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IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Design of a CSK-CDMA Based Indoor Visible Light Communication Transceiver Using Raspberry Pi and LabVIEW

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DOI: https://doi.org/10.30880/ijie.2019.11.08.012
Received 27 August 2019; Accepted 1 October 2019; Available online 15 December 2019

Abstract: Visible Light Communication (VLC) has drastically drawn the attention of both academia and industry as it can offer simultaneous lighting and data communication in an indoor environment. Additionally, VLC also tender a viable means to assuage the radio spectrum crunch. However, the data rate of the VLC system is choked because of the limited modulation bandwidth of Light Emitting Diode (LED), baseband modules, and intersymbol interference (ISI). In this article, an indoor VLC based software-defined radio (SDR) is designed and implemented that make use of Color Shift Keying (CSK) modulation, Code Division Multiple Access (CDMA) technique, and Raspberry Pi (RPi) to enabled the ISI free high data rate communication. The SDR is designed in LabVIEW software interfaced with the MATLAB and tested for text transmission. Numerous experiments were conducted on SDR at different alignments of transmitter and receiver. Our findings through experimentation showed that the SDR delivers an improved data rate of 2.645 $Mbps$. Over and above, MATLAB based simulation packages are also conceived that validate the effectiveness of the proposed CSK-CDMA based VLC system. The bit-error-rate (BER) results of the proposed system are compared with the traditional CSK-OOK based VLC system. The results are quite impressive and show remarkable coding gain.

Keywords: Code Division Multiple Access (CDMA), Color Shift Keying (CSK), LabVIEW, Light Emitting Diode (LED), Raspberry Pi (RPi), Software-defined Radio (SDR), Visible Light Communication (VLC)

1. Introduction

The entrance of Fifth-generation 5G wireless communication systems has revolutionized the telecommunication industry. The services offered by the 5G communications are ultra-high data rates, reliability, and scalability of communications, low cost, and power consumption, ubiquitousness, and low latency, etc. [1-3]. Conventional radio frequency (RF) based wireless networks try to meet the aforesaid services at a bottleneck of RF spectra. Currently, the investigators put their significant work efforts in seeking substitutes for RF. In this connection, Visible Light Communication (VLC) has to turn out to be an exhilarating technology that employs visible light media to transmit and receive the information signal in future 5G/6G indoor wireless communication networks.

A VLC system is designed for short-range communications that exploit recently developed solid-state lighting infrastructures available in houses and offices such as Light Emitting Diodes (LED) for concurrent delivering of both enlightenment and data transmission [4]. Hence, the total cost of the system is reduced. Besides this, the other key merits of the VLC system include license-free visible light spectrum, ultra-high transmission speed, power efficiency,

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information security, and hazardless environment [4-8]. Despite the aforementioned useful VLC advantages, there still occur a number of open research challenges, which need to be addressed properly for physical deployment. The first and foremost open challenge experienced by VLC is the small modulation bandwidth of LED that chokes the overall data rate of the processor it is driven by [9,10]. It is primarily related to LED manufacturing and thus beyond the scope of our work. Other challenges to VLC are the designing of an uplink communication system [11], dimming and brightness control [12], limited range [13], low data rates due to baseband modules [14], multipath effects and intersymbol interference (ISI) [15].

The existing work is done to improve the data rates and the elimination of ISI effects of the VLC system by accompanying the advanced modules and appropriate signal processing techniques. In this connection, Gilani et al. designed and implemented a serial communication-based VLC system that is adept at transmitting a text message at the communication range of approximately $2m$ [16]. The system uses an RS-232 protocol to exchange the text data from one computer to the other. Nevertheless, the designed prototype works only with lower transmission rates and does not account for ISI. Later, a customizable VLC transceiver prototype is designed in [17] by using the STM32F4Discovery board. The transceiver is proficient in performing the audio communication but the system is performance-wise imperfect as the audio signal is disturbed when the STM board processes it. In a similar perspective, Khalid et al. [14], proposed a Code Division Multiple Access (CDMA) technique for the VLC system that evades the ISI. This system is implemented using National Instruments (NI) based on cDAQ component tools interfaced with LabVIEW. The conceived prototype is well efficient in carrying out the synchronization and signal conditioning of the received signal as both operations are consummate in the software domain. However, the baseband cDAQ modules employed in the work can only provision transmission rates up to $10\ Kbps$. Therefore, the effective data rate conveyed by the prototype is $2\ Kbps$.

In [13], the same workgroup prolongs their foregoing work and conceived a state-of-the-art VLC testbed by engaging the universal asynchronous receiver-transmitter (UART) module programmed in MATLAB that permits the serial communication. The testbed is able to support variable transmission rates and thus attains a maximum data rate of $60.23\ Kbps$. Later, a Raspberry Pi (RPi) based VLC system is realized in [16]. Although the system was implemented successfully, yet it only supports the transmission speed of 5 Kbps. Moreover, in a brightly lit room, the performance of the prototype was not satisfactory. In this continuum, a combination of Color Shift Keying (CSK) with Pulse Position Modulation (PPM) and Complementary PPM (CPPM) was recommended to boost up the capacity and mitigation of ISI [17]. However, these methods do not provide the data rate as achievable with pure CSK because of the extra time slots obligatory in PPM and CPPM. A CSK-CDMA based VLC system is introduced in [20]. For CDMA spreading, Prime Codes are used as signature waveforms. However, the high side lobes of the auto-correlation function make the system not appropriate for physical deployment, as it is difficult to attain accurate synchronization [21].

In lieu of briefly discussed literature review, a fully organized VLC prototype is compulsory that provides satisfactory results in terms of higher data rates and minimization of ISI. From this perspective, the current work implements the CSK-CDMA based VLC system with advanced broadband modules (RPi). For spreading, instead of using Prime codes the work employs the most optimal codes termed as optical orthogonal codes (OOC). These codes are characterized by the parameters $(n, w, \lambda_a, \lambda_c)$, where n denotes the length of the spreading code, w exhibits the weight of the code i.e., number of 1's in the code, λ_a and λ_c are the auto-correlation and cross-correlation constraints respectively. To test the error performance of the proposed system, simulation packages are conceived in MATLAB tool and the bit-error-rate (BER) results are compared with CSK-OOK based VLC system in the presence of line-of-sight (LOS) environment. The rest of the paper is grouped into the subsequent sections: Section 2 familiarizes with the whole system model of the CSK-CDMA based VLC system. While Section 3 deliberates the simulation setup and deliver the meticulous argument on simulation outcomes. Section 4 contributes to the implementation and working of software-defined radio (SDR). This section also confers the key performance metrics and delivers an exhaustive discussion on the cost analysis of the SDR. The last section of the study will deliver the concluding statements.

2. System Modeling

This section acquaints with the complete system model of the proposed CSK-CDMA based indoor VLC system. To implement the CSK modulation, two different colors LED transmitters are considered in the work that is spatially separated from each other. Likewise, on the receiver side, two photo-diodes with optical filters are used. The optical channel model used in this article is borrowed from our earlier work [22] where the indoor environment has dimensions $4m \times 4m \times 3m$. The proposed system can be realized as the MIMO-VLC system and its graphic representation is exhibited in Figure 1.

In the CSK-CDMA transmitter, the binary data is first fed into the splitter that equally split the data into two rows. These rows are then individually inputting to the spreading block where OOC is used to encode/spread the rows. An OOC is a family of unipolar spreading waveforms having code length of n and weight w respectively. The OOC codeword length and weight are selected to be 7 and 3 respectively, while the thorough discussions on the structure of OOC codes are given in [23]. The resultant spread signals are modulated to two spatially separated LED transmitters and then hurled to the free-space.

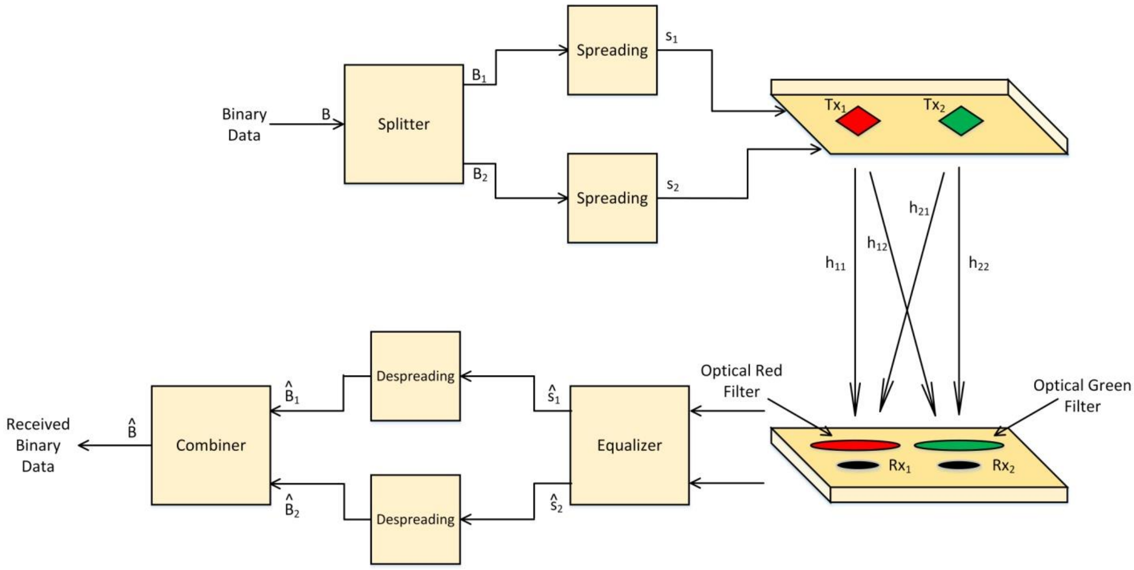

Fig. 1 – System modeling of proposed CSK-CDMA based indoor VLC system

In Figure 1, two receivers with optical filters are placed. The receiver 'Rx_1' only collects the signal coming from 'Tx_1' and filter out the 'Tx_2' signal. Similarly, the receiver 'Rx_2' only collects the signal from 'Tx_2'. Hence, the inter-channel interference (ICI) is eliminated and the MIMO channel matrix is reduced to a diagonal matrix expressed as [24-26]:

$$H_{VLC} = \begin{bmatrix} h_{11} & 0 \\ 0 & h_{22} \end{bmatrix} \quad (1)$$

Moreover, the LEDs wavelength used in the work ranges from 380 to 780 nm, which is smaller than the collective area of the photo-diode. Therefore, the multipath fading can also be ignored because of high spatial diversity. The receiver also equipped with a sub-optimum linear zero-forcing equalizer that thwarts the effects of the optical channel. The equalized signal is then supplied to individual despreading blocks where the same OOC codes are used to recover the binary data. In the next step, a combiner is used that combines the rows to form a single row received binary data.

Table 1 - Simulation parameters of VLC channel and CSK-CDMA system

Parameters	Values
Data Bits	10^5
OOC length	7 −bits
Modulation	OOK
LED colors	Warm white, Green
Channel	line of sight (LOS) VLC channel
Dimensions of a room	4m × 4m × 3m
Illuminance angle	$5^\circ - 15^\circ$
Semi-angle at half power	15°
Field of view of a receiver	15°
SNR range	0 − 15 dB
Equalizer	Zero-forcing
Noise	AWGN

3. Simulation Results

To appraise the overall performance of the recommended CSK-CDMA based VLC system, simulation packages are devised in MATLAB® software. The transmitter generates the binary data of length 10^5 with equal probability of 1's and 0's. The other parameters compulsory for simulating the LOS free-space optical channel and system are enumerated in Table 1. For the traditional CSK-OOK system, the binary data split up into two equal bitstreams and supplied to the OOK modulator. While in the CSK-CDMA system, CDMA operation is performed on the split bitstreams. Next, the CSK data is transferred via an optical channel. The optical receivers congregate the visual signals with the aid of optical filters and transform back to electrical signals. Afterward, a zero-forcing equalizer is employed that tries to confiscate the channel impairments. The equalized bitstreams are then decoded with the same codewords that are used for the spreading. In the last phase, the decoded bitstreams are combined to form a single bitstream and erroneous bits are counted.

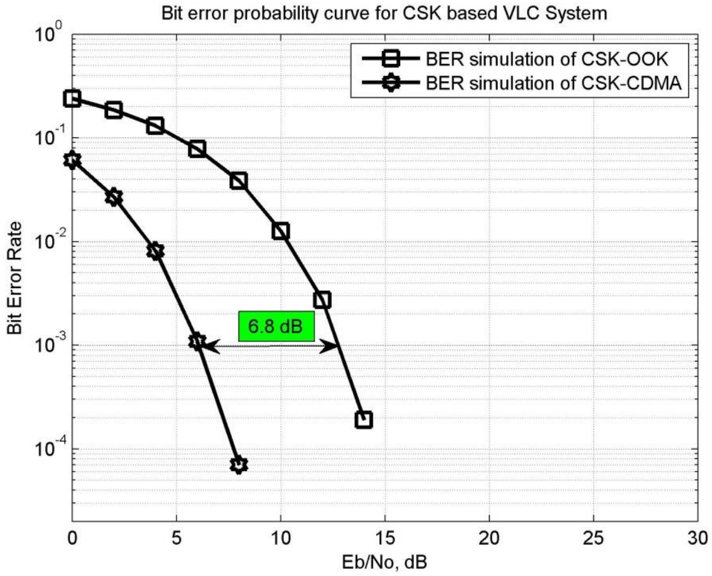

Fig. 2 – Performance comparison of proposed and traditional CSK based VLC system

The simulation results of the suggested and customary CSK based VLC systems are showed in Figure 2. It is noteworthy that the error performance of the CSK-CDMA based VLC system is superior to the traditional CSK-OOK system. At fixed BER of 10^{-3}, the proposed system attains a considerable coding gain of approximately 6.8 dB and it can also be viewed by comparing both simulation results.

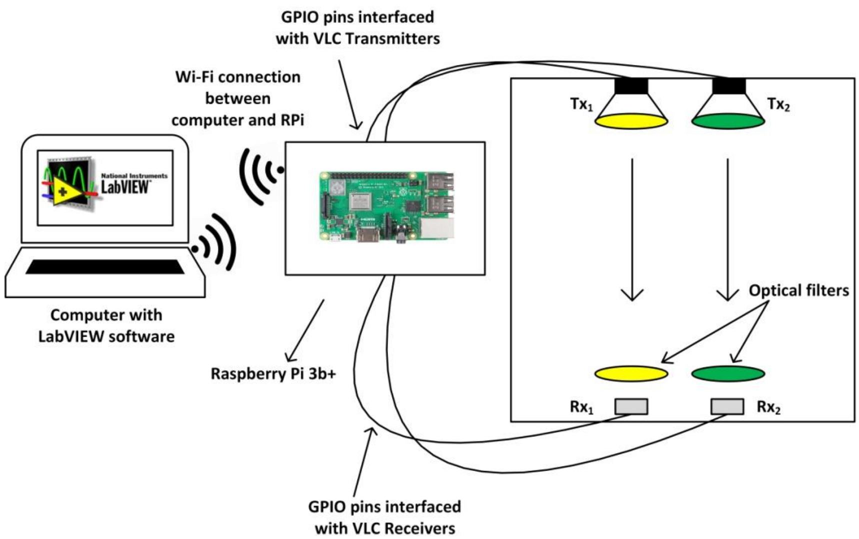

Fig. 3 – Block diagram of hardware setup

4. Hardware Setup, Experimentation, and Discussions

The current section endows with the complete hardware equipment considered necessary for the designing of the proposed VLC system. For the implementation of CSK based VLC modem, the prototype requires two transmitters and two receivers arranged in a 2×2 MIMO configuration. The block diagram of the prototype is demonstrated in Figure 3. For the software support of the prototype, LabVIEW is interfaced with the MATLAB. This can be consummate by installing the MATLAB RT module driver in LabVIEW libraries. Each transmitter of the prototype used a LED driver circuit and an array of LEDs while each receiver is outfitted with the optical filter, photo-diode, and an amplifier circuit. For implementing CSK, two different colors LEDs (warm white and green) are used. The hardware support is provided by the RPi 3b+ module, which is interfaced with the LabVIEW. Initially, the goal is to perform parallel communication using an RPi 3b+ module by interfacing it with the MATLAB tool. However, it was noticed during the interfacing that the MATLAB is single-threaded software and parallel transmission is not possible using RPi. Parallel computations can be executed within a MATLAB script, but not in real-time with hardware interfaced with it. For this reason, the proposed work was implemented in LabVIEW that by default able to executes commands in a parallel fashion.

The designed prototype act as a state-of-the-art SDR that is able to transmit and receive a text message on a stand-alone computer. The connection made between the computer and the RPi was wireless over Wi-Fi connectivity [27]. A 16 character long message was taken in LabVIEW and encoded into serial 128 bits (8 bits for one character). The serial data is equally split into two rows to transmit by each transmitter. Both rows are then spread individually by two 7 −bits long OOC codewords. After spreading, the length of each row is 448 bits. These are the total bits transmitted by each transmitter. The final bits are fed to the physical layer by means of RPi. For transmission/reception, the General Purpose Input Output (GPIO) pins of an RPi are used. Four GPIO pins were configured, two as transmitters and two as receivers. The RPi's transmitter pins are connected with LED driver circuits and the receiver pins with the photo-diodes. It is notable that the driver and amplifier circuits used in the current work are taken from our earlier work and the thorough discussion on these circuits can be getting from [22].

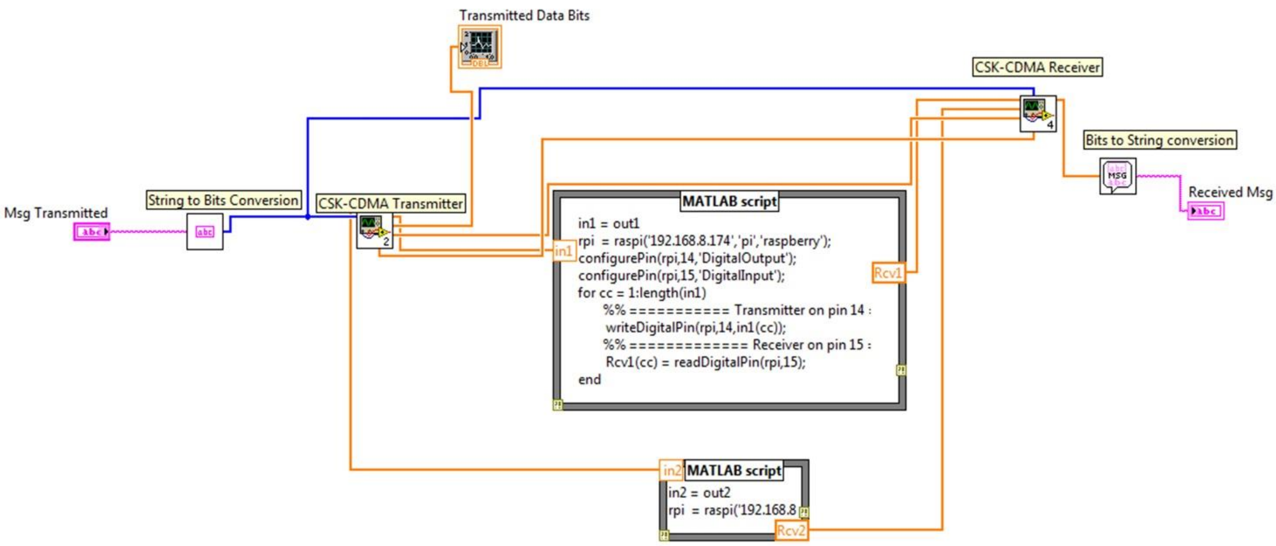

Fig. 4 – Virtual Instrument diagram of the SDR

On the receiver, after optical-to-electrical convergence, the received signal contains partial 1's and 0's. To change these partial 1's and 0's into strong 1's and 0's signal conditioning is performed in the software domain. The signal conditioning is attained in two steps. In the first step, the mean and maximum values of the received signal are computed. Afterward, the division operation is carried out between the values that yield a threshold value. The second step of the signal conditioning involves the comparison between the threshold value and the received signal. If the received signal value is larger than the threshold then the received value is taken as 1 otherwise it is considered as 0. In a similar fashion, the comparator approach is completed for the other received data values. Figure 4 exhibits the LabVIEW based virtual instrument (VI) diagrams of the designed SDR. The transmission rate was obtained from the baud-rate of the RPi 3b+. The mathematical expression for the calculation of baud-rate is expressed as:

$$baudrate = \frac{System\_clock\_freq}{8*(baudrate\_reg+1)} \qquad (2)$$

The pins assigned for communication purposes are of mini UART type pins whose baud-rate register value is given as 16 and the clock frequency for the system is set as 250 MHz. By using the aforesaid values in Eq. 2, the baud-rate is calculated as 1.838 Mbps. As OOK modulation is employed in the work, the transmission rate is equal to the baud-rate. Using this rate, the total symbols transmitted by each transmitter are 4102.679 symbols/s. Hence, the effective data rate comes out to be 0.525 $Mbps$. Furthermore, the error-free successful transmission is done at the range of 1.36m in a glisteningly lighted room. Above this transmission range, the errors take place in the received signal and the signal conditioning could not remunerate these errors. It is noteworthy here that the aforementioned transmission range and data rate is achieved without adding header and tail bits.

If the system clock frequency of RPi is increased to the maximum limit of 1.4 GHz, then by using Eq. 2 the transmission rate is computed as 10.294 MHz. At this rate, the prototype faces the synchronization problem that is handled by the add-on of header and tail bits. A total of 50 bits were added, 25 bits as header and 25 for tail bits making a total length of 498 bits. Now the total symbols transmitted by each transmitter are 20670.682 symbols/s. The effective data rate, in this case, was found to be 2.645 Mbps. Also, the transmission range in a glisteningly lighted room is reduced to $1.14m$. This is because by increasing the transmission rate the energy required per bit also increases, which ultimately reduces the transmission, range. It is pertinent to mention here that the data rate obtained in both cases is surely higher than our earlier works [13,14,22].

4.1 Cost Analysis of designed SDR

The ongoing subsection delivers an ample cost analysis of the designed SDR and compares it with the cost of the prototypes designed in our earlier works. As discussed earlier, the current work exploits an RPi 3b+ module to interface the physical layer with the stand-alone computer. The cost of the RPi module is 35 USD while the cost of the development of the transmitter and receiver is 12 USD. Hence, the total cost of SDR is 47 USD. The prototype conceived in [13] is implemented with the aid of the UART PL-2303HX USB module. For the MIMO-VLC system, four such USB modules are required. The price of a single USB module is 7.40 USD. This means that the overall cost in the implementation of the MIMO-VLC system is 41.6 USD. However, it is prominent that the utilization of the PL-2303HX USB module in the MIMO-VLC system designed cannot fulfill the high data rate demands of the user.

The SDR conceived in [22] was developed by the use of NI cDAQ modules. To support the physical layer, cDAQ-9174 chassis with the NI 9201 (DAC) and NI 9263 (ADC) modules are used. The cost of a single set of cDAQ modules is 2,241 USD. Again, for the MIMO-VLC system, two sets of the cDAQ modules are required and the overall cost in the implementation of SDR is 4,506 USD. On comparing the above costs, it is estimated that the RPi based developed SDR is the cheapest solution for the ISI free high data rate VLC system(s).

5. Concluding Remarks

This paper presents the design and realization of a CSK-CDMA based complete state-of-the-art VLC transceiver that is proficient in transmitting/receiving a text message in an indoor environment. The transceiver is developed by the use of the RPi 3b+ module, which is interfaced with the LabVIEW software. Moreover, the designed prototype is analyzed based on two key performance metrics, namely, transmission range and data rate. During the experimentation, it is noteworthy that the change in the baud rate of the RPi 3b+ module will affect the two-performance metrics. If we choose the moderate baud rate to say $250\ MHz$ then the prototype achieves the maximum coverage area of $1.36m$ in a glisteningly lighted room. However, the data rate of the prototype is $0.525\ Mbps$. Upon increasing the baud rate, the data rate of the transceiver increases but at the same time coverage area reduces. The work also provides the computer-generated BER based performance comparison results. The proposed CSK-CDMA modem is compared with the traditional CSK-OOK modem in the presence of a LOS environment. The BER results are remarkable and show the coding gain of $6.8dB$. From both simulation and hardware-based numerical results, it is depicted that the designed prototype could become an appropriate candidate for future developing 5G communications.

Acknowledgment

The authors would like to gratitude The University of Lahore and the COMSATS University Islamabad for providing us the working environment and the physical resources.

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