Remote and On-Site Laboratory System for Low-Power Digital Circuit Design

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This dissertation is dedicated to my parents, my husband, and my family

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Declaration

I certify that the PhD thesis titled ”Remote and On-Site Laboratory System for Low-Power Digital Circuit Design” has been completed by me without any other outside help and I have used the resources mentioned at the end of the thesis. It is in partial fulfilment of the requirements for the Doctor of Engineering to the Faculty of Science and Technology of the University of Siegen. Its results are from my own research, and this study has not been submitted for any higher degree in any other university or institution.

Shatha Sail AbuShanab

Bonn, 15.08.2018 *Shatha*

Place, Date Signed

Abstract

The design of an efficient digital circuit in term of low-power has become a very challenging issue. For this reason, low-power digital circuit design is a topic addressed in electrical and computer engineering curricula, but it also requires practical experiments in a laboratory. This PhD research investigates a novel approach, the low-power design laboratory system by developing a new technical and pedagogical system. The low-power design laboratory system is composed of two types of laboratories: the on-site (hands-on) laboratory and the remote laboratory. It has been developed at the Bonn-Rhine-Sieg University of Applied Sciences to teach low-power techniques in the laboratory. Additionally, this thesis contributes a suggestion on how the learning objectives can be complemented by developing a remote system in order to improve the teaching process of the low-power digital circuit design. This laboratory system enables online experiments that can be performed using physical instruments and obtaining real data via the internet. The laboratory experiments use a Field Programmable Gate Array (FPGA) as a design platform for circuit implementation by students and use image processing as an application for teaching low-power techniques.

This thesis presents the instructions for the low-power design experiments which use a top-down hierarchical design methodology. The engineering student designs his/her algorithm with a high level of abstraction and the experimental results are obtained and measured at a low level (hardware) so that more information is available to correctly estimate the power dissipation such as specification, latency, thermal effect, and technology used. Power dissipation of the digital system is influenced by specification, design, technology used, as well as operating temperature. Digital circuit designers can observe the most influential factors in power dissipation during the laboratory exercises in the on-site system and then use the remote system to supplement investigating the other factors. Furthermore, the remote system has obvious benefits such as developing learning outcomes, facilitating new teaching methods, reducing costs and maintenance, cost-saving by reducing the numbers of instructors, saving instructor time and

simplifying their tasks, facilitating equipment sharing, improving reliability, and finally providing flexibility of usage the laboratories.

The assessment section of this thesis describes teaching activities performed during the four years spent designing and developing the low-power design on-site and remote systems. The on-site system and the remote system were used by Electrical Engineering students at the Bonn-Rhine-Sieg University of Applied Sciences. The low-power design laboratory system is the first system for low-power education and the remote system is one of only a few available laboratories in Germany. Teaching activities performed during the Summer Semester 2015 were concerned with teaching low-power techniques in the hands-on laboratory using only the on-site system, and during the Summer Semester 2016 focused on teaching the low-power design laboratory using the on-site system and the remote system. The assessment in Summer Semester 2015 evaluates the effectivity of using the laboratory system in teaching the concepts of low-power design in order to further improve and develop the system. The aim of assessment for the Summer Semester 2015, as well as Summer Semester 2016, is to study the achieved learning objectives, the laboratory reports with and without the support of the remote system, and to analyse the students' use of the remote system by the students. The assessment and the students' opinions provide positive feedback on this approach and verify that the low-power design on-site and remote laboratory system is indeed a successful and motivating learning tool, and also the remote system is a positive and effective complementary tool for remotely reusing the on-site system and achieving additional learning objectives that cover most conceptual theories in low-power digital circuit design.

Zusammenfassung

In den Studiengängen Elektrotechnik und Informatik stellt der Entwurf energieeffizienter digitaler Schaltkreise Studierende vor große Herausforderungen. Daher wird dieses Thema in den jeweiligen Lehrplänen nicht nur theoretisch behandelt, sondern auch in Form praktischer Versuche im Labor aufgegriffen. Um Studierenden die praktischen Low-Power Techniken im Labor im Präsenzlabor zu vermitteln, wurde dazu an der Hochschule Bonn-Rhein-Sieg EduPow, ein Low-Power Design System, entwickelt. In dieser Dissertation wird diskutiert, wie das Erreichen der Lernziele durch ein Remote-System ergänzend unterstützt werden kann, um die Vermittlung digitaler Low-Power Schaltkreise zu verbessern. Diese Arbeit untersucht den methodischen Zugang des Low-Power Laborsystems als neues technisches und didaktisches Konzept. Das Low-Power Laborsystem stellt Online-Experimente zur Verfügung, die über das Internet mit existierender Hardware durchgeführt werden und somit reale Ergebnisse liefern. Die Studierenden erwerben Kenntnisse zu Low-Power Techniken am Beispiel von Bildverarbeitungsalgorithmen. Zur Implementierung der Schaltkreise wird als Designplattform ein FPGA(Field Programmable Gate Array)-System eingesetzt.

Diese Dissertation stellt die Versuchsanleitungen für Low-Power Experimente vor. Dabei wird eine hierarchischen Top-Down-Design-Methodologie verfolgt: Die Studierenden der Ingenieurwissenschaften entwerfen Algorithmen auf einer hohen Abstraktionsebene; die Versuchsdaten werden auf einem niedrigen (Hardware-)Niveau erhoben und gemessen, um mehr Informationen zur korrekten Abschätzung des Energieverlustes zur Verfügung zu haben. Der Energieverlust eines digitalen Systems wird durch Spezifikation, Design, verwendete Technologie sowie Betriebstemperatur beeinflusst. Nahezu alle diese Faktoren können in Laborübungen sowohl im Low-Power System im Präsenzlabor wie auch im Remote-System beobachtet bzw. bereitgestellt werden. Darüber hinaus hat das Low-Power Remote System offensichtliche Vorteile, wie die Entwicklung von Lernzielen, die Ermöglichung neuer Lehrmethoden, die Reduzierung von Kosten und Wartung, Kostenersparnis durch eine Verringerung der Anzahl von Lehrpersonen, Ersparnisse bei der Lehrzeit der Dozenten

und Arbeitserleichterung, erleichterte gemeinsame Nutzung von Ausstattung, eine Verbesserung der Verlässlichkeit und schließlich eine flexible Nutzung der Labore.

Im Abschnitt „Assessment“ dieser Dissertation werden die Lehrtätigkeiten beschrieben, die über einen Zeitraum von drei Jahren zu Design und Entwicklung des Low-Power Systems im Präsenzlabor und des Low-Power Remote Systems vollzogen wurden. Das Low-Power System im Präsenzlabor und das Low-Power Remote System wurden von Studierenden der Elektrotechnik an der Hochschule Bonn-Rhein-Sieg genutzt. Dieses Low-Power Remote System ist eines von wenigen in Deutschland. Die Lehre von Low-Power Techniken im Sommersemester 2015 erfolgte ausschließlich in den Low-Power System-Laboren im Präsenzlabor; im Sommersemester 2016 wurde sowohl in den Laboren im Präsenzlabor wie auch im Low-Power Remote System gelehrt. Die Evaluation im Sommersemester 2015 zielte darauf ab, die Effektivität der Nutzung eines Low-Power Designsystems in der Lehre zu erheben, um das System zu verbessern und weiterzuentwickeln. Das Ziel im Sommersemester 2015 und 2016 war es, die erreichten Lernziele und die Laborberichte mit und ohne Unterstützung des Remote-System zu untersuchen, wie auch die Nutzung des Low-Power Remote Systems durch die Studierenden zu analysieren. Der Evaluationsprozess und die sehr positiven Rückmeldungen der Studierenden zu diesem Ansatz deuten darauf hin, dass Low-Power Systeme im Präsenzlabor wie auch Low-Power Remote Systeme erfolgreiche und motivierende Lernwerkzeuge sind.

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List of Abbreviations

AJAX	Asynchronous JavaScript and XML
ASICs	Application Specific Integrated Circuits
BBB	BeagleBone Black
CAD	Computer-Aided Design
CMOS	Complementary Metal Oxide Semiconductor
DIP	Dual Inline Package
DMM	Digital Multimeter
DVI	Digital Visual Interface
EDA	Electronic Design Automation
EJS	Easy Java Simulations
FFs	Flip-Flops
FIR	Finite Impulse Response
FPGA	Field Programmable Gate Array
GUI	Graphical User Interface
HDL	Hardware Description Language
HDMI	High-Definition Multimedia Interface
HTTP	Hypertext Transfer Protocol
IDE	Integrated Development Environment
I/O	Input/Output
JSON	JavaScript Object Notation
LED	Light Emitting Diode
LUT	Look-Up Table
PLL	Phase-Locked Loop
RCL	Remote-Controlled Laboratory
RExLab	Remote Experimentation Laboratory
RT	Register-Transfer
SVD	Singular Value Decomposition
TEC	Thermoelectric Cooling

TPL	Textual Programming Language
UI	User-Interface
VHDL	VHSIC Hardware Description Language
VPL	Visual Programming Language

1 Introduction

1.1 Introduction to Digital Circuit Design Education

Technology has rapidly developed from simple chips with several transistors to more complex chips containing billions of transistors. The exponential increase in the number of transistors per chip will continue over the years leading to increasingly complicated functions on one chip. Consequently, digital systems have become widespread in our everyday electronic devices. The increasing demand for low-power digital systems especially the portable ones requires circuit design engineers who can design low-power electronic systems. Engineering studies are an applied science and, therefore, for most courses, there are laboratories that provide the students with a better understanding of theoretical concepts [1–5]. Low-power design has been addressed in the curricula when an electrical and computer engineering curriculum was developed. Thus, it is valuable to have a real application for teaching low-power design techniques, which assists the students in gaining their learning outcomes by proving the concepts and theories, and by minimizing the gap between engineering education and the industry's requirements for low-power design systems, as shown in Figure 1.1.

This thesis introduces a novel system which is called the low-power design laboratory system for educational purposes. The low-power design laboratory system that has been developed at the Bonn-Rhine-Sieg University of Applied Sciences is composed of two types of laboratories: the on-site (hands-on) laboratory and the remote laboratory as presented in Figure 1.2. A special FPGA-board has been developed called EduPow board that is used for teaching low-power digital design in hands-on lab sessions [6–8]. The purpose of the laboratory system is to provide engineering students with low-power digital design skills.

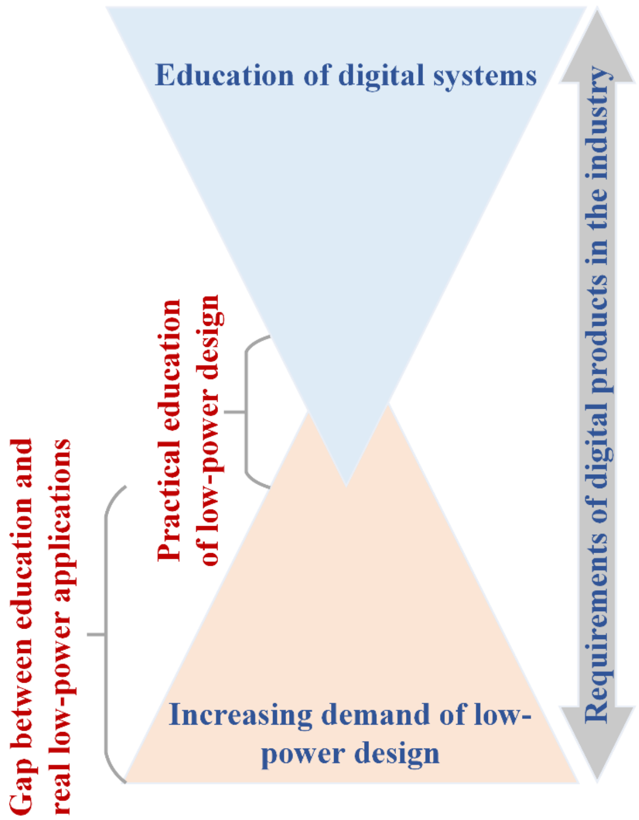

Figure 1.1: The gap of low-power design between engineering education and real applications in the industry

The development of the internet and of communication technology adds new methods for teaching and training, enabling the e-learning approach to occupy a larger part of academic learning methodologies. Recently, the laboratory environments have changed due to the development of technologies that have opened many doors in education. This improvement has offered opportunities to explore new teaching methodologies that make use of these technologies to enhance science and engineering laboratories, and resultantly, remote laboratories have been developed in several universities to obtain realistic results from physical instruments that can be accessed via the internet. These laboratories provide flexibility for the location of both teacher and student [1] [3]. This thesis is an example of such a laboratory where the low-power design remote system for teaching low-power techniques has been developed.

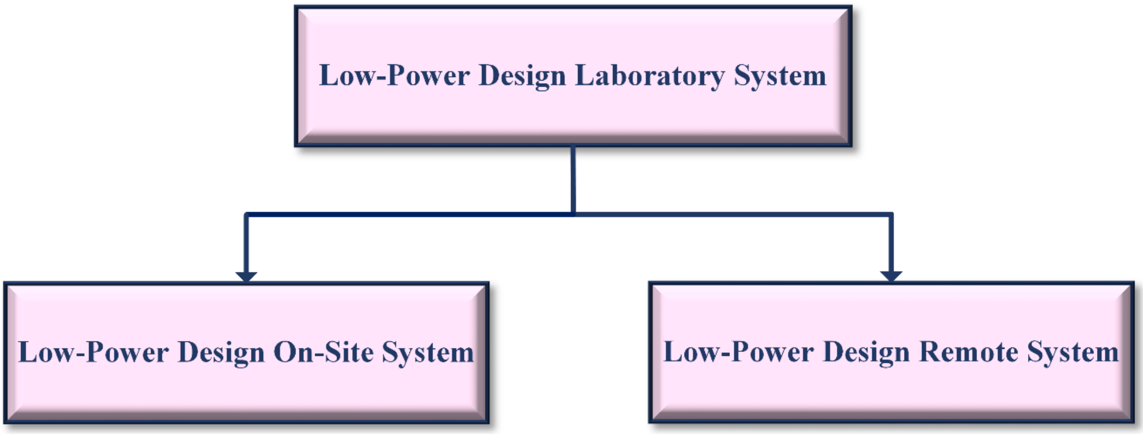

Figure 1.2: The low-power design laboratory system

Thus the remote system has been developed as a supplement to the on-site system, which enable students to estimate the power dissipation of their digital designs remotely as well as to achieve further learning objectives.

1.2 Motivation

The motivation of this PhD research is to prove that the development and implementation of the realistic laboratory system for teaching low-power design for hands-on and distance laboratory exercises with the limited resources -that are available in most universities- is an effective technique to complement the on-site system. The additional motivation is:

- The need for the laboratory system that specifically address teaching low-power design within a specific area in and a consolidated way.
- The need for training engineering circuit designers who require low-power design skills for industry.

1.3 Contributions

Numerous publications indicate researchers' interest in low-power design and the factors influencing power dissipation. It is therefore important to teach the low-power design concepts to undergraduate engineering students and allow them to practice these concepts. This PhD thesis presents unique research highlighting different aspects relating to the development and implementation of a new approach or a new system for low-power digital design training and education. This approach is a hybrid laboratory system: on-site system and remote system. After a prototype of the low-power design laboratory system is designed and implemented, the assessment process is carried out in order to evaluate the performance of the laboratory experiments using the laboratory system. The major contributions can be summarized as follows:

- Proposing the innovative low-power design laboratory system. The proposed laboratory system is good methodology for best practice to use in teaching low-power concepts in laboratory sessions. The system uses an FPGA as a design platform to simplify performing the experiments and obtain accurate results. Additionally, the system supports students in developing, designing, modifying their digital circuits, as well as verifying a successful implementation with real applications and at the hardware level.
- Using the low-power design laboratory system experimentally, either in a hands-on laboratory setting or remotely, to estimate the dissipated power of a complete and complex digital circuit, which is implemented by circuit designers.
- Designing digital circuits at a high level of abstraction by students independently of the underlying technologies used. Thus, they can benefit from more information during applying the abstract level in the laboratory system in which the results are obtained at the low (hardware) level.
- Improving teaching low-power design by reusing the on-site system remotely and reproducing a reliable and flexible system as regards to time and place. The remote system is more effective in assisting students to gain their low-power design skills and also achieves complement learning objectives that cover most conceptual theories in low-power digital circuit design.
- Applying expensive or scarce FPGA technology is not a limitation, as this laboratory system can be available remotely for circuit designers.
- Developing the remote laboratory instructions that can be not only easily used by students, but also the real practical concepts enable them to understand how a digital system works and so deepens the low-power design knowledge.
- Obtaining real data from the physical system on-site or remotely, without any simulation or mathematical modelling. In this way, students work with this laboratory system in a real application with an accurate and reliable implementation.

1.4 Objectives

By developing and implementing the low-power design laboratory system, the following objectives and goals can be fulfilled:

- Achieving as many learning objectives as possible allows students to observe most influencing factors on the power dissipation of their digital circuit design using the on-site system and to complement the others with using the remote system.
- Designing the algorithm using a top-down hierarchal design flow that simplifies the design process. The design takes place at the high level of abstraction and the real data is measured at the low level from the hardware devices. The low level provides more information, which is required for accurately measured values that are not available at the high level.
- Reproducing the remote laboratory system (experiment and instruments) as much as possible in order to allow students to change seamlessly from performing the experiments in the on-site system to remote physical instruments in the remote system.
- Accessing the remote system from any computer connected to the internet via any standard browser without installing additional software.
- Offering a real view of physical instruments used in the remote system allows the students to easily recognise the instruments used in a hands-on laboratory.

1.5 Research Methodology

The methodology of this research is conducted using several sequential stages and continuous aspects. They assist in clearly defining the research objectives. The methodology can be divided into three categories:

- Outlines of lecture sessions that are employed to identify the conceptual theories or define the learning objectives for the laboratory experiments. Designing the laboratory system for educational purposes requires a good design that considers the learning objectives of the course and works to improve the students understanding.
- Instructions that are necessary to decide on the design and implementation of the new educational system to enable the concepts and knowledge to be delivered to the students and facilitate them achieving the learning objectives.

This stage includes technical implementation methodology that is focused on the development of an effective on-site and online remote experiment.

- Assessment, which is essential to decide how well the learning objectives have been achieved and the results have been explained to the student in the new laboratory system. Assessment methodology is concerned with the development of an appropriate educational experimental design for measuring instruments, obtaining experiment real data, and analysing and assessing the experimental results.

As Figure 1.3 shows, the three stages help to develop and implement the new educational system. Further details are discussed and displayed in the following chapters. The next section provides an overview of the thesis outlines and its structure.

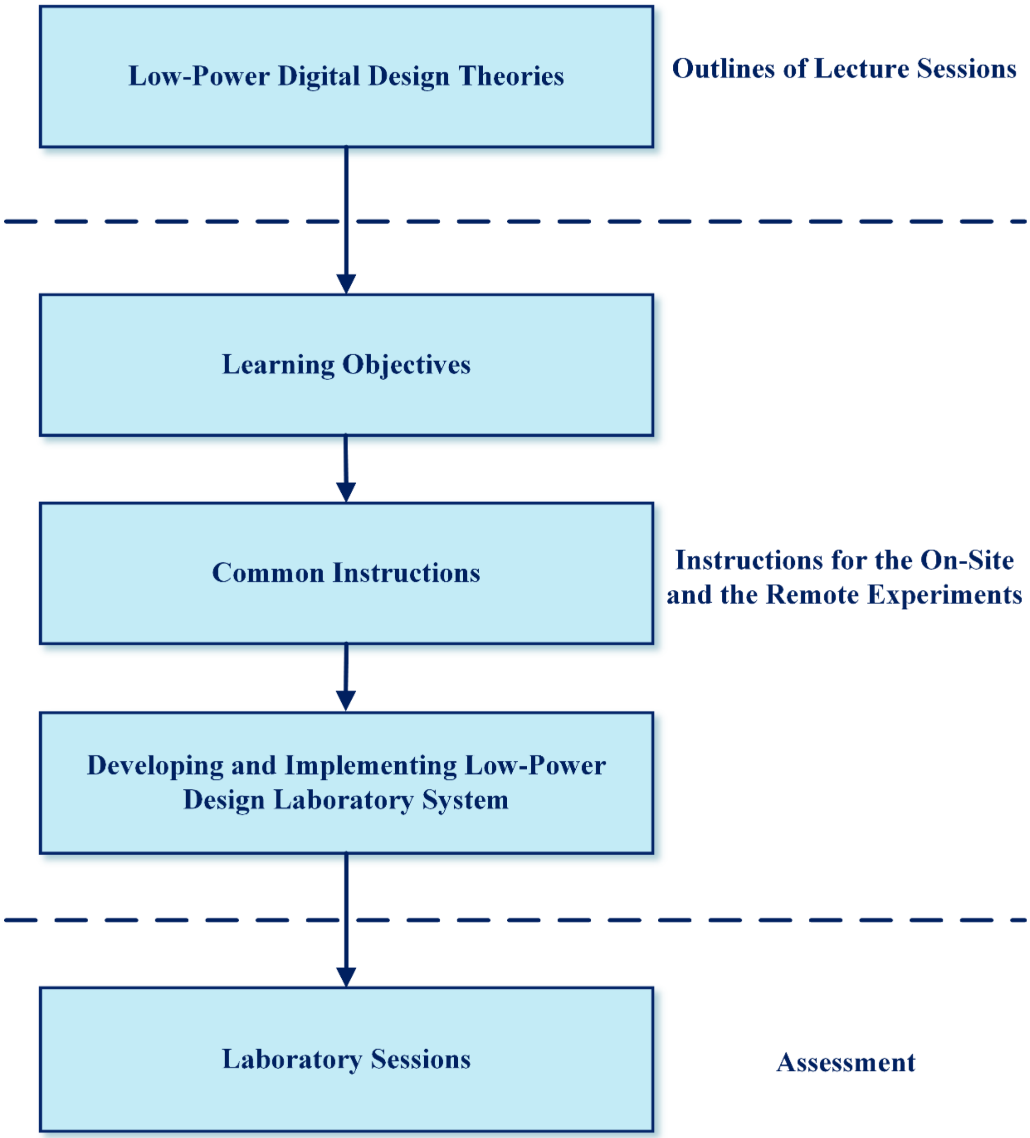

Figure 1.3: The sequential stages of the methodology used

1.6 Thesis Outlines

This section provides a brief overview of this thesis which presents the design and the implementation of the low-power design laboratory system. The thesis document is divided into twelve chapters. This chapter provides an introduction to the research. Chapter Two introduces power dissipation in digital systems and demonstrates the low-power techniques. In Chapter Three, the methodologies and the categories of proposed tools for teaching low-power design in laboratories that have been found in the existing literature are described. Chapter Four discusses a literature review of laboratories and the new technologies that influence changes in the learning in the science and engineering laboratories. It also provides definitions, requirements, advantages and disadvantages of hands-on laboratories, simulation or virtual laboratories, and remote laboratories. Chapter Five presents an overview of the laboratory system and how low-power design techniques can be applied during the laboratory experiments at different levels of the design stage. Chapter Six discusses the concepts of designing and implementing the remote system. Chapter Seven introduces the system architecture of the developed remote system and illustrates the components of the remote system such as interface and control, how each component interacts with others and the roles of each component used in building the completed remote system. Chapter Eight illustrates the instructions, and operation and procedures involved how a client accesses and interacts with the remote experiment via the internet. Chapter Nine presents the learning objectives that are achieved through performing the laboratory experiments. Chapter Ten presents technical performance results of the laboratory system and demonstrates a number of the laboratory exercises. The penultimate chapter explains the assessment methodology and presents the results of the assessment for the laboratory system. A brief summary of the thesis, conclusions and future work can be found in the final chapter.

2 Low-Power Digital Circuit Design

2.1 Introduction

The low-power digital circuit design has been an important research field over the past twenty years. Power efficiency was one of the main challenges during the technology transition from vacuum tube to bipolar, and then to complementary metal oxide semiconductor (CMOS) technologies [9] [10].

Digital circuit designers are facing challenges in reducing the power dissipation and meeting the design requirements of the digital systems. These challenges, especially power dissipation, are particularly essential for portable powered devices. The power dissipation can be reduced by using specific low-power design techniques. This research will focus only on digital circuit design based on CMOS devices since CMOS technology is the most widely used in recent digital systems [9] [11].

This chapter first introduces why power dissipation has become one of the most essential requirements in a digital circuit design, then the sources of power dissipation in a digital circuit are investigated, and finally recently proposed low-power design techniques are explored in the digital circuit design stage.

2.2 Digital Circuit Design Constraints

The continuous growth of the semiconductor industry has led to denser, faster, and cheaper stuctures following Moore's law [12]. The industry shows an exponential increase in the chip speed, functional complexity, and billions of transistors are integrated into one chip as shown in Figure 2.1.

Digital circuit designers have now to work with challenging constraints if they are to meet digital design requirements: circuit performance, design area, manufacturing cost, reliability, and power dissipation.

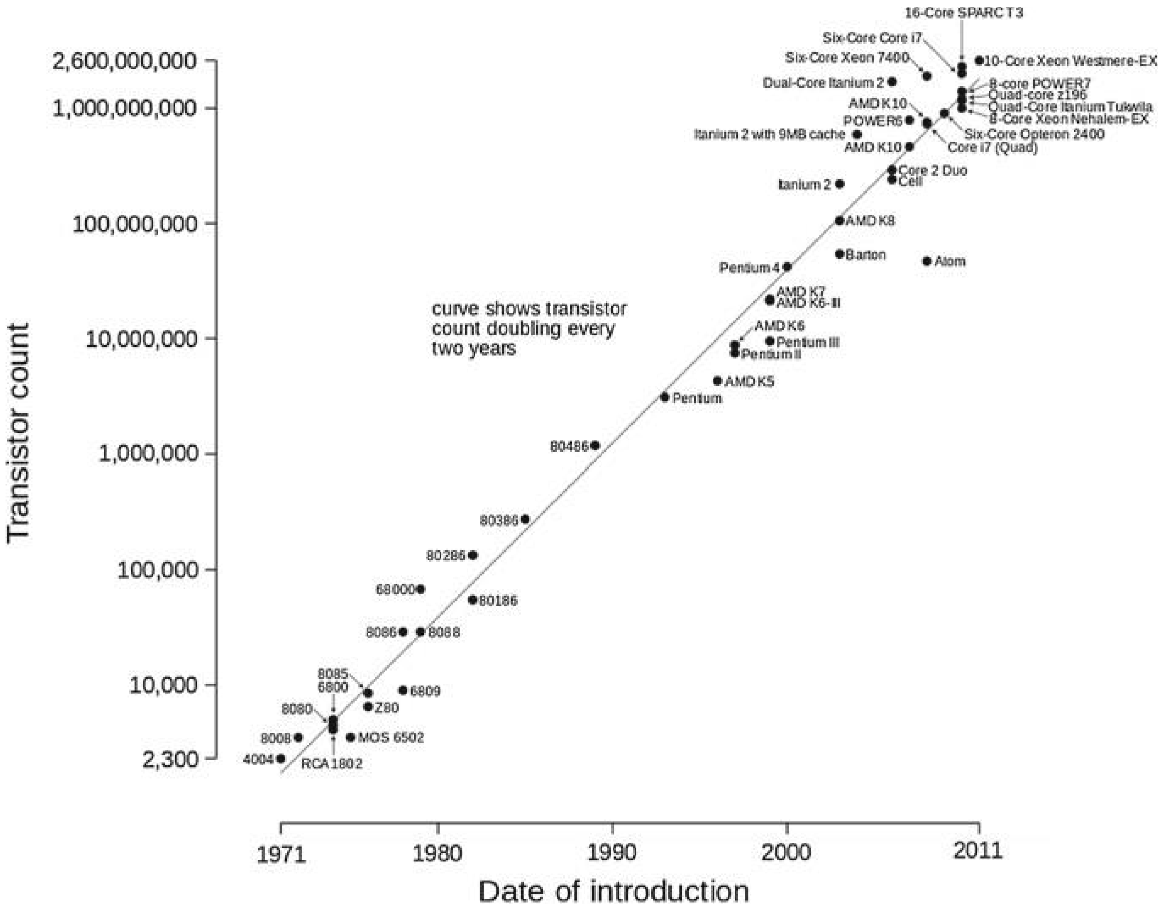

Figure 2.1: Illustration of a number of transistors per chip since 1971; note the logarithmic vertical scale [13]

High circuit performance requires using more computational processes and more complex functions which decide its circuit area and power dissipation. The cost of silicon is proportional to its area. The power dissipation and temperature density of the digital circuit become one of the most important constraints due to their influence on reliability. All these factors have an impact on and specify the cost of digital systems [9] [14] [15].

The digital circuit designers should understand any risk and required specification of the digital design and that is not only meeting its cost budget. The manufacturing cost can be reduced in the context of the design area, the system performance, the reliability, and the power dissipation. Therefore, it is essential to explore all possible solutions to achieve a tradeoff in these factors.

2.3 Why Low-Power Digital Circuit Design

Low-power digital systems have become very demanding, especially in portable devices. Most digital circuit designers and manufacturers are interested in improving the devices' performance with low-power dissipation for the following reasons [9] [10] [11] [15] [16]:

- **Increasing requirements for long-life battery powered electronic devices.** The continuous growth of the portable electronic devices which demand high-speed computations and complex functionalities. Digital devices have limited battery resources, the energy in battery-powered devices is fixed, and the long-life of the battery is determined by the average power dissipation for non-rechargeable batteries or the time between charging rechargeable batteries. Portable powered devices with the absence of low-power design will either have a short battery life or a heavy battery package even with new battery technologies, both of which are not desirable.
- **Increasing demands for smaller, less expensive, and more reliable electronic devices.** Part of the power is consumed in the form of heat growing with the complex functionalities and high-speed computations of digital systems. The performance of a digital circuit is influenced by the operating temperature since reliability is affected by heat. Therefore, cooling the operating temperature is essential for a reliable and stable performance of electronic products. The cooling techniques are using heat sinks and/or fans to eliminate unwanted heat which also consumes a sizable power budget, therefore, increasing the overall weight and cost.
- **Need for less noisy electronic devices.** Digital systems which consume a lower amount of power generate little heat, but more heat requires cooling techniques to remove the waste heat, such as fans along with heatsinks, which impact on the environmental rooms/offices.
- **Need for green electronic devices.** Although the power dissipation of electronic devices is only a small part of the total electrical power budget; this issue has changed significantly in the last few decades, since the wide use of portable electronic devices in our everyday lives.

2.4 Sources of Power Dissipation in Digital Circuit

Most components in digital systems are currently fabricated using CMOS technology. The main sources of power dissipation in digital CMOS circuits are dynamic and static power [9] [14]. The total power dissipation for any CMOS digital circuit is the total sum of the dynamic and the static power as described in Equation 2.1.

$$P_{total} = P_{dynamic} + P_{static} \tag{2.1}$$

2.4.1 Dynamic Power Dissipation

The dynamic power includes the switching and the short-circuit currents in the transistors of the digital circuits. Dynamic power dissipates when the digital circuit is active during changing states of the logic gates in the digital circuit.

Short-circuit power dissipates due to the presence of a direct current path from the power supply to the ground during the rise and fall times of transition intervals, so the short-circuit power is a function of the rise and fall times, and the load capacitance.

The Equation 2.2 describes the short-circuit power [15] [17]:

$$P_{short-circuit} = I_{sc} * V_{dd} \tag{2.2}$$

Where I_{sc} is the short-circuit current during switching, and V_{dd} is the supply voltage. From Equation 2.2, the short-circuit power is proportional to the short-circuit current, and the supply voltage. Short-circuit power is estimated to 10-15% of the dynamic power dissipation. Thus it is small and constant compared to overall dynamic power dissipation for specific technologies, for this reason, it will be neglected in this chapter [9] [18].

When the logic level of the logic gates transits between ‘0’ (low voltage) and ‘1’ (high voltage), the parasitic capacitances are charged and discharged, which is called switching power dissipation, the repeated capacitances charge and discharge on the outputs of gates in chips, and that dissipates most of the overall power [9] [15] [17].

In the current CMOS circuits, dynamic power is the main sources of power dissipation, the dynamic power dissipation is given in the Equation 2.3 which can be managed through the design stage [9] [10].

$$P_{dynamic} = S * C_L * V_{dd}^2 * f \tag{2.3}$$

Where $P_{dynamic}$ represents the dynamic power dissipation of a digital circuit; S represents the average number of transitions across the entire digital circuit per clock cycle; C_L

represents the capacitance of a digital circuit; V_{dd} represents the supply voltage, and f represents the clock frequency. Dynamic power dissipation for any CMOS digital circuit is the function of the switching activity, the capacitance load, the voltage, and the clock frequency. The dynamic power for a typical digital circuit may contribute nearly 80% of the total power [9] [10] [14–16] [18].

2.4.2 Static Power Dissipation

There are six leakage current categories in CMOS technology; Figure 2.2 illustrates the sources of the leakage current categories. I_1 is the reverse-bias p-n junction leakage; I_2 which flows between the source and drain when the gate voltage becomes below the threshold voltage, is the subthreshold leakage current; I_3 occurs by oxide tunneling electrons from the substrate to the gate and from the gate to the substrate through the gate oxide layer; I_4 is the gate current that occurs due to electrons or holes gaining sufficient energy; I_5 is the gate induced drain leakage due to the high field effect in the drain junction; and I_6 is the channel punch through current due to channel length reduction and an increase in the reverse bias across the junctions which become nearer. I_1 and I_3 leakage currents are in both ON and OFF states, while I_2, I_5, and I_6 leakage currents occur in OFF-state leakage currents, and I_4 can be in the OFF state, but mostly occurs during the transition of the transistor.

The most dominant leakage currents in recent CMOS technologies are the subthreshold leakage (I_2) and the gate tunneling leakage currents (I_3). Subthreshold leakage current contributes more than the gate tunneling leakage current to the overall leakage power, especially at higher environmental temperature. However, gate leakage current is expected to increase with the smaller geometry of chip's size.

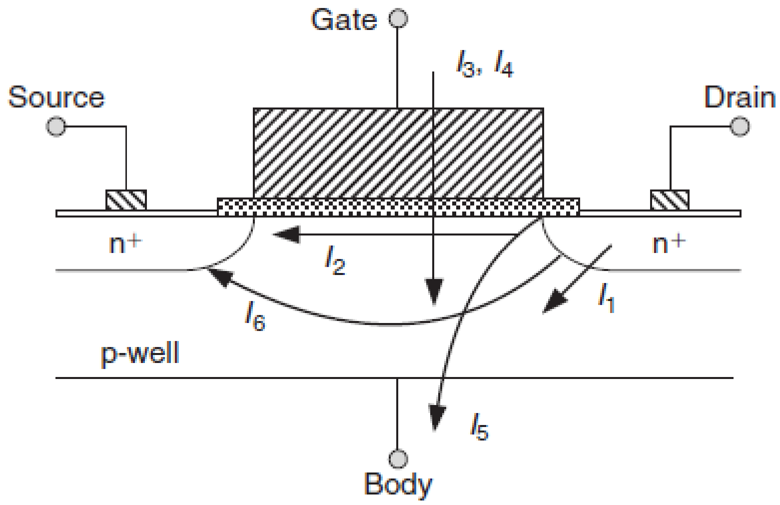

Figure 2.2: The sources of leakage currents in deep submicron transistor [19]

The subthreshold leakage current (I_2) power is given in Equation 2.4 and Equation 2.5 [14].

$$I_2 = I_0\, e^{(V_{gs} - \frac{V_{th}}{nV_T})}\ [\ 1\ -\ e^{-\left(\frac{V_{ds}}{V_T}\right)}\ ] \tag{2.4}$$

$$I_0 = (W \mu_0\, C_{ox}\, V_T^2\, e^{1.8)})/L \tag{2.5}$$

Where the V_{gs} is the gate-to-source voltage; the V_{th} is the threshold voltage; the n is the subthreshold swing coefficient; the V_T is the thermal voltage; the V_{ds} is the drain-to-source voltage; the W is the effective transistor width; the μ_0 is the carrier mobility; C_{ox} is the gate oxide capacitance; and L is the effective transistor length.

$$P_{leakage}\ =\ f(V_{dd}, V_{th}, \frac{W}{L}) \tag{2.6}$$

Equations 2.6 shows that leakage currents depend on device gate dielectric thickness. The thickness of the transistor gate layer is decreased to improve circuit performance and also threshold voltages are scaled as the transistor size shrinks which have an impact on increasing the leakage current. Thus the leakage currents influence digital circuit's performance, power dissipation, operating temperatures, and reliability. Leakage power dissipation which was ignored in the past has become a primary concern in digital circuit design [9] [11] [16–20].

Referring back to the equations for a total power dissipation of a digital circuit, it is obvious that power dissipation can be minimized by using specific low-power design techniques that address one or more of the influencing parameters at a specific level in the design stage.

2.5 Low-Power Digital Design Techniques

Digital circuit can be designed using different low-power techniques that can have a significant influence on its power dissipation. Power reduction can be performed in the design stage and may well address categories of power such as dynamic or static power with good understanding of the sources of power dissipation. Addressing the low-power design from the early stage of design provides enriched probabilities to achieve a significant reduction of the power and avoid expensive redesign stage. This section focuses on low-power digital design techniques in the design stage.

2.5.1 Complexity of the Design Circuits

Power dissipation will grow as the application's operations increase. The complexity of applications means an increase in the number of functional units and long paths which also increase the overall design area and power dissipation of the digital circuit [9] [11] [12] [15]. However, digital circuit design should satisfy the design's requirements, rather than exceed it. Therefore, the strong demand for high-performance digital systems requires skills design and knowledge in new methodologies that support low-power design.

2.5.2 Frequency Scaling

Lowering the operating frequency is very effective to reduce the power dissipation in a digital circuit (refer to the Equation 2.3). However, the execution time will be longer in carrying out the same task with this technique. Lowering the operating frequency may be applied in digital systems when the full speed is not required [9] [11] [14].

2.5.3 Voltage Scaling

Supply voltage scaling has been the most adopted method to reduce the power dissipation of a digital circuit, reducing the supply voltage by scaling the device is one of the effective low-power design techniques referred to Equation 2.3 [9–11].

The disadvantage of reducing the supply voltage can increase the delay that causes decreasing the throughput of a digital circuit. Therefore, the speed performance of the digital system is increased, and then the supply voltage scaling is decreased until the system speed returns to its original execution time, but with a lower power dissipation. Additionally, reducing the supply voltage will result in lowering the threshold voltage that causes the leakage current to grow exponentially, referred to Equation 2.4 [14–16] [18].

2.5.4 Glitches

A dynamic hazard is an additional source of dynamic power dissipation, the value of which should be minimized through a design of digital circuits. A dynamic hazard occurs when an input signal of a gate changes its value, which causes unwanted transitions at the outputs of a digital circuit, also known as glitches. The events of dynamic hazards are detected through timing analysis of a digital circuit [9] [11] [16].

A typical example of the effect of glitches is demonstrated in Figure 2.3, which shows the simulated response of a digital circuit of NAND gates, the input NAND gates changes from 1 to 0. At the beginning, the output result is 1, but one of the input is 1 for a particular delay, then the output signal changes from 0 to 1 when the true input of the gate goes low.

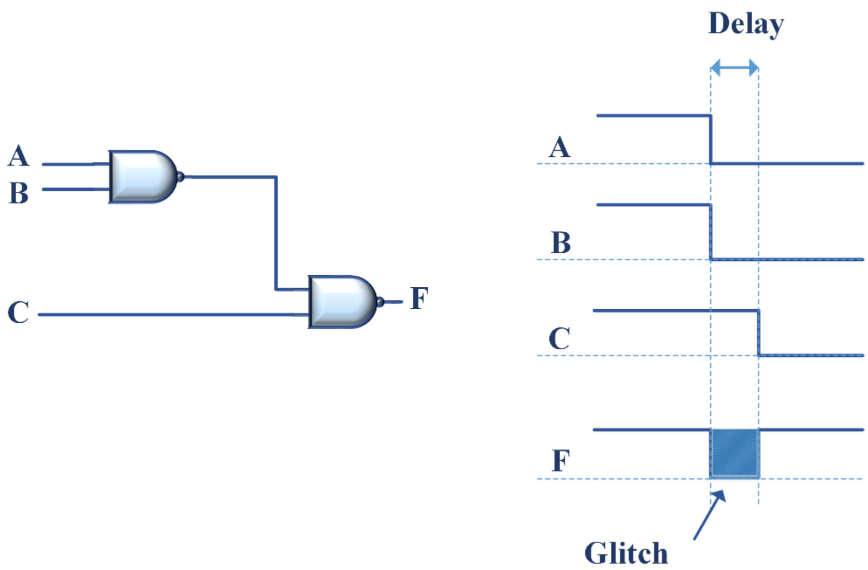

Figure 2.3: Glitches in a digital circuit

Glitches may occur due to unbalance in the data path lengths of the digital circuit, which can be solved using different techniques, for example, reconstructing the digital design.

When the design is balanced as regards its data paths, the timing paths are the same length, and so glitches are reduced. Figure 2.4 demonstrates a solution to a glitch by reconstructing the digital circuit, where a digital circuit in a and b are equivalent, but topologically different, the function F = A.B.C.D is analysed. Figure 2.4 shows the simulated response of a digital circuit of AND gates, all input AND gates change from 0 to 1. At the beginning, all the output results are 0, but some input is 1 for a particular delay, and then the output signals change from 0 to 1 when the true input signals of the gates become high. The reconstructed digital circuit in Figure 2.4b shows balanced as regards its data paths so the timing paths are nearly the same length. As a result, the delay length is reduced.

Long chains of a digital circuit also result in a glitch. Glitches can be reduced by inserting flip-flops in a long digital circuit, but the inserted flip-flops add capacitances to a digital circuit that consumes additional dynamic power [9] [11] [19].

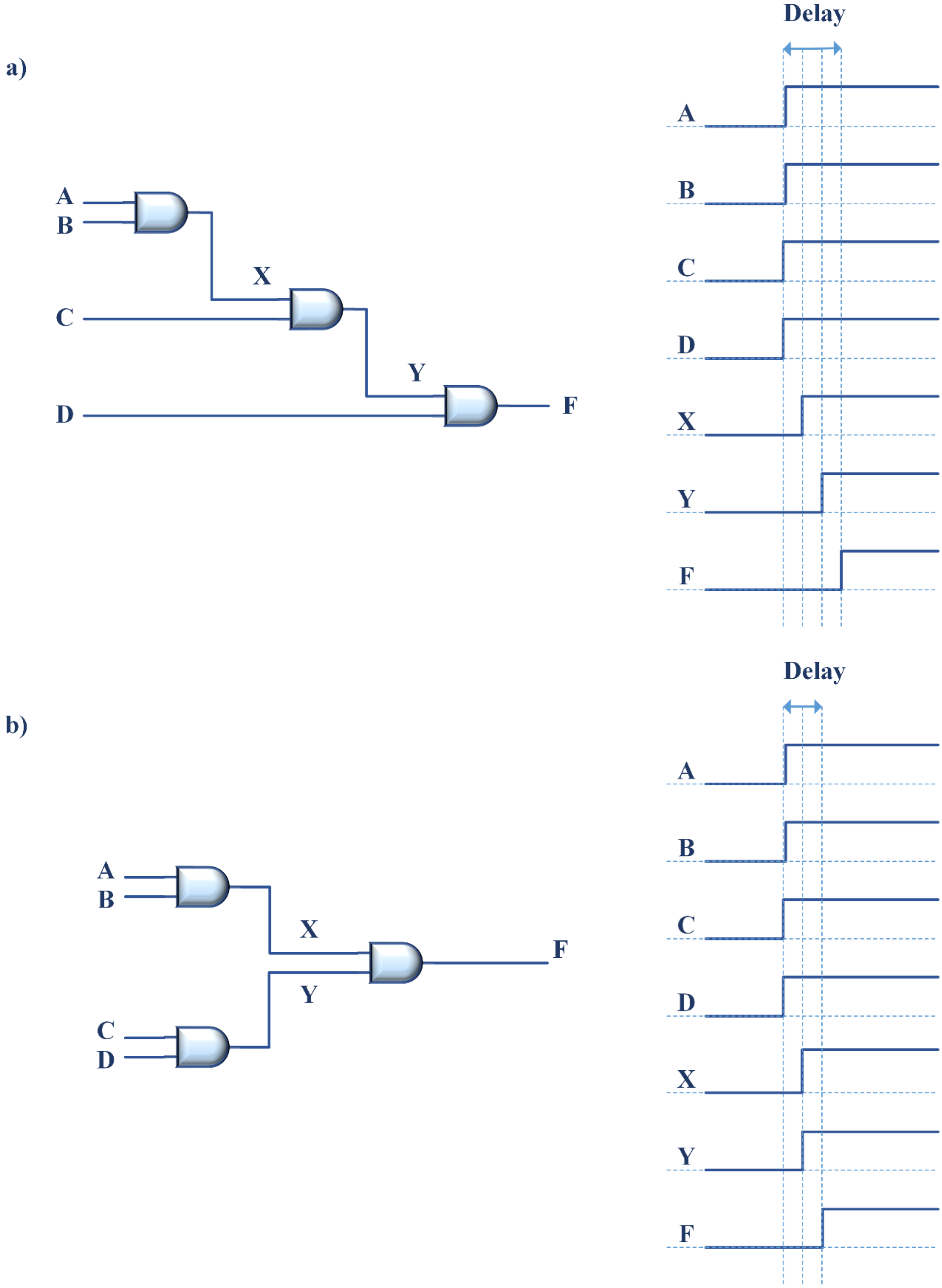

Figure 2.4: (a) A digital circuit without balanced data path lengths. (b) A reconstructed digital circuit with balanced data path lengths

2.5.5 Clock Gating

In a digital circuit, the clock cycle drives a large number of capacitive loads that is connected to numbers of sequential components. The reduction of the dynamic power can be achieved through removing the unwanted toggled signals in every clock cycle. This technique is used to reduce the switching activities by adding latches/registers with an AND gate that can be controlled by an enable signal of the digital circuit. This is illustrated in Figure 2.5, the signals of the digital circuit remain stable as long as the latches/registers clock is disabled [9] [11] [16].

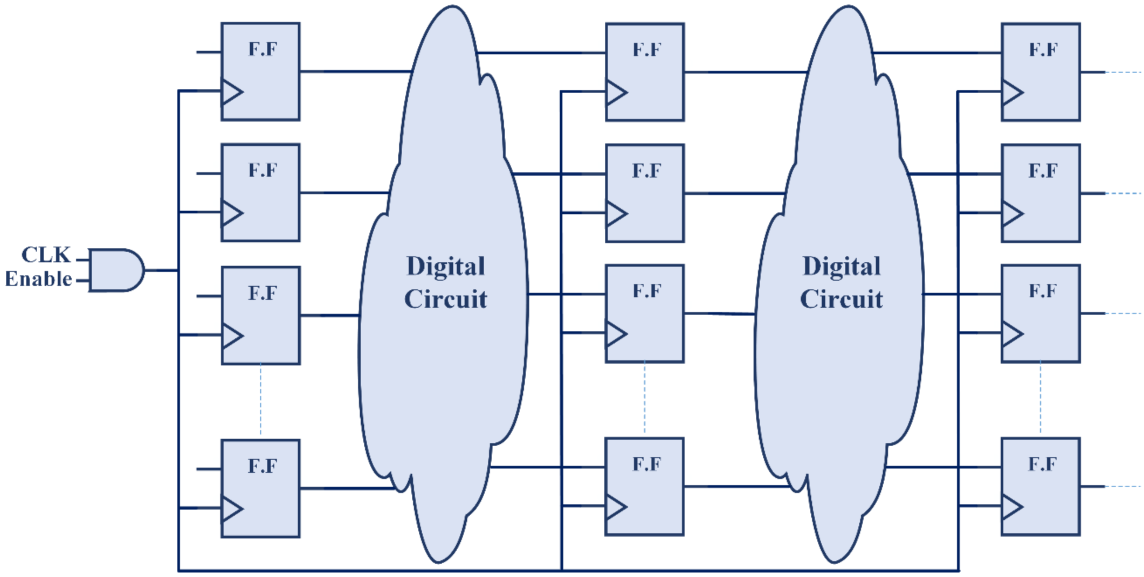

Figure 2.5: Digital circuit with clock gating

2.5.6 Data Gating

The output of a digital circuit may toggle from values to other values which are unwanted data. These redundant transitions cause significant power dissipation. Data gating can reduce redundant transitions which are unwanted computation, so the output of a digital circuit will be stable. Figure 2.6 shows how data gating is applied, the input signals of the multiplier in Figure 2.6b are isolated so that a digital circuit is prevented unwanted operations if the multiplier's results will not be selected. The digital circuit suppresses the redundant switching activities. However, the additional power is wasted by the added gates but eliminating the unnecessary toggled data also allows some power to be saved [9].

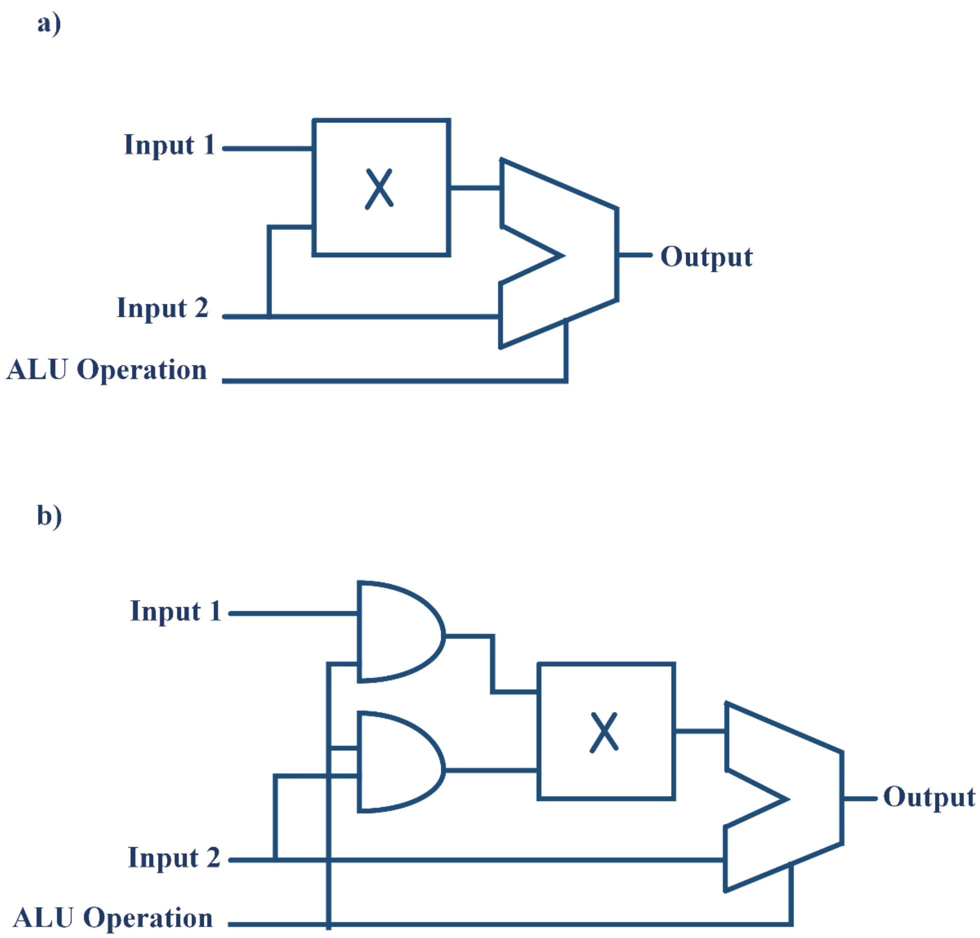

Figure 2.6: Digital circuit with data gating

2.5.7 Used Resources in a Digital Circuit

A digital circuit consists of sets of interconnected functional units and control units. The functional units include: arithmetic units, logic elements, memory cells, and registers. The control units are, for example, multiplexers which send signals to functional units with scheduling time for an appropriate sequence of processes. Each unit consumes a different fraction of the power. For example, the power dissipation increases with an increase in a size of the memory. Additionally, the power can be saved by a suitable utilization of registers. Thus the power dissipation of a digital circuit is dominated by a specification of the design as a type of resources, a number of resources, and the execution time needed to carry out an operation. All these parameters determine the performance and the power dissipation of the digital circuit [9] [15–18].

2.5.8 Reducing the Capacitance

Dynamic power dissipation in CMOS technology is proportional to the capacitance C in Equation 2.3. Continuous CMOS technology scaling reduces all dimensions of transistors, the delay, and the capacitance. A complex computing process requires more transistors which will increase internal capacitances and more switching speed resulting in dissipating higher power. The power dissipation of a digital circuit that utilizes a larger area on a chip can be decreased at the technology level through using smaller node technology which causes a smaller area on a chip to implement the digital design [9] [10] [14–17].

Figure 2.7 demonstrates the scaling trend for the CMOS feature size for different technology generations published by the International Technology Roadmap for Semiconductors (ITRS) [19].

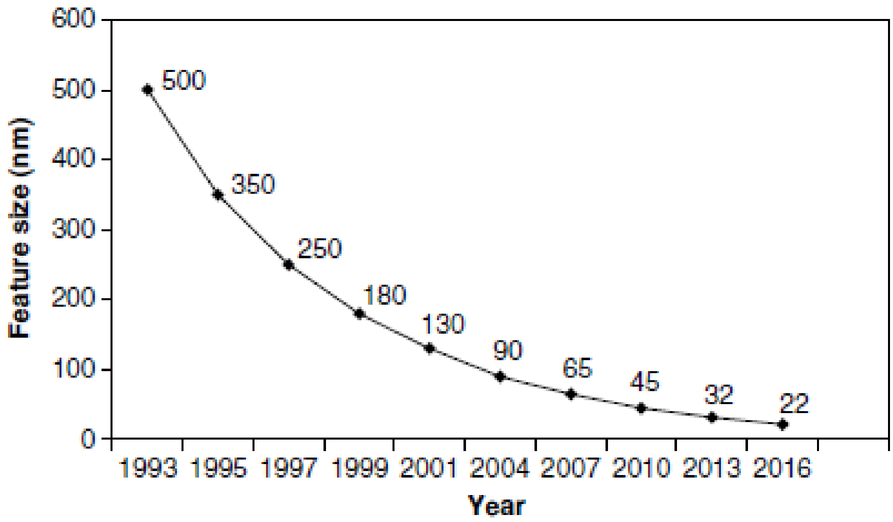

Figure 2.7: Gate scaling of CMOS technologies [19]

3 The State-Of-the-Art

3.1 Introduction

Power dissipation has become one of the main constraints in a digital circuit design and requires more consideration in the early design stage. Consequently, many researchers have proposed and developed different power estimation tools and techniques that can be applied at different levels of the design stage.

In this chapter, low-power digital circuit design in Electrical Engineering education and the enhancement of laboratory experiments in teaching low-power design techniques are discussed. An overview of the methodologies and the categories of suggested tools to estimate the power dissipation of a digital circuit that have been proposed in the existing literature are presented. Teaching low-power design laboratory at the Bonn-Rhine-Sieg University of Applied Sciences is introduced.

3.2 Low-Power Digital Circuit Design in Electrical Engineering Education

In general, undergraduate engineering students often have basic knowledge about and skills required for digital circuit design from the semester courses Digital Electronics, Digital Logic Gate Characteristics, and Introduction to VLSI Technology and Design. Meeting the constraints of the digital circuit is an important topic in circuit design courses. A few years ago, there was a lack of low-power design education in the electrical and computer engineering curriculum. 62% of textbooks on digital circuit design have not covered power dissipation of the digital design [21], so they do not provide sufficient knowledge for graduates in their future jobs as circuit designers; their design will lack low-power design knowledge and skills. In recent years, industry has begun to require circuit designers to be experienced in low-power techniques to enhance designing digital systems. Circuit designers have to achieve some trade-off between performance and power dissipation of their design. Consequently, teaching low-power design for electrical and computer engineering students is essential and valuable, low-power digital circuit design has been included in the curricula when an electrical and computer engineering curriculum was developed. Additionally, textbooks are now available that cover the low-power design theories. The courses aim to provide engineering students with the current low-power design solutions required in future circuit designers' tasks.

3.3 Enhancing Laboratory Experiments in Teaching Low-Power Design

Engineering education aims to produce graduate engineers who have the ability to design; where design thinking combines theory and practice. Design skills are hard to learn and also to teach. To obtain sustainable knowledge, students need to understand the design theories by practicing the theories in laboratory experiments. Most engineering courses to achieve better learning outcomes include the following [1] [22] that are also shown in Figure 3.1:

- Resources such as instructors, books, and tools.
- Materials and theories which are covered in lecture sessions in classes.
- Laboratory experiments which enable the students to learn design skills and knowledge.

Figure 3.1: The requirements to achieve better learning outcomes for an engineering courses

The lectures provide the theories and knowledge for engineering students and laboratory experiments develop the practical skills; in which the students can apply their knowledge in real applications. The laboratories offer the required instruments and tools to overcome the complexity of courses to provide a link between the theories and the laboratory experiment results. Learning objectives that are achieved by following up the lecture sessions with laboratory experiments are the most effective as the students gain more information than when they only attend the lectures. Therefore, laboratory exercises should be a part of engineering courses in many engineering programs.

Low-power digital design has been addressed in the curricula when an electrical and computer engineering curriculum was developed. Low-power design theories from textbooks provided during the lectures guide the student through the design stage. Therefore, the laboratory exercises should be available when teaching low-power design techniques, as they allow engineering students to directly apply their knowledge and to analyze and solve the challenges faced. Using real applications in laboratory exercises assist students in becoming familiar with physical instruments, and thus, in turn improve the learning outcomes by proving the concepts and the theories. Additionally, these laboratory exercises with real applications serve to minimize the gap between engineering education and industry's requirements. Thus, a tool or a method must be available that enables students to estimate the power dissipation of their digital design during the design process. For this reason, the low-power design laboratory system has been designed and developed for low-power education with laboratory exercises.

3.4 Categories of Tools for Teaching Low-Power Design Laboratory

Power estimation can be defined as the method for calculating energy and power dissipation at a particular level in the design process. There are only a limited number of tools that specialize in estimating the power dissipation of digital circuits. Studies dealing with the problem of power estimation have proposed different methodologies to estimate the power at a level of the design stage: transistor-level, logic gate-level, register-transfer- (RT) level, and system-level. The estimated power at the different level is a tradeoff between accuracy and estimation time.

3.4.1 Transistor-Level Approaches

The power of the digital circuit design can be estimated at the transistor-level by measuring the average current flow from the circuit power source. The power estimation methods that are based on transistor-level provide more accurate information where glitches and short-circuit currents are taken into consideration. The models for components such as transistors, capacitances, and resistors are close to the real values. However, they can only be applied to small digital circuits. SPICE [23] is an example of a transistor-level simulator, a growth in the digital circuit's size will increase the complexity of the calculation and require long estimation time.

Alipour, Hidaji, and Pour [24] propose the method which uses models for transistors in simulated techniques to achieve an almost accurate model for each transistor. However, the method is, in practice, not feasible for large digital circuits due to the long processing time needed. Further limitation is the length of input vectors, these must be short to avoid long estimation time. To reduce the length of the input vectors, Marculescu and Ababei propose a technique that causes approximately 5% loss in the accuracy of the power estimation [25]. Furthermore, the sizes of transistors are also relevant in the accuracy of the power estimation in digital circuit design, so many tools are available that provide transistors size characteristics [26–28]. PowerMill [29] is also proposed as a transistor-level power simulator; it uses an event-driven timing simulation algorithm based on a table-driven model of the device, and nonlinear iteration and circuit partitioning.

3.4.2 Logic Gate-Level Approaches

The power dissipation of a digital circuit at the logic gate-level is estimated for a gate at each transition by calculating the parasitic gate and the wire capacitances and by obtaining each gate’s switching activity. There are several approaches to estimate power dissipation at the logic gate-level techniques that are based on probabilistic or statistical methods and the obtained information is stored in the module library for components of digital circuits. The accuracy of power estimation at the gate-level depends on accurate records of the switching activities in a given digital circuit. For a large digital circuit, considerable records are required which in turn slow down the simulation speed.

Nocua, Virazel, Bosio, Girard, and Chevalier present a hybrid power estimation at the gate-level [30]. It is based on a hybrid approach that obtains information from different abstraction levels. The approach measures data in order to create a gate-level power estimation database and then develops the model based on the characteristics. The data is measured by using SPICE to determine the transistor-level parameters under different conditions such as polarization, temperature and load values. Additionally, an activity file is generated in which all the switching activities per gate are recorded, so the information necessary to estimate the power of this model has to be read and extracted from the memory.

Kagaris and Haniotakis deals with the transistor-level implemented on a gate in order to minimize the number of transistors in the digital circuit and considers the switching activity of each particular input [31].

3.4.3 Register Transfer-Level Approaches

The power dissipation at register transfer-(RT) level is estimated for each component in a digital circuit by developing a model that is more complex than at gate-level. The frequently used RT-level components are arithmetic components, multiplexers, comparators, registers, multiply accumulate units, and ALUs.

Damaševičius proposes a framework to estimate area, power and delay characteristics of a digital circuit at the RT-level using SystemC modelling language [32]. In this framework, the dynamic power is analyzed based on the state of the modelled circuit. The switched capacitances consist of the input, output of the logic gate, and the type of the components. The speed of this estimation framework in SystemC reduces when the functionality and complexity of a modelled digital circuit is increased.

Other approach proposes another power estimation technique for a digital circuit [33–36]. This approach is based on a look-up table (LUT) in which the power model requires statistical information about input signals. Different functional simulations are performed with various input statistical values to build the model. This power estimation model does not include interconnects among different IP macro-blocks and other parameters as glitch activities.

Verma, Shekhar, Maheshwari, Virdi, and Srivastava estimate the power dissipation of a digital circuit targeted to FPGAs [37]. This approach suggests estimating the dynamic power by assuming the capacitance charging and discharging values using vectors to generate the switching activity of digital circuit design and using the Matlab program. The power dissipation by each component as multipliers, adders, flip-flops and number of slices are characterized using a power model. This approach takes into account the static power in its power estimation but considers it as a constant value.

3.4.4 System-Level Approaches

The power estimation techniques at a system-level require high-level system descriptions using abstract models for the capacitance and switching activity. Digital circuits have become more and more complex and thus it is necessary to have more systematic and accurate power estimation approaches. The power estimation at the higher level of abstraction is faster, but the accuracy will be reduced due to the limited physical information of the components.

Research from both industry and universities have presented approaches for achieving low-power dissipation. They use either a direct measurement technique or power model based methods. In general, the power estimation techniques from the underlying hardware provide accurate results [38]. The highest accuracy is achieved after the implementation (hardware level). Several studies use the implemented architecture on an FPGA to estimate the power dissipation of digital circuits. Becker, Huebner, and Ullmann discuss measuring the power during real runtime applications for an implemented digital circuit on an FPGA [39]. The measuring equipment includes a computer, control software, and an oscilloscope with a computer interface. The shunt resistor is connected to an opened bridge on the board for measuring the input current of the FPGA. The oscilloscope is used to sample the voltage over the shunt resistor and to store the data into its memory. The measured data is saved in a file needed for calculating the power using the MATLAB software.

The power estimation approaches at the lowest levels of the design process are quite accurate, but the estimation techniques can only be used when a digital circuit is completed. Additionally, the power dissipation is related to the switching activity in a digital circuit, this switching activity should be used to estimate the power. This information is usually obtained by probabilistic or/and statistical models at a high level of abstraction in the design process. Power estimation techniques at a high level will not provide as accurate information as at a low level. However, they are fast, especially in complex and large digital circuits. A number of power estimation techniques at a low level of the design process, such as transistor-level or gate-level can provide more accurate estimated results, but they also may become unpractical for large and complex digital circuits which need to account all capacitances and resistances from each transistor and interconnecting wire that build the digital circuits.

3.5 Teaching Low-Power Design Laboratory at the Bonn-Rhine-Sieg University of Applied Sciences

The main difficulties with most previous power estimation approaches result from trying to imitate a physical implementation of digital circuits in high-level models. The details of digital circuits are based on probability and related mathematical formulae that cannot account for all digital circuit characteristics such as the effect of temperature on semiconductor devices and the time constraints of the circuit design. Additionally, the previous estimation approaches suffer from lower accuracy and more complexity, making them difficult to use in educational laboratories.

The low-power design laboratory system is proposed as an educational tool to overcome some of these difficulties when teaching low-power techniques with laboratory exercises at the Bonn-Rhine-Sieg University of Applied Sciences. The low-power design laboratory system is a new approach based on an FPGA as a design platform where the digital circuits are implemented by circuit designers, and it uses image processing as an application for teaching the laboratory exercises that is more motivating and interesting [7]. Therefore, a laboratory system must be developed an especially designed FPGA-board that facilitates the evaluation of the power dissipation of the implemented digital circuits and contains all required components and instruments to use image processing as an application. Furthermore, this PhD thesis aims to improve and develop the laboratory system to enable the remote operation of the low-power experiments.

The on-site system and the remote system use a top-down hierarchy design approach that involves defining the functionality and performance of a digital circuit at the high level, and the performance and the power of the design are estimated only after implementing a design circuit. Additionally, addressing the low (hardware) level helps the students to learn low-power design techniques to:

- Examine the fuctionality of students' digital circuits.
- Estimate the power dissipation during runtime of a real application that provides realistic power measurements from electronic devices.
- Estimate the power dissipation of complete and complex implemented digital circuits.

4 Remote Laboratories in Engineering Education

4.1 Introduction

Laboratory experiments in engineering curricula play an important role in science and engineering education in order to deepen the knowledge and to acquire skills for the students. It is essential to include laboratory experiments to demonstrate theories and concepts. In the past, educational laboratories were always hands-on laboratories. They have been further developed and have benefited from continuous progress development in technologies and tools that assist in introducing new methods to deliver laboratory experiments to students.

This chapter investigates the categories of engineering laboratories with regard to their usage and purpose or their methods of delivering the knowledge to students. The definition, advantages, and disadvantages of the various types of these laboratories are discussed, an overview of remote laboratories in the literature is presented, and finally, the low-power design remote system is defined.

4.2 Categories of Laboratories

Most of engineering knowledge and skills are transferred in the laboratories. Therefore, it is clear that laboratories are essential in educational engineering. Engineering laboratories can be divided into three basic categories regarding their purpose and usage as the following [1]:

- Development laboratories: Development laboratories are used to find the solution for specific problems.
- Research laboratories: Research laboratories are intended to discover additional knowledge which can be added to overall scientific knowledge.
- Educational laboratories: Education laboratories are used by students, particularly undergraduates, to understand new knowledge and theories, or to evaluate a new system. It is necessary to design laboratory experiments with

regard to defined learning objectives in order to acquire knowledge. This PhD research introduces the laboratory system which belongs in the category of this type of laboratory.

Different technologies have changed the environment of laboratories that enable the student and the laboratory to be at two different locations. Therefore, different types of the laboratory have appeared beside hands-on laboratories in the form of either software or both software and hardware. Additionally, some approaches focus on online-learning in order to build systems combined of laboratory experiments and theories for engineering education. Educational laboratories can be classified into three categories that are based on the mode in which results of experiments are delivered [1] [3] [40–42]:

- Hands-on laboratories.
- Virtual laboratories or simulations.
- Remote laboratories.

4.2.1 Hands-on Laboratories

Educational laboratories started with the classical form of hands-on laboratories in which students and equipment occupy the same physical place [3]. Hands-on laboratories are an effective method to gain practical skills by dealing and practising with real physical instruments and obtaining real data. The students in hands-on laboratories have interaction with laboratory instruments where unexpected results occur probably due to an apparatus problem, an error or noise, or other uncontrolled or environmental real parameters. Hands-on laboratories require some space for students with experimental instruments, additionally, this type of laboratories suffers from some restrictions such as limited available time, not enough instruments, expensive equipment, hazardous process, as well as the need for instructors to be present [2].

4.2.2 Virtual Laboratories or Simulations

The second type is called virtual laboratories or simulations that support the distance learning approach by enabling students to perform their laboratory exercises from any computer which has the simulation software, and can be in or at a distance from the hands-on laboratories. In multiple approaches, many software simulations for engineering laboratory experiments have been developed to assist the educational process in deepening the students' knowledge. The virtual laboratories or simulations mimic the behaviours of real laboratory instruments where experimental results are based on calculations and mathematical models. Additionally, entire infrastructures of virtual laboratories or simulations are implemented by computer generated graphics. In some advanced virtual laboratories, the processed data from simulated experiments depends on experimental results that were executed in real laboratories trying to provide a more realistic and reliable environment [3] [40] [41].

In engineering laboratories, simulations have been used to demonstrate theories and knowledge as an addition to lectures or as a replacement for the actual laboratory experiments. There are common uses for virtual laboratories or simulations in engineering education as follows [1] [3]:

- Using the virtual laboratories or simulations as a pre-lab practice to encourage engineering students to expect the experimental results in an actual experiment.
- Reducing the required laboratory space for the students, instruments, and instructors.
- Using this virtual laboratory or simulation because the physical laboratories are too costly, or the experiments are often too unsafe for undergraduate students.

In general, virtual laboratories or simulations cannot totally replace physical hands-on laboratories because this type of laboratories has the following restrictions [1] [3]:

- Most simulations are based on mathematical models that give inaccurate results from analyzing complex experiments.
- The students need to learn how to deal with and use simulation software to perform their exercises that require additional effort and time.
- Some simulation software is expensive. The cost of software is not necessarily less than the cost of a hands-on laboratory.

4.2.3 Remote Laboratories

The last type is known as remote laboratories or as online laboratories trying to combine e-learning and the internet technology. Remote laboratories are designed as web-based laboratories to enable the remote control of physical instruments [43]. This type of laboratory is considered to be distance learning so that it is not necessary for students to be physically present in hands-on laboratories. Some approaches may put remote laboratories in the same category as virtual laboratories or simulations. However, remote laboratories are different from virtual laboratories in the degree of the reliable and accurate description of physical experiments.

The difference between hands-on and remote laboratories is the distance between the laboratory experiments and the students. In some hands-on laboratory experiments, instruments might be also mediated through a computer, although the laboratory instruments and students are in the same location. Thus, the process of the laboratory experiments may not differ greatly, whether the students are in the laboratory with the instruments or not. In remote laboratories, a remote server communicates between student/client and physical laboratory instruments where the student's computer is connected to the internet, and it provides the student with the experimental results from the physical instruments whenever needed and regardless of where the student is. Remote laboratories offer synchronous access to instruments and enable students to transmit experiment parameters and then obtain results from carrying out physical experiments with selected parameters [1–3] [43].

The first remote laboratories to access laboratory equipment via the internet for educational purposes are developed and implemented by Aburdene, Mastascusa, and Massengale [44], then Boroni, Goosey, Grinder, Ross, and Wissenbach propose Web Labs [45]. They suggest models for remote laboratories as a solution for sharing expensive equipment to perform laboratory experiments in classrooms or from other partner universities.

Remote laboratories are not a new approach but their numbers are increasing due to the progress and development of technologies and tools that support implementing remotely experiments. The main advantages of remote laboratories are [1] [3] [43]:

- Facilitating the delivery of experimental results though enabling the access to real physical equipment, and reinforcing students' learning practical education.
- Providing a supplement for students with a possibility to repeat laboratory experiments.
- Obtaining real results from physical instruments that prove theories.
- Assisting students to recognize and explain differences between theories and experimental results that include experimental error or unexpected results.
- Facilitating the sharing of equipment between partner universities within the same or different countries.

- Reducing the economic cost of instruments and equipment.
- Providing online learning to better fit in students' schedules who are located on or off campus.

4.3 The State-of-the-Art of Remote Laboratories

In literature, many researchers have developed and designed remote laboratories where a student can interact via an internet connection to carry out a particular experiment. One example is Loureiro who has developed two remote plasma experiments, the Langmuir Probe and the Paschen Curve, and added to the remote laboratory called e-lab [46]. Students can control and perform these remote experiments by using a graphical user interface (GUI) instead of a hands-on control process. There are solid, liquid, and gaseous states of matter, as well as plasma state. Plasma state is the fourth state for matter; it has special characteristics and properties such as temperature, density, and conductivity. It is created from a gaseous state at low pressure related to the atmospheric pressure. In a hands-on laboratory, this processes requires additional technical equipment which is also costly. The e-lab is based on remote experienced control (ReC) located at Instituto Superior Técnico (IST) of Lisbon University and programmed in Java, which is used to remotely control the plasma experiments via the internet. Students can select an experiment to perform, change parameters such as pressure, visualize an executed experiment in real time as a video stream and/or real-time plotted results, and obtain results from the performed experiment. The e-lab has five types of servers that are linked together in a network and all the experiments are connected to this network. Most experiments in the e-lab use a dspicnode controller board and data acquisition with additional auxiliary board to control a real-time experiment. A dspicnode control and data acquisition board are based on a dsPIC30F4011 microprocessor that allows to control and access the relay and flow valve, voltage measurement, and current measurement. The communication between remote experiments and a dspicnode board is implemented using a protocol designated ReC Generic Driver. The used protocol includes two parts; one is written in Java that is developed by Linkare to build an interface between the e-lab and the controlled hardware. The second is implemented on a dspicnode, which is written in C language and developed within the e-lab. In this system, for each new experiment a XML file is required to define in order to add a new hardware, which enables the communication protocol between elements.

Al-Zoubi, Hammad, Ros, Tobarra, Hernández, Pastor, and Castro have developed and designed another remote laboratory for renewable energy courses [47] [48]. This remote laboratory proves and satisfies renewable energy theories with low-cost implementation for educational purposes in Jordanian universities. The remote laboratory consists of software and hardware components. The software components can be summarized as a remote-control server is used on RESTful web services with LabVIEW which manages all students' accesses to enable them to perform their experiments, and then to transmit experimental results from the physical laboratory to the students. However, LabVIEW requires users to install a LabVIEW Runtime Engine plug-in in each web browser in order to visualize a remote panel on it, and load the remote panel into a webpage which is slow. The remote lab uses RESTful web services instead TCP or UDP socket to allow requests by using the Asynchronous JavaScript and XML (AJAX) technology. This way enable students to create a client application. The using HTTP protocol causes a little delay between a client's request and the execution of this request. Experimental results are formatted using JavaScript Object Notation (JSON) instead of XML in an effort to decrease the required bandwidth during the transmission of data. The remote laboratory contains some federation management platforms from WebLab Deusto in order to manage user sessions, reserve a scheduling, and control an access. The eolian and solar laboratories are developed with Lego Mindstorms NXT v2.0, and its renewable energy kit. Each experiment/robot connects to a PC by means of a USB or Bluetooth to interact with sensors and motors. Additionally, programming language and libraries (Java, Python, C...) are used to control experiments/robots. Students can communicate with hardware through a webpage which is built based on HTML5, jQuery, and the Bootstrap library. A webpage of a remote experiment is provided with video images using an IP webcam which provides the students with information about what happens in the experiment, and a graphical plot to present values from the experimental data.

Vagas, Sukop, and Varga have developed and proposed an industrial robot that is another remote laboratory application for educational purposes, teachers of secondary schools, and company employees to gain knowledge in industrial robotics [49]. The implementation of a remote laboratory is based on an Arduino platform and Easy Java Simulations (EJS), the graphical interface is built using EJS or applets, and Moodle. An applet is placed on a Moodle course for users which requires additional communication protocols to transmit information to the server. Results from applications are connected with external software tools from Arduino. Users require the internet access, a web browser, Java, Java 3D runtimes components and an EJS jar file to perform the training remotely. A server which is a PC sends commands from a user's computer to an Arduino board, an IP camera sends video streams during the processes to the user when interacts with an Arduino module from an application. An Arduino module controls the process and establishes a communication that includes commands to be executed in an industrial robot Almega AX-V6 and then obtain results.

Alves and Lobo have also developed and implemented a remote re-configurable logic laboratory which is designed to enable remote access to an FPGA (Field Programmable Gate Array) board, it provids basic stochastic computing circuit and enable testing circuits at high clock speed with real hardware [50]. An Altera DE2 FPGA board is used, a web server which is accessed via the internet is connected via USB to the FPGA by JTAG. A webcam is connected to the server to send a video stream of the operation process that displays results on the 16x2 LCD and the 7-segments. The switches and buttons on a board are virtualized with a web page interface using PHP dynamic functionalities to control the FPGA board via the JTAG port.

A remote laboratory for teaching programming and fundamentals of robotics using an Arduino board has been developed by Lima, Carlos, Simão, Pereira, Mafra, and Silva [51]. This remote laboratory is another application in the educational field. A remote laboratory is built with two user interfaces: one interface is created to enable a Visual Programming Language (VPL) for beginner students to be used on a mobile application, and another interface offers an environment which is similar to the Arduino Integrated Development Environment (IDE) using a Textual Programming Language (TPL) on a web application. The difference between the two interfaces is a graphical user interface (GUI). The implementation of this remote laboratory is based on the Remote Experimentation Laboratory (RExLab), which also provides support for other remote laboratories. The Arduino laboratory is available on the RELLE (Remote Labs Learning Environment) that has been developed by RExLab. Block language or Arduino language that is based on C/C++ is used to program and interact with an Arduino board and other electronic components. A program is transmitted to run remotely on the microcontroller, a video stream is transmitted during the operation process for a student's program on the board. A Raspberry Pi 2 B is used as a web server, and to control an Arduino board.

Another development is proposed by Siddiqui and Mane for a remote laboratory [52]. This remote laboratory includes two type of servers; the first is a computer server that acts as a web server remote laboratory gateway to serve as a webpage and clients management. The other is an embedded web server; its main function is to control the experiments such as an interface between the client and experimental instruments. A Raspbian server pack is installed on the Raspberry Pi that is used as an embedded web server. An experiment module includes a microcontroller and additional I/O circuits. Students can interact with the microcontroller experiments and with the I/O circuits through a menu on the webpage. Linux Arduino IDE that is used to program the microcontroller includes: a text editor, GNU C compiler for Arduino microcontroller family and required libraries to generate an executable file, a tool for converting an executable file to a hex file, and a tool for dumping a hex code into a flash memory of the microcontroller. The Arduino that is installed over the Raspbian OS on the Raspberry Pi compiles the file, and then a machine dependable executable code is obtained to be run from the shell. Addtionally, a USB webcam is also used to enable students observing the real-time visuals for some remote experiments.

Guerra, Cardoso, Sousa, and Gomes present a developed remote laboratory for the course "Networks and Multimedia" in Informatics using the Python program [53]. The course aims to provide basic knowledge of elementary data structures and algorithms. A web platform integrates and controls different technologies such as wireless sensor networks, virtual sensor networks, and data acquisition boards that are connected with Raspberry Pi accessible RESTful API via the internet. Additionally, a web platform interface includes a file submission and download, a camera visualization, and a web socket communication running on a Raspberry Pi. One task for students is to build a Python application that displays, and collects data from sensors, and then describes the statistical data. A remote laboratory for the Python program simulates real conditions for the obtained data on the air temperature, humidity, and luminosity via the internet in real time, and remotely from the real system.

Singh, Chatterji, and Shimi propose another application for remote laboratories using the new technology available with National Instruments LabVIEW remote panels. It is developed for Instrumentation and Control Engineering experiments and conducting three experiments remotely [54]. The developed laboratory besides using LabVIEW virtual instrumentation also requires using Dreamweaver, Orcad, and Mikro C compiler to enable web control and to monitor experiments which complement traditional laboratory experiments. Remote experiments are performed with the LabVIEW based front end software installed in the students' PCs to display online experiments. The data is taken from different sensors and sent to the microcontroller, then the microcontroller processes the data and transmits it to the PC via a USB interface, and characteristics of the different sensors which are obtained from remote experiments are plotted on a graph. The required data is uploaded using the LabVIEW program via the internet. When the remote experiments are completed, a LabVIEW ends the experiment and prepares the system to be ready for the next experiment.

Fotopoulos, Fanariotis, Orphanoudakis, and Skodras have developed and designed another remote laboratory based on a low-cost FPGA development board [55]. An Altera DE0-Nano that contains the Altera Cyclone IV FPGA chip is used in the remote laboratory. The remote laboratory is developed based on an Open Multimodal Laboratory facility at the Digital Systems and Media Computing Laboratories in the Hellenic Open University. The courses include laboratory exercises in a form of VHDL (VHSIC Hardware Description Language) design experiments that students can conduct experiments from their PCs through a graphical web interface and Altera's Quartus II EDA (Electronic Design Automation) software that is installed on the remote server. The application server is used an Ubuntu Linux 14.04 LTS machine with additional software and programs that are required to support remote experiments such as: Apache HTTP server, C++ RTMP server, Avconv Video Converter, PHP 5.5, MySql server, and shell in a box. An Arduino Uno rev3 is used as middleware between a web interface and an FPGA board. This enables interacting with and controlling an FPGA board by students through graphical interface buttons, which are located on an image of a DE0-Nano board for students and a live video showing a physical experiment while operating remote experiments. The system allows students to access remote experiments in the time slot intervals that can reach to 1 hour and are reserved online. A shell in a box is used to enable administrators to access the system for maintenance purposes.

A remote laboratory using an FPGA laboratory platform for computer system experiments and enabling students doing laboratory exercises to use a real hardware by Zhang, Chen, Ma, Tang, Niu, Li, and Liu is presented [56]. The remote laboratory consists of FPGA laboratory boards and at a minimum of one server. The server program is built over Node.js that is an event-driven asynchronous I/O framework. The exchange of data between students and server is written in JavaScripts, and using a C++ implementation of socket IO. MongoDB is used as a database to store user information. An FPGA board is visualized with the main panel that contains three types of components: LED (Light Emitting Diode) and segment display, DIP (Dual Inline Package) switch, and button. A web user interface (UI) is written in HTML, CSS and JavaScripts. The serial communication includes two methods that are provided on UI: simple serial input box and terminal emulator. A simple serial input box in which students can enter text and click on a send button, then the board sends a reply on receiving text area to test a hardware design by students. An unix-like shell is required to work with all target operating system types, the platform provides a terminal emulator based on the xterm.js library. A timing diagram display with WavaDrom is implemented using BeagleLogic to display signals of the memory bus on a web page to find out any timing problems. The laboratory system uses a Xilinx Artix-7 series FPGA, and four 2 MB 16-bit SRAM are organized to be two independent units. The address, data and control signals of two units are independently routed to an FPGA. Simple I/O components are provided for students such as a 32-bit DIP switch, 2 push-button with hardware debouncing and 4 push-button without debouncing, and two 7-segment displays, as well as 16 LEDs, all components are connected to FPGA. Additionally, several wires are connected to an FPGA in order for the controller to emulate peripherals through these wires, and a parallel-to-DVI encoder chip on a board to generate a graphical output. The way to configure an FPGA is through JTAG; the slave serial configuration mode of Xilinx FPGA is selected to monitor the status of configuration. I/O signals for an FPGA, such as LED and switch connections are routed to Zynq for displaying and controlling remotely. A controller system is implemented from a Xilinx Zynq-7 SoC FPGA integrated an ARM Cortex-A9 processor into the FPGA fabric, that is connected to the server using 1000M.

The previous approaches from the literature of the remote laboratories show that each remote laboratory is developed and designed for particular educational and training purposes, these remote systems allow integration and management of various physical resources. Different hardware and software can be found in the literature to deliver input/output of an experiment to/from physical instruments remotely. The laboratory instruments vary regarding the laboratory exercises that need different or additional hardware/software to deliver, control, and execute the remote experiment. Thus, there are no standard technologies used in implementing remote systems to allow a remote experimentation.

4.4 The Low-Power Design Remote Laboratory

The low-power design remote laboratory is a system consisting of hardware and software components that enable students to perform the low-power design laboratory experiments remotely via an internet connection. To make this possible, the on-site system requires additional hardware and software to facilitate accessing the physical instruments that are connected to the server; students can remotely perform and control experiments via sending commands between the client and the laboratory server. The remote system has been developed and designed as a complement to the on-site system in order to improve teaching the low-power design techniques. However, the low-power design laboratory system is the first system for low-power education and the remote access is one of only a few available laboratories in Germany. Furthermore, the remote system allows resources and approaches to be shared between institutes, and thus improve engineering education worldwide.

When introducing this new laboratory system it should be carefully considered what must be included in the outlines of the course, what engineering circuit designers must be able to do when they complete their education, and how the new laboratory system can facilitate achieving these learning outcomes. Although a remote laboratory provides many educational benefits, its learning outcomes completely depend on how well the instruction to operate remote experiments in the laboratory system is designed and how students can learn new knowledge and skills efficiently by using the remote system. As teaching in an engineering laboratory is based on learning by doing and from trial and error, the development and the design process of the new educational system is a critical phase in order to promote effective instructions that should be similar to instructions which students often follow in the hands-on laboratory. This complements the teaching of theoretical and conceptual knowledge in low-power design. In addition, a design of instructions enhances further learning and also integrates a higher way of thinking into laboratory work. These challenges are taken into consideration the development and design of the remote system.

The following chapters explain in more details the development and the implementation with all the software and hardware components required in order to realize the low-power design laboratory system.

5 The Low-Power Design Laboratory System

5.1 Introduction

A digital design process typically includes both software and hardware components, so low-power techniques can be applied at different levels of the design stage in order to achieve the most potential for power reduction.

The low-power design laboratory system is developed and designed in a special way that enables students to apply these techniques at different levels of the design stage. Thus, students can observe each influencing factor on the power dissipation of their design during the laboratory experiments in the on-site system and supplement the others during the remote system.

In this chapter, an overview for the methodology used of the laboratory experiments is presented, the levels of the design stage at which low-power techniques can be applied using the laboratory system are discussed, and the remote system is explored as a supplement for teaching low-power design laboratory in addition to the on-site system.

5.2 Teaching the Low-Power Design Laboratory Based on an FPGA

The platform is monitoring methodology in completing a successful design stage as well as testing and verifying the functional process of the algorithm using real data. FPGAs enable circuit designers to implement a complex digital circuit at a relatively high frequency. Current FPGAs provide circuit designers with various logic resources such as flip-flops, multipliers, memory blocks, and high-speed input/output interfaces. These resources support implementing even a complex digital circuit on an FPGA chip. Furthermore, FPGAs have characteristics which facilitate teaching the low-power laboratory experiments, such as [9] [19] [57]:

- Reusability. This is the main feature of this device which improves the educational process because students can implement and verify their design on the FPGA more than once time, in order to meet requirements of the design.

- Repeatability. Slightly different routing of a design gives nearly the same power dissipation.
- Linearity. A digital circuit which is twice as large dissipates nearly twice the power.
- Observability. For example, long interconnections lead to a considerable increase in power dissipation.
- Conceptualization. Concepts learned from FPGAs are applicable to application specific integrated circuits (ASICs), most digital circuits are prototyped and tested on an FPGA before being implemented on an ASICs.

Additionally, the curricula of engineering education must respond according to the increasing need for highly practical knowledge in the industry. Electrical engineering education is always exploring and developing new concepts and designs. This provides knowledge to students who will work in this field of industry that requires conceptual understanding as well as practical knowledge. Teaching based on FPGA technology that has a trend towards a high abstraction level has been integrated into engineering education contexts and has become a part of the curriculum at many universities. Furthermore, the use of this technology can provide a particular level of realism to the education experience [58–60].

5.2.1 The Methodology Used in the Low-Power Design Experiments

For the FPGA technologies used, the abstraction level is a common and independent level that eases, enhances, and simplifies designing a digital circuit with resources increasing following to Moore's Law. The rapid change in developing the technology is adopted in the implementation of the laboratory system. It is essential that the engineering student realizes the present of the technology as well as expecting where the technology will to be in the future. Consequently, hardware description language (HDL) is adopted to accomplish a digital circuit that describes a large digital circuit using a text-based language without the need for schematics. HDL provides the students to design and verify the functionality of a large and complete digital circuit at a high level of abstraction. An HDL allows Computer-Aided Design (CAD) to create the gate-level of a digital circuit to implement on a hardware device (FPGA). There are two hardware description languages in use today: VHDL and Verilog. VHDL is used in teaching the laboratory experiments. VHDL stands for Very High Speed Integrated

Circuit Hardware Description Language. The descriptions of the behaviours of the larger digital circuits are well-defined and easier to understand despite of the large documents which relate to the size of digital circuits [61] [62]. Thus, the instructions of the laboratory experiments using top-down hierarchical design methodology. By using HDL abstraction, the students can specify how a digital circuit will operate independently of the hardware details such as the CMOS technology devices used. This provides flexibility to implement the digital circuits on different FPGA technologies at the low (hardware) level, where more information and details will be available in order to verify the functionality and to estimate the power dissipation correctly. Additionally, the hardware level attempts to provide reliability in a way that has resulted in some problems faced. Figure 5.1 illustrates the structure of the laboratory experiments.

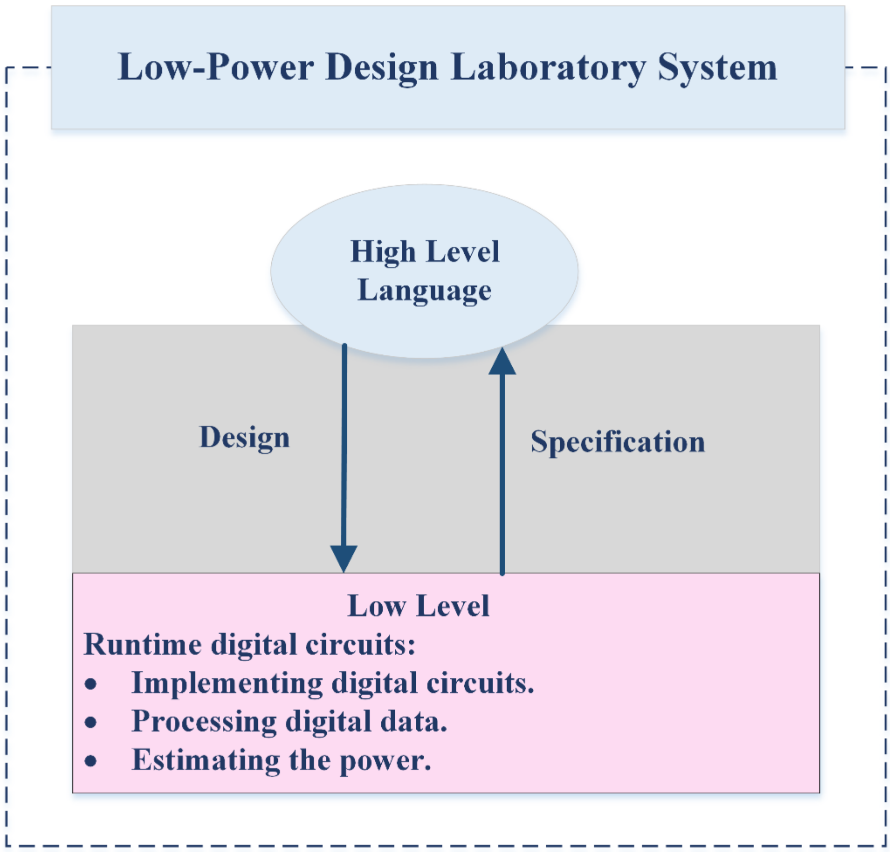

Figure 5.1: The structure of the low-power design experiments

5.2.2 Using Image Processing as an Application for Teaching the Laboratory Experiments

Image processing is proposed as an application to teach the low-power laboratory experiments. A digital image processing topic requires students to have mathematical basis knowledge of topics such as vectors and matrices, as well as to have as programming skills, all of which are obtained from their engineering studies [63] [64]. Applying image processing algorithms on an FPGA facilitates teaching the laboratory experiments as follows:

- Solving the input signal pattern problem of power estimation techniques. A previous overview of the literature shows that most power estimation approaches require information about input signals in order to estimate the power correctly. Different models generate the input from statistical or mathematical models. The laboratory system uses a real application to enable the experiment to be performed with real input data; the video signal is used as an input to the laboratory system and is processed by the implemented digital circuit on an FPGA, and the output (processed) video signal is the output of the laboratory system.
- Retaining student' attention during laboratory experiments. Students can observe the performance and the quality of the image resulting from their algorithms that give real details of the processed (output) image, and enable students to analyze the experimental results. For example, the processed image by the implemented digital circuits has a strong connection between its quality and its power dissipation.
- Offering the possibility to apply different image processing algorithms. This processing provides a real task with the capacity to fully cover and analyze low-power design theories. In this topic more of the learning objectives in regarding the theories are achieved.
- Decreasing the running time and the complexity of the laboratory experiments. Design circuits are considered a difficult topic to teach and to learn. Furthermore, this processing is one of the highly-significant topics when teaching the improvement of algorithms taking into account to dissipate significantly less power [65] [66].
- Helping the students to reinforce their learning by using recently-acquired knowledge with a new application in the laboratory. The learning process needs to be reformed, students should learn about a difficult topic in a practical way rather than memorizing theories from lectures or text books [67] [68]. The experimental results from processed images can help the students to retain the knowledge gained in the lectures more successfully.

- Providing innovative training and being more motivating and attractive to the students. Image processing is widely found in electronic devices and one of the fastest growing areas in industry applications [63] [64].

5.3 The Levels in the Design Stage of the Laboratory Experiments

The design and implementation of the laboratory system enables the students to observe most influencing factors on the power dissipation of their digital design.

It is hard to apply low-power techniques in a large and complex digital circuit, power reduction should be considered in early design stage, after this stage may be complicated to implement or may not be implementable. By using the laboratory system the student can apply various low-power design techniques at different levels in the design stage while performing the laboratory experiments. The main aim of the laboratory experiments is the ability to estimate power dissipation during the design stage, before and after a specific technique is applied at particular level. In this way, the laboratory experiments are performed to precisely understand when and how applying low-power techniques while designing the digital circuits. Design stage during the laboratory exercises can be categorized into four different levels: specification level, abstraction level, technology level, and environment level at which student can apply low-power techniques as illustrated in Figure 5.2.

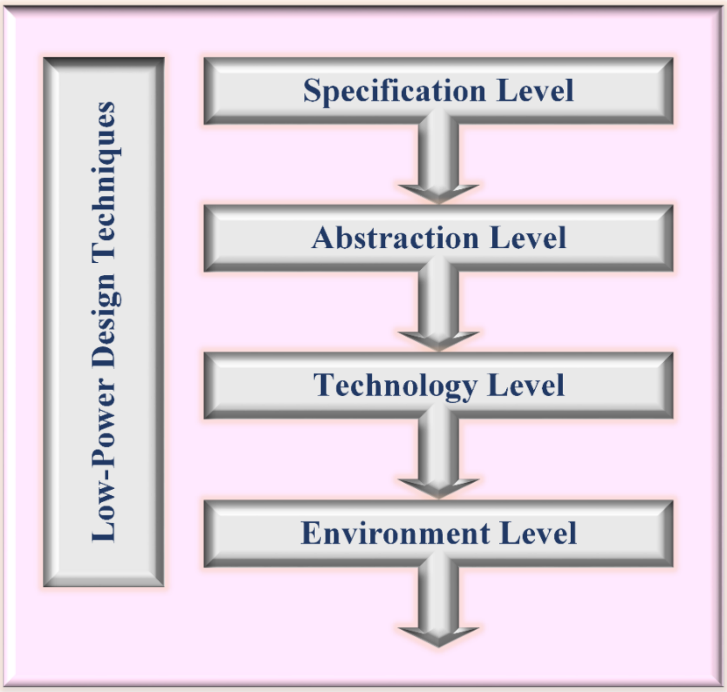

Figure 5.2: The levels of the design stage during the laboratory experiments

1. **Specification Level.** The design of a digital circuit begins with the specification. The specifications determine the functionality of the digital circuit; what its design must meet without indicating how it can be achieved. At specification level the complexity and number of operations of a digital design that are determined affect the dissipated power of the design, so the increase in the number of functions translates into a resultant increase in the whole area and power dissipation.
2. **Abstraction Level.** This level allows the students to describe a complete and complex digital circuit into smaller functions with their specific tasks and components. At this level students consider how to represent their digital designs that meet the specifications. Thus, abstraction level is a potential level for applying many low-power techniques when the design can be coded with various schemes using of the arts hardware design language for power reduction.
3. **Technology Level.** At technology level, the components of the digital circuit that are defined at abstraction level are implemented for each function in the total design, and then students can estimate the power dissipation using the laboratory system. Accurate power estimations exist only for the lower level of the design stage after technology mapping and implementing the digital design. Every CMOS technology generation improves circuit's performance, increases transistor density, and reduces power dissipation following Moore's law. This level is essential and valuable to be adopted in developing and designing the laboratory system.
4. **Environment Level.** The leakage currents in a digital circuit depend on operating temperature more than computational process. In the advanced CMOS technology, leakage power dissipation becomes dominant as results of the scaled threshold voltages as the shrinking nanometer-size feature. Therefore, for reliability, the laboratory system enables to operate the digital circuit with different operating temperature conditions in the laboratory experiments.

To achieve the highest power reduction, the power should be explicitly considered during these design levels. However, the abstraction level has more potential for power reduction.

5.4 The Low-Power Design On-Site System in Combination with the Remote System

The focus of the developed low-power design laboratory system is to provide a system to teach how both dynamic and static power dissipation can be reduced during real application with real hardware system to reinforce knowledge and skills of engineering students, and to support them professionally in their future design circuit jobs. Thus, a supplemental investigation of the on-site system with the remote system is made.

A novel method of developing the remote system approach is to complete the learning objectives for teaching low-power design laboratory. The remote experiments are performed via distance learning and are not only a way to perform a laboratory experiment as well as trying to find new experiments that meet the remaining learning objectives and can be applied at different levels of the design stage. The following sections discuss how the remote system can supplement the on-site system regarding to learning objectives achieved at different levels of the design stage, environmental restrictions, and budget.

5.4.1 Learning Objectives Achieved at Different Levels of the Design Process

Most learning objectives are covered during the levels of the design stage through using the on-site system and the others are complemented through using the remote system. However, any development and improvement such as providing modern or expensive CMOS technology to the system will be added to the remote system for economic reasons; it is not necessary to duplicate the laboratory equipment. Some additional experiments will be available only to the remote system to avoid some human errors that lead to damage the equipment such as providing the control of the operating temperature. The low-power design laboratory system with support of the remote system can achieve additional learning objectives regard to:

- Specification Level. The dependency between specification and dissipated power is difficult for an inexperienced designer to estimate. The low-power design laboratory system uses an FPGA technology that allows the measurement of the power at low (hardware) level in the design process. The hardware level provides more information that enables the performance, real time constraints, and dissipated power to be examined in order to achieve the aim of power reduction. The remote system will include different, expensive, scarce, or modern FPGA technology that enables the students to work with complex functional designs.

- Abstraction Level. This level describes the details in implementing a specific function in the design stage such as resources used to build a digital circuit. Every FPGA technology provides different and more/less resources to implement a digital circuit, which can be available and updated with the remote system than the on-site system.
- Technology Level. The remote system provides a choice of different technologies. Currently, the on-site and the remote systems include the Altera FPGA Cyclone IV and in addition, the remote system offers a different technology the Altera FPGA Cyclone V. Furthermore, the remote system could include more FPGA technologies such as Altera MAX 10 in the future.
- Environment Level. Most simulations are carried out at 25 °C where CMOS technology has usual behaviour [23]. In the remote system, the power dissipation is estimated at a different measured environmental temperature. Therefore, the remote system is developed to allow the digital circuits to be operated where the environmental temperature can vary.

5.4.2 Organizational Restrictions

In a hands-on laboratory, the instruments are available for specific time slots determined by class schedule and instructor time. The remote system enables the student to access the physical laboratory instruments from any computer connected to the internet and at any time. The remote system will provide the ability to overcome any restrictions on a physical hands-on laboratory or its availability.

5.4.3 Economic Budget

In the on-site system, eight systems for use by the laboratory groups and two backup systems are needed for each FPGA technology. However, in the remote system, there is no need to duplicate the numbers of the laboratory system: one system for using the online remote experiment and the backup system will be required for each technology of FPGA. Therefore, the remote system is a low-cost implementation for varying numbers of students who can perform the laboratory experiments via the internet. The consequence of this is low-cost of maintenance of hardware and software, as well as lower costs of instructors needed.

Table 5.1 illustrates the complementary features of the on-site system and the remote system as regards the learning objectives achieved, environmental restrictions, and budget. (++) in Table 5.1 indicates that the laboratory system offers more advantages than (+).

Table 5.1: The complementary features of the low-power on-site system and the remote systems

				Hands-on	Remote
1	Learning objectives	1.1	Specification Level	+	++
		1.2	Abstraction Level	+	++
		1.3	Technology Level	+	++
		1.4	Environment Level		++
2	Organization restrictions	2.1	Available time	+	++
		2.2	Required space	+	++
3	Economics budget	3.1	Low-cost of implementation	+	++
		3.2	Low-cost of maintenance	+	++
		3.3	Low-cost of instructor needed	+	++

6 Concepts of the Low-Power Design Remote System

6.1 Introduction

The low-power design laboratory system is defined as a hybrid laboratory model that provides two different accesses to the laboratory: the on-site system and the remote system.

In general, using common concepts with the on-site system and the remote system guide the learning process, when students perform the laboratory experiments, analyze and evaluate their experimental results to lead to a better learning knowledge.

The challenge in developing and designing the laboratory system is the ability to focus on the contents of the educational process. Additionally, the value of the remote laboratory is achieved not through the access to physical systems, but through linking its resources with the learning objectives for the students.

This chapter discusses the concepts for developing the remote system. The functional requirements and the general architecture of the remote system are presented.

6.2 Studies for the Concepts of Developing the Low-Power Design Laboratory System

Educational laboratories are focused on covering and extending the course materials throughout the laboratory exercises and repeating the practice in order to improve teaching process. The educational concepts are studies to improve and complement the learning objectives of teaching low-power digital design theories through practising additional remote laboratory experiments. From a technical point of view, designing and implementing the on-site system and supplement with the remote system is a complex task. Thus, developing the laboratory system with clear concepts is necessary to success the outcomes, and to achieve the same standard for using the on-site system and the remote system. The following points should be studied when developing the concepts for designing and implementing the remote system [1] [68–70]:

1. Laboratory experimental tasks.
2. Laboratory instruments interfaces.
3. Laboratory technology used.
4. Laboratory assessment methodology.

Figure 6.1 shows the considerations that are taken into account during developing and implementing the low-power design laboratory system.

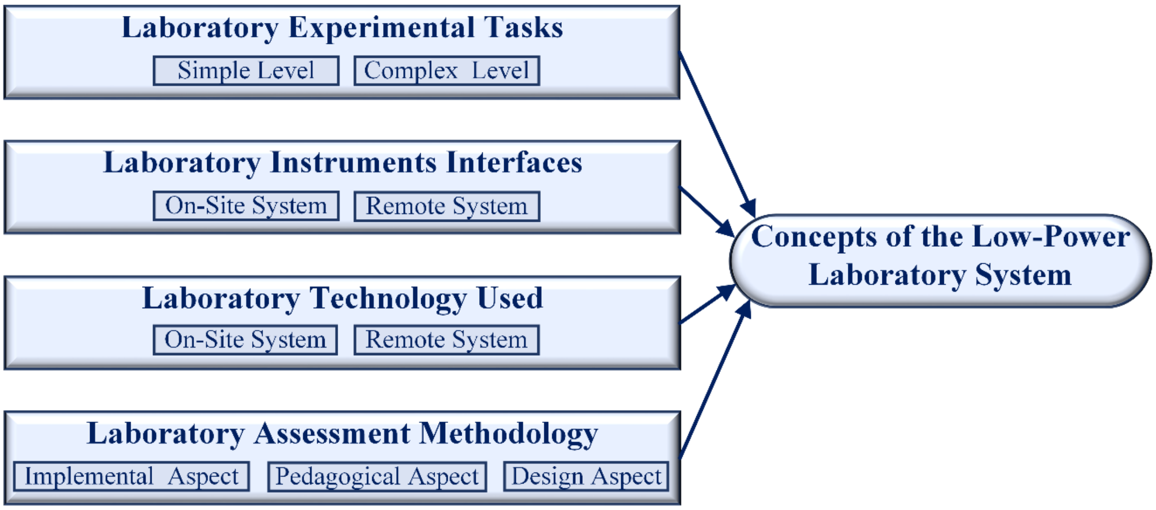

Figure 6.1: Studies for the concepts of developing the laboratory system

6.2.1 Low-Power Design Laboratory Experimental Tasks Concept

When the laboratory exercises are designed taking into account to be on levels of student interest, they range from simple level to complex level. The remote system provides advanced levels for improving a hands-on laboratory practice; students who are highly motivated may be bored when working with a simple task: some students prefer to practice with complex algorithms where they cannot predict what will happen. Engineering design circuits are needed to investigate working on their design and recognize the changes when they apply optional techniques, verify the functionality, and evaluate the performance. Not all students will take advantage of the increased complexity in a hands-on laboratory [69–71].

6.2.2 Low-Power Design Laboratory Instruments Interfaces Concept

In developing a new educational system it is necessary to include several opportunities. These opportunities are based on the students' knowledge of the topic. The laboratory exercises can be improved with supplementary features that support the characteristics of learning environments [1] [72]:

- The students do not need additional information or software about how to perform the remote experiment.
- Active learning for students in an educational laboratory can be made more attractive to involve complex thinking that does not require complicated instructions.
- The remote system provides a degree of freedom for students to build their digital circuits while practicing their remote experiments in a way similar to hands-on experiments.
- Engineering students not only learn low-power design techniques but also become familiar with common industrial infrastructures and digital systems. Therefore, it is essential to provide an environment that is based on components that have industrial applications.

6.2.3 Low-Power Design Laboratory Technology Used Concept

One purpose of developing a new educational engineering system is to be able to add new or different CMOS technologies in the digital circuit design, that enables students to understand the influence of using different CMOS technologies in designing digital circuits. Therefore, the range of complex functionality levels of the laboratory experiments can be extended and updated. It is not only sufficient that undergraduate engineering students have skills and can work with new technology and tools but they must also have enough knowledge and experience in using them appropriately. The laboratory system is developed to practice in a real application used which students can enjoy and be motivated to learn. Therefore, the engineering students will practice with industry applications where practical thinking reflects students' knowledge and skills while solving real problems [68] [69] [72].

6.2.4 Low-Power Design Laboratory Assessment Methodology Concept

The new educational system should be designed, taught, and then assessed to equip engineering students with the knowledge and practical skills specified in the learning outcomes. The assessment is necessary to ensure the achievement of system objectives and satisfactory system performance. This assessment study involves what engineering students practice in the low-power design laboratory system and identify the educational outcomes for developing their abilities.

The assessment focuses on implemental, pedagogical and theoretical, and design aspects of the laboratory system and the measured impact of the remote system as a supplement to a hands-on laboratory [73–75]:

- The implemental aspect. The technology used and its functionality in implementing the new learning system need to be explored in order to deliver an appropriate educational environment for experimentation, and also to design a friendly user interface which is independent of the delivery technique.
- The pedagogical and theoretical aspect. The experimental practice in the laboratory is line with the course context, the instructions for the laboratory exercises should impact on the learning process.
- The design aspect. The interface of the experimental equipment must be investigated so it leads to improved learning results.

Therefore, the assessment methodology of the performance and the educational values of using the laboratory system will include defining the following [1] [71]:

- Outcome indicators that appraise the degree of achieving the learning objectives to assess the implemental aspect of the laboratory system.
- An understanding of low-power design knowledge through studying students' reports to assess the pedagogical and theoretical aspect of the laboratory system.
- Studuing and analysing further details from the students' reports and their comments to assess the design aspect of the laboratory system.

Additionally, the valuable assessment should be supported by new criteria in designing a learning system, that requires laboratory instructions as follows [1] [71]:

- Clear learning objectives related to references.
- Use of up-to-date tools.
- Outcomes are not too complicated to evaluate.
- Motivation to continue practising the theory.

6.3 Functional Requirements of the Low-Power Design Laboratory System

There are challenges and limitations in the development and implementation of the low-power design laboratory system: what kind of features are required, how educational concepts can be included in the laboratory experiments, how the remote experiments can be performed in a way that does not differ from hands-on experimental instructions, and how the interface can be created for a real-time experiment.

The main goal of the remote system is to provide an online workbench where students can perform remotely their experiments as if experimenting in a hands-on laboratory. Thus, the remote system is developed as a complement to the on-site system for:

- Investigating a new laboratory tasks. The remote system can be used for experiments too costly for a hands-on laboratory where new technology is used, or for safety issues where experiments using a changeable operating temperature.
- Motivating students to continue learning objectives themselves. A number of learning benefits can be achieved as advanced reasoning and critical thinking skills, deeper understanding of topics, lower stress, and higher self-appreciation.
- Completing unintended or uncompleted laboratory tasks. Students can perform the laboratory exercises in a hands-on laboratory during learning hours under the supervision of instructors, a hands-on laboratory suffers from limited available time that may not permit for some students to perform unintended or uncompleted laboratory exercises. The remote system assists students to be an alternative way to complete their laboratory exercises with a flexibility independent of time and place.
- Preparing for an exam. The performed remote experiments are interactive and permit real-time access to repeat/check performing the laboratory experiments. The remote system is like a digital library that can be used by students as a supplementary class material and permit students to practice theories to gain deeper understanding and knowledge.

Figure 6.2 illustrates the requirements of the low-power physical laboratory system. Dealing with these challenges is closely related to understanding the functionalities and structures of the physical equipment with which the students interact through the web applications of the remote system. From the instructions of the low-power design physical laboratory system, the following elements should be present in the remote system and can be also found in the on-site system:

- Platform for implementing the student's digital design.
- Input image that is required to be processed by the implemented digital circuit.
- Output image display that is required to verify the functionality of the digital circuit.
- Digital multimeter that is necessary to estimate the current for calculating the power dissipation of the digital circuit.

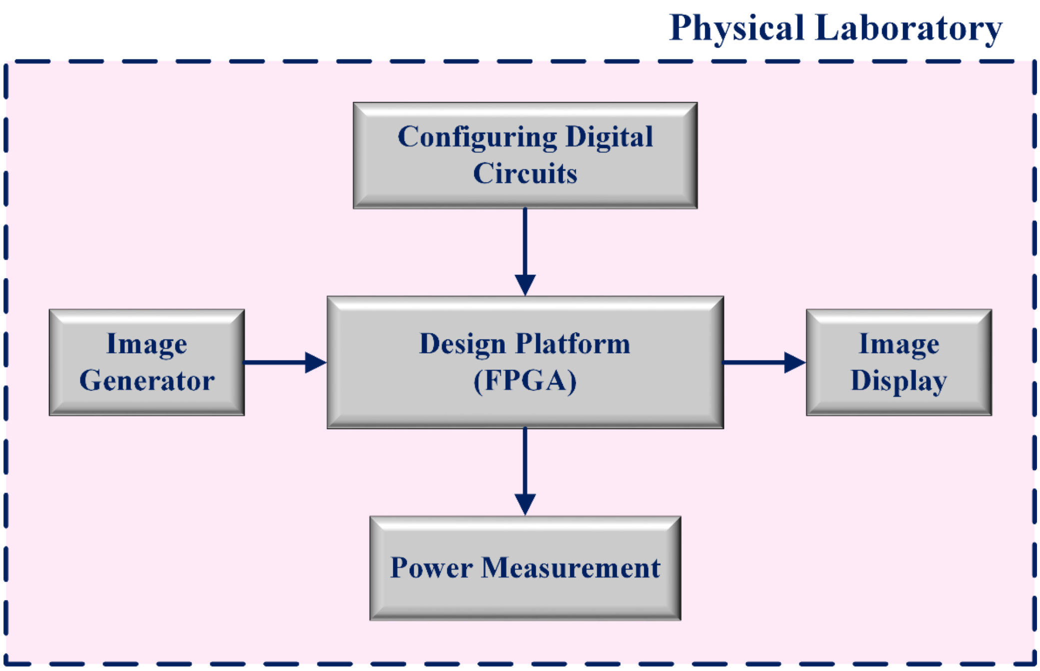

Figure 6.2: Physical requirements for the low-power design laboratory system

6.4 Basic Architecture of the Low-Power Design Remote System

The idea of developing the remote laboratory is to provide a realistic setting of the laboratory experiments that allows students to improve their practical skills. Therefore, these remote laboratories are often built from physical and industrial components.

Figure 6.3 illustrates the basic architecture of the remote system. The basic architecture is composited of three parts: remote client, remote server, and laboratory experiment.

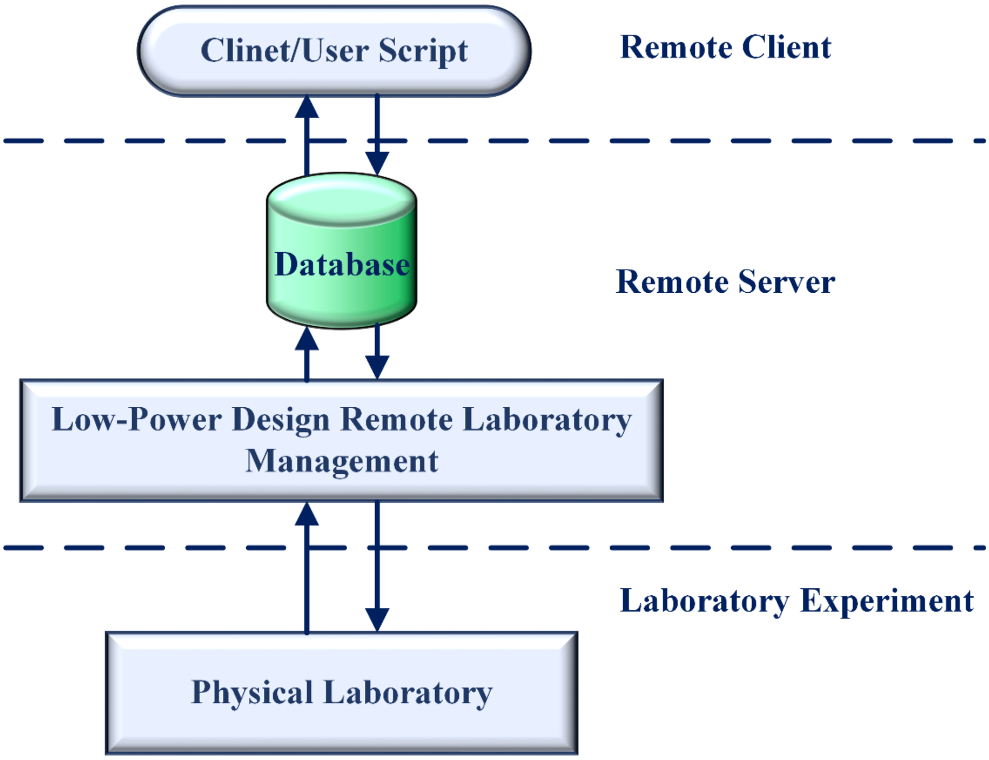

Figure 6.3: Basic architecture of the remote system.

- Remote client. An internet connection is used for the user access to and interaction with the remote experiments.
- Remote server. This remote server allows the client to access and share the remote instruments that are connected to and communicate with the server. The database assists in the management of tasks, such as user account authentication, access time, and statistics process.
- Laboratory experiment. The laboratory contains the physical components of the remote system within which the students' input and output data are organized using a remote server.

The integration and interoperability of all the parts in the remote system are necessary in order to combine all their services in the ways in which the learning objectives are met. Software and hardware parts are needed to establish and control the communication between these parts. Alternatives have been investigated to implement the remote system to reuse the on-site system remotely to achieve additional learning objectives. This approach focuses on increasing educational contents by finding new experiments that achieve the additional learning objectives to be performed remotely; it is necessary to facilitate the connection of hardware and software without the need of additional programming tasks by clients, this feature allows students to focus on the educational contents of the remote experiments rather than spend time programming extra client applications. Also, it is essential for new technology to be able to be added without a great effort on the administrator.

7 Developing and Implementing of the Low-Power Design Remote System

7.1 Introduction

The low-power design remote system is a system composed of software and hardware components that allows access to physical instruments in a laboratory via the internet. Such remote laboratories can be called online laboratories. The students use a communication network to perform a remote experiment by interacting with a webpage on their computers that are connected to the internet from any place and at any time.

This chapter explains the implementation of the software and the hardware with all the required components that enable access to the physical instruments.

7.2 Technical Implementing of the Low-Power Design Remote System

The software and the hardware components are integrated within the remote system in which each component plays a role in the system functionality. The stages of the process are sometimes in a linear chain and sometimes interconnected and concurrent. All components are integrated into an educational environment with easy-to-use user-interface (UI) components.

The architecture of the low-power design remote system with its components and subsystems is shown in Figure 7.1. The remote system includes the following:

- Student/Client.
- Remote server.
- Specially designed FPGA-board.
- Image generator.
- Frame/Video grabber.
- Digital multimeter (DMM).

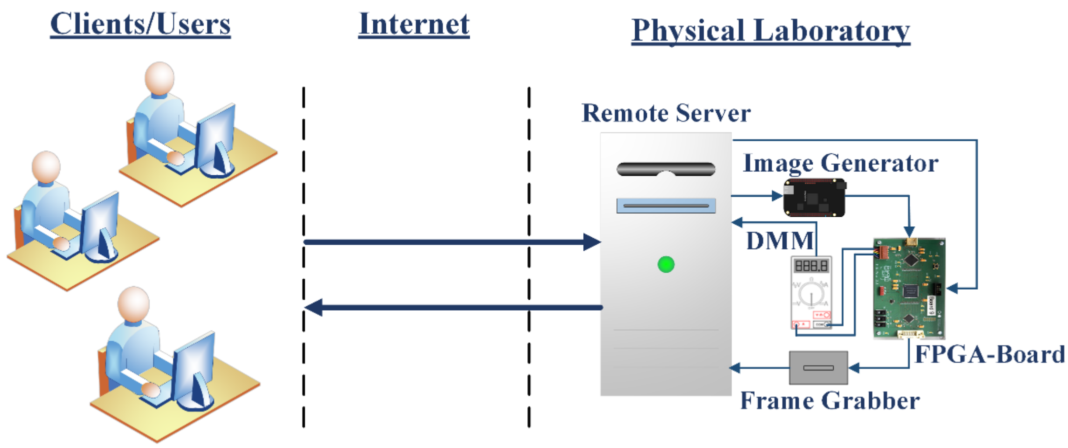

Figure 7.1: Architecture of the low-power design remote system

The remote system is based on a client–server structure using a TCP/IP connection. Figure 7.2 shows the schematic overview of the used software on both client and server sides that consists of three main parts:

- The students/clients can access via an internet connection.
- The remote server is the middleware responsible for exchanging the information between the student's computer and the remote server.
- The physical laboratory contains all real laboratory instruments that are required to perform the laboratory experiments.

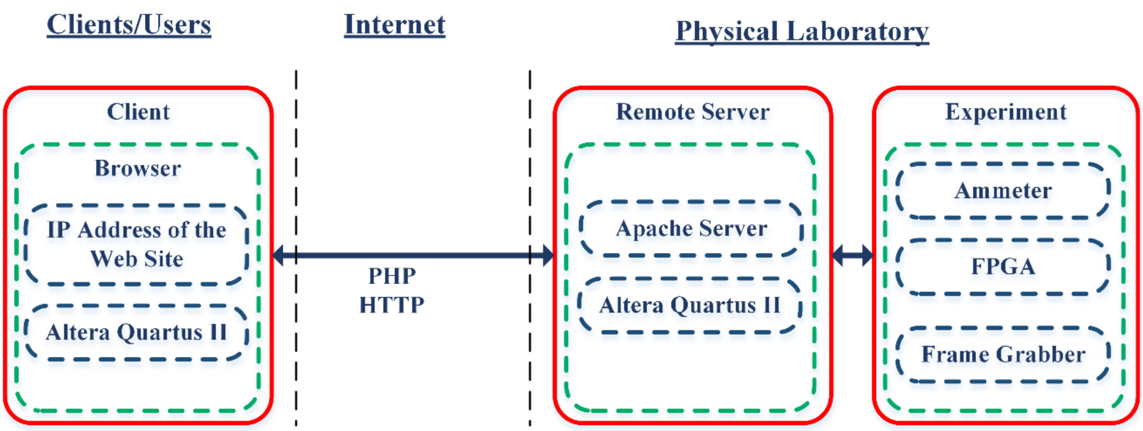

Figure 7.2: Schematic overview of the software architecture on both client and server sides

The next sections discuss more detailed information about the architecture of the remote system.

The remote server manages the requests from students/clients, and accordingly sends the necessary information within the client graphical user interface (GUI) to enable the remote experiment with the real components and instruments that are in the physical laboratory.

In order to define those components, knowledge is needed about educational objectives of the remote system but not only programming experience. The architecture of the remote system is implemented to succeed the concept for teaching low-power design techniques. The developing and implementing stage also takes into account ergonomic aspects for providing effective human-computer interaction [76] [77]. The remote system with it components are shown in Figure 7.3. The following sections discuss the role and the technical features of these components.

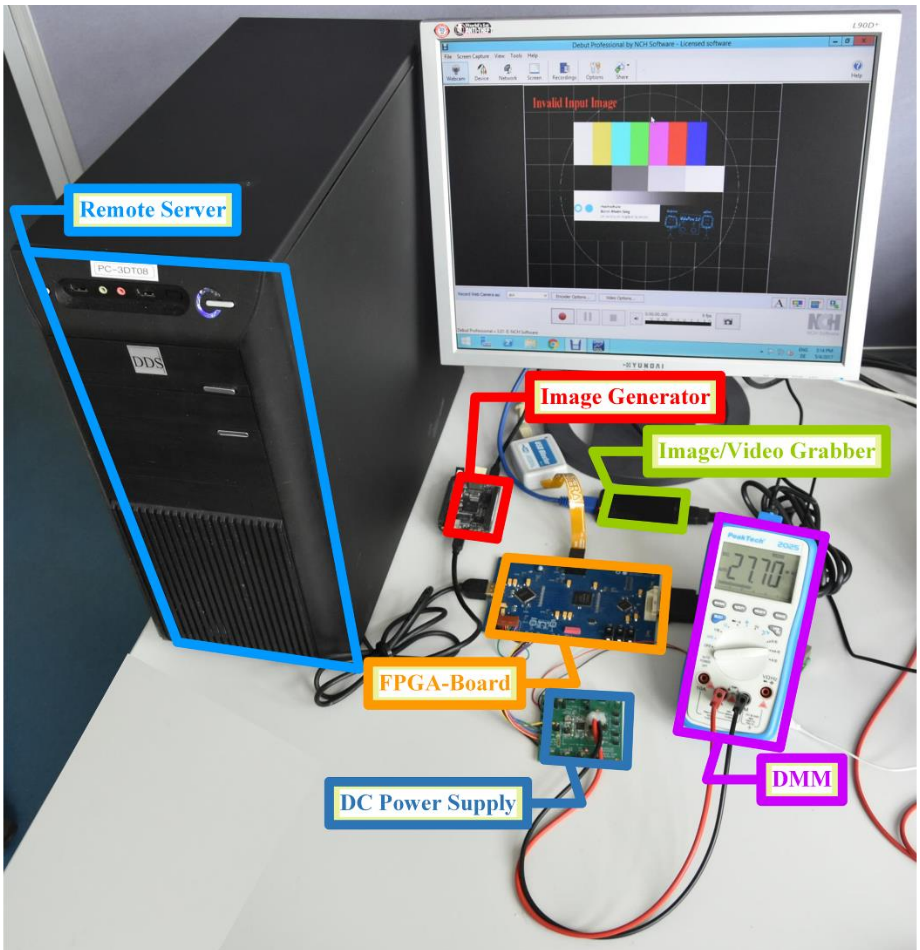

Figure 7.3: The low-power design remote system

7.2.1 Student/Client

The student/client can access the remote system from any computer over the internet using any standard browser such as Microsoft Internet Explorer, Mozilla Firefox, or Chrome to exchange data between the user-interface (UI) and the remote server. Using a standard browser reduces the requirement for additional software on the student's computer and decreases the required time needed by the students to learn how to operate the remote experiment [1] [76] [77].

7.2.2 Web-Client Graphical User Interface

The graphical user-interface (GUI) is the frontal webpage of the remote system. Building the student GUI as a web application facilitates access to the laboratory system from any standard web-browser installed on a student's computer. It is hosted in an Apache Hypertext Transfer Protocol (HTTP) server which uses the secure protocol HTTP Secure (HTTPS) and provides many features that facilitate the implementation of the low-power design remote system. The developed user-interface uses the scripting language PHP, HTML, and CSS which interact together with a MySQL database to develop a dynamic web application. The HTML and CSS arrange the appearance and mark-up of the webpages, while PHP displays the webpages and interacts with MySQL to store and retrieve data for the system [78] [79]. PHP is a server-scripting language, which is free and is a powerful tool for building dynamic and interactive web applications. PHP is necessary to upload the files into the remote server. For some applications PHP is also required to manage, rename, move, or delete the files that students upload. Additionally, PHP enables the remote system to run the requested programs on the remote server, the operating system of the remote system is required to interact with other software on the remote server [78] [80]. The web-client GUI receives input data from the students and sends it to the remote server, and then the remote server updates its contents of GUI that receives experimental results.

7.2.3 Remote Server

The remote server is the middleware over the internet that establishes the communication between the student/client and the remote physical laboratory. At the remote server end, physical laboratory instruments are connected to the remote server. Nowadays, most instruments such as digital multimeters (DMM) are provided with a USB connection and software that are installed on the remote server to allow communication with instruments made by manufacturers. This technological development makes remote laboratories through the internet possible; these instruments measure the values and send them to other subsystems.

The remote server processes individual data, which are running Microsoft Windows Server Standard 2012 R2 and execute PHP scripts to control the remote experiments and transmit the experimental results back to the remote server, then finally to the remote client. The role of the remote server can be defined as the following:

- Authentication. On the remote server, every registered student has an account, in which his/her login name and password, data regard of the accessed are stored in the database. When a student requests access to the remote experiment, the remote server examines whether his/her account is authorized for the access. When the login name and password entered by a student are correct, the remote server establishes a connection between the student/client and the remote experiment. Consequently, there are two types of accounts. The first type is instructor accounts that can: add, modify, remove user accounts, and add and remove experiments; enable active specific components to appear to the student in each experiment, monitor a scheduled access; the teacher/administrator can view the students/clients who access, and the time and the date of received data from their experiment access. The second type is student/client accounts: they are added by the instructor and are registered in the low-power design course.
- Managing access time. Another task of the remote server is to manage the students' access to the remote system. The time session starts with the active experiment session and compares it with the maximum limited time before sending the data to be executed on the physical instruments. This is to avoid hazards or collisions that may be caused by sending data from two synchronous users simultaneously to the physical instruments. The common problem of the remote system is that users cannot use the same resource at the same time; commonly it is required to manage and limit time access. The user can give instructions to the remote experiment; another user can carry out the remote experiment as soon as the first student‘s access is completed. It is important to create mechanisms to automate the end and change the session that restrict the activities according to the limited time access.
- Controlling. The role for controlling the access defines a set of roles and their rights to a protected access session. The user is granted the rights to access a set of activities to interact with the instruments inside the system. The scripts for controlling the experiments are implemented with an appropriate sequence of functions to be performed in the remote experiment. After completion of the

remote experiment prompted by the client request, the control program retrieves the initial state and waits for the next experimental request.

- Storing the data. The remote server stores data from physical equipment and from remote students/clients in a file. This data is managed and then transferred from it to remote client webpage or physical laboratory.

Most of the undergraduate instruments laboratories in the universities around the world have a common scheme as function generators, DMMs, or DC power supplies regardless of their industrial or manufacturer's model. The laboratory instrument drivers are installed in the remote server to enable communication between the remote server and instruments connected to the remote server. All applications and data management are executed on the remote server and the results are displayed on the user’s screen by letting them interact with physical experiments remotely.

The database is needed to enable accessible the operation of the remote system. Tables with the distinctive constraints of the system are applied. The remote server requires the name of the database associated with the remote system in order to run or stop the remote experiment. When an access command is sent, the connection with the related database is opened, the constraints associated with the remote system (student name, experiment period, duration limit, etc.), the system constraints are retrieved from the database. In each experiment session, the values of constraints of the remote system are read and saved into a table in the database. This method enables the remote system to provide the client with real-time operation of the remote experiment. The accessing request sent by the remote client, the related database is updated with new values of constraints correspond to the remote experiment status. When the remote experiment is completed, the database is updated with the stop values and the connections with the database are closed, the remote system can also deactivate the remote client e.g. when an experimental time is longer than the duration limit.

7.2.4 The Developed Experiment FPGA-Board

An especially designed FPGA-board which is called EduPow board has been developed to enable the evaluation of the power dissipation of the implemented digital circuits at the Bonn-Rhine-Sieg University of Applied Sciences [8] [81]. The designed FPGA-board contains all required components and instruments as is shown in Figure 7.4 in order to use image processing as an application to teach low-power design techniques. The designed FPGA-board includes the following:

- The FPGA chip. One important component which plays a central role in the designing process is an FPGA technology, on which the digital circuit is implemented by the student, and then the input image is processed by the implemented digital circuit.
- Configuring the FPGA. The interface is connected with the USB-Blaster to configure the FPGA, where an external USB-Blaster from Altera is connected to the JTAG interface on the FPGA-board.
- Input image. High-definition multimedia interface (HDMI) is used to provide an input video signal to be processed by an implemented digital circuit on FPGA.
- Output image. Digital visual interface (DVI) is used to provide an output of the processed video signals.
- DC power supply. The used FPGA in the designed FPGA-board requires a dc voltage source that supplies the need for three different voltages for I/O, PLL (Phase-Locked Loop), and core supply. The ADP5052 evaluation board from Texas Instruments and Analog Devices is chosen to provide different dc voltages for the used FPGA [82]. A DMM device is connected to measure the core current of the FPGA.

An FPGA technology is used as a design platform that provides a flexible environment in which students can implement their digital circuits and verify the functionality. FPGA provides a certain range percentage of different resources that are required to implement a student's digital circuits. Usage of a new technology in educational laboratories allows the students to work and practice with a real-world case that is more interactive and efficient [83].

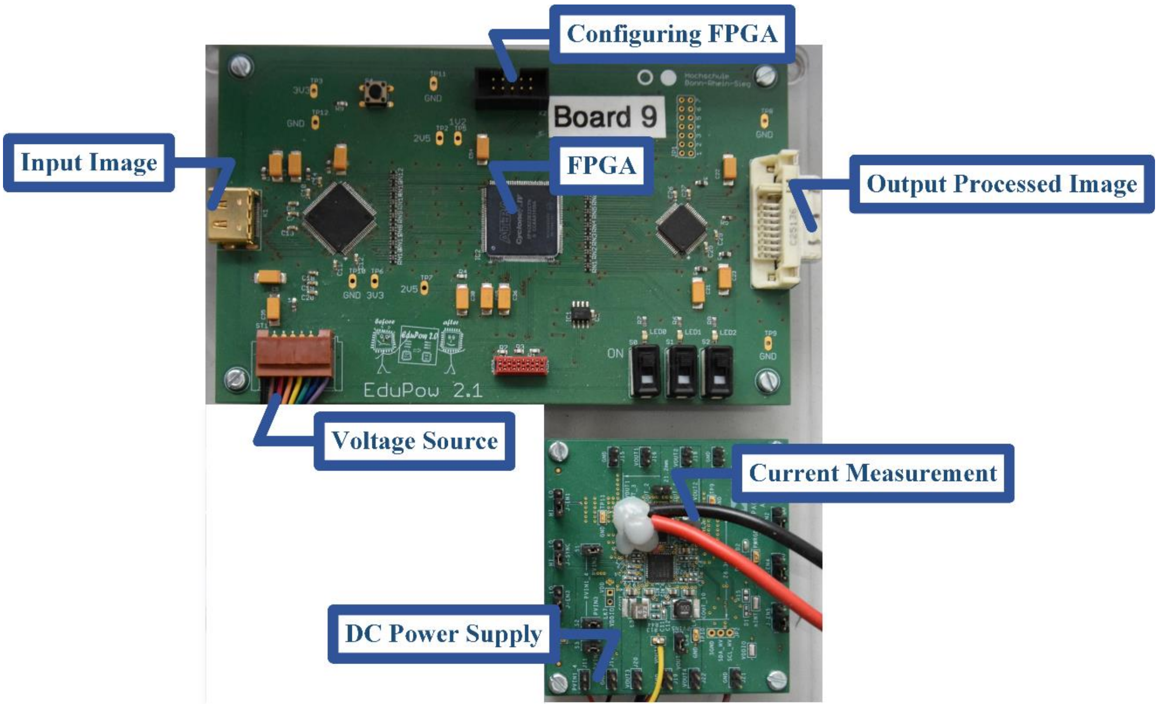

Figure 7.4: The developed experiment FPGA-board

The process of decoding video signals is not carried out within the FPGA which helps the students to focus on learning low-power design techniques and not on the image conversion step. The input video signals that are received from HDMI are decoded to their three main colour components: Red (R), Green (G), and Blue (B), with an eight-bit resolution for each colour, the control signals for horizontal and vertical synchronization, data enable, and pixel clock. Additionally, the output (processed) signals are decoded from these components to the differential DVI signals.

One of the aims of this thesis is to achieve advanced learning objectives, such as to offer different FPGA technologies so that students can realize the influence of using different CMOS technologies in designing digital circuits; therefore this design must be flexible in order to be applied various FPGA technologies for the remote experiments. Thus, the designed FPGA-board can be implemented with different FPGA technologies. This is very beneficial in the remote system; more complex digital circuits can be implemented. Thereby, different measurements for the implemented digital circuits on different FPGA technologies can be performed in order to evaluate the power dissipation of the student's design. Currently, the Altera Cyclone IV FPGA is available at a hands-on laboratory and the low-power design remote system, and the Altera Cyclone V FPGA is only available on the remote system. The student/client can design different digital circuits that will be implemented on FPGA using the remote system.

7.2.5 Image Generator

BeagleBone is used as an image generator to provide the image for the input video of the FPGA-board. BeagleBone is a low-cost processor, open source Linux computing platform, open-hardware, support open-software libraries, and single-board computer [84] [85]. The BeagleBone is the option suggested for the integration with the remote system, Linux offers a device driver support USB peripheral that makes it possible to be connected directly to the remote server without the need for a complex and/or costly interface for real-time control tasks. The BeagleBone Black (BBB) is used in this remote system with 1 GHz processor, 512 MB of DDR3 memory, eMMC storage, Ethernet, and HDMI video support. A BBB board package includes a USB 2.0 cable to connect the BBB to the remote server. The BBB is powered directly using a USB connection from the remote server, the BBB has a micro HDMI framer that is connected to the HDMI input of the FPGA-board. Its memory availability and capacity is limited, it works in real-time where its output displays the current uploaded image by the client in real time.

The Debian which is an open-source distribution of Linux is used on the BBB board to provide complete control and responsibility over the remote system configuration. The BBB is connected to the remote server in the USB client mode that displays the contents of the BBB's FAT partition and to transfer/exchange to it [85]. The display image is uploaded by the client to the remote server and then the remote server loads the image to the BBB. Python, a computer programming language, is used to automate the execution of the task on the BBB [86] [87]. The Debian system is configured to start running a python program automatically on boot at start-up. The display size of the image is configured through the Python script using a width of 1280 pixel and a height of 1024 pixel display that is also used in the on-site system. The remote system requires a specific setting every time the client uploads an image, a change needs to recall the image and display methods to keep the input image updated from the remote server and display an uploaded image until completing the remote experiment measurements. When the remote experiment measurements is completed, the default status is restored.

7.2.6 Frame/Video Grabber

Frame/Video grabber and image capture software are required in the remote experiment. A frame/video grabber is an electronic device that is connected to the remote server via a USB interface. An image/video grabber imports the output image from an external device. Image capture software is a convenient and easy tool that is installed on the remote server for capturing the output image from video source DVI of the FPGA-board; the output image is the processed image by an implemented digital circuit on FPGA that can be displayed on student's computer screen. The captured image is transferred to and saved in the remote server; the stored image type is .jpg and image resolution is assumed with a width of 1280 pixel and a height of 1024 pixel. Then the saved image is resized to allow easy handling of the images for the final visible for the client.

7.2.7 Measurement of the Power Dissipation

The supply voltage of the FPGA core is considered to be stable; only the current that is drawn by the FPGA in real-time is measured using a digital multimeter (DMM) with a USB connection; the core current depends on the implemented digital circuit on the FPGA and its application. The DMM has a USB connected to the remote server to transmit the reading to the server, and then to the client.

The DMM product from PeakTech 2025 has a tool which is used here as a practical application-software that enables measurement recordings with a USB interface. Its software is installed on the remote server, where measured values which are minimum, maximum, and average values are continuously saved as a table in XML format [88].

7.2.8 Changeable Operating Temperature

The operating temperature plays a significant role in the performance of the digital circuits. Thermoelectric cooling (TEC or Peltier) is proposed to be used as an efficient removing heat for some microelectronic processors. The TEC module consists of two semiconductor types: one is n-type and other is p-type in order to have different electron densities, the semiconductors are arranged thermally in parallel and electrically in series and then joined with a thermally conducting plate on each side. A thermoelectric cooler is a solid-state active heat pump which transfers heat from one side of the module to the other based on the direction of the current. It can be used either for heating or for cooling and so acts as a temperature controller that either heats or cools. The advantages of TEC devices are that they have: a small size, a flexible shape, a long life, and no circular liquid or moving parts. When operated as a TEC device, a DC voltage is applied across the device, a DC electric current flows through the device, and the heat transfers from one side to other, and as a result, one side quickly becomes hot and another side quickly becomes cold. The hot side is attached to a heat sink in order to keep its temperature around ambient temperature, while the cool side has a lower value than room temperature [89–91].

In the remote system, the TEC device is used to achieve temperature reduction for the FPGA chip on the designed FPGA-board. The cold side of TEC is attached to the FPGA chip, and a heat sink with a fan is included to remove the heat from the hot side of the TEC device. Figure 7.5 illustrates the integrating of the TEC device on the designed FPGA-board. Using this model, the student can investigate the effect of temperature reduction on a FPGA chip while running a computational process. The TEC module is not shown in Figure 7.3 and Figure 7.4 so it is an addition to the remote system.

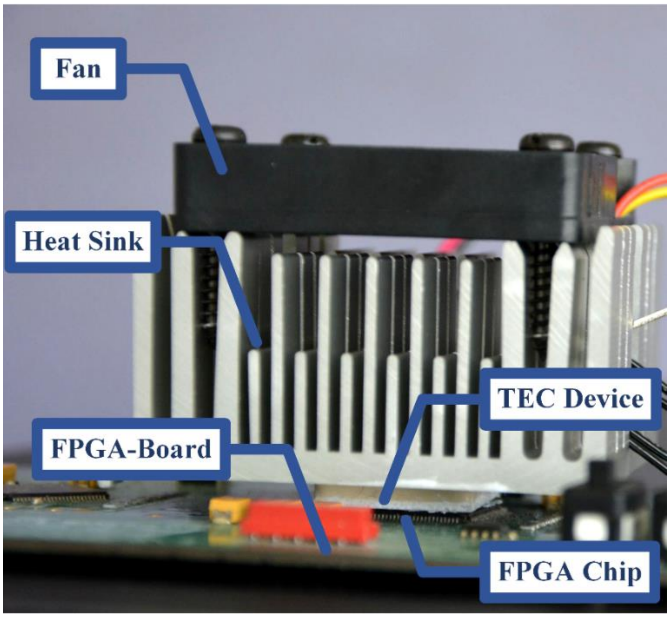

Figure 7.5: The integrated TEC module with the remote system

8 User Interface of the Low-Power Design Remote Experiments

8.1 Introduction

This chapter presents the instructions and required software for the low-power design experiments, how the user-interface (UI) of the remote experiment allows the student to perform the laboratory experiments through causing real responses from the remote physical instruments just as the students in the physical hands-on laboratory is described, and finally the highlights and the aims of implementing of the remote experiment's user-interface are summarized.

8.2 Instructions for the Low-Power Design Laboratory Experiments

The interface and operation of remote access are developed and implemented the same as the on-site system in order to minimize additional instructions necessary to execute the remote experiments. Thus, there is no significant difference between the on-site system and the remote system. Generally, the low-power design laboratory experiments include the following instructions using the on-site system or the remote system:

1. Design specification. The laboratory exercises are given for the students, the students propose the algorithms for their digital circuits to perform a specific task and satisfy the design's specifications.
2. Describing the digital circuits and creating a configuration file. The student/client can write the algorithm using hardware description language (HDL), compile, fix the code, and generate the configuration file that is required to implement the digital circuit.
3. Implementing the proposed digital circuits. The compiler generates configuration file that meets the specifications' design, the configuration file is used to program the FPGA, and then the digital circuit is implemented in the FPGA.

4. Verifying the functionality of the implemented digital circuit. After the digital design is implemented in the FPGA, it is required to verify whether the digital design meets timing and functions appropriately at the hardware level.
5. Measuring the power dissipation of the running digital circuits. The student measures the core current of the FPGA using digital multimeter (DMM).
6. Analysing the experimental results. The students analyse and compare the experimental results before and after using low-power design techniques.

8.3 Instructions for the Low-Power Design Remote Laboratory Experiments

The common instructions for the laboratory experiments setup are divided into two parts:

- The abstraction phase (locally). In this phase, the student designs the digital circuits locally on a student's computer without an internet connection. The students can describe their algorithms using hardware description language; they create the digital circuit to be implemented in the FPGA device. The proposed digital circuits are compiled to fix the errors faced. At this point, the students make pin assignments and timing constraints that are essential for building a functioning digital design. The students who successfully complete the design stage can transfer to the hardware phase.
- The hardware phase (remotely). Here, the student verifies the functionality of the proposed design, which may need to be modified in order to meet the target performance. After compiling and fixing the errors in their design, the student is ready to program the FPGA on the FPGA-board with the compiled SRAM object file (.sof). The student just programs the FPGA using the USB-blaster circuitry on the FPGA-board in the on-site system or by uploading .sof file to the remote server using an internet connection. When the student verifies the design in hardware, he/she will observe the runtime behaviour of the digital circuit design and ensure that it is functioning appropriately. At the low (hardware) level, there is more information that is not available at high (abstraction) level such as latency, thermal effect, and technology used.

Figure 8.1 shows the instructions flow that the students should achieve during their remote laboratory tasks. Students can use revisions of their designs with different options of low-power design techniques and compare the power dissipation of their designs to determine the best low-power design. However, the dividing of the design instructions into local phase and remote phase is to achieve an efficient time of setting up the remote experiments.

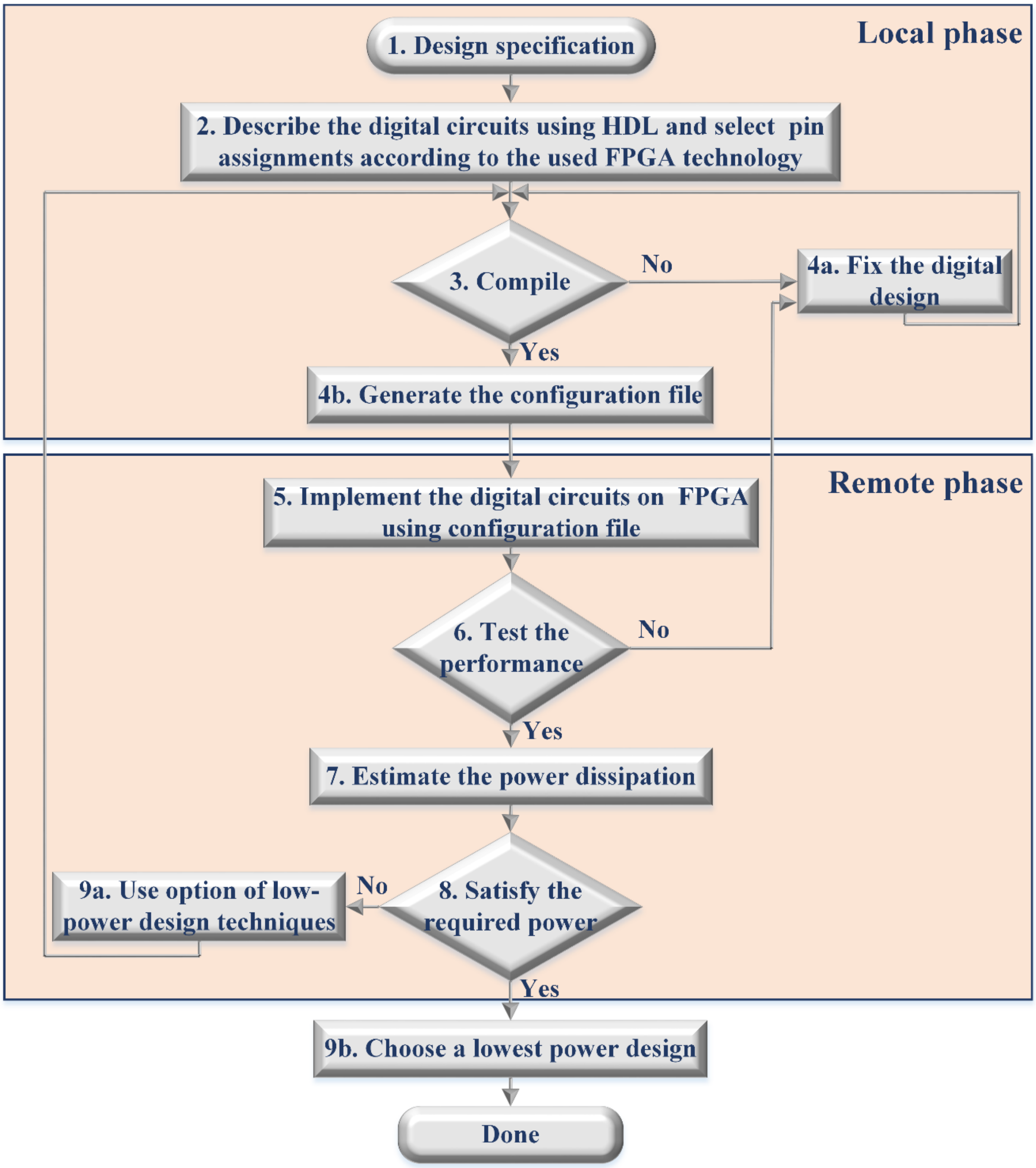

Figure 8.1: The instructions flow for the low-power design remote experiments

8.4 Requirements for the Low-Power Design Experiments

The student is required to have the following before he/she begins the low-power design experiment using the on-site system or the remote system:

- Familiarity with the digital circuit design and Electronic Design Automation (EDA) tools as well as what an FPGA is.
- An understanding of the concepts of low-power design techniques as explained in the lectures and textbooks.
- The Altera Quartus II software on the computer being used. Altera FPGA is used in the laboratory system; Altera Corporation provides Quartus II software for programming their FPGAs [92].
- The installation of the device family support to the Quartus II software. The device family depends on the experiment in which the student will verify whether his/her digital design is truly working. Currently, the laboratory system offers Altera Cyclone IV device in both the on-site system and the remote system, and Altera Cyclone V device is only available in the remote system [92].

Furthermore, the remote experiment only requires any standard browser and an internet connection. The remote system is independent of the client’s computer hardware and software; the remote experiment runs on the remote server and physical resources connected to the remote server.

8.5 Procedures of the Low-Power Design Experiments

The instructions for the low-power design remote experiment is nearly the same as for the regular hands-on experiment except the data from and to the remote experiment is delivered over the Internet. The design of the remote experiments takes into account creating a realistic impression; the students realize that the other side is not a software package but that they are controlling and taking measurements from the physical devices. The following sections describe the procedures for performing the remote experiment.

8.5.1 Authentication Webpage

The student/client gets the digital circuit design ready, with the adjusted pin assignments and the device support. The student/client can access the remote system through the webpage over the internet using a web browser such as Microsoft Internet Explorer, Mozilla Firefox, or Chrome to exchange data between the user-interface and the remote server. Once a student activates the IP address of the remote server webpage in the address bar of the web browser, the web browser loads the start webpage of the remote experiment: an authentication webpage. The authentication webpage of the remote system is shown in Figure 8.2.

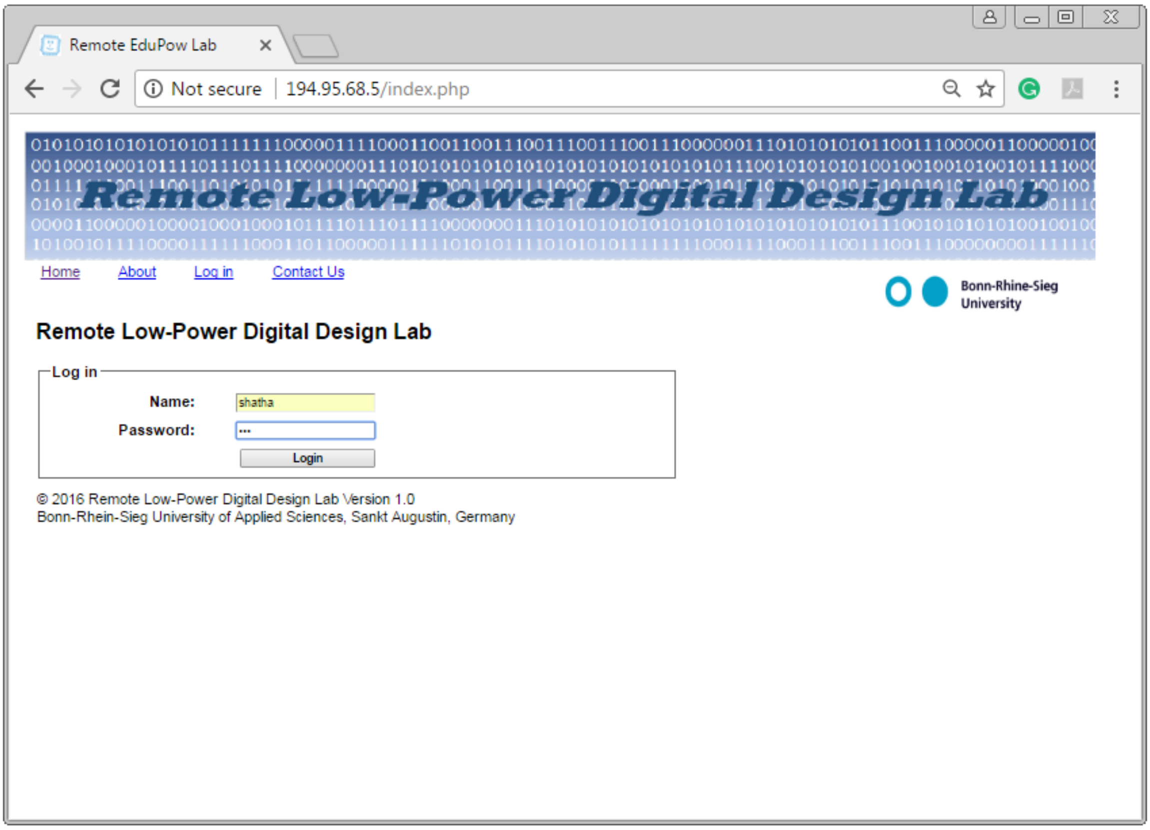

Figure 8.2: The authentication webpage of the remote experiment

The authentication webpage contains two input fields to give the login name and the password of the student account that allows access to the remote experiment. The login name and the password are previously given by the laboratory instructor to every student registered in the low-power design laboratory. If the remote system is available online, the remote server compares the entered name and password with the stored data in the database, and if matched, the student/client is permitted to access the remote system and the upload webpage that is shown in Figure 8.3 is activated unless a session from another client is running at the same time. A mechanism for checking whether the remote system is currently available or not occupied is included in its design.

If the student requests the cancellation of the current experimental session and wants to start a new session, he/she can click on "log out", that will send a command to the remote server in order to retire the default status of all hardware and software components in order to be ready to implement another remote experiment.

8.5.2 Upload Webpage of the Remote Experiment

Via the upload webpage remote experiment, the student can upload the configuration file (.sof) that is required to implement his/her digital circuit in the device and also upload the image to be processed by the implemented digital circuits. Some students prefer to use different input images; the student can upload his/her desired image. At the bottom of the experiment upload webpage, there is a button labelled “Start”, which can be clicked to activate further applications. By clicking on the “Start” button, the client/student sends a digital circuit design and an input image through the experiment page. The experiment page transfers the input data to the remote server via the TCP/IP model. The remote server executes the described functions for each instrument to be performed. At this point, the student is informed that the remote system handles the uploaded experimental data as shown in Figure 8.4.

While a student is carrying out the remote experiment, no other students are permitted to access the remote system at the same time. This means that the time connected to the remote system is limited in order to organize students’ accesses to the physical instruments. The maximum time available for executing the remote experiment is therefore limited and can’t exceed the limitation set.

Generally, when a student performs a remote experiment, there are allowable sets to upload files containing all acceptable extensions, and which conform to the size limitations. If there is an incorrectly uploaded file, a text message is sent to the client GUI that appears on the client’s screen; the client is informed why the uploaded file is unacceptable.

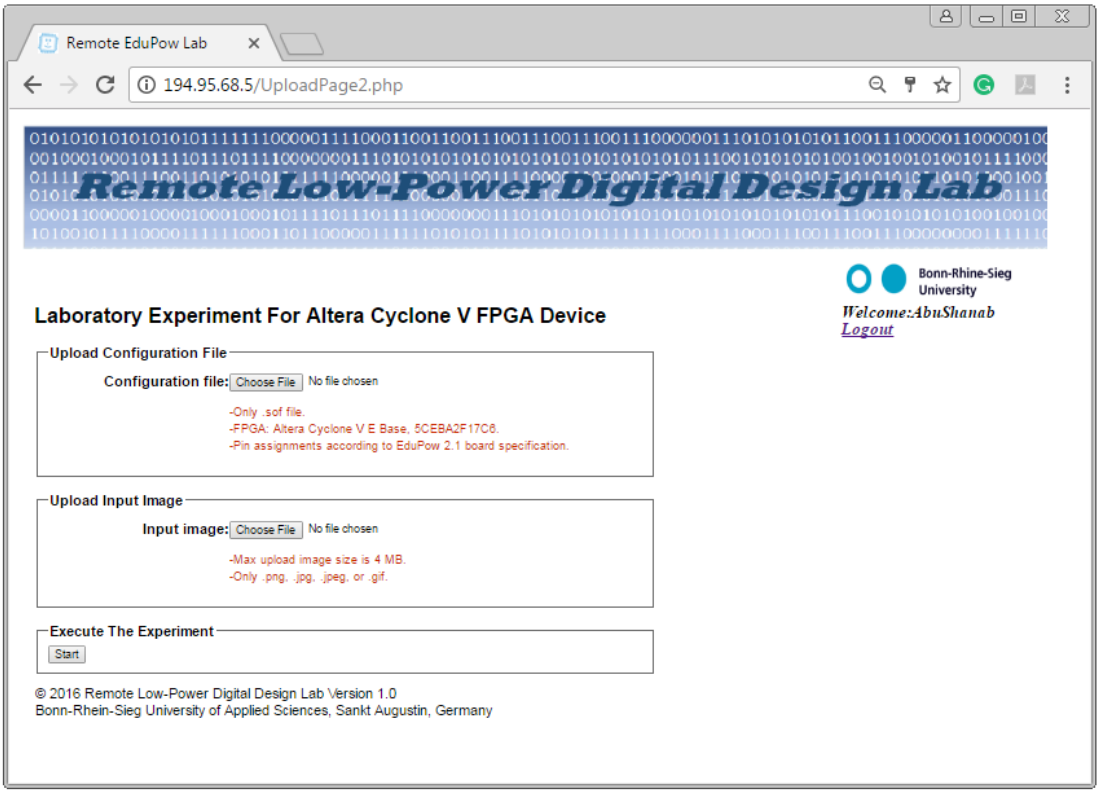

Figure 8.3: Upload webpage of the remote experiment

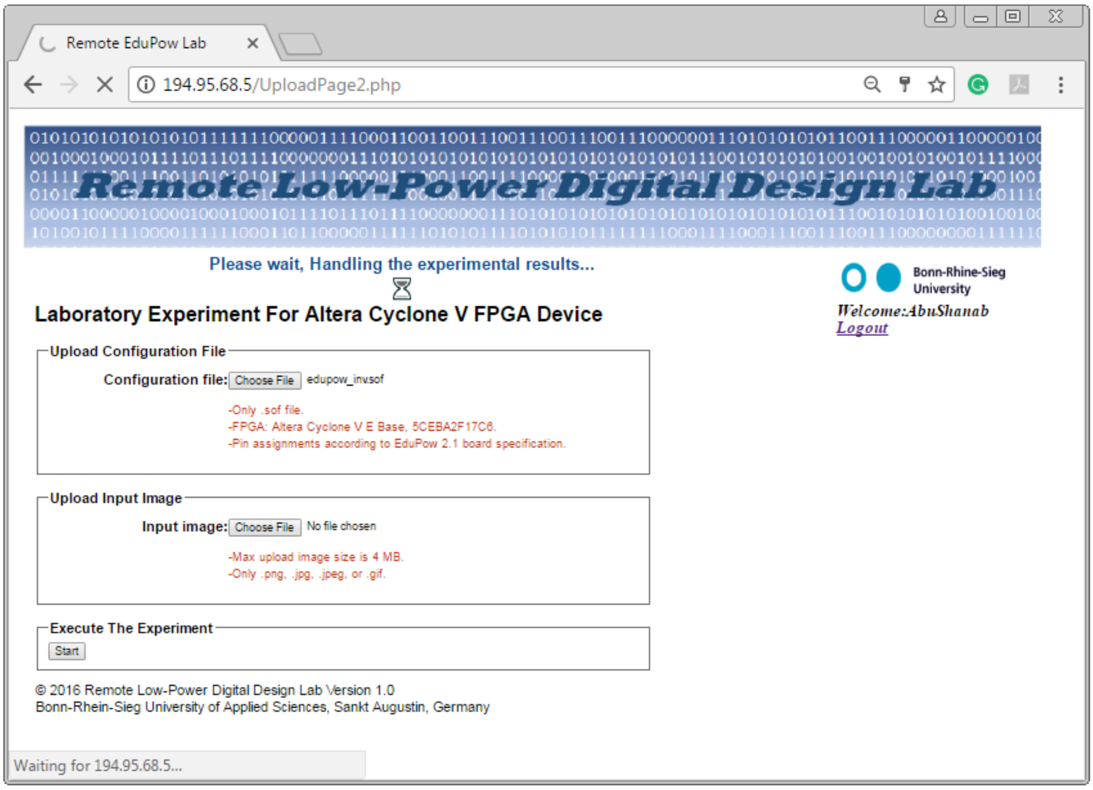

Figure 8.4: Webpage informs that the remote system is handling the experimental data

8.5.3 Webpage of the Experimental Results

Typically, at the end of any hands-on session, the students receive experimental results. After execution, the remote experimental data is measured and sent to the remote server. The measured data is given as graphical instrument interfaces as shown in Figure 8.5.

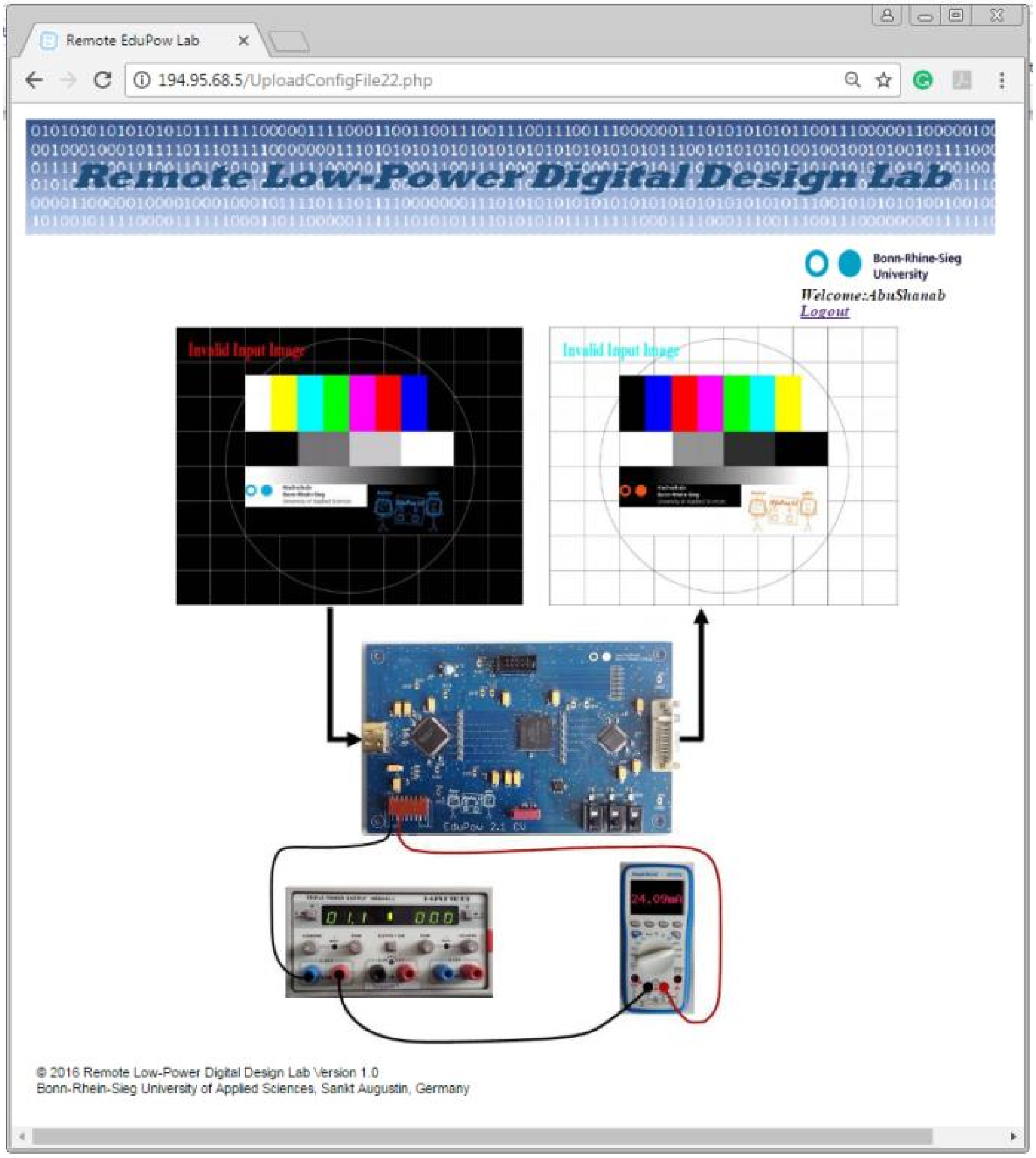

Figure 8.5: The webpage of the experimental results from the remote experiment

The available components on the output interfaces are:

- Input image (top left side in Figure 8.5). The input image is either uploaded by the student or the remote system uses a default image.

- Output (processed) image (top right side in Figure 8.5). It is one of the experimental output that is processed by the student's implemented digital circuit.
- The designed FPGA-board (central device in Figure 8.5). In this example, Cyclone V FPGA technology is used in implementing the FPGA-board.
- A DC power supply (bottom left side in Figure 8.5). It shows the voltage core that is applied to the FPGA device.
- Digital multimeter (DMM) (bottom left side in Figure 8.5). It measures the core current of the FPGA device that is another output from the experiment.

The remote server manages and displays the data from the remote experiment that consists of computer graphics for the used physical instruments, image-captured from the remote experiment, and the measured values. The student can save his/her experimental results from the computer screen that include not only the power dissipation of his/her digital circuit but also the origin and the processed image by his/her digital circuit. The student can verify the functionality of a proposed algorithm and determine whether the expected results are achieved in order to evaluate the success of the laboratory experiment.

Once the client finishes the remote experiment and the results are displayed on the client's screen, the session and tasks are closed and cleared. Afterwards, the control software includes the name of the database, the username, and the session ID of the remote client. The control software ends the connection with the database as it is going to complete the tasks, a default status is set and also the used equipment in the remote experiment retrieves their default status.

Figure 8.6 is the remote experiment design flow that summarizes the access and the performed processes of the laboratory experiment.

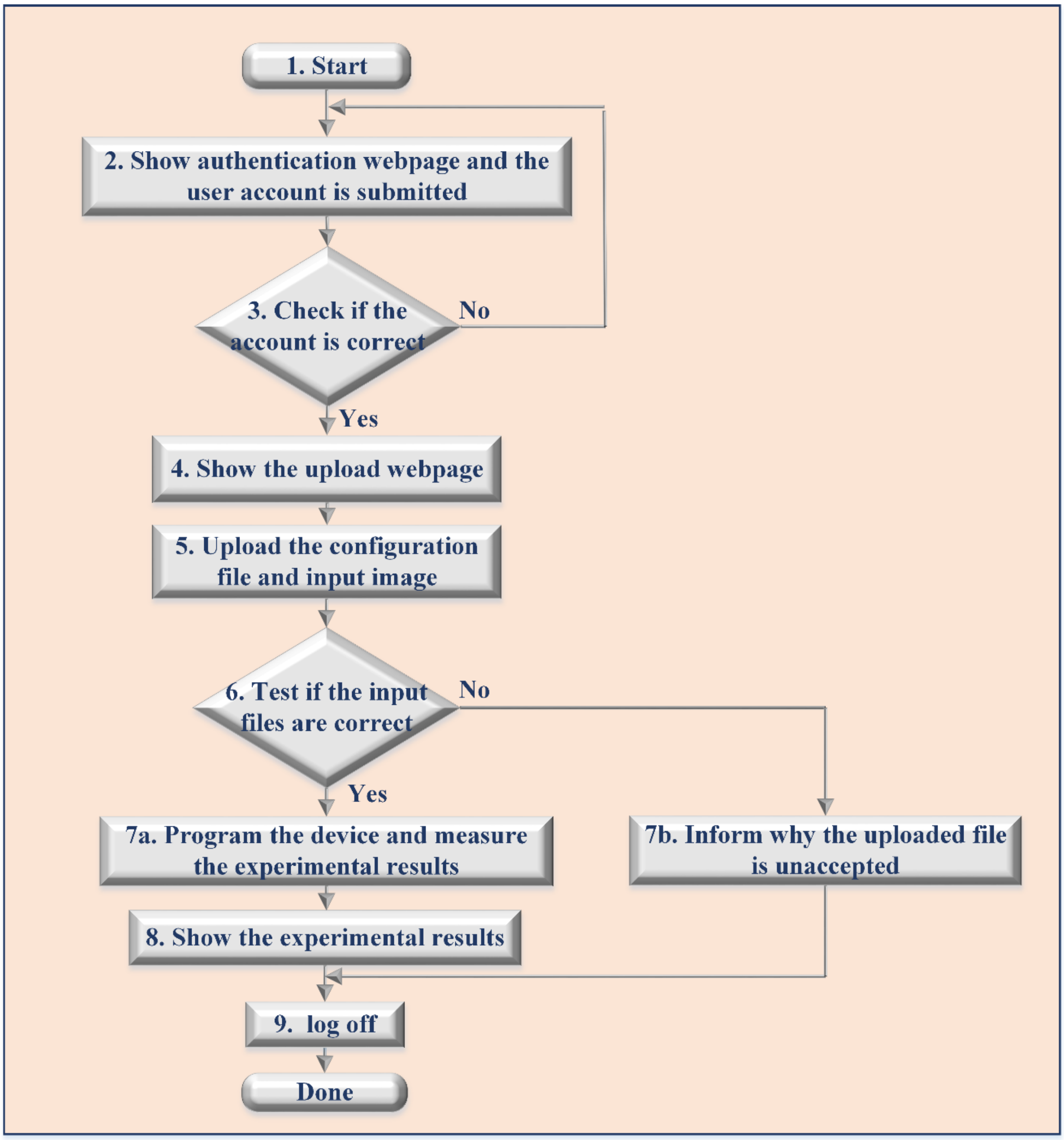

Figure 8.6: The design flow of the remote experiment

8.6 The Highlights of the Remote Experiment's User Interface

This approach focuses on increasing learning outcomes; it is necessary to develop user interface of the remote experiment that allows students to concern on educational concepts. Therefore, the remote experiment is designed to be similar as possible as when a student is located in a hands-on laboratory environment, where the GUI of the remote system is the mediator between a student and the remote server. The following summarizes the highlights of the design of the remote experiment's user interface:

- Enabling the remote client layer to reuse the on-site system remotely through a web browser. The webpage interface is developed to be ease of use and to give clear feedback on the remote experiment performed in order to may have an impact on the learning outcomes.

- For the purpose of usability of remote experiments, the DDM that is used to measure the core current is displayed with its measured values on the student's screen. Additionally, the DC voltage source that is applied to the core of the FPGA device through the design process is useful to be displayed to student/client in order to give a clear understanding of the power calculation workspace.
- Offering the opportunity for students to build their digital design circuit without any restrictions. This facilitates remembering and underlying the concepts, and also giving them a choice to select the input image that they desire to be processed.
- On the webpage of experimental results, setting up computer graphics of the laboratory instruments and elements used overlaid on real-time image-capture makes the learning environment realistic. This aims to provide engineering students a similar experience to a hands-on environment laboratory. For example, the student recognizes the instruments used, so he/she can read the measured value on the instrument's screen such as voltage or current values.
- The students do not need to use the remote system all the time while working on the remote experiment. The instructions for the remote experiment setup are divided into two parts, the abstraction phase and the hardware phase. The student needs to solve almost all design problems at the abstraction phase without an internet connection, when students have a successful and complete digital design, he/she can transfer to the hardware phase and access the remote system to verify the functionality of the design which means that he/she will not occupy the remote system during the complete experiment. The students only need time on the remote instruments when they have the completed design with the information required for implementing their digital circuits on the hardware device.

9 Using the Laboratory System as Supplement Learning Tool for Low-Power Education

9.1 Introduction

Using the low-power design laboratory system for estimating power dissipation of a complete and running digital circuit helps the students to understand the concepts of low-power design technologies. The laboratory system enables them to concentrate their efforts on low-power techniques at different levels of the design stage in order to provide a complete overview of the contribution for each influencing parameter to the overall power dissipation.

The potential of the new educational system depends on how well engineering students understand the concepts and the theories, and how much of the material from lectures and textbooks is covered and can be extended by this system.

In this chapter, the laboratory system is appraised with an emphasis on how low-power design techniques can be taught, or more correctly learned.

9.2 Educational Setting

In the Bonn-Rhine-Sieg University of Applied Sciences, electrical engineering students take a course "Introduction to the Digital Design" including a hands-on laboratory in the second year in which an FPGA-board is used with the hardware description language (HDL). An elective low-power design course is offered as an extension of the Digital Design course, and for this course the low-power design laboratory system is developed for use in a hands-on laboratory as well as remotely over the internet to deepen the students' knowledge of low-power design techniques in the digital circuits.

The options of low-power techniques that are described in Chapter Two are covered using the on-site system and the remote system. The remote system is developed to complement the learning objectives when teaching low-power design techniques. This remote system enables the students to examine the correct behaviour of their algorithms over the entire process and during real runtime application remotely.

9.3 The Learning Objectives of the Low-Power Design Laboratory Experiments

Methods for assessing the effectiveness of the laboratory system begin with the learning objectives. It is valuable to assess how these learning objectives are achieved, the difficulties and faced logic problems are also examined to assess the practical knowledge and, skills of engineering students in a combination of the on-site system and the remote system.

By completing the laboratory exercises using the on-site system and the remote system, the following learning objectives are achieved:

Objective 1: An ability to understand the influence of switching activities on the power dissipation of the digital circuit design.

Switching activity dissipates the power when the data toggles at each node in the digital design every clock cycle [9] [10]. There are large numbers of nodes and complex interactions between these nodes in the student's digital circuit which make it difficult to understand or recognize the effect of switching activities in the design stage. Through the laboratory experiments, the students can easily observe and understand that switching activities depend on both design of the digital circuit and the data that is processed by the implemented digital circuit. Each pixel in the digital image represents a colour, the RGB is used to represent colours in the laboratory experiments. The colour components are: red, green, and blue which together form the different colour values. Each colour component of RGB requires 8 bits to represent each colour binary value that can range from 00000000 to 11111111; the integer values are 0 to 255, the total number of bits required to represent a colour value is 24 bits. For example, a digital image with black colour and white colour has only two possible values, for each component of RGB is 00000000 for black colour and 11111111 for white colour. When the student alternates the colour image with black and white image, he/she can notice the influence of the switching activities on the power dissipation where the transition of the signals on each node in the digital circuit for the black and white image has a higher power dissipation due to the change from black colour (00000000) to white colour (111111111) or vice versa.

Objective 2: An ability to understand the influence of the resources utilization on power dissipation.

Power depends on a utilization of the chip, power dissipation rises when the number of used elements increases in implementing the digital circuit [9] [11] [14]. While performing the laboratory experiments, engineering students can identify the effect of decreasing/increasing the utilization of resources on power dissipation. Additionally, the students can observe that the power dissipation is assumed to rise with the increase of a design area, with additional specification of a digital design that has significantly increased resources.

Objective 3: An ability to distinguish the influence of using different resources in implementing the digital circuit design on power dissipation.

Using the FPGA device as a design platform in the laboratory system provides various resources to implement the digital circuits such as flip-flops (FFs), look-up tables (LUTs), and memory cells; each unit dissipates a different fraction of the power. The students can design their digital circuit with different possible resources and then estimate the power dissipated of their designs. The students can identify how each type of resources has different features and also a different influence on the power dissipation of the digital design. For example, the student can save power by using memory cells instead of logic elements [9] [14] [19].

Objective 4: An ability to understand the influence of increasing the functionality and the complexity of the digital circuits on dissipated power.

Increasing the complexity of the digital circuit design means additional functionality that requires increasing the number of logic block, the number of paths, and the length of paths resulting in higher power dissipation [9–11]. In teaching via the low-power design laboratory, the students need to meet but not exceed the requirements of their digital design and estimate the power dissipation. For example, a FIR 9-taps filter that has a better performance consumes a higher power dissipation than a FIR 5-taps filter.

Objective 5: An ability to understand the effect of time-constraint of the design circuits on power dissipation.

Timing analysis is used to determine the speed of the placed and routed slack to discover the critical paths in the digital circuit design [9] [10] [16]. During the laboratory experiments, the students face errors of the timing constraint in the digital circuit design. If the timing slack errors occur due to an unbalanced computing process or delays during operation. Through these practical low-power design exercises, the students can understand that the time-constraint is one of the design requirements. The information from timing analysis can summarize the delays after placing and routing in the digital circuit design. Delays in computing process or unbalanced data in the digital design that dissipate additional power can be solved using low-power design techniques such as rearranging the design to have shorter paths per computational cycle.

Objective 6: An ability to understand the influence of the digital circuits' environmental temperature on power dissipation.

The leakage currents increase with the scaling down of technology node size; additionally the leakage current increases with rising environmental temperature resulting in higher power dissipation [9] [14]. The student can identify the effect of changing the operating temperature on the power dissipation of the digital circuit by running the digital circuit under different operating temperatures. Since heat is a result of power dissipation, low-power design ensures a more reliable system by limiting the heat produced.

Objective 7: An ability to understand the influence of different CMOS technologies on power dissipation.

Power dissipation can be decreased by reducing the load capacitance; this can be done by using small technology node [9] [11] [17]. The students can understand this connection by implementing their digital circuit design using various CMOS technologies. Different FPGA devices are offered in the laboratory system. Hardware-to-hardware comparisons with different CMOS technology generations can only be performed if an appropriately designed circuit is implemented and tested under the same conditions to act as a bridge between power dissipation and functional characteristics of the technology.

Most concepts of low-power design techniques as explained in the lectures and textbooks are covered via teaching the laboratory with using the laboratory system. Objective 6 and Objective 7 are additional and complement learning objectives, which can only be achieved using the remote system as well as the others can be achieved using the on-site system or the remote system. Figure 9.1 clearly shows the achieved learning objectives when the on-site experiments are complemented by the remote experiments. It is noticeable that the additional and complemented concepts can be applied and proved using the remote system.

The Learning Objectives of Low-Power Design Laboratory System

The Low-Power Design Remote System

The Low-Power Design On-Site System

Objective 1: An ability to understand the influence of switching activities on the power dissipation of the digital circuit design.

Objective 2: An ability to understand the influence of the resources utilization on power dissipation.

Objective 3: An ability to distinguish the influence of using different resources in implementing the digital circuit design on power dissipation.

Objectives 4: An ability to understand the influence of increasing the functionality and the complexity of the digital circuits on dissipated power.

Objective 5: An ability to understand the effect of the time-constraint of the design circuits on power dissipation.

Objective 6: An ability to understand the influence of the digital circuits' environmental temperature on power dissipation.

Objective 7: An ability to understand the influence of different CMOS technologies on the power dissipation.

Figure 9.1: The achieved learning objectives using the laboratory system

10 Technical Performance Results of the Low-Power Design Laboratory System

10.1 Introduction

The performance results of the hybrid low-power design laboratory system containing the on-site system and the remote system are discussed regarding to technical mechanism of the laboratory system. Different low-power experiments of the developed laboratory system are discussed based on the system technical performances. In this chapter, a number of laboratory exercises of successful learning objectives is demonstrated, and the experimental results, observations and measured values of the system are discussed and displayed. Additionally, the time taken to complete low-power design experiments using the on-site system versus the remote system has been evaluated.

10.2 Overview of the Low-Power Design Laboratory Experiments

The learning objectives of the laboratory experiments prove the theories that students learn from the lectures and textbooks; these theories need better explanation through practical exercises in the laboratory. The next sections display a discussion and description for a part of the laboratory experiments applied to different levels in the design stage: specification level, abstraction level, technology level, and environment level. The laboratory exercises are given to students by the instructor. Figure 10.1 shows the representation of the design on abstraction and hardware level. It describes the required instructions to perform the laboratory experiment starting at high (abstraction) level using VHDL and ending at low (hardware) level using FPGA as a design platform where the digital circuit is implemented and then the power dissipation is measured.

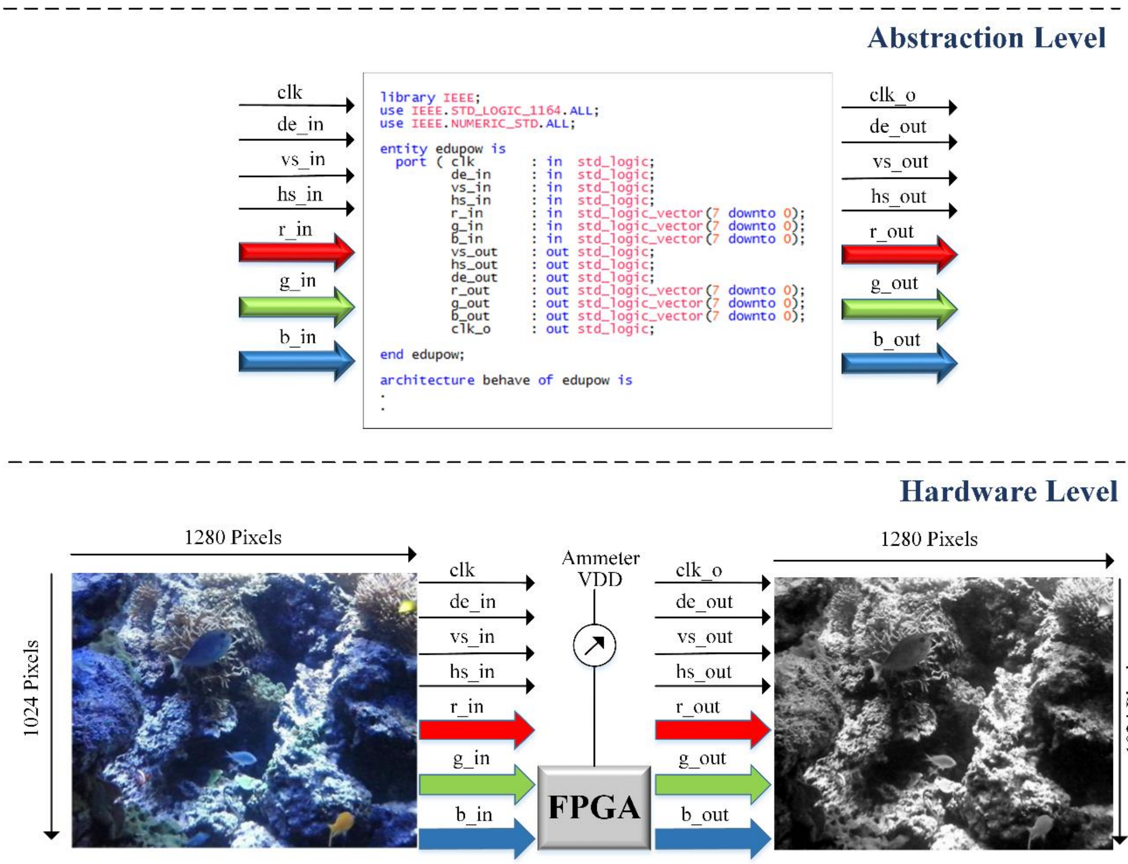

Figure 10.1: The description on abstraction level is implemented on hardware level

10.2.1 FIR Laboratory Exercise

A finite impulse response (FIR) is one of the most fundamental filters used in image and video processing applications which contain contrast improvement, sharpening, target matching, and feature enhancement. An FIR high pass is selected and designed to be a part of the laboratory exercises for teaching low-power design techniques. The FIR laboratory exercises are briefly reviewed and discussed with their experimental results during the levels of the design stage.

A FIR filter is implemented from multipliers, adders, and delays in the hardware level (on FPGA). Figure 10.2 shows an n-tap FIR filter consisting of n-1 delay elements, n multipliers, and n-1 adders or accumulators. x (n) is the input, the C0 to Cn-1 are the tap coefficients, and y (n) is the output.

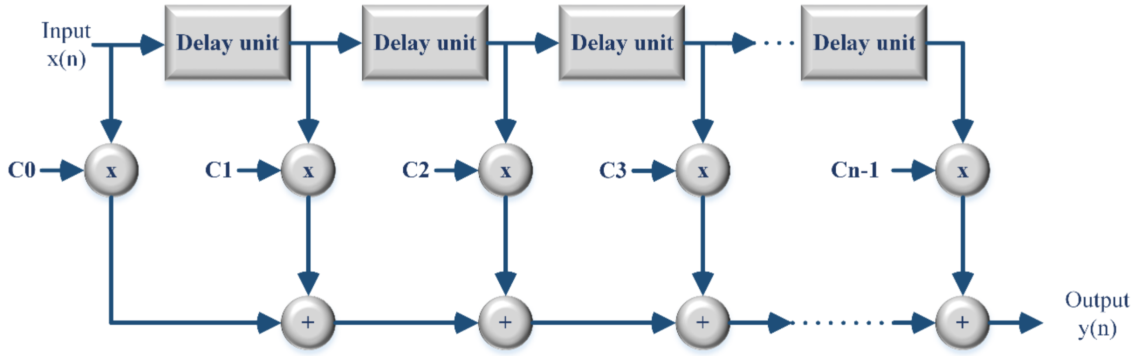

Figure 10.2: n-taps FIR filter diagram

The number of taps or multipliers is a key property of the FIR filter, so the number of taps equals the number of multipliers. The input and output of the FIR filter are the pixels that are required firstly for the vertical lines process and secondly for the horizontal lines process for the input image. The design of the FIR filter can be easily modified to implement higher taps by the students.

10.2.2 Delay Chain Laboratory Exercise

The digital circuit in this laboratory exercise uses a chain for a delay signal exercise that is implemented in n-array so the input signals are transmitted to the next row of the array for nth times, finally, the nth row is transmitted as output signals. The input signals are 24 bits for RGB colours and 3 control signals; 8 bits for each colour, as demonstrated in Figure 10.3.

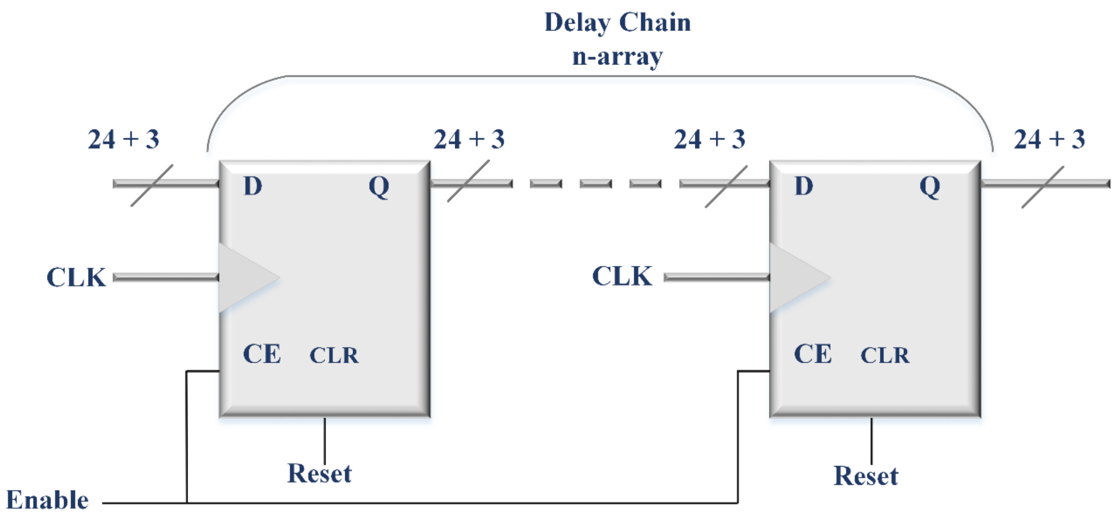

Figure 10.3: The delay chain of the digital circuits contains n-array for each input signals

10.3 Experimental Results during the Levels of the Design Stage

Using the laboratory system in teaching low-power design techniques enables the students to apply these techniques at different levels of the design stage. Thus, students can understand each influencing factor on the power dissipation. In this section, the experimental results for each level in the design stage are presented as the following:

1. **Specification Level.** The experimental results of implementing 3-taps, 5-taps, 7-taps, and 9-taps FIR filters on the Altera Cyclone V FPGA prove that the digital design's power dissipation is based on the number of operations in the algorithm as shown in Table 10.1. The numbers of taps should reflect the switched capacitances that determine the activities with respect to the circuit's size and complexity, which is established according to the specification level at the design process.

Table 10.1: Experimental results for implemented 3-taps, 5-taps, 7-taps, and 9-taps FIR filters

Cyclone V	3-taps	5-taps	7-taps	9-taps
Logic Utilization (in ALM)	174 (2%)	219 (2%)	299 (3%)	588 (6%)
Total block memory bits	98,304 (5%)	196,608 (11%)	294,912 (16%)	393,216 (22%)
V core (V)	1.1	1.1	1.1	1.1
I core (mA)	42.16	57.94	64.60	80.03
Power (mW)	46.38	63.73	71.01	88.03

Figure 10.4 shows the power dissipation for each FIR filter that is implemented on and measured from the Altera FPGA Cyclone V.

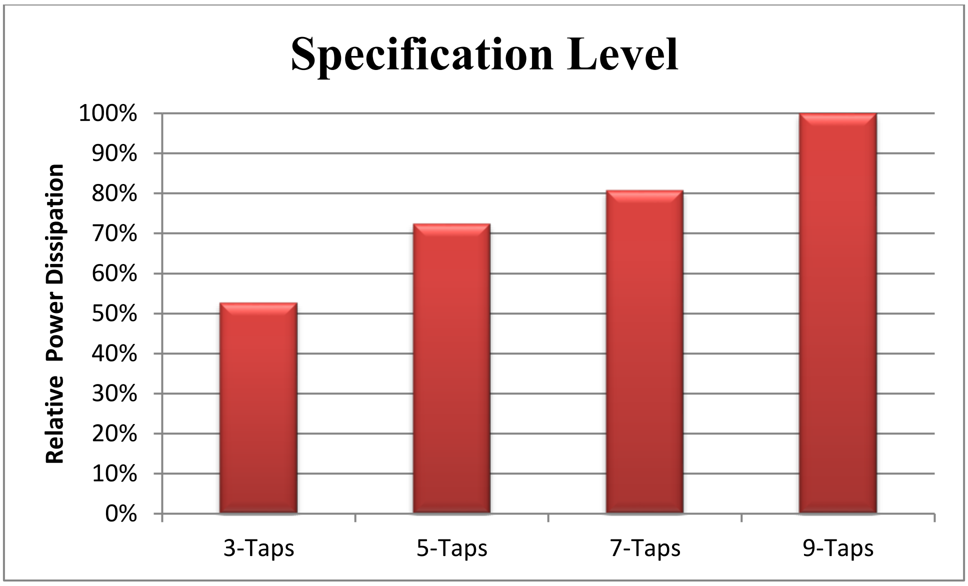

Figure 10.4: The experimental results at specification level

2. **Abstraction Level.** The delay chain laboratory exercise studies the influence of utilization on the power dissipation, satisfying utilization of the FPGA bases on the size of array. The elements for the delay can be selected in the abstraction level in the design stage. In this laboratory exercise, digital circuit has no delay, two circuits contain only FFs, and two other contain memory cells (RAM). The design is easy to understand and can be modified by students. Table 10.2 and Figure 10.5 show the experimental results that show the utilization of FPGA and the power dissipation of each utilization implemented on the Altera FPGA cyclone IV.

Table 10.2: Experimental results of the implemented 0, 400, and 800 delay chains

Cyclone IV	0	400 (LEs)	800(LEs)	400 (RAM)	800 (RAM)
Logic Utilization	0 (0%)	10,854 (49%)	21,654 (97%)	49 (<1%)	51 (<1%)
Total block memory bits	0 (0%)	0 (0%)	0 (0%)	10,800 (2%)	21,600 (4%)
Vcore (V)	1.2	1.2	1.2	1.2	1.2
I core (mA)	10.99	89.3	149.7	12.44	14.06
Power (mW)	13.19	107.16	179.64	14.93	16.87

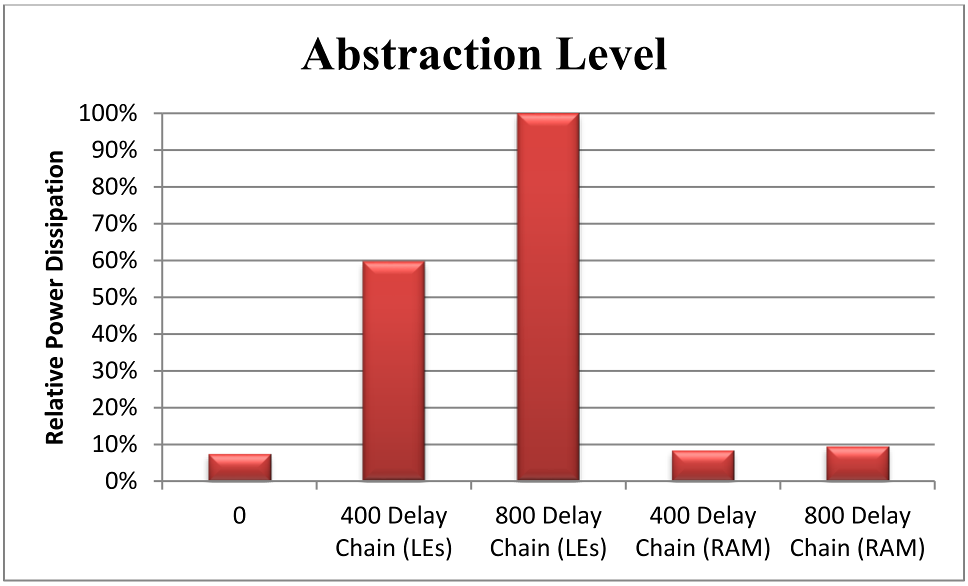

Figure 10.5: The experimental results at abstraction level

3. **Technology Level.** The influence of CMOS technology at the technology level of the design stage provides another learning objective in teaching the laboratory experiments. Figure 10.6 shows the results from the previous exercises when the FIR filters are implemented on different CMOS technologies: the Altera FPGA Cyclone IV and the Altera FPGA Cyclone V.

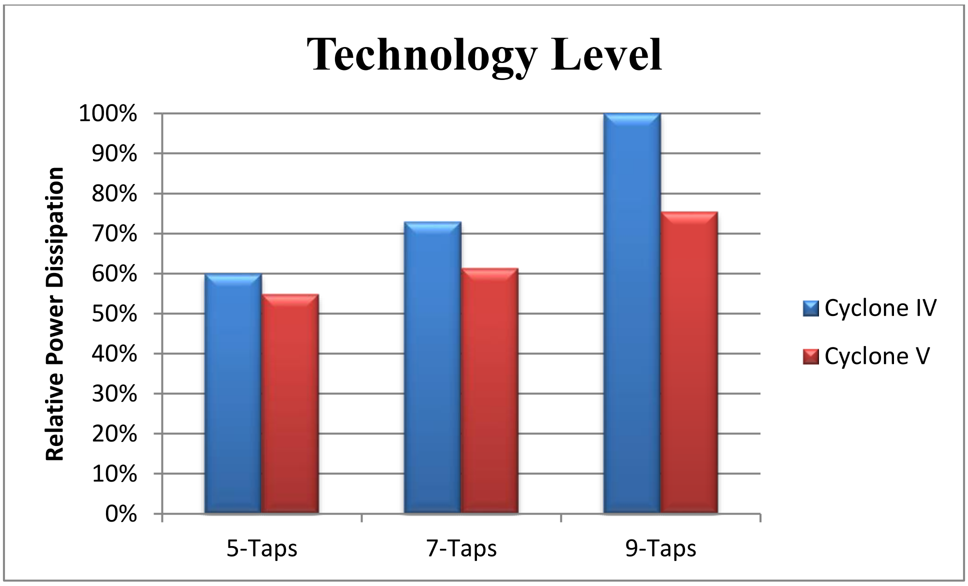

Figure 10.6: The experimental results at technology level

4. **Environment Level.** The influence of static power dissipation is another learning objective that is proven in teaching the laboratory experiments. Figure 10.7 shows the relative power dissipation of the implemented 3-taps, 5-taps, 7-

taps, and 9-taps FIR filters on the Altera FPGA Cyclone IV with different operating environmental temperature, approx. 20°C and approx. 1°C.

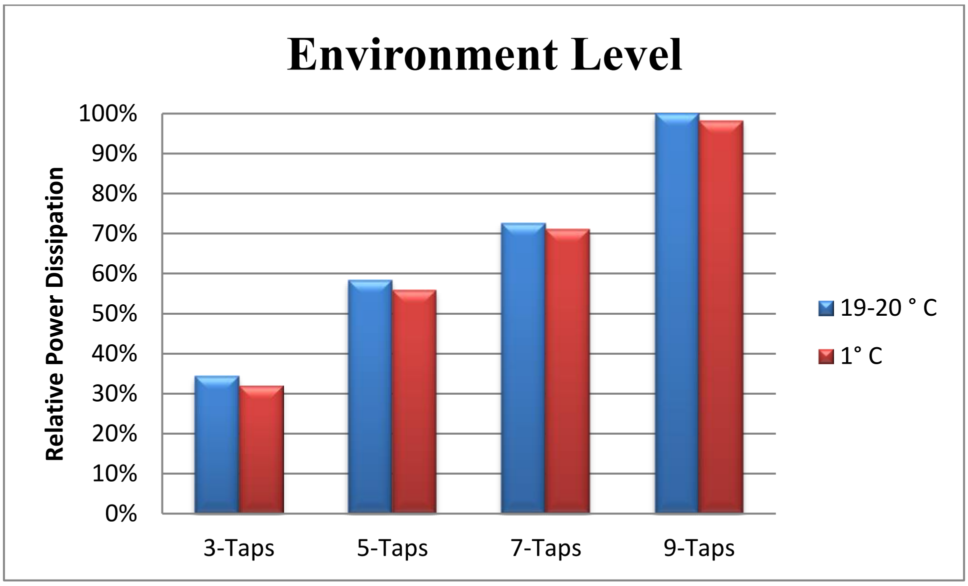

Figure 10.7: The experimental results at environment level

10.4 Required Time Taken for the Low-Power Design Laboratory Experiments

It is possible for the low-power design laboratory experiments to be performed in a hands-on laboratory or remotely. The students can follow nearly the same instructions and observe the same experimental results from both laboratory types. The on-site system and the remote system have nearly the same instructions that divide the time taken to perform the laboratory experiment into three parts: the design and the description of the digital circuit, the compilation time of the design, and the programming of the FPGA device. All parts except the final one are carried out on the student's computer without the physical devices. In the final part, the student is required to use the physical laboratory instruments either in a hands-on laboratory or remotely. After these steps, the measured values are ready to read. The expected time spent in the completion of the laboratory exercises is summarized in Table 10.3.

Table 10.3: The time taken to complete the laboratory experiments

Note: the laboratory experiments have been performed using a Lenovo Intel Core i3 laptop

	Description of the digital circuits (minutes)	**Compilation Time (minutes)**	**Programming the FPGA (minutes)**
On-site system	~10:00-20:00	~1:38 - 2:17 Cyclone IV ~1:42 - 4:35 Cyclone V	~00:02 Cyclone IV ~00:05 Cyclone V
Remote system	~10:00-20:00	~1:38 - 2:17 Cyclone IV ~1:42 - 4:35 Cyclone V	~2:00 - 3:00

Generally, these expected times were based on the delayed responses during the user's experience of performing the laboratory exercises or the internet in the remote experiment. Some delays in the completion of an experiment by students were based on various parameters such as the complexity of the experiment task, clarity of the objective to be achieved by the student, proficiency of the language used to describe the digital circuits, as well as the speed of the used computer's processor.

10.5 Summary

All the experimental results show that the specification of the design, the resources used in the digital circuit, the CMOS technology used, and the environmental temperature model are independent and free to be used and modified at a particular level in the design stage. Thus, using of the laboratory system enables the students to implement their digital circuit and to meet the performance targets of reliability while observing almost all factors influencing power dissipation.

The time taken to complete the laboratory experiment indicates that student who will use the remote system only needs 2-3 minutes longer per experiment, so student can save the travel time to the campus laboratory, as well as the preparation before and the disassembly of the experiment afterwards. The efficient use of time in the remote system motivates and encourages the students to carry out additional training outside a hands-on laboratory. Furthermore, the student needs to solve almost all design problems faced before accessing the remote experiment session, which means that he/she will not occupy the remote system during the complete experiment.

11 The Evaluation of the Low-Power Design Laboratory System

11.1 Introduction

An assessment is necessary for a new laboratory system in order to ensure the fulfilment of system objectives, satisfactory system performance of its both hardware and software components and the contents of the system's infrastructure. Additionally, problems that can occur while performing the experiment as well as some suggestions for improving to the laboratory experiments can be identified.

The performance and educational values of using the low-power design laboratory system in teaching the laboratory experiments are assessed on the basis of learning activities completed by the students. The analysis of the students' performance and the submission reports provide important information that has been implemented in the design and development stage of the laboratory system [93–95]. Consequently, one of the objectives of this PhD thesis is to study to what extent effectively using of the laboratory system assists the students in understanding and reinforcing their low-power design theoretical concepts.

This chapter describes the assessment process that includes the study of students' reports, the usage of the remote system, as well as the students' comments. The results of the assessments are discussed and summarized.

11.2 The Assessment Methodology of the Low-Power Design Laboratory System

The assessment part of this thesis was carried out from Summer Semester 2015 (SoSe15) using only the on-site system and Summer Semester 2016 (SoSe16) using the on-site system and the support of the remote system. It describes the activities carried out by the instructors and the students using the laboratory system. The students in both semesters were given the same specific tasks, these tasks are especially challenging for an in-depth understanding of the low-power design theories and techniques applied to the laboratory system.

In Summer Semester 2015, 42 electrical engineering undergraduate students participated in the hands-on laboratory. The low-power design laboratory conducted practical experiments in a hands-on laboratory using only the on-site system.

In Summer Semester 2016, 21 electrical engineering undergraduate students participated in the research. This semester had additional support from the low-power design remote system. Undergraduate students were divided into 11 pairs, each pair was given an account and a password. Additional (optional) experiments were given, which could be performed using the remote system. During the remote exercises the students were able to observe the following influencing factors on the power dissipation:

- Technology. The remote system provides the students with a different FPGA technology; the Altera FPGA Cyclone IV technology is available in the on-site system and the remote system, further the Altera FPGA Cyclone V technology is available only through using the remote system.
- Changeable operating environmental temperature. The remote system offers the opportunity to run the digital design under different environmental temperature conditions using a TEC device.

The assessment process for the SoSe15 and the SoSe16 in order to evaluate the performance of the students and the laboratory system includes:

- The submitted reports by the students after completing the laboratory exercises.
- The usage of the remote system as new tools to deliver the experimental results.
- The students' comments that reflect cognition and skills.

11.2.1 The Students' Reports

Generally, laboratory reports are essential for every laboratory session in the semester. In the low-power design laboratory, the students performed their laboratory experiments by following the instructions as a sequence of tasks in which they designed the digital circuits, practiced with the tools and the equipment to gather enough experience, obtained and analyzed the experimental results, and wrote and submitted reports [96–98].

The students' reports submitted by the students from SoSe15 sessions and SoSe16 sessions have been evaluated with regard to the laboratory exercises which have been implemented to achieve the defined learning objectives. The learning objectives were defined while implementing the laboratory experiments for teaching the low-power design laboratory. The discussion and description of the learning objectives by the students reflects their acquired knowledge [97] [99] [100]. The students' reports were a valuable and useful method for evaluating the success of using a new laboratory system in teaching in a laboratory [101]. The assessment process involves a number of criteria when evaluating the reports:

- Have all the laboratory exercises been performed? This criterion is necessary to establish why a particular exercise has not been performed.
- Has evidence about the efficacy of the obtained experimental results been presented? This criterion is to verify that the obtained experimental results are clear and understandable. The students can analyse and explain the experimental results logically with regard to the theories when the experimental results are correct.
- To what extent the low-power concepts implemented and explained with clarity through the laboratory experiments? This criterion is to show that the learning objectives of teaching low-power design concepts are achieved and expected from the theories. The laboratory experiments should be examined to establish if they apply and support the theories that are explained in the lectures.
- Has the information in the report been carefully checked? The contents of the report and the language used should be correct in describing the experiments, displaying the experimental results, and discussing the results in relation to the theories.

If all these criteria are fulfilled, this is an efficient technique to teach the low-power design theories and concepts and the usage of the laboratory system is innovative. The access to the remote system was optional for the students in the assessment, which meant that they could choose to complete further laboratory exercises remotely before writing their reports. Most students attempted to complete the laboratory exercises during the hands-on laboratory sessions. The remainder completed their laboratory exercises using the remote system. The number of times the remote system was accessed per student provides data on typical student use of the remote system outside the hands-on laboratory session.

The results from the study of the students' reports show that the learning objectives were mostly achieved, and students who accessed the remote system achieved and understood more learning objectives than using only the on-site system. Table 11.1 presents the percentage rate of the achieved learning objectives from the study of the students' reports from SoSe15 sessions and compared with from SoSe16 sessions.

Table 11.1: The percentage rate of the achieved learning objectives from the study of the students' reports from SoSe15 sessions compared with from SoSe16 sessions.

The Learning Objectives of the Laboratory Experiments	SoSe15	SoSe16
Objective 1: An ability to understand the influence of switching activities on the power dissipation of the digital circuit design.	86%	91%
Objective 2: An ability to understand the influence of the resources utilization on power dissipation.	100%	100%
Objective 3: An ability to distinguish the influence of using different resources in implementing the digital circuits design on power dissipation.	90%	91%
Objective 4: An ability to understand the influence of increasing the functionality and the complexity of the digital circuits on dissipated power.	86%	82%
Objective 5: An ability to understand the effect of the time-constraint of the design circuits on power dissipation.	95%	82%
Objective 6: An ability to understand the influence of the digital circuits' environmental temperature on power dissipation.	0%	36%
Objective 7: An ability to understand the influence of different CMOS technologies on the power dissipation.	0%	45%

Table 11.2 presents the percentage rate of the learning objectives that can be achieved using only the on-site system in SoSe 15 and that can be complemented through using the support of the remote system in SoSe16. It clearly shows the success of learning objectives is higher when the on-site experiments are complemented by the remote experiment. 29% of the learning objectives were not achieved/included in the students' reports where only the on-site system was used. These results mean that the students

who used the remote experiments can gain more knowledge of low-power design and theories. It is noticeable that additional concepts can be applied and proved using the remote system. This effect serves to improve the students' skills and deepen their knowledge.

Table 11.2: The percentage rate of the achieved learning objectives using the laboratory system in SoSe15 compared with in SoSe16.

Semester	Learning objectives		Total
	On-site system	Optional support using remote system	
SoSe15	71 %	Not applicable	71 %
SoSe16	71 %	29 %	100 %

Additionally, the students are asked in the reports to note any problems they faced such with the description of the laboratory exercises or configuration of the hardware or the software components. This was in order to use these notes to improve the laboratory experiment if needed and to evaluate the performance of the laboratory system.

11.2.2 The Usage of the Low-Power Design Remote System

After teaching with the laboratory system in the SoSe16 sessions using the support of the remote system, the student access of the remote server was evaluated to establish the percentage rate of the students who were interested in using the remote system. The rate was 42% as can be seen in Figure 11.1.

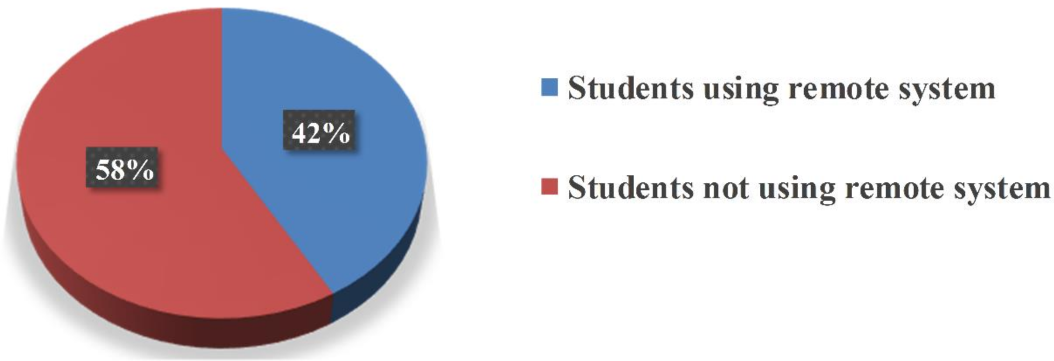

Figure 11.1: Usage of the remote system

Moreover, the student access data was analyzed to calculate the percentage rate of the students who accessed the additional remote experiments. These percentage can also be seen in Figure 11.2:

- To apply different CMOS technologies nearly 63% of the total access.

- To apply changeable environmental temperature with a percentage rate 37% of the total access.

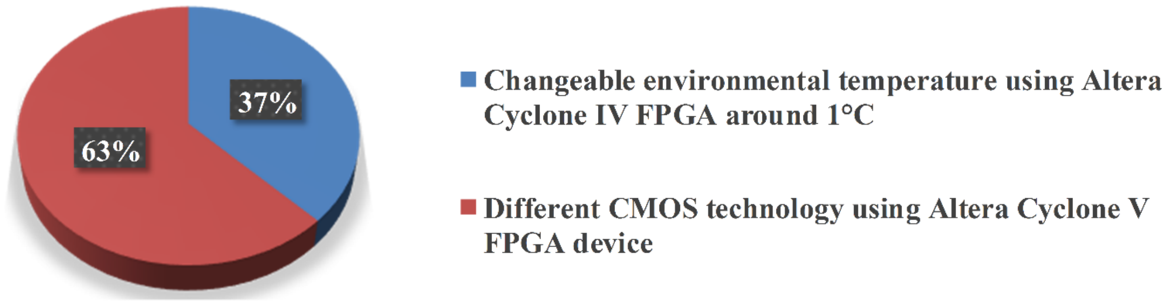

Figure 11.2: Usage of the remote system for additional learning objectives

11.2.3 Students Comments

In the students' reports, some significant comments were made:

- In the students' calculations of the power dissipation, the students conducting the remote experiments understood how the core voltage of the FPGA device differs and how, with the shrinking of the nodes in the CMOS technology the voltage scaling also decreases. However, the students using the remote system noted in their reports that the voltage applied to the Altera FPGA Cyclone V device differs and is less than the voltage applied to the Altera FPGA Cyclone IV device. Through adding the element that is virtualized the applied voltage in the remote experimental results enabled the students to acquire additional knowledge [95] [102].
- One student mentioned that the remote system can be used to perform the laboratory experiments while travelling. This technique offers 24/7 availability of the laboratory and enables students to manage their time between their study, travel, and work.
- Another student pointed out that the remote system opens new opportunities for more training with advanced experiments in addition to a hands-on laboratory. This opportunity is particular to students who are more motivated and interested in this topic.
- Some students could not understand that the remote experiments were actually performed in real time at a distance and asked to visit the room where the remote system is located. Having seen the remote server with all the physical instruments, they were surprised and impressed to see the remote system that

was being used for the first time in the Department of Electrical Engineering, Mechanical Engineering and Technical Journalism (EMT) of the Bonn-Rhine-Sieg University of Applied Sciences, Germany.

11.3 Discussion of the Results from the Evaluation Process

The results from the analysis of the evaluation process provide the following:

- The study of the students' reports. This included the description of the learning objectives, and the presentation as well as the discussion of the experimental results. The potential of this new technical design for the laboratory system, the on-site system and the remote system, depends on how well engineering students understand the theoretical concepts and appreciate the extent to which the remote system can reinforce the low-power design theories. The results show that the laboratory exercises were fully completed, and most students understood the learning objectives when using the laboratory system.
- The number of students using the remote system. The remote laboratory provides the students with additional (optional) laboratory exercises to be performed with a flexibility independent of time and place. The percentage rate of the students who performed the additional exercises indicates that the on-site system or the remote system motivates and encourages them to learn more. They are performing additional or advanced experiments where they find an exciting technical system design to try out, prove more theories from their lectures, and obtain the results from real engineering applications.
- The students' comments. The feedback from students' comments indicates that the students generally accepted the combination of the on-site system and the remote system well. The new system suggests new techniques and opportunities to perform the laboratory experiments in and away from the campus. This promotes the continuous development of the laboratory system to effectively teach more low-power design concepts.

11.4 Summary

There are no fixed methodologies to assess a new laboratory system as regards which technologies should or should not be used in its design in order to deliver the experimental results to students in implementing a hands-on or a remote laboratory. The number of the concepts that are needed for developing and designing a new technical system should be clearly defined and identified beforehand. Testing a new innovative system by involving participants is necessary to demonstrate that a system works and students follow the experiment instructions successfully.

The low-power design laboratory experiments should serve as proof of the learning objectives, and enable the students to see the connection between the theories and the laboratory experiments. It enables the students to learn by trial and error or to learn by doing consequently the learning objectives are achieved effectively, the laboratory system has not been implemented only because it is a new technical system. The students' performance reveals that nearly all of the learning objectives have been achieved by performing the laboratory experiments. Additionally, the results are encouraging to develop additional learning objectives in designing low-power digital circuits. Thus, the laboratory system which is the new approach and system for teaching the low-power design concepts by using top-down hierarchal design methodology based on an FPGA device as a design platform fulfils the objectives of the research.

The laboratory experiments have been evaluated by the students using the laboratory system, the results of this evaluation can be concluded that the development and implementation of the laboratory system is a useful tool for the teaching and learning of low-power design concepts to strengthen the students' knowledge in this field.

12 Conclusion and Future Works

12.1 Summary

This PhD research introduces a new hybrid laboratory system: on-site system and remote system for low-power design education. The laboratory system is called the low-power design laboratory system. Its technical development and implementation are based on the educational concepts. The main results from this research can be summarized in two sections: the research, and the design and implementation both of which are discussed in the following sections.

12.1.1 The Research

This PhD research achieves the novel concepts that have been developed and designed:

- The low-power design on-site and remote laboratory system. The laboratory system aims to teach low-power design practical exercises in a laboratory. It is a new system where the students use high (abstraction) level to design their algorithm and the experimental results are measured at low (hardware) level. This design simplifies the design process and is efficient usage of time and effort.
- The remote system. It is required to study the characteristics of the learning environment, and the methods of accessing learning resources in the laboratories in order to complement the learning objectives. By using the remote system to teach low-power design concepts is not only a way to deliver the physical experimental results but also to achieve complement learning objectives. The remote operation of the laboratory system is one of a few in Germany.
- Standardized instructions for using the on-site system and the remote system. It is necessary to study the generic architecture of remote laboratories used for various applications in engineering education, the accessible technologies, and

graphical user-interface for developing the remote system. Additionally, the scenarios for integrating the remote laboratory type with the on-site laboratory type in order to implement the same instructional laboratory regardless of whether the student uses the on-site system or the remote system.

12.1.2 Development and Implementation

This research includes additional technical aspects which have been developed and implemented and can be summarized as follows:

- Supplement laboratory experiments have been developed and added to the remote system. They aim to cover nearly almost all the low-power design concepts.
- The technique of integrating the remote system with the on-site system is a unique practical system for the low-power design laboratory experiments. Complementing the access to the on-site system with the remote system will increase the effects of the system. Consequently, the remote system has been deployed so that the laboratory system can be accessed independent of place and time and it also supports the sharing of resources within a university as well as between universities.
- The on-site or the remote laboratory experiments aim to reduce the gap between academia and industrial applications, especially those that require low-power design skills and an understanding of the behaviour of digital circuits. These laboratory experiments have not been previously found in the literature either regarding hands-on or remote laboratories.
- The on-site and remote laboratory prototype has been developed and implemented and then the system evaluated according to the usage by the students that provided successful outcomes.

12.2 Conclusion

Teaching digital circuit design is improved through teaching low-power design with laboratory experiments. This PhD thesis presents a new educational laboratory—the low-power design laboratory system—that can be used in electrical and computer engineering curricula as well as in other areas that require the teaching of low-power techniques of digital circuit design.

This thesis introduced a novel system, the low-power design on-site system and the remote system for teaching low-power design techniques of digital circuit design. The low-power design theories are put into practice with a real application. The laboratory system uses image processing to apply a real application in teaching the laboratory experiments that is more motivating and interesting. It is based on FPGA as a design platform, where the digital circuit is implemented and the experimental results are measured.

The laboratory system is a system consisting of hardware and software components that are integrated within the remote system in which each component plays a role in the system functionality; this facilitates accessing the physical instruments remotely via an internet connection. However, the low-power design laboratory system is the first system for low-power education and the remote access is one of only a few available laboratories in Germany. Thus, the laboratory system allows resources and approaches to be shared between institutes, and thus improve engineering education worldwide.

The laboratory experiments uses top-down hierarchical design methodology. The students starts at high (abstraction) level to describe how a digital design operates using VHDL independently of the CMOS technology devices used, and ends at low (hardware) level by implementing the student's design on FPGA, where the functionality is verified and the power dissipation is estimated correctly. The power estimation tool is at the hardware level in order to provide the information needed for correct power estimation.

The instructions for the remote experiment are similar to the physical on-site experiment and aim to emphasize the low-power design concepts rather than the technical details of the laboratory experiment. Furthermore, designing of the instructions of the remote experiment consists of local phase and web-based remote phase to make the setting up of the remote experiment time efficient.

Using the laboratory system the engineering students can observe all influencing factors on power dissipation of the digital circuit during different levels of the design stage: specification level, abstraction (design) level, environment temperature level, and used technology level. The laboratory system enables students to observe nearly all these influencing factors using the on-site system and to complement the others with using the remote system.

The implementation of the on-site system and the remote system have received very positive feedback from the students. While practising low-power design techniques in the laboratory the engineering students can acquire their skills in low-power design. Furthermore, the students' reports demonstrate the good definition and explanation of the learning objectives for using the laboratory system in the laboratory sessions. The results from the assessment indicate that the hybrid laboratory, the on-site system supplement with the remote system, is a successful and effective tool to complement the learning objectives that cover most conceptual theories in low-power digital circuit design.

12.3 Suggestions for Future Works

In this thesis, the low-power design laboratory system has been clearly described and proven to be affordable and available with the current instruments and technologies. Additionally, it can be accessed through any standard browser. However, the remote system is now accessible as an open educational resource: https://www.h-brs.de/de/fpga-vision-lab but there are still further development and improvements that can be implemented and added on the remote system:

- The remote system can be more comprehensible by using also the video processing as well as the image processing. The client can upload the videos as an input data to be processed by the implemented digital circuit on the FPGA device.
- Future works should focus on achieving further learning objectives such as:
    - Changing the voltage source of the FPGA core.
    - Taking more readings for power dissipation with different temperature conditions.
    - Providing the students with a graph of the measured values.
- The efforts should focus on the configuration of the remote system to be available and accessed by more than one student. This is explained in Chapter Eight, where the new remote experiment session is not accessed if the previous session is currently being used. The simplest solution is a queuing mechanism or can be implemented with other methods.

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List of Publications

1. ***S. AbuShanab***, M. Winzker, R. Bruck, and A. Schwandt, *"A Study of integrating remote laboratory and on-site laboratory for low-power education,"* in IEEE Global Engineering Education Conference (EDUCON), 2018: 18-20 April 2018, Santa Cruz de Tenerife, Canary Islands, Spain.
2. ***S. AbuShanab***, M. Winzker, and R. Bruck, *"Development and implementation of remote laboratory as an innovative tool for practicing Low-power digital design concepts and its impact on student learning,"* in 15th International Conference on Remote Engineering and Virtual Instrumentation (REV), 2018: 21-23 March 2018, University of Applied Sciences Duesseldorf, Germany.
3. M. Winzker, R. Kiessling, A. Schwandt, C. Sosa Paez, and ***S. AbuShanab***, *"Teaching across the ocean with video lectures and remote-lab,"* in IEEE World Engineering Education Conference (EDUNINE), 2018: 11-14 March 2018, Buenos Aires, Argentina.
4. ***S. AbuShanab***, M. Winzker, and R. Bruck, *"Remote low-power digital design system,"* in IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AEECT), 2015: 3-5 November, 2015, Mövenpick Resort & Spa Dead Sea, the Dead Sea, Jordan, Amman, Jordan.
5. A. Schwandt, M. Winzker, and ***S. AbuShanab***, *"Design of lab exercises for teaching energy-efficient digital design,"* in IEEE Global Engineering Education Conference (EDUCON), 2015: 18-20 March 2015, Tallinn University of Technology (TUT), Tallinn, Estonia, Tallinn, Estonia.
6. ***S. AbuShanab***, M. Winzker, and R. Bruck, *"Teaching low-power design with an FPGA-based hands-on and remote lab,"* in IEEE Global Engineering Education Conference (EDUCON), 2015: 18-20 March 2015, Tallinn University of Technology (TUT), Tallinn, Estonia, Tallinn, Estonia.