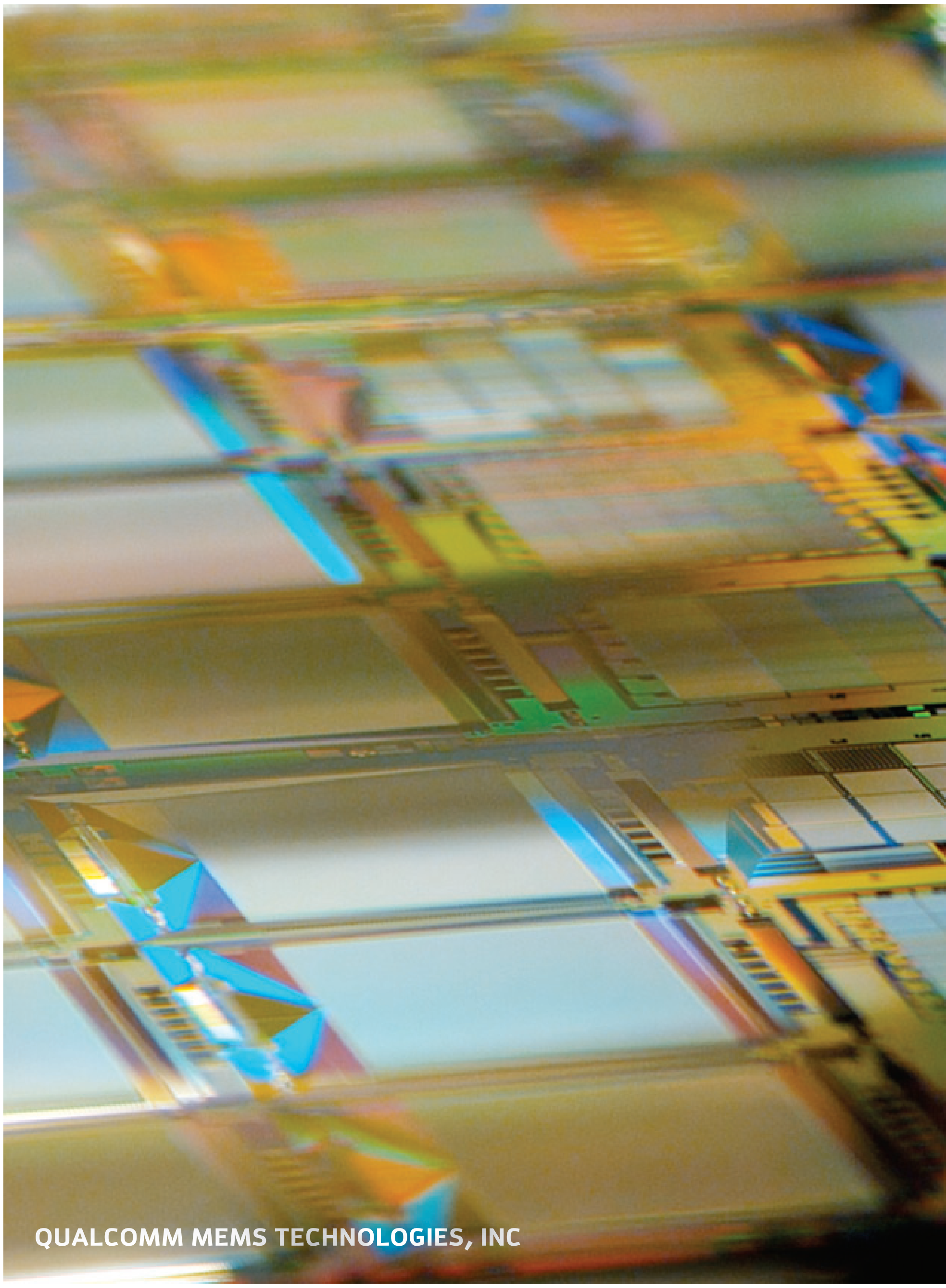
Mobile Color Depth



QUALCOMM MEMS TECHNOLOGIES, INC

mirasol®
Displays by Qualcomm

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Executive Overview

The perception of display performance is the result of a combination of display characteristics, viewing environment and human vision. Common use of displays provides ample evidence that performance depends upon viewing environment, yet no allowance is made for this in typical display metrics. Instead, display performance is typically described by contrast ratio, color gamut and bit depth. While these three metrics describe specific aspects of a display, the first two metrics themselves interact and change with environment, but are measured only in dark room conditions, while the third is not a measurement at all, but rather a configuration of the electronic drive circuitry. As a result few display experts, let alone consumers, can extrapolate performance to real world viewing conditions and compare one display versus another. This leaves the consumer without a useful guide and arbiter of display performance. Mobile Color Depth (MCD) is a metric that fills this void – based upon display performance in real world conditions and upon existing vision science – describing the number of perceived colors a display can generate in a particular viewing environment.[1] With these two specifications – the viewing environment and the number of perceivable colors, Mobile Color Depth provides both the industry and the consumer with a simple, single metric to compare the real world viewability of one display versus another.

Introduction

Current display metrics do not properly express the observed performance of displays. The published values for contrast, color gamut, and bit depth are at best relevant when displays are viewed in total darkness. Consequently, liquid crystal displays (LCDs) and organic light emitting diode (OLED) displays deliver impressive specifications, but when these displays are taken into bright daylight they become difficult and occasionally impossible to read. This performance degradation occurs continuously as ambient light levels increase from darkness to bright daylight. Even as the viewing environment reaches office conditions, the actual viewing performance is significantly and noticeably different from dark-room performance. This is particularly important for mobile consumer devices that are increasingly becoming a part of our lives. Mobile devices, including handsets, are commonly used across the entire range of viewing environments – from darkness to brilliant sunshine.

The disparity between specification and actual visual experience occurs because display performance is not independent of viewing condition and because current display metrics are typically expressed in terms of ‘addressable levels’ rather than ‘perceptual levels.’ Addressable levels represent the number of discrete electronic states that the system can present to the display medium. In the case of a LCD for instance, the display driver circuits apply a number of voltage levels to the liquid crystal material. There is no direct correlation between these electronic levels and the number of perceptual levels a user sees when viewing the display. What matters to the user of course is the visual perception of the image, rather than the input to the display.

While bit depth is referenced to the configuration of the driver electronics of the display, the other common display specifications of contrast ratio and color gamut are based upon laboratory measurements. The laboratory measurements are obtained in a totally dark environment and have been widely critized[2] for not correlating with real world viewing impressions. Every day, and in every viewing condition throughout the day, each of us uses our own eyes to judge the image quality of the displays we use. Therefore it is desirable to base a metric upon realistic viewing environments and quantifiable measurements of the human visual system. Such a metric could tell us (before we make a purchase decision) how well a particular display, and a product with that display, will perform in real-world situations. The question becomes, ‘How can the industry best describe the visual performance of a display?’ This has particular relevance to displays used in mobile devices. A response to this question is the creation of a new metric, named ‘Mobile Color Depth.’

Mobile Color Depth Defined

The mobile color depth metric is the result of work that shows that throughout typical viewing conditions the number of colors perceivable on a display is significantly lower than the number of color states addressable by the display drive electronics.[3, 4] In fact, the number of separately perceivable colors proved a more reliable predictor of display performance than any other metric. Consequently the numeric value of mobile color depth is simply the number of individually perceivable colors produced by the display under the viewing conditions of interest.

Mobile color depth not only provides a strong indicator of the display's overall performance, it is correlated to the display's contrast ratio and the display's color gamut as well. Displays with greater contrast and larger color gamut will be capable of portraying more colors than those with less contrast and less color gamut. For conventional displays, as ambient light increases in the viewing environment not only perceivable color depth, but perceivable contrast ratio and perceivable color gamut diminish as well.

Mobile color depth is based upon the vision science concept of a just noticeable difference (JND). This psychophysical measure allows researchers to quantitatively describe what viewers can and can not discriminate in an image. A color JND is the smallest color difference discernable by average human vision. From databases of JND studies, models of the human visual response can be created, and one such model, S-CIELAB[5, 6, 7], was used to define the mobile color depth metric. Observer tests were conducted to verify that the S-CIELAB results correlated with real world display viewability.

The result is a simple, single number metric that represents how a given display will perform in any given usage scenario. A display with a larger MCD value will be easier and more pleasing to see and use.

Methodology

Computing the Mobile Color Depth metric for a given display consists of a straightforward, step-by-step method. The MCD metric is equal to the number of individually resolvable colors provided by the display under a particular viewing condition. Thus, calculating the metric is an exercise in 'counting' these resolvable colors and specifying the viewing environment in which the counting occurred.

STEP ONE: The display manufacturer's specifications for addressable bit depth and gamma curve are obtained. These parameters will be used in the color counting process.

STEP TWO: The spectral characteristics of the display's emissive primary colors (if present) are measured, along with the display's reflectance of ambient light. The display's white state, black state and primary color states (typically red, green, and blue) are independently measured. This data can then be used to calculate the display's performance characteristics in different viewing conditions. This testing calculates the performance boundary of the display – the value of full white, full black, full red, full green and full blue. These values are calculated for the viewing environment of interest. For mobile displays typical viewing environments include a 'dark' environment, a home 'living room', an 'office' and an outdoor 'sunlit' environment.

STEP THREE: Using the published addressable level and gamma curve specifications together with the white, black and primary color calculations, a luminance versus addressed-level plot, such as the representative one shown in figure 1, is made.

Since MCD is applicable to displays utilizing static solid colors as well as spatially or temporally dithered colors, it is now that each of the spatial or temporal dither patterns (if dither is used in the display) is viewed. Dither pattern colors are compared to static solid versions of the same average color in the vision science S-CIELAB model. Any dither pattern color perceived as being more than one JND divergent from the solid color is removed from further consideration. In the case of spatial dither, this can be the result of a coarse dither pattern that the S-CIELAB model predicts will be perceived as a pattern of two or more colors. An included spatial dither pattern color may be comprised of multiple pixels, each with different colors, but the pattern is fine enough that the observer can not discern the detail. In this latter case, the observer perceives the average color. A simple example is a black and white checkerboard pattern. If the checkerboard is sufficiently coarse, the observer will discern the white and black squares. If the pattern is fine enough, the observer will see a 50% gray field. Clearly, colors containing visible dither noise are removed since these colors would be undesirable in an image while those resulting in the perception of the average color are retained

In figure 1 the squares on each of the primary color curves are symbolic of the individually addressable color points from black to a full primary color (red, green and blue). Having just discarded any of these colors with visible dither noise, the remainder are entered into the S-CIELAB vision model. The color coordinates for each addressable level are calculated using the manufacturer's bit depth specification and gamma curve. With the color coordinates of each addressable level in hand, the S-CIELAB model is used to determine whether each level is more or less than one JND from its neighboring levels.

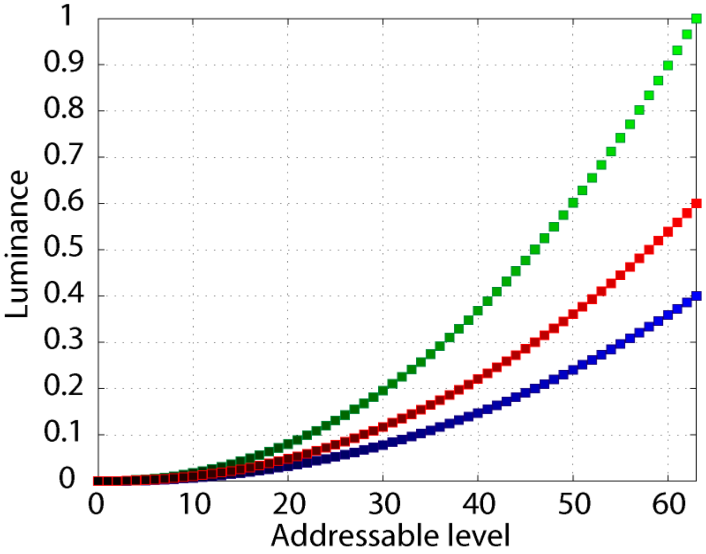

Figure 1. Representative plot of luminance versus addressable level for a display with 6 bits (64 levels) per primary channel.

STEP FOUR: This step represents the heart of the MCD metric process. It is an iterative procedure that considers each addressable level in turn, starting from black and determines if that level is noticeably different (more than one JND) from the level that came before it. Redundant levels, those whose colors can not be discerned from its neighbors, are removed from the palette. The number of colors remaining (visually just indistinguishable levels, as explained below) after the completion of the iterative process is the numerical value of MCD.

The process may be best understood by considering figure 2. This figure is an enlargement of the lower left-hand segment of the plot from figure 1, showing only the red color levels. Level 0 is the black state measured as described above. Level 1 is the first addressable red level above black. Small areas of the black color and the color of the first red level above black are printed side-by-side in figure 3. The S-CIELAB model is used to determine if the two colors are more or less than one JND apart. In this case, they are not. Therefore, Level 1 is discarded form the palette since it is redundant.

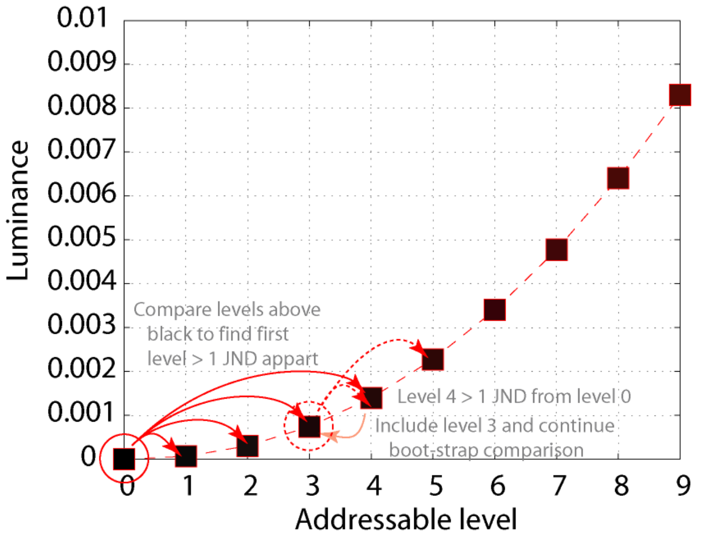

Figure 2. Detail of the lower left section of figure 1, showing only the red color luminance versus addressable level color points. Level 0 (black) is compared to its neighbors until a level is found with a color difference greater than 1 JND (in this case Level 4). To prevent a noticeable contour in a continuous color gradient, the level just below that of 1 JND (Level 3 in this case) is added to the palette. The iterative counting is continued by comparing the levels above Level 3 until one is found with a color just less than 1 JND apart.

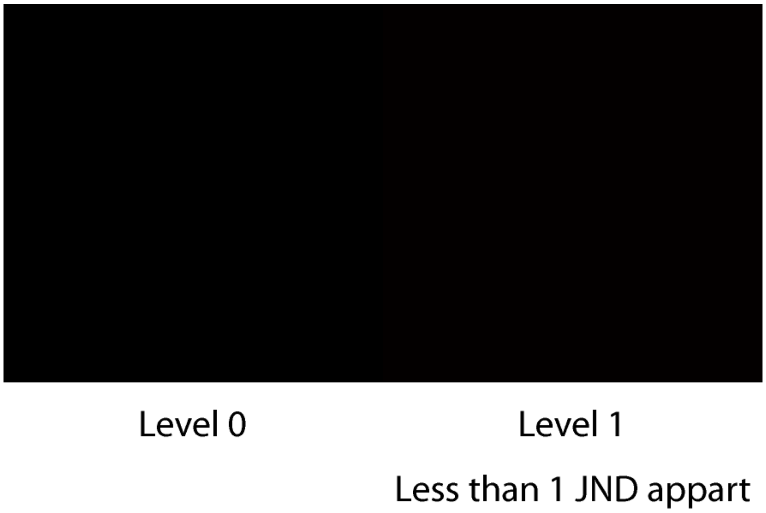

Figure 3. Comparison of colors between Level 0 (black) and Level 1 (red addressable color level just above black). These colors are less than 1 JND apart, so Level 1 is discarded from the color palette.

Next, Level 2 and Level 0 are compared. Once again there is not a JND between Level 0 and Level 2. Level 2 is discarded as well. The same is true of Level 3 and Level 0, but clearly, as shown in figure 4, there is a JND between Level 0 and Level 4. One's first instinct might be to include Level 4 in the palette, but if that were done, a border discontinuity would be visible between the Level 0 color and the Level 4 color when a smooth intensity ramp was applied to the display. Therefore, Level 3 is returned to the palette as the color just below 1 JND above Level 0 (black). Since the color of Level 3 was less than a JND from the color of Level 0, there will be no visible flaw in a smooth ramp from Level 0 through Level 3.

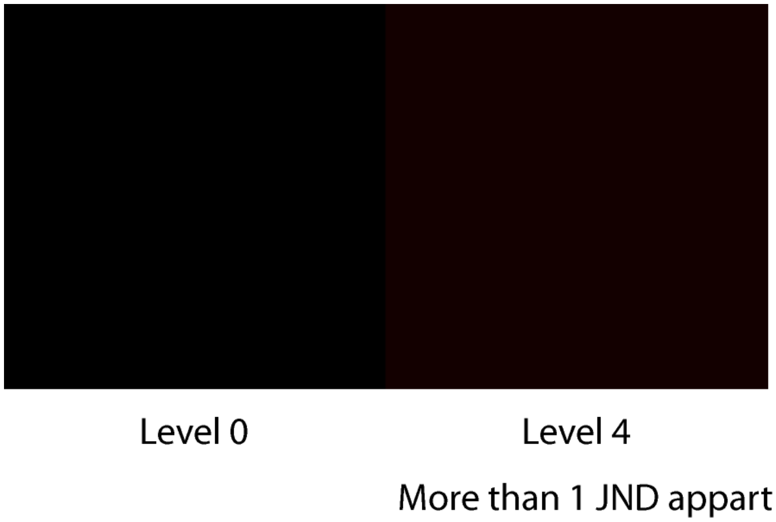

Figure 4. Comparison of colors between Level 0 (black) and Level 4 (red addressable color four levels above black). These colors are greater than 1 JND apart. To avoid a discontinuity in a color ramp, the level just below 4 is included in the palette. The iterative search continues to fill the color palette by looking for the color level just below 1 JND above Level 3.

With Level 3 as the next included palette color above Level 0, the iterative procedure begins again, with Level 3 as the reference. The color of Level 4 is compared to the color of Level 3, and either kept or rejected. Eventually, a red color just less than one JND above Level 3 is discovered and added to the palette. That new palette color is compared to the color of ongoing levels and the process continues until the entire red scale is populated. Each palette color is not-quite-noticeably-different from its neighbor, but no redundant colors have been included.

The procedure continues with the green primary and then the blue primary. When all of the primary palettes have been determined, the counts of each primary are multiplied (RED_n x GREEN_n x BLUE_n = MCD) to yield the value of mobile color depth. To complete the metric, the viewing environment used as the basis of the calculation is included. To ease comparison with convention, the MCD number may be rounded to the nearest binary value.

Application to mirasol® displays

Qualcomm MEMS Technologies developed the mirasol display technology with the goal of creating the first low-power; multimedia-capable display that is clearly viewable across a broad spectrum of lighting conditions.[8, 9] Using mirasol displays in real-life environments makes this clear. Part of this performance is due to the reflective nature of mirasol displays. While conventional displays will have MCD metrics that vary as a function of viewing environment, mirasol displays will have constant MCD values for conditions brighter than a typical home living room. In the following, the mobile color depth metric is applied to three mirasol displays.

A 1.4” QCIF (176x144) mirasol display was evaluated in the ‘office’ environment. The mirasol display used 18 bits of dithered color and 6 bits of directly addressable color to achieve a nominal number of 193x193x193 = 7.2 million colors. After the JND process was applied to the dither states, 193, 179, and 193 levels remained. After the iterative counting process was completed there remained 18x18x11 = 3500 colors.

Similarly a 2.2” 384x288 demonstration mirasol display, representative of future commercial displays, was evaluated in the ‘office’ environment. This display also used 18 bits of dithered color and 6 bits of directly addressable color to achieve the same 7.2 million nominal levels. However, after the JND process was applied to the dither states, 193, 191, 193 levels remained. After the boot-strap counting process was completed, there were 45x73x19 = 62,415 colors. This increase is due primarily to increased contrast and resolution (223 ppi versus 160 ppi).

Finally a 5” 384x288 demonstration bichrome mirasol display was evaluated in the same ‘office’ environment. This display used 6 bits of dither and 1 bit of directly addressable color to achieve 65 nominal levels. However, after the JND process was applied to the dither states 40 levels remained. After the iterative counting process was completed, 22 shades remained.

These MCD metrics provide real-world predictions of the performance of these displays across the range of lighting conditions from living room to bright sunlit outdoors.

Conclusions

To provide consumers and the display industry with a means to compare real-world viewing impressions of display performance, a new metric is required. This new metric should be based on existing vision science and display performance in real-world viewing conditions and capture the human perception of a display. Mobile color depth provides such a metric, utilizing existing vision science concepts of a just noticeable difference and models of human perception along with display performance in realistic viewing environments. The adoption of mobile color depth by the display industry brings clarity to discussions of display performance to both display experts and consumers.

Inputs to the MCD metric are the display's addressable color specification, the display's gamma curve specification, and a small number of straightforward, real-world measurements. These input data are evaluated using the S-CEILAB vision model and an iterative color counting method to calculate the number of just- discernable colors that constitute the useable extent of the display's palette under a given viewing condition.

The Mobile Color Depth metric is simply the number of these useable, real-world colors for the stated viewing condition. By basing the metric on the perception of colors and the viewing environment, it becomes possible to make a simple and direct comparison of display to display performance.

Notes:

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White Paper

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