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Energy efficient LED displays

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ENERGY EFFICIENT

LED DISPLAYS

by

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ABSTRACT

Energy Efficient LED Displays

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In this research work, an innovative pixel architecture RGBW, consisting of red (R), green (G), blue (B), and white (W) LEDs, is designed and implemented for color generation. Energy consumption of new pixel architecture consisting of RGBW LEDs is compared to standard architecture consisting of RGB LEDs. Human perception experiments are conducted to study the differences in perception between the two architectures when the same colors are generated using RGBW vs. RGB. Measurements of power for a 32inch x 16inch LED display has proved up to 18% power savings for low saturated colors, up to 8% for high saturated colors and up to 30% for white color using RGBW as a substitute. In addition, experiments on human perception have shown that majority of test subjects could not differentiate between most colors displayed using RGB and RGBW showing that RGBW is an excellent substitute for RGB. Statistic analysis has shown that 90% of test subjects found the colors to be the same, whereas 86% test subjects found the intensities of the colors to be the same.

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CHAPTER 1

INTRODUCTION

Communication is very fundamental to our modern way of life. It is critical for survival and enrichment of our lives. Display technology is one of the effective tools of communication since a display is worth of thousands of words. Currently, several leading display technology industries are competing with each other to develop and market economical and efficient display technology with the best quality. In 1970s, none could have predicted that Liquid Crystal Displays (LCD) would replace Cathode Ray Tubes (CRT) [2]. Nowadays, as LCD TVs dominated CRT TVs, it is predicted that Light Emitting Diode (LED) flat screens will replace the LCD screens in the next decade [3].

The factors, which give LED displays advantage over the other displays, are: response time, size, weight, viewing angle, brightness, life time, and power consumption. The factors that limit CRT, LCD and Plasma displays are cost, size, brightness and image retention [1]. LED displays are finding applications in household appliances, traffic signaling, emergency lighting (exit Signs), bill boards and displays for entertainment industry [1].

An LED is a simple PN junction diode, which emits photons of specific color, when it is forward biased. This emission process called injection electroluminescence occurs when minority carriers of opposite electrical charge, i.e., electrons and holes, recombine releasing photons of energy equal to the energy band gap of semiconductor material of which the diode is fabricated. Two material systems dominate the commercial LED market, AlInGaP for red to yellow color and InGaN for violet color [7].

Commercialization of LED technology was started in 1962, by various industries like Bell Labs, Hewlett-Packard® (HP®), IBM®, Monsanto®, and RCA®. HP and Monsanto were the first one to introduce the first commercial 655nm red LEDs in 1968 using gallium arsenide phosphide [4]. For a short span of time, these LEDs were incorporated in pocket calculators and digital watches, but, were soon replaced by LCDs.

Shuji Nakamura of Nichia Corporation of Japan [5] invented the first blue LED based on InGaN with high brightness, which rapidly led to the development of the first white LED. It is primarily a blue LED coated with phosphor to produce a white light.

Today's commercial white LEDs were implemented by work with GaN semiconductor materials by Dr Shuji Nakamura at Nichia Corporation in Japan in the 1990s [5]. The 'whiteness' of white LED is derived from the narrow-band blue that is naturally emitted by GaN LEDs, and a wide range yellow produced by a phosphor coating on the die which absorbs certain amount of the blue and converts it to yellow. Philips-owned company Lumileds introduced the first successful high-power white LEDs, using larger die (1 mm x 1mm) for intensity and complex packages to dissipate the heat generated in order to prevent the performance degradation of the LED.

Current rapid advancements in LED technology are yielding commercially viable LED display technology. Technical factors that make the LED technology the best of all available display technologies are: less power consumption for the same light output (higher energy efficacy), wider Correlated Color Temperature (CCT), extremely long life span, durability, and no UV radiation. LED technology is also used in recent Television sets. Televisions lit with LEDs are proven to be efficient in terms of energy, size, weight,

brightness when compared to the old CRT televisions, but they are also more expensive [6]. The cost is expected to come down with wider adoption of the LED TV sets.

LED displays are prevalent in the entertainment and commercial advertisement industry. One of the largest LED display screens is used in the Fremont Street Experience in Las Vegas, Nevada. In spite of rapid expansion of the LED display market, the technology has a few major drawbacks: power consumption degradation of display and the cost. The topic of this thesis is to improve the energy efficiency of LED display technologies without compromising on the visual quality of the displays. In order to achieve this goal; a new pixel architecture including a white LED is introduced to the traditional RGB LED configuration. A 32inch x 16inch display board containing RGBW LED's is built with the necessary hardware and software and used for the testing. Experiments were conducted to test the energy efficiency of our unit compared to the standard RGB LED pixel configuration. Additionally, experiments were conducted to investigate how human beings perceive the display in comparison to a standard RGB LED display in terms of video quality.

A survey and comparison of various display technologies is presented in chapter 2. Theoretical foundation of this work is in chapter 3. Design of the video processing and display is presented in Chapter 4. Results and discussions of human experiment and energy measurements are in chapter 5. Conclusions and future works are in chapter 6.

CHAPTER 2

COMPARISON OF DIFFERENT DISPLAY TECHNOLOGIES

In this chapter, a brief review of various display technologies with their history, working principle and advantages is presented. Additionally, various display technologies are compared and contracted.

2.1 Liquid Crystal Display (LCD)

Liquid crystals were first found in cholesterol extracted from carrots by an Austrian botanist and chemist, Friedrich Reinitzer in the year 1888 [8]. Richard Williams, a researcher at David Sarnoff Research Center (RCA labs), in Princeton, New Jersey, had generated stripe-patterns in a thin layer of liquid crystal material by the application of a voltage in 1962 [8]. According to the IEEE, a group of engineers and scientists guided by George Heilmeier, Louis Zanoni and Lucian Barton, at RCA labs [8] invented a method to control the light reflected from liquid crystals and demonstrated the first liquid crystal display (LCD) in the period between 1964 and 1968. Their work initiated a worldwide industry that is now yielding millions of LCDs.

Liquid Crystal Display (LCD) technology has become a critical facet of the electronics industry because they offer some real advantages over other display technologies. They are thinner, lighter, yield high picture quality and use less power. The size and weight of an LCD monitor can be upwards of 80% lighter than an equivalent dimension Cathode Ray Tube (CRT) screen [9]. This makes it possible for users to have larger screens for their computers than was possible before. LCD’s are smaller and lighter, energy efficient and causes less eye fatigue. Therefore they are used in many

applications like laptops, digital clocks, watches, microwave ovens, CD players, IPods and in many other electronic devices [1].

To create an LCD, 2 pieces of polarized glasses are used. As shown in Figure 2.1 (a), it has a mirror (A) in the far end of the display, which makes it reflective. Then, a glass filter (B) with a polarizing film on the bottom side, and a negative electrode plane (C) made of indium-tin oxide on top are added. A common electrode plane covers the entire area of the LCD. Above that is the layer of liquid crystal substance (D). Another piece of glass (E) with an electrode in the shape of the rectangle on the bottom and a polarizing film (F) on top are added which are inclined at an angle of 90^0 to the first one [10].

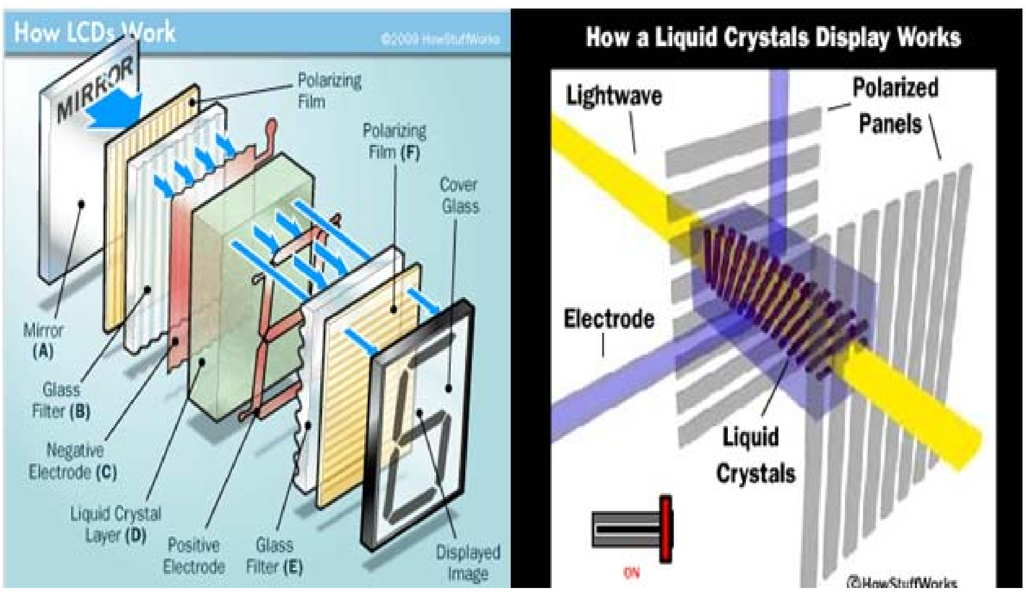

Figure 2.1 A schematic diagram showing how LCD works [10]

The light is polarized when it strikes the first filter. The molecules in each layer then guide the light to the next layer. When the light passes through the liquid crystal layers, the molecules also change the light's plane of vibration to match their own angle. When

the light reaches the far side of the liquid crystal substance, it vibrates at the same angle as the final layer of molecules. The light will pass through when the final layer coincides with the second polarized glass filter.

Liquid crystal materials do not emit light of their own. Based on this, we have two types of LCD’s, backlit and reflective. Small and inexpensive LCDs are mostly reflective. They reflect light from external light sources to display an object. Thus they use front illumination. LCD watch is based on this principle. Backlit LCD’s are transmissive type and utilize rear illumination [1]. These are simple displays which are used to show the same information again and again. For example, microwave clock is based on this principle.

There are two types of architectures for LCD displays: active matrix and passive matrix. Active-matrix LCDs depend on thin film transistors (TFT). In general, TFTs are tiny switching transistors and capacitors. A schematic diagram of TFT active matrix array is shown in Figure 2.2. They are arranged in a matrix on a glass substrate. These substrates are made from a transparent conductive material usually indium tin oxide. To find the exact location of a pixel, the correct row is switched on, and then a charge is sent to the proper column. The capacitor at the designated pixel receives a charge as all the other rows that the column intersects are turned off. The capacitor can hold the charge until the next refresh cycle [10]. By carefully controlling the amount of voltage supplied to a crystal, the crystal can be made to untwist only enough to allow some light through. By doing this precisely with very small increments, LCDs can create a gray scale. The response time of active matrix has improved tremendously and yielded brighter and sharper images than passive matrix.

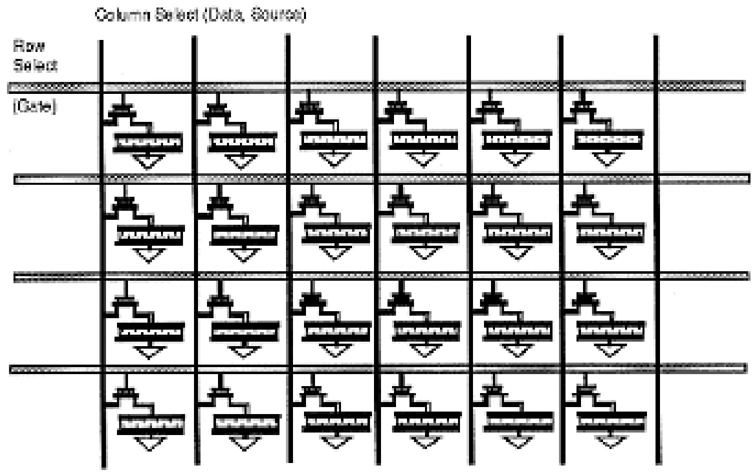

Figure 2.2 A schematic diagram showing simple TFT Active Matrix Array [11]

Passive-matrix LCDs use a simple grid to supply the charge to a particular pixel on the display. Creating the grid is a tedious process. The process starts with two glass layers called substrates. One is aligned to have columns and the other rows. These rows or columns are connected to integrated circuits that control when a charge is sent down to a particular column or row. The liquid crystal material is sandwiched between the two glass substrates, and a polarizing film is added to the outer side of each substrate. To turn on a pixel, the integrated circuit sends a charge down the correct column of one substrate and a ground activated on the correct row of the other. The row and column intersect at the designated pixel, and that delivers the voltage to untwist the liquid crystals at that pixel. This topology becomes less viable with the increase of pixels, since it increases the response time resulting in a poor contrast [1].

2.1.1 Color LCD

An LCD that shows all the colors must have three sub-pixels with red, green and blue (RGB) color filters to create each color sub pixel. By controlling the voltage applied,

intensity of each sub-pixel can be varied over a range of 256 shades. By combining the 256 shades of each sub-pixel a palette of 16.8 million colors (256 shades of red x 256 shades of green x 256 shades of blue) can be achieved. Color LCDs require enormous number of transistors [10].

The major advantages of LCD technology are:

Sharpness: Image is perfectly sharp at the native resolution of the panel.

Contrast/Brightness: Using high peak intensities very bright images can be produced. Hence it is mainly used for brightly lit environments.

Viewing Angle: The viewing angles for LCD TVs are slightly more than Plasmas. A typical LCD viewing angle is 175^0. By this, the picture can be viewed from the dead center, up to 87^0 on either side [12].

Life Span: It is measured in half life hours (50% of actual brightness). Most LCD TVs have a half life of about 30,000 hours (16 years if viewed at 6 hours per day) [12].

Advantages of LCDs like durability, low price, wide range of sizes and less thickness have made a significant impact on the display market. However, LCDs have its drawbacks such as low contrast ratio, image scaling, ghosting (resulting from low response time), limited viewing angle, fragile, and dead pixels which limited their usage to certain applications such as billboards and for some entertainment displays [1].

2.2 Field Emission Display

The development of Field Emission Display (FED) systems was first started in 1991 by Silicon Video Corporation, later by Candescent Technologies [13]. Thin CRT displays, which used metal emitters, were made of tiny molybdenum cones known as Spindt tips. But present FED research focuses on carbon nanotubes (CNTs) as emitters.

Motorola's named it as nano-emissive display (NED) for their carbon-nanotube based FED technology. They demonstrated a prototype model in May 2005, but have halted its FED-related developments due to high capital cost [13].

Around early 1990's, one of the technologies emerged as the future of flat panel displays was the FED or Field Emission Display. The FED is a vacuum electron device, having similar features as the vacuum fluorescent display (VFD) and the CRT. The image in a FED is created by impinging electrons from a cathode onto a phosphor coated screen. In a CRT, the electron source is made up of up to three thermionic cathodes. A set of electromagnetic deflection coils rasters the electron beam across a phosphor screen, which is typically held at a potential of 15–30 kV. In a FED the electron source consists of a matrix-addressed array of millions of cold emitters. This field emission array (FEA) is placed in close proximity (0.2–2.0 mm) to a phosphor faceplate and is aligned such that each phosphor pixel has a dedicated set of field emitters. In addition to the anode and cathode, a FED contains of ceramic spacers to prevent the structure from collapsing under atmospheric pressure, a frame coated on both sides with low-melting glass frit, a getter used to remove residual gases inside the package, row and column drivers, and an anode power supply. A schematic diagram of FED is shown in Figure 2.3.

In recent years, many other field emission structures have been demonstrated using various semiconductor micro-fabrication techniques. Spindt tip, which is also known as 'cone-in-a-well' emitter structure, continues to be the best choice for current generation FED applications. In this process, metal cones with tip radii less than 300 Å are deposited by electron beam evaporation into the emitter wells [15]. The process is self-limiting,

self-aligned, and unlike many of the other FEA fabrication schemes, does not require the use of single crystal silicon.

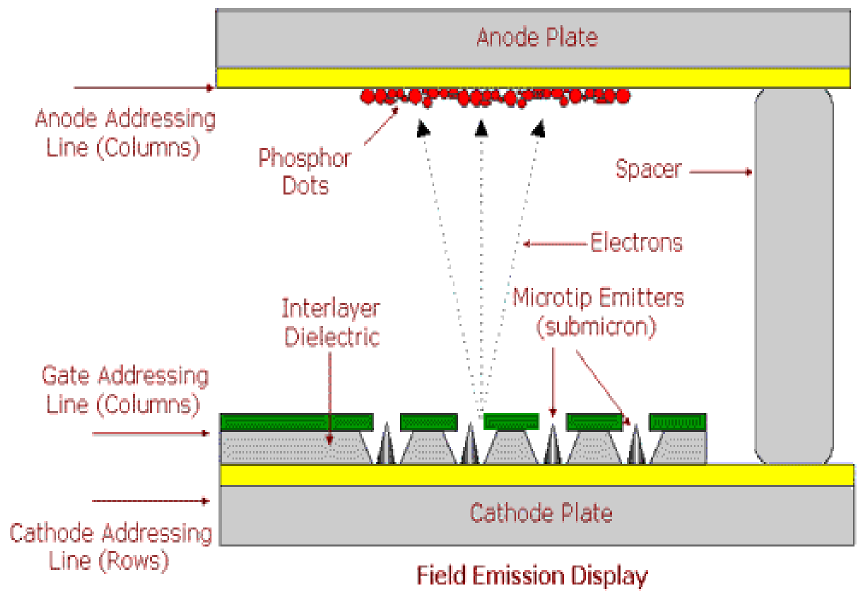

Figure 2.3 A schematic diagram showing field emission display [14]

2.2.1 Fabrication of field emission cathodes for display application

There are two types of field emission displays: 1) Low voltage field emission display (LVFED) and 2) High voltage field emission display (HVFED). LVFEDs are simpler to fabricate than HVFEDs because they do not require any additional features to handle the high anode voltage across the narrow vacuum gap [15]. These features include display structural modifications, coatings and specialized driving schemes, which make the fabrication of the display more expensive and complicated. Consequently, LVFED prototypes were the first to appear at display conferences and tradeshows, and have now entered into a commercial production phase at PixTech and Futaba.

FED panels operating in the range of 3-7 kV are referred as high voltage, or HVFEDs. While no HVFEDs are currently available on a commercial basis, virtually every FED Company is actively pursuing a high voltage design. HVFED design requires complex and expensive display components in order to insure stable panel operation for longer life span. The high anode voltage applied across a ~1 mm gap can cause both sudden catastrophic failures as well as a rapid decrease in emission current. These failure mechanisms as well as phosphor aging, limit the usable lifetime of the panel. For most applications like laptop displays, a minimum lifetime of 10,000 h is required whereas automotive displays require a shorter lifetime of ~3000 h [15].

The major advantage of FED over CRTs is that the electrons in a FED are not produced by heat. Hence, the display does not warm up and does not produce large amounts of unwanted heat. It has several advantages over LCDs as well: FED requires no back light and is very light. It has a very wide viewing angle, very high contrast ratio, has excellent color properties and its response time is very short. The first generation of FEDs used very tiny, conical electron emitters also called as spindt tip. Nanotubes are potentially a more efficient electron emitter than the Spindt tip [14]. Many challenging problems which include high voltage stability, spacer visibility and display lifetime have been successfully resolved. The high capital cost of a FED factory creates significant risk for any company based on this technology.

2.3 Plasma

Plasma technology was invented at the University of Illinois in 1964 by Donald Bitzer, H. Gene Slottow, and graduate student Robert Willson [16]. Larry Weber

developed the first prototype of a 60-inch plasma display that combines many of the industry's desirable features such as large size, high definition, and thickness [16].

For the past 75 years, majority of televisions have been built around the same technology: the cathode ray tube (CRT). In a CRT, a gun emits a beam of electrons (negatively-charged particles) inside a large glass tube. The electrons excite phosphor atoms along the wide end of the tube, which causes the phosphor atoms to light up. CRTs produced crisp and vibrant images but the major disadvantage is its size. To increase the size of the screen in a CRT set, the length of the tube must be increased which made it bulky. At that time, a new alternative emerged in the display market which is plasma flat panel display. Plasma televisions when compared to larger CRT sets have very wide screens with a thickness of only about 6 inches [17]. The main idea behind a plasma display is to illuminate tiny, colored fluorescent lights to form an image. Each pixel is made up of three fluorescent lights – red, green and blue. The plasma display varies the intensities of these fluorescent lights to produce a full range of colors.

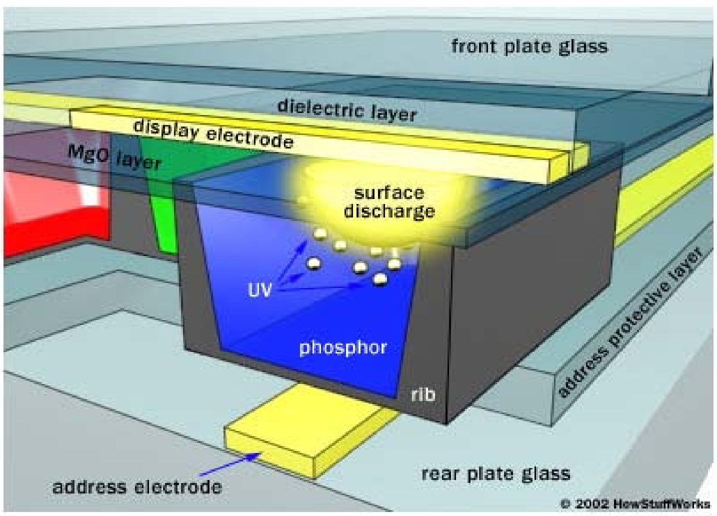

Figure 2.4 A schematic diagram showing how plasma display works [17]

Plasma is a gas made up of free-flowing ions and electrons. The negatively charged electrons perfectly balance the positively charged ions in the plasma. By introducing free electrons into the gas by applying an electrical voltage across it, the situation leads to the flow of electric current. In plasma with an electrical current running through it, negatively charged particles flow towards the positively charged area of the plasma, and positively charged particles flow towards the negatively charged area. In this process, particles collide each other constantly.

These collisions excite the neutral gas atoms in the plasma to an excited state. When the atom returns to its ground state, it release photons specific energy. Mostly Xenon and neon atoms are used in plasma screens [17]. They release ultraviolet light photons when they are excited which are invisible to the human eye. These ultraviolet photons can be used to excite visible light photons. The composition of plasma display panel (PDP) is shown in Figure 2.5.

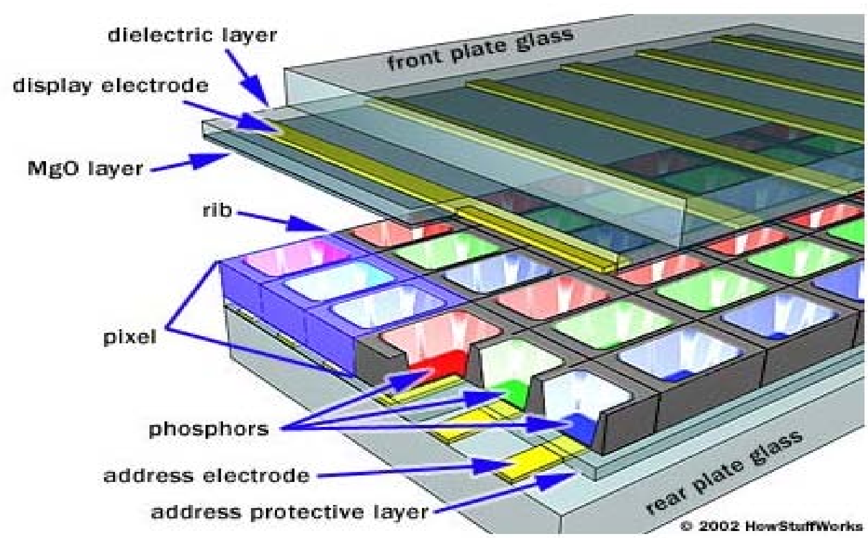

Figure 2.5 A schematic diagram showing the composition of plasma display panel [17]

The driving circuitry of the plasma display technology is very complex. The driving circuit produces the high voltage and high frequency pulses to the scan electrodes to drive a plasma display. The address-electrodes are located under the cells perpendicular to the display electrodes. A large amount of displacement and discharge current is required for charging the panel capacitance and supporting the plasma discharge. So, it is very much necessary to use switches which can cope up with high peak and root mean square (RMS) currents, thus resulting in an expensive system [18]. A schematic circuit for the panel driving system is shown in Figure 2.6.

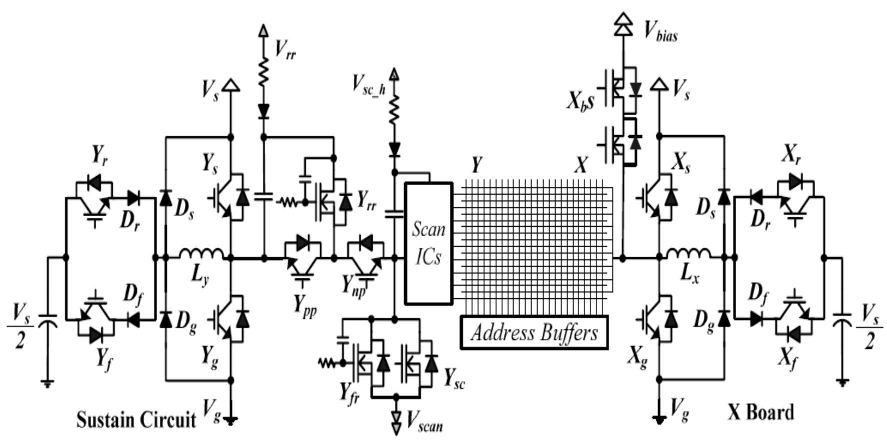

Figure 2.6 A schematic diagram of a PDP driving system [18]

The advantages of plasma over LCD are: larger screen size availability, excellent contrast ratio and ability to render deeper blacks, high level of color accuracy and saturation and excellent motion tracking in fast moving images. They produce very large and thin screens with very bright image and a wide viewing angle. Contrast ratios for plasma displays are as high as 30,000:1 [19]. However, plasma display technology has its challenges too. For the cell to respond quickly, each cell on a plasma display has to be

precharged before it is illuminated. The cells cannot achieve a true black due to this precharging [18]. Also, with phosphor-based electronic displays, the phosphor compounds, which emit the light, lose their capacity to emit light with use, which causes burn in. A charge build-up in the pixel structure occurs, when a group of pixels run at high brightness for longer time, resulting in a ghost image [1].

2.4 Light Emitting Diode (LED) Displays

A British experimenter H. J. Round of Marconi Labs, discovered electroluminescence in the year 1907 by using a crystal of silicon carbide and a cat's-whisker detector [20,21]. Braunstein observed infrared emission generated by simple diode structures using gallium antimonide (GaSb), GaAs, indium phosphide (InP), and silicon-germanium (SiGe) alloys at room temperature and at 77 Kelvin [42]. In 1961, two American scientists Robert Biard and Gary Pittman at Texas Instruments [22] discovered that GaAs emitted infrared radiation when voltage was applied and achieved the patent for the infrared LED. The first practical visible-spectrum (red) LED was developed in 1962 by Nick Holonyak Jr, while working at General Electric Company [42]. Thus Holonyak is named as the "father of the light-emitting diode" [23].

LEDs are made of p and n-type semiconductors that generate narrow-spectrum light when electrically biased in the forward direction of the p-n junction. This effect is a form of electro-luminescence where in a material emits light in response to an electric current passed through it, or to a strong electric field. Energy and hence the color of the light depends on the energy gap of the material.

In silicon or germanium diodes, the electrons and holes recombine by a non-radioactive transition which produces no light emission, because these are indirect band

gap materials. The materials used in LEDs have a direct band gap with energies corresponding to near-infrared, visible or near-ultraviolet light. Red LEDs are based on aluminum gallium arsenide (AlGaAs). Blue LEDs are made from indium gallium nitride (InGaN) and Green LED’s are made from aluminum gallium phosphide (AlGaP) [24].

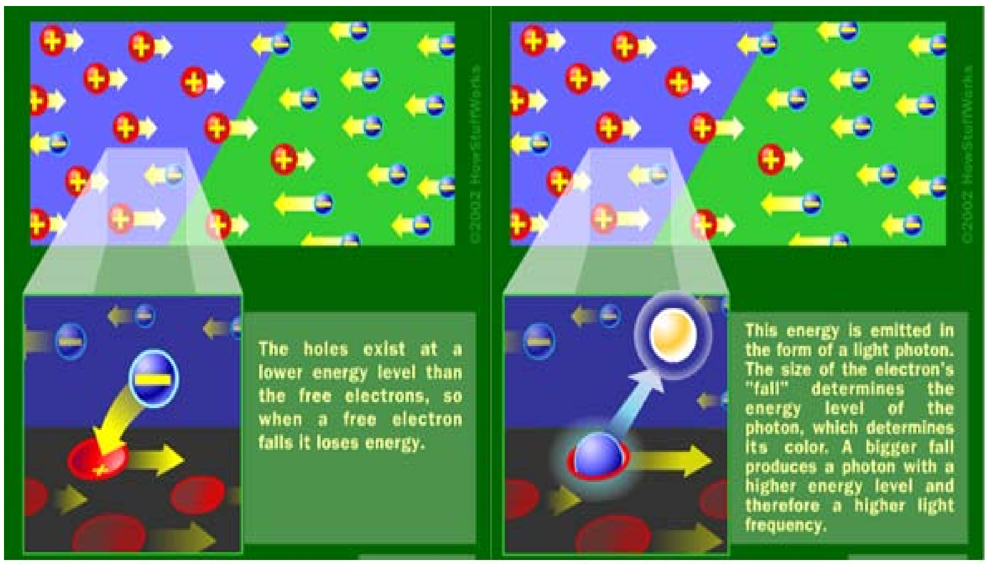

Figure 2.7 A schematic diagram showing how LED works [26]

There are two types of LED panels: conventional and surface mounted device (SMD). Conventional panels use discrete LEDs (individually mounted LEDs) and are usually used for outdoor applications. SMD panels are mostly used for indoor display applications where it requires a minimum brightness of 600 candelas per square meter (cd/m^2). This technology is reaching the outdoor market as well where it requires higher brightness of ~5,000cd/m^2 under high ambient-brightness conditions [25]. An SMD pixel consisting of red, green and blue diodes which are very small and closely set together are mounted on a chipset as shown in the Figure 2.7.a and 2.7.b. With this topology, the

maximum viewing distance is reduced by 25% from the discrete LED display with the same resolution [1].

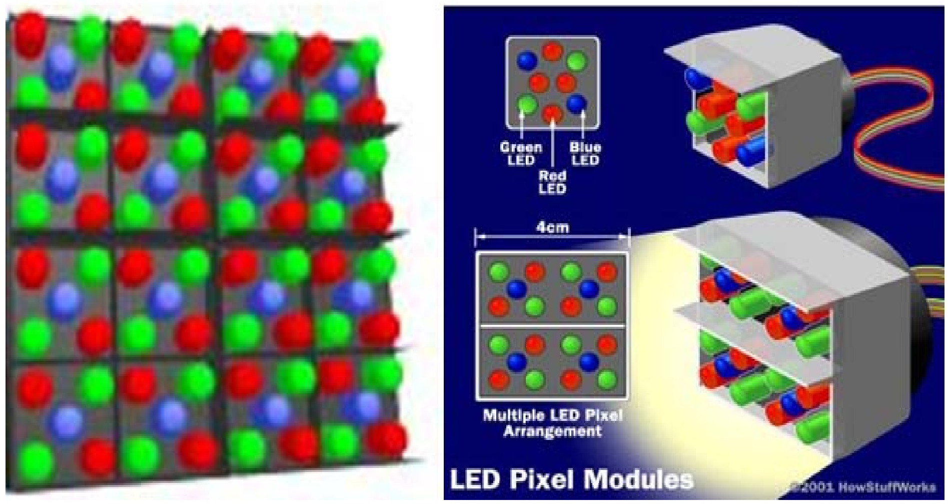

Figure 2.8 A schematic picture showing 4x4 LED display matrix and LED pixel Modules [1]

LEDs have many advantages over other display technologies. They are more efficient as the light produced per watt is more when compared to incandescent. Red, green and blue (RGB) LEDs do not require color filters to produce different colors as seen in colored bulbs. Color depends on the semiconductor used in fabricating the LED. LEDs are available in different sizes to fit in certain indoor applications. LEDs take very few seconds to emit with full brightness. Thus, the response time is very high. The lifetime of LEDs is typically 35,000 – 50,000 hours, which is far more compared to incandescent lights (1,000-2,000 hours) and fluorescent bulbs (10,000-15,000 hours) [27]. On the other hand, LED displays are more expensive than conventional display technologies. Its expense is mainly depends on low lumen output, drive circuitry and power supplies

required. Sufficient heat sinking should be provided for longer life span. Rayleigh scattering means that LEDs can cause more light pollution than other light sources. It is, therefore, very important that LEDs are fully shielded when used outdoors [25]. Definitely, LED technology will emerge as a best display technology by improving the overall stability and reliability of the display.

2.5 Summary

In this section, various properties of different display technologies are compared and contracted. Table 2.1 shows the comparison with different display properties on the row header and the technologies on the column header.

Table 2.1 Comparison of Display Technologies

Property	CRT	LCD	FED	PLASMA	LED
Contrast	High	Low	Medium	Medium	High
Longevity (hours)	80000+	50-75k+	-	80k+	50-75k
Burn-in	Low risk	No	Low risk	Yes	No
Viewing Angle	180^0	120^0	-	~180^0	140^0 - 70^0
Fully Digital Display	No	Yes	No	Yes	Yes
Max Resolution	720p 1080i	1280 x 1024	800x600	1920x1080	1920x1080
Weight (lbs)	60-300	20-100	-	50-150	-
Set Depth	16"-30"	2"	-	3-6"	depends
Screen Size	9"-40"	1"-57"	18”-36”	30"-76"	depends
Power consumption	High	Low	Medium	Medium	Low

CHAPTER 3

UNDERSTANDING COLORS

In this chapter various terms used in this thesis are defined and explained.

3.1 Definition of the terms.

Contrast Ratio:	Contrast ratio is the difference between the brightest whites and the blackest blacks that a television or video projector can display. High contrast ratios deliver whiter whites and blacker blacks and a greater degree of gray values in between. If the contrast ratio is low, even if the image is bright, your image will look washed out.
Gray Scale:	A series of shades from white to black. The more shades, or levels, the more realistic an image can be recorded and displayed. Scanners differentiate typically from 16 to 256 gray levels.
Half Life:	The period of time it takes before the screen dims to half its original brightness. TV's lifespan is measured in terms of half-life.
Image Scaling:	The process of converting the resolution of an image or a video to a higher or lower resolution to fit the standard screens is called is Image scaling.
Viewing Angle:	It is the maximum angle at which a display can be viewed with acceptable visual performance.

Electro-luminescence:	The generation of light by applying electricity to a material such as a semiconductor or phosphor. LEDs, Organic LEDs (OLED), laser diodes are example of such.

3.1.1 Definitions of Colorimetry

Color:	It is the byproduct of the spectrum of light, as it is reflected or absorbed, as received by the human eye and processed by the human brain. The inherently distinguishable characteristics of color are hue, saturation and brightness.
Hue:	It is the feature of a color perception.
Saturation:	It is the feature of a color perception determining the degree of its difference from the monochromatic color perception most resembling it.
Chromaticity:	It is the feature of a color perception composed of the features hue and saturation.
Brightness:	It is the feature of a color perception ranging from very dim or black to very bright.
Lightness:	It is the feature of a color perception ranging for light diffusing objects from black to white.

3.1.2 Psychophysical Concepts Related to Color-Matching as defined by the authors in [28]:

Color stimulus:	It is radiant energy of given intensity and spectral composition, producing a sensation of color when entering the eye.

Spectrum color:	It is the color of monochromatic light, light of a single frequency.
Achromatic color:	It is a color of a light chosen because it usually yields an achromatic color perception under the desired observing conditions.
Primary colors:	They are the colors of three reference lights. The additive mixture of such colors produces nearly all other colors in the color gamut visible to the human eye.
Tristimulus values:	They are the relative amounts of the three reference lights required to give by a linear combination a match with the color or light considered.
Color–matching functions:	They are the tristimulus values, with respect to three primary colors, of monochromatic lights of equal radiant energy, regarded as functions of the wavelength that depend on the human eye sensitivity.
Chromaticity coordinates:	They are the ratios of each tristimulus value needed to produce a certain desired color by a linear combination.
Dominant wavelength:	It is the wavelength of the spectrum color that, when additively mixed in suitable magnitudes with a specified achromatic color, yields a match with the color considered.
General Illumination:	It is a term used to distinguish between lighting that illuminates tasks, spaces, or objects from lighting used in indicator or purely decorative applications. In most cases,

general illumination is provided by white light sources, including incandescent, fluorescent, high-intensity discharge sources, and white LEDs. Lighting used for indication or decoration is often monochromatic, as in traffic lights, exit signs, vehicle brake lights, signage, and holiday lights.

3.1.3 Basic photometric concepts and units as defined by the authors in [28]:

Luminous flux:	It is the magnitude derived from radiant flux by evaluating the radiant energy according to the human eye sensitivity which is determined by its action upon a selective receptor in the eye, the spectral sensitivity of which is defined by a standard relative luminous efficiency function.
Lumen (lm):	It is the unit of luminous flux and is defined by the luminous flux emitted within unit solid angle by a point source having a uniform luminous intensity of one candela.
Luminous intensity:	It is the proportion of the luminous flux emitted by a point source in an infinitesimal cone containing the given direction, by the solid angle of that cone.
Candela (cd):	It is a unit of luminous intensity.
Solid-state lighting (SSL):	It is the technology which uses semi-conducting materials to convert electricity into light. SSL is an umbrella term encompassing both light emitting diodes (LEDs) and organic light emitting diodes (OLEDs).

Luminous efficacy (lm/w): It is the most commonly used measure of the energy efficiency of a light source. It is stated in lumens per watt (lm/W), indicating the amount of light a light source produces for each watt of electricity consumed.

Correlated color temperature (CCT): It is the measure used to describe the relative color appearance of a white light source. CCT indicates whether a light source appears more yellow/gold/orange or more blue, in terms of the range of available shades of "white." CCT is given in Kelvin's (unit of absolute temperature).

Color rendering index (CRI): It indicates how well a light source renders colors of people and objects, compared to a reference source.

3.2 The EYE and Human Perception

In this section, a brief description of the anatomy of the eye along with a description of the various subparts is presented.

Anterior Chamber:

The cavity in the front part of the eye between the lens and cornea is called the Anterior Chamber. It is filled with aqueous, a water-like fluid. This fluid is continuously generated and absorbed to control intraocular pressure.

Cornea:

The transparent, outer window and primary focusing element of the eye is called Cornea. The outer layer of the cornea is known as epithelium. Its main job is to protect the eye. The epithelium is made up of transparent cells that have the ability to regenerate quickly.

The inner layer of the cornea is also made up of transparent tissue, which allows light to pass through.

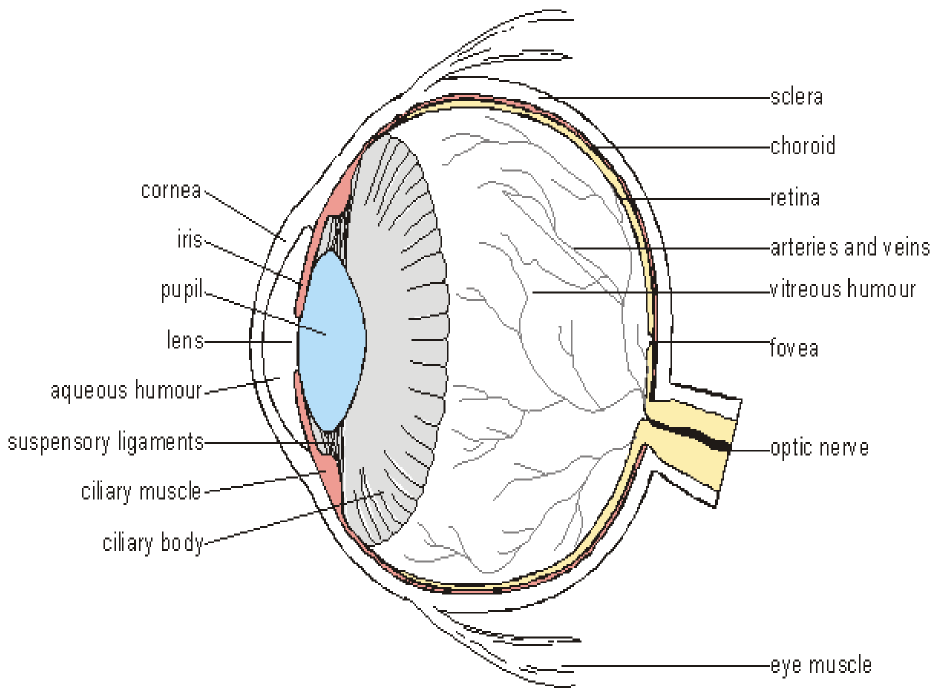

Figure 3.1 Important Parts of an EYE [28]

Lens:

The lens is a biconvex multi layered structure, enclosed in, which is connected to ciliary muscles by means of zonule fibers.

Retina:

The membrane lining the back of the eye that contains photoreceptor cells is retina. These photoreceptor nerve cells react to the presence and intensity of light by sending an impulse to the brain via the optic nerve. In the brain, the multitude of nerve impulses received from the photoreceptor cells in the retina are assimilated into an image.

Fovea:

The fovea is the retinal area where vision is more acute.

Macula:

The part of the retina which is most sensitive, and is responsible for the central (or reading) vision. It is located near the optic nerve directly at the back of the eye (on the inside). This area is also responsible for color vision.

Pupil & IRIS:

The dark opening in the center of the colored iris that controls how much light enters the eye. The colored iris functions like the iris of a camera, opening and closing, to control the amount of light entering through the pupil. It acts like the diaphragm of a camera, dilating and constricting the pupil to allow more or less light into the eye.

Sclera:

The white, tough wall of the eye. Few diseases affect this layer. It is covered by the episclera (a fibrous layer between the conjunctiva and sclera) and conjunctiva, and eye muscles are connected to this.

Conjunctiva:

A thin lining over the sclera, or white part of the eye. This also lines the inside of the eyelids. Cells in the conjunctiva produce mucous, which helps to lubricate the eye.

Optic Nerve:

The optic nerve is the structure which takes the information from the retina as electrical signals and delivers it to the brain where this information is interpreted as a visual image. The optic nerve consists of a bundle of about one million nerve fibers.

Photo Receptors:

The Rod cells are more sensitive than the Cone cells but the Cone cells have a higher acuity than Rod cells. Rods cells have monochromatic vision and Cone cells have tri-chromatic vision. Cone cells see in bright light and Rod cells see in black and white and in dark light. There are three different coloured Cone cells. These are red, green and blue.

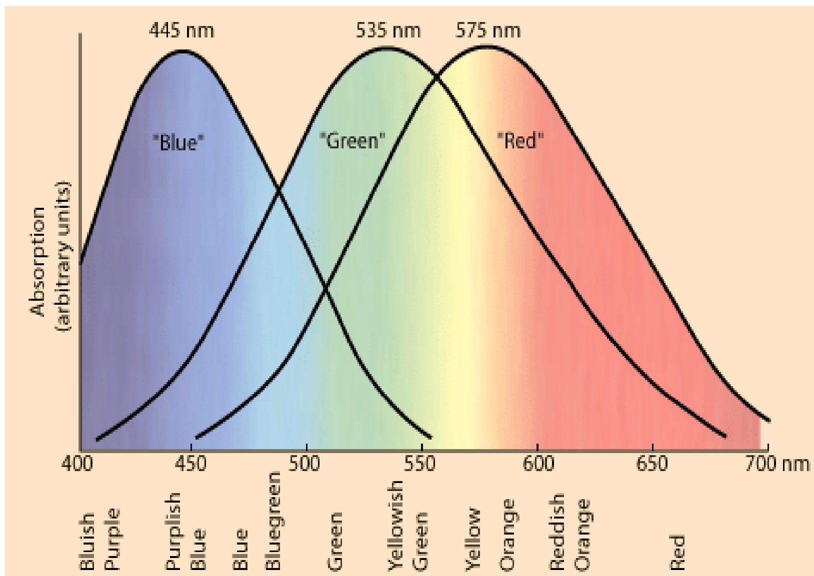

Figure 3.2 A schematic diagram showing the different response curves for cones [29]

Eye is an organ that detects the incident light and converts it into electro chemical impulses in neurons. Visual perception is the ability to interpret information from the effects of visible light reaching the eye. The resulting perception is called vision or eyesight.

The retina contains two types of photoreceptors: rods and cones. The rods are more numerous nearly 120 million and so they are more sensitive than the cones but are not sensitive to color. The rods are more efficient photoreceptors than the cones. They are

responsible for dark-adapted or scotopic vision. The optimum dark-adapted vision is obtained only after a short period of darkness, because the rod adaption process is much slower than that of the cones. While the visual resolution is better with the cones, the rods are better motion sensors. Motion detection is better with peripheral vision since it is with rod vision. The rods have a sensitive photo pigment called rhodopsin [29]. Cones are less numerous nearly 6 to 7 million and can be divided into red cones (64%), green cones (32%), and blue cones (2%) based on measured response curves as shown in the Figure 3.2. They are responsible for eye's color sensitivity. Blue cones are highly sensitive and are mostly concentrated outside the fovea. There are some distinctions in the eye's blue perception due to this. Green and red cones are concentrated in the fovea centralis. The cones are responsible for daylight vision or photopic vision. They are less sensitive to light than the rods but have high resolution vision. The eye moves continually to keep the light incident from the object of interest falling on the fovea centralis where the cones are more concentrated [29].

3.2.1 Photoptic and Scotoptic Vision

Scotopic vision is the eye's dark adapted (night time) sensitivity. In the nights, the vision shifts toward the blue end of the visible light. Its sensitivity is shifted to peak at 507 nm and drops to 10^{-4} at 340 and 670 nm as shown in Figure 3.3. The eye's daylight sensitivity is called photopic vision which shifts toward the green end of the visible light with a peak at 555 nm and drops to 10^{-4} at 380 and 750 nm. The interpretation of graph explains that human vision is more sensitive to blue at night and green in day vision [1].

The scotopic vision is primarily rod vision, and the photopic vision includes the cones. The curves in the Figure 3.3, represent the spectral luminous efficacy for human

vision. The lumen is defined such that the peak of the photopic vision curve has a luminous efficacy of 683 lumens/watt. The efficacy of the scotopic vision equals the efficacy of the photopic value at 555 nm [29]. This was done by taking a person with normal vision, and having them compare the brightness of monochromatic light at 555 nm, where the eye is most sensitive, with the brightness of another monochromatic source of differing wavelength. To achieve a balance, the brightness of the 555 nm source was reduced until the observer felt that the two sources were equal in brightness. The fraction by which the 555 nm source is reduced measures the observer's sensitivity to the second wavelength [29].

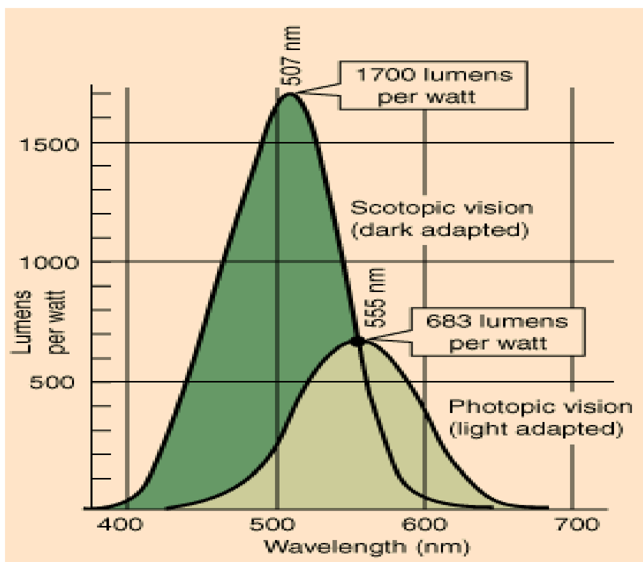

Figure 3.3 A schematic diagram showing the spectral luminous efficacy for human vision [29]

3.3 Color Interpreted by the Brain

Sources of light are either monochromatic or mixtures of various wavelengths of light. Some monochromatic colors can be reproduced by combining different light

sources. Orange, for example, is a monochromatic color that can also be produced by the combination of red and green light. In Newton's experiment [30], he found a different third color when he experimented to see what happens when mirrors are placed so as to superimpose on a white screen, two beams of monochromatic light from different regions of the spectrum. This intermingled light was not monochromatic, because Newton found that when it passed through another prism two beams emerged with the two original monochromatic colors. From the above observations, Newton has concluded that the notion of color applies to the perception we have, not to the light itself [30]. Two different wavelengths on the light spectrum which have the same effect on the three color receptors in the human eye will be perceived as the same color. For example, white light that is emitted by fluorescent lamps has a spectrum consisting of a few narrow bands, while daylight has a continuous spectrum. But humans perceive them as very similar. The human eye cannot distinguish between such light spectra just by looking into the light source, although reflected colors from objects can look different, because the absorption behavior of the object may be different for different parts of the spectrum.

3.3.1 Color Matching Function (CMF)

Despite having infinite variety of colors, the color of single lights can be reduced only to three variables. This property of human color vision, which is known as trichromacy, can be explained by a color matching function (CMF). For example, imagine there are two light sources. One is produced by a mixture of three primary colors: red, green and blue and the other light can be produced of any arbitrary color and intensity. A person is able to make the two lights appear identical, simply by adjusting the relative intensities of the red, green and blue lights. The color matching functions or CMFs are obtained from

a series of such matches, in which the subject sets the intensities of the three colors required to match a series of monochromatic (single wavelength) lights of equal energy that traverse the visible spectrum [31].

Let Q be the vector representing a particular color and R, G, and B are the unit vectors representing three fixed primaries and the vector equation is given as

$$Q = R\mathrm{R} + G\mathrm{G} + B\mathrm{B} \tag{3.3.1}$$

The above equation states that the given color is matched by a linear combination of quantities R, G, B of the respective primaries [30]. The scalar multipliers *R, G*, and *B* are the tristimulus values of the given color with respect to the set of primaries R, G, and B. This three dimensional vector space is called as *RGB* tristimulus space. Given that P_λ is the spectral energy distribution of color Q, then Q can be considered as an additive mixture of colors whose corresponding stimuli are the monochromatic components P_λ of the original stimulus out of which the color Q is composed. If $R_\lambda\, d\lambda$, $G_\lambda\, d\lambda$, and $B_\lambda\, d\lambda$ are the tristimulus values of $Q_\lambda\, d\lambda$ and *R, G, B* are those of Q, then [28]

$$Q = \int_\lambda Q_\lambda\, d\lambda \tag{3.3.2}$$

and

$$R = \int_\lambda R_\lambda\, d\lambda, \quad G = \int_\lambda G_\lambda\, d\lambda, \quad B = \int_\lambda B_\lambda\, d\lambda \tag{3.3.3}$$

Using Equation 3.3.2 and 3.3.3, Equation 3.3.1 can be written as

$$Q = \int_\lambda Q_\lambda\, d\lambda = R \int_\lambda R_\lambda\, d\lambda + G \int_\lambda G_\lambda\, d\lambda + B \int_\lambda B_\lambda\, d\lambda \tag{3.3.4}$$

Given that $\bar{q}_\lambda$ is the tristimulus value of spectrum for the color Q, one can conclude that the corresponding stimuli represent monochromatic and contain the same constant radiant flux. These values are denoted by $\bar{r}_\lambda$, $\bar{g}_\lambda$, $\bar{b}_\lambda$ which denote the color matching properties of the human eye in the particular primary system, R, G, B, and are called

color matching functions as shown in Figure 3.3. Therefore, the set of equations in (3.3.2) and (3.3.3) above can be rewritten as follows:

$$Q = \int_\lambda P_\lambda \, \bar{q}_\lambda \, d\lambda \tag{3.3.5}$$

$$R = \int_\lambda P_\lambda \, \bar{r}_\lambda \, d\lambda, \quad G = \int_\lambda P_\lambda \, \bar{g}_\lambda \, d\lambda, \quad B = \int_\lambda P_\lambda \bar{b}_\lambda \, d\lambda \tag{3.3.6}$$

This implies that the tristimulus values *R*, *G*, *B*, the coefficients of the unit vectors R, G, B in the linear equation (3.3.1), can be represented as the multiplication of two amounts the spectral energy distribution and the matching function which adapts the radiant flux observed by the human eye to the corresponding, wave length dependent, luminance flux. In other words, *R*, *G*, and *B* are the weighted average of the spectral energy distribution. Thus, Q is the summation of the product of those weighted averages by the RGB unit vectors.

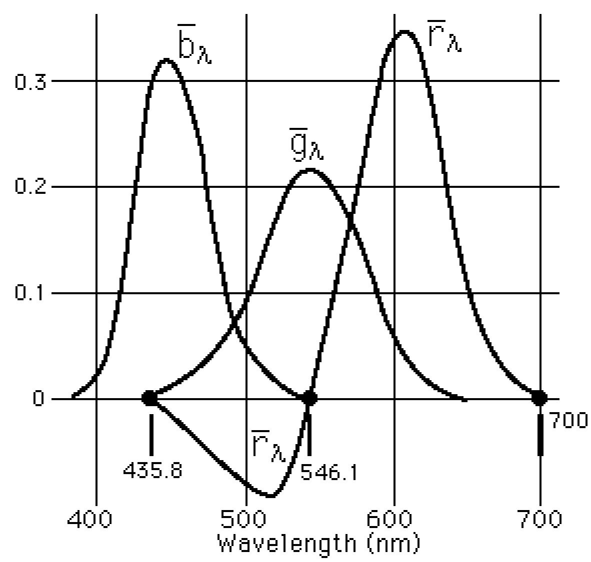

Figure 3.4 Color- matching functions $\bar{r}_\lambda$, $\bar{g}_\lambda$, $\bar{b}_\lambda$, in the primary system R, G, B [29]

The color matching functions are based on 3 laws, Grassmann's laws of additive color mixture (1853), which state [30]:

1. Any four colors Q, R, G, and B are always linearly dependent. In other words, the following relationship must hold

$$QQ+RR+GG+BB = 0$$

And the scalar multipliers, Q, R, G, B are not all 0.

2. The color of a mixture of colors Q and Q_1 is the same as that of a mixture Q and Q_2, if Q_1 matches Q_2, although the spectral energy distributions $\{P_{1\lambda}\, d\lambda\}$ and $\{P_{2\lambda}\, d\lambda\}$ of the color stimuli corresponding, respectively, to Q_1 and Q_2 may be different.

3. A continuous change in the spectral energy distribution $\{P_\lambda\, d\lambda\}$ of the color stimulus of color Q results in a continuous change of Q.

3.4 Color Spaces

A color space is an abstract mathematical model describing the way colors can be represented as tuples of numbers, typically in terms of color components. There are different color spaces for different applications noticeably in image processing. The choice of color space is most important as it greatly influence the results of the processing [33]. Color spaces can be divided into 3 categories: human visual system (HVS) based color spaces, application specific color spaces, and CIE color spaces.

3.4.1 HVS Color Spaces

Human visual system (HVS) color spaces include three color spaces: 1) RGB color space, 2) the opponent colors theory based color spaces and 3) the phenomenal color spaces. The RGB color space was the first attempt to simulate light in the human eye based on the HVS [33]. The color is described with three components: R, G and B. The

value of these components is the sum of the respective sensitivity functions and incoming light.

$$R = \int_\lambda S_\lambda R_\lambda \, d\lambda, \quad G = \int_\lambda S_\lambda G_\lambda \, d\lambda, \quad B = \int_\lambda S_\lambda B_\lambda \, d\lambda \qquad (3.4.1)$$

where S_λ is the light spectrum, R_λ, G_λ, B_λ are the sensitivity functions for the *R*, *G* and *B* sensors respectively. The RGB color space is device dependent since the RGB values depend on the specific sensitivity function. Capturing, printing, and displaying devices are based on the RGB color space.

A German physiologist called Ewald Hering proposed the opponent colors theory in late 1900's. He stated that certain hues were never perceived to occur together, i.e., a color perception is never described as reddish-green or yellowish-blue, while all other combinations are possible. He also stated that there were three types of photo receptors: white-black, yellow-blue and red-green, which was in contrast with the theory of trichromacy. Later researchers found out that there is a layer in the HVS that converts the RGB values from the cones into an opponent color vector [33]. This vector has an achromatic component (White-Black) and two chromatic components (Red-Green and Yellow-Blue). This transformation is done in the post receptors retina cells called ganglion cells. A simple model of this transformation is given as

$$RG = R - G$$

$$YeB = 2B - R - G$$

$$WhBl = R + G + B \qquad (3.4.2)$$

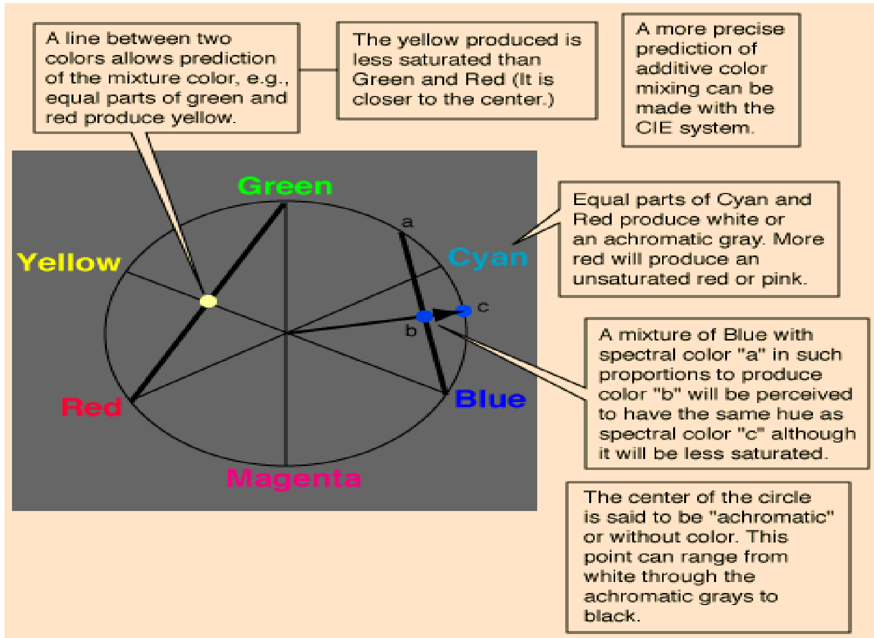

Figure 3.5 Newton color circle predictions[29]

Isaac Newton, One of the pioneers of color science arranged colors in a circle called the Newton’s color circle. Newton's color circle is a better way to summarize the additive mixing properties of colors. R,G,B known as the additive primary colors, and their complementary colors are placed across from them on the circle [29]. The colors fall on the circle according to their wavelengths of the corresponding spectral colors as shown in the Figure 3.5. This circle although it neglects the brightness property but uses the attributes of hue and saturation for describing colors as shown in Figure 3.6, where the hue is represented by the angle, saturation by the radius, and value or luminance by the hypotenuse formed by the line that extends on the surface of the cone from zero brightness, the apex of the cone [33].

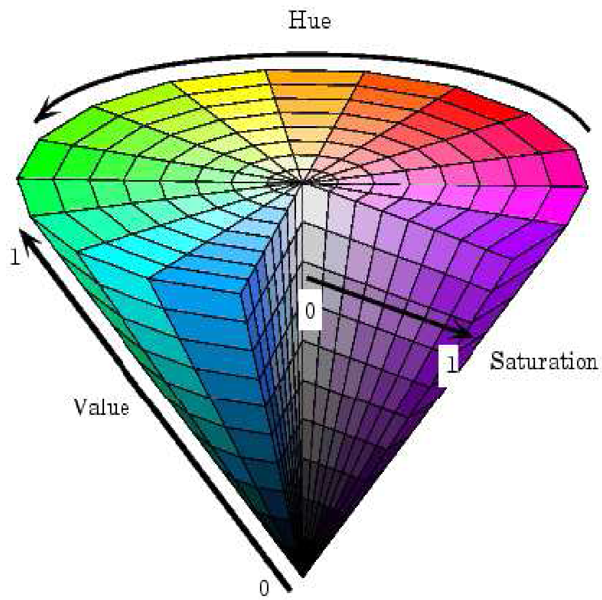

Figure 3.6 A schematic diagram representing the phenomenal color space [32]

HSV (hue, saturation, value) color spaces are also phenomenal color spaces which are obtained by linear transforming the RGB space. Therefore they inherit all the shortcomings of the latter (device dependency, nonlinearity). A consistent model suggested by Travis for HSV transformation from RGB is given below [43]:

Saturation is presented as:

$$S = \frac{\max(R,G,B) - \min(R,G,B)}{\max(R,G,B)} \tag{3.4.3}$$

Value is defined as:

$$V = \max(R,G,B) \tag{3.4.4}$$

Hue is defined as:

H = 5 + B' when R = max(R,G,B), G = min(R, G,B)

H = 1 - G' when R = max(R,G,B), G $\neq$ min(R, G,B)

H = R' + 1 when G = max(R,G,B), B = min(R,G,B)

$$H = 3 - B' \quad \text{when} \quad G = \max(R,G,B),\ B \neq \min(R,G,B)$$

$$H = 3 + G' \quad \text{when} \quad B = \max(R,G,B)$$

$$H = 5 - R' \quad \text{otherwise}$$

where

$$R' = \frac{\max(R,G,B) - R}{\max(R,G,B) - \min(R,G,B)}$$

$$G' = \frac{\max(R,G,B) - G}{\max(R,G,B) - \min(R,G,B)} \qquad (3.4.5)$$

$$B' = \frac{\max(R,G,B) - B}{\max(R,G,B) - \min(R,G,B)}$$

then H is converted to degrees by multiplying by 60.

3.4.2 Application Specific Color Spaces

The major applications where the usage of color spaces is essential are printing, televisions and cameras. CMY (Cyan-Magenta-Yellow) color space is a subtractive color space which is mainly used in printing applications. The three components: cyan, magenta and yellow represent three reflection filters.

Simple transformation from RGB to CMY color space is given by:

$$C = 1 - R$$

$$M = 1 - G$$

$$Y = 1 - B \qquad (3.4.6)$$

Early TV systems transmitted only a luminance component. As the need for color TV's was growing, research was started to encode RGB values in the TV signal and to make it compatible with the old system. They decided to add two chrominance components R-*Y* and *B*- *Y*. This system successfully minimized the bandwidth of the composite signals. Because the HVS is far less sensitive to chrominance data than to luminance, these two components can be transmitted with a smaller bandwidth.

In the European PAL standard the RGB signals are encoded in the YUV space with the following equations:

$$
\begin{aligned}
Y &= 0.299R + 0.587G + 0.114B \\
U &= -0.147R - 0.289G + 0.437B = 0.493\,(B - Y) \\
V &= 0.615R - 0.515G - 0.1B = 0.877\,(R - Y)
\end{aligned}
\qquad (3.4.7)
$$

The YUV space can be transformed in a phenomenal color space, with Y representing the V (value) component, as:

$$
\begin{aligned}
H_{UV} &= \tan^{-1}\left(\frac{V}{U}\right) \\
S_{UV} &= \sqrt{U^2 + V^2}
\end{aligned}
\qquad (3.4.8)
$$

Photo color space was defined by Kodak in 1992 for the storage of digital color images on Photo CDs [33]. The transformation from the RGB components to Photo YCC values is done in the following steps:

1. Gamma correction from RGB values to R0G0B0

2. Linear transformation from R0G0B0 to Y0C0C0

3. Quantization of Y0C0C0 to 8-bit YCC data.

3.4.3 The CIE Color Spaces

The CIE XYZ color space was derived from a series of experiments done by W. David Wright [34] and John Guild [35] in the late 1920s. Their experimental results from which the CIE XYZ color space was derived, were combined into the specification of the CIE RGB color space. The International Commission on Illumination (CIE) laid down the CIE 1931 standard colorimetric observer in 1931. This is the data on the ideal observer on which all colorimetric is based [33]. A very important characteristic of the CIE XYZ color space is the device independency. Every color space that has a transformation from the CIE XYZ color space (RGB_{709}, CIELab, and CIELuv) can also be regarded as being device independent. The CIE XYZ color space is widely used as a reference color space and is as such an intermediate device-independent color space [33]. The CIE color model chromaticity is shown in Figure 3.6. It shows the color gamut for the (x y) coordinates and the wavelengths are denoted by the values surrounding the color gamut.

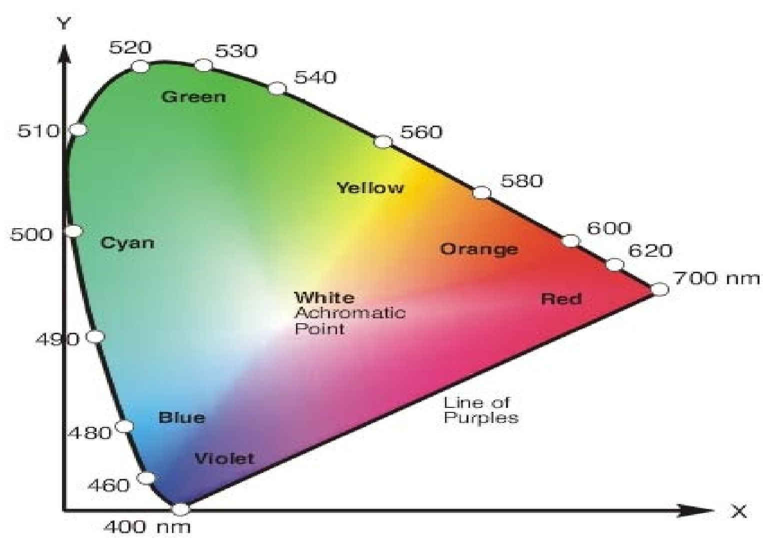

Figure 3.7 The CIE color model mapped to X and Y coordinates [36]

The transformation from CIE XYZ to CIELUV is performed with the following equations

For $\frac{Y}{Y_n} > 0.01$

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16$$

$$u^* = 13L^*\left(u' - u_n'\right) \quad (3.4.14)$$

$$v^* = 13L^*\left(v' - v_n'\right)$$

else

$$L^* = 903.3\left(\frac{Y}{Y_n}\right) \quad (3.4.15)$$

where

$$u' = \frac{4X}{X + 15Y + 3Z}$$

$$u_n' = \frac{4X_n}{X_n + 15Y_n + 3Z_n}$$

$$v' = \frac{9Y}{X + 15Y + 3Z}$$

$$v_n' = \frac{9Y_n}{X_n + 15Y_n + 3Z_n} \quad (3.4.16)$$

The transformation from CIE XYZ to CIELAB is performed with the following equations:

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right] \qquad (3.4.17)$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}}\right]$$

where L^* represents lightness scale and it depends only on Y the luminance value, for both the color spaces CIELUV and CIELAB; the tristimulus values X_n, Y_n, Z_n are those of the nominally white object-color stimulus [33].

CHAPTER 4

THEORETICAL AND PRACTICAL MODELING OF RGBW PIXEL BASED LED DISPLAY

Theoretical and practical approach of a new pixel architecture including a white LED to the standard design is explained in this chapter. Based on a theoretical model and test measurements (using a video display prototype) for the new method (RGBW), the advantages compared with the RGB LED display technology will be demonstrated. The hardware and software used for the testing are explained in detail.

4.1 A New Pixel Architecture with a White LED

The recent improvements in high-power LED technology with 100+ lumens per LED chip and efficacy exceeding that of incandescent lamps brings the solid-state lighting (SSL) close to a reality [38]. Even though, the rapid developments in SSL has witnessed high power LEDs obtaining luminous efficacies of 150 lm/w [37] , efficiency of LED displays could be further improved by introducing a white LED to the pixel. There are several approaches to generate white light with LEDs. One approach is to use phosphor based White LED. Another approach is to use RGB LEDs to give white light. The advantages of RGB-LEDs are that they provide a light source that can have a variable color point, and theoretically can provide the highest efficiency LED-based white light [38]. A major challenge for RGB LEDs is to maintain the desired white point within acceptable tolerances. This constraint depends on luminous efficacy, wavelength of manufactured LEDs and the changes in LED characteristics that occur with temperature and time [39].

By introducing the white LED into the traditional pixel architecture, usage of less efficient green LED will be reduced. Also, usage of red and blue LEDs will be reduced since the intensities are minimized thus increasing the life span of LEDs. Moreover, less complicated feedback control schemes for RGB LEDs will be required in order to maintain achromatic point (AP) since pure white light is used to achieve the white point. This results in achieving more uniform white color point integration with the added benefits of a less complicated control circuitry.

4.2 Theoretical Analysis of the New RGBW Pixel

In this work, the standard pixel architecture RGB is changed to RGBW by including a new pixel white LED. In each frame of a video or a still image, every pixel may have a certain intensity of white. That is, certain hues can be modeled as the addition of a certain amount of white and some intensities of two of the three colors R, G and B. For every pixel that has some amount of white in it or the color which is not fully saturated; the maximum luminance flux of white of the color is supplied using the white LED to retain the saturation level required. As a result, the intensity of one of the three colors will be completely eliminated and the other two will be reduced in intensity as it is shown in the Figure 4.1. It explains the process of conversion from RGB to RGBW through an example. Let the source data be B = 45, G = 90, and R = 75. First, the three data sources RGB are compared with each other to obtain the source with the minimum intensity which in this case is B. Then, the value of the minimum intensity will be subtracted from all the three sources. Then we get B = 0, G=45 and R=30. Finally, the value of minimum intensity (45 in this case) will be supplied to the W. The final data sources RGB and W are shown in the example in figure 4.1.c

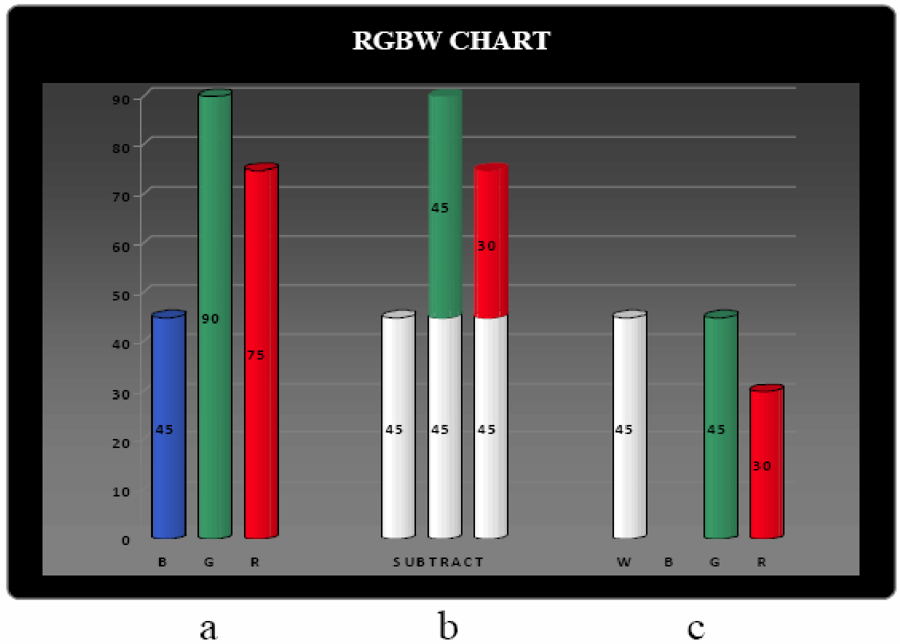

Figure 4.1 RGBW chart. Y axis represents 255 different possible levels of digital color intensities that correspond to an eight bit data bus for each color. (a) Intensity levels for RGB in a pixel (b) Identified intensity of white in the pixel (c) B completely eliminated, white LED introduced and R and G reduced [1]

The combination of wavelengths of light to produce a particular perceived color will be different. The intensity of white in a certain color affects its saturation [28]. A perfect saturated color will not contain the element of white; therefore only monochromatic and dual chromatic colors can be perfectly saturated. Hence, it can be stated that by eliminating the white component, the hue will not change but its saturation level will change, which could be compensated by adding a white light from any other light source such as a white LED. The human eye cannot differentiate between similar hues that are produced by different wavelengths of light. However, it may affect the way colors of objects are perceived by the human eye when these light sources are used for ambient

lighting applications. Since this project is only applicable to display systems, it can be concluded that using the white LED in such systems in order to display colors will not affect the human perception. Figure 4.2 shows the traditional and new pixel architecture LED boards.

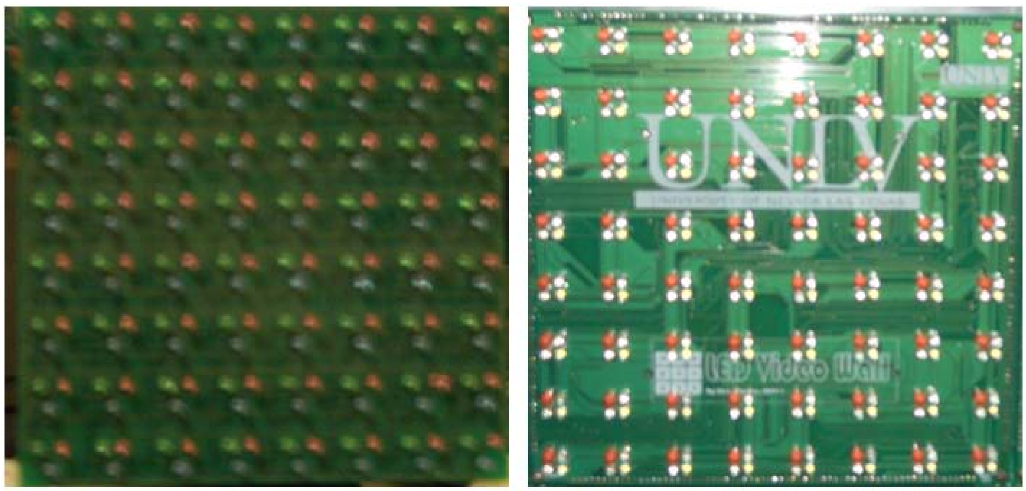

Figure 4.2 LED boards showing traditional and new pixel architecture

4.3 The RGBW LED Display Prototype

4.3.1 Hardware

To drive the LED display panel, Altera ® DE2 development and education board that is shown in the Figure 4.2, is used. The DE2 Kit provides several features that need to develop many advanced digital designs using Altera Cyclone Device. The features of DE2 are given in the following:

DE2 Board Information

FPGA

- Cyclone II EP2C35F672C6 with EPCS16 16-Mbit serial configuration device

I/O Interfaces

- Built-in USB-Blaster for FPGA configuration
- Line In/Out, Microphone In (24-bit Audio CODEC)
- Video Out (VGA 10-bit DAC)
- Video In (NTSC/PAL/Multi-format)
- RS232
- Infrared port
- PS/2 mouse or keyboard port
- 10/100 Ethernet
- USB 2.0 (type A and type B)
- Expansion headers (two 40-pin headers)

Memory

- 8 MB SDRAM, 512 KB SRAM, 4 MB Flash
- SD memory card slot

Displays

- Eight 7-segment displays
- 16 x 2 LCD display

Switches and LEDs

- 18 toggle switches
- 18 red LEDs
- 9 green LEDs
- Four debounced pushbutton switches

Clocks

- 50 MHz clock
- 27 MHz clock
- External SMA clock input

The following is a list of the DE2 components and features that are used in the project as listed in the user manual of the DE2 board [40]:

- Altera Cyclone® II 2C35 FPGA device
- Altera Serial Configuration device - EPCS16
- USB Blaster (on board) for programming and user API control; both JTAG and Active Serial
- 512-Kbyte SRAM

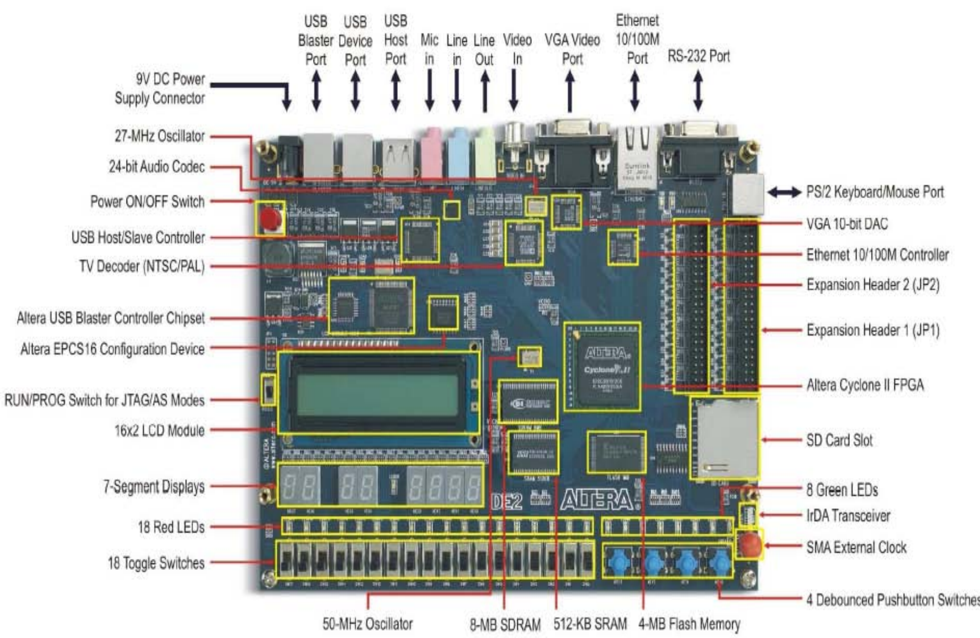

Figure 4.3 Altera ® DE2 development and education board [40]

- 8-Mbyte SDRAM
- Expansion headers (76 signal pins)
- 4-Mbyte Flash memory
- 18 toggle switches
- 18 red user LEDs
- 50-MHz oscillator and 27-MHz oscillator for clock sources
- VGA DAC (10-bit high-speed triple DACs) with VGA-out connector

4.3.2 The LED Driver

The STP16CP05 is a monolithic, low voltage, low current power 16-bit shift register modeled for LED panel displays. The STP16CP05 contains a 16-bit serial-in, parallel-out shift register that feeds a 16-bit, D-type storage register. Figure 4.3 shows the pin-out of the chip used. In the output stage, sixteen regulated current sources provide from 5 mA to 100 mA constant current to drive the LEDs. The output current setup time is 40 ns (typical), enhances the system performance. The LED's brightness can be controlled by using an external resistor to adjust the STP16CP05 output current. The STP16CP05 assures a 20 V output driving capability, allowing the users to connect more LEDs in series. The high clock frequency, 30 MHz, makes the device compatible for high data rate transmission. The 3.3 V voltage supply is useful in many applications that interface with a 3.3 V micro controller.

Key features as listed in the data sheet of the LED driver chip are [41]:

- Low voltage power supply down to 3 V
- 16 constant current output channels
- Adjustable output current through external resistor

- Serial data IN/parallel data OUT
- Can be driven by a 3.3 V microcontroller
- Output current: 5-100 mA
- Max clock frequency 30 MHz
- Electro Static Discharge (ESD) protection 2 kV HBM, 200 V MM

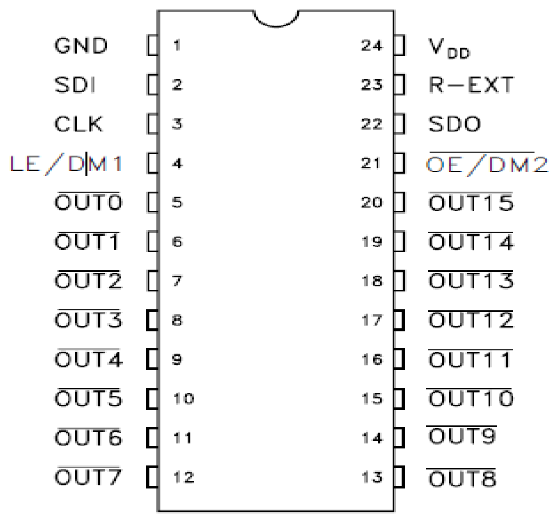

Figure 4.4 A schematic diagram showing Low voltage 16-bit constant current LED sink driver (STP16CP05) [41]

The timing diagram provided in the data-sheet needs to be considered in the software design and is shown in Figure 4.4. Latch and Output Enable are level sensitive and are not synchronized with rising-or falling edge of CLK signal. When LE/DM1 terminal is low, the latch circuit holds the previous set of data. When LE/DM1 terminal is high level, the latch circuits refresh new set of data from SDI chain. When OE/DM2 terminal is low level, the output terminals - Out0 to Out15 respond to data in the latch circuits, either '1'

for ON or '0' for OFF. When OE/DM2 terminal is at high level, all output terminals will be switched OFF.

4.3.3 Quartus II Software

Quartus II is a software tool designed by Altera for analysis and synthesis of hardware description language (HDL) designs, which enables the developer to compile the designs, perform timing analysis, examine RTL diagrams, simulate a design's reaction to different stimuli, and configure the target device with the programmer. Design entries can be done using several methods like altera- HDL (AHDL), electronic design interchange format (EDIF), block diagram/schematic, state machine file, system verilog, TCL script file, Verilog HDL and VHDL. The Quartus II software has unique features in field programmable gate array (FPGA) design flow methodology, system design, timing-closure methodology, in-system verification technology, and third-party electronic design automation (EDA) support [40]. Figure 4.5 shows a high-level example of some of the Quartus II software FPGA design flow options.

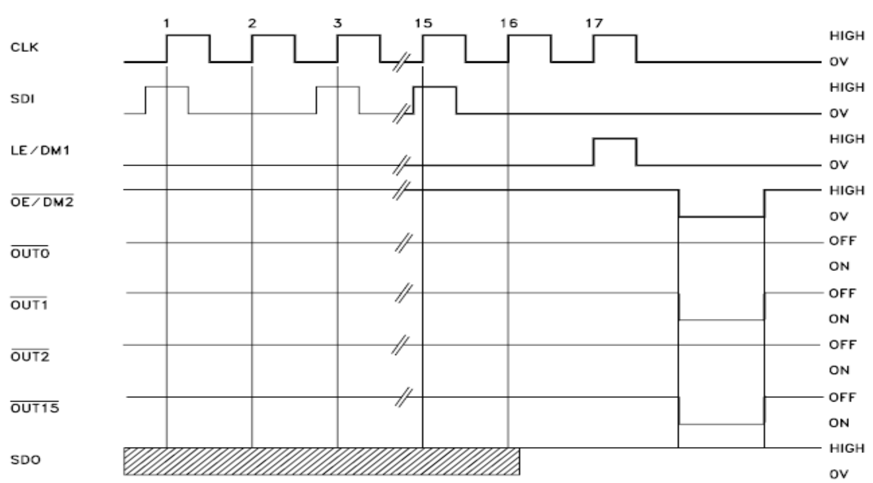

Figure 4.5 A timing diagram showing the pin’s statuses of the LED driver chip [41]

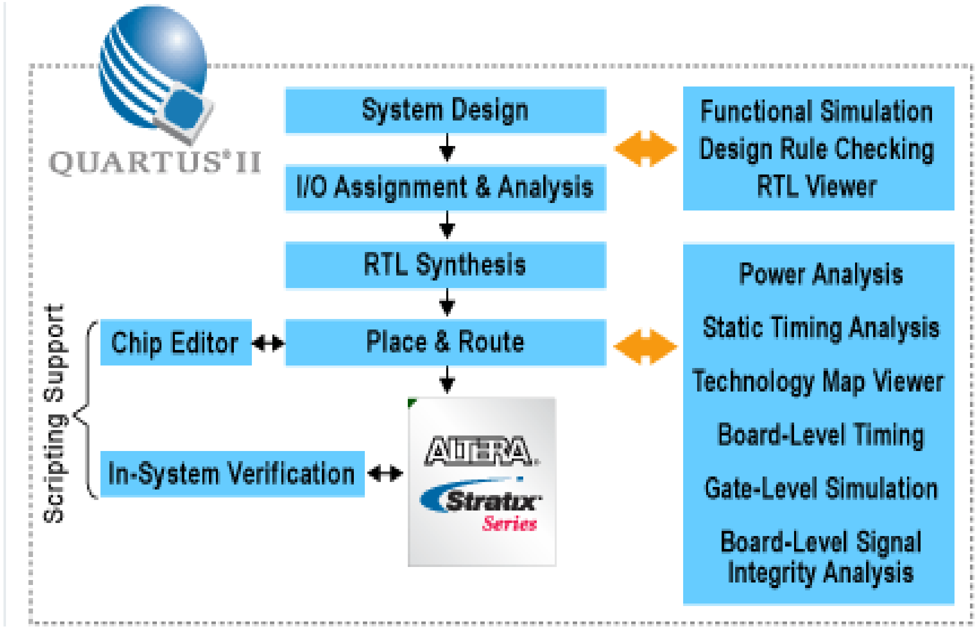

Figure 4.6 FPGA design flow [44]

4.4 Video Processing

The DE2 board provides a variety of resources, including the FPGA Cyclone® II EP2C35672C6 device (consists of 105 M4K RAM blocks), SDRAM (8 Mbytes), flash (4 Mbytes), SRAM (512 Kbytes), a VGA digital-to-analog converter (DAC), TV decoder ADV7181B, infrared data association (IrDA) transceiver, an SD card interface etc. This FPGA based set up box (STB) design is used to implement real-time processing, display, and playback of audio/video as well as e-photo album and music playback functions. The system uses system-on-a-programmable-chip (SOPC) technology with a Nios® II processor embedded in an FPGA. Using the software tools and SOPC concepts, we implemented an FPGA-based STB demonstration system that is capable of performing embedded real-time video processing. The video source is input through the video in port. It passes through the TV decoder chip (ADV7181) on the DE2 board. The analog

video signals input through the video in port are converted to NTSC-format system digital video signals that comply with the ITU-R656 standard. Then, the signals are sent to the FPGA internal video decoding module, which converts the YCbCr (luminance and chroma) color difference signals into RGB signals. Next, the signals go through the video processing module, which performs 16:9 resolution processing, 4:3 resolution processing, or cutting. The system stores the processed video signals in the video buffer module. It reads the data in the buffer module, conducts analog-to-digital (ADC) conversion with the XSGA 10-bit DAC chip (ADV7123), and outputs the signals through the VGA interface [44]. Figure 4.6 shows the block diagram of the design.

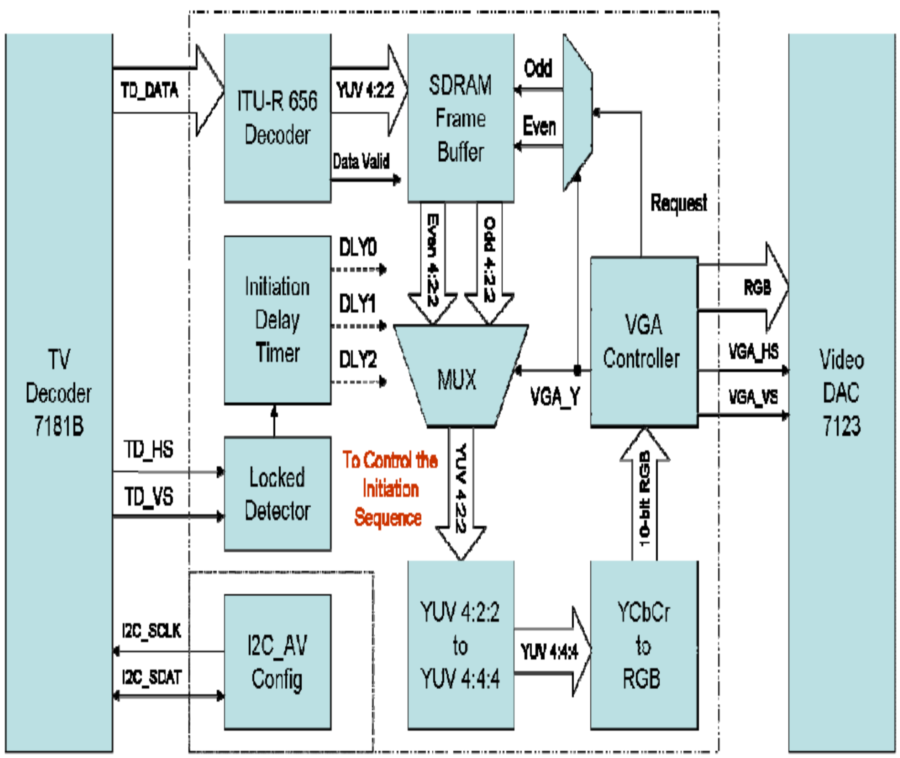

Figure 4.7 Video Processing Algorithm [40]

There are 2 main blocks in the design circuit: TV_to_VGA and I2C_AV_Config. The TV_to_VGA block consists of decoder, SDRAM frame buffer, YUV422 to YUV444 converter, YCrCb to RGB, and video graphics array (VGA) controller. When the bit stream is programmed into the FPGA, the register values of the TV decoder chip are used to set the TV decoder via the I2C_AV_Config block. It uses the I2C protocol to communicate with ADV7181B decoder. The ITU-R 656 decoder block extracts YCrCb 4:2:2 video signals from the ITU-R 656 data coming from the TV decoder ADV7181B. It also generates a data valid control signals. As the video signal from the TV decoder is interlaced, it is required to perform de-interlacing on the input data. Interlacing is a method to improving the picture quality of a video signal without consuming extra bandwidth. SDRAM frame buffer and a multiplexer (MUX) to select the field which is controlled by the VGA controller are used to perform the de-interlacing. The YUV422 to YUV444 block converts the YCrCb 4:2:2 video data to the YCrCb 4:4:4 (YUV 4:4:4) video data format. Finally, the YCrCb_to_RGB block converts the YCrCb data into RGB to send the data to VGA. The VGA Controller block generates standard VGA horizontal (VGA_HS) and vertical sync signals (VGA_VS) in order to display on a VGA monitor. A timing diagram of horizontal and vertical synchronization signals for a 25MHz clock is shown in the Figure 4.8.

The monitor screen for a standard VGA format contains 640 columns by 480 rows of picture elements called pixels as shown in Figure 4.8. An image is displayed on the screen by switching on or off individual pixels. The monitor continuously scans through the entire screen turning on or off one pixel at a time at a very fast speed. The process of scanning starts from row 0, column 0 at the top left corner, and moves to the right until it

reaches the last column in the row. When the scan reaches the end of a row, it continues at the beginning of the next row. When the scan reaches the last pixel at the bottom right corner of the screen, it goes back to the top left corner of the screen, and repeats the scanning process again. To minimize flickering on the screen, the entire screen must be scanned 60 times per second or higher. During the horizontal and the vertical retraces, all the pixels are turned off.

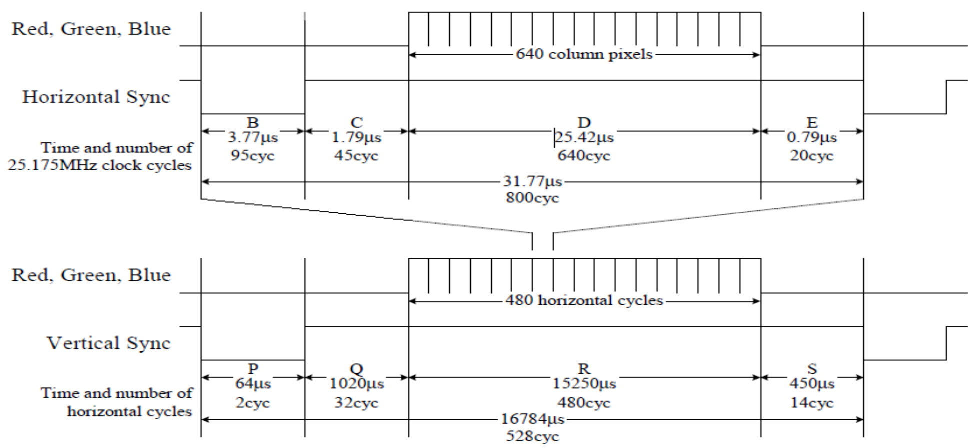

Figure 4.8 Horizontal and vertical synchronization signals timing diagram [45]

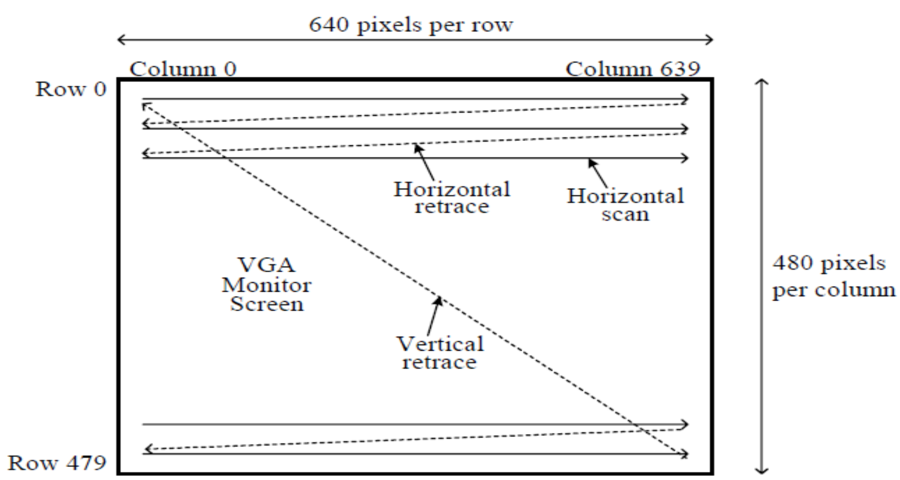

Figure 4.9 The monitor screen for a standard VGA format [45]

The VGA monitor is regulated by five signals: horizontal synchronization (sync), vertical sync, red, green and blue. The three color signals, together known as the RGB signal, are used to maintain the color of a pixel at any location on the screen. These three RGB color signals are connected such that they can individually turned on or off and hence each pixel can display eight (2^3) colors. The horizontal and vertical sync signals are used to control the timing of the scan rate. The horizontal sync signal determines the time to scan a row, while the vertical sync signal determines the time to scan the entire screen. By controlling these five signals, images are formed on the monitor screen.

The logical implementation of the design is shown in the following schematics Figures 4.10 (a thru f). The complete schematic file is split into different parts due to its large size. Figure 4.10.a shows the implementations of I2C where the register values of the TV decoder chip ADV7181B are used to set the TV decoder.

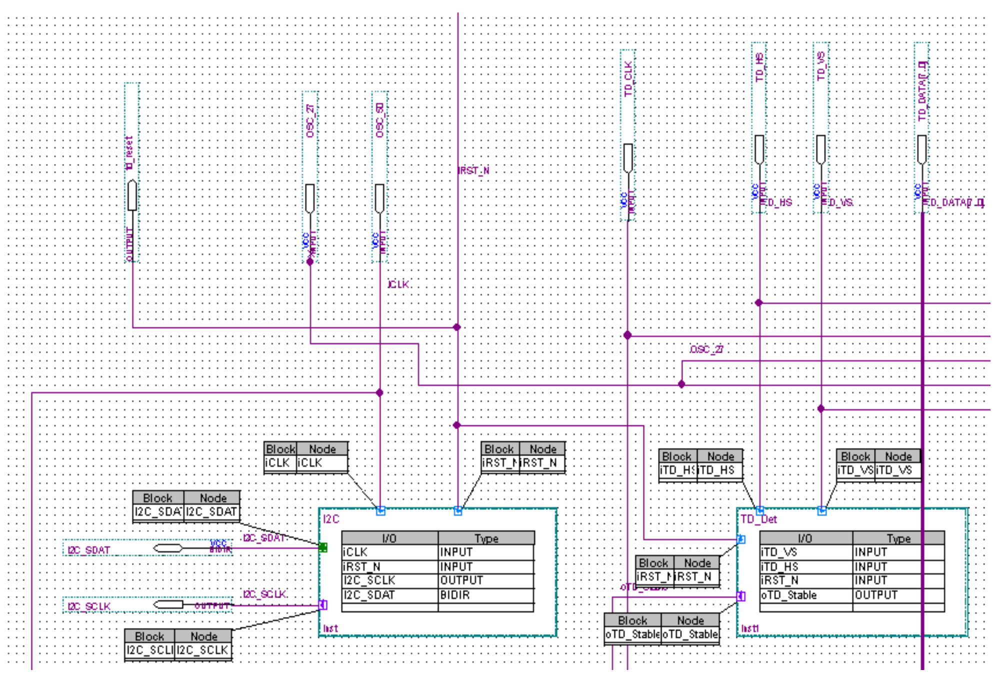

Figure 4.10.a A schematic diagram showing the implementation of the I2C

The decoder block extracts YCrCb 4:2:2 video signals from the input data coming from the TV decoder ADV7181B. It also generates a data valid control signals. SDRAM frame buffer and a multiplexer (MUX) to select the field which is controlled by the VGA controller are used to perform the de-interlacing. The yuv422to444 block converts the YCrCb 4:2:2 video data to the YCrCb 4:4:4 video data format. Finally, the RGB block converts the YCrCb data into RGB to send the data to VGA. The generator block generates standard VGA horizontal (OVGA_HS) and vertical sync signals (OVGA_VS) in order to display on a VGA monitor. The design process is shown in the following Figures 4.10.b to 4.10.f.

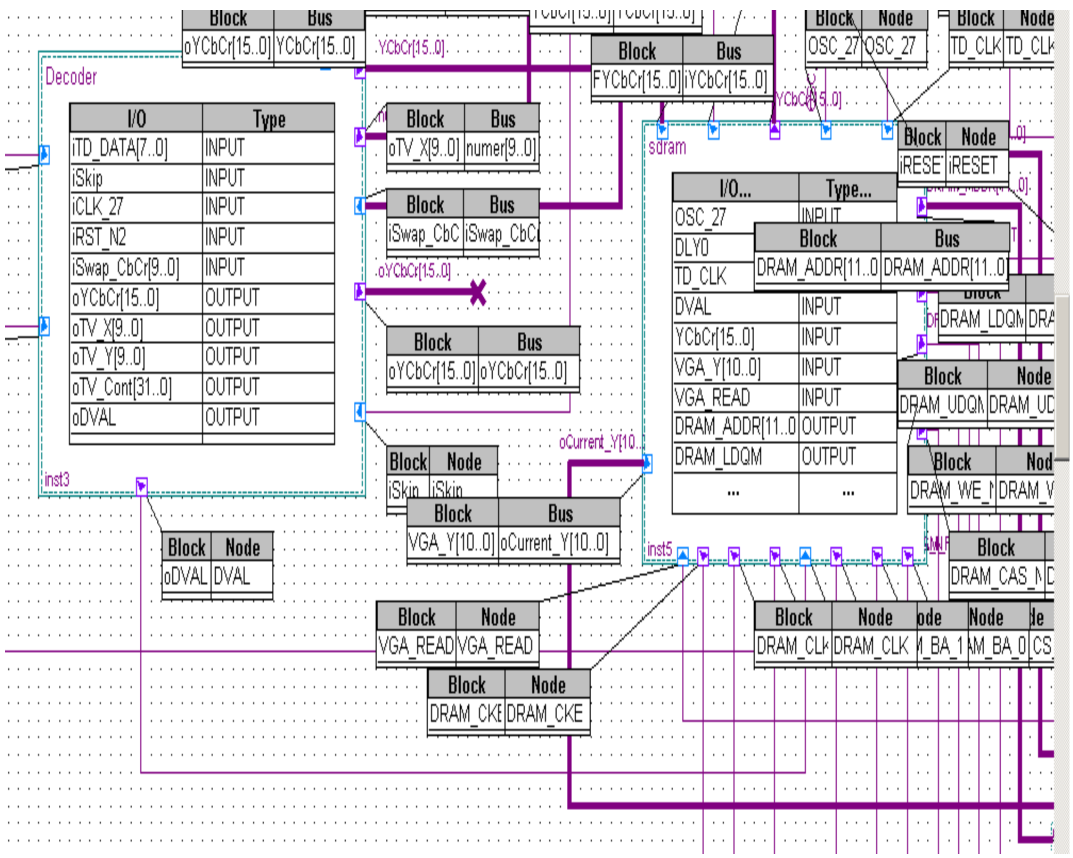

Figure 4.10.b A schematic diagram showing the decoder and SDRAM frame buffer blocks.

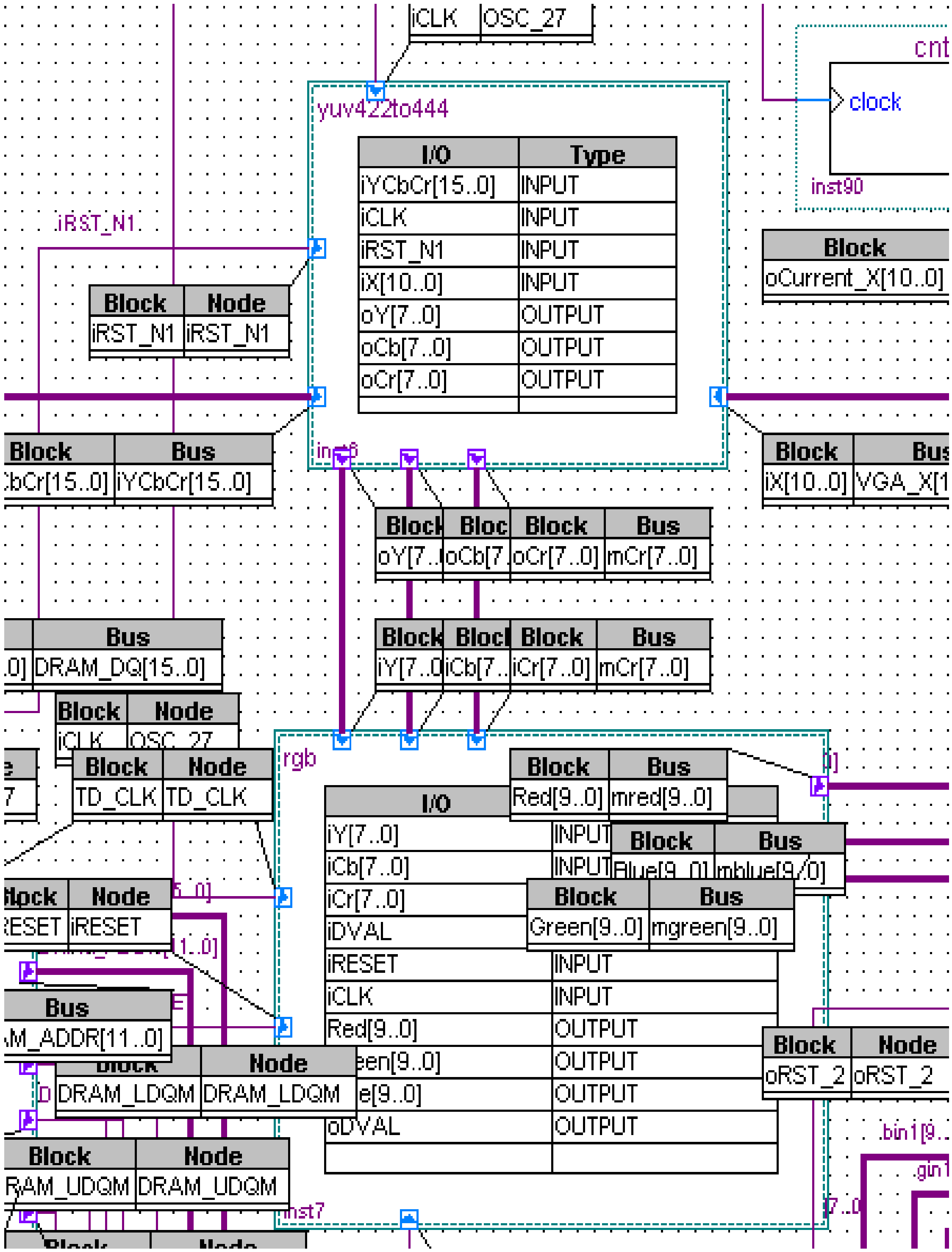

Figure 4.10.c A schematic diagram showing the yuv422 to yuv444 converter and RGB converter.

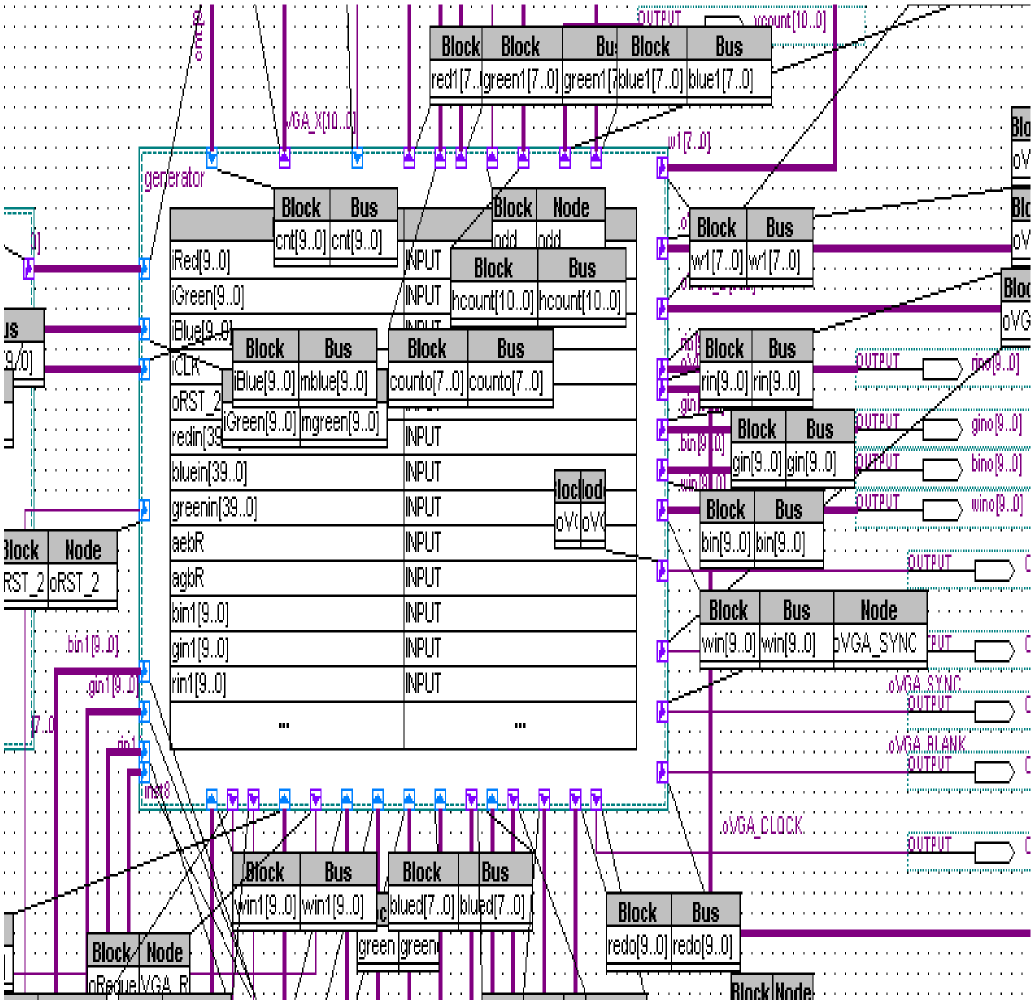

Figure 4.10.d A Schematic diagram showing the generator which generates the synchronization signals.

After receiving the RGB data from the RGB convertor, it is sent as input to the RGB to RGBW convertor where the data is compared with each other to determine the color that has the minimum value as shown in Figure 4.9.e. The logic levels of the comparator's outputs are used along with a lookup table to set the multiplexer to the value that needs to be subtracted from RGB and fed to the white LED.

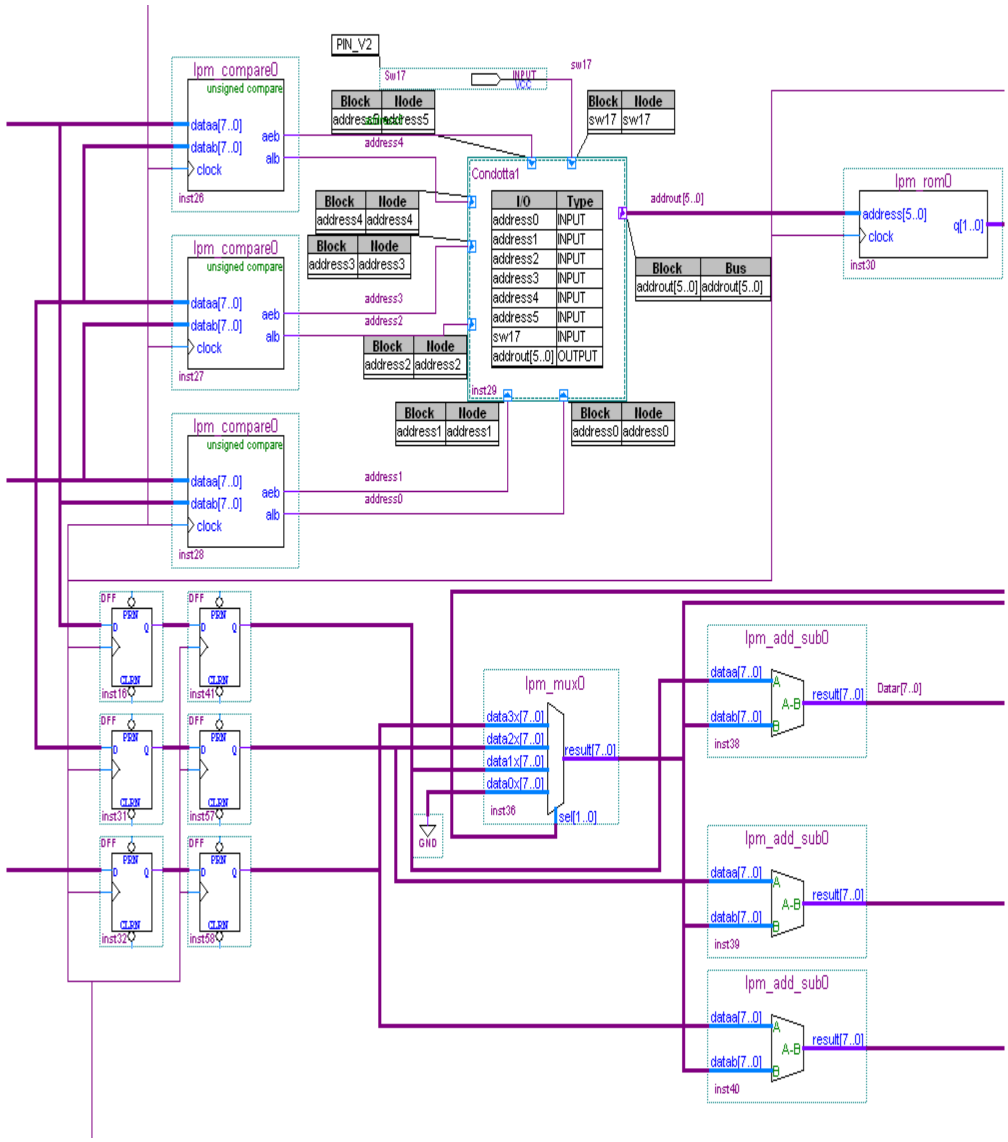

Figure 4.10.e A schematic diagram showing the implementation of the RGB to RGBW converter.

After the conversion of RGB to RGBW, the RGBW data is inputted to the memory to crop the data to 32inch x 16inch video display. The 8 bit RGBW data lines are pulse width modulated which provides the ability to display 256 different intensities.

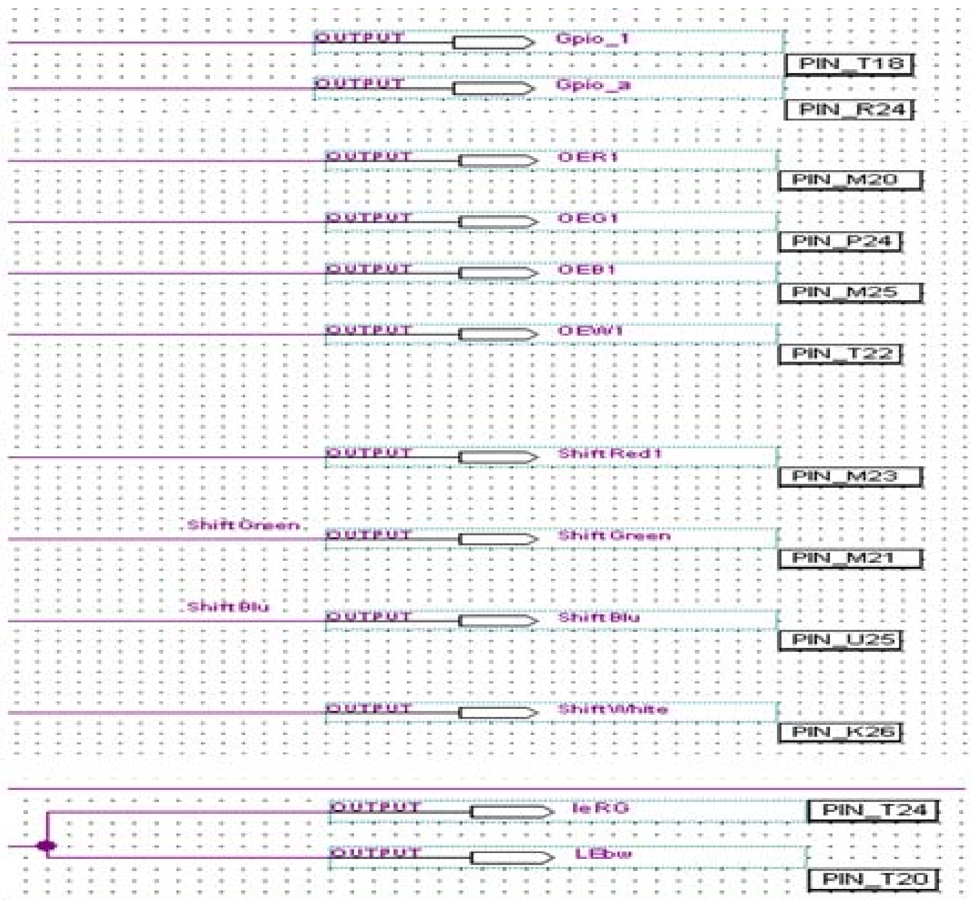

Figure 4.10.f A schematic diagram showing the pins for clock, data signals, LE and OE.

After outputting each bit, latch enable (LE) has to be pulsed once and then output enable (OE) has to be pulsed. The duration of the OE pulse width determines the intensity of the LED for each level from lowest 0^{th} bit to highest 7^{th} bit. Figure 4.9.f shows the pin configuration for clock, data, Latch enable and Output enable. These signals are fed to the display board to display the desired video.

CHAPTER 5

EXPERIMENTS, RESULTS AND DISCUSSION

Results and discussions are presented in this chapter. Experiment details based on human perception of colors from two different technologies (RGB and RGBW) and energy calculations based on measured currents are presented and discussed.

5.1 Human Perception Experiments

5.1.1 Experimental Procedure

To conduct human perception experiments, it is required to have a special approval (refer to Appendix II) since human subjects were involved. To test on how people perceive the difference between the traditional (RGB) and the new (RGBW) LED display architectures, it was necessary to conduct an experimental survey which involves sample of people. To obtain the approval, the Institutional Review Board (IRB) reviews the research project which involves human subjects to ensure subjects are not subjected to unjustified risks and that test subjects are given informed consent at the time of participation. In addition, researchers must undergo IRB training through the collaborative institutional training initiative (CITI). Researchers focused on Biomedical Science (Biomed) must complete the CITI Biomedical Research Course Modules which gives the guidance to researchers in order to minimize risks.

Recruiting of subjects was done at UNLV, an educational institution and they were selected at random; therefore, majority of subjects were students between the ages of 18 and 30. Majority of them were willing to take the survey directly after a brief explanation about the experiment. They were instructed that they would have to compare colors displayed on LED display panel and to make a note of perceptual differences they notice.

Upon their arrival to the display setup where the experiment was conducted, more detailed instructions were given to them along with a handout that contains detailed instructions (refer to Appendix III for the informed consent), the approval and the survey questions (refer to Appendix IV).

Seven different colors with 76 subjects were tested. Every subject was shown a pair of colors and asked to determine whether the color and intensity are:

- Identical
- almost the same
- slightly different
- completely different

Subjects were divided into four different groups. For the first experimental group, each color was displayed twice with RGB. This set is one of the control groups. This group consists of 14 subjects. For the second group, each color was displayed twice once with RGB and once with RGBW. This set is one of the experimental groups which consist of 24 subjects. Figure 5.1 shows the colors shown to the human subjects using two different technologies. For the third group, each color was displayed twice first with RGBW and then with RGB. This is second experimental group which consist of 23 subjects. For the final group, each color was displayed twice with RGBW and it is the second control group which also had 15 subjects. The purpose behind the control groups 1 and 4 was to assess the reliability and consistency of the results obtained in groups 2 and 3.

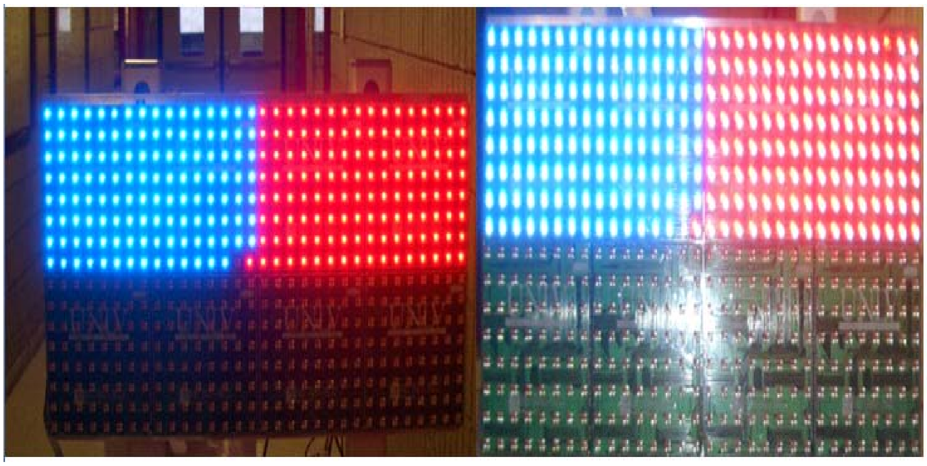

Figure 5.1 Colors shown using two different technologies

5.1.2 Results and Discussion

Data of human perception for all the seven colors are shown in the following Table 5.1 and Table 5.2.

Table 5.1 Human Perception data for the colors (i) Pale blue (ii) Magenta (iii) Cyan (iv) Yellow (v) Purple (vi) Light green and (vii) White where (4) Identical, (3) almost the same, (2) slightly different, (1) completely different.

Pale blue	**4**	**3**	**2**	**1**	**Total**
RGB - RGB	12	2			14
RGB - RGBW	18	5		1	24
RGBW -RGB	21	2			23
RGBW -RGBW	12	1	1	1	15

(i)

Magenta	**4**	**3**	**2**	**1**	**Total**
RGB - RGB	12	2			14
RGB - RGBW	18	5		1	24
RGBW -RGB	21	2			23
RGBW -RGBW	12	1	1	1	15

(ii)

Cyan	4	3	2	1	Total
RGB - RGB	9	5			14
RGB - RGBW	16	6	1	1	24
RGBW -RGB	21	2			23
RGBW -RGBW	12	2	1		15

(iii)

Yellow	4	3	2	1	Total
RGB - RGB	9	5			14
RGB - RGBW	16	6	1	1	24
RGBW -RGB	21	2			23
RGBW -RGBW	12	2	1		15

(iv)

Purple	4	3	2	1	Total
RGB - RGB	10	1	3		14
RGB - RGBW	18	2	3	1	24
RGBW -RGB	21	1		1	23
RGBW -RGBW	10	4		1	15

(v)

Light green	4	3	2	1	Total
RGB - RGB	10	1	3		14
RGB - RGBW	18	2	3	1	24
RGBW -RGB	21	1		1	23
RGBW -RGBW	10	4		1	15

(vi)

White	4	3	2	1	Total
RGB - RGB	12	1		1	14
RGB - RGBW	15	7	1	1	24
RGBW -RGB	16	6	1		23
RGBW -RGBW	15				15

(vii)

Table 5.2 Human Perception data for the colors based on intensity (i) Pale blue (ii) Magenta (iii) Cyan (iv) Yellow (v) Purple (vi) Light green and (vii) White where (4) Identical, (3) almost the same, (2) slightly different, (1) completely different.

Pale blue	**4**	**3**	**2**	**1**	**Total**
RGB - RGB	11	2		1	14
RGB - RGBW	18	3	2	1	24
RGBW -RGB	18	3	2		23
RGBW -RGBW	8	4		3	15

(i)

Magenta	**4**	**3**	**2**	**1**	**Total**
RGB - RGB	11	2		1	14
RGB - RGBW	18	3	2	1	24
RGBW -RGB	18	3	2		23
RGBW -RGBW	8	4		3	15

(ii)

Cyan	**4**	**3**	**2**	**1**	**Total**
RGB - RGB	9	4		1	14
RGB - RGBW	20	2		2	24
RGBW -RGB	21	1	1		23
RGBW -RGBW	6	6	1	2	15

(iii)

Yellow	**4**	**3**	**2**	**1**	**Total**
RGB - RGB	9	4		1	14
RGB - RGBW	20	2		2	24
RGBW -RGB	21	1	1		23
RGBW -RGBW	6	6	1	2	15

(iv)

Purple	**4**	**3**	**2**	**1**	**Total**
RGB - RGB	11	1	1	1	14
RGB - RGBW	13	8	3		24
RGBW -RGB	17	3	2	1	23
RGBW -RGBW	10	2	1	2	15

(v)

Light green	4	3	2	1	Total
RGB - RGB	11	1	1	1	14
RGB - RGBW	13	8	3		24
RGBW -RGB	17	3	2	1	23
RGBW -RGBW	10	2	1	2	15

(vi)

White	4	3	2	1	Total
RGB - RGB	9	4		1	14
RGB - RGBW	14	8	2		24
RGBW -RGB	11	8	3	1	23
RGBW -RGBW	9	4		2	15

(vii)

Most subjects found all the colors to be identical or almost the same in terms of the color and the intensity. In the experiment involving with white, it appears that most subjects perceived minor difference in color and intensity as it is expected because of the architecture as it does not allow a separate calibration control for the white LEDs.

5.1.3 Statistical Analysis

5.1.3.1 Theory of Statistical Analysis

The binomial probability model is applicable for the data collected from experiments 1, 2, 3 and 4, as shown in the following. Binomial probability in general deals with the probability of several successive decisions, each of which has two possible outcomes. Let X denote the number of subjects out of N_i for Experiment i *(i* = 1, 2, 3) who determined that the colors shown were “Identical or Almost the Same”. The probability distribution of X then can be modeled by the following binomial probability distribution:

$$P(X = x) = \binom{N}{x} p_i^x (1 - p_i)^{N-x}, x = 1,2,\ldots,N \quad (5.1)$$

where p_i is the proportion of subjects in the total population who concluded that the colors produced with the two technologies are "identical or almost the same". The population proportion pi is estimated by the sample proportion

$$\hat{p}_i = \frac{x_i}{N_i} \tag{5.2}$$

where x_i is the number of subjects who determined the colors in two trials were identical, for experiment i (i = 1, 2, 3). Confidence intervals for p_i can be computed using approximated formula for 95% confidence as shown in the following:

$$p_i(95\%Confidence - Intervals) = \hat{p}_i \pm 1.96 \times \sqrt{\frac{\hat{p}_i(1 - \hat{p}_i)}{N_i}} \tag{5.3}$$

Accurate confidence intervals can be calculated using the MINITAB software package. The later approach is used in this work. The 95% confidence interval for p_i *has* the property that the repeated use of the formula for computing the 95% confidence interval, over similar experiments, will include the true unknown p_i 95% of the time.

5.1.3.2 Data Analysis

Using the data obtained from the Table 5.1 and equation 5.3 the estimate, p_i and the upper and lower 95% confidence intervals were determined using the software MINITAB and are presented in Table 5.3 for all the seven colors. The data for "Identical" and "almost the same" were combined together to calculate the estimate p_i. Thus, values of $\hat{p}_i$ indicate that the pair of colors appear the same. The 95% confidence interval (U95, L95) indicates the distribution or the variability of the data.

Table 5.3 $\hat{p}$, L95, and U95 values after the statistical analysis of the data for pale blue and magenta.

	Pale blue- Magenta based on color				Pale blue - Magenta based on intensity			
	RGB - RGB	RGB- RGBW	RGBW- RGB	RGBW- RGBW	RGB- RGB	RGB- RGBW	RGBW- RGB	RGBW- RGBW
L95	0.8074	0.7888	0.8779	0.5954	0.6613	0.6764	0.7196	0.4490
$\hat{p}$	1	0.9583	1	0.8667	0.9286	0.8750	0.9130	0.7333
U95	1	0.9989	1	0.9834	0.9982	0.9734	0.9893	0.9221

As shown in Table 5.3 and Figure 5.2, 97% (+3% /-14%) of test subjects for pale blue and magenta, found the colors shown through RGB and RGBW to be “almost the same or identical”. 89% (+8% /-9%) of subjects found that there is no difference in the intensity.

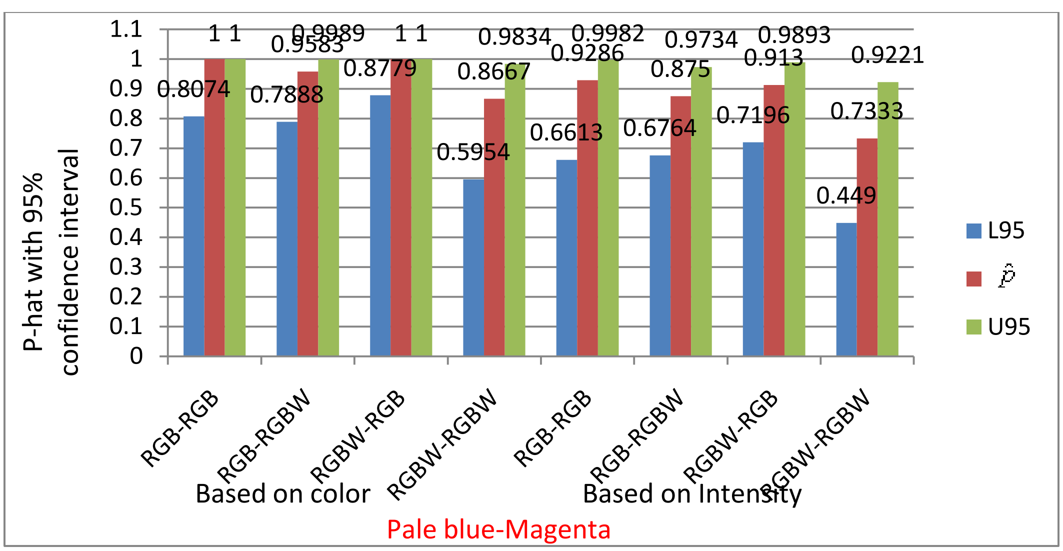

Figure 5.2 Estimate, $\hat{p}$, with 95% confidence interval for pale blue and magenta.

Table 5.4 $\hat{p}$, L95, and U95 values after the statistical analysis of the data for cyan and yellow.

	Cyan -Yellow based on color				Cyan –Yellow based on intensity			
	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW
L95	0.8074	0.7300	0.8779	0.6805	0.6613	0.6764	0.7805	0.4490
$\hat{p}$	1	0.9167	1	0.9333	0.9286	0.8750	0.9565	0.7333
U95	1	0.9897	1	0.9983	0.9982	0.9734	0.9989	0.9221

As shown in Table 5.4 and Figure 5.3, 95% (+4% /-10%) of test subjects for cyan and yellow, found the colors shown through RGB and RGBW to be “almost the same or identical”. 91% (+7% /-17%) of subjects found that there is no difference in the intensity.

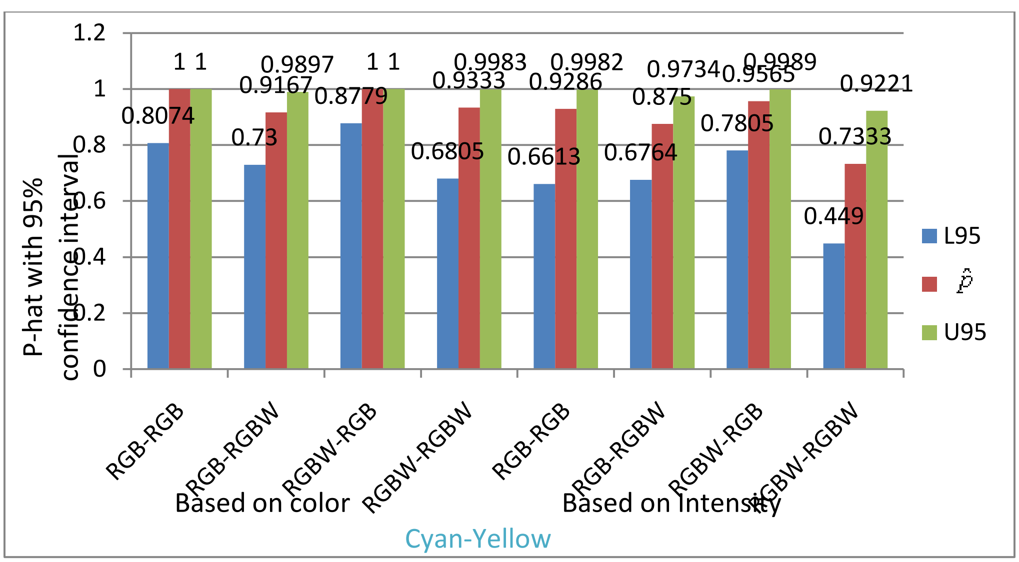

Figure 5.3 Estimate, $\hat{p}$, with 95% confidence interval for Cyan and Yellow.

Table 5.5 $\hat{p}$, L95, and U95 values after the statistical analysis of the data for purple and green.

	Purple-Green based on color				Purple-Green based on intensity			
	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW
L95	0.5435	0.6262	0.7805	0.6805	0.4920	0.6764	0.6641	0.5191
$\hat{p}$	0.8125	0.8333	0.9565	0.9333	0.7857	0.8750	0.8696	0.8
U95	0.9595	0.9526	0.9989	0.9983	0.9534	0.9734	0.9722	0.9567

As shown in Table 5.5 and Figure 5.4, 91% (+7% /-18%) of test subjects for purple and green, found the colors shown through RGB and RGBW to be identical. 86% (+10% /-18%) of subjects found that there is no difference in the intensity.

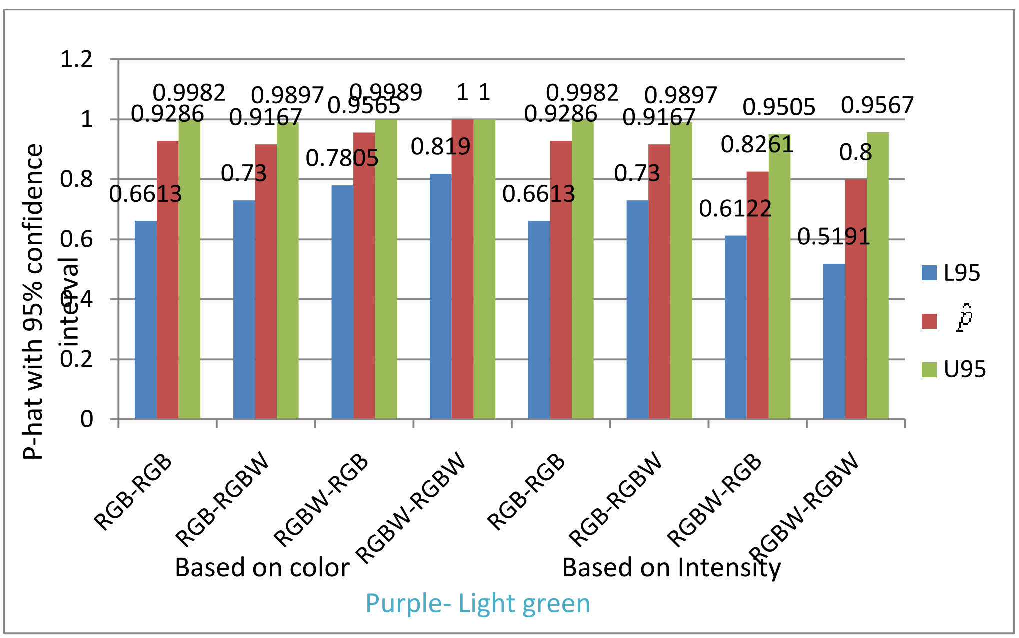

Figure 5.4 Estimate, $\hat{p}$, with 95% confidence interval for Purple and Green.

Table 5.6 $\hat{p}$, L95, and U95 values after the statistical analysis of the data for white.

	White based on color				White based on intensity			
	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW
L95	0.6613	0.7300	0.7805	0.8190	0.6613	0.7300	0.6122	0.5191
$\hat{p}$	0.9286	0.9167	0.9565	1	0.9286	0.9167	0.8261	0.8
U95	0.9982	0.9897	0.9989	1	0.9982	0.9897	0.9505	0.9567

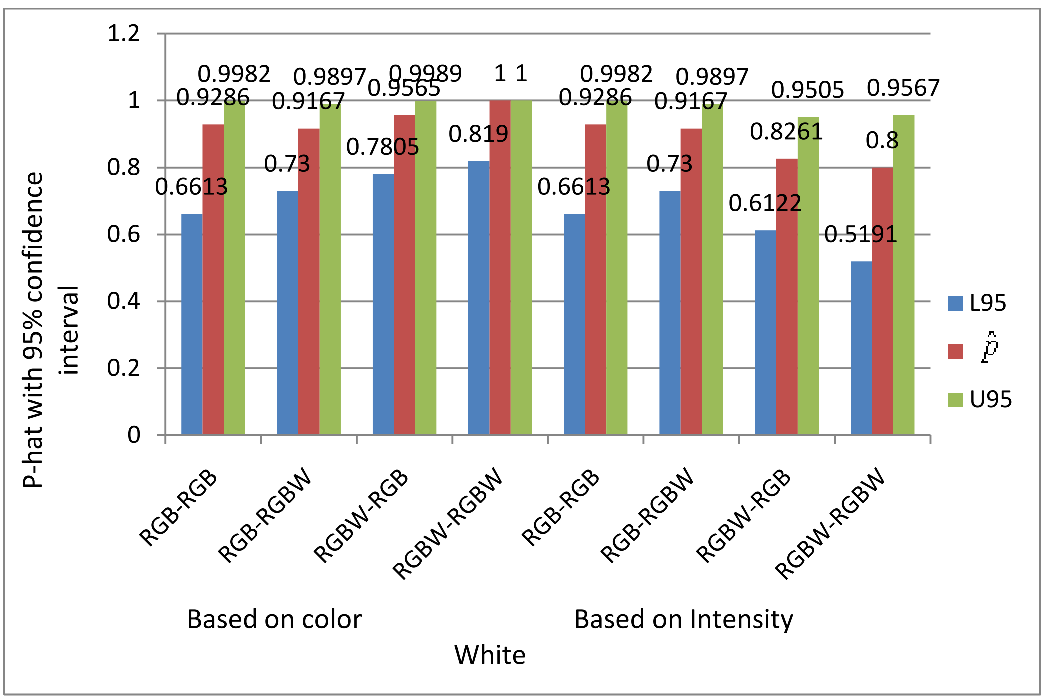

Figure 5.5 Estimate, $\hat{p}$, with 95% confidence interval for white.

It appears that white color created by RGB, as shown in Table5.6 and Figure 5.5, is perceived the same as that by RGBW to 93% (+5% /-16%) of the subjects. Only 86% (+10% /-19%) of the subjects found that the intensities are identical. The white LEDs in

the prototype that was used for this design did not have independent intensity control. Therefore maintaining the intensity to be identical between the two whites was a challenge.

5.2 Energy Measurements and Calculations

5.2.1 Experimental Procedure

As the consumption of power is directly proportional to the current supplied due to constant voltage, current flowing through the display board for seven different colors are measured separately. The colors are divided into four patterns with the combination of 2 colors in 3 patterns and white in the last pattern. For every pair, the current flowing to the 32inch x 16inch pixel display is measured for RGB and for RGBW and then calculated the power savings.

5.2.2 Results and Discussion

The power consumption by the 32inch x 16inch pixel LED display are measured for the seven colors using RGB and RGBW in terms of current supplied and listed in Table 5.2. It is noted that the current values are in the range of 1A - 12A.

Table 5.7 Measured currents for RGB, RGBW

	I (RGB) [A]	I (RGBW) [A]
Pale blue	5.4	4.4
Magenta	5.18	4.3
Cyan	9.8	8.93
Yellow	10.02	9.25
Purple	6.62	6.54
Light green	10.0	9.2
White	12	8.6

The power consumed (P) by the 32inch x 16inch pixel LED display is given by:

$$P = V \times I \tag{5.4}$$

where 'V' is the voltage supplied to the board, and 'I' is the current flowing through the device. For this display, the voltage required was 5V.

5.3.3 Data Analysis

The amount of power savings as a result of using RGBW alternative to RGB, P_s, is given by:

$$\%\,P_s = (P_{RGB} - P_{RGBW}) / P_{RGB} \times 100 \tag{5.5}$$

Table 5.8 Power consumed by pixels for RGB, RGBW and % power savings of RGBW over RGB

	P (RGB) [W]	P(RGBW) [W]	P savings %
Pale-Blue	27	22	18.5
Magenta	25.9	21.5	17
Cyan	49	44.6	9
Yellow	50	46.25	8
Purple	33.1	32.68	2
Light green	50	46	8
White	60	43	29

Using the data presented in table 5.5 and the equations 5.4 and 5.5, P_{RGB}, P_{RGBW}, and $\%P_s$ were calculated and reported in Table 5.6 for all the seven colors. % power saving for various colors is plotted in Figure 5.2.

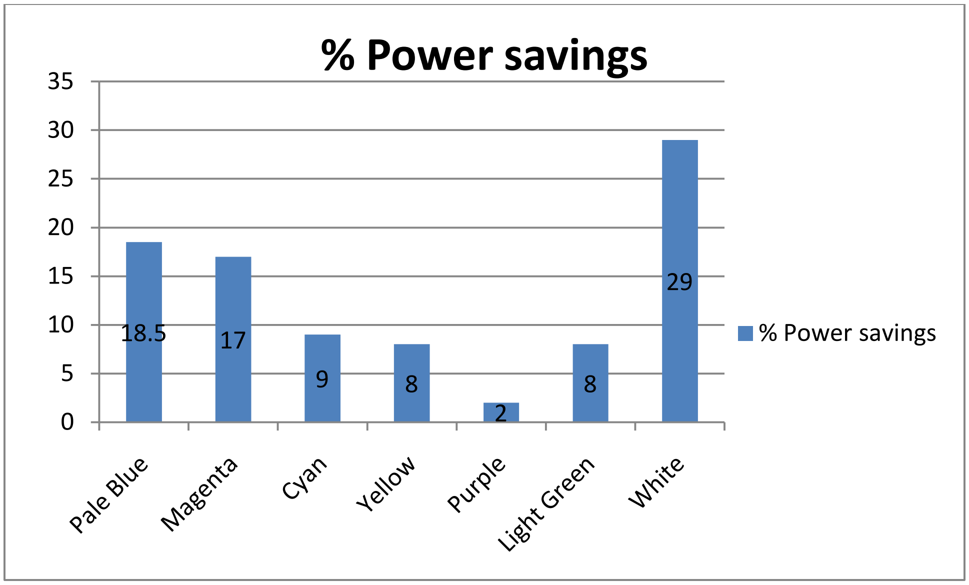

Figure 5.6 The % power savings for seven colors.

The data presented in Figure 5.6 shows the power savings for all the colors (pale blue, magenta, cyan, yellow, purple, green and white). Power savings for the colors, such as magenta, pale blue and cyan is much higher than power savings for yellow, light green and cyan since the white content is less in high saturated colors. Power savings for the white is higher than any other color. As demonstrated, using the new RGBW pixel architecture saves power in most cases predominantly in case of the color which has more white content.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

In this research work, an innovative pixel architecture RGBW, consisting of red (R), green (G), blue (B), and white (W) LEDs, is designed and implemented for color generation. Energy consumption of new pixel architecture consisting of RGBW LEDs is compared to standard architecture consisting of RGB LEDs. Human perception experiments were conducted to study the differences in perception between the two architectures where same colors are generated using RGB and RGBW. Measurements of power for a 32inch x 16inch LED display has proved up to 18% power savings for low saturated colors, up to 8% for high saturated colors and up to 30% for white color using RGBW as a substitute. Most colors have witnessed over 20% power savings. In addition, experiments on human perception have shown that majority of test subjects could not differentiate between most colors displayed using RGB and RGBW in terms of color and intensity showing that RGBW is an excellent substitute for RGB.

Future research may include:

- Using high efficient white LED in the pixel along with the RGB.
- To display the real video efficiently using RGBW.
- To achieve precise color balance in order to display millions of colors accurately.
- Using the video scaler in the video processing to downscale or upscale to match any resolution of the display panel.

APPENDIX I

VERILOG CODE OF THE SOFTWARE IMPLIMENTATION

GENERATOR.V

```
module generator(
iRed,
iGreen,
iBlue,
oCurrent_X,
oCurrent_Y,
oAddress,
oRequest,
aclr7,
redd,
greend,
blued,
w7,
rest,
counto,cnt,
hclk,hblk1,vblk,odd,vvs,   //counter for memory

rmem,gmem,bmem,red1,green1,blue1,w1,

//	VGA Side
oVGA_R,
oVGA_G,
oVGA_B,
oVGA_HS,
oVGA_VS,
oVGA_SYNC,
oVGA_BLANK,
oVGA_CLOCK,
hcount,vcount,
rin1,gin1,bin1,win1,
rin,gin,bin,win,
redin ,
greenin,
bluein,
agbR,
aebR,
//GPIO_1,
redo,greeno,blueo,

//	Control Signal
```

```
iCLK,
oRST_2          );
//      Host Side
input           [9:0]   cnt;
input           [9:0]   iRed,bin1,rin1,gin1,win1,rmem,gmem,bmem;
output          [9:0]   rin,gin,bin,win;
input           [9:0]   iGreen;
input           [9:0]   iBlue;
input           [39:0]  redin,greenin,bluein;
output          [21:0]  oAddress;
output          [10:0]  oCurrent_X,hcount,vcount;
output          [10:0]  oCurrent_Y;
output                          oRequest;
//      VGA Side
output reg      [9:0]   redo,greeno,blueo ;
output          [9:0]   oVGA_R;
output          [9:0]   oVGA_G;
output          [9:0]   oVGA_B;
output          [7:0]   counto;
//output    [10:0] hcont,vcont;
output  reg                     hclk;
output  reg                     oVGA_HS;
output  reg                     oVGA_VS;
output  reg             aclr7;
output  reg                     odd ;
output                          oVGA_SYNC;
output                          oVGA_BLANK;
output rest;

output   reg                    hblk1,vblk ;
output                          oVGA_CLOCK;
input           [7:0]           redd,greend,blued,w7;
output     [7:0]        red1,green1,blue1,w1;
//output                [35:0]  GPIO_1;
//      Control Signal
input                           iCLK,vvs,aebR,agbR;
input                           oRST_2;
//      Internal Registers
        reg     [10:0]  H_Cont;
        reg     [10:0]  V_Cont;
////////////////////////////////////////////////////////////
//      Horizontal      Parameter
assign rest = oRST_2 ;
assign counto = V_Cont[10:3] ;
parameter       H_FRONT     =       16;
parameter       H_SYNC      =       96;
```

```
parameter	H_BACK	=	48;
parameter	H_ACT	=	640;
parameter	H_BLANK	=	H_FRONT+H_SYNC+H_BACK;
parameter	H_TOTAL	=	H_FRONT+H_SYNC+H_BACK+H_ACT;
////////////////////////////////////////////////////////////
//	Vertical Parameter
parameter	V_FRONT	=	11;
parameter	V_SYNC	=	2;
parameter	V_BACK	=	31;
parameter	V_ACT	=	480;
parameter	V_BLANK	=	V_FRONT+V_SYNC+V_BACK;
parameter	V_TOTAL	=	V_FRONT+V_SYNC+V_BACK+V_ACT;
////////////////////////////////////////////////////////////
			//	This pin is unused.

assign  oVGA_CLOCK	=	iCLK;
//assign	oVGA_SYNC	=	oVGA_HS && oVGA_VS;
assign  oVGA_SYNC =	1'b1;


assign   hcount	=	H_Cont ;
assign   vcount	=	V_Cont ;
assign  oVGA_BLANK	=	((H_Cont>  0  &&  H_Cont<799  )  &&  (V_Cont>0
&& V_Cont < 525 ));   // 0,799 // 0,525
assign  oVGA_R	=	iRed;
assign  oVGA_G	=	iGreen;
assign  oVGA_B	=	iBlue;


assign  red1 = redd ;
assign  green1 = greend ;
assign  blue1 = blued ;
assign  w1 = w7;

assign  rin = rin1;
assign  gin = gin1;
assign  bin = bin1;
assign  win = win1;


always@( posedge iCLK )
begin
if	( H_Cont > 619 && H_Cont < 652 ) begin

				hblk1 <= 1'b1 ;
				end
```

```
else begin
hblk1 <= 1'b0 ;
end

end



assign  oAddress       =     oCurrent_Y*H_ACT+oCurrent_X;
assign  oRequest       =     ((H_Cont>=H_BLANK    &&    H_Cont<H_TOTAL)&&
(V_Cont>=V_BLANK && V_Cont<V_TOTAL));
assign  oCurrent_X     =     (H_Cont>=H_BLANK)      ?      H_Cont-H_BLANK
        :      11'h0   ;
assign  oCurrent_Y     =     (V_Cont>=V_BLANK)      ?      V_Cont-V_BLANK
        :      11'h0   ;


//Horizontal Generator: Refer to the pixel clock
always@(posedge iCLK or negedge oRST_2)
begin
if(!oRST_2)
begin
H_Cont              <=     0;
oVGA_HS             <=     1;
hclk         <=     1;
end
else
begin
if(H_Cont<H_TOTAL)
H_Cont       <=     H_Cont+1'b1;
else
H_Cont       <=     0;
//      Horizontal Sync
if(H_Cont==H_FRONT-1)                   //      Front porch end
oVGA_HS      <=     1'b0;
if(H_Cont==H_FRONT+H_SYNC-1)            //      Sync pulse end
oVGA_HS      <=     1'b1;
end
end

//      Vertical Generator: Refer to the horizontal sync
always@(posedge oVGA_HS or negedge oRST_2)
begin
if(!oRST_2)
begin
V_Cont              <=     0;
```

```
oVGA_VS      <=      1;
end

else
begin
if(V_Cont<V_TOTAL)
V_Cont          <=      V_Cont+1'b1;
else
V_Cont          <=      0;
//        Vertical Sync
if(V_Cont==V_FRONT-1)                    //        Front porch end
oVGA_VS<=  1'b0;
if(V_Cont==V_FRONT+V_SYNC-1)        //        Sync pulse end
oVGA_VS<=  1'b1;
                                                                        // 276 ,,,,302    //288 //5,31
          if        ( V_Cont > 276 && V_Cont < 302 ) begin
                              vblk <= 1'b1 ;
                              end
                              else begin
                              vblk <= 1'b0 ;
                              end
          end
end


always@( negedge oVGA_VS )
begin

odd <= !(odd) ;
end

endmodule
```

APPENDIX II

BIOMEDICAL IRB – EXPEDITED REVIEW

APPROVAL NOTICE

UNLV
UNIVERSITY OF NEVADA LAS VEGAS

NOTICE TO ALL RESEARCHERS:

Please be aware that a protocol violation (e.g., failure to submit a modification for <u>any</u> change) of an IRB approved protocol may result in mandatory remedial education, additional audits, re-consenting subjects, researcher probation suspension of any research protocol at issue, suspension of additional existing research protocols, invalidation of all research conducted under the research protocol at issue, and further appropriate consequences as determined by the IRB and the Institutional Officer.

DATE: February 5, 2010

TO: **Dr. Rama Venkat**, Electrical and Computer Engineering

FROM: Office for the Protection of Research Subjects

RE: Notification of IRB Action by Dr. John Mercer, Chair
Protocol Title: **University of Nevada Light Emitting Diode Display Engineering (NV)**
Protocol #: 1001-3348M

This memorandum is notification that the project referenced above has been reviewed by the UNLV Biomedical Institutional Review Board (IRB) as indicated in regulatory statutes 45 CFR 46. The protocol has been reviewed and approved.

The protocol is approved for a period of one year from the date of IRB approval. The expiration date of this protocol is February 1, 2011. Work on the project may begin as soon as you receive written notification from the Office for the Protection of Research Subjects (OPRS).

PLEASE NOTE:
Attached to this approval notice is the **official Informed Consent/Assent (IC/IA) Form** for this study. The IC/IA contains an official approval stamp. Only copies of this official IC/IA form may be used when obtaining consent. Please keep the original for your records.

Should there be *any* change to the protocol, it will be necessary to submit a **Modification Form** through OPRS. No changes may be made to the existing protocol until modifications have been approved by the IRB.

Should the use of human subjects described in this protocol continue beyond February 1, 2011 it would be necessary to submit a **Continuing Review Request Form** *60 days* before the expiration date.

If you have questions or require any assistance, please contact the Office for the Protection of Research Subjects at OPRSHumanSubjects@unlv.edu or call 895-2794.

APPENDIX III

INFORMED CONSENT

INFORMED CONSENT
Department of Electrical and Computer Engineering

TITLE OF STUDY: University of Nevada Light Emitting Diode Display Engineering (NV)

INVESTIGATOR(S): Dr. Rama Venkat

Contact Phone Number: 895-1094

Purpose of the Study

You are invited to participate in a research study. The purpose of this study is to obtain data "how human beings perceive a variety of colors generated by two methods of LED Display lighting (Red-Green-Blue (RGB) & Red-Green-Blue-White (RGBW))".

Participants

You are being asked to participate in the study because the quality of display is a perceived characteristic and hence data based on human perception is absolutely necessary. If you know that you are color-blind, please let us know as the research involves viewing various colors generated by two different technologies we are comparing.

Procedures

If you volunteer to participate in this study, you will be asked to do the following:

- Stand 50 feet away from a 32inch x 16inch screen where same color from two different technologies and sometimes the same technology will be displayed. Some of you will be assigned to the control group and others to experimental group. You will not know which group you belong to. Only the researcher will know.
- Observe the color and record on a form if the colors are:
  - Identical
  - almost the same

- completely different
- unsure

- If you are not sure, then you can ask the researcher to repeat the procedure for another viewing of the colors.
- If you are uncomfortable with viewing the colors or any other part of the experimentation, you can withdraw by letting the researcher know.

Benefits of Participation

There may not be direct benefits to you as a participant in this study. However, we hope to learn if the new technology we are developing, which we know saves energy, provides the same quality of colors in a display.

Risks of Participation

There are risks involved in all research studies. This study may include only minimal risks. State the level of anticipated risks (i.e. you may become uncomfortable when answering some questions). Te study involves minimal risk only as the subjects will be viewing colors of same brightness as they see in real life. At any time during the experimentation, if the subject is uncomfortable and does not want to continue, he/she can withdraw by letting the researcher know.

Cost /Compensation

There will not be financial cost to you to participate in this study. The study will take 30 minutes of your time. You will not be compensated for your time.

Contact Information

If you have any questions or concerns about the study, you may contact Dr. Rama Venkat at 895-1094. For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted you may contact the UNLV Office for the Protection of Research Subjects at 702-895-2794.

Voluntary Participation

Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with the university. You are encouraged to ask questions about this study at the beginning or any time during the research study.

Confidentiality

All information gathered in this study will be kept completely confidential. No reference will be made in written or oral materials that could link you to this study. All records will be stored in a locked facility at UNLV for at least 3 years after completion of the study. After the storage time the information gathered will be deleted.

Participant Consent:

I have read the above information and agree to participate in this study. I am at least 18 years of age. A copy of this form has been given to me.

______________________________________ ____________________

Signature of Participant Date

____

Participant Name (Please Print)

Participant Note: Please do not sign this document if the Approval Stamp is missing or is expired.

APPENDIX IV

HUMAN EXPERIMENT QUESTIONNAIRE

Questionnaire for the Subjects

Part 1

Circle "Yes" or "No" for the following questions.

1.	Are you 18 years or older (adult)?	Yes	No
2.	Are you color-blind (if know)?	Yes	No
3.	Are you sensitive to any colors?	Yes	No
4.	Are you sensitive to normal day-to-day light intensity?	Yes	No

Part 2

For each display of two color pattern that you are asked to view, please answer the following. If you are not sure, please ask the researcher to repeat the experiment.

(a) On a scale of 0 through 4, how similar are the two colors?
(0=unsure, 1=completely different, 4=identical)

(b)On a scale of 0 through 4, how similar are their intensities?
(0=unsure, 1=very different, 4=identical)

Pattern 1

Describe color 1: ________ color2: _________

Describe color 1: ________ color2: _________

(a)___________ (b) ___________

Pattern 2

Describe color 1: ________ color2: _________

Describe color 1: ________ color2: _________

(a)___________ (b) ___________

Pattern 3

Describe color 1: _________ color2: __________

Describe color 1: _________ color2: __________

(a)____________ (b) ____________

Pattern 4

Describe color: _________

Describe color: _________

(a)____________ (b) ____________

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