49-2: Field-Sequential-Colour Display with Adaptive Gamut

Johan Bergquist* **and Carl Wennstam**
Multimedia Technologies Laboratory, Nokia Research Centre, Tokyo, Japan

Abstract

The minimum necessary gamut is calculated frame-by-frame and the primaries are desaturated dynamically by simultaneously turning on several backlight colours during each primary field. Depending on the display response, this leads to better backlight utilization, increased luminance, and/or enhanced moving image quality. For a fast-response, three-primary field-sequential-colour display, the luminance can be increased by up to 300% for unsaturated content.

1. Introduction

The display power of a mobile phone is typically 20-30% of the total system power so stand-by and transflective modes, automatic backlight dimming, and screen saving are frequently used. On the other hand, high-bandwidth wireless infrastructures, digital TV broadcasting, and miniaturised gigabyte local storage will enable ubiquitous multimedia consumption on mobile devices, which require continuous and full display operation. This together with a moderate progress in battery technology and escalating CPU performance requirements will drain the battery unacceptably fast. At the same time, requirements on colour gamut, outdoor contrast, and moving image quality are higher than for traditional mobile applications.

The objective of this work is to explore ways of lowering display backlight power consumption and maximise image quality in a highly dynamic fashion by adapting the display driving to the image content and luminous environment.

2. Luminance enhancement technologies

There are many ways to lower LCD backlight power consumption, alternatively enhance the luminance at constant power. One way is to employ an extra white primary "colour". This has been proposed both in the spatial [1] and temporal [2] domain, *i.e.* RGBW sub-pixels in a colour-filter based display and RGBW colour fields in field-sequential-colour displays (FSCDs). While this provides 50% higher white luminance, it also results in 25% lower luminance of fully saturated images.

To achieve *both* higher luminance *and* wider gamut, the white subpixels/temporal fields can be replaced by a bright colour, *e.g.* yellow [3] or cyan [4]. Further relaxation of the luminance/gamut trade-off can be achieved by adding more primaries either spatially, temporally or a combination thereof [5]. However, this leads to increased complexity in colour space conversion, lower spatial resolution and/or increased requirements on device response speed.

Another approach [6] is to utilise the lower retinal resolution in the blue, a primary which therefore can be spatially subsampled. The released footprint can instead be used for more luminous primaries and/or a white subpixel. A more advanced approach [7] takes into account also the limited *temporal* chromatic resolution of the eye and subsamples both spatially and temporally. Both these approaches, however, employ fixed spatial/temporal patterns and therefore have limited flexibility when trading gamut for luminance.

Another way to save backlight power is to shift the image histograms to higher transmittance values and decrease the backlight to maintain the luminance. This has been proposed both for conventional [8] and FSCDs [9]. This not only saves power but also increases dark-room luminance- and colour-contrast by reducing the amount of leaked light of the low grey levels. The drawback of this approach is that a larger bit depth is needed to maintain the dynamic range of the image. The effect can be seen as posterising, tone rendering curve (TRC) clipping, and grey level quantisation artifacts. Reducing the effective colour depth also makes it more difficult to perform additional gamma correction.

3. Advantages of field-sequential-colour

Because of their spatio-temporal flexibility, direct-view FSCDs offer several fundamental advantages over conventional transmissive and emissive displays. The lacking sub-pixels and colour filters give high transmittivity, large aperture ratio, and the possibility of at least three times higher pixel density. Furthermore, the primary chromaticities are determined solely by the light sources which enables wider gamut, scalable number of primaries, white point adjustment without loss of colour depth, and therefore also large flexibility in choosing backlight chromaticity – inexpensively ranked LEDs can also be used. Pixels are rotationally invariant so landscape and portrait modes are equally legible. The high transmittance also enables a monochrome reflective display mode. Finally, the duty driving of the backlight ensures high moving image quality.

4. Implementation issues

Despite the intrinsic advantages of FSCDs, implementation and commercialisation in direct-view displays has been held back by lacking fast-response liquid crystals (LC), high cost and low luminous efficiency of non-white LEDs, moderate need for high-resolution displays with wide gamut, and poor visibility in ambient light. Recently, however, there is an increased interest in wide-gamut, high-information content mobile displays [10]. Fast LCs such as optically compensated bend (OCB) [11] have been implemented in LCDTVs [12] and highly saturated LEDs with high luminous flux have successfully been developed [13].

An inherent problem of FSCDs is the saccadic colour break-up [14] artifact which can be completely eliminated only by increasing the frame rate to several thousand Hz. The narrow field-of-view of small- and medium-sized displays, however, relaxes the requirements on frame rate and, as explained below, modulating the backlight in certain ways can reduce the colour break-up significantly.

Another drawback of FCSDs is the need for continuous white balancing due to the temperature dependence of LED

---

[*] Corresponding author: johan.bergquist@nokia.com

ISSN0006-0966X/06/3701-0000-$1.00+.00 © 2006 SID

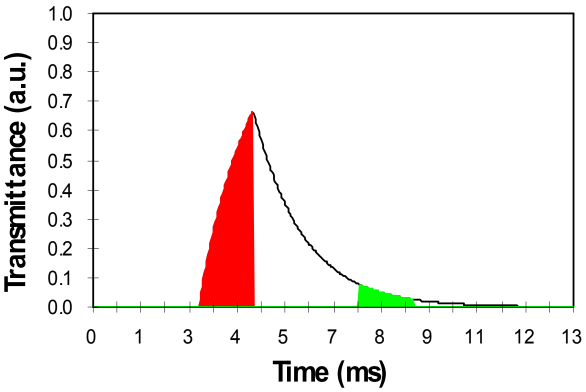


Figure 1. Transmission limited by slow optical rise.

wavelengths, although the increased cost for this is offset by the opportunity of using inexpensive, low-ranked LEDs.

4.1 Display addressing and LED duty

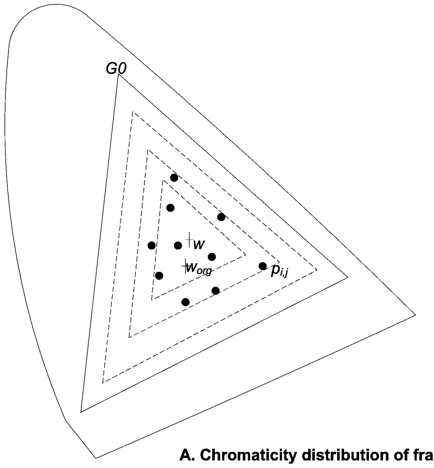
In contrast to FSCDs implemented in LC on silicon (LCOS) or in a Digital Micromirror Device™, direct-view operation requires substantial scanning time for writing the image data to all pixels before the backlight can be turned on. Even with infinite LC response, the LED on-time is limited to a fraction of the field period and the advantage of high transmittance is thereby offset by a lower time-averaged luminance. The maximum LED field duty d can be expressed by

$$d = 1 - 2Nf / f_{max} \tag{1}$$

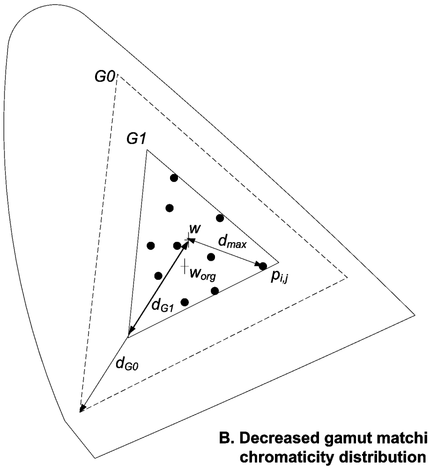
where N is the number of pixels, f is the field rate, and f_{max} is the maximum bandwidth limited either by the TFTs or the gate/source drivers. The factor two comes from the fact that the display data voltage has to be sent twice but with opposite polarities in order to prevent ionisation of the LCs. For example, a 320x240 display running at 225 Hz field rate with 50 MHz bandwidth gives a maximum duty cycle of 31%. Since the LC response is finite, the actual LED duty is often shorter to let the pixels in the last row settle before the LED is switched on. If this is not done, the pixels addressed at the top of the display will have higher transmittance than those at the bottom, which results in luminance non-uniformity. The solution to this is a scanning backlight [15] which is synchronised with the LCD pixel addressing. Segments of the backlight can thereby be switched even before all pixels have been addressed and differences in pixel settling time will be reduced and luminance uniformity improved.

4.2 Liquid crystal response

Shortening the LED duty cycle does not in principle affect the luminous efficiency because the LEDs consume power only when lit. In order to achieve the desired average display luminance, however, the number of LEDs or their current has to be increased to compensate for the shorter duty. What rather affects the luminous efficiency, is the finite optical rise time of the LC. This is illustrated in figure 1 for full screen red data on an RGB FSCD with 75 Hz frame rate, 30% field LED duty, and optical 10%-90% rise and fall times of 3 ms (exponential rise and decay assumed in this example). As shown, the long fall time also causes some of the green light to leak into the red, causing colour distortion. This leakage can be reduced by further shortening the LED duty.



A. Chromaticity distribution of frame



B. Decreased gamut matching chromaticity distribution

Figure 2. Original (*G0*) and shrunk (*G1*) gamut for pixels p_{ij}. *W* is the white point and desaturation factor is 1 - d_{G1} / d_{G0}

Response depends in many LC modes on the grey levels between which the transition occurs and, as a result, the actual transmittance of the LCD in one colour field depends on the grey level of the previous field. Similar memory effects can be seen even in fast displays as result of the dynamic DC dielectric constant of the LC. To remove this memory effect, resetting the LC (black field insertion) has been suggested, both for OCB[16] and twisted nematic [17] LC modes. However, this means that also black data needs to be written to the display, thereby shortening the available time slot for LED illumination further. Increasing the number of LEDs is a solution but it is costly and increases foot print. Therefore, we are suggesting the concept of adaptive gamut.

5. Adaptive gamut

The basic idea is to analyse all pixels in each frame of image data and calculate the minimum gamut necessary to reproduce the image. The primary colours are then desaturated dynamically and uniformly for each frame so that the pixel chromaticites exactly fall within the gamut, while keeping the white point constant. This is graphically depicted in figure 2. For contents not centered around the nominal white point, it is, in principle, also possible to

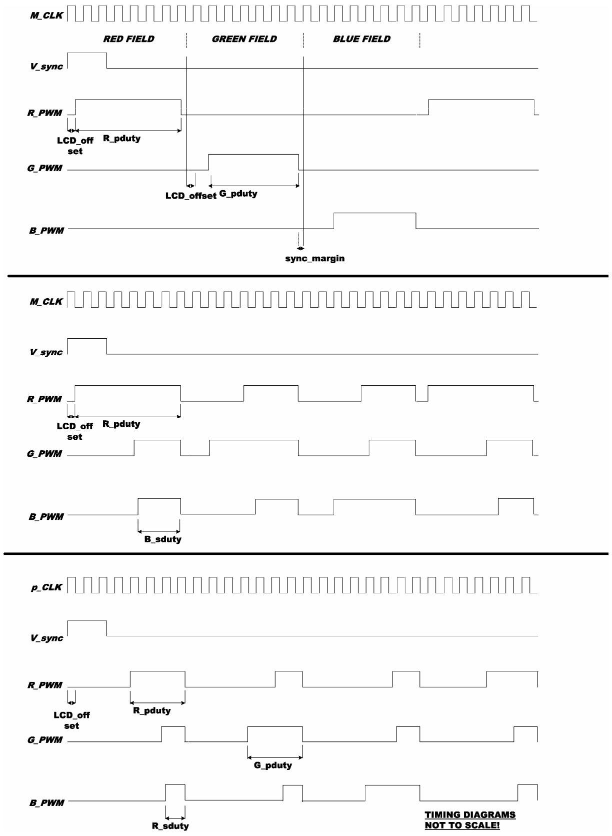


Figure 3. Display and LED timing for a conventional FSCD (top), primary desaturation (mid), and after luminance compensation (bottom)

move the white point dynamically to the centre of the pixel chromaticity distribution. In this work, however, we limit ourselves to a constant white point.

Desaturation increases the luminance so it is necessary to dynamically adjust also the luminance of each frame in order to avoid flicker. In bright environments, one might further reduce gamut to boost luminance. In this case, some pixels will be out of gamut but luminance contrast can be improved. This is similar to transflective displays which have very limited gamut in the reflective mode in return for high reflectance and hence better character readability in the outdoors.

Figure 2A shows the gamut of a saturated RGB FSCD, *G0*, and the chromaticities p_{ij} of the image pixels *ij* as determined from the digital values and colour management profile, *i.e.* a transformation into a device-independent, uniform colour space. W_{org} and *W* are example of white points before and after white balancing (necessary in RGBLED systems). Figure 2B shows the reduced gamut (*G1*) for the particular set of pixel chromaticities. The triangle is scaled by a factor equal to the ratio of the distances d_{G1} and d_{G0} from the white point to one of the triangle corners. Similar scaling can be done in polygons in a multiprimary display. d_{G1} is determined geometrically from d_{max}, the longest distance between the white point and any of the pixel chromaticities.

The gamut scaling is implemented by fractionally turning on the other primary colours during each field (see figure 3). For the red field in a three-primary display, for example, the green and blue LEDs are also turned on for a short time. The eye will integrate over the whole field and hence see a slightly desaturated red. The same procedure is repeated for the other primaries. To avoid flickering and luminance variations, the luminance is brought back to the original value by uniform scaling as shown at the bottom of figure 3.

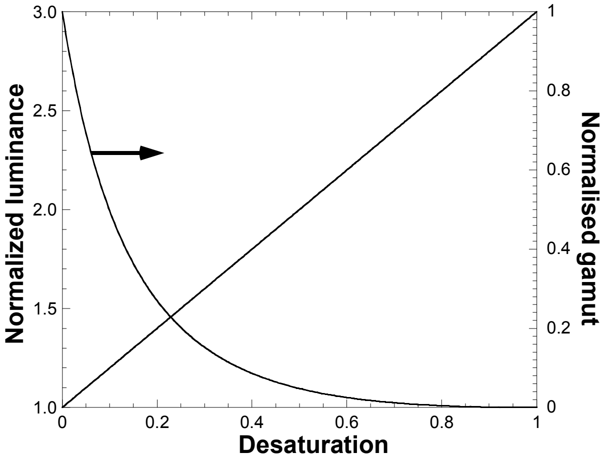


Figure 4. Normalised gamut and luminance as functions of primary desaturation in a three-primary FSCD

7. Results and Discussion

The actual gamut and luminance depend on the LED chromaticities, light guide efficiency, and LCD transmittance so we have normalised the results to the gamut and luminance under normal FSCD operation. The calculation is done as follows: First, we obtain the tristimulus values for each saturated primary *i*, X_i, Y_i, and Z_i, and calculate the original gamut by transforming XYZ into the CIE 1976 (*u'v'*) colour space and define the gamut as the area of the triangle (polygon in the case of multiprimary display). The original white luminance is simply the sum of all Y_i. The tristimulus values of the desaturated primaries *i* are then given by

$$X'_i = X_i + d\sum X_{i\neq j} \quad (2)$$

$$Y'_i = Y_i + d\sum Y_{i\neq j} \quad (3)$$

$$Z'_i = Z_i + d\sum Z_{i\neq j} \quad (4)$$

Where *d* is the desaturation factor which takes a value 0 - 1 and is defined as (see figure 2)

$$d = 1 - d_{G1} / d_{G0} \quad (5)$$

The gamut after desaturation is calculated in the same way as the original gamut and is shown together with the luminance as functions of desaturation in Figure 4. Although the gamut decreases sharply by increasing desaturation, reasonable gamut is achieved when using highly saturated LEDs. Recent RGB LEDs [13], for example, offer gamuts of more than 150% of *u'v'* NTSC gamut.

Compared to a conventional FSCDs, there is no difference in luminance for a frame with any pixel with a fully saturated colour. However, typical contents is not fully saturated so there will always room for some gamut shrinking. Although the proposed scheme provides *global* luminance increase, an inherent disadvantage compared to RGBW or RGBY pixels is that *local* brightness enhancement in saturated images is impossible. Also, an image which is unsaturated except for a single saturated pixel makes it impossible to apply the algorithm without desaturating also the single pixel. A more advanced algorithm can be developed which, in addition to the pixel chromaticity distribution, also analyses the *cluster sizes* of saturated pixels and predicts their visibility. For sufficiently small cluster sizes, desaturation can be done without any visible artifacts. Scanning backlight can also ease the situation since desaturation can be done independently of each backlight section.

The extreme case with completely desaturated colours will boost the luminance by *n* times (*n*=number of primaries) compared to a conventional FSCD. Desaturation with white LEDs will increase luminance even further. Fully achromatic applications such as text and certain user interfaces (UI) thereby benefit from large luminance boosts and/or backlight power savings. The scheme can also offer the user the option of longer battery life if fainter colours can be accepted.

The dynamic luminance preservation could create unwanted flicker if the content changes quickly. This has been observed in dynamic gamma correction/backlight modulation in colour-filter-based LCDs [8] but was solved by applying a low-pass filter on the backlight modulation signal.

Since the luminance preservation is accomplished by shortening the LED duties, improvement in moving image quality is expected [18], particularly for unsaturated contents. It is well-known that colour break-up (CBU) is most visible for unsaturated content on dark backgrounds, *e.g.* scrolling text. CBU can be reduced by employing multiprimary FSCDs because the non-RGB primaries stimulate several types of photoreceptors simultaneously [19]. A special case of the proposed adaptive gamut can achieve a similar effect by replacing the RGB primaries with CMY. This is easily done by transforming the image data to CMY and turning on GB, BR, and RG LEDs in a sequence. While the gamut will be smaller than RGB FSCD, contents prone to large CBU is less saturated and could be shown in the CMY space instead..

9. Conclusion

A field-sequential-colour display where the primaries can be dynamically desaturated, is proposed. It enables continuous trading of gamut for luminance, backlight power saving, increased moving image quality, and/or decrease in colour break-up.

10. Acknowledgements

The authors would like to thank Mr. Masayo Okita of Hunet Display Technologies and Mr. Teppo Lohiniva of Lumileds Inc. for fruitful discussions and for sample preparation.

11. References

[1] B.-W. Lee, K. Song, Y. Yang, C. Park, J. Oh, C. Chai, J. Choi, N. Roh, M. Hong, K. Chung, S. Lee, C. Kim, “Implementation of RGBW Color System in TFT-LCDs”, SID Symposium Digest, Vol. **33**. pp. 111-113, 2004.

[2] Fujitsu patent pending JP-2002-318564

[3] M.B. Chorin, “Improving LCD TV color using Multi-Primary technology”, Paper PC2-2, FPD International Forum, Yokohama, 2005

[4] K. Endo, “New mobile technologies creating a host of new mobile equipment”, Paper B1-4, FPD International Forum, Yokohama, 2005

[5] H. Sugiura, H. Kaneko, S. Kagawa, M. Ozawa, H. Tanizoe, H. Katou, T. Kimura, H. Ueno, “Six-Primary-Color 23-in WXGA LCD using Six-Color LEDs”, SID Symposium Digest, Vol. **34**. pp. 1124-1127, 2005

[6] C. H. B. Elliott, S. Han, M. H. Im, M. Higgins, P. Higgins, M. Hong, N.-S. Roh, C. Park, K. Chung, “Co-Optimization of Color AMLCD Subpixel Architecture and Rendering Algorithms”, SID Symposium Digest, Vol. **31**. pp. 172-175, 2002

[7] L. D. Silverstein, “STColor: Hybrid Spatial-Temporal Color Synthesis for Enhanced Display Image Quality”, SID Symposium Digest, Vol. **34**. pp. 1112-1115, 2005

[8] A. Konno, Y. Yamamoto, and T. Inuzuka, “RGB Color Control System for LED Backlights in IPS-LCD TVs”, SID Symposium Digest, Vol. **34**. pp. 1380-1383, 2005

[9] W. Cheng, “Power Minimization of LED Backlight in a Color Sequential Display”, SID Symposium Digest, Vol. **34**. pp. 1384-1387, 2005

[10] J. Bergquist, “Visual Ergonomics Challenges in Information-Intensive Mobile Displays”, IDW Proceedings, pp. 1487-1490, 2003

[11] T. Uchida, K. Saitoh, T. Miyasita and M. Suzuki, “Field sequential full color LCD without color filter for AMLCD”, Proc. 17th IDRC, p 37, 1997

[12] H. Maeda, “Recent Development of OCB-Mode LCD for TV Application”, Paper C5-4, FPD International Forum, Yokohama, 2005

[13] http://www.lumileds.com

[14] T. Järvenpää, “Measuring Color Breakup of Stationary Images in Field-Sequential-Color Displays, SID Symposium Digest, pp. 82-85, 2004

[15] K. Sekiya, T. Kishimoto, K. Wako, S. Nakano, H. Ishigami, K. Käläntär, K. Shimabukuro, D. Kunioka, T. Miyashita, and T. Uchida, ”Spatio-Temporal Scanning LED Backlight for Large Size Field Sequential Color LCD”, IDW Proceedings, pp. 1261-1264, 2005

[16] H. Nakamura, K. Miwa, and K. Sueoka, ”Modified drive method for OCB LCD”, Proc. 17th IDRC, pp. L66-69, 1997

[17] M. Okita, US Patent 6,424,329

[18] T. Kurita, “Requirements for LCD to gain high moving image quality - improvement of quality degraded by hold-type display”, AM-LCD Digest pp. 1-4, 2000

[19] D. Eliav, E. H. A. Langendijk, S. Swinkels, and I. Baruchi, “Suppression of Color Breakup in Color-Sequential Multi-Primary Projection Displays, SID Symposium Digest, Vol. **34** pp. 1510-1530, 2005