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Estimating OLED Display Device Lifetime from pixel and screen brightness and its application

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Abstract

In this paper we discuss a model to estimate the power consumption and lifetime (LT) of an OLED display based on its pixel value and the brightness setting of the screen (scbr). This model is used to illustrate the effect of OLED aging on display color characteristics. Model parameters are based on power consumption measurement of a given display for a number of pixel and scbr combinations. OLED LT is often given for the most stressful display operating situation, i.e. white image at maximum scbr, but having the ability to predict the LT for other configurations can be meaningful to estimate the impact and quality of new image processing algorithms. After explaining our model we present a use case to illustrate how we use it to evaluate the impact of an image processing algorithm for brightness adaptation.

Introduction

In this article we will review current industry definitions of OLED lifetime (LT) and methods used to model this parameter. We propose a revised model and demonstrate its use to evaluate the lifetime of an OLED display as a function of the content displayed. We then continue with a description of two experiments we conducted on a Google Pixel 2 XL where we describe how the display gamut is modified as a function of simulated OLED aging and how our model can be applied to evaluate the impact of image processing algorithms on OLED color characteristics as a function of OLED aging.

In the following sections you will find a definition of OLED lifetime, existing models and their limitations. Most of the described approaches were designed to model differences in OLED material and OLED structure. We extend the individual OLED lifetime model to an OLED display lifetime model. Our model links power consumption measurements to the parameters of the model we discuss: the OLED LT is dependent of both the pixel values and the brightness setting of the screen. This section also explains how we retrieve information from an OLED display, including current density for the different OLED color emitters.

The experiment section presents two experiments based on the OLED display LT model we propose, including an experiment to estimate the gamut volume reduction over time and the study of display degradation after modifying the image content. Finally we discuss the results and follow-up projects initiated by this work.

Defining OLED Lifetime

Within the OLED display literature, OLED LT typically describes the intensity of light emission from an individual OLED emitter when driven at a constant set of conditions as a function of time. The resulting intensity decay function demonstrates how the intensity of a given OLED emitter decreases over time (t) as compared to its original value L_0. Often terms such as $LT95$, $LT70$ or $LT50$ are applied, referring to the number of hours required for the ratio of $L(t)/L_0$ to obtain 0.95, 0.7 or 0.5, respectively.

It is worth noting that these metrics were originally created by OLED material manufacturers for the purpose of differentiating various materials and material structures from one another [19, 15]. Materials having a longer $LT70$ or $LT50$ would logically produce displays having more stable light output. In the early days of OLED collection of this data was relatively straight forward as material lifetimes were relatively short, thus collecting these values required days or weeks of testing. As advances in OLED occurred, making OLED displays practical, these values have been extended into the $10s$ and $100s$ of thousand hours making collection of this data time consuming. Therefore, devices are often exposed to stressful situations [9], such as increasing surrounding temperature, providing higher current than needed, or exposing the OLED to light sources without the usual protection filters to accelerate OLED aging. In these approaches knowledge is required about the material to relate the measured intensity degradation to the intensity degradation of the OLED emitter under standard use, to establish the relationship between the accelerated and the representative time scale.

It is worth noting, however, that these standard industry definitions provide insight into the relative aging of two emissive materials or two OLED structures when evaluated under similar conditions. These definitions provide very little insight into the lifetime of an OLED display or changes in the color characteristics of an OLED display as it ages.

Models of Individual OLED lifetime

Various mathematical functions have been explored for describing the intensity decay function of an OLED emitter[12]. For example, Birnstock and colleagues [4] discuss the use of the double exponential function shown in Equation 1.

$$L(a,b,\alpha,\beta,t) = L_0(a\exp(-\alpha t) + b\exp(-\beta t)) \tag{1}$$

The first term in double exponential formulation represents a rapid loss of luminance that occurs early in the life of an OLED while the second term represents a more gradual decay which occurs once the display has undergone an initial aging period. Although this model can provide a good fit to OLED aging, recently the stretched exponential model [11, 8, 3, 6] shown in Equation 2 has gained acceptance.

$$L(t, \tau, \beta) = L_0 \exp(-(t/\tau)^{\beta}), \tag{2}$$

In this model t is the time in hours, τ is the decay time constant, β the stretch factor according to [5]. The fact that this model has fewer parameters makes it easier to fit. While this model appears to represent OLED lifetime each OLED material will have specific parameters values for a given test condition. That is, a blue or red OLED emitter will have different τ and β for each test condition and these values can vary as a function of temperature, current, or other factors.

For example, using values $LT95$ and $LT50$ from a material information sheet [18] presented in Table 1 can allow us to obtain τ and β using curve fitting technique.

	$LT95$	$LT50$	τ	β
orange	23000h	600000h	958989	0.792
green	18000h	400000h	624755	0.833
blue	700h	20000h	32387	0.77

Table 1. $LT50$ **and** $LT95$ **for three color OLED emitters assuming** $LT100 = 1h$ **from [18].**

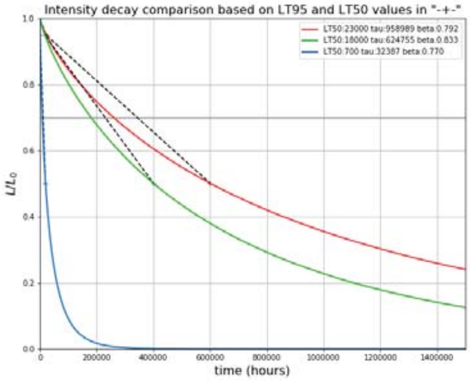

Figure 1. *Based on the three reference points for each OLED color emitter their intensity decay function is plotted. Curve fitting technique are used to obtained τ and β parameters.*

While the data in Table 1 are a few years old, it is interesting that the lifetime of the various emitters are not equal. In fact, we can see that the blue OLED example has a shorter LT as its half-time is reached after only a few hundred hours, the intensity decay curves in Figure 1 illustrate these differences.

The modeling approach as described is powerful as it permits us to understand the entire decay function of each material as a function of time. Unfortunately, this approach considers a single operating condition for the OLED emitter, e.g., one current and temperature. As has been well documented [5, 14], current and to a lesser degree temperature, will significantly affect OLED lifetime. Therefore, this model does not permit us to estimate the different current values that will be employed to control the display as the display is driven to different pixel and *scbr* values.

The existing models are not sufficient to relate the LT model to the power consumption, color performance or perceived lifetime of the display. As we have seen in the technical specs [19] shared by the OLED makers the efficiency and current density is sometimes given in addition to $LT50$ but again only for individual drive conditions, which often represent relatively extreme values. To estimate display characteristics, it is important to extend these models to include parameters relevant to the entire display.

OLED Display lifetime model

To understand the effect of algorithm development on display power and lifetime, it is important to not only develop a luminance decay function which permits one to provide a relative comparison between OLED material and device configurations, but that captures relative changes in the light output of the display in response to changes to the information that is displayed. Such a lifetime model must, therefore, be sensitive to changes in current input into the display.

Importantly, L_0 varies as a function of current density. Normalizing the curves such that all of the curves have the same origin, it becomes obvious that as the current increases, the rate of luminance decay increases as shown in Figure 2 using functions fit for Equation 2 to the data from Meerheim and colleagues[16]. As shown in that figure, the decay of the OLED depends on both the materials within the OLED and the current per area used to drive the OLED (the two colors black and blue describe material differences when the different shapes describe different current drive). Each of these parameters have similar effects on the light output as a function of time.

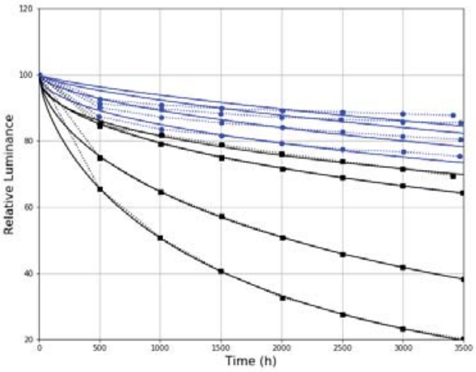

Figure 2. *Intensity decay curves for various currents and two different material according to [16]. Curves computed from fitting Equation 2.*

In the current work, we wish to understand the effect of image content and *scbr* on display color changes which occur as a result of OLED aging. Unfortunately, we lack the intensity decay function for each of the three colored OLED emitters in our test OLED display or the measurement of luminance for each channel over time. As a result we can't really use Equation 2 without diverting from the material properties, which we don't know neither.

What we have is the display power consumption profile at time t_0 for different current drive (i.e. different pixel values) and display brightness (i.e. different *scbr*). For practical reasons we choose to represent OLED luminance decay using a mathemati-

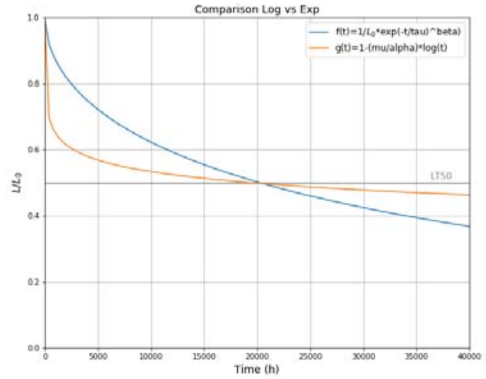

Figure 3. *Comparison of mathematical function for the intensity decay curves. The log function we proposed has a faster early drop than the exponential function.*

cal function that follows the previously discussed OLED display properties of intensity degradation in relation to the current drive. Therefore we propose the use of a log intensity decay function to describe the loss in luminance intensity of an OLED emitter with time as follows:

$$F(t, \mu_d) = 1 - \mu_d \log(t) \tag{3}$$

where

$$\mu_d = \frac{d(p, scbr)}{\alpha} \tag{4}$$

is the parameter for a given OLED emitter dependent of the current density $d(p, scbr)$ where p is the pixel value, $scbr$ the display screen brightness and α a constant.

It is worth noting that the mathematical function *log* we choose to model the lifetime on an OLED display has a different shape that the *exp* stretched function used to model the lifetime of OLED emitter. Figure 3 illustrates this difference. If the overall relationship intensity decay versus time is respected the *log* model has a very strong drop off which we can't verify at the moment.

Display power profile

To quantify the power consumption of an OLED display a Pixel 2 XL smart-phone was obtained. To isolate the power consumption of the display, it was necessary to disable as many of the cell phone the tasks as possible. Therefore, flight mode is activated, all wireless communications and automatic notifications are switched off [7]. A native Android OS version was ran with an application to display the images during measurement. We display images of single color (e.g., red, green or blue) such that all pixels on the screen are set to the same digital value.

We use a PowerMonitor device from Monsoon [17] to record the device activity as described in [10]. In Python programming we are able to automate measurement sequences such that each reference image is measured 10 times over a 60 second period. Figure 4 illustrates 7 measurements corresponding to a black image, two images of pure red, two images of pure green and two images of pure blue of respectively 128 and 255 code values.

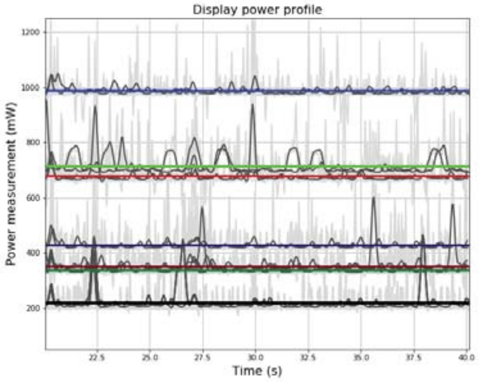

Figure 4. *The figure above highlights the last* 20*seconds of* 7 *measurements taken for a period of* 60*s each. The colored flat lines represent the average measurement of each measurement plotted in light gray. This is the average value that we use later in our model. From top to bottom are the measurement of maximum blue, green and red (each image has* 255 *code value for the corresponding color channel), then middle blue, red and green (each image has* 128 *code value for the corresponding color channel) and finally a black image with* 0 *code value for each color channel.*

Current density

Having the power consumption measurements of single color images for various *scbr* allows us to compute the corresponding *current density* for these combinations as follows:

$$d(p, scbr) = \frac{current(p, scbr)}{area} \tag{5}$$

where *current* is the measured current of an image where all pixels have the same value (e.g. $red = 255$ when $green = 0$ and $blue = 0$) and *area* is the surface occupied by the given OLED emitter.

Different OLED displays have pixels with different sizes and shapes of light-emitting elements. The Google Pixel 2 XL device has a PenTile RGBG layout. Therefore, the green pixels have an higher resolution than the red and blue pixels. The information we need is the ratio of each OLED emitter on the display surface.

Estimation of the sub-pixel areas

Looking at Figure 5 we can estimate the total *area* covered by the red, green and blue pixels in the Google Pixel 2 XL. As shown, the sub-pixels areas do not cover the entire display surface and have different coverage of the display area. Having the value of the display diagonal, the proportion of the display area covered by each color of light-emitting element and its resolution we can deduce the *area* in cm^2. This information is then fed into Equation 5 and the resulting current density can be used as an input in Equation 3.

As noted earlier in Figure 2, OLED decay occurs more rapidly at higher current densities than for lower current densities and typically occurs more rapidly for higher energy emitters (e.g., blue) than lower energy emitters (e.g., red). As the decay functions for the OLEDs in the Pixel 2 XL are not known, we must make additional assumptions regarding these functions to explore

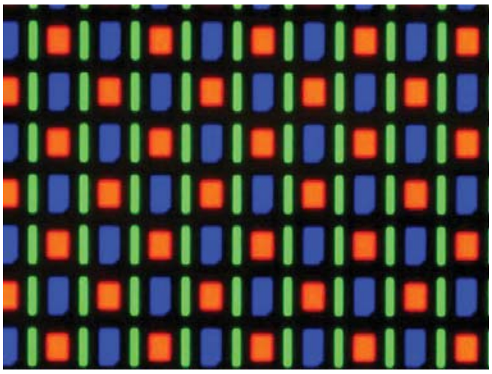

Figure 5. *Microscope image of an OLED display with the RGBG pixel matrix distribution. We can observe the double occurrence of green pixel comparing to the blue and red pixels.*

the effect of these decay functions on shifts in color with age. In this example, it is assumed that the designers of the Pixel 2 XL optimized the area of the three different colored emitters such that at high *scbr* each emitter will have similar intensity decay functions. This assumption should avoid the appearance of color shifts due to one color emitter having an intensity decay function which drops faster than the others. As a result, we have chosen the parameters for the intensity decay function such that each color channel has a similar life expectation setting with $LT50$ assumed to be 20000h.

From the power measurements we compute the current density $d(255, 100\%)$ for each OLED color emitter and adjust the μ_d parameter using optimization techniques in Equation 4 such that $F(20000, \mu_d) = 0.5$. That is we select the α parameter for each primary assuming the display is driven to the maximum possible current density. For later use of the function in Equation 3 the α parameter is then fixed and the current density is re-computed. Example of decay curves obtained for the red channel for two *scbr* values and two different pixel values in Figure 6.

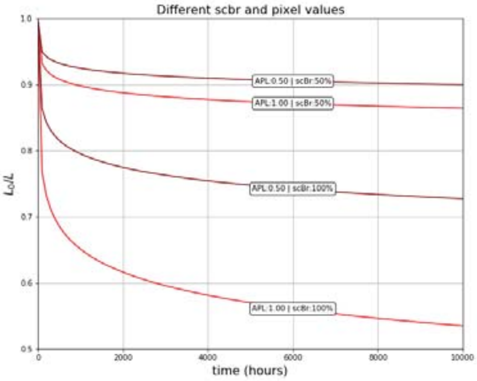

Figure 6. *In that figure we are showing the intensity decay curves for the red channel for two APL and $scbr$ values. It is interesting to reveal which parameter, APL versus $scbr$ has the strongest impact on the simulated OLED LT. The lower is the $scbr$ the slower is the intensity curve decaying.*

Experiments

Two experiments were conducted to illustrate the use of the proposed OLED LT model. The first experiment evaluates display gamut compression over time. The second experiment attempts to determine the impact of algorithms that modify images according to the ambient light condition on OLED LT.

Gamut compression over time

Starting from a standard sRGB gamut we evaluate how its volume is reduced after $t = [100, 1000, 2000, 5000, 10000, 20000]$ hours assuming $scbr = 100\%$. We define the orignal gamut by the matrix $\mathbf{M_{ori}}$ as follows:

$$\mathbf{M_{ori}} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \tag{6}$$

where each column represents the CIEXYZ values of each display primary. The prediction of CIEXYZ values for a pixel combination $\mathbf{p} = [r,\ g,\ b]^T$ is then obtained by doing [20]:

$$\mathbf{c} = \mathbf{M_{ori}} . \mathbf{p} \tag{7}$$

and $\mathbf{c} = [X,\ Y,\ Z]^T$. We need to define the modified matrix $\mathbf{M_{mod}(t)}$ that represents how the gamut properties change over time. We verified by measurement that only the Y value of each primary is affected by the OLED lifetime and that their respective chromaticities remain unchanged, e.g. for the red $Y'_R = F_R(t).Y_R$ using Equation 3.

Starting from a pixel $p = [r,\ g,\ b]^T$ in the modified gamut we want to know the corresponding values $p' = [r',\ g',\ b']^T$ in the original gamut. Having the two matrices defined the operation to obtain p' is the following:

$$\mathbf{p'} = (\mathbf{M_{ori}^{-1}} . \mathbf{M_{mod}(t)}) . \mathbf{p} \tag{8}$$

To express $\mathbf{M_{mod}(t)}$ we need to isolate the Y from the gamut matrices, starting with

$$\mathbf{c} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = Y \begin{bmatrix} X/Y \\ 1 \\ Z/Y \end{bmatrix}, \tag{9}$$

we can re-write the matrix of CIEXYZ primaries as

$$\mathbf{M_{ori}} = \mathbf{P} . \mathbf{L_{ori}} = \begin{bmatrix} \frac{X_R}{Y_R} & \frac{X_G}{Y_G} & \frac{X_B}{Y_B} \\ 1 & 1 & 1 \\ \frac{Z_R}{Y_R} & \frac{Z_G}{Y_G} & \frac{Z_B}{Y_B} \end{bmatrix} \times \begin{bmatrix} Y_R & 0 & 0 \\ 0 & Y_G & 0 \\ 0 & 0 & Y_B \end{bmatrix} \tag{10}$$

and the modified gamut as:

$$\mathbf{M_{mod}} = \mathbf{P} . \mathbf{L_{mod}} = \begin{bmatrix} \frac{X_R}{Y_R} & \frac{X_G}{Y_G} & \frac{X_B}{Y_B} \\ 1 & 1 & 1 \\ \frac{Z_R}{Y_R} & \frac{Z_G}{Y_G} & \frac{Z_B}{Y_B} \end{bmatrix} \times \begin{bmatrix} F_R(t, \mu_d) Y_R & 0 & 0 \\ 0 & F_G(t, \mu_d) Y_G & 0 \\ 0 & 0 & F_B(t, \mu_d) Y_B \end{bmatrix} \tag{11}$$

where $F_R(t, \mu_d)$, $F_G(t, \mu_d)$ and $F_B(t, \mu_d)$ are the ratios for each primary computed using Equation 3 a time t. Therefore Equation 12 can be re-written as follows:

$$\mathbf{p'} = ((\mathbf{PL_{ori}})^{-\mathbf{1}} . \mathbf{PL_{mod}}) . \mathbf{p} = [r',\ g',\ b']^T \tag{12}$$

From Equation 12 we compute different set of points (all combinations of RGB code values $\in [0,\ 4,\ 8,\ 12,\ \dots,\ 255]$) for each time t we want to evaluate the gamut compression. Computation is performed in CIEXYZ space, but for visualisation purposes we show how is the gamut compressed in CIExyY space: original gamut in Figure 7 after $10000h$ in Figure 8. We can observe that the gamut is mostly compressed along the Y axis.

The color gamut volumes are computed using the convex-hull [2] algorithm in $3dim$ from the Python SciPy library [13] in CIExyY space and CIELab space and presented in the Table 2.

time (h)	volume (xyY)	volume (Lab)
1	100%	100%
100	75.9%	75.5%
1000	64%	63.4%
2000	60.5%	59.8%
5000	55.8%	55%
10000	52.3%	51.4%
20000	48.7%	47.9%

Tabel 2. This table presents how the gamut will be compressed over time. Volume is computed from a cloud of point in RGB space converted to CIExyY and CIELab spaces.

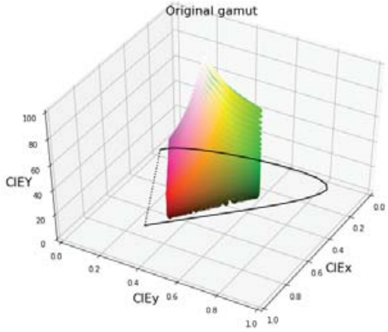

Figure 7. *Original RGB gamut in CIExyY space from a cloud of* 35937 *points spanning regularly the RGB cube.*

From image to APL representation

In the previous example in Figure 6 we simulated the intensity decay function over time using the average picture level (APL). As we were simulating a display with all pixels turned on to the same value, the APL representation was appropriate. Ultimately, we would like to evaluate the impact of different image content on the display LT.

By comparing the LT decay curves from an histogram image representation (see Figure 9) to its APL representation we verified that the APL representation of an image was acceptable for our experiment. In Figure 10 the magenta and black dashed lines overlap, indicating that computing LT with the average current density or computing the weighted average of LT values produced similar LT estimates.

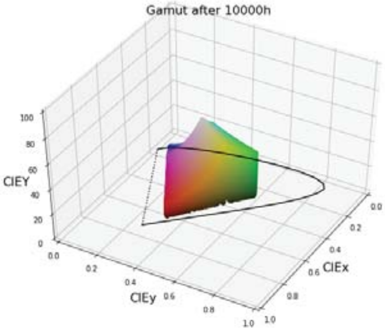

Figure 8. *Visualization of the sRGB gamut in a CIExyY space at* $time = 10000h$ *at maximum* $scbr$*. Volume is equivalent to* 52.3% *of the original one in Figure 7 in CIExyY space and* 51.4% *in CIELab space.*

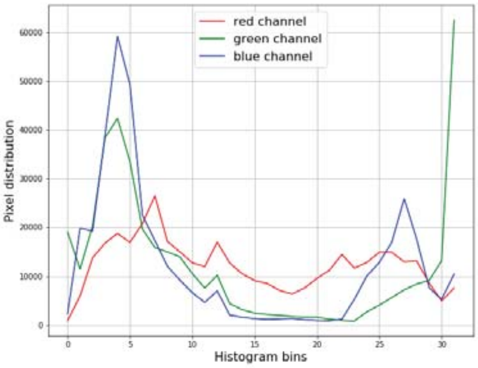

Figure 9. *Histogram visualization for each channel of the image presented in Figure 11 for* 32 *bins.*

Evaluation of brightness algorithm over time

In the second experiment sought to estimate the impact of algorithms such as a luminance re-targeting [21, 1] (LRT) algorithm on OLED and LT. LRT can be used to reduce the luminance display while maintaining the perceived image quality.

Applying these LRT algorithm without dimming the display (ie. lower $scbr$) typically increases the brightness of the image, which for an OLED display guarantees to lift up its power consumption and fasten its aging. In our previous article [10] we have shown that each pixel in an OLED display counts, the display power consumption is directly content dependent.

Similarly, increasing the APL for the same $scbr$ accelerates the loss of luminance intensity as a function of time and that for the same APL and different $scbr$ the relationship changes as observed earlier in Figure 6.

In our test we investigate 100% and 60% reduced $scbr$ and applied LRT algorithms for $5K$, $10K$ and $25K$ lux ambient light condition. This specific $scbr$ value is obtained from the luminance

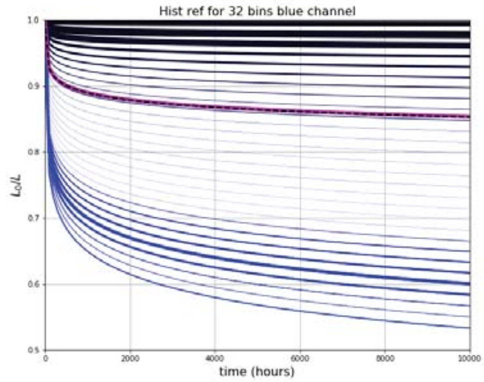

Figure 10. *Visualization of the blue channel histogram of the image presented in Figure 11 where eah decay curve is scaled according to the number of pixels in the corresponding bin.*

profile we have conducted on the test display.

We did select 32 test images including natural scene (18 images), faces (4 images), synthetic automotive dashboard contents and snapshots of social network (10 images) and show one example in Figure 11. The image quality is evaluated by experts on the following setup: comparing original versus processed by LRT images without dimming (both displays at 100% *scbr*) and with dimming (both displays at 60% *scbr*), this for various controlled ambient lighting conditions.

We used our lifetime model to compare intensity decay curves for our test cases, the average APL for each channel of the whole image set of LRT processed images is $[0.43,\ 0.41,\ 0.42]$ for red, green and blue channels respectively, a little bit higher than the one of original images with $[0.31,\ 0.32,\ 0.32]$ for the $10K$ case. Corresponding decay curves for the red and blue channel are presented in Figure 12 and Figure 13. Those decay curves allow to compare the LT values for the same number of hours between scenario or numbers of hours for the same LT value. Because of the choice made of a log function for the decay curve the numbers we obtained my not be taken for granted.

We can extent this time study and use all the data from the decay curves by defining the metric $Q_{LT}(\mathbf{conf})$ that represents the *amount of light output* that we gain or loss depending of the algorithm applied. This metric consists of a sum of integral over time for each decay curve as follows:

$$Q_{LT}(\mathbf{conf}) = \sum_{R,G,B}^{i} \int_{1}^{LT50} F_i(t,\mu_d)dt \tag{13}$$

where the result for the original images at $scbr = 100\%$ is our reference $Q_{LT}(\mathbf{ori})$. Same formula used for the processed images at $scbr = 60\%$ gives us $Q_{LT}(\mathbf{pro})$. We reduced the time interval to $[1,\ LT50]$ (which we have set to $LT50 = 20000h$) and we obtain for this amount of hours a relative increase of 8.5% of the ligth output of display for the test configuration of $5K$ ambient ligth, 8.2% for $10K$ and 8% for $25K$.

Figure 11. *Snapshots of similar OLED displays under ambient light* $10K$ *showing the original image (top) at* $scbr = 100\%$*, original image (middle) at* $scbr = 60\%$ *and processed image at* $scbr = 60\%$*.*

Discussion about lifetime interpretation

The lifetime model is interesting because it is adding another dimension to the image quality evaluation. We are now able to say *"we know an OLED display will degrade over time*" but this image processing algorithm applied to these images on those OLED displays with those luminance properties will not be an accelarator of this inevitable degradation. On the contrary it will virtually extend its lifetime as we slow down the intensity decay and increase the ligth output of the display.

The challenge in this model is to relate a known phenomenon of "*OLED material aging*" to an actual "*calibrated and functionning OLED display*". OLED materials are degrading over time, the intensity of the color emitter will decay at constant current and will decay faster when more current provided is increased. The approach we proposed extends a physical model to a functionning display model.

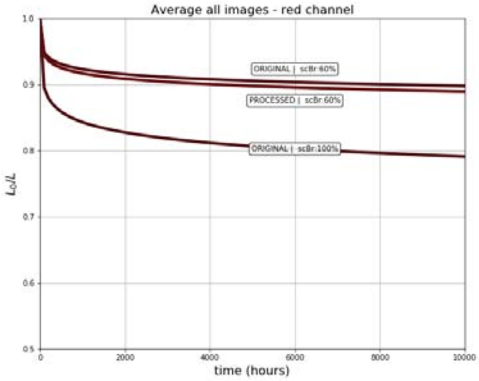

Figure 12. *Comparison of the intensity decay of the red channel for the average of all original and process images for a* $10K$ *ambient light.*

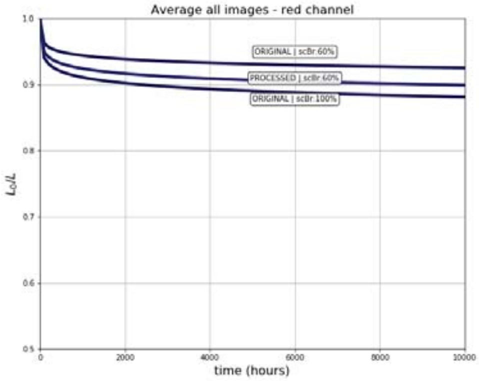

Figure 13. *Comparison of the intensity decay of the blue channel for the average of all original and process images for a* $10K$ *ambient light.*

Conclusion and Future Works

In this article we have presented a model to predict OLED lifetime as a function of current drive. We extended the existing models for single OLED emitter materials to a full OLED display. We explained our method based on assumptions that were required due to the lack of OLED material information.

Most of the existing OLED lifetime models only consider extreme conditions (e.g. predict lifetime of a display showing a full white image at maximum available device brightness *scbr*). Our approach relies on the display power consumption profile which we apply to obtain the current density of any pixel and *scbr* combination. The model we discussed uses this current density as a parameter to estimate the corresponding intensity decay curve parameters. We choose an alternative mathematical function to the traditional exponential function to approximate the shape of the intensity decay curve under various current densities applied to drive the OLED display. Our model maintains the relationship of higher current drive resulting in faster OLED aging. The model was extended to take into account code values in individual images as compared to existing models which usually compute lifetime for a material at a single current density.

Our proposed model was applied to estimate the gamut compression which occurs over time due to OLED luminance decay with time. Additionally we took advantage of the model by employing it as a tool to evaluate the quality of an image processing algorithm. With our model, we could predict how the image processing algorithm will impact the OLED display lifetime.

In future work we will seek to improve the realism of our lifetime prediction. However, this improvement is likely ot require access to the material information of the OLED color emitters within a target display to provide a more realistic OLED display lifetime model.

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