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Rapid Prototyping of Lighting Control System Using Reconfigurable Device

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Abstract: The developed system provides an energy efficient lighting management strategy in which the controller controls the lighting level in a room based on the occupancy of the room and the natural daylight available in the room. For the digital control of LED lamps, the design contains a lighting controller implemented on Spartan XC3S400-PQ208 FPGA. The lighting system is controlled as per the PWM signals generated in the FPGA according to the logic developed based on the illuminance level. The LED is controlled using a driver which changes the light output with respect to the PWM signals generated. This research is the rapid prototype of a big system, so that by taking the advantage of FPGA, more number of logics can be added into the developed control system. Through this prototype, it is possible to develop a more convenient and cost effective solution to our home automation problems and reduce the energy wastage and thereby the electricity charges.

Key words: Lighting control, energy efficiency, LED lighting, visual comfort, automation, occupancy

INTRODUCTION

Automatic lighting control is a technology developed to minimize the energy wastage by turning off artificial lights when it is not required. Energy efficient systems tend to use LED lights which provide scope for digital control, better energy saving and longer life span. In present day, focus of lighting has changed to more artistic or practical applications. The introduction of new luminaires not only offered optimum control but also provide opportunity to produce maintained illumination levels (Newsham and Arsenault, 2009; Bellia *et al*., 2015). One of the most common methodologies for automated lighting control system involves the use of photo sensors and occupancy sensors. However, a more efficient system can be designed by combining occupancy dependent and daylight based lighting control.

Most of the electricity which is generated is consumed by the lighting system (Colaco *et al*., 2008; Papantoniou *et al*., 2017). Hence, for developing an energy efficient system, dimming control can be incorporated in the lighting system. This can be possible by using LED as the light source which can be successfully dimmed using power electronic converter circuits to explore the best energy saving possible. This dimming control method is user-friendly and can be employed for use in offices, classrooms, buildings, hotel rooms and conference halls. In today's world where saving energy is the need of the hour, a dimmable lighting module can replace the traditional light source to add various advantages (Hung *et al*., 2011). The advantage of using LED is its durability, efficiency and cost effectiveness and low power requirement. LED lamps find applications in areas where high efficiency is mandatory at low levels such as flashlights, bicycle lights, solar powered gardens, etc. Majority of the research in this area has been done using MATLAB and Simulink Models (Colaco, 2011; Kurian *et al*., 2008), hence, this research is based on FPGA implementation of the lighting control systems. FPGA is preferred over microcontroller because of its hardware based parallel architecture, low power consumption, flexibility and suitability for real time applications. Camera based lighting control system also is an area which is progressing in lighting control (Newsham and Arsenault, 2009; Colaco *et al*., 2008; Guillemin and Morel, 2001). In addition to reduction of energy consumption, there is recognition that lighting control systems can contribute to green building certifications (Newsham and Arsenault, 2009; Kurian, 2006; Wen and Agogino, 2011). The goal of this research is to incorporate FPGA based prototyping to create an economical solution for reducing energy costs while improving individual lighting comfort levels. Automatic control of artificial and natural lighting provides visual comfort and optimizes energy efficiency. FPGA based controllers provide sequential functionality and they have concurrent architecture (Zhao *et al*., 2005). Lalpuriya *et al*. (2013) have used FPGA based wireless control system. Sweatha *et al*. (2013) implemented a design where the central FPGA controller for lighting

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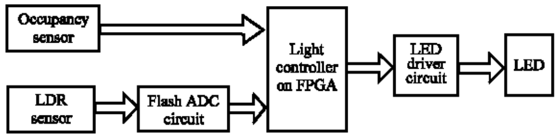

Fig. 1: Overall control system block diagram

system which communicates with a Bluetooth module. Cooper (2011) and Pang *et al*. (2002) presents the concept that the red and amber LEDs are affected the most by heating.

An automatic light control system is developed with photo sensor and occupancy sensor. Energy efficiency is achieved by proper occupancy sensing and daylight artificial light integration. A lighting control system based on the output from the light sensor and occupancy sensor to control the dimming of LED lamps for contributing to energy efficient lighting management is developed. The dimming control of LED lamp is carried using PWM based LED driver. Through the modification of the developed prototype we hope to achieve a more cost effective, energy effective and convenient solution to our home automation problems and reduce the energy wastage and thereby the electricity charges.

MATERIALS AND METHODS

System description: This study explains the block diagram representation of the prototype. It demonstrates an automatic approach in the lighting field and contains discussions about the generation of PWM pulses to control the brightness of LEDs and illustrates it. The approach is first validated using simulation tools and then put into existence by successful hardware implementation. The results were also validated accordingly. The overall block diagram given in Fig. 1 is the main methodology to carry out the research.

The entire design is divided into three parts-sensor input circuit, controller design for PWM generation and output LED driver circuit. The occupancy sensor and LDR sensor outputs are given to the FPGA. The FPGA processes these inputs to generate an output signal depending upon an algorithm. The output PWM signal is given to a LED driver circuit which controls the LED lamp.

Controller design algorithm: Based on the occupancy of the room and the amount of light available in the room, different sensor outputs are generated. These are given as input to the controller. The control algorithm gives priority to occupancy over light sensor. Only when occupancy is detected, the light control algorithm is taken into account which is given as following:

Since, the daylight illuminance vary, 10-90% of artificial illuminance is supplied on the workplane by the

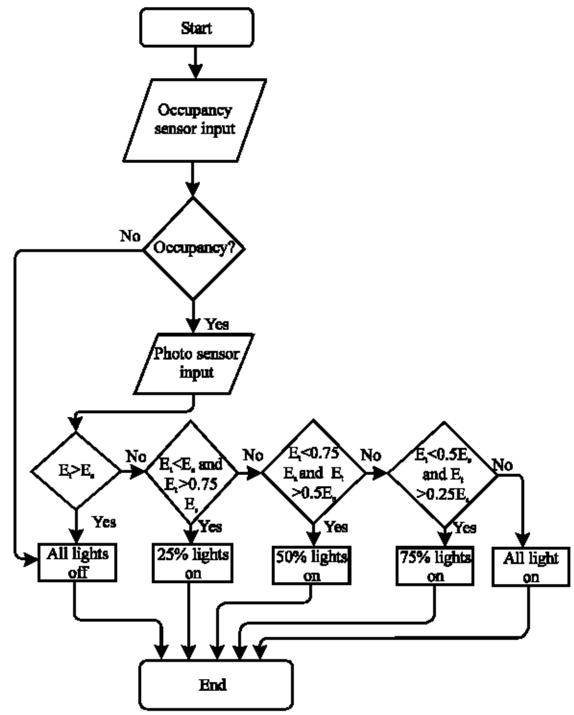

Fig. 2: Flowchart of light control system

Table 1: Control algorithm (Kurian *et al*., 2008)

Relation between task illuminance (E_{task}) and set point (E_s)	Control signal
$0.1E_s<E_{task}<E_s$	$1-(E_{task}/E_s)$
$E_{task}>E_s$	0
$E_{task}<0.1E_s$	1

control signal generated according to Table 1. For this research, the set the value of illuminance of the test room is taken as 500 lux. This preset value of illuminance is divided into different ranges for the controller design. The set value of illuminance is compared to the illuminance of the test room. As the task illuminance falls in different ranges, different dimming levels are obtained and accordingly the brightness level of the LEDs can be altered automatically. Dimming level based on illuminance is taken for controlling the artificial light.

The flow chart used for the development of the lighting control system is as shown in Fig. 2. The entire system will check the test room occupancy and if there is occupancy then the controller works based on the photo sensor signal. If E_t task illuminance is greater than E_s-set point illuminance then all lights in the room should be off which is the same output if there is no occupancy. If any other condition comes according dimming level appropriate PWM signal with mentioned duty cycles will be generated and lights will be in dim condition. If the illuminance level at workplane is 50 then all lights will be on.

Sensor circuit design: The design contains a Passive Infrared Sensor (PIR) motion sensor to check the occupancy of a room (Caicedo *et al*., 2011) and a photo-sensor or light dependent resistor to measure the amount of daylight in a room. The measured values from the sensor are converted into voltage before feeding to the controller.

Occupancy sensor: This sensor detects human presence by using infrared radiation and gives output in the form of voltage. The sensor used is panasonic passive infrared sensor. It works at 3 A, 220-240 V. When the sensor detects occupancy in its range, it gives an output voltage of 230 V AC. To convert it into the required voltage level that can be fed to the FPGA board, an analog circuit is designed containing a 230/12 V step down transformer and a bridge rectifier circuit to convert the AC voltage into DC voltage. To further step down the voltage to 5 V which is the input to the FPGA board, LM 7805 V regulator is used. When occupancy is detected, the output voltage is 5 V which corresponds to logic high 1 and when no occupancy is detected, the output voltage is 0 V which correspond to logic low 0. Depending upon the condition of the working area, logic high or logic low is fed to the FPGA board.

LDR sensor: Voltage divider rule is applied to get the output voltage across the LDR for specific illuminance conditions within permissible limits. For 0, 125, 250, 375, 500 lux the voltage value obtained is from 9.8-1.47 V. This indicates that the output of signal conditioning unit detect the variation in illuminance. Both the occupancy sensor and light sensor circuits are designed to convert the respective quantities measured by these sensors into voltage values in accordance with the input voltage limit of the FPGA board. These analog voltage signals have to be converted into their digital equivalent before being fed to the FPGA controller. For the occupancy sensor, the obtained output is directly converted in the form of logic high and low signals but for LDR sensor, an additional ADC circuit is used to convert the measured voltage values into their digital form depending upon the ADC design and then fed to the FPGA controller.

ADC design: On conducting the LDR testing, the voltage values corresponding to the different set ranges of illuminance is obtained. These voltage values need to be converted into digital form so that, they can be given to the FPGA controller. For this purpose, a hardware ADC circuit is designed using comparator IC LM339 to compare the set ranges of illuminance with the test room illuminance and generate logic high or low accordingly. The IC LM339 is a quad comparator with four comparators fabricated on a single chip. It consists of 4 independent voltage comparators designed to operate over a wide voltage range (0-5V). It is designed to directly interface with TTL and CMOS. The output is 'high' when the voltage on the non-Inverting (+IN) input terminal is greater than the Inverting (-IN) input terminal. The output is 'low' when the voltage on the non-Inverting (+IN) input is less than the Inverting (-IN) terminal input. Analysis based on the digital output of the LDR sensor output is represented in Table 2.

Table 2: Duty cycle percentage with respect to illuminance

Illuminance (Lx)	Voltage (V)	Digital output	Duty cycle (%)
$E_t>500$	$V<1.42$	0000	0
$500>E_t>375$	$1.42<V<1.75$	0001	25
$375>E_t>250$	$1.75<V<2.3$	0011	50
$250>E_t>125$	$2.3<V<3.95$	0111	75
$Et<125$	$V>3.95$	1111	95

Fig. 3: Experimental setup

PWM generation: With PWM the light level produced by the LED is very linear. VHDL programming is used to generate PWM pulses on Spartan 3 FPGA from Xilinx Family. The PWM signals are given to the led driver circuit which in turn controls the switching of the LED light. The generated PWM pulses have a frequency of around 20 kHz which is required for the optocoupler. The duty cycle changes automatically depending upon the change in set and task illuminance levels. The on-board clock frequency of 4 MHz is divided into 20 kHz frequency and the PWM signals are generated based on counter concept. Depending upon the digital output of the comparator that is given to the I/O pins of FPGA controller, different duty cycles are generated. This generated PWM signal with varying duty cycle is fed to the LED driver circuit as shown in Fig. 3-7.

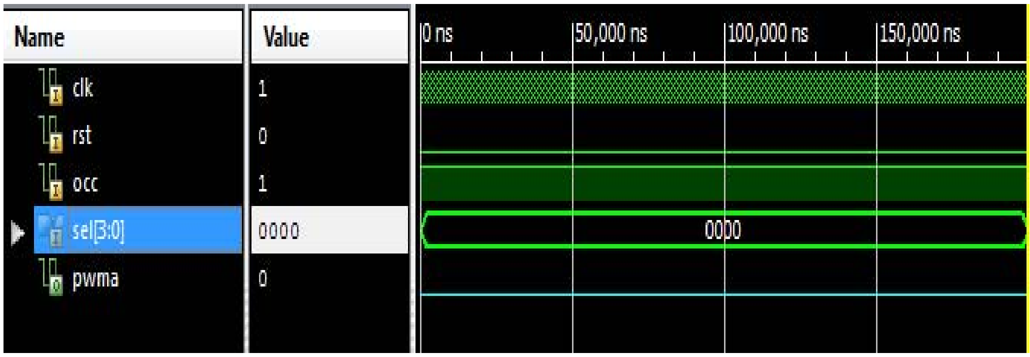

Fig. 4: PWM signal with 0% duty cycle

Fig. 5: PWM signal with 25% duty cycle

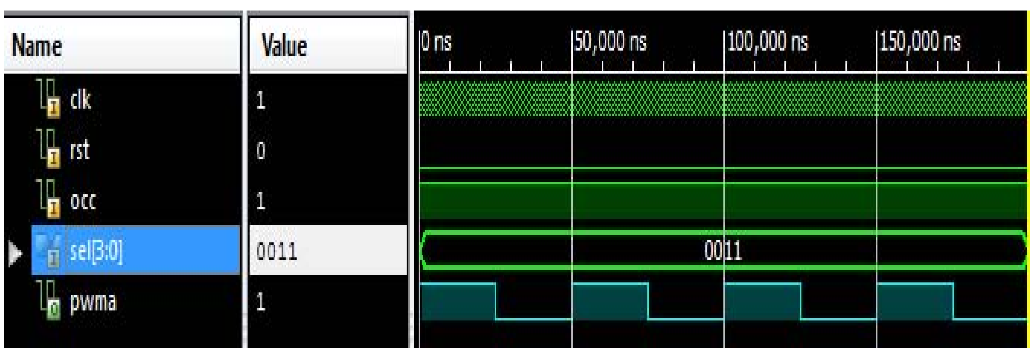

Fig. 6: PWM signal with 50% duty cycle

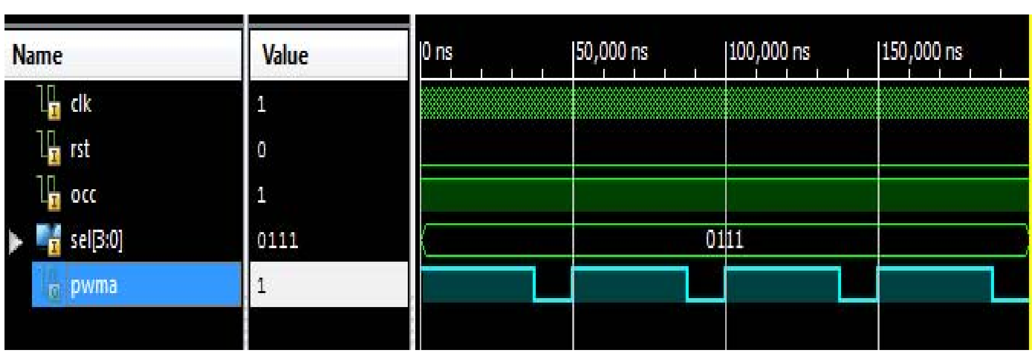

Fig. 7: PWM signal with 75% duty cycle

FPGA based implementation: The light controller is implemented on Xilinx Spartan-3 XC3S400 in PQ208 pin package. Spartan-3 IM Board (MXS3FK-IM) provides an easy method to use development platform for realizing various designs around SPARTAN-3 FPGA. It requires a 9V regulated power supply which is present along with the board. On-board 3.3, 2.5, 1.2 V regulators are present. It has 70 I/O pins for user control. The clock source is a 4MHz clock oscillator which is considered as the standard and is used as the on-board system clock.

LED driving/switching: The PWM output signal from the FPGA is fed to the LED driving circuit. The driver can automatically control the lamp brightness depending upon the change in the input PWM signal. LED is controlled using a driver which changes the light output with respect to the change in duty cycle of the PWM pulses. In this research, the generated PWM pulses have a voltage of 3.6 V (TTL high). Optocoupler TLP250 is used to transfer electrical signals between two isolated circuits FPGA and LED. It has been designed to provide complete electrical isolation between input and output circuits.

RESULTS AND DISCUSSION

The distinct phases in the research as discussed in the previous headings are executed using simulation and synthesis tools and demonstrated by developing a suitable hardware module. The results obtained at various stages are exhibited and their discussion regarding the significance and justifications for deviations are emphasized in the discussion. This section also demonstrates the results obtained in hardware implementation. The PWM signals for five levels of dimming of the LED luminaire are shown in this section. The complete experimental set up for the developed system is also shown in Fig. 8.

Sensor circuit design results

LDR sensor: Experiments are conducted to get the required voltage values corresponding to different illuminance values. The LDR sensor circuit is set up in a dark room with a single light source. To eliminate any chances of error, no additional light is allowed to enter the room other than the source. A torchlight/flashlight is used a source here. Light with different intensity ranges is focused on the LDR. The light sensed by the LDR is converted into voltage on the basis of the design specified in the previous study. The converted voltage value for different illumination levels is discussed here. At E = 252.8 lx; voltage measured is V = 2.23 V at E = 338.3 lx; V = 1.913 V at E = 377.1 lx; V = 1.78 V. The measured voltage value from the LDR sensor is used for the construction of the comparator circuit. The comparator circuit uses the predetermined voltage values as reference values. The LDR sensor circuit is used to sense the light at particular illumination level and is given as input voltage to the comparator circuit.

(a)

(b)

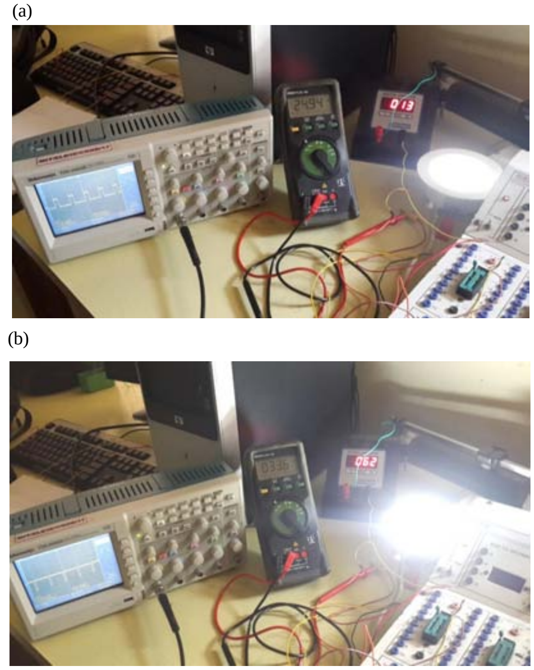

Fig. 8: a) Lamp brightness for 25% duty cycle and b) Lamp brightness for 95% duty cycle

Simulation results: The simulation is carried using Xilinx ISE design suite. If occupancy is low, output PWM signal is low, independent of the illuminance level. Etask is greater than 500 lux, hence, duty cycle of PWM signal is 0 as shown in Fig. 8. The ADC output select signal is becoming 0000 (Table 2) in the simulation. In the next figures as the Etask decreases, the duty cycle of output PWM signal increases. And finally it has a duty cycle of 100%.

After the successful simulation of the code, it is synthesized on the FPGA kit and the output was verified by obtaining the PWM waveforms of the desired duty cycle on the Cathode Ray Oscilloscope (CRO). Figure 9 demonstrate, the complete experimental setup.

Hardware test results of LED lamp: By connecting the entire set up, the 4 dimming levels of LEDs powered by an AC source and controlled by the LED driver are displayed in this study. The results are shown for 0, 25, 50, 75 and 95% intensity level based on the occupancy detected by

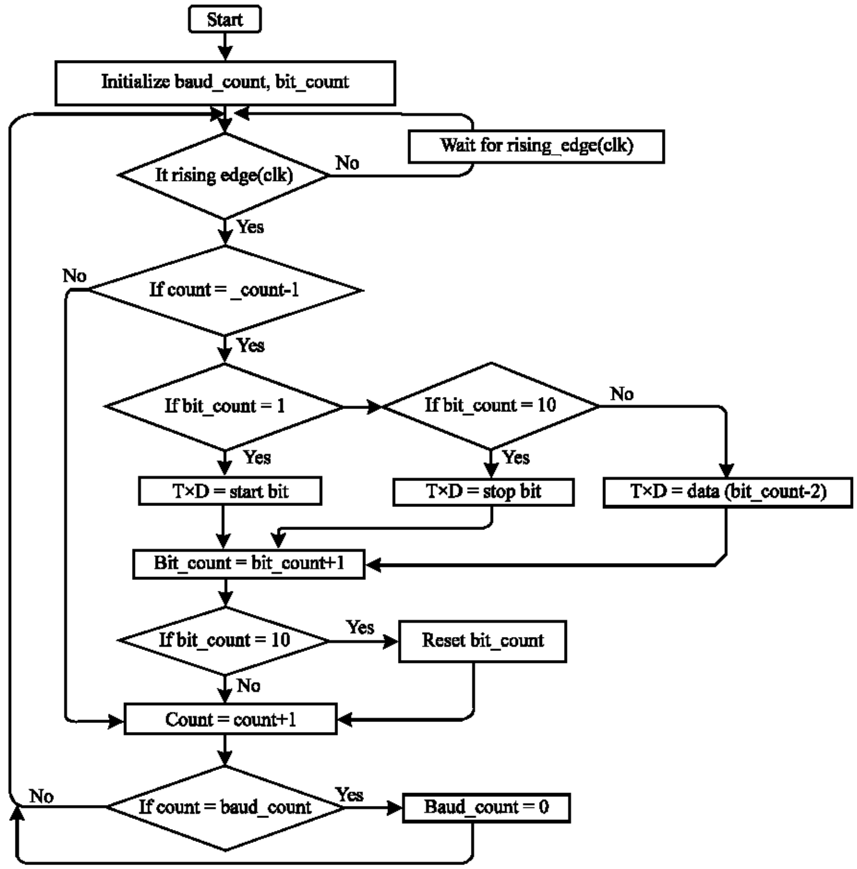

Fig. 9: Flow chart for serial transmission of PWM pulse

the occupancy sensor and the amount of light present in the working area as measured by the photo sensor. The operation is done for the variation in intensities at different levels, so as to obtain distinctive dimming levels.

The readings of the voltage across the LED lamp load and the current driven by the load and the lumen output as measured from the luminance meter are summarized in Table 3. We did the experiment in lighting lab, MIT, manipal to measure the lumen output using goniophotometer. At different duty cycles we measured the lumen output. The area is considered as 1 m^2. First the light intensity is calculated from the illuminance, then the average illuminance for each zone with zone degree as 5. Then zonal factor is calculated and thus, the luminous flux.

PWM pulse transmission based on UART: According to the control signal generated for the illuminance control of zone, the signal is transmitted through the serial port of the computer. In the zone if there is no occupancy illuminance level will not be checked and if there is an occupancy it will be checked. Then, it will be compared with the set point value. The control signal is incremented if the required light level has not achieved. Code has been written for UART serial transmission of the PWM pulses with the below mentioned flowchart. This is used for the wireless communication of PWM pulses through ZigBee transceiver.

Table 3: V, I and Lumen output results

Light level (%)	Voltage (V)	Current (mA)	Lamp output (Lm)
0	1.180	0	0
25	24.930	13	135
50	27.640	29	266
75	31.300	49	392
95	33.640	63	518

Serial transmission simulation result: The simulation of the code for UART serial transmission of the PWM pulses from the FPGA is done as given in Fig. 10.

The duty cycle selected for this simulation is 50%. Hence, it is visible that one section contains 1 low ‘start bit’, 8 ‘data bits’ which are the PWM pulses and at the end 1 high ‘stop bit’. The same section is repeated to form a train of pulses. At the receiver end, the start and stop bits are removed and then the PWM signal can be further used.

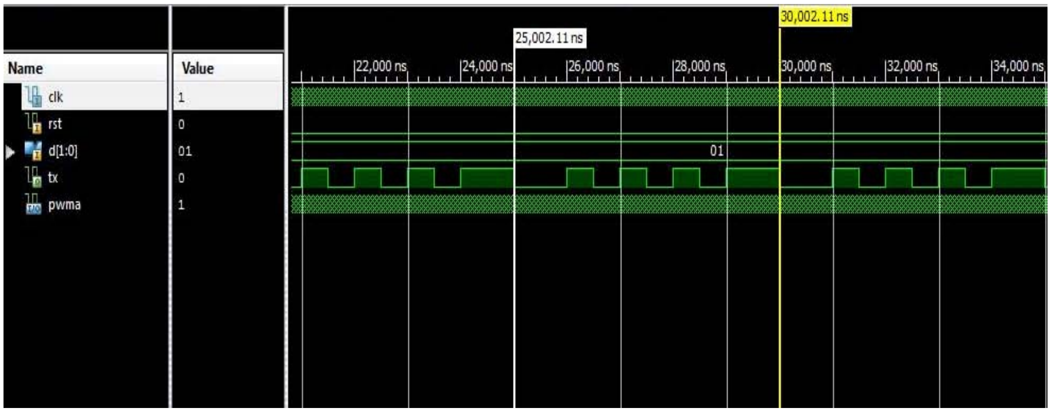

Fig. 10: Serial transmission of PWM pulses

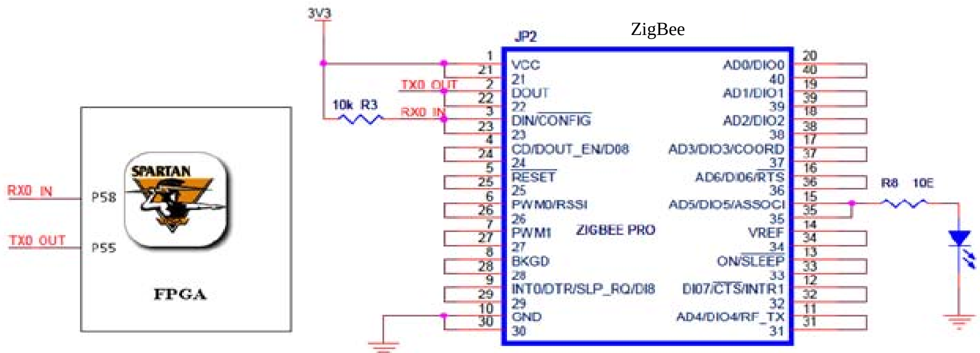

Fig 11: FPGA and ZigBee interfacing

For the control signal transmission through wireless communication method the ZigBee PRO was used with the following pin diagram interfacing ZigBee with Spartan FPGA (Fig. 11).

CONCLUSION

A reconfigurable architecture for real time LED based lighting control system is developed. This research illustrates the use of occupancy sensor and light sensor for sensing their respective quantities and converting them into suitable voltage range for feeding to the input pins of the FPGA based controller. The hypothesis of obtaining distinctive dimming levels using digital controller is accomplished using LEDs. The different intensity level is to be obtained by changing the dimming level automatically based on the sensor output. The work took shape by utilizing the simulation tools for PWM generation and then spawned to existence by development of suitable hardware unit. These results are persuasive with the design constraint of the driver circuit consisting of MOSFET used to drive the LEDs. The hardware results are also conclusive towards the projected objective of the research. These results signify the prominence of proposed concept being valid. It provides a user friendly and automatic approach to the home automation problems. Through this prototype, there is hope to achieve a cost effective alternative to automatic lighting control technology. To make the system practically more feasible, a number of luminaires can be connected and can be controlled accordingly. The work can be extended by incorporating temperature sensor for thermal comfort as well. This system can be made more advanced by implementation of wireless communication for control of luminaires using ZigBee. Wireless technology can also be designed at the input side, so that, a number of sensors can be connected together and the output of the sensors can be wirelessly transmitted to the FPGA to ensure automatic and smooth operation at the input side too. The driver circuit can be made more robust, so that, it can change its parameter and can be used in slightly different requirements .This option can be looked into in the future to make the driver more sophisticated.

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