LINKING THEORY AND PRACTICE USING TELECOMMUNICATIONS INSTRUCTIONAL MODELLING SYSTEM - TIMS

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Abstract
The following paper presents one approach on how to improve the linkage between presented theoretical content of the lectures in telecommunications courses by demonstrating real signals representing given theory by means of modelling. This is realized with Telecommunications Instructional Modelling System - TIMS from EMONA, Australia. In order to reduce the cost of the lab equipment, experiments are demonstrated by the teacher. All of the bellow mentioned experiments are suited for undergraduate and graduate students participating in telecommunication courses.

Key words: *experiment, modelling, telecommunications*

1. INTRODUCTION

In the recent years it is possible to observe a decreasing interest of students to enrol in technical university programs. Information technologies and telecommunications namely are not an exception. To address this problem a system of modelling experiments in undergraduate and graduate courses applied in the Institute of Telecommunication of the Faculty of Electrical engineering and Information Technology of Slovak University of Technology (IT-FEI-STU) in Bratislava, Slovakia has developed. A quite a large set of experiments based on pedagogical experience aimed to increase the interest of students about the telecommunications was created by the author: (Rakus D4, D5 2011) and (Rakus D6, D7 2012). Mentioned laboratory experiments were written with the emphasis on their direct use by the teacher without necessity to gather the additional information sources. They provide a basic theory necessary to understand the given topics. Condensed versions of the experiments are given in (Hooper, Rakus et al 2013). They serve mainly teachers as quick links to given topics or may inspire further ideas about experiment expansions. TIMS experiments serve as a supplementary teaching material at IT-FEI-STU to accompany the following subjects: digital communications, mobile and satellite communications I, II and III. The paper is organized as follows. In section 2. motivation, target objective and the description of the proposed experiment setup is given. One example of the experiment: "Experimental BER measurement of coherent BPSK signalling using TIMS" is presented in section 3. Description of used methodology for the evaluation of the contribution of the demonstration experiment is given in Section 4. Section 5. concludes the paper.

2. DESCRIPTION OF THE EXPERIMENT SETUP

It is a commonly known fact that one appropriate picture can replace "thousands" of words. This especially can be mentioned with technical sciences. This can be very well illustrated on the case of Parseval theorem for power signals. Assuming only real power signals Parseval theorem can be expressed as:

$$P_x = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} x^2(t)dt = \sum_{n=-\infty}^{\infty} |c_n|^2 \quad (1)$$

, where P_x is the normalized signal power, $x(t)$ analytically describes signal in time domain, T is signal period, $|c_n|$ are complex Fourier coefficients and n is the index of harmonics. The outcome of (1) expressed in words: "signal power calculated in time domain is equal to signal power calculated in frequency domain". Looking at (1) this simple outcome might not be evident to student at first glance. Let us expand this example further by using the simple harmonic signal, which can be described in time domain as:

$$x(t) = A\cos\left(2\pi f_0 t\right) \quad (2)$$

, where A is signal amplitude and f_0 is signal frequency. Time plot of (2) is shown on Figure 1.

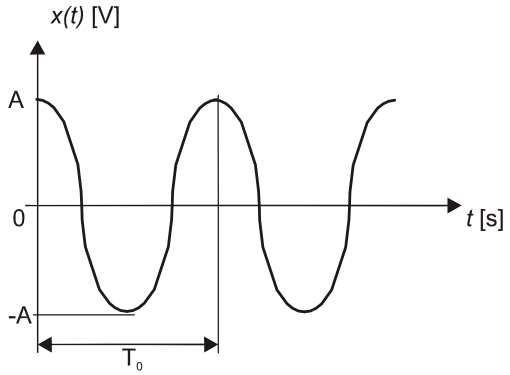


Figure 1. Harmonic signal in time domain.

In order to calculate $|c_n|$ we need to know the signal representation in frequency domain - its amplitude spectrum, denoted as $X(f)$. The standard way for obtaining signal amplitude spectrum is to perform Fourier transform on it:

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi f t}dt \quad (3)$$

For simple harmonic signal, defined in (2) its amplitude spectrum is:

$$X(f) = \frac{A}{2}\left[\delta(f - f_0) + (\delta + f_0)\right] \quad (4)$$

Frequency plot of (4) is shown on Figure 2.

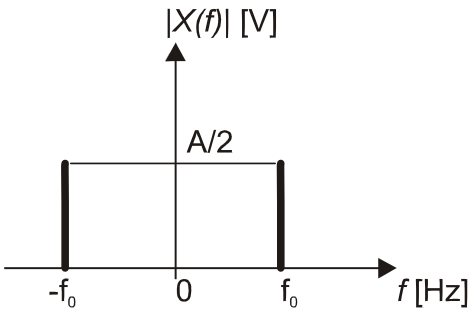


Figure 2. Amplitude spectrum of harmonic signal.

For students looking at (2) and (4) my not invoke, that it is the same signal but observed from two different points of view, see Figure 3:

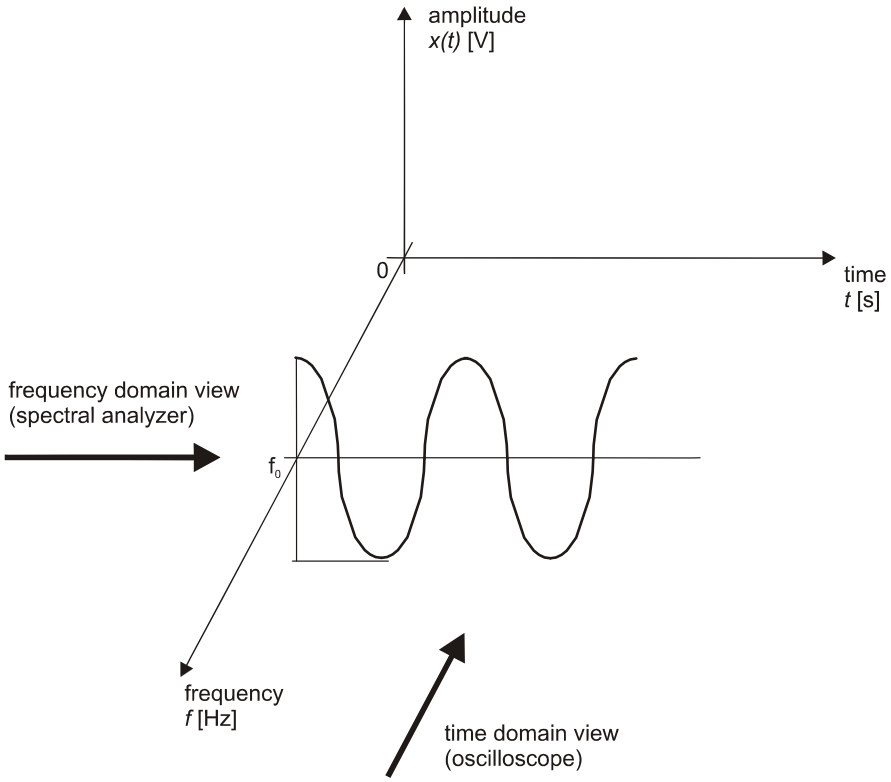


Figure 3. Time domain versus frequency domain.

By looking at Figure 3. it is evident that time domain and frequency domain are two different points of view for looking at the same signal. Fourier transform (3) serves as a "transition procedure" from one domain to another. Therefore it is intuitive that (1) has to hold. The goal of this simple example was to show on how important it is to let the students know that a rather complex theory can be demonstrated by using simple signals. One way how to bridge lectured theory with experience in the area of telecommunication is using Telecommunications Instructional Modelling System - TIMS (TIMS). TIMS can model various sub blocks of physical and link layer of the most up-to-date communication systems. With support of efficient ADC (internal or external e.g. from PICO technology (PICO)) and suitable software all observed signals can be displayed in time or frequency domain. Used control software enables to store and also to measure various parameters of the observed waveforms. The ideal teaching process of telecommunication subjects using TIMS is depicted on Figure 4.

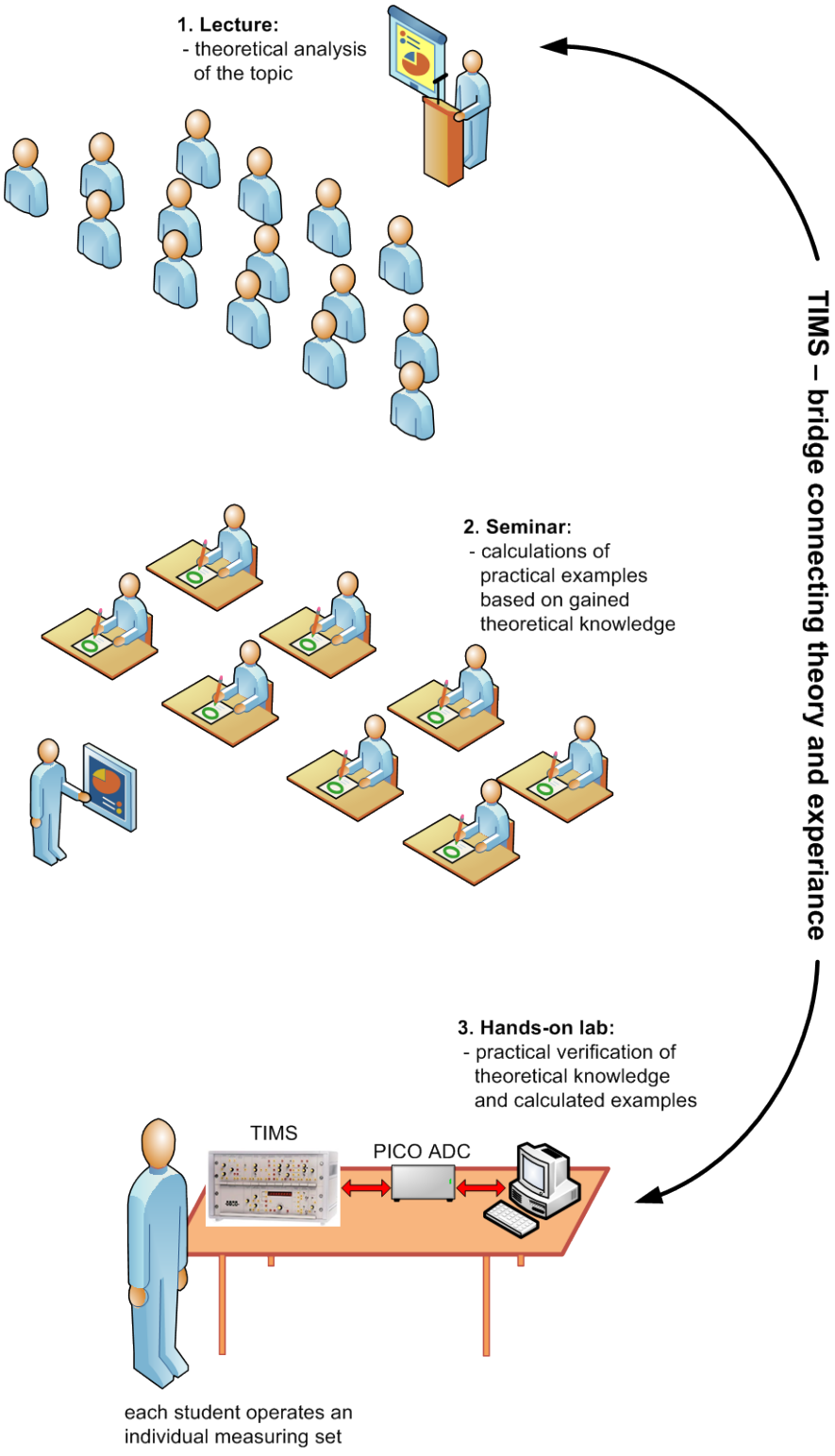


Figure 4. Ideal scenario.

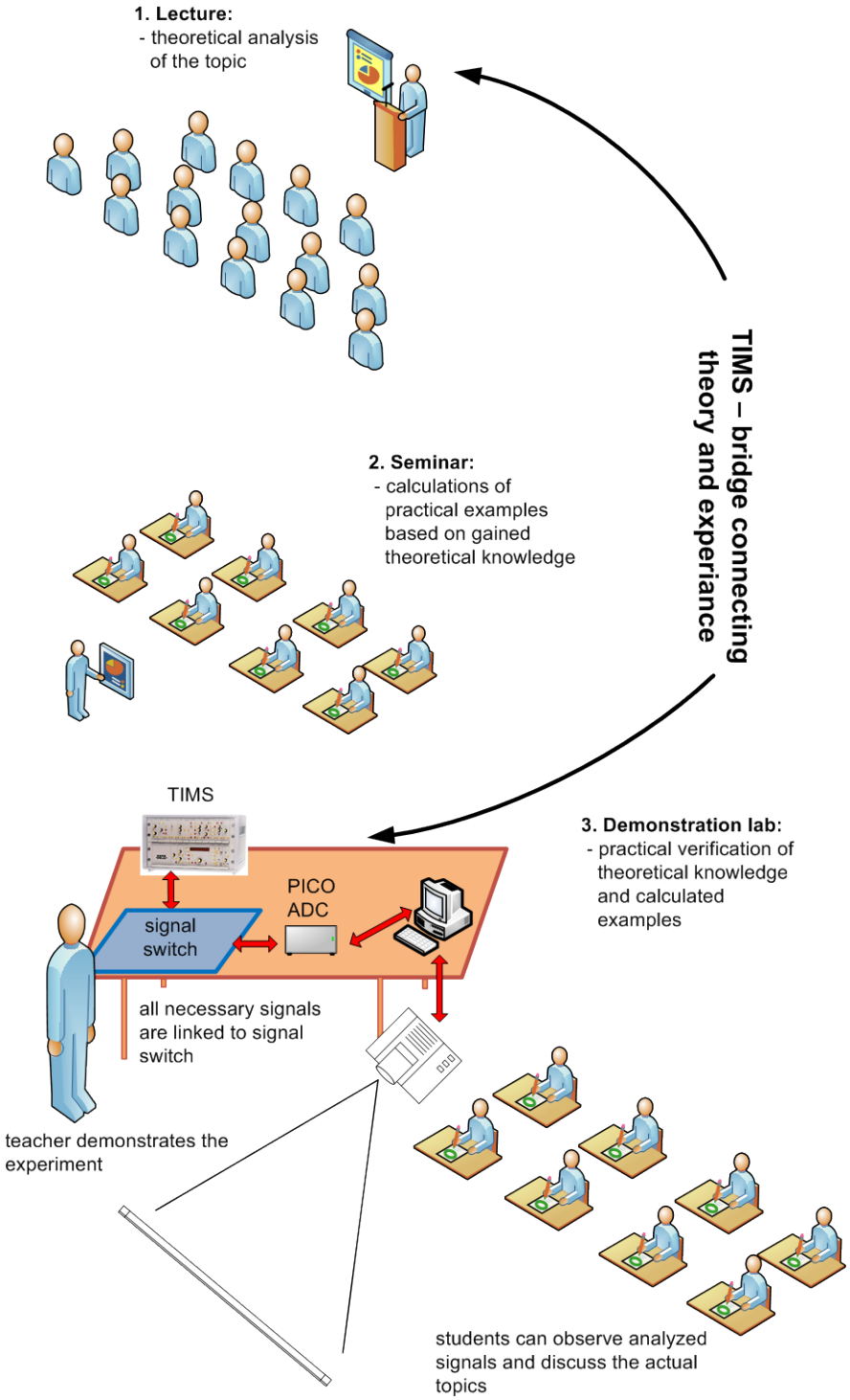


Figure 5. Cost-effective demonstration scenario.

Teaching scenario shown on Figure 4. is ideal but relatively costly, since each student (or couple of students) operates a complete measuring set. The advantage of this approach is a true "hands-on" experience of each student. One alternative to this approach is to use "demonstration" scenario shown on Figure 5. In order to demonstrate complex sub blocks with many signals it is convenient for teacher to connect all displayed signals to central signal switch. This switch is interconnected with used ADC by means of 3 BNC cables (assuming 4CH oscilloscope). Trigger for the scope is taken directly from TIMS. Then all concerned signals can be easily displayed in natural sequence using particular signal

switch on the central signal switch panel. This eliminates problematic constant change of interconnections of the measuring device inputs to the modelling system during seminar. This scenario is currently used on subjects: digital communications, mobile communications I and II on IT-FEI-STU. One example of the application of this approach is described in the next section.

3. EXAMPLE OF THE REALIZED EXPERIMENT: "EXPERIMENTAL BER MEASUREMENT OF COHERENT BPSK SIGNALLING USING TIMS".

The aim of the presented experiment is to point at the power of modelling to link rather complex theory with real measurable outcome confirming this theory. More experiments can be found on (TIMS).

The bit error rate (BER) is one of the basic measures for the assessment of the quality of transmission in digital communication systems. This section describes in a simple way a practical BER measurement of coherent Binary Phase Shift Keying (BPSK) which is in-line with a classical textbook derivation of bit error probability. The goal of the experiment is a direct comparison of practically measured BER with theoretically predicted bit error probability using waterfall curves. The first part of the experiment contains the minimum theoretical background necessary to comprehend the topic.

The following theoretical introduction is taken from (Sklar 2003) and it is limited to the description of the main principles of the band pass demodulation and detection of binary signals. More complex view reader can find in (Benvenuto 2002) and (Proakis 2001). The theoretical part is split into three logical parts: transmitting side, channel and the receiving side.

Transmitting side:

BPSK signal can be analytically described as:

$$s_i(t) = \sqrt{\frac{2E_b}{T_b}} \sin\left[\omega_c t + \Phi_i(t)\right] \qquad \begin{matrix} 0 \le t \le T_b \\ i = 1,2 \end{matrix} \tag{5}$$

, where ϖ_c is carrier radian frequency and T_b is bit duration. Signal amplitude is expressed as:

$$A = \sqrt{\frac{2E_b}{T_b}} \tag{6}$$

, where E_b is bit energy. The phase term $\Phi_i(t)$ have discrete values given by:

$$\Phi_i(t) = (1+i) \times \pi \quad i = 1,2 \tag{7}$$

Let signal $s_1(t)$ represents binary 1 and $s_2(t)$ binary 0. In order to perform BPSK modulation the original UNRZ data signal $d(t)$ has to be mapped to BPNRZ signal, denoted as $d(t)_{\text{BPNRZ}}$. BPSK modulator is realized as a simple analog multiplier. One input of the modulator is BPNRZ data signal: $d(t)_{\text{BPNRZ}}$. The other input of the modulator is connected to RF carrier signal: $A\sin(2\pi f_c t)$. Since $sin(x)$ is an odd function after multiplication with a constant (which alternates sign) the phase of the resulting signal is either 0° or 180° . It is possible to show that the envelope of a single sided base band amplitude spectrum $|X_d(f)|$ of a random data signal has shape of $|si(x)|$ function. If we multiply random data signal (mapped to BPNRZ signal) with carrier signal in time domain this will results in frequency shift of base band signal spectrum to band pass with centre on carrier frequency. Thus band pass signal bandwidth (null-to-null) equals to twice base band signal bandwidth:

$$W_{BPSK\ null-to-null} = \frac{2}{T_b} \tag{8}$$

Channel:

To simplify the analysis we will assume an ideal distortion less channel.

Note: in the experiment a noise generator approximating AWGN channel will be used.

Receiving side:

On the receiving side an inverse operations as on the transmitting side have to be performed. The first step is to translate the received signal from band pass to base band be means of demodulator. Demodulation of BPSK signal is performed by analog multiplication of BPSK modulated signal by locally generated carrier signal (frequency and time synchronized) in an analog multiplier. The output signal of the BPSK demodulator has double the frequency of a locally generated carrier signal and its envelope bears the information about transmitted data (the intelligence):

$$d(t)A^2\sin^2\left(2\pi f_c t\right) = d(t)\frac{A^2}{2}\left[1-\cos\left(4\pi f_c t\right)\right] \tag{9}$$

An optimum receiving filter is a matched filter (MF). Its output sampled at bit intervals produces test statistic. Based on test statistic detection block decides about which symbol was probably transmitted. Intelligence can be recovered by using MF, realized as a correlator. The output of correlator (without AWGN) is:

$$\int_0^{T_b} d(t)A^2\sin^2\left(2\pi f_c t\right)dt = \pm\frac{A^2T_b}{2} \tag{10}$$

To determine bit error probability of coherent BPSK signalling it is assumed that only AWGN is present in the channel. Let us suppose that signal $s_1(t)$ has been transmitted. Then the received signal, denoted as $r(t)$ can be expressed as:

$$r(t) = s_1(t) + n(t) \tag{11}$$

Signal components a_i of test statistic $z_i(T_b)$ have to be calculated:

$$z_i(T_b) = a_i(T_b) + n(T_b) \qquad i = 1,2 \tag{12}$$

$$\begin{aligned} a_1(T_b) &= E\left\{z_1(T_b)/s_1(t)\right\} = E\left\{\int_0^{T_b} r(t)s_1(t)dt\right\} \\ &= E\left\{\int_0^{T_b}\left[s_1(t)+n(t)\right]s_1(t)dt\right\} = \frac{2E_b}{T_b}\int_0^{T_b}\sin^2\left(\omega_c t\right)dt = E_b \end{aligned} \tag{13}$$

, where $E\{z_1(T_b)/s_1(t)\}$ is the expected value of $z_1(T_b)$, given that signal $s_1(t)$ was transmitted. This follows since $E\{n(t)\} = 0$. Similarly: $a_2(T_b) = -E_b$. Energy of signals $s_1(t)$ and $s_2(t)$ can be calculated as:

$$E_i = \int_0^{T_b} s_i^2(t)dt = \int_0^{T_b}\left[\pm A\sin\left(\omega_c t\right)\right]^2 dt = \frac{A^2T_b}{2} \quad i = 1,2 \tag{14}$$

The test statistic is formed from the difference of the correlators outputs: $z(T_b) = z_1(T_b) - z_2(T_b)$. In case of antipodal signalling the optimum decision threshold equals to:

$$\gamma_0 = \frac{a_1 - a_2}{2} \tag{15}$$

Based on the value of the test statistic $z(T_b)$ a decision (detection) is made in regards to the digital meaning of that sample, representing a given symbol (bit). Detection is performed by choosing one of

$$z(T_b) \underset{H_2}{\overset{H_1}{\gtrless}} \gamma_0$$

the two possible (binary) hypotheses: H_1 or H_2 by comparing the value of the test statistic $z(T_b)$ with the threshold value γ_0:

(16)

The inequality (16) indicates that hypothesis H_1 is chosen if $z(T_b) > \gamma_0$, and hypothesis H_2 is chosen if $z(T_b) < \gamma_0$. If $z(T_b) = \gamma_0$, the decision can be an arbitrary one. Choosing H_1 is equivalent to deciding that signal $s_1(t)$ was sent and hence a binary 1 is detected. Similarly, choosing H_2 is equivalent to deciding that signal $s_2(t)$ was sent and hence a binary 0 is detected. There are two ways errors can occur. An error e will occur when signal $s_1(t)$ was sent, and channel noise results in the receiver output signal $z(t)$ being less than decision threshold γ_0 . The probability of such event is:

$$p(e/s_1) = p(H_2/s_1) = \int_{-\infty}^{\gamma_0} p(z/s_1)\,dz \tag{17}$$

Since conditional probability density functions (PDF) are symmetrical an analogical equation to (17) holds for $p(e/s_2)$. The probability of an error is the sum of the probabilities of all the ways that an error can occur. For binary case the bit error probability can be expressed as:

$$P_b = \sum_{1}^{2} p(e/s_i)P(s_i) \tag{18}$$

By Combining (17) and (18) probability of bit error can be calculated:

$$P_b = p(e/s_1)P(s_1) + p(e/s_2)P(s_2) = p(H_2/s_1)P(s_1) + p(H_1/s_2)P(s_2) \tag{19}$$

If the priori probabilities of transmitted signals are equal then (19) it can be rewritten to:

$$P_b = \frac{1}{2}\left[p(H_2/s_1) + p(H_1/s_2)\right] \tag{20}$$

Because of the symmetry of conditional PDFs, it holds that:

$$P_b = p(H_2/s_1) = p(H_1/s_2) \tag{21}$$

The probability of a bit error, P_b is numerically equal to the area under the "tail" of either conditional PDFs, falling on the "incorrect" side of the threshold. Therefore P_b can be expressed as (assuming that noise is AWGN):

$$P_b = \int_{\gamma_0}^{\infty} p(z/s_2)\,dz = \int_{\gamma_0}^{\infty} \frac{1}{\sigma_0\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{z-a_2}{\sigma_0}\right)^2\right] dz \tag{22}$$

, where σ_0^2 is the variance of the noise at the output of the correlator. If the correlator input signal contains only AWGN signal (and no data signal) it can be shown that:

$$\sigma_0^2 = \frac{N_0}{2}E \Rightarrow 2\sigma_0 = \sqrt{2N_0E} \tag{23}$$

, where E is signal energy. (23) assuming that the input signal is correlated with the signal prototype. Let: $u = (z - a_2)/\sigma_0$, then $\sigma_0\,du = dz$ and P_b can be expressed as:

$$P_b = \int_{\gamma_0}^{\infty} \frac{1}{\sigma_0\sqrt{2\pi}} \exp\left[-\frac{u^2}{2}\right] du = Q\left(\frac{a_1 - a_2}{2\sigma_0}\right) \tag{24}$$

, where $Q(x)$ is the complementary error function. By applying (13), (14) and (23) to (24) the bit error probability at the output of the detector can be derived:

$$P_b = Q\left(\frac{a_1 - a_2}{2\sigma_0}\right) = Q\left(\frac{E_b - (E_b)}{\sqrt{2N_0E_b}}\right) = Q\left(\sqrt{\frac{2\bar{E}_b}{\sqrt{N_0}}}\right) \tag{25}$$

, where $\bar{E}_b$ is the average signal energy per bit. In case of equally likely signalling ($P(s_1) = P(s_2)$) it is clear that:

$$\bar{E}_b = \frac{A^2 T_b}{2} \tag{26}$$

Experimental BER Measurement of Coherent BPSK signalling

In the following experiment BER of coherent BPSK signalling will be measured assuming an ideal distortion less channel and perfect time (phase) synchronization. As a data source PN generator will be used. For the BER evaluation the output signal from the receiver is compared bit–by–bit with the locally generated replica of transmitted signal. Correlation of the measured BER with theoretically predicted P_b will be demonstrated using the waterfall plot. Block diagram of measurement set-up is shown on Figure 6. Details of the experiment can be found in (Rakus D4-03 2011). After initial setup and wiring-up BPSK transmitter, students can compare observed BPSK signal using oscilloscope with its analytical description (5), see Figure 7. Data signal for the experiment is obtained from PN generator, clocked with f_{CLK} = 2.083 [kHz], derived from 100 [kHz] Master clock signal divided by 48.

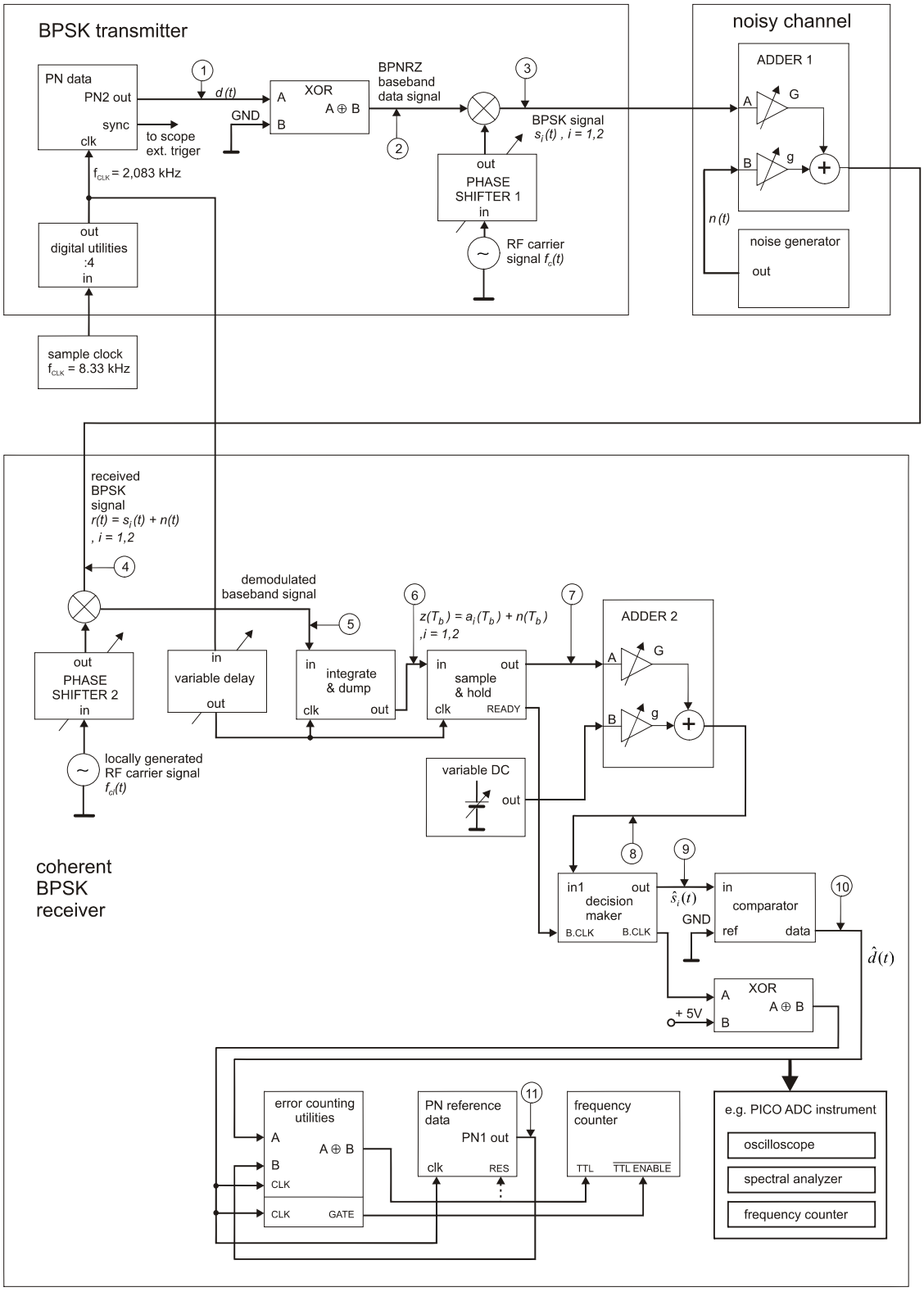


Figure 6. Block diagram of experiment setup.

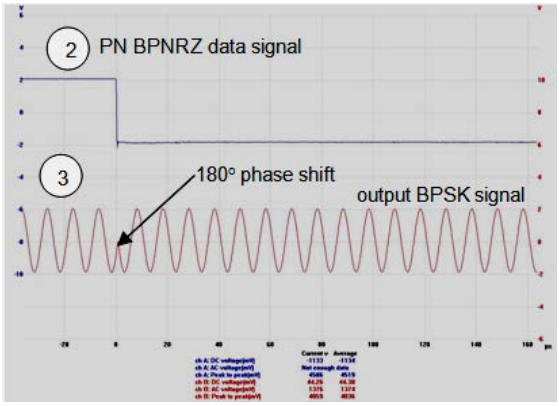


*Figure 7. Negative pulse of PN BPNRZ data – signal and output BPSK signal – check points **2** and **3** on the block diagram.*

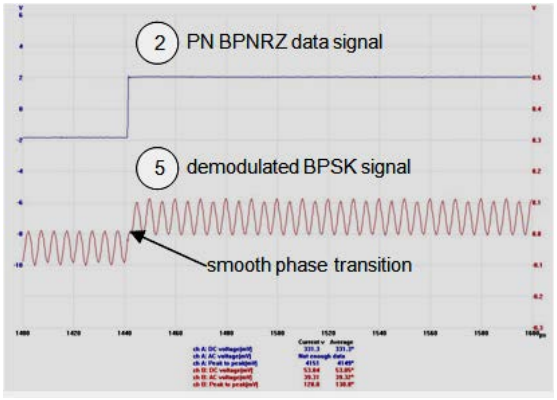


*Figure 8. Output signal of the BPSK demodulator check points **2** and **5** on the block diagram.*

Thus data bit duration T_b = 480 [μs], what students can easily verify by oscilloscope. Initially the noise is not present in the channel; therefore it is necessary to disconnect the output of the noise generator from the input B on ADDER 1 module (see Figure 6). On the receiving side students can compare observed demodulated BPSK signal, see Figure 8, with its analytical expression (9). Receiving filter – a matched filter is realized as a correlator therefore it has to be time synchronized with the input signal. As it follows from (Sklar), the output of a matched filter can be replaced with a correlator output only at the end of the symbol (bit in this case) interval, therefore it is important a proper timing of an integration, see Figure 9. For the further detection process it is important the value of test statistic $z(T_b)$ – a value of the integration at the end of a bit time interval T_b. To preserve this value for the detection process the output of a correlator is fed to the sample & hold circuit. This supplies sampling. Sample & hold a circuit holds the value of $z(T_b)$ for the whole bit time duration, see Figure 10.

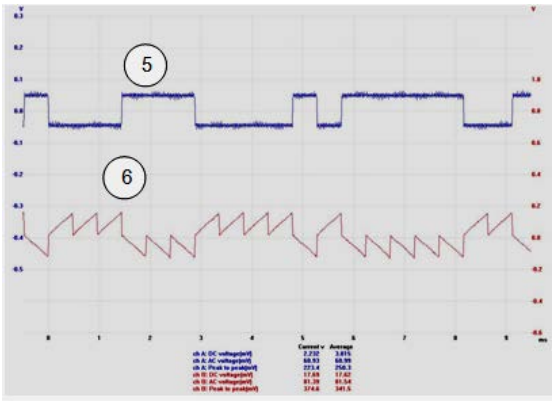


*Figure 9. Input and output of the correlator (without noise) – check points **5** and **6** on the block diagram.*

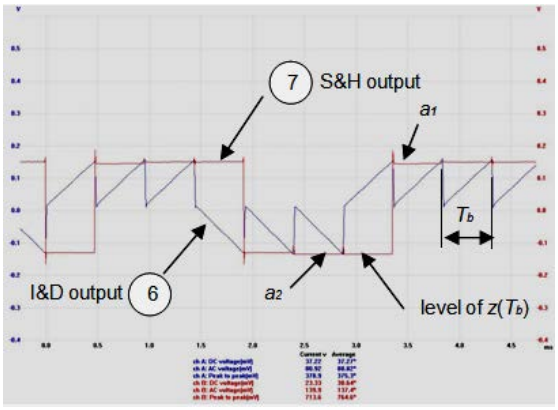


*Figure 10. Input and output of the sample & hold (without noise) – check points **6** and **7** on the block diagram.*

Using an oscilloscope it is possible to verify that the output signal of a comparator – received data signal $\hat{d}(t)$, is the same (time shifted) as the transmitted data signal $d(t)$, see Figure 11.

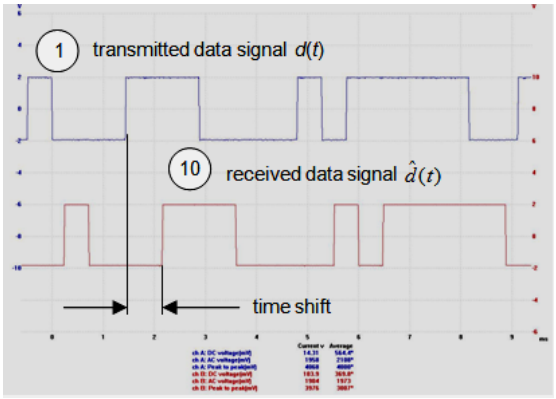


Figure 11. Comparison of transmitted and received data (without noise) – check points

1 and **10** on the block diagram.

To align reference signal and received data signal a sliding-window correlator is used. As a first step it is necessary to measure the noise level at the input of the decision maker block, therefore transmitted signal has to be temporarily disconnected from input A of ADDER 1 and the output of the noise generator has to be reconnected to the input B of ADDER 1 (see Figure 6). Initially signal-to-noise ratio (SNR) will be set to 0 [dB], later the noise level will be decreased in 2 [dB] steps, what will provide higher SNR. At the beginning of BER measurement the noise level on the noise generator is set to +22 [dB]. Using an oscilloscope measurement options students can measure the average DC and AC value of the noise at the decision maker input – check point **8** on the block diagram. Maximum number of samples per scope trace: 50 000, and no. of readings: 200 provide an adequate accuracy. Displayed DC voltage is the average voltage during one complete cycle. Displayed AC voltage is the *rms* sum of the reading minus the DC voltage for one complete cycle. Therefore the *rms* value of the noise equals to:

$$n_{rms} = \sqrt{DC^2 + AC^2} \tag{27}$$

To maintain the accuracy of BER measurement from now on all measured values of the analyzed signals will be **average** values, as all entries are in (27). Students can create their own tables for processing of measured and calculated values. In the next step the noise has to be disconnected from input B of ADDER 1 and transmitted signal reconnected to the input A of ADDER 1 (see Figure 6). To set *SNR* = 1 signal level at the input of the decision maker has to be set (with gain control G on ADDER 1) to the **same *rms*** value as is ***rms*** value of the noise. This takes a while and a little extra calculation. This set-up is extremely important for the accuracy of BER measurement. Students can calculate the signal *rms* value using (27). Realized matched filter converts both noise and the signal to the square signal of the same width. Taking the base band bandwidth of the signal as $1/T_b$, then $W = R$ and:

$$\frac{E_b}{N_0} = \frac{S}{N} = SNR \tag{28}$$

The average signal power can be calculated as: $S = s_{rms}^2$. Similarly the average noise power can be calculated as: $N = n_{rms}^2$. Therefore by setting *rms* value of the signal to the same *rms* value of the noise at the input of the decision maker with regard to (28) E_b/N_0 is now set to 0 [dB]. Using an oscilloscope, students can measure values of signal components a_1 and a_2 of test statistic $z(T_b)$ at the decision maker input – check point **8** on the block diagram. Derived formula for P_b (24) assumes that noise at the detector input is AWGN, what means that: $m_x = 0$ and $\sigma_x^2 = 1$, where m_x denotes mean and σ_x^2 denotes variance. However noise in this experiment does not have normalized normal distribution, although its distribution is very close to normal distribution see (Radzyner, Rakus et al

2011). For this reason (24) cannot be used directly and particular mean and variance of random variable at the input of the decision maker has to be taken into account. In order to use tabulated (or pre-programmed) *Q* function for not normalized normal distribution its argument has to be changed:

$$Q_n(x) = Q\left(\frac{x - m_x}{\sigma_x}\right) \tag{29}$$

, where $Q_n(x)$ denotes complementary error function for $N(m_x, \sigma_x^2)$, where: $m_x \neq 0$ and $\sigma_x^2 \neq 1$. Let particular measured values of signal components are:

$$a_1 = +0.267[\text{V}] \quad \text{and} \quad a_1 = -0.279[\text{V}] \tag{30}$$

An optimum threshold value γ_0 can be expressed using (15):

$$\gamma_0 = \frac{0.267 - 0.279}{2} = -0.006[\text{V}] \tag{31}$$

Conditional probabilities can be then calculated as:

$$p(1/0) = Q\left(\frac{-0.006 + 0.279}{0.2736}\right) = Q(0.9978) \cong 15.87 \times 10^{-2} \tag{32}$$

and:

$$p(0/1) = \Phi\left(\frac{-0.006 - 0.279}{0.2736}\right) = \Phi(-0.9978) = Q(0.9978) \cong 15.87 \times 10^{-2} \tag{33}$$

,where standard deviation σ_x is value of the AC component of the noise. One period of used PN data sequence is 127 [b] long, and contains 63 zeros and 64 ones. A priori probabilities can be simply calculated as:

$$P(0) = \frac{63}{127} \cong 0.4961 \quad \text{and} \quad P(1) = \frac{64}{127} \cong 0.5039 \tag{34}$$

Since P(0) ≅ P(1), then P(0) = P(1) =1/2 and further if conditional probabilities are symmetrical: p(1/0) = p(0/1) then bit error probability can be calculated using (20) and (21) as:

$$P_b = \frac{1}{2} \times \left[p(1/0) + p(0/1)\right] = p(0/1) = 15.87 \times 10^{-2} \tag{35}$$

For the actual *BER* measurement noise has to be reconnected to input B of ADDER 1 (see Figure 6). The test sequence (transmitted data) will have fixed length of *r* bits. *BER* measuring device is then comparing the received sequence with the locally generated replica of transmitted test sequence. The result of this comparison outputs the number of errors denoted as *l* , occurred during the transmission of test sequence. Examined *BER* is defined as: *BER* = *l*/*r*. For each point of measured *BER* curve, a test sequence of *r* bits has been transmitted. The size of *r* depends on the expected *BER* value. The smaller *BER* value, the longer the test sequence *r* has to be. *BER* tends to the probability of bit error P_b (derived for a given signalization scheme) when *r* tends to infinity:

$$P_b = \lim_{r \to \infty}(BER) \tag{36}$$

In real *BER* measurement *r* has to be finite and has to have suitable length. Therefore a compromise between accuracy and time of the measurement has to be found. In (Stevan 1989) using Chebyshev inequality a formula for a required size of test sequence *r* was derived:

$$r \leq \frac{1 - P_b}{P_b\, k^2 (1 - S)} \tag{37}$$

, where P_b is theoretical bit error probability. Confidence S, defines the probability that a random variable (*BER*) will be within the limits $\pm\varepsilon$ around the mean value P_b. $\varepsilon = kP_b$, k is real. Comparison of the received sequence with the locally generated replica of transmitted test sequence is performed by clocked XOR gate using Error Counting Utilities module. Initially the length of the test sequence is set to $r = 4 \times 10^3$ [b]. Number of errors are displayed on frequency counter switched to counting mode. Frequency counter always displays one confidence count, therefore measured *BER* is:

$$BER = (\text{displayed value} - 1) / r \tag{38}$$

It is recommended to perform *BER* measurement 5 times and use the average value of *BER* for plotting waterfall curve. Next the noise level on Noise generator has to be set to +20dB. The noise level is now decreased by 2 dB, what corresponds to $E_b/N_0 = +2$ [dB]. Average DC and AC components of the noise have to be measured using the above described way. P_b and *BER* for $E_b/N_0 = +2$ [dB] has to be calculated using (35) and (38). a_1, a_2, and γ_0 are the same as in previous *BER* measurement since only the noise power (and thus σ_x) has been changed. *BER* is measured using the above described way as for $E_b/N_0 = 0$ [dB]. Next the noise level on Noise generator has to be set to +18dB. The noise level now corresponds to $E_b/N_0 = +4$ [dB]. To maintain required accuracy, according to (37), the length of a test sequence has to be increased. Therefore pulse count. on the Error Counting Utilities module has to be set to 4×10^4. For $E_b/N_0 = +6$ [dB] and +8 [dB] the length of the test sequence has to be increased to 4×10^5. For $E_b/N_0 = +10$ [dB] the length of the test sequence has to be further increased to 4×10^6. This is the border E_b/N_0 ratio what can be used for this particular measurement, whilst maintaining reasonable accuracy and measurement time. Now students can plot theoretical calculated P_b versus measured *BER* using waterfall curves, see Figure 12.

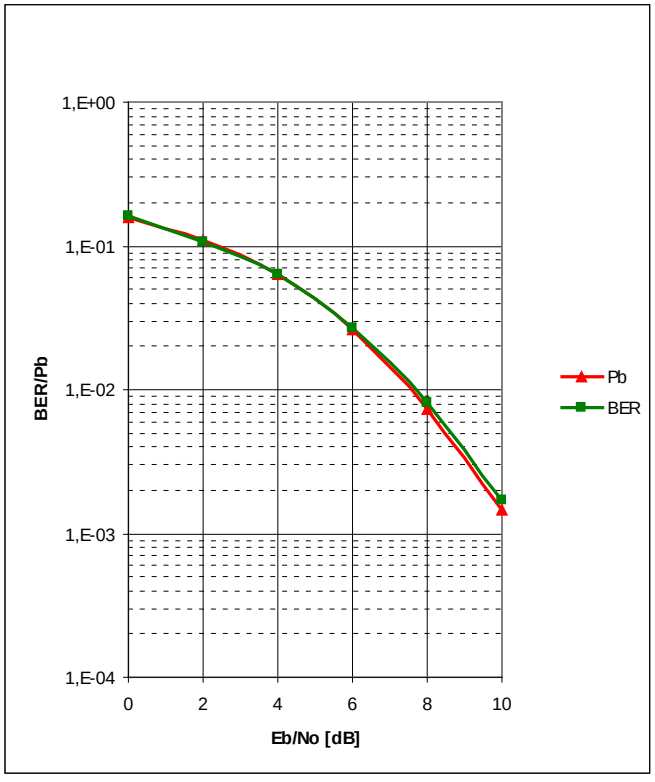


Figure 12. P_b versus measured BER for coherent BPSK signalling.

4. METHODOLOGY OF THE EVALUATION OF THE CONTRIBUTION OF THE REALIZED EXPERIMENTS

Currently "demonstration" approach as was shown on Figure 5. is an integral part of the educational process in the undergraduate and graduate courses at the Institute of Telecommunications at FEI-STU Bratislava. Namely in these subjects, see Tables 1. and 2.

Undergraduate study	
Subject	experiment
Digital communications	line codes and their spectra
Mobile and satellite communications I.	time and frequency domain, verification of Parseval theorem for harmonic and non harmonic signals
	frequency bands, base band vs. band pass spectra
	constellations of MPSK and M-ary QAM modulations

Table 1. Exploiting TIMS demonstration experiments in undergraduate study.

Graduate study	
Subject	experiment
Mobile and satellite communications II.	3 channel DS SS/BPSK CDMA system
	3 channel FH SS/BFSK CDMA system
	single channel TH SS/BPSK system

Table 2. Exploiting TIMS demonstration experiments in graduate study.

The survey of the contribution of the demonstration experiment to the better comprehending of the lectured theory was performed using questionnaire. The questionnaire (see Table 3.) was simple targeting two main points:

1. does the demonstration of the experiments help students to better comprehend lectured theory
2. would student prefer to perform "hands-on" experiments (if possible)

In the survey participated 73 undergraduate students taking subject "digital communications". The survey was performed on the seminars. Students which filled out questionnaire were divided into 8 seminars with 9 students (in the average) in each.

Question	**Possible answers**
1. Do you think that demonstration of the real signals modelled by TIMS contributed to your better understanding of the lectured theory?	☐ strongly agree ☐ agree ☐ disagree ☐ strongly disagree
2. Did the presented demonstration help you to link lectured theory and reality?	☐ strongly agree ☐ agree ☐ disagree ☐ strongly disagree
3. Do you prefer realization of the similar experiments in a "hands-on" manner by students themselves?	☐ strongly agree ☐ agree ☐ disagree ☐ strongly disagree
4. Do you think that the individual simulation (by students) of the experiment using simulation software TutorTIMS prior seminar will increase the comprehension of the lectured theory?	☐ strongly agree ☐ agree ☐ disagree ☐ strongly disagree

Table 3. Questionnaire.

Survey questions were evaluated using a four-level Likert scale, with 4 meaning strongly agree and 1 meaning strongly disagree. Results of questionnaire are in Table 4. Table 4 clearly reveals that using TIMS as a complement to teaching of telecommunications courses helps students understanding of the lectured matter. The other important outcome from Table 4 is that students would prefer an individual "hands-on" labs and pre-lab learning using simulation tool TutorTIMS. In order to gather more statistically reliable data in the near future it is planned to perform a similar survey also in the subjects of the graduate study of telecommunications at IT-FEI-STU in Bratislava.

Answer	**Question n.1**	**Question n.2**	**Question n.3**	**Question n.4**
"strongly agree"	42,47%	54,79%	47,95%	57,53%
"agree"	50,68%	39,73%	30,14%	27,40%
"disagree"	6,85%	5,48%	17,81%	13,70%
"strongly disagree"	0,00%	0,00%	4,11%	1,37%

Table 4. Questionnaire results.

5. CONCLUSION

Statistical testing of the usefulness of the demonstration experiments (as a complement to standard teaching methods) performed using modelling system TIMS clearly proved its suitability in education process. The described "demonstration" approach is a middle way solution in cases when limited budget does not allow to create "hands-on" lab sets for each student. The suggested use of signal switch greatly simplifies teacher's job, since he/she does not have to pay great attention to manual signal switching. As one example of bridging theory and experience was described an experiment verifying bit error probability formula for coherent BPSK signalling. In the above-described experiment students can practically “touch” the theory of the detection of signals in Gaussian noise. Especially the function of a matched filter is “demystified” when they can observe the effect of MF on noise by means of real signals. Through the experiment students practically measure *BER* of coherent BPSK signalling using an ideal distortion less channel. Based on the theoretical background a bit error probability was derived. Comparison of theoretically predicted bit error probability with the actually measured BER was demonstrating on waterfall curves. Good accordance of measured *BER* with the theory (see Figure 12) proves the validity of the used measurement method. Our experience with the "demostration" approach from Figure 5 in the educational process proves the justification of using modelling methods in education as an important complement to theoretical lectures.

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REFERENCES

Rakus, M. et al.: Volume D4 Further Advanced Digital Experiments, Communication Systems Modelling with TIMS, Emona Instruments Pty Ltd, Australia, 2011. ISBN 978-1-921903-00-7

Rakus, M.: *Volume D5 Basic Spread Spectrum Experiments*, Communication Systems Modelling with TIMS, Emona Instruments Pty Ltd, Australia, 2011. ISBN 978-1- 921903-01-4

Rakus, M.: *Volume D6 Advanced Spread Spectrum Experiments*, Communication Systems Modelling with TIMS, Emona Instruments Pty Ltd, Australia, 2012. ISBN 978-1-921903-09-0

Rakus, M.: *Volume D7 Advanced BER Experiments*, Communication Systems Modelling with TIMS, Emona Instruments Pty Ltd, Australia, 2012. ISBN 978-1-921903-10-6

Hooper T. Rakús, M. et al: *LabSheet Experiments*, Communication Systems Modelling with TIMS, Emona Instruments Pty Ltd, Australia, 2013. ISBN 978-1-921903-03-8

TIMS homepage: www.qpsk.com

PICO Technology homepage: www.picotech.com

Sklar, B.: “*Digital Communications – Fundamentals and Applications*”, Prentice Hall PTR, second edition, 2003.

Benvenuto, N., Cherubini, CH. “Algorithms for Communications Systems and their Applications,” John Willey & Sons, 2002.

Proakis, J. G. “Digital Communications,” McGrawHill, fourth edition, 2001.

Rakus, M.: D4-03: *BER Measurement of Coherent BPSK Signaling in an Ideal Distortionless channel*, Volume D4 Further Advanced Digital Experiments, Communication Systems Modelling with TIMS, Emona Instruments Pty Ltd, Australia, 2011. ISBN 978-1-921903-00-7

R. Radzyner. Rakus M. et al.: *S1-14: Random signal Analysis: AWGN and erfc*, Volume S1, TIMS Signals & Systems Experiment Manual, Communication Systems Modelling with TIMS, Emona Instruments Pty Ltd, Australia, 2011. ISBN 978-1-921903-02-1

Stevan, B.: "*Techniques for Bit Error Rate Measurement Using Chebyshev Inequality*", Electronics Letters, vol. 25, no.14, July, 1989.