Energy Management for IoT

Lab 2: Energy Efficient Displays

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1 Introduction

In this technical report, lab 2 of the course "Energy Management for IoT" will be described.
The goal of this second lab is to understand how image manipulation and Dynamic Voltage Scaling (DVS) can be used to trade off image quality and power saving in emissive displays.
More specifically, we will evaluate in a case study how power consumption changes as a function of:

- Displayed colors
- Input current

In order to characterize a certain transformation, we will follow a precise flow for each test image:

- Estimate power consumption for the original image
- Apply a certain transformation on the image
- Compute power consumption and distortion w.r.t. the original one for the transformed image
- Evaluate the power consumption/image distortion tradeoff

The report is divided into 2 sections, and each section is in turn composed of a first part where we briefly present the approach chosen to face the problem and fulfill the requirements, and a second part where we present the obtained results by means of tables and graphs.
A brief theoretical introduction has been inserted prior to the core of the report, in order to have a common groundwork for the two sections, thus avoiding spreading information here and there between the *Workflow* and the *Results* parts.

2 Background

OLED vs LED

Organic Light Emitting Diode (OLED) is an evolution of Light Emitting Diode (LED) technology, which has dominated the display market for many years. OLED displays are defined as *emissive*, while LED ones as *transmissive*; the main difference between an emissive and a transmissive display is that the former does not need any external lighting to emit light because it is composed of a film of organic compound which is able to emit light in response to an electric current.
The absence of a backlight carries with it a series of advantages both in terms of visual quality and power consumption:

- First and foremost, in LED displays, the black color is produced by crossed polarizers, which still leak a fraction of the light falling on them, while OLED displays generate black by simply shutting off pixels (no current flows through them). This ends up in better black levels and reduced power consumption to generate black because pixels in this state do not consume any power.
- On top of that, OLED pixels are independent from each other meaning that edges can be better defined, thus ensuring more sense of depth and higher contrast.
- To continue, another big advantage in today's market is the possibility of making curved and flexible screens.

For what concerns power consumption, we need to go a little bit deeper into the topic because it is more complex than it seems.
We cannot indeed say OLED is better than LED in any possible situation. For example, by displaying a very bright and white-oriented image, the sum of each pixel's power consumption could be even bigger than the power consumed by the backlight. This means that for a completely black screen OLED will be far more efficient, while for an all-white screen, LED will be more efficient. It is estimated that for around 50–60% white image the power consumption will be the same.
It is not possible to reduce the power consumption of an OLED display by simply reducing the backlight intensity as we do for LED, but we can do something similar by applying DVS to scale the supply voltage. The result will be a power saving at the expense of reduced color luminance and color distortion in displayed images.

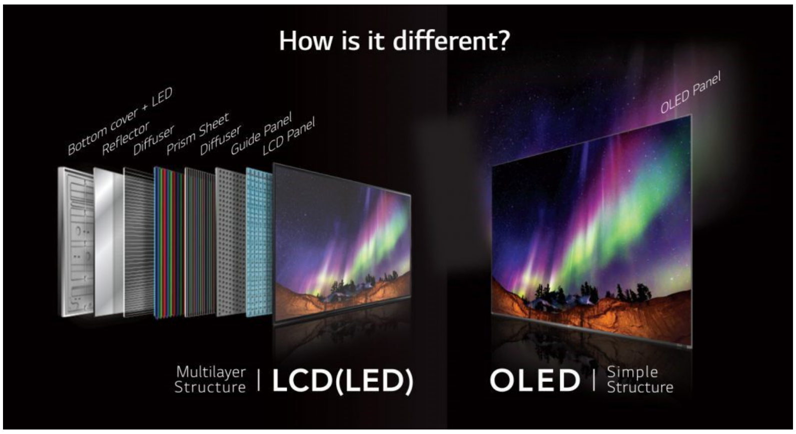

Figure 1: Difference between an OLED and a LED display structure

Color spaces and image transformations

Besides input current, the power consumption of an OLED display is directly impacted by the image shown. This means that it is possible to slightly modify the colors emitted by pixels to decrease power consumption. In order to do it, it's possible to operate on different color spaces, which are models that can describe specific and measurable ranges of colors and luminance values, able to tell the capabilities of a device to reproduce color information. To understand this concept, three different color spaces used in this laboratory experience will be introduced:

- **RGB**, a model similar to the human visual system that stores individual values for red (R), green (G), and blue (B), from which you can obtain all the possible colors.
- **L*a*b***, based on a three-dimensional real number space that presents one channel for luminance (L) and two channels for the color description (a and b).
- **HSV**, a representation of points in an RGB color model that uses cylindrical coordinates, with three parameters indicating the perceived color (Hue), the amount of white component (Saturation), and the brightness (Value).

Each channel of these three color spaces is represented by a pixel matrix that stores the values for the corresponding visual characteristic, according to the range adopted by the model. Applying an image transformation consists of changing the matrices' data cells to affect the image shown.

Dynamic Voltage Scaling

DVS is a power management technique that scales the supply voltage of a component, in our case an OLED display, to reduce power consumption. Indeed, this method reduces the maximum input current of the pixels. The downside of this method is the increment of distortion since the RGB colors of some pixels change. An option to improve the image quality, lowered by the DVS, implies applying some visual compensations, such as enhancing the brightness before scaling the voltage.

3 Part 1: Energy Efficient Image Processing

3.1 Workflow

The goal of this section is to understand how power consumption of an OLED display can vary based on the image shown and how image transformations can be used to decrease it.
To have a wide test set, we used images from the USC SIPI database, the BSDS500 training set and 5 images representing screenshots of our computer.
In order to evaluate the benefits of an image transformation, we followed a precise process on each image:

- Compute power consumption of the original image
- Apply the transformation
- Compute power consumption and distortion w.r.t the original image of the transformed image
- Evaluate the power consumption/distortion tradeoff

At the end we compared the results trying to find the best option among the transformations.
The power model used is a very simple but effective one: the power of each pixel depends on the pixel color in terms of Red-Green-Blue (RGB) components, and the weight of each color has been determined experimentally.
The power of an image is evaluated as the sum of the power contributions of each single pixel and a constant indicating static power independent of pixel values. More in detail, the model used is:

$$P_{pixel} = w_R * R^\gamma + w_G * G^\gamma + w_B * B^\gamma$$

$$P_{image} = w_0 + \sum_{i=1}^{N} P_{pixel,i}$$

γ	w_0	w_R	w_G	w_B
0.7755	1.48169521*10-6	2.13636845*10-7	1.77746705*10-7	2.14348309*10-7

For what concerns the distortion instead, we worked in the L*a*b* space due to the presence of a notion of Euclidean distance between colors that lets us define what is the distance between two images.

$$\epsilon(I_i, I_j) = \sum_{k=1}^{N} (\sqrt{(L_{i,k} - L_{j,k})^2 + (a_{i,k} - a_{j,k})^2 + (b_{i,k} - b_{i,k})^2}$$

For simplicity reasons, the comparison was done working with percentages.

$$dist = \frac{\epsilon(I_{mod}, I_{or})}{W * H * 100^2 * 255^2 * 255^2} * 100(\%)$$

Let's see now more in detail which transformations we decided to test. We will analyze the obtained results later.

Hungry Blue

This transformation belongs to the category of pixel-wise transformations, and it is realized in the RGB space.
As you can see from table 4.2, w_G is the highest coefficient, meaning that blue is the most expensive color in terms of power consumption.
The idea of this transformation is then to reduce the amount of blue color for each pixel by a given constant.

Dimming Edges

This transformation belongs to the category of pixel-wise transformations, and it is realized in the RGB space again, but the result is very similar to a brightness reduction in the Hue-Saturation-Value (HSV) space.
The idea of this transformation is to reduce each of the three colors of a pixel by the same amount, thus reducing the overall brightness. The reduction however is not uniform, but it is proportional to the distance of the pixel from the center of the display.
A distance threshold from where the brightness degradation begins can be selected in order to have a different behavior; the threshold can be of course put equal to 0, and it will result in a more aggressive transformation, keeping only the central pixel unaltered.
The final result will be an image very similar to the original one close to the center, and darker toward the edges.

Histogram Equalization

The idea of this transformation is to flatten the image's histogram, by working on luminance in the HSV space.
This algorithm is very basic and its outcome strongly depends on the original histogram: if the original image is already quite dark we will end up having an increase in luminance and in turn an increase in power consumption. Hence the transformation is not always beneficial in terms of power savings.
Due to this behavior, we decided to omit the results of the transformation.

Contrast-Up Brightness-Down

This transformation belongs to the brightness/contrast transformations category and is realized in the HSV space.
This solution has been found by finely tuning the S and V values of the HSV space to an optimal point. It acts again on the V component, making the dark zones completely black and reducing the bright zones to a cap of around 70% of the full brightness.
In order to compensate for the luminance reduction, the S value is this time increased, so that colors are moved away from the white component and are pushed towards a color similar to the original one.

3.2 Results

Hungry Blue

The results of this technique are strictly related to the presence of blue in the image; if the image presents a massive blue component the power saving will be high, as well as the distortion, and vice versa.
We report here the results obtained on our test set by means of tables, images, and graphs.

image	k=5	k=10	k=20	k=40	k=50	k=100	k=150	k=200	k=255
4.1.02 power [%]	5.0908	9.4112	16.1831	23.1846	25.0462	29.3111	30.3778	30.483	30.4894
4.1.02 distortion [%]	0.6656	1.214	2.0245	2.8709	3.0968	3.5451	3.609	3.6126	3.6127
4.1.03 power [%]	0.9861	1.9809	3.9986	8.1657	10.3333	21.5715	34.4473	35.7139	36.093
4.1.03 distortion [%]	0.7644	1.5282	3.0515	6.0594	7.5218	13.8067	16.9094	17.1179	17.1545
4.1.04 power [%]	1.1817	2.376	4.8052	9.8596	12.5125	26.4028	34.5959	36.5633	37.2029
4.1.04 distortion [%]	0.791	1.5844	3.1765	6.363	7.9375	13.9506	15.9377	16.2446	16.2949
4.1.05 power [%]	1.0167	2.0443	4.1353	8.4944	10.7951	22.2635	27.5236	32.5279	35.4341
4.1.05 distortion [%]	0.7645	1.5283	3.0504	6.0322	7.4487	12.5988	15.1612	16.6323	16.8765
4.1.06 power [%]	1.0653	2.1422	4.3348	8.9147	11.3424	22.1322	28.917	35.1133	37.4816
4.1.06 distortion [%]	0.7767	1.556	3.1207	6.2523	7.7782	13.1325	15.9753	17.3374	17.487
4.1.07 power [%]	0.8806	1.7704	3.5806	7.3658	9.352	18.1708	27.2582	31.2784	31.2784
4.1.07 distortion [%]	0.7071	1.409	2.7929	5.4345	6.6542	11.4694	14.051	14.4314	14.4314
4.2.01 power [%]	1.4402	2.9086	5.9438	12.5421	16.077	23.6559	25.8388	27.2332	27.9318
4.2.01 distortion [%]	0.7872	1.568	3.0878	5.7572	6.7705	8.5507	9.152	9.4069	9.4478
4.2.02 power [%]	0.7197	1.4447	2.9114	5.9186	7.4644	15.7918	25.7939	29.7228	30.1393
4.2.02 distortion [%]	0.6834	1.3637	2.7134	5.351	6.6259	12.1609	15.1452	15.7089	15.7548
4.2.03 power [%]	1.2018	2.4232	4.9191	10.0034	12.4729	22.1486	27.7538	30.8776	32.2307
4.2.03 distortion [%]	0.7367	1.4624	2.8694	5.4199	6.5221	10.294	12.1021	12.8395	12.9721
4.2.04 power [%]	1.1516	2.3181	4.7008	9.7208	12.4185	24.5433	29.3585	30.4062	30.4149
4.2.04 distortion [%]	0.7665	1.5331	3.0618	6.0433	7.4207	11.5402	12.4604	12.5605	12.5608
4.2.05 power [%]	0.7576	1.5202	3.0611	6.2107	7.8226	16.2964	25.3778	34.6952	36.7248
4.2.05 distortion [%]	0.7287	1.4576	2.9155	5.8234	7.2672	14.0677	19.2291	21.4092	21.5454
4.2.06 power [%]	1.286	2.6014	5.2938	10.2934	12.2661	19.4	25.4885	31.7927	33.0234
4.2.06 distortion [%]	0.7605	1.5025	2.9034	5.2188	6.1271	9.5533	11.8939	12.8961	12.9536
4.2.07 power [%]	1.4486	2.9002	5.8189	11.6507	13.9309	21.1804	22.951	23.7442	23.816
4.2.07 distortion [%]	0.6235	1.2151	2.2901	3.9445	4.4826	5.7425	6.0759	6.163	6.1662
desktop power [%]	1.7464	3.5323	7.2587	14.737	17.952	28.1223	33.1513	34.8668	35.275
desktop distortion [%]	0.8274	1.6402	3.1928	5.823	6.8475	10.082	11.3733	11.6313	11.6626
game power [%]	4.4919	8.9867	16.3021	25.2116	28.5013	33.1451	33.843	34.3423	34.6441
game distortion [%]	0.7689	1.459	2.5395	3.8595	4.2607	4.7385	4.843	4.8979	4.9106
house power [%]	0.9654	1.9479	3.925	7.7836	9.6921	18.7811	26.0562	32.1051	32.9729
house distortion [%]	0.7119	1.4135	2.7735	5.2912	6.4488	11.1405	13.9877	15.0461	15.0939
internet power [%]	2.2525	4.6265	8.9926	14.53	16.9084	26.6683	32.2327	33.5471	34.1518
internet distortion [%]	0.748	1.4567	2.6817	4.4779	5.2046	7.5604	8.3085	8.4594	8.4968
pdf power [%]	0.8999	1.8033	3.6273	7.3808	9.3291	18.2642	23.2768	28.7648	35.6682
pdf distortion [%]	0.7294	1.4545	2.8896	5.672	6.9813	11.8942	14.9609	17.1598	18.1009
vscode power [%]	3.8924	7.9439	16.7452	32.088	33.0365	34.477	35.2006	35.8589	36.0874
vscode distortion [%]	0.9524	1.8839	3.4305	5.0209	5.1528	5.3847	5.5172	5.5884	5.6038

It is possible to see how each image behaves differently. This is due to the different amounts of blue color present in each of them.
For what concerns image distortion, we go from a minimum of 0.6656% for image *4.1.02* to a maximum of 18.1009% for image *pdf*. We consider acceptable a value of distortion around 3%; with this constraint, the best result in terms of power savings is obtained with image *4.1.02* ($\approx$ 25%), while the worst is probably obtained with image *4.2.05* ($\approx$ 3%).
The average power saving is $\approx$ 17.35%, while the average distortion is $\approx$ 7.11%.

We show now some representative examples of transformation outputs, to highlight differences w.r.t. the original image.

(a) original 4.1.02
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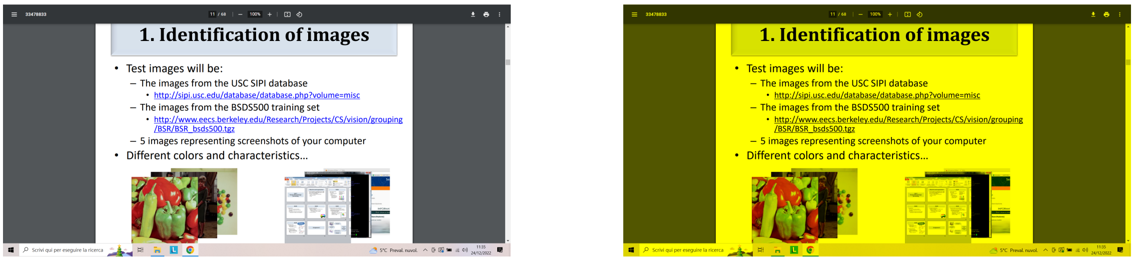
(b) 4.1.02 with blue value reduced by k=5

(c) 4.1.02 with blue value reduced by k=255

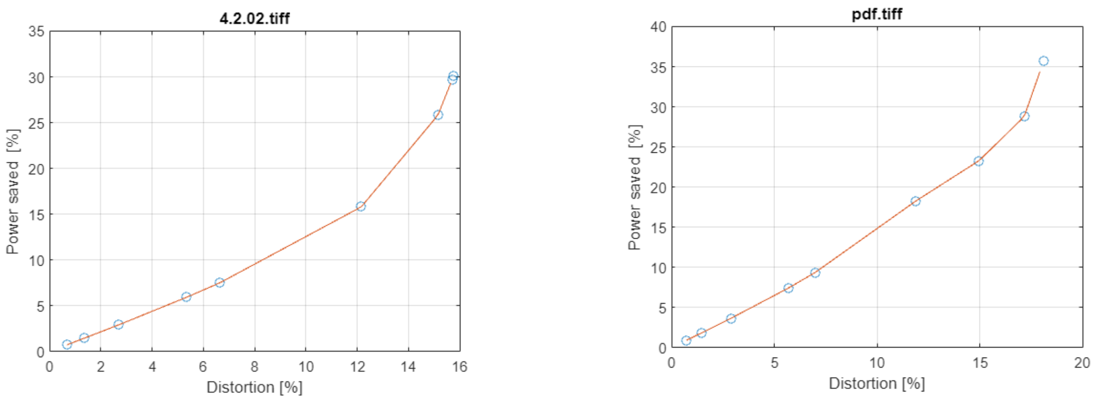
Figure 2: Comparison between the original 4.1.02 image and the modified ones with the best power saving percentage and lower distortion percentage



(a) original pdf

(b) pdf with blue value reduced by k=255

Figure 3: Comparison between the original pdf image and the modified one with the highest distortion percentage



(a) 4.2.02 chart with the Distortion v. Power saved relation

(b) pdf chart with the Distortion v. Power saved relation

Figure 4: Distortion v. Power saving plot for some of the modified images. The trend is similar for all other images.

Dimming edges

Differently from the *Hungry Blue* technique, in this case, each image is affected in the same way by the modification. The lowest the selected threshold, the highest the power saving.
What this time plays a key role in the transformation is the resolution of the image. We decided to use a static assignment to the thresholds vector, but it is also possible to adapt it to the image resolution.
We report here the results obtained on our test set by means of tables, images, and graphs.

image	k=0	k=5	k=10	k=20	k=50	k=100	k=150	k=200	k=500
4.1.02 power [%]	47.4409	44.7937	42.2066	37.1911	23.5439	6.5732	0.2755	0	0
4.1.02 distortion [%]	2.7786	2.6468	2.5133	2.2437	1.4569	0.4115	0.0183	0	0
4.1.03 power [%]	47.476	44.8415	42.2598	37.2539	23.5751	6.6053	0.3327	0	0
4.1.03 distortion [%]	8.6656	8.206	7.7491	6.8519	4.3644	1.229	0.0622	0	0
4.1.04 power [%]	46.5301	43.913	41.3447	36.3506	22.6759	6.1993	0.273	0	0
4.1.04 distortion [%]	8.0518	7.6137	7.1788	6.3255	3.9678	1.0989	0.0511	0	0
4.1.05 power [%]	47.2649	44.6357	42.0585	37.056	23.3806	6.467	0.2939	0	0
4.1.05 distortion [%]	8.9733	8.4928	8.016	7.0797	4.4888	1.2518	0.0582	0	0
4.1.06 power [%]	46.4583	43.836	41.2662	36.2912	22.8521	6.5133	0.3075	0	0
4.1.06 distortion [%]	8.5049	8.0373	7.5743	6.67	4.2043	1.1957	0.0568	0	0
4.1.07 power [%]	47.8683	45.2365	42.6552	37.6388	23.7828	6.3851	0.2733	0	0
4.1.07 distortion [%]	11.0602	10.4618	9.8697	8.7102	5.5	1.4913	0.0651	0	0
4.2.01 power [%]	42.8292	41.5421	40.2672	37.752	30.5155	19.7183	10.9711	4.8109	0
4.2.01 distortion [%]	9.3812	9.1128	8.8458	8.3162	6.7791	4.4507	2.5205	1.1092	0
4.2.02 power [%]	45.8428	44.5334	43.2366	40.6805	33.3151	22.1778	12.8525	5.8803	0
4.2.02 distortion [%]	12.2898	11.9498	11.6113	10.9398	8.9867	6.0029	3.4822	1.5891	0
4.2.03 power [%]	45.2127	43.9062	42.6119	40.0623	32.7151	21.7309	12.7601	5.9536	0
4.2.03 distortion [%]	8.7141	8.4696	8.2259	7.7423	6.3369	4.2216	2.4849	1.1685	0
4.2.04 power [%]	46.1388	44.8274	43.5284	40.9684	33.5976	22.4643	13.099	5.9897	0
4.2.04 distortion [%]	9.3173	9.0606	8.8048	8.2975	6.8237	4.5831	2.6881	1.2373	0
4.2.05 power [%]	47.0744	45.7553	44.4501	41.8751	34.4523	23.2001	13.6734	6.3585	0
4.2.05 distortion [%]	10.7937	10.501	10.2096	9.6312	7.947	5.3699	3.1739	1.4793	0
4.2.06 power [%]	45.0046	43.7001	42.4081	39.8599	32.5132	21.4623	12.387	5.6941	0
4.2.06 distortion [%]	8.3304	8.0984	7.867	7.4061	6.0566	4.0089	2.3271	1.0767	0
4.2.07 power [%]	46.2232	44.9056	43.6016	41.0326	33.6419	22.5294	13.3206	6.4085	0
4.2.07 distortion [%]	10.5419	10.2489	9.9567	9.3775	7.7007	5.1713	3.0575	1.4529	0
desktop power [%]	43.3129	42.8784	42.4458	41.5855	39.0396	34.9187	30.9638	27.2024	9.5784
desktop distortion [%]	6.1689	6.1108	6.0527	5.9365	5.5892	5.0174	4.4603	3.9245	1.3793
game power [%]	44.4569	44.0063	43.5579	42.6664	40.0332	35.757	31.6188	27.6345	9.0529
game distortion [%]	2.3004	2.2805	2.2605	2.2204	2.0995	1.8961	1.6916	1.488	0.4974
house power [%]	47.576	46.2514	44.9406	42.3593	34.9186	23.6283	14.0705	6.6535	0
house distortion [%]	10.2869	10.0093	9.7328	9.1841	7.5836	5.1299	3.0429	1.4309	0
internet power [%]	38.5895	38.1647	37.7409	36.8956	34.3883	30.3415	26.4747	22.8343	7.1159
internet distortion [%]	3.6804	3.6407	3.601	3.5217	3.2848	2.8976	2.5241	2.1702	0.6475
pdf power [%]	40.9264	40.4902	40.0558	39.1913	36.634	32.4959	28.5286	24.762	7.9019
pdf distortion [%]	8.1399	8.0585	7.9769	7.8137	7.3243	6.5154	5.7261	4.9693	1.5618
vscode power [%]	46.9729	46.5222	46.0739	45.1896	42.5645	38.3231	34.2388	30.3283	11.3417
vscode distortion [%]	2.4506	2.4329	2.4151	2.3797	2.2714	2.0874	1.8999	1.7112	0.6795

In this case, the difference in power saving between the two images is dependent on the color present at the edges. Brighter the color, the higher the amount of color reduction possible.
This will of course end up in more power saved but also more distortion.
For what concerns image distortion, we go from a minimum of 0% for many images to a maximum of 12.2898% for image *4.2.02*. We consider acceptable a value of distortion around 3%; with this constraint, the best result in terms of power savings is obtained with image *4.1.02* ($\approx$ 47.5%), while the worst is probably obtained with image *4.2.02* ($\approx$ 10%).
The average power saving is $\approx$ 27.63%, while the average distortion is $\approx$ 4.7%.

We show now some representative examples of transformation outputs, to highlight differences w.r.t. the original image.

(a) original 4.1.02
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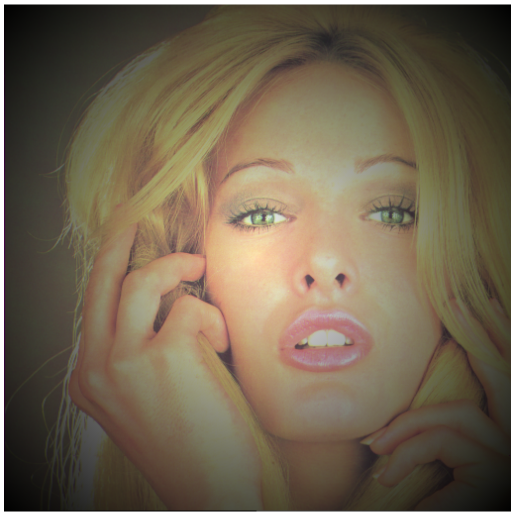
(b) 4.1.02 with blue value reduced by k=50

(c) 4.1.02 with blue value reduced by k=0

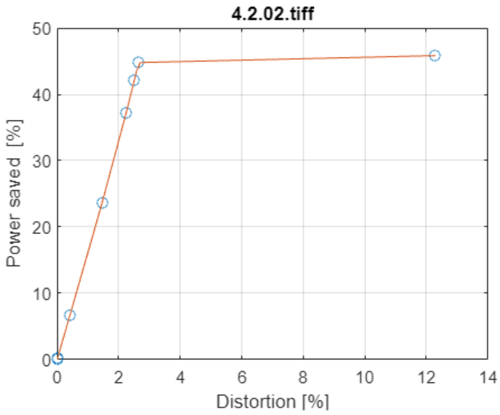
Figure 5: Comparison between the original 4.1.02 image and the modified ones with the best power saving percentage

(a) original 4.2.02

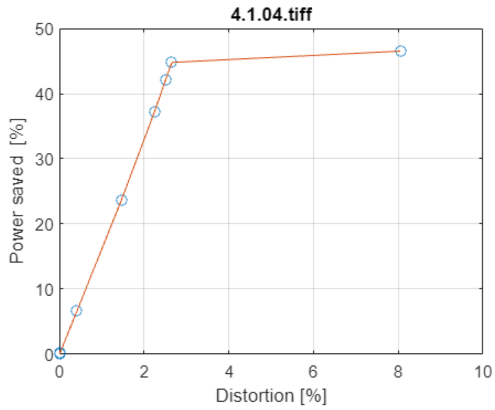


(b) 4.2.02 with k=0

Figure 6: Comparison between the original 4.2.02 image and the modified one with the highest distortion percentage



(a) 4.2.02 chart with the Distortion v. Power saved relation



(b) 4.1.04 chart with the Distortion v. Power saved relation

Figure 7: Distortion v. Power saving plot for some of the modified images. The trend is similar for all other images and the plateau depends on the image resolution.

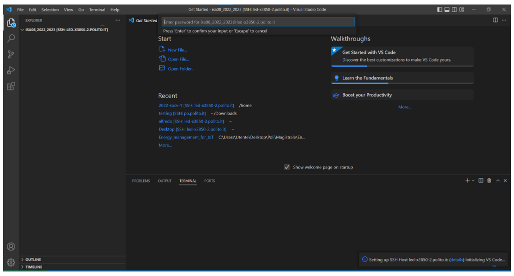
Contrast-up Brightness-Down

This technique has no tunable threshold, so we report here the results obtained with the best setup we were able to find "manually".
We report here the results obtained on our test set by means of tables, images, and graphs.

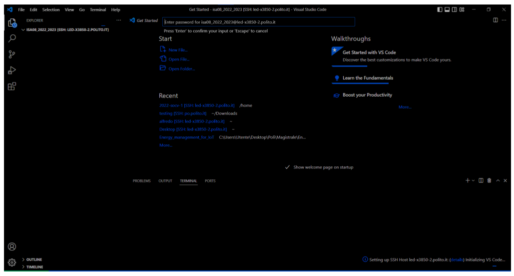
image	result
4.1.02 power [%]	66.1676
4.1.02 distortion [%]	2.9543
4.1.03 power [%]	4.8429
4.1.03 distortion [%]	1.3224
4.1.04 power [%]	15.1786
4.1.04 distortion [%]	3.6229
4.1.05 power [%]	16.4779
4.1.05 distortion [%]	4.2038
4.1.06 power [%]	18.0894
4.1.06 distortion [%]	3.8702
4.1.07 power [%]	13.8990
4.1.07 distortion [%]	3.4117
4.2.01 power [%]	36.9524
4.2.01 distortion [%]	5.6801
4.2.02 power [%]	24.4515
4.2.02 distortion [%]	6.1338
4.2.03 power [%]	20.4836
4.2.03 distortion [%]	3.8892
4.2.04 power [%]	26.0003
4.2.04 distortion [%]	5.5210
4.2.05 power [%]	11.9272
4.2.05 distortion [%]	3.4238
4.2.06 power [%]	19.1025
4.2.06 distortion [%]	3.8429
4.2.07 power [%]	25.2396
4.2.07 distortion [%]	4.4339
desktop power [%]	31.4123
desktop distortion [%]	5.2486
game power [%]	91.6425
game distortion [%]	3.5773
house power [%]	14.0973
house distortion [%]	3.5707
internet power [%]	30.8271
internet distortion [%]	2.2687
pdf power [%]	21.2245
pdf distortion [%]	4.2293
vscode power [%]	94.0840
vscode distortion [%]	3.5757

The transformation brings to 0 every V value below 0.3 and to 0.7 every V value above 0.7. In addition, it multiplies every S value by 1.5.
As you can see from the results, here the benefits of an OLED display are evident. When showing dark zones we can completely turn off the pixel to save a large amount of power.
This is an evidence of why is beneficial to set a dark mode in every possible application while using this kind of display.
For what concerns image distortion, we go from a minimum of 1.3224% for image *4.1.03* to a maximum of 6.1338% for image *4.2.02*. We consider acceptable a value of distortion around 3%; with this constraint, the best result in terms of power savings is obtained with image *vscode* ($\approx$ 94%), while the worst is probably obtained with image *4.1.03* ($\approx$ 5%).
The average power saving is $\approx$ 30.63%, while the average distortion is $\approx$ 3.93%.

We show now some representative examples of transformation outputs, to highlight differences w.r.t. the original image.



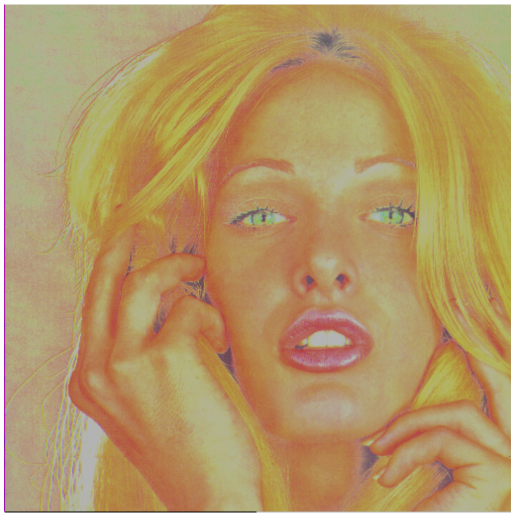
(a) original vscode



(b) modified vscode

Figure 8: Comparison between the original vscode image and the modified one with the best power saving percentage

(a) original 4.2.02



(b) modified 4.2.02

Figure 9: Comparison between the original 4.2.02 image and the modified one with the highest distortion percentage

4 Part 2: Dynamic Voltage Scaling

4.1 Workflow

The aim of the second part of this laboratory experience was to apply DVS on some images in order to decrease power consumption and find an image compensation to increase the perceived image quality.
In order to implement this method, we calculated the current flowing through the cell of each image using the following function:

$$I_{cell} = (p_1 * V_{dd} * D_{RGB})/255 + (p_2 * D_{RGB})/255 + P_3$$

p_1	p$_2$	p$_3$	default V$_{dd}$
4.251*10-5	-3.029*10-4	3.024*10-5	15V

In addition, the default values of the cells are used to evaluate power consumed, according to the model:

$$P_{panel} = V_{dd} * \sum_{i=1}^{W} P_{pixel,i} * \sum_{j=1}^{H} P_{cell(i,j)}$$

For what concerns DVS, a function called $displayed\_image(I\_cell, V_{dd}, mode)$ has been provided to simulate the effects of the scaled voltage on the image, changing the RGB values in case the corresponding I_{cell} is greater than the maximum imposed current.

As a first step, we decreased the starting voltage (15V) of some pictures, till the distortion reached a limit value of $\approx 3\%$, still considered acceptable for the image quality. We managed to change the supply voltage down to a minimum value of 12V, below which the distortion increased too much.
After collecting the power consumption results, we tried to find a suitable transformation in HSV color space to improve the perceived quality of the images.
An option was the brightness scaling, or rather increasing the V parameter to balance the luminance loss. In order to apply this strategy, we added to each cell of the V matrix a lower value equal to 0.01, to not exceed the distortion limit, multiplied by the difference between the original voltage and the scaled one, to increase the brightness proportionally.
To push more with the power reduction, we decided to add a further transformation, based on contrast enhancement, to both improve the saved power and the image quality. In practice, we acted again on the V component, saturating the value lower than 0.3 to 0, and reducing the bright zones to a value of 0.7, performing then compensation by increasing the S parameter (a method similar to the one applied in the first part of the lab).

4.2 Results

We report here the results obtained by applying the DVS without any image transformation, starting from the default supply voltage of 15V (no DVS applied) down to a value of 12V.

image	$V_{dd} = 15$	$V_{dd} = 14$	$V_{dd} = 13$	$V_{dd} = 12$
4.1.05 power [%]	0	0.0670	3.1533	8.9798
4.1.05 distortion [%]	0	0.0353	1.2868	2.5498
4.1.06 power [%]	0	0.1641	4.6885	12.2015
4.1.06 distortion [%]	0	0.0593	1.0693	2.3938
4.1.07 power [%]	0	0	1.7451	12.2345
4.1.07 distortion [%]	0	0	1.3936	5.0899
4.2.01 power [%]	0	0.4979	5.3641	12.1574
4.2.01 distortion [%]	0	0.1800	1.8908	4.4288
4.2.02 power [%]	0	4.1280	10.9971	20.8117
4.2.02 distortion [%]	0	2.3868	5.3734	8.7961
4.2.03 power [%]	0	0.5092	2.6757	7.6626
4.2.03 distortion [%]	0	0.2893	1.4107	2.9003
4.2.04 power [%]	0	0.4464	3.5260	9.1201
4.2.04 distortion [%]	0	0.2311	1.7275	4.0507
4.2.05 power [%]	0	0.0074	5.5208	16.9681
4.2.05 distortion [%]	0	0.0077	1.3077	3.7630
4.2.06 power [%]	0	0.1497	3.2520	10.3423
4.2.06 distortion [%]	0	0.1184	0.9502	2.3523
4.2.07 power [%]	0	0.0101	1.6792	7.6509
4.2.07 distortion [%]	0	0.0072	0.8537	3.3707
house power [%]	0	0.0555	3.2985	11.8338
house distortion [%]	0	0.0446	1.0953	3.0975

Here are reported instead the results obtained by applying the DVS with the image compensation. It is important to specify that when the voltage considered is the default one (15V), no image transformation has been applied.

image	$V_{dd} = 15$	$V_{dd} = 14$	$V_{dd} = 13$	$V_{dd} = 12$
4.1.05 power [%]	0	10.8080	12.5919	17.0642
4.1.05 distortion [%]	0	2.3503	3.1166	3.8004
4.1.06 power [%]	0	12.4034	12.9472	16.0949
4.1.06 distortion [%]	0	2.6090	3.1065	3.8935
4.1.07 power [%]	0	10.8150	12.5755	18.6272
4.1.07 distortion [%]	0	2.2596	3.0665	3.8950
4.2.01 power [%]	0	15.5643	18.5890	25.4505
4.2.01 distortion [%]	0	2.8499	3.2731	4.2851
4.2.02 power [%]	0	23.2469	24.9886	30.4577
4.2.02 distortion [%]	0	5.4076	5.7723	6.8884
4.2.03 power [%]	0	11.4398	12.8682	16.7032
4.2.03 distortion [%]	0	2.4958	3.0832	3.9124
4.2.04 power [%]	0	13.3531	16.0682	22.0231
4.2.04 distortion [%]	0	2.4266	3.1441	4.0118
4.2.05 power [%]	0	12.4784	14.4490	20.1027
4.2.05 distortion [%]	0	2.8431	3.7279	4.6076
4.2.06 power [%]	0	11.1493	12.5101	16.7170
4.2.06 distortion [%]	0	2.2710	2.8342	3.7661
4.2.07 power [%]	0	9.1572	11.6736	17.6675
4.2.07 distortion [%]	0	2.0152	2.6695	3.5287
house power [%]	0	10.6518	12.2086	17.2615
house distortion [%]	0	2.4595	3.2087	4.0056

Analyzing the data obtained, it is possible to see how the DVS applied after the image compensation produces better values for what concerns power consumption, and a slight rise of the distortion as expected.
Indeed, the average power saving with compensation is $\approx 11.83\%$, with a maximum of 30.46%, against the value of $\approx 4.13\%$ of the ones without compensation, while the average distortion is respectively $\approx 2.58\%$ and $\approx 1.47\%$.
We report here two examples of images, making the comparison with the results obtained by the normal DVS method and by the one with the luminance/contrast correction.

(a) original 4.1.05

(b) 4.1.05 with DVS

(c) 4.1.05 with compensation

Figure 10: Comparison between the original 4.1.05 image, the modified one with DVS at 12V and the one with compensation

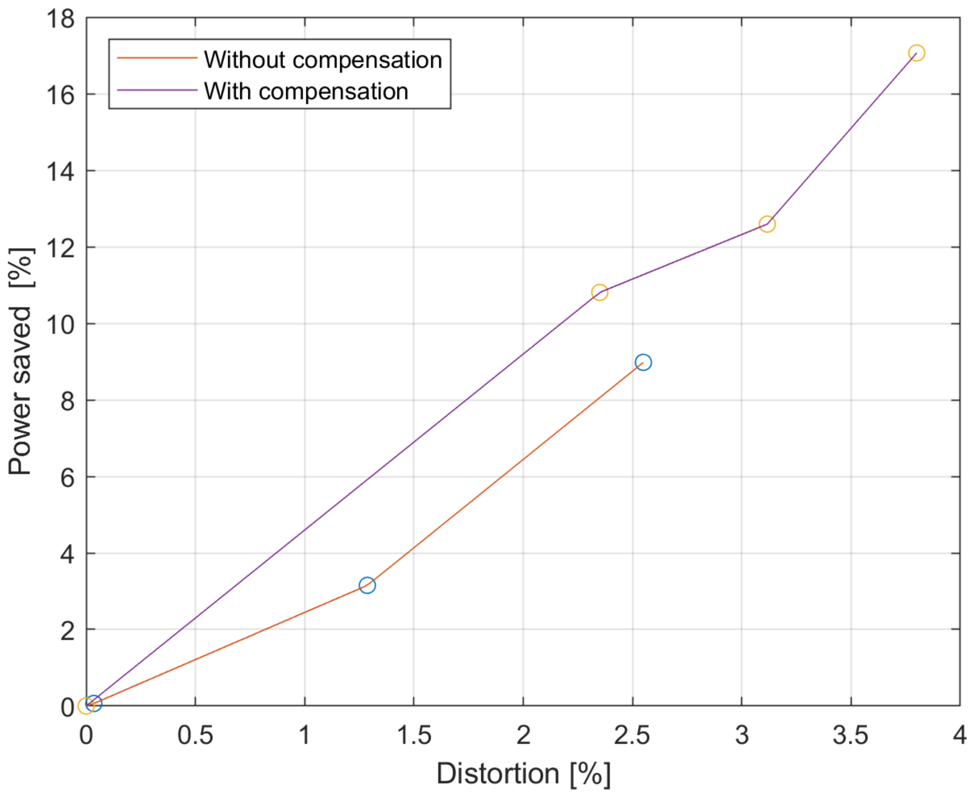


Figure 11: 4.1.05 charts with Distortion v. Power saved relation

(a) original 4.2.06

(b) 4.2.06 with DVS

(c) 4.2.06 with compensation

Figure 12: Comparison between the original 4.2.06 image, the modified one with DVS at 12V and the one with compensation

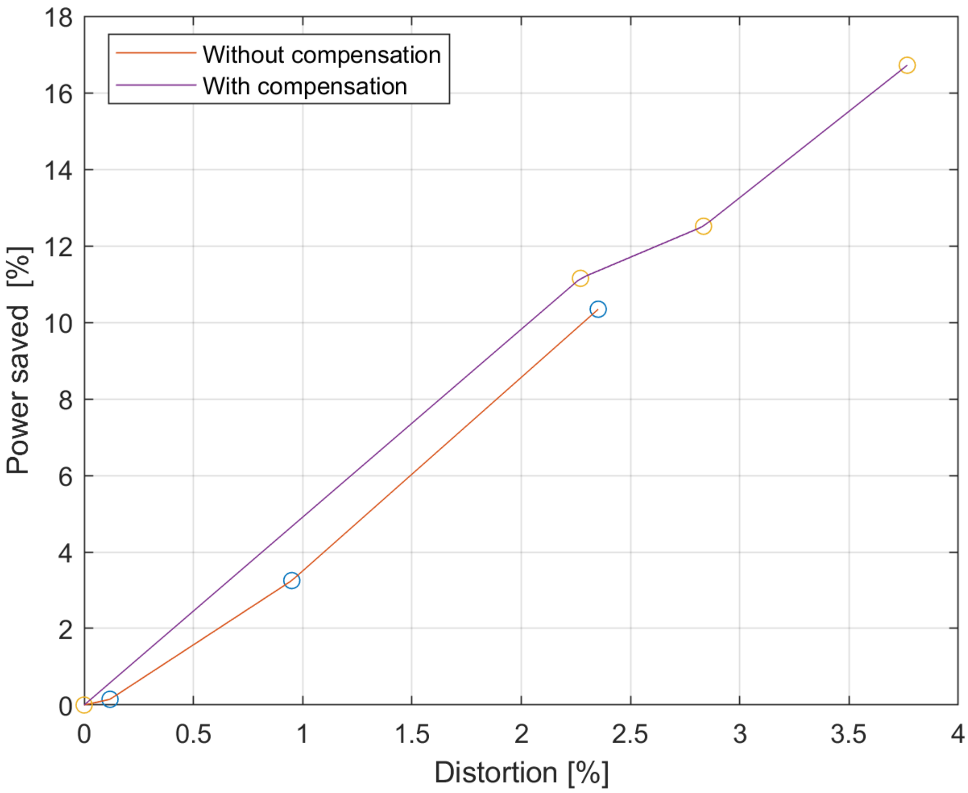


Figure 13: 4.2.06 charts with Distortion v. Power saved relation

5 Conclusion

To sum up, in this laboratory we explored some techniques designed to reduce power consumption in OLED displays.
From the data collected in both the first and the second part, it's possible to observe how the brightness scaling, including the DVS, and the contrast enhancement are suitable methods to bring down the power consumption while keeping into account its relationship with the image distortion.

Acronyms

LED Light Emitting Diode

OLED Organic Light Emitting Diode

DVS Dynamic Voltage Scaling

RGB Red-Green-Blue

HSV Hue-Saturation-Value