

## A MATLAB Based Cellular Mobile Communication Laboratory

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### ABSTRACT

**In this paper, we present a novel MATLAB based Cellular mobile communication (CMC) laboratory course that comprises a total of ten experiments, covering the fundamental design parameters, considerations, and estimations of CMC both in the radio interface and core network levels. In the radio interface side, estimation of path loss, fading, power delay profile, and received bit error probability, while in the core network side, estimation of link budget of earth-satellite-earth communication, inland microwave communication, and radio resource allocation and scheduling are included. In addition, a fundamental to the MATLAB is also introduced at the very beginning for allowing students to understand of how to code in MATLAB. The laboratory was offered in fall 2012 at American International University-Bangladesh (AIUB) for three sections each with a group of 40 students. The student's comments on understanding, achieved knowledge, overall satisfaction, importance of the laboratory course, and any changes on the existing course content are documented and assessed.**

### KEYWORDS

Cellular mobile communication, experiment, laboratory, MATLAB, software tool.

### 1 INTRODUCTION

CMC is one of the fastest growing sectors in telecommunication industry worldwide. The users of CMC have increased rapidly in the last two decades globally. User demands for rich multimedia services at high data rates are ever increasing. Telecommunication vendors and operators have been consistently putting significant efforts to fulfill the user needs.

To address the high demand of CMC services, hands-on experienced workforce is a prerequisite that are primarily supposed to be provided by the universities. As mentioned in the table I of reference [1], a number of universities have already offered laboratory courses related to the mobile wireless communication with emphasizing on hardware, software, or a combination of hardware and software. Several publications, for example [1], addressed the importance of wireless communications laboratory to complement the course while few others addressed with specific areas such as cellular network planning [2], wireless networks and mobile systems [3], wireless and mobile embedded systems [4]. However, because most universities lack heavily from sufficient funding, resources, and facilities, it is difficult to setup physical laboratory of CMC to provide students with hands-on experiences. This huge investment for physical setup can be saved by developing a virtual environment using

MATLAB software tools. With a software based CMC laboratory, students can model many features of CMC, analyze and evaluate the performance in both link and system level. However, since a CMC laboratory based on MATLAB tool is not obvious, in this paper we present a novel MATLAB based CMC laboratory.

The paper is organized as follows. In section 2, the methodology used to develop each experiment is discussed. All experiments of the laboratory are briefly described in section 3. The laboratory assessment is incorporated in section 4. We finish the paper with a conclusion in section 5.

## **2 LABORATORY DEVELOPMENT METHODOLOGY**

In this section, we describe how the development of each laboratory experiment is carried out. We consider a stepwise approach to develop each experiment as follows. *Step01: introduction* into which relevant background, problem statement, objective, and significance of the experiment is described. *Step02: system or link model* that incorporates three parts: conceptual model, analytical model, and simulation model. The conceptual model incorporates the system or link architecture and configuration. The analytical model incorporates necessary mathematical expressions that transform the conceptual model into a methodical demonstration. The simulation model incorporates typical simulation parameters, assumptions, and scenarios which are used to simulate the system or link behavior based on the analytical model for performance evaluation. In addition, simulation experimental

procedure of each experiment such as simulation algorithm is included. *Step03: performance analysis and evaluation* where the simulation result at system or link level is analyzed and performance is evaluated with regard to realistic results. *Step04: predefined experimental question-answer* into which a number of predefined questions are included, and students are asked to answer these questions using MATLAB simulator to investigate the degree of change in performance with the variation of system or link parameters. *Step05: references* section cites all the materials that are used for developing the experiment and recommended for further study. *Step06: appendices* include mainly help documents, e.g. relevant MATLAB functions and simulation m-files including MATLAB codes for performance measures of an experiment.

## **3 LABORATORY EXPERIMENTS**

In this section, we describe all the experiments of CMC laboratory concisely in terms of major objectives and significance, necessary mathematical expressions and illustrations, and relevant performance analysis and evaluations. A detailed description of each experiment can be found emailing to either of the authors.

### **3.1 Experiment 1: Introduction to MATLAB**

Because the CMC laboratory is MATLAB simulator based, it is essential for the students to get familiarized with the use of this tool. In line with so, this experiment is designed to give students an overview on how to define and use operators, functions, variables, etc. in MATLAB. More specifically, we

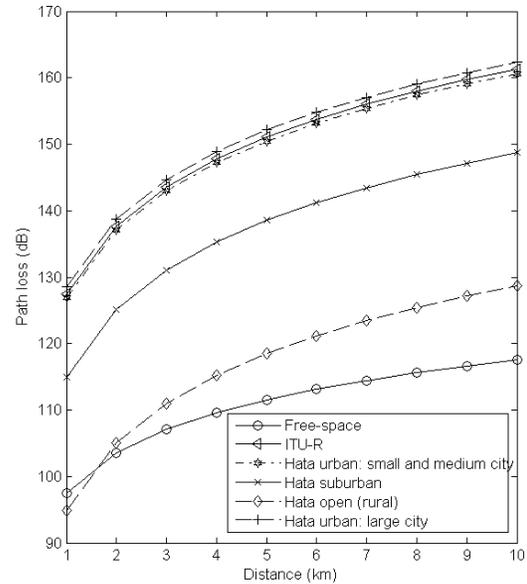
emphasize considerably on common mathematical functions, complex numbers, elementary matrices, vector and matrix calculations, numerical operations and transformations of matrices, operator precedence, general and logical functions, data manipulation commands, and graphics. However, because of MATLAB's wide spread applications, we limit our focus on using those instructions that are more relevant to simulate the objectives of this laboratory experiments only.

### 3.2 Experiment 2: Propagation Models and Path Loss Estimation in Cellular Mobile Communication

In this experiment, we primarily carry out the impact of carrier frequency ( $f$ ) and distance ( $d$ ) on path loss. In addition, a sensitivity analysis is carried out that provides critical parameters such as base station (BS) antenna height ( $h_b$ ), mobile station (MS) antenna height ( $h_m$ ) is incorporated for the system design and planning purpose.

We consider the very optimistic Free-space model, the very pessimistic International Telecommunication Union Radiocommunication Sector (ITU-R) model, and the more realistic Hata model. All models are conceptually and analytically described, followed by respective simulation performance evaluation. We finish this experiment with a comparison of these path loss model simulation results as shown in figure 1.

### 3.3 Experiment 3: Estimation of Received Bit Energy for Data Rates in Wireless Communication



**Figure 1.** Path loss versus distance estimation ( $f(\text{MHz})=1800$ ;  $h_m (m)=3$ ,  $h_b (m)=50$ ,  $d (km)=1$  to  $10$ ).

In this experiment, students can understand how the received signal strength varies with the physical parameters of the environment. The received signal and noise strengths respectively are the function of energy per bit ( $E_b$ ), and noise spectral density ( $N_0$ ). Hence, estimating the required received energy per bit over  $N_0$  ( $\frac{E_b}{N_0}$ ) is inevitably a crucial need for designing reliable wireless communication systems. This estimation provides students with information regarding fundamental trade-offs between received power and channel bandwidth requirements, for example, for a given bandwidth (BW), the channel capacity depends directly on  $\frac{E_b}{N_0}$  [5].

Denote data rate by  $R$  (bits/s), the bandwidth utilization of a radio channel link  $v$  can be mathematically expressed as follows.

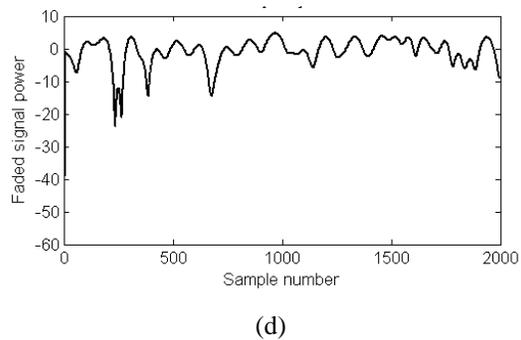
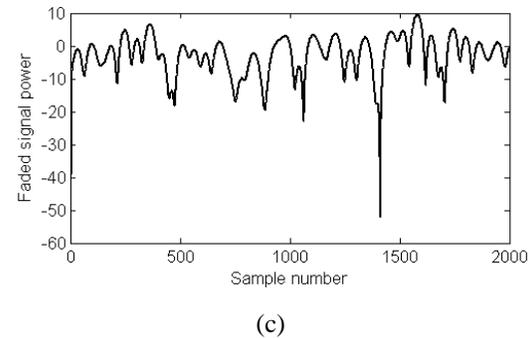
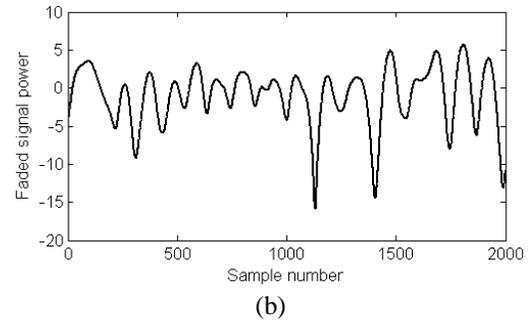
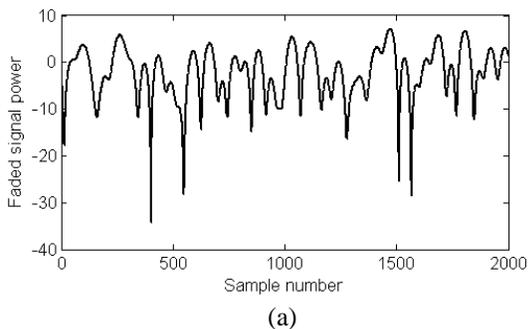
$$v = \frac{R}{BW} \quad (1)$$

Hence, by plotting  $\frac{E_b}{N_0}$  as a function of  $\nu$ , students are able to define regions that are constrained either by received power or available channel bandwidth as given in [5].

### 3.4 Experiment 4: Multipath Fading in Cellular Mobile Communication

In this experiment, students simulate the small-scale multipath fading effect on the transmitted signal. For non line-of-sight (NLOS) case, the received signal envelope follows Rayleigh distribution, and hence, the fading effect is simulated using built-in Rayleigh channel fading function in MATLAB. However, when at least one LOS component is present, the received signal envelope follows Rician distribution, and hence, the fading effect is simulated using built-in Rician channel fading function in MATLAB.

The fading effect is investigated under both frequency-flat and frequency-selective channel conditions in order to understand the effect of multipath propagation over the single path. The effect of change in Doppler spread, symbol duration, and the Rician K-factor on the channel response is also analyzed. Figure 2 shows an example of Rayleigh fading as well as Rician fading channel responses for frequency flat as well as frequency selective fading.



**Figure 2.** Frequency flat (a) Rayleigh fading and (b) Rician fading channel responses and frequency selective (c) Rayleigh fading and (d) Rician fading channel responses.

### 3.5 Experiment 5: Power-Delay Profile and Doppler Spectrum for Channel Classification in Cellular Mobile Communication

This experiment provides students with how to classify channels by evaluating power-delay profile and Doppler spectrum in cellular mobile communication. Power-delay profile and Doppler spectrum are major indicators for designing channel bandwidth ( $B_s$ ) and transmitted symbol duration ( $T_s$ ).

In multipath channels, the transmitted signal propagates over various paths, and each path is characterized with relative power and delay. The power-delay profile of the channel is an indication of the expected degree of dispersion of the transmitted signal that defines the maximum possible transmission bandwidth ( $B_c$ ) by evaluating delay spread of the channel for proper reception.

Similarly, the spectral broadening or Doppler spread ( $f_d$ ) of the transmitted signal, caused by the degree of relative motion between BS and MS, defines the maximum possible transmitted symbol duration ( $T_c$ ). Based on the relative magnitude of  $B_c$  over  $B_s$  and  $T_c$  over  $T_s$ , the channel can be classified as given in table 1.

**Table 1.** Channel classification in mobile communication.

Channel classification		
Parameter	Condition	Channel type
Delay spread	$B_c \gg B_s$	Frequency flat
	$B_c < B_s$	Frequency selective
Doppler spread	$T_c \gg T_s$	Slow fading
	$T_c < T_s$	Fast fading

### 3.6 Experiment 6: Design of Cellular Mobile System

This experiment gives the students an overview on cellular mobile system design. With changing system scenario, students are able to understand how the system design parameters and requirements change for optimal performance.

The design of cellular mobile system depends on several issues. Hence, we restrict the scope of system scenario considerations to carrier-to-interference level, cell structure, system and channel bandwidths, environmental profile, cell

splitting and sectorization strategy, receiver filter characteristics, traffic distribution, trunked system nature, and coverage area.

Given such an explicit system scenario, students are able to estimate system design requirements and parameters such as frequency reuse factor, minimum co-channel cell reuse ratio, spectral efficiency, system capacity, minimum adjacent channel frequency separation, number of cells required for the coverage area, channel allocations with or without sectorization, new transmit power after cell splitting, traffic intensity, bit transfer capacity, and trunking efficiency [6].

Figure 3 shows an example scenario of the effect of sectorization on channel, a total of 125 channels, allocation for fixed channel assignment in the 7-cell cluster. Denote cells by A, B, C, D, E, F, and G, figure 3 shows the channel allocation to each cell with no sectorization. However, when sectorization is considered, the channel allocation only for the sector 1 of each cell is shown. Similarly, the channel allocation to other sectors such as 2 and 3 for 3-sectored cell and sectors 2, 3, 4, 5, and 6 for 6-sectored cell can be estimated. Note that with sectorization, the capacity is improved by a factor of 3 and 6 respectively for 3-sectored cell and 6-sectored cell as compared with the capacity with no sectorization, however, results in an increase in call blocking rate.

Cell index	No sectorization
A	1 8 15 22 29 36 43 50 57 64 71 78 85 92 99 106 113 120
B	2 9 16 23 30 37 44 51 58 65 72 79 86 93 100 107 114 121
C	3 10 17 24 31 38 45 52 59 66 73 80 87 94 101 108 115 122
D	4 11 18 25 32 39 46 53 60 67 74 81 88 95 102 109 116 123

E	5 12 19 26 33 40 47 54 61 68 75 82 89 96 103 110 117 124	
F	6 13 20 27 34 41 48 55 62 69 76 83 90 97 104 111 118 125	
G	7 14 21 28 35 42 49 56 63 70 77 84 91 98 105 112 119 0	
Sector index	With sectorization	
	3-sectored cell	6-sectored cell
A1	1 22 43 64 85 106	1 43 85
B1	2 23 44 65 86 107	2 44 86
C1	3 24 45 66 87 108	3 45 87
D1	4 25 46 67 88 109	4 46 88
E1	5 26 47 68 89 110	5 47 89
F1	6 27 48 69 90 111	6 48 90
G1	7 28 49 70 91 112	7 49 91

**Figure 3.** Fixed channel assignment to cells in a 7-cell cluster with no sectorization, 3-sectored cell, and 6-sectored cell.

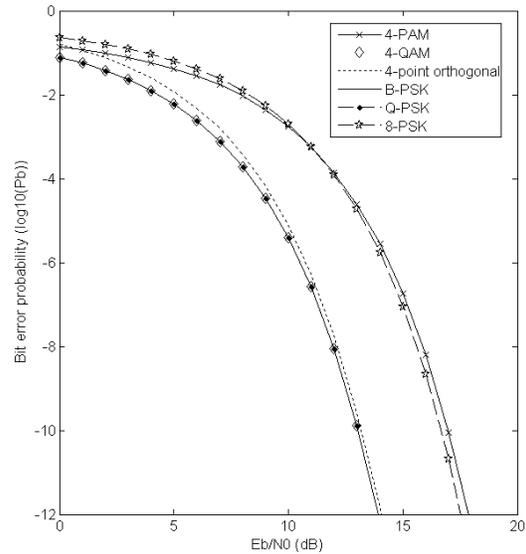
### 3.7 Experiment 7: Estimation of Bit Error Probability of Modulation Schemes

In this experiment, we are primarily concerned with finding an appropriate modulation scheme at the transmitting side using bit error probability measurement. We consider modulation schemes such as M-point pulse amplitude modulation (M-PAM), M-point phase shift keying (M-PSK), M-point quadrature amplitude modulation (M-QAM) and M-point orthogonal signal sets. We then draw a conclusion, based upon the results obtained from these considered schemes, on selecting an appropriate modulation scheme that can be well suited in power-limited region and bandwidth-limited region.

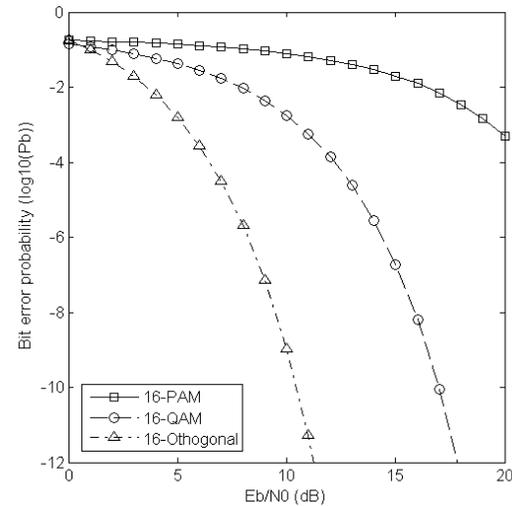
The followings (figures 4 and 5) are example line graphs for bit error probability versus  $\frac{E_b}{N_0}$ , and it can be

found that irrespective of the degree of modulation, PAM is susceptible more to bit errors than PSK, QAM and orthogonal signal sets. In addition,

increase in the degree of modulation results in more bit errors for PAM, PSK, and QAM.



**Figure 4.** Bit error probability for 4-PAM, 2×2 QAM and 4-point orthogonal signal sets.



**Figure 5.** Bit error probability for 16-PAM, 4×4 QAM and 16-point orthogonal signal sets.

However, the opposite is the case for orthogonal signal sets. Overall, PAM and QAM schemes are bandwidth-efficient, and orthogonal signal sets are power-efficient [7].

### 3.8 Experiment 8: Radio Resource Allocations and Scheduling in Cellular Mobile Communication

Radio resource allocation and scheduling is one of the important areas in mobile communication that needs considerable attention to address several significant issues such as spectral efficiency, energy efficiency, and quality of service. Scheduler defines the specific usage of physical resources such as time, frequency, and power. In this experiment, students evaluate the performance of the generic schedulers such as Round Robin (RR), Max-SNR, and Proportional Fair (PF) in terms of average cell spectral efficiency and Jain's fairness index in a macrocell of LTE-Advanced systems.

The system model considers a dense urban deployment. A single macrocell is considered. A number of macro users (per cell for a 3-sector site) are assumed within the macrocell coverage (figure 6). Figure 6 shows the cell layout in the system architecture, where macro users are distributed randomly and uniformly throughout the macrocell.

The throughput in any arbitrary resource block (RB) can be expressed in terms of the mutual information (MI) by employing Shannon's formula as given below [8] [9].

$$\phi(\gamma) = \begin{cases} 0, & \gamma < -10dB \\ \alpha \log_2 \left( 1 + 10^{\frac{\gamma(dB)}{10}} \right), & 0dB \leq \gamma \leq 22dB \\ 4.4, & \gamma > 22dB \end{cases} \quad (2)$$

where  $\gamma$  is the SINR at any RB in a particular transmission time interval (TTI);  $\alpha = 0.6$  is the implementation loss factor.

The average MI ( $\bar{\phi}$ ) over all RBs over all users in a component carrier (CC) is obtained, and then the effective

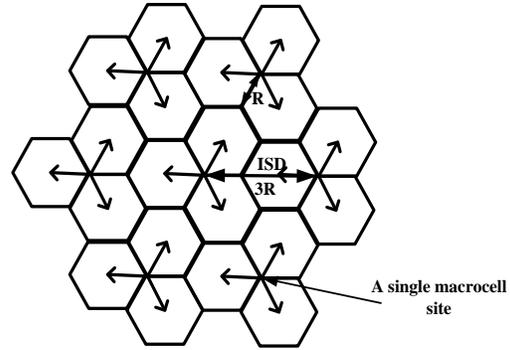


Figure 6. Cell layout in the system architecture [8].

SINR,  $\gamma_{eff}$  per RB per TTI is estimated from the average MI by inverse mapping. The inverse mapping function can be mathematically expressed for as

$$\gamma_{eff}(\bar{\phi}) = 10 \log_{10} (2^{\frac{\bar{\phi}}{\alpha}} - 1) \quad (3)$$

Hence, the system level spectrum efficiency per RB per TTI can be expressed as

$$R_{sys} = \alpha \log_2 (1 + \gamma_{eff}) \quad (4)$$

Jain's fairness index is adopted for the evaluation of the user fairness performance to define the degree of fairness among users. Mathematically, the fairness index can be expressed as follows [10].

$$F_J = \frac{\left( \sum_{k=1}^K u_k \right)^2}{K \sum_{k=1}^K u_k^2} \quad (5)$$

where  $K$  represents the total number of user and  $u_k$  represents the total number of RB allocated to user  $k$  over the simulation runtime.

Simulation parameters and assumptions are adopted mainly from [11], which are based on the system architecture explained. The spectral efficiency performance and the fairness performance of these schedulers are shown in figure 7. From figure 7, it can be found that RR scheduler provides the best fairness but the least spectral

efficiency performance. On the contrary, *Max-SNR* scheduler provides the best spectral efficiency but the worst fairness performances. However, the PF scheduler provides a trade-off between fairness and spectral efficiency performances by taking the user previous resource allocation history into account.

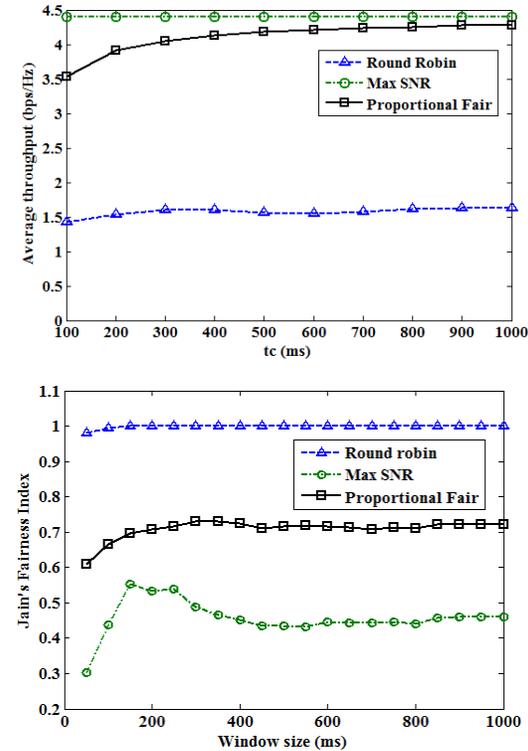


Figure 7. Spectral efficiency and fairness performances of generic resource schedulers.

### 3.9 Experiment 9: Design of Inland Digital Microwave Link

In this experiment, students study the basic concepts of high frequency wave propagation, optical and radio horizon, ducting phenomenon, Fresnel zones, earth bulge, and factor  $k$ : a ratio of effective earth radius to the true earth radius and its effect on the link range. Figure 8 shows an example point-to-point microwave backhaul between

transmitter and receiver with gain and loss in different parts.

Given that transmit power is 0 dBW, total cable loss is 4 dB, carrier frequency is 6 GHz, intermediate frequency bandwidth of the receiver is 10 MHz, receiver is at room temperature, and 90% radio link reliability, students can estimate the effective isotropic radiated power (*EIRP*), free-space path loss of the hop, power flux density at the receiver front end, receiver noise threshold, antenna aperture diameter, and the received power. Figure 9 is a simulated result for a single hop microwave link. All gains and losses are shown along with the signal propagation from transmitter to receiver.

### 3.10 Experiment 10: Design of Satellite Link

Satellite backhaul in mobile systems is a solution where other alternative backhaul technologies are not feasible such as islands, remote locations [12]. Typically, a long-distance network through satellite link is designed and established through geostationary earth orbit (*GEO*) satellites at frequencies in C band (6-4 GHz) and in Ku band (14-12 GHz). In this experiment, students study the fundamental issues and constraints in designing earth-satellite-earth communication link as given in figure 10.

Refer to figure 10, given the parameters such as transmit power, satellite antenna gain, uplink and downlink slant range, and satellite antenna gain-to-noise temperature ratio, we can estimate the earth station-satellite-earth station link budget. In addition, uplink carrier-to-noise ratio,  $(C/N)_u$ , downlink carrier-to-noise ratio,  $(C/N)_d$ , and the total link carrier-to-noise

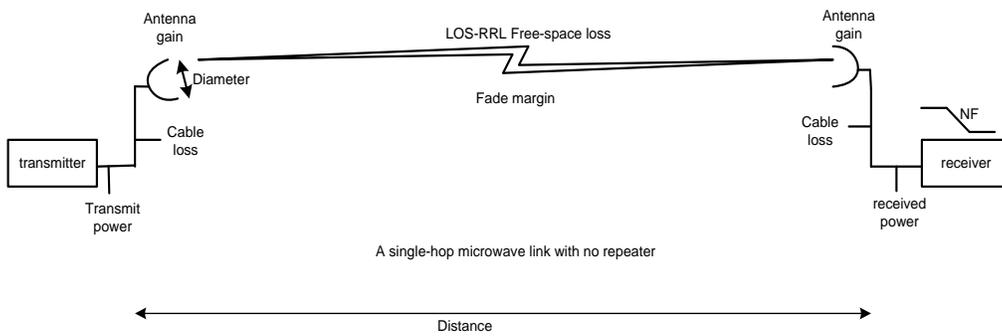


Figure 8. A typical single hop microwave communication link.

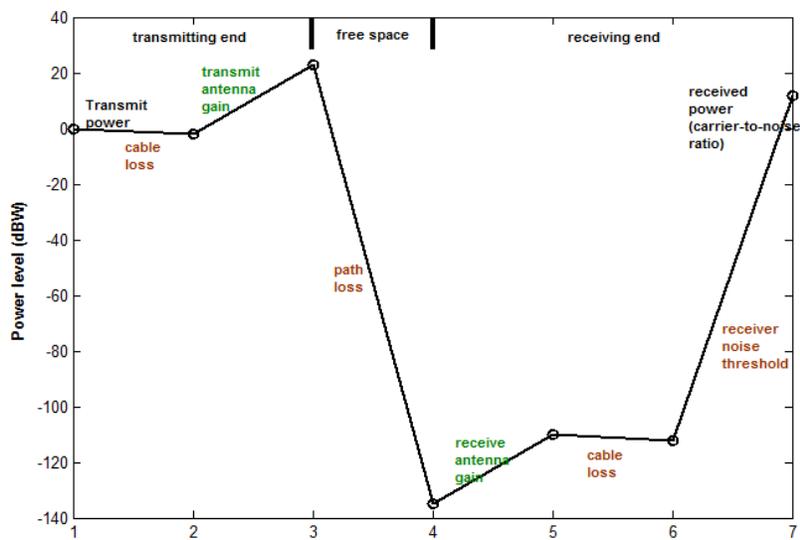


Figure 9. Typical link budget estimation of a LOS microwave link.

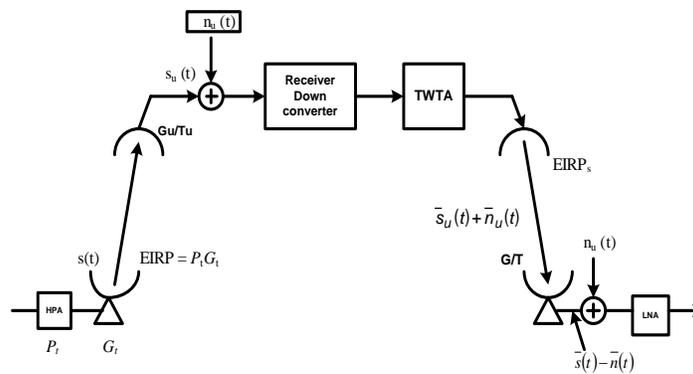


Figure 10. Basic earth-satellite-earth communication link [13].

ratio,  $(C/N)_{total}$  can also be estimated. If  $(C/N)_u \gg (C/N)_d$ , then  $C/N \approx (C/N)_d$ . In this case the satellite link is said to be downlink-limited. When  $(C/N)_u \ll (C/N)_d$ , then  $C/N \approx (C/N)_u$ , and the satellite link is said to be uplink-limited.

We consider both single carrier and multi-carrier per transponder for the link budget estimation and carryout an analysis of how multi-carrier scenario affects the link performance. Followings as given in table 2 are parameters that are considered as an example scenario to estimate the satellite link performance for the operation of single carrier per transponder.

**Table 2.** Default simulation parameters and scenarios for satellite link [13].

Parameter	Value
Transponder operation band	14/12 GHz
Noise bandwidth	46 MHz
Satellite antenna gain-to-noise ratio	-1.6dB/K
Satellite saturation EIRP <sub>s</sub>	44 dBW
Satellite TWTA $BO_i$	11 dB
Satellite TWTA $BO_o$	6 dB
Earth station transmit antenna gain	57.6 dB
Earth station receive antenna gain	56.3 dB
Earth station carrier power fed to antenna	174 W
Maximum uplink and downlink slant range	37,506 km
System noise temperature $T_s$	160 K
Uplink tracking loss	1.2 dB
Downlink tracking loss	0.9 dB
Interference into or from adjacent satellite, terrestrial interference, etc. and any influence by the atmosphere	Negligible

The simulation output gives the desired link budget along with other measures as given in table 3 for single carrier per transponder operation.

**Table 3.** Output simulation parameters and values for satellite link.

Parameter	Value
Carrier EIRP	80.0055 dBW
Uplink free space loss	206.8463 dB
Uplink carrier-to-noise ratio	23.3591 dB
Satellite EIRP	44 dBW
Downlink free space loss	205.5074 dB
Downlink carrier-to-noise ratio	24.8926 dB
Total satellite link (earth-satellite-earth) carrier-to-noise ratio	127.2986 dB
Satellite characteristics	uplink limited

#### 4 LABORATORY ASSESSMENT

In order to assess the significance of the CMC laboratory, we carried out a student survey within the registered students of the CMC laboratory of fall 2012 semester at AIUB. The total number of students participated in the survey was ninety one. The survey questions were categorized into two parts: part I incorporates general questions and part II incorporates query based questions, with five questions in each part (table 4). Students were asked to put a tick on either Yes or No, with an option for making comments, explaining the reasons for their opinions.

Figure 11 shows the response of the students for each question of the survey (table 4). From figures 11 (a) and (b), it can be found that overall most of the students

**Table 4.** Student survey questions of CMC laboratory assessment.

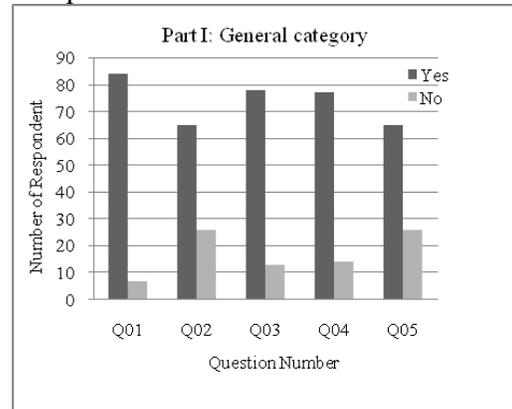
No	Question
Part I: General category	
Q01	The laboratory experiments are relevant and helpful for understanding the contents of the course cellular mobile communication.
Q02	The experiments of the lab are easy to understand and have been written properly with sufficient details.
Q03	The lab provides sufficient realization of the practical aspects of cellular

	mobile communication using MATLAB software tool.
Q04	The lab is helpful for further research and professional career development in mobile communication.
Q05	The lab is equipped with sufficient resources for simulation.
Query based	
Q06	Is the laboratory time of three hours duration sufficient for the experiments?
Q07	Is there any prerequisite the students should complete before they enroll for the lab?
Q08	Should there be any changes in the content, strategy, methodology, etc. of the lab?
Q09	Is there any deficiency in the lab experiments that should be addressed?
Q10	Is there any comment on improving the lab?

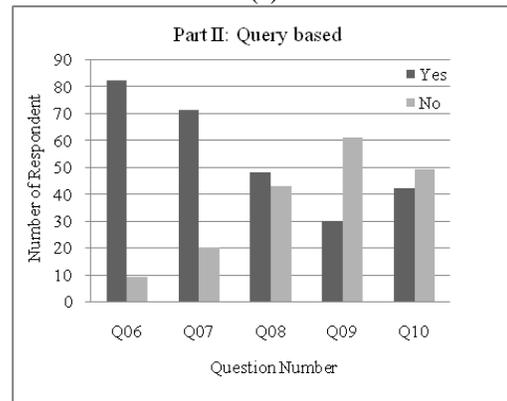
responded to Yes. Particularly, majority have agreed upon questions 01 through 05, i.e. the laboratory is relevant and helpful for understanding the CMC course, provides sufficient realization of the practical aspects of CMC, and is helpful for further research and professional career development in mobile communication. In addition, according to the majority of the students, the experiments have been written properly with easy to understand features, and the lab is equipped with sufficient resources for simulation.

From figure 11 (b), for query based questions, 06 to 10, majority of the students responded in question 06 to 07 to Yes, meaning specifically, the laboratory time is sufficient, and the students should complete prerequisites such as digital signal processing, telecommunications engineering, and how to work with MATLAB. In question 08, students responded almost equally, meaning, they were confused. In question 09, majority opinioned there was no significant deficiency in laboratory experiments. Moreover, in the final question 10, students were asked to make comments on improving the

laboratory. Selected few comments made by a considerable number of students are as follows: “arrangement of few field visits to telecommunication industry may facilitate students gaining some real life experiences”, “few practical types of equipment can be introduced”, and “understanding of MATLAB coding should be a prerequisite”.



(a)



(b)

**Figure 11.** Response of the students to the survey questions (a) general category (b) query based.

## 5 CONCLUSION

In this paper, we introduced a MATLAB based cellular mobile communication (CMC) laboratory course. The laboratory course comprises of ten experiments, covering the fundamental design parameters,

considerations, and estimations of CMC both in the radio interface and core network levels. A survey over ninety one students was carried out to assess the importance and impact of the laboratory.

Almost all students found the laboratory experiments relevant and helpful for understanding the CMC theory course and for further research and professional career development. Since the laboratory is just MATLAB software based, the laboratory can be offered at affordable cost to provide students to gain practical realization of the CMC theory course concepts at the university. The authors would be pleased to share the laboratory course materials with any individual or institution interested in it and can be reached at either of the authors email addresses.

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