A new dithering algorithm, “Hi-FRC”, is presented. It enables full (16,777,216) color on an LCD panel with 6-bit source D-IC’s, compared to conventional FRC which can display only 16,194,277 colors. In addition, an LCD panel with Hi-FRC can meet the color grayscale linearity requirements of TCO’03 due to its ability to improve the color shift problem.

1. Introduction

Thin film transistor liquid crystal displays (TFT-LCD) have been replacing cathode ray tubes (CRTs) in over 50% of monitor applications [1]. Currently, the main models used in monitor applications are 15” XGA and 17” SXGA, while 19” SXGA panel usage is growing rapidly [1]. Over 80% of LCDs used as monitor panels use 6-bit source drivers. Thus, a dithering algorithm is needed and applied because the input image source is 8-bit. The dithering algorithm is also called Frame Rate Control (FRC), because the algorithm uses temporal averaging by changing data frame by frame. Conventional FRC can only show 16.2M colors, not the full 16.7M colors, due to limitations of the dithering algorithm. This paper proposes a novel dithering algorithm which enables a full color image even with 6-bit driver ICs. In addition to higher color depth, it can improve color performance.

2. Conventional Dithering Algorithm

6-bit driver ICs can generate only 64 analog levels. Input 6-bit data ranges from 0 to 63, that is, from 0 to 252 (=63x4) in an 8-bit expression. Fig. 1 shows a spatial dithering and temporal averaging pattern of a conventional FRC algorithm. According to the lower 2-bits of 8-bit input data, a spatial and temporal averaging of 6-bit data is determined as shown in Fig. 1.

Temporal Averaging: Let’s assume the input is a full screen of half-bright 127 gray level. The lower 2 bits are (11)2. Fig. 2

Figure 1: Spatial dithering and temporal averaging pattern of conventional FRC

Figure 2: Temporal average of FRC algorithm to display luminance of gray levels 127 and 126
shows the explanation of the temporal averaging for the upper left pixel. The sequence of the upper left pixel data is 124 ⇒ 128 ⇒ 128 ⇒ 128 ⇒ 124... Thus, the temporal average value is (124+128+128+128)/4 = 127. The other pixels have different data sequences, but have the same average value of 127. For the same reason, the upper left pixel in the full page pattern of 126 gray shows the sequence of 128, 124, 128, and 124. Thus, all pixels have the same temporal averaging value of 126.

Spatial Averaging: Fig. 3 shows two units of 4 pixels. The two units, however, have the same average value of 127. The total spatial average is also 127. Through all frames, the spatial averaging of the two units of 4-pixels shown in Fig. 1 is maintained as 127.

The conventional FRC algorithm is a very effective method to simulate an 8-bit-like display only using 6-bit driver ICs. However, it is not a perfect scheme for a full-color display. The FRC algorithm cannot display 256 distinguishable luminance levels for each of red, green and blue. Fig. 4 shows the measured data and the reason why the FRC algorithm cannot display full 256 luminance levels. To display gray level 255 (white), the FRC algorithm should ideally generate a data sequence of 252⇒256⇒256⇒256. 252 is 63x4 and 256 is 64x4. However, the value of 256 (64x4) is out of the range of a 6-bit driver IC, which spans 0 (000000₂) to 63 (111111₁₂). For this reason, the upper 3 input data values (255, 254, 253) have the same luminance level as 252. Thus, only 253 luminance levels are available in the conventional algorithm. Even though the input image data is full color (256x256x256 = 16,777,216 ~ 16.7 M), the total number of available colors in a 6-bit LCD with conventional FRC is 253x253x253 = 16,194,277 (~16.2 M colors).

3. Hi-FRC for Higher Color Depth

A novel FRC algorithm which enables more than 16.2M colors, “Hi-FRC”, is now presented. A schematic diagram of Hi-FRC is shown in Fig. 5. Conventional FRC reduces 2 bits from an 8-bit input. Hi-FRC reduces 3 bits from 9-bit expanded data as shown in Fig. 5. 9-bit data can have more than 500 levels. The key idea for Hi-FRC to display higher color depth is to select the 256 different levels from among more than 500 levels.

Concept: Table 1 shows an example of Hi-FRC with full color depth. The 255 gray level input is transformed to 504. Through the 8 frames, input data of the source driver IC is maintained at 504 (63x8) as shown in Table 1. The 254 gray level input has an
expanded data value of 502. The input data sequence is comprised of 496 (62x8) through 2 frames and 504 during the other 6 frames. The temporal average is (496x2 + 504x6)/8 = 502. In this way, all 256 input gray values have 256 distinguishable luminance levels.

$$c_1 \cdot 504 = (111111000)_2 = 63x8, \quad 496 = (111110000)_2 = 62x8$$

<table>
<thead>
<tr>
<th>Bbit</th>
<th>9bit</th>
<th>frame 1</th>
<th>frame 2</th>
<th>frame 3</th>
<th>frame 4</th>
<th>frame 5</th>
<th>frame 6</th>
<th>frame 7</th>
<th>frame 8</th>
</tr>
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<tbody>
<tr>
<td>255</td>
<td>504 = 504+0000</td>
<td>504</td>
<td>504</td>
<td>504</td>
<td>504</td>
<td>504</td>
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<tr>
<td>254</td>
<td>502 = 496+1110</td>
<td>496</td>
<td>496</td>
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<td>496</td>
<td>496</td>
<td>496</td>
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<tr>
<td>253</td>
<td>500 = 496+1000</td>
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<tr>
<td>252</td>
<td>498 = 496+0100</td>
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<td>251</td>
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<tr>
<td></td>
<td>504 = 111111000 = 63x8, 496 = 111110000 = 62x8</td>
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</table>

Table 1: An example of Hi-FRC for higher color depth

Temporal Averaging: Lower 3-bit data values are 000, 001, 010, ..., 101, 110, 111. For data with 0 least significant bit (LSB) such as 000, 010, 100, and 110, there is no difference from the conventional FRC of 00, 01, 10, 11, conceptually. Thus, we will present the temporal averaging of the data with 1 LSB such as 001, 011, 101, and 111. Through the 8 frames, for 001 data, the data sequence of 000 during 4 frames and 010 during 4 frames can make a temporal average through 8 frames to be 001 as shown in Fig.6. Conceptually, 000 has the same FRC pattern as 00 in conventional FRC.

![Temporal averaging concept of Hi-FRC](image)

Spatial Averaging: Fig. 7 shows the example of a spatial dithering concept. For the case of 011, Hi-FRC needs 64 pixels (8x8) for spatial averaging. 32 pixels on upper left and lower right have 010, but 32 pixels on upper right and lower left have 100. By this reason, the spatial average is 011.

![Spatial dithering concept of Hi-FRC (011)](image)

Experimental Results: Fig. 8 shows the measured data of a 6-bit LCD panel with an application of Hi-FRC. As shown in Fig. 8, the measured results say that Hi-FRC can generate 256 luminance levels. Thus, a 6-bit LCD panel with Hi-FRC technology can display full colors (16.7 M colors).

![The measured luminance according to 256 input gray when Hi-FRC is applied](image)

5. Hi-FRC for High Color Performance

The color shift phenomenon of TN mode can be improved by Hi-FRC. Hi-FRC uses the data expansion to 9-bit from 8-bit. If there are differences between the expanded data of red, green, and blue, the color shift phenomenon can be improved as presented at SID’03 [2]. Then, a monitor with Hi-FRC function can meet the color gray scale linearity requirements of TCO’03 [3], even in TN mode. Fig. 9 shows the application results of Hi-FRC. If the expanded RGB data are the same, the blue gamma curve is located above the green and red curves. But, 9-bit addressing in combination with the lookup table enables overlapping RGB curves. Then, the color shift (ΔCCT: correlated color
temperature) can be improved to 1500K from 3000K at gray level 64. The $\Delta u'v'$ value as defined in TCO’03 is reduced from 0.23 to 0.15. As shown in the figure, Hi-FRC technology enables TN mode to meet TCO’03 color grayscale linearity limits ($\Delta u'v' < 0.02$).

![Figure 9: Comparison of RGB gamma curves](image1)

(a) Same expanded RGB data

(b) Overlapping expanded RGB data

Figure 9: Comparison of RGB gamma curves

![Figure 10: Comparison of correlated color temperature](image2)

6. Conclusion
We have proposed a new dithering algorithm, “Hi-FRC”, to enable full (16,777,216) color on an LCD panel with 6-bit source D-IC’s. Conventional FRC can display only 16,194,277 colors. Thus, Hi-FRC results in a higher performance LCD panel without any additional cost. In addition to higher color depth, Hi-FRC enables better color performance on an LCD panel. Conventional TN mode cannot meet the color grayscale linearity requirements of TCO’03. As shown in the experimental results, Hi-FRC enables TN mode to meet TCO’03 color grayscale linearity limits.

References
[3] TCO’03 Displays, Flat Panel Displays, TCOD1024 Ver 1.1, 2002