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Comparative study on low power display technique based on LCD systems with back-light as LED

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Abstract

With advancement of technology, end-users are stuffed with many kinds of portable handheld gadgets along with an enormous number of interactive multimedia communication and applications functionalities. These devices consume much power, especially for displaying their services or functions. In distinction, the battery, which is the main power supplier for such devices, has a much lower capacity growth compared to the power demands. This gap has motivated many researchers to study low-power display techniques. The invention of a light emitting diode (LED) in the meantime, as a new backlight source for a display panel. LEDs have been adopted in the most widely used Liquid Crystal Display (LCD) system. This paper compares noticeable low-power display techniques based on LCD systems, especially associated with an LED backlight unit as its light source. We classify these techniques namely into namely: a) low-power techniques with backlight dimming, b) low-power techniques with dynamic voltage scaling, c) software-based low-power techniques, and d) hardware-based low-power techniques, and review the core of each technique briefly. Out of many techniques used in a color sequential LED-backlit display concurrent brightness and contrast scaling technique achieved the largest power saving ratio by up to 90% of the total system power with a small distortion level.

Keywords: Backlight dimming, dynamic voltage scaling, Light emitting diode backlight unit, Liquid crystal display -system, Low-power display techniques

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1. Introduction

Nowadays, our lives are tightly related with electronic devices, from those which have big form factors and are used in a fixed way such as personal computers (PCs) to a smaller one which is portable such as notebooks, even to handheld devices which can be gripped in our hands like smart phones. The functionalities of handheld devices are very diverse: From a simple computing function by calculators to multimedia processing by a high-end computing system with audio, video, animation supports like portable media players (PMPs) and communication functionalities by cell phones, personal digital assistants (PDAs), netbooks, etc. One thing they have in common is that they usually use display modules to show their messages or graphics to the users. Such display modules have evolved from the era of Cathode Ray Tube (CRT) to the era of Liquid Crystal Display (LCD), plasma, Digital Light Processing (DLP), and Liquid Crystal on Silicon According to our observations, the most widely used display technology nowadays is LCD.

In recent years, most of the handheld devices have been equipped with high-quality color thin-film transistor (TFT) LCDs to support rich multimedia applications. This is because a TFT-LCD allows users to get a better viewing experience compared to its successor, a passive-matrix LCD. Thus, the end-users will be provided a lot of chances of facing rich multimedia applications and high-quality contents with the help of this kind of display module.

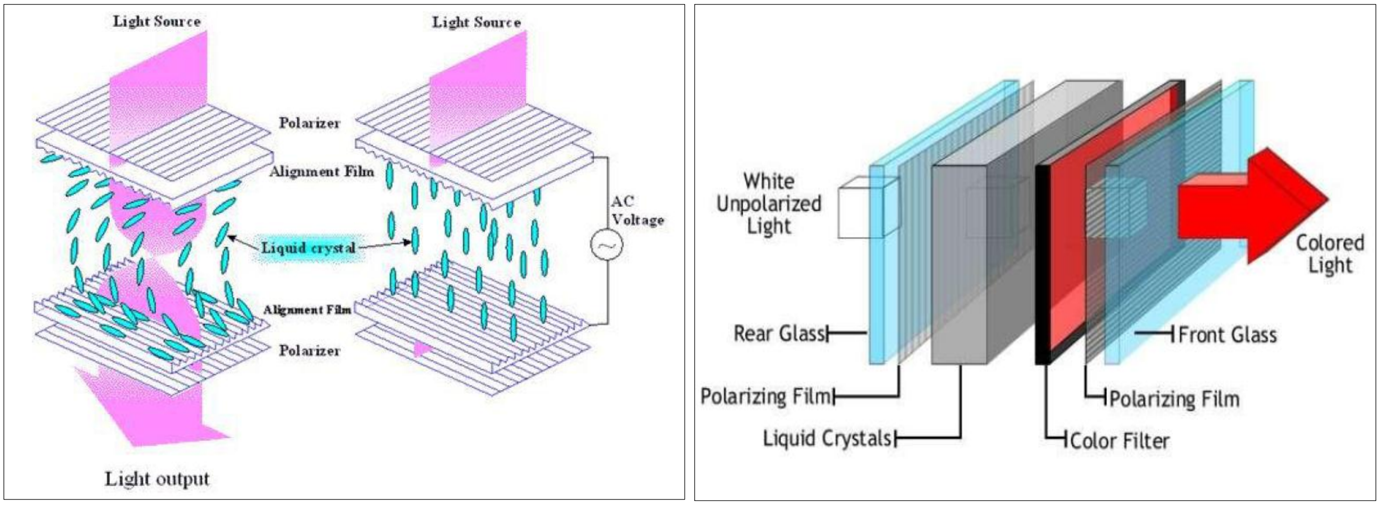


Fig 1: A typical TFT-LCD architecture

An important fact is that handheld devices are battery-driven in performing their functionalities to supply the power for their electronic components. Especially, a big power may be required to execute an I/O-bound multimedia application. Unfortunately, the battery capacities are increasing at a much slower pace than the power needs [1]. The power needs of a handheld device mostly come from a central processing unit (CPU), a main memory, a communication module, and an LCD [2], depending on the usage patterns. It has also been realized that an LCD subsystem is one of the most power-consuming elements. In an LCD subsystem, the most power-consuming hardware component is a backlight unit (BLU), which can consume about 20-40% of the total system power [3]. This observation has inspired many researchers to save the power consumption of a handheld device by reducing the power of an LCD BLU to give the end-users better experience in using plentiful multimedia applications with no concern of a limited power resource.

Besides powering down a BLU, there are other approaches in optimizing energy consumption of an LCD subsystem. In this paper, we seek to survey crucial and effective low-power techniques for LCD subsystems, especially including light emitting diode (LED) BLU-based LCDs. This paper is organized as follows. In Section 2, we give an overview of an LCD system, especially the one using LED as a backlight source. From Sections 3 to 6, we group low-power display techniques into several categories and investigate detailed techniques belonging to each category: Backlight dimming, dynamic voltage scaling, software-based approaches, and hardware-based approaches. Section 7 concludes our work and presents future works.

2. Low-power LCD Systems

The development of LCDs has been possible since some researches on liquid crystal molecules and their applications succeeded. These molecules can react to the modulation of electricity fields or the difference of voltages. An LCD is mainly made by placing and aligning these molecules between two transparent electrodes (on glass substrates) and two perpendicular polarizing layers along with a color filter layer and a light source to produce images or patterns. The principle of displaying an image or making a pattern in an LCD is aligning the liquid crystals electronically in an appropriate way to let the light from a light source (which is located on the back of LCD panel) passed or blocked to an outer layer. One polarizer layer is formed in a horizontal axis while the other is formed in a vertical axis.

The most popular configuration type of liquid crystal molecules is twisted nematic (TN), where the molecules twist by 90° when no voltage is applied and become perpendicular with the filter layers when some voltage is applied. From these behaviors, thus, there are two types of LCDs based on the default color displayed when no voltage is applied (in its off state). The first is a normally white LCD, which means that it displays white (in a color LCD) or gray (in a monochrome LCD) color when no voltage is applied because the liquid crystals are twisted and the light from the first polarizer can be passed to the second one. The second is a normally black LCD, which means that it displays a black color when no voltage is applied because the liquid crystal molecules are perpendicular to the polarizer layers, causing the light blockage. [Figure 1] shows an example of a normally black LCD.

An LCD consists of many pixels which are typically organized in a matrix form. In earlier large LCDs, the electrode layers on one side are grouped and wired (typically in columns) and each group gets its own voltage source while the others on the other side are grouped (typically in rows) and each group gets a voltage sink [5]. To activate a pixel, they make a unique combination of column and row groups, which leads to a unique source and sink for the pixel. Once a pixel has been activated, it must retain its state until the next refresh operation without a settled electrical charge. This configuration is known as a passive-matrix structure.

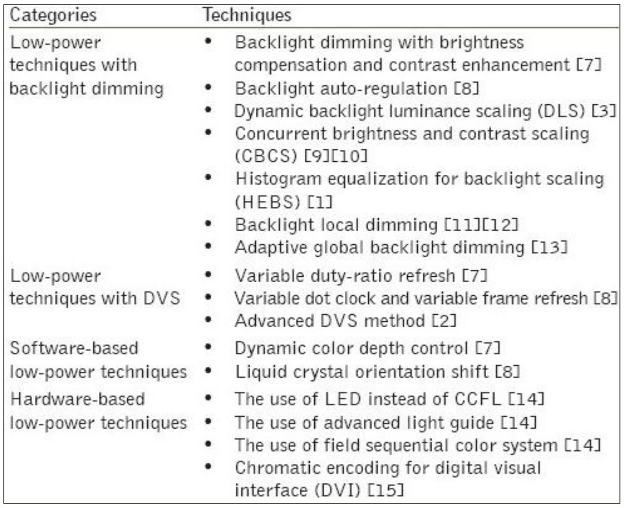
The need and development of larger LCDs have made this configuration become less feasible due to low display performance. Modern LCDs use an active-matrix structure, which dedicates a TFT to each pixel for retaining an electrical charge. Thus, they can drive each column and each row independently, and a pixel can be activated by the given correct voltage on its column and waits for the next refresh operation on its row, being scanned sequentially. To produce a color, each pixel is covered with a color filter layer, which consists of red, green, and blue (RGB) regions, being divided into three sub-pixels with an independent TFT on top of each sub-pixel. Then, the liquid crystals in each sub-pixel are aligned so that the combination of those three can produce a single color for a user's eyes.

Further, to ensure that the display is visible to users' eyes, an LCD needs a light source. Most LCDs use a backlight as their light source. A backlight module typically consists of a lightening device within a light guide, whose purpose is to distribute the light equally to the next layer. Earlier backlights had adopted cold-cathode fluorescent light (CCFL) as a lightening device, which is placed on the top or on the top and the bottom of the light guide. A CCFL bulb is known to contain hazardous chemical substances, such as mercury, which should be treated well when someone needs to demolish it [6]. In addition, a CCFL also needs a high-voltage power supply to work and thus requires an inverter to transform a direct current (DC) from batteries to an alternating current (AC). Due to these facts, the industries have begun to use an LED as a substitution for a CCFL. An LED offers some advantages over a CCFL, such as a smaller factor size, lower production cost, lower power consumption, wider color gamut, and is mercury-free. These merits should be considered by researchers when they want to make researches on a low-power LCD display system.

The shift from CCFL to LED in BLUs is an important issue in the development of LCD systems. A noticeable observation is that the use of LED has significant influences in developing new low-power techniques. Starting from the original behavior, which can produce enough luminance with lower power consumption than a CCFL does, LED is becoming a good alternative to CCFL. This is the reason why we focus on the techniques employing LED-backlit LCDs and we also try to adapt CCFL-based approaches to LED-backlit LCDs. Now we draw a big picture of low-power display techniques for LED-backlit LCD systems. There are two main classes of techniques for lowering the power consumption of a display module [1]. The first is those that focus on a digital/analog interface between a graphic controller and an LCD controller, and the second is those that focus on a video controller and an

LCD backlight. Based on the above observations, we categorize the previous works into four groups: 1) low-power techniques with backlight dimming, 2) low-power techniques with dynamic voltage scaling (DVS), 3) software-based low-power techniques, and 4) hardware-based low-power techniques, as shown in [Table 1].

Table 1: Classification of low-power techniques for light emitting diode backlight unit-based liquid crystal display systems



Categories	Techniques
Low-power techniques with backlight dimming	• Backlight dimming with brightness compensation and contrast enhancement [7] • Backlight auto-regulation [8] • Dynamic backlight luminance scaling (DLS) [3] • Concurrent brightness and contrast scaling (CBCS) [9][10] • Histogram equalization for backlight scaling (HEBS) [1] • Backlight local dimming [11][12] • Adaptive global backlight dimming [13]
Low-power techniques with DVS	• Variable duty-ratio refresh [7] • Variable dot clock and variable frame refresh [8] • Advanced DVS method [2]
Software-based low-power techniques	• Dynamic color depth control [7] • Liquid crystal orientation shift [8]
Hardware-based low-power techniques	• The use of LED instead of CCFL [14] • The use of advanced light guide [14] • The use of field sequential color system [14] • Chromatic encoding for digital visual interface (DVI) [15]

3. Low-power techniques with backlight dimming

We begin with the most popular group among low-power techniques, which uses BLU dimming as a main approach. We will survey all the techniques related to CCFL as well as LED. This is because the techniques which still use CCFL as their backlight source can also be applied in an LED-backlit BLU. All the techniques target at finding a best method in dimming the BLU with minimum distraction for users.

3.1 Backlight dimming with brightness compensation and contrast enhancement

In [7], the authors introduced a backlight luminance dimming technique with brightness compensation or contrast enhancement. They modeled the intensity perceived by human eyes as a linear function of LCD transmittance, backlight luminance, and image luminance. Transmittance (or transmissivity) is simply the fraction of the light transmitted from a backlight unit to an outer layer. Luminance can be described as the amount of the light emitted by a light source. Thus, when backlight luminance is reduced, the image luminance should be enhanced in order to maintain the perceived intensity. Brightness compensation is more preferred for an image with a continuous color spectrum in its histogram and it transforms the RGB values of each pixel to new ones, which are obtained from a transformation function involving the backlight luminance changes. This transformation may cause some brightest pixels to be saturated. In the mean time, contrast enhancement is used for images with distinct color spectrums and it leads to more readable display and more aggressive power saving.

The following transformation function directly calculates original RGB values and backlight luminance changes. For brightness compensation, they found the new RGB values to be from the experiments, the authors reported that the power saving reaches up to 200 mW, or around 6% of the total system power, while reducing the backlight luminance from 45 to 32 cd/m 2. For contrast enhancement, the experiments reported that the power saving amounts to 480 mW maximally, or around 15% of the total system power, by reducing the backlight luminance from 45 to 15 cd/m 2.

$$new\_RGB = min\left(1, original\_RGB + \left(1 - \frac{new\_backlight\_luminance}{old\_backlight\_luminance}\right)\right)$$

$$new\_RGB = min\left(1, \frac{original\_RGB * old\_backlight\_luminance}{new\_backlight\_luminance}\right)$$

3.2 Backlight Auto-regulation

The brightness compensation works well only for small backlight luminance changes and it becomes ineffective for larger backlight luminance changes [8]. A technique called backlight auto-regulation was devised as an alternative, which promises to produce a significant power saving. This technique employs an on-board environment luminance sensor to determine the appropriate backlight needs based on an ambient light condition. The adjustment of input voltage for the backlight driver to modify the luminance has been made. Power saving ratio becomes more significant, reaching up to 74% as the environment becomes darker and the backlight luminance becomes lower. This is a very simple backlight dimming technique with the support of a light sensor. But since this technique does not employ any image enhancement technique along with backlight dimming, it can be used without degrading image visibility only in smaller ambient light conditions. The idea was very natural and seems easy to be implemented. We expect that there will be still many chances to enhance this idea.

3.3 Dynamic backlight luminance scaling

Dynamic backlight luminance scaling (DLS) offers four different image compensation algorithms along with backlight dimming. In [9], the authors introduced a distortion ratio, which symbolized the difference between an original image histogram and an image histogram after backlight scaling. This ratio is used to obtain a proper low threshold and/or high threshold of pixel values from an image histogram. The first algorithm, brightness compensation, uses a pixel-by-pixel color transformation function which involves a high threshold. A high threshold can be described as a maximum pixel value in the histogram, which is considered to be displayed well to the users with a certain distortion ratio. This algorithm is well used for an image with a continuous histogram. Their pixel transformation also involves the color depth of the image. With this compensation, the pixels in the brightest area will be distorted, while the others do not suffer from color and brightness changes.

For the images with discrete histograms, they offered the second algorithm called image enhancement, which employs histogram stretching and histogram equalization. The former stretches the histogram using a low threshold and a high threshold, which means that it truncates data in the brightest and darkest areas above and below the thresholds. Thus, it can achieve backlight dimming by twice the amount of the brightness compensation achievement. In order to maximize the readability of the displayed image, they offered to use the latter, which is histogram equalization. This algorithm spreads the histogram of an original image so that the adjacent values in the histogram have almost the same level of frequencies. This approach is not applicable to streaming images due to the color changes of most pixels. But it can produce better readability than histogram stretching as long as the image has a discrete spectrum. The complexity and overhead of brightness compensation and contrast enhancement techniques come from the construction of a transformation function and the transformation process itself. Especially, histogram stretching may have better performance than brightness compensation, but it requires doubled cost and complexity compared to brightness compensation or histogram equalization.

The third algorithm is context processing, which is used primarily to enhance the result of histogram equalization. Although histogram equalization sometimes offers better image readability, some colors in the minority may be transformed into new ones. Thus, we need to be able to distinguish a small foreground object from its background, which is allowed by re-stretching its color to maximize the distance between those colors. This algorithm requires context information for the application and information about the color of the background, and it does not suffer from the overhead of constructing a transformation function because it is not based on an image histogram. As a result, they claimed that the DLS technique can reduce the total power consumption by 20-80% with an acceptable distortion ratio. Unfortunately, we should pre-define the distortion ratio by ourselves, which means that we cannot accurately and automatically fix an appropriate distortion rate for different images.

3.4 Concurrent brightness and contrast scaling

We find that the DLS technique has two main drawbacks, which are its unmeasured distortion of a resultant image and its limited applicability due to high-time cost of manipulating pixels one by one [1]. Moreover, DLS uses a brightness-invariant approach, which considers that there is no image fidelity loss if every pixel in a backlight-scaled image has the same brightness as one in an original image. The authors of [9] stated that brightness-invariant backlight scaling is usually too conservative to deliver great energy savings. Then, they proposed the use of a contrast metric for measuring the image fidelity after backlight scaling in their technique, which is called concurrent brightness and contrast scaling (CBCS). They also added a logic which controls the distribution of output voltages to an original voltage divider in implementing a scaling function of LCD's transmissivity. This consequently eliminated the pixel-by-pixel manipulation on the image. A voltage divider is a specific hardware designed to produce fixed voltages required by a source driver for setting a certain level of LCD's transmissivity.

They clearly modeled the observed luminance of a transmissive object as a product of the backlight luminance and transmissivity of TFT-LCD. The modified voltage divider was used to implement a programmable LCD reference driver (PLRD) which takes two input arguments, a lower bound and an upper bound, as guidance in modifying the voltage to control the transmissivity of an LCD panel. The relation between a luminance function and those two bounds is shown in [Figure 2], where x shows a pixel value, t is the transmissivity of a pixel value, and b is a backlight factor.

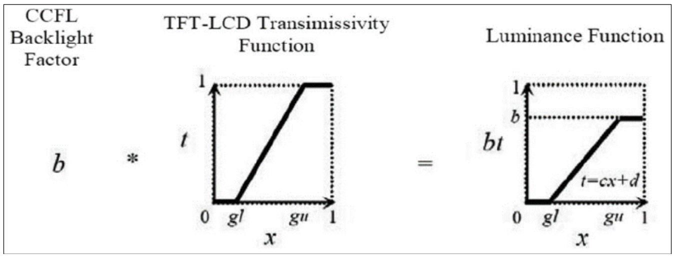


Fig 2: The luminance function of normalized pixel values [9].

The lower bound gl and the upper bound gu show the darkest and brightest pixel values that will not be distorted (saturated) in the image compensation result after backlight scaling. The principle of CBCS is to scale the brightness and contrast simultaneously to balance the contrast loss and the number of saturated pixels. The goal is to find the optimal bounds where the overall contrast fidelity reaches its maximum. A large overall contrast fidelity (almost or the same as 1, which is the original image contrast) is better. They found the optimum bounds by using this in a number of experiments. From their experiments, they claimed that CBCS can achieve a significant power saving of more than 50% with small contrast distortion for still images. They did not If we associate those techniques with a kind of a backlight source, we will find that the techniques in subsections 3.1, 3.2, 3.3, and 3.4 are originally proposed for CCFL-based BLUs. Since they do not practically involve the characteristic of CCFL to achieve the result, they can also be applied on an LED-based BLU without major changes. Such application appears in [10], where CBCS was applied to a color sequential LED-backlit platform. The difference is that while the original CBCS was applied to a single white CCFL backlight, they used an LED backlight, in which the color conduct experiments on streaming images can be modified according to the needs in the range of RGB colors.

Table 2: Comparison of CCFL and LED.

	CCFL	LED
Size	Thicker and heavier	Thinner and lighter
Cost	Cheaper and more cost effective	More expensive, but are becoming more affordable as more laptop manufacturers are using LED backlights
Power	Higher power consumption and heat generation	Lower power consumption and heat generation
Brightness	Lower brightness	Generally higher brightness
Finish	Available in Matte or Glossy	Available in Matte or Glossy
Lifespan	Shorter lifespan	Last longer than CCFL's

Since a color sequential system displays RGB images sequentially in a very fast shifting time, the lower and upper bounds of CBCS should be individually determined for each primary color (i.e. RGB). Fortunately, the lower bounds are the same for all primary colors. But the upper bounds for each primary color should be calculated separately using their histogram information. The backlight factors are also different for each primary color. This technique can achieve significant power savings from 25 to 90% of the total power consumption with 10% contrast distortion.

3.5 Histogram equalization for backlight scaling

To dim the backlight with a pre-defined distortion ratio, histogram equalization for backlight scaling (HEBS) has been proposed, which tries to find an appropriate pixel transformation function for each displayed image [1]. The authors criticized the original CBCS as a technique that cannot maximize the potential of a dynamic backlight scaling scheme in saving power due to its overestimation in measuring distortion, and they also insisted that CBCS maximizes only the number of preserved pixel values or minimizes the number of saturated pixels. They argued that the image distortion should be considered as a complex function of visual perception, and it should be measured by combining the mathematical differences between pixel values (histograms) and the characteristic of a human visual system. HEBS works on an image histogram and a transformation function which transform an original histogram into a new uniformly distributed one with a specified minimum dynamic range. Dynamic range is a ratio or range between the brightest and the darkest available pixel values in an image. A new histogram should be different minimally from the original one of a backlight-scaled image. After they get the histogram transformation function, they define a dynamic linear function to transform an original image to a desired resultant one. Practically, since it is difficult to measure a distortion degree, this technique needed a number of experiments to get a mapping table of dynamic ranges to distortion ratios from some benchmark images. An example of a mapping result is shown in [Figure 3]. The results are then used to specify the minimum dynamic range in a new uniform distribution histogram.

The HEBS technique depends on empirical results from repeated experiments. The authors reported 45-65% power savings with 5-20% distortion ratios. They insisted that they employed a more accurate definition of image distortion and a human visual system model, but the paper itself did not explain it clearly.

3.6 Backlight Local Dimming

So far, we have presented several backlight dimming techniques which dim all the light sources together with the same dimming factor. Those approaches belong to a kind of backlight dimming scheme called a global backlight dimming scheme. There are backlight dimming techniques which employ a different approach, where they can dim each light source individually with different dimming factors. These approaches belong to a local backlight dimming scheme.

Beginning from the will to reduce the backlight leakage, the authors of [11] took an approach to dim the backlight on the dark image regions. Hence, when the intensity becomes smaller, the light leakage will become lesser. Light leakage happens in an LCD panel when the liquid crystals cannot fully block the light even when displaying a fully black pixel. Their approach simply divides the image and LEDs into multiple regions virtually [Figure 3] without physical isolators, and it calculates the appropriate backlight intensity for each LED region based on a corresponding image region's histogram. Then, to enhance the visibility of a small bright object in a very dark region, it improves the brightness of all regions that have intensities above the average value. To ensure the uniformity and to smoothen the light field, it also applies spatial filter calculation to modify the intensity of each region based on surrounding regions' intensities. Finally, to avoid flicker problems on image changes, this approach modifies each region's intensities using the information of the previous frame's intensities by applying a temporal filter.

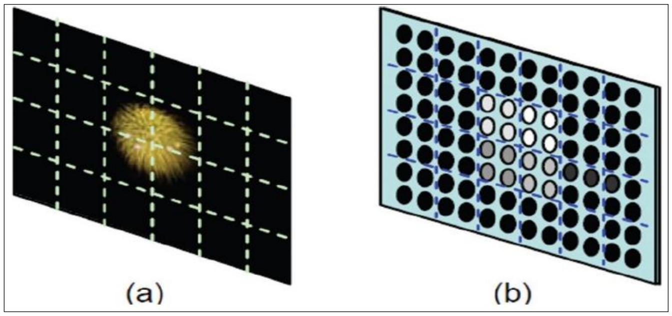


Fig 3: Backlight local dimming system [11]: (a) image regions (b) LED regions.

Local dimming can dim the area of the screen that needs it, while keeping the bright parts of the screen bright. Local dimming was developed to improve this aspect of LED LCD performance. In the process of dimming the parts of the screen that should be dark (a character in shadow, perhaps), and keeping bright the parts of the screen that should be bright (a nearby well-lit window, say), you can improve the apparent contrast ratio. As LCD technology advanced, and hence local dimming will lead the LCD industry towards the cheaper, thinner edge-lit methods, local dimming was adapted to work with these TVs too.

3.6.1 Full-array local dimming

This is the full Monty. The full array local dimming refers to an array of individual LEDs behind the LCD panel, all pointing out through the screen toward your eyeballs. If the front LCD layer was removed and the LED backlight exposed, whereas individual control of all these LEDs would be ideal (though rarely implemented), the most common method is a set number of "zones." Depending on the TV, these could number in the dozen or more. Each zone has a certain area of the screen. Also, if a zone is lit, and an adjacent zone isn't lit, you could see a halo/bloom as that part of the screen becomes brighter than its neighboring zone and is known as "blooming."

At its best, full-array backlit local dimming produces the best images you can get with LCD. The full array local dimming is best to develop the HDR content with an LCD. The downside is size and cost. The LEDs have to be set back from the screen a little (the farther away, the fewer you need to cover the same area), so there's additional depth compared to the edge-lit models. The top-of-the-line models from most manufacturers are full-array... but not always. The edge-lit TVs are thinner and cheaper to produce, they're far more common.

3.6.2 Edge-lit local dimming

The most common variety of LCD is edge-lit. With edge-lit LCDs, all the LEDs are placed along the edge of the TV screen, facing the center of the screen. Depending where the LEDs are along all four sides of the screen, just the right and left, just the top and bottom, or just the bottom or the top, edge-lit local dimming can have diverse performance.

3.6.3 Global dimming/Back-lit

One last trick isn't really "local" dimming as much as it's just "dimming," or maybe "global dimming." The entire image will get darker with dark scenes, and stay bright with bright scenes. In this technique the entire backlight functions as one single light. This is most common among the LCD TVs which are least expensive.

If anything should appear, the LEDs kick back on, and the black level jumps up, revealing the TV's true (and far more muted) contrast ratio. There are few energy-saving benefits to turn off the LEDs, but visually this is can be distracting. Another variation of this model senses the scene’s average brightness and, during darker scenes, ratchets down the whole backlight. Also the black levels improve because the whole screen is darker, but this is at the expense of bright highlights. Sometimes this causes visible fluctuations in overall brightness. From all of the steps above [as illustrated in [Figure 4]a], we can see that this approach does not employ any brightness compensation steps after backlight dimming, which leads to detail and brightness lost in dark image regions.

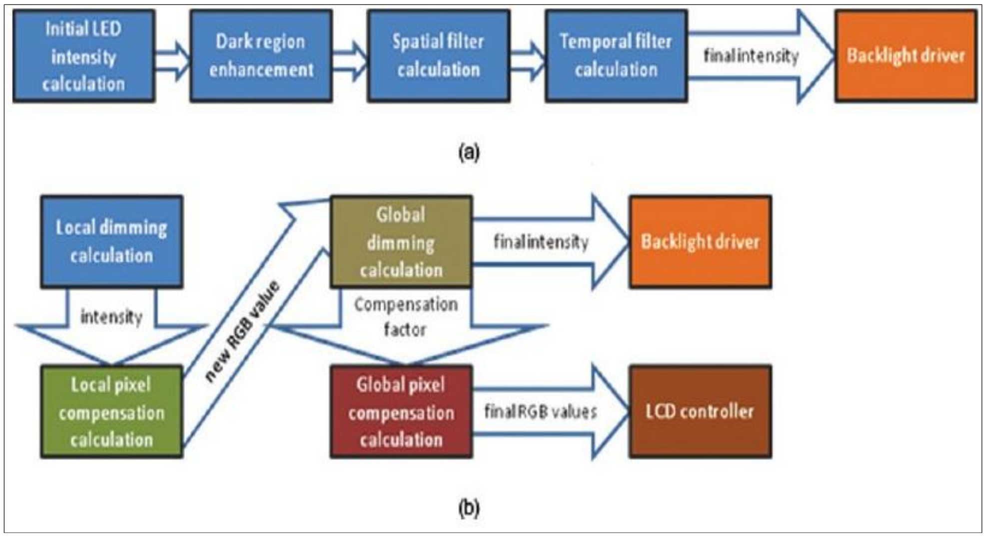


Fig 4: (a) Backlight local dimming; (b) backlight dimming with local and global pixel compensations.

The authors of [12] have improved this weak point by combining local and global backlight dimming schemes, as illustrated in [Figure 4]b. First, their work calculates the regions' intensities using the steps above, and it adds a calculation of local pixel compensation, which produces a new histogram. Then, by using the new RGB values from the calculation, it defines a critical gray level heuristically as a compensation factor, and it dims the backlight and modifies the pixel values using the critical gray level factor. This enhancement improves the achieved static contrast, reduces more light leakages, and preserves image detail and brightness in the dark image regions. However, these local backlight dimming techniques did not focus on power saving. Thus, they did not report the power saving achievement.

3.7 Adaptive Global Backlight Dimming

he above two techniques are only suitable for large-scale LCDs because of their high cost and complexity [13]. Thus, the authors of [13] tried to make improvement by executing an effective backlight-dimming algorithm and a contrast enhancement algorithm simultaneously.

3.7.1 Adaptive Dimming

The luminance for LCD TVs can now be controlled spatially as well as temporally, especially with the introduction of LEDs as a backlighting source. By tailoring the backlight to generate light only at the time and location where is it actually needed, image contrast can be improved, and at the same time less power is consumed. This technique is frequently referred to as "dynamic backlighting" or "adaptive dimming" and requires special driving electronics and algorithms to achieve an optimal system performance.

Adaptively dimming the backlight significantly improves the performance of an LCD module and enables better contrast and power efficiency. When the backlight in the darker parts of images is dimmed, the light leakage through the liquid crystal is reduced and the dynamic range is increased as well, thus improving the contrast of the panel. Also, the average power consumption is reduced because the LEDs are creating less light, they need less energy. Dimming also often improves picture quality for different viewing angles. It is also possible to use the power saved by dimming in darker areas to locally boost the luminance of bright areas of images, thus achieving a more vivid picture. For this approach, LEDs can be conditionally boosted in luminance by being driven at a higher than nominal current for a short period of time. However, special care must be taken in the thermal design of the backlight and LED drivers to prevent overheating of the LEDs.

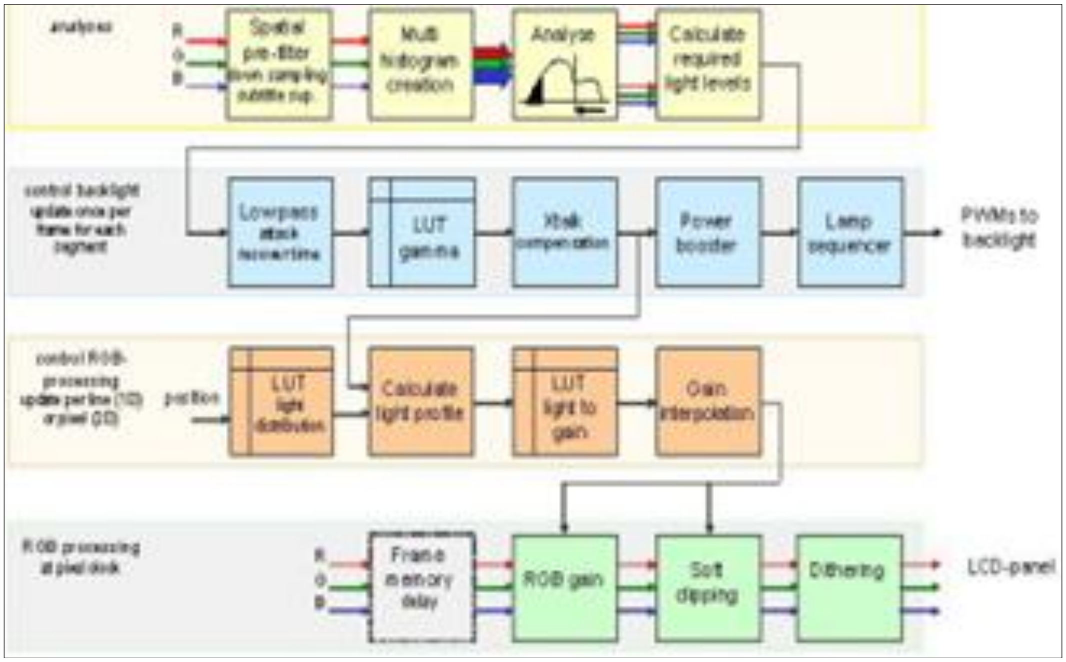


Fig 5: Adaptive backlight dimming [13].

4. Low-power techniques with dynamic voltage scaling

The second group is low-power techniques utilizing dynamic voltage scaling as their main approach. In a Complementary Metal-oxide-semiconductor (CMOS) based circuit, the dynamic power is known to be proportional to the square of an applied voltage [16]. Thus, if the voltage goes low, considerable power saving may be obtained. But, this will accompany a certain degree of a propagation delay. Of course, the voltage scaling here does not occur in a backlight driver, but in other significant components like CPU or LCD, which can affect the overall power consumption.

4.1 Variable Duty-ratio refresh

The authors of [7] created a detailed energy model of a handheld embedded system with a high-quality LCD, as shown in [Figure 7]. The part surrounded by a dashed line shows an LCD module. This model is based on the measured power consumption of each component in the device and can show which component is a big power consumer.

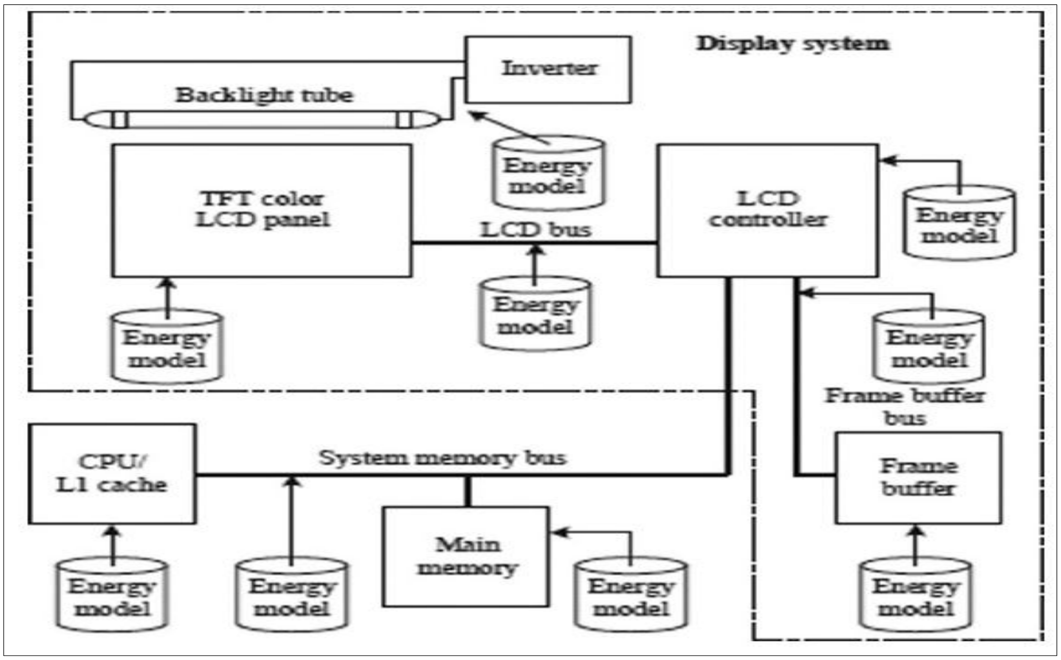


Fig 6: Detailed energy model of a handheld embedded system [7].

To reduce LCD power consumption, they introduced a technique called variable duty-ratio refresh. They adjusted an LCD refresh rate to a minimum level where the flicker is invisible to user's eyes. This modification is implemented using a Display Timing (DTMG) signal, and it can achieve power saving by up to 8% with an optimum display result.

This technique was considered ineffective because it requires additional hardware, and it cannot gain more significant power savings since it does not allow a complete shutdown of a display controller [8].

4.2 Variable Dot Clock and Variable Frame Refresh

In [8], the authors wanted to enhance variable duty-ratio refresh by introducing variable dot clock and variable frame refresh techniques, which are applied on a software basis without any hardware modification. The former appropriately modifies the clock frequency which reaches an LCD controller without causing a flicker. Since they use a normally white LCD, the result shows that the power consumption can be saved more while a full black image is displayed in comparison with a full white one when this technique is applied. The latter also has an advantage over the variable duty-ratio refresh. The principle is to fix the display refresh rate to a different level from the configured one by keeping the LCD controller disabled for a certain time according to user interaction. When the LCD controller is disabled via register programming, the display is not refreshed. The CPU enters the idle mode and the power saving could become greater. We can modify the frame refresh rate as long as a flicker is not shown, but we should consider the overhead of switching the LCD controller to on/off states. Variable dot clock can achieve power savings by up to 37% for static images, while the variable frame refresh can achieve power savings by up to 33% when the LCD controller is disabled.

4.3 Advanced Dynamic Voltage Scaling Method

Another technique involving DVS in the method can be seen in [2]. The authors focus on reducing the system power. From their observations, the authors found that the CPU's frequency and voltage determine the LCD's frequency and voltage [Figure 7]a, and there are some special points where LCD's frequency does not increase even when CPU's frequency increases. Thus, they try to keep the CPU frequency and voltage as low as they can in order to reduce the LCD voltage and to keep the display quality from degradation at those special points. The display quality is preserved by adjusting the brightness and contrast. This technique is designed to eliminate the unnecessary independent control of the LCD's frequency [Figure 7]b, referred as a conventional DVS method [2]

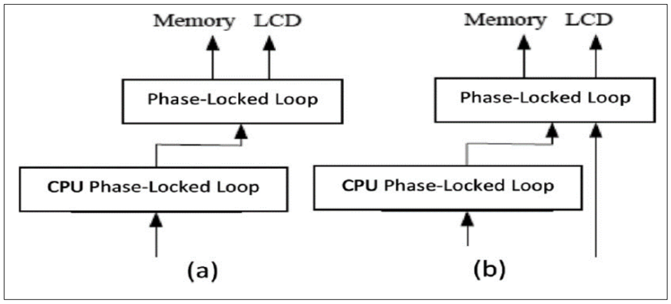


Fig 7: LCD frequency architecture [2]: (a) interlocking (b) independent.

5. Software-based Low-power Techniques

The third group employs software-based methods as their main approach including modification of pixel organization in a frame buffer.

5.1 Dynamic Color Depth Control

Most commercial colour display systems support colour-depth control. When we reduce the colour depth, the frame buffer memory offers wider screen or a larger number of pages. However, we do not expect energy savings. The LP064V1, the LCD panel for the reference platform, supports the maximum 18bit colour depth. So, desirable pixel size is 16bit. Fig. 6 (a) shows typical pixel organization for 16bit colour depth. In this paper, we modify the pixel organization as Fig. 6 (b).

The purpose of the new pixel organization is to save energy when we decrease the colour depth. Instead, we do not expect larger screen or a larger number of pages. During the rendering process, the CPU draws image or text in full colour depth. During the sweep process, the LCD controller adjusts the colour depth to save energy. The new pixel organization enables the shutdown of the LSD (Least Significant Device) when we use 8bit depth. Modern LCD controllers, including the controller in the reference platform, have bus arbitration logic inside, and thus the CPU does not have the control over he frame buffer. So, the new pixel organization does not need to modify any existing software, meaning this causes no compatibility issues.

Since the power down of the SDRAM is done at device level, i.e. only the whole chip can be sent to the power-down mode, we can control the colour depth in two levels under 16bit pixel with an 8bit SDRAM configuration.

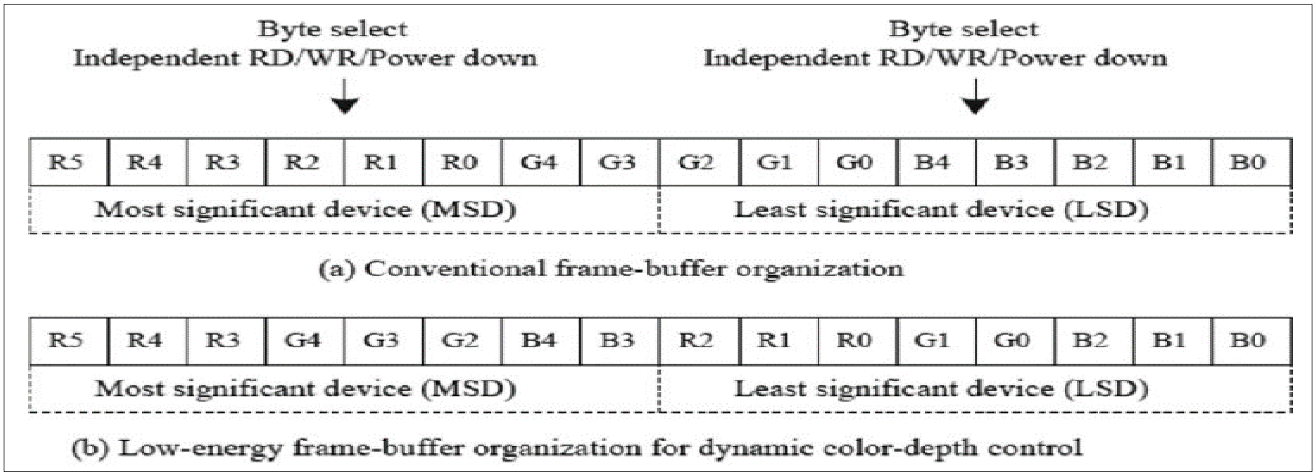


Fig 8: Low-energy frame buffer structure for dynamic color depth control

The energy gain is somewhat application dependent. As a result, we save 315.7mW, 250.2mW, 253.0mW, 251.8mW and 250.1mW for an MPEG4 player, an MP3 player, an image viewer, a document viewer and a text editor, respectively.

5.2 Liquid Crystal Orientation Shift

The previous work in [8] creatively proposed a power saving method which utilizes the benefit of low energy consumption in displaying an LCD screen's default colors. They encouraged applications to shift the color of inactive or insignificant screen regions toward white in a normally white LCD. As we know, in a normally white LCD, the color of white will naturally appear when no voltage is applied. This method relies on the capability of their OS driver to dynamically specify a set of rectangular areas which will be shifted toward white. It claimed to achieve total power reduction by up to 15.3% when displaying a full white image in comparison with a full black one.

6. Hardware-based Low-power Techniques

The last group depends on hardware components to reduce power consumption. In recent years, the advanced technologies have invented many enhanced hardware display components with more powerful capabilities than the standard one. However, the use of these components still leaves many issues to investigate in the aspect of power.

6.1 The use of light emitting diode instead of cold-cathode fluorescent light

Previously, we already discussed some aspects of LED and CCFL. In [14], we find more encouragement to use LEDs due to their advanced technology. The author listed a low-power white LED (20 mA) and a simultaneous red, blue, and green (3-in-1 RGB) LED as new efficient backlight sources for LCDs. A 3-in-1 RGB LED can obtain a wider color gamut and better pre-mixed colors, which are still a problem in a traditional LED. They also stated that the development of surface-emitting LEDs increased the efficiency of traditional edge-emitting LEDs through a "flip-chip" bonding technique. Referring to [14], a surface-emitting LED does not employ a reflector to emit the light in the forward direction (since a traditional LED needs to be packaged in forwarding the light like a surface emitter), but it extracts the light more efficiently after the removal of the electrode's contact pad, which resides on the top surface of a traditional LED and application of surface roughening [Figure 9]. This treatment can increase the light extraction level by up to 50%.

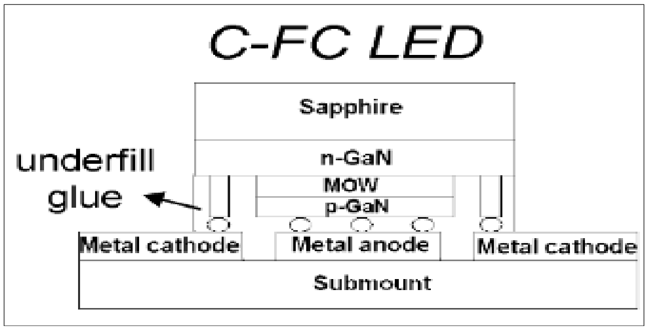


Fig 9: Surface-emitting LED based on "flip-chip" technique with surface roughening [14].

The author also listed an alternative approach for efficient light extraction by placing photonic lattice microstructures on the top surface of LEDs [Figure 10]. This treatment can gain up to 95% of light output, which is more efficient in comparison with the application of surface roughening.

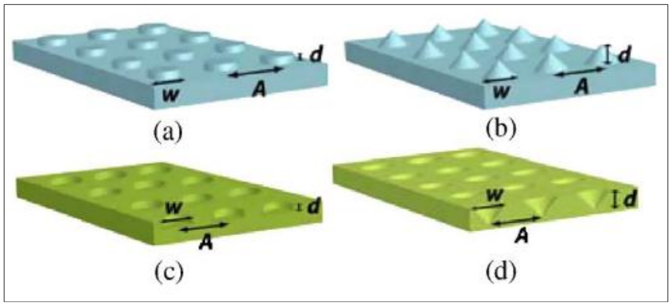


Fig 10: Photonic lattice microstructures on top of LEDs [14].

The author is also concerned about LED limitations. Since LEDs are not identical in their electro-optical characteristics, the manufacturers usually do a binning process to solve this problem. Also, there is a need for an LED drive circuit to employ temperature sensors and color sensors to help itself in stabilizing the color gamut of an LED and preventing its life and brightness degradation. These should be faced because an LED can suffer changes in spectrum shifts, chromaticity, brightness, luminous efficiency, and degrades its life in a junction temperature of 60°C.

6.2 The use of advanced light guide

We already mentioned the role of a light guide in Section 2. Observations in [14] listed some enhancements in a light guide such as a thinner form-factor (from 0.6 to 0.3 mm), the use of only one micro-lens film which is sufficient enough, and the need of smaller amount of white LEDs to achieve adequate lighting for mobile display application. A double-grooved prism, a substitute for a prism sheet and a patterned reflector at the rear of a light guide can also reduce the cost of an edge-lit backlight lighting scheme, which places LEDs on the edge of a light guide. Further, the works in [14] recommended the use of an edge-lit backlight scheme to fulfill 200-300 nits luminance requirements and a direct-lit backlight scheme, where LEDs are placed on the bottom of a light guide or a reflector to fulfill 300-500 nits luminance requirements efficiently.

6.3 The use of field sequential color operation

In addition to the explanation in Section 3, a field sequential color operation splits every frame into red, green, and blue sub-frames and it rapidly displays each sub-frame sequentially [14]. Each RGB color is given by the LEDs as its light source, and thus, the presence of a color filter is no longer needed, leading to more efficient light extraction. The operation of this mode was claimed to have a better LED color purity (due to the removal of a color filter), low power consumption, high light transmission and high resolution of LCDs, high response speed of LCDs, and high response time of LEDs coupled with a superior color spectrum with narrow peaks [14].

6.4 Digital visual interface using chromatic encoding

The system consists of a mainboard (including the CPU, memory, video controller, etc.), a display, and a DVI connection in between. The pixel data is prepared by the application and stored in the frame-buffer by the CPU via memory-write instructions. The video sub unit fetches the pixel data from the frame-buffer and then generates the proper video signals through the DVI. The pixels on the display are scanned in a left-to-right, top-down fashion. Therefore, the data of two adjacent pixels on the same row will be sent to the channel alternately such signals are displayed in a left-to-right, top-down fashion, in a typical portable embedded system as shown in [Figure 11]. Each RGB color has its own data channel along with one clock channel.

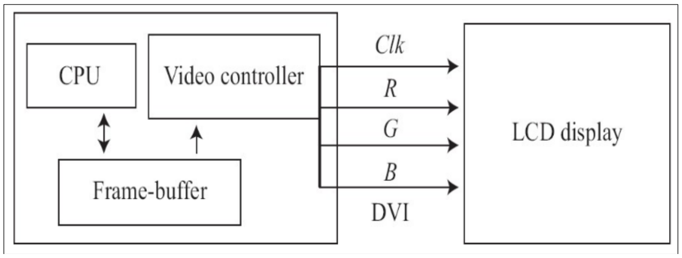


Fig 11: The target system using a DVI

In DVI, each 8-bit source word is encoded to a 10-bit code word to minimize intra-word bitwise transitions in order to reduce power consumption. The enhancement of this transition minimization operation was done in [15] to gain optimal power reduction. The proposed encoding framework to implement a memory bus encoding in display module consists of two stages: spatial encoding and chromatic encoding. Based on the correlation analysis, the spatial encoding is performed before the chromatic encoding. The spatial encoding (F and D) subtracts the Previous (west) pixel value from the current one, the chromatic encoding (C and E) takes the differences between the three colour channels, and encodes the signed binary numbers by the codebook lookup. In this paper, an encoding algorithm is described by (F, D, C, E) [15]. These final data will further be decoded by a receiver module before they are sent to an LCD controller.

This paper reviewed recent noticeable low-power techniques for LCD systems, focusing on the ones with an LED backlight unit as its light source. We found that such techniques can be categorized into four groups mainly as backlight dimming, DVS, software-based approaches, and hardware-based approaches.

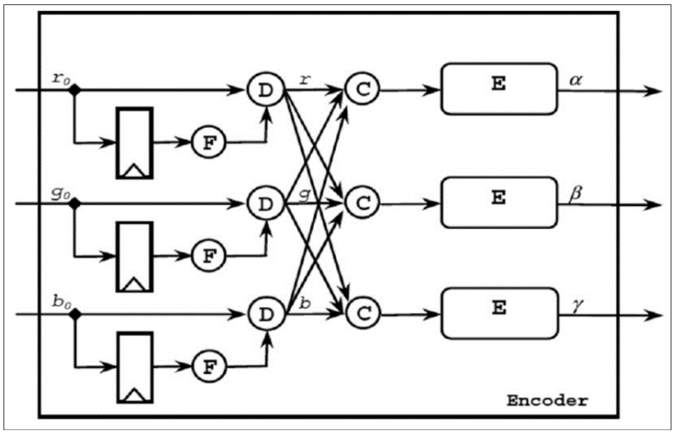


Fig 12: Chromatic encoding framework [15].

7. Conclusion and future work

Overall, the largest power saving ratio comes from the CBCS technique in a color sequential LED-backlit display system, achieving up to 90%. This achievement is also supported by a very minimal heuristic factor in its calculation, a well-perceived final image quality with small distortion level, and a low overhead cost due to the absence of pixel-by-pixel manipulation process. We also found that a backlight dimming approach is likely to be a significant power saver. From the DVS group, the advanced DVS method achieves the second largest power saving ratio, up to 41%. From the software-based group, a power saving ratio of up to 15.3% comes from the liquid crystal orientation shift method, which encourages applications to turn insignificant or inactive display areas into a screen's default color. From the hardware-based group, although they did not explicitly show their power savings ratio, we may say that all of them have significant contribution in saving power consumption at least. The remaining consideration will be the implementation cost of these hardware-based techniques.

One of the lessons for the next research is that we should try to avoid ineffective factors as much as possible in our approach. In existing works, we found that they have the forms of heavy dependence on heuristic values, manual and experimental variables assignment for different displayed images, limitation of the implementation for static images only, high overhead cost due to pixel-by-pixel transformation, the absence of practical definition and implementation of distortion, and the fixation on a point of view that they see brightness as the only possible aspect to determine image fidelity. We should try to utilize the latest feasible display technologies in making a more power-efficient LCD-based display system, while overcoming the demerits of existing approaches.

For future research, we may need to combine the benefit of using a local backlight dimming scheme with appropriate quality compensation techniques, field sequential color operation, liquid crystals orientation shift, dynamic voltage scaling schemes, advanced display hardware components, 3-in-1 RGB LEDs, along with an optimal encoding in video interface, into a single system. To this end, the most important thing is that we should study and devise not simple concatenation of such techniques but synergistic and harmonic fusion. On the other hand, we should try to develop a low-power technique and renew the old ones to fit the advanced hardware technologies such as incoming LED BLU-based LCD systems.

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