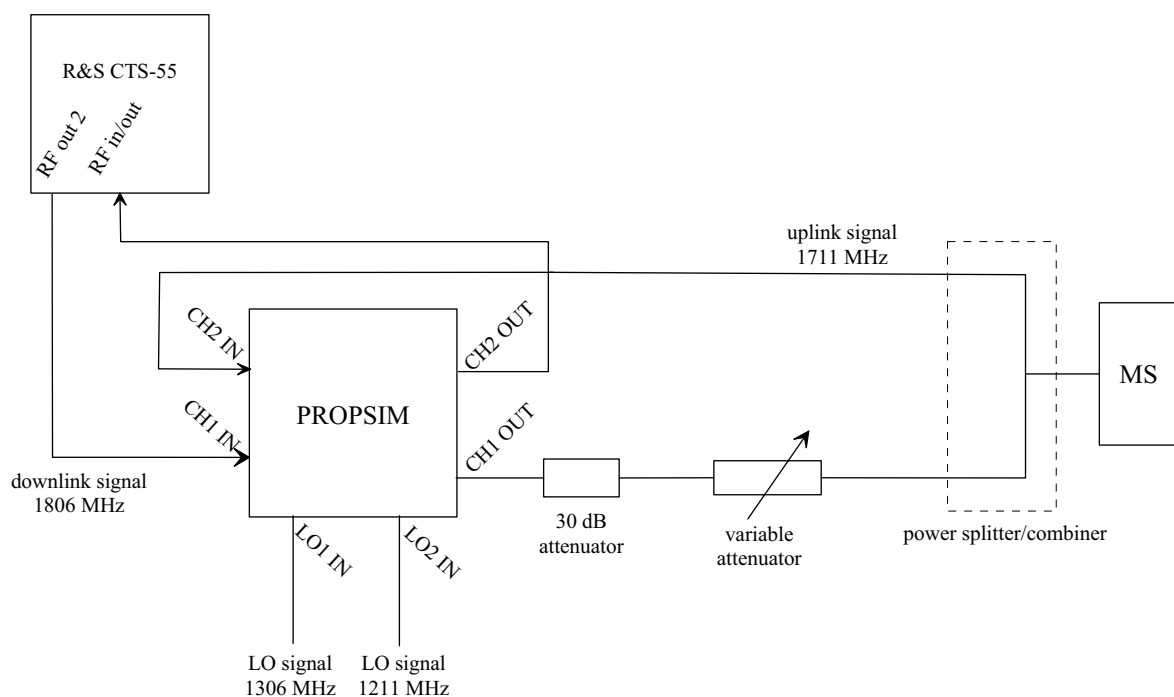


Figure 3. BER measurement set-up.

L4 (Fading vs static channel)

Measure BER curve as a function of the received downlink signal level. For easy comparison choose the downlink levels so that FER goes from 0 to about 30-40% in both cases. Use the following channels:

- a) 1-tap static channel. Use channel model file *1tapcon.sim*.
- b) 1-tap Rayleigh, MS speed 50 km/h. Use channel model file *1tapray.sim*.

- c) Plot FER curves of both measurements into one chart. Repeat for RBERIb and RBERII. Compare the results. How much better does the static channel perform than the 5-tap Rayleigh?
- d) What are the countermeasures against fading used in GSM and CDMA systems?
- e) Compare measurement results of part c) with the requirements given in GSM spec. 05.05. See Appendix 2 of laboratory work #1.

L5 (The effect of channel coherence)

Measure the error curves as a function of MS speed when the average downlink received level is about -95 dBm. Use MS speeds $\{0.5, 5, 50, 150, 250\}$ km/h.

- a) 1-tap Rayleigh. Use channel model *1tapray.sim*.
- b) 5-tap Rayleigh. Use channel model *5tapds16.sim*.
- c) Plot the FER curves into the same graph. Repeat for RBERIb and RBERII. Comment on the results. What differences are there? What causes the poor performance when MS speed is slow, and how is this mitigated in existing mobile communication systems? Speculate on the reason for the poor BER performance in the flat fading when MS moves fast?

L6 (The effect of delay spread)

Investigate how delay spread affects BER behaviour. Use channel models *5tapdsXX.sim*. $XX \in \{16, 20, 24, 28, 32, 36, 40\}$ is the delay spread in micro seconds. Use MS speed 50 km/h and minimum attenuation. Explain the measurement results.

Some instructions for the lab report

Do not forget to include your email addresses to your lab report (for sending boomerang info). You should write the laboratory report with a word processor. There are no strict requirements on the format of the report, except that it must be readable and understandable. Anyone reading your report should be able to follow your line of reasoning and, if necessary, be able to repeat your actions and verify the results. To make the report more readable you should embed figures, tables etc to your report (not everything to appendices). Long MATLAB scripts and functions should be put into appendices.

For plotting figures, excellent black&white printing quality is obtained by using the command `print picname -deps2 -tiff`. The EPS picture file can be inserted into the document and resized according to one's needs without degradation in quality. For 3D pictures the EPS files might be quite large (looking for a solution to this one...). Use `subplot` when applicable.

The report does not have to be long but you should include at least:

- Answers to the questions presented above along with the appropriate figures.
- MATLAB scripts, functions and/or command line actions documented along with brief comments. Without this it is very difficult to verify what you have done. Do not, however, pile your report full of non-important MATLAB code (thus making it unreadable). The `diary` function might be useful.
- A section on what were the most difficult parts, and how did you solve them.