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Evaluation of Crosstalk Metrics for 3D Display Technologies with Respect to Temporal Luminance Analysis

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***Abstract*—Crosstalk is one of the most important parameters of the 3D displays' quality . Different crosstalk definitions exist, which makes crosstalk measurement and comparison difficult. We take a step back and focus on a detailed 3D display luminance analysis. The conclusions we draw from the temporal luminance analysis can be used to propose an effective approach to crosstalk measurements. In scope of the presented work we have measured four different 3D displays.**

***Keywords*-Crosstalk, Objective Metric, 3D display, Luminance Measurement, Shutter Glasses**

I. Introduction

Todays multimedia services are being extended to a new dimension by introduction of 3D content playback and broadcasting. Many newly released movies have theirs 3D versions available in the theaters. 3D broadcasts are available in the offer of digital satellite broadcasters. Also first models of the 3D capable mobile terminals, such as laptops and smart phones, are hitting the market. This evolution towards 3D is by many aspects similar to the recent progress form Standard Definition Television (SDTV) to High Definition Television (HDTV).

There are many objective factors which influence the perception of 3D content. Each element of the 3DTV system is affected by technical constraints. The most significant factor is the crosstalk [1], [2], which can be roughly described as a failure in separation of left and right views in display systems. From end–user perspective high crosstalk level results in ghosting, loss of contrast, loss of 3D effect and depth resolution. All this contributes to the viewers' discomfort [3], [4] which diminishes the 3D quality of experience.

Crosstalk definitions [1], [2] do not specify how it should be measured. In order to measure a failure in a separation of left and right views different objective crosstalk metrics are proposed [4], [5]. Each of the proposed objective crosstalk metrics is based on comparison of the luminance measured for different 3D views and/or for different input luminance sequences. Therefore, it is important to identify parameters which influence the luminance level and how they effect it.

We noticed that the measured luminance pattern for the same sequences depends strongly on the display technology. This makes proposing a general objective crosstalk metric difficult since different technologies have to be taken into account.

We show that previously proposed objective crosstalk metrics are correct for polarized displays. Nevertheless, they are not able to predict correctly all the effects observed for a shutter glasses technology. To our best knowledge proposed metrics are based on an assumption that we can see a part of the left view in the right one and vice versa ("leaking" effect). As we show in this paper in case of the shutter glasses technology it is difficult to distinguish and measure left and right images separately. Therefore, such approach to crosstalk measurement in case of this technology is not recommended.

The main outcome of our experiments is the explanation why polarized and shutter glasses displays reveal such different crosstalk effects. The main research value of this paper is showing that the crosstalk observed for the shutter glasses technology can be reliably explained by detailed analysis of temporal luminance changes. We proved also that observed effects are different for different shutter glasses technologies.

The remainder of this paper is organized as follows. In Section II different crosstalk objective metrics are presented. In Section III our measurement set is described and a mathematical notation introduced. In Section IV obtained results are presented. In Section V detailed temporal analysis of luminance changes is presented. The paper is concluded in Section VI.

II. Crosstalk Objective Metrics

Problem of crosstalk is complex as there are numerous and simultaneous factors driving this effect. An obvious source of crosstalk is poor quality of the display design and limitations of the technology. Apart from that crosstalk might occur when the viewer's head position tilt with respect to a screen is somewhat different from the one foreseen by a display designer. For time-multiplexed displays (i.e. shutter glasses) incorrect synchronization (timing errors) between the display and the LCD shutters is claimed to be the main reason for crosstalk. In addition, imperfect

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light extinction of liquid-crystal shutters in an opaque state (light leakage) may introduce additional crosstalk [6]. It was observed that when either contrast or binocular parallax of an image is increasing, the visibility of crosstalk (ghosting) also increases [7]. Another variable which impacts crosstalk visibility is a camera base distance [8] .

There are many different objective crosstalk metrics proposed in literature [4], [5]. Moreover, there is no common terminology nor definition for crosstalk. Crosstalk is often referred as ghosting, system crosstalk, viewer crosstalk, leakage, 3D contrast, extinction and extinction ratio. Unfortunately, this huge diversity causes chaos and makes it difficult to compare the results of measurements.

For instance, in [5] a definition is proposed which is divided into two parts being related to a display system perspective and a viewer-oriented perspective. System crosstalk is "the degree of the unexpected leaking image from the other eye". Whereas, viewer crosstalk is defined as "the ratio of the luminance of unwanted ghost image, which leaks from the image for the other eye, to the luminance of the correct information received by the viewer's eyes." Both crosstalk components for the viewer's left eye are defined as:

$$SystemCrosstalk = \frac{\beta_2}{\alpha_1} \tag{1}$$

$$ViewerCrosstalk = \frac{\mathbf{B}\beta_2}{\mathbf{A}\alpha_1} \tag{2}$$

Where: α_1 – the percentage part of the left-eye image observed at the left eye position, β_2 – the percentage part of the right-eye image leaked to the left-eye position, **A** – the luminance of a particular point in the left eye image, and **B** – the luminance of the same corresponding point (same x,y location) in the right-eye image.

Very interesting approach was presented in [2] as author defines crosstalk as a sort of image distortion.

$$R_l'(x,y) = min(R_l + \frac{R_r * p}{100}, 255) \tag{3}$$

$$G_l'(x,y) = min(G_l + \frac{G_r * p}{100}, 255) \tag{4}$$

$$B_l'(x,y) = min(B_l + \frac{B_r * p}{100}, 255) \tag{5}$$

Where: R_l', G_l', B_l' represent new values of the left image with induced crosstalk; R_l, G_l and B_l the original values of the left image; R_r, G_r and B_r represent original values of the right image; p - a certain percentage of the right image is added to the left image. Even more formal mathematical definition was presented in [9].

All these definitions assume that we have full knowledge and control over right and left views. It is true for a technology where left and right views do not influence each other like in the case of polarized displays or anaglyph images. As we show such assumption is not true in case of shutter a glasses technology.

III. Experiment Design

Authors of this paper cooperate with VQEG (Video Quality Expert Group) on a crosstalk test plan in which goal is to extend knowledge on how the crosstalk influences viewer's 3D perception. A part of the preparation for this experiment were measurements of the crosstalk by each involved laboratory. During our experiments we have found that in case of shutter glasses obtained results cannot be explained by the "leaking" effect. In order to explain experiment outcomes we decided to run a specific experiment focused on detailed luminance measurements for different displays.

The experiment consists of measurements of the display luminance for different input sequences which vary in terms of luminance levels. Each step of the test sequence presents different luminance levels being uniform over a whole display area. Nevertheless, the luminance for the left and right view may be different. Each step of the sequence is displayed for one second. The luminance level of a sequence at particular step can be treated as an input of the 3D display system and glasses-through or directly measured display luminance level is its output (response).

In order to perform such experiment we have developed a custom measurement device (see Section III-A) and specific luminance sequences (see Section III-C).

A. Measuring Device

For luminance measurements we try to use Spyder 2 colorimeter, MAVOLUX 5032B digital lightmeter as well as OceanOptic HR 4000 spectrophotometer. These devices, however, did not meet our requirements. The light sensor of Spyder is too large to put it directly behind the glasses. MAVOLUX has an insufficient sensitivity whereas the OceanOptic has not been equipped with an attachment for luminance (cd/m^2) measurements. Additionally, all the reported devices are too slow in terms of sampling frequency. That is why we have designed, built and calibrated a custom photometer dedicated to luminance measurements which features both a fast sampling rate and a high resolution. The device consists of a high sensitive photodiode, amplifier with 8 different ranges, an A/D converter (12-bits, 8 kHz sampling rate), and USB interface.

The device calibration has been done by means of Spyder 2 colorimeter. In Fig. 1 we have compared results from measurements of a light source with the help of Spyder 2 and a custom photometer. As a light source we have used HYUNDAI LCD W240S monitor which generates a stable image without a flicker effect.

We were able to observe single luminance level changes which prove a high resolution of the custom photometer. Moreover, results obtained with Spyder 2 colorimeter are almost identical with outcomes for the custom photometer (Fig. 1).

Fig. 1 and all other figures in this paper are locally normalized i.e. we divided the obtained results by the maximum

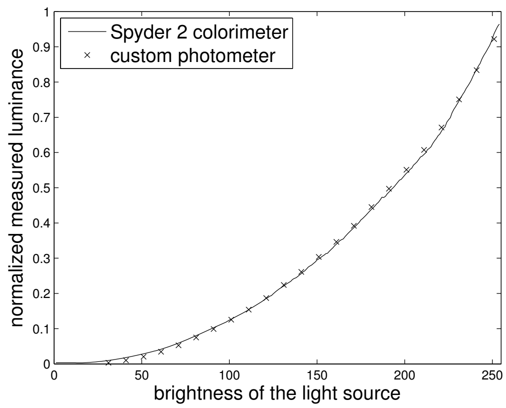

Figure 1. Measured luminance of the light source measured by Spyder 2 colorimeter and custom photometer.

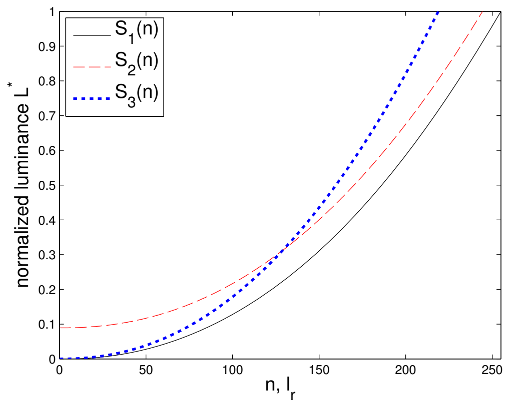

Figure 2. Theoretical crosstalk pattern based on the assumption that crosstalk "leaks" from the other view.

value. Since the presented results are based on shapes not the numerical values this presentation methodology does not influence the obtained conclusions.

B. Measuring Settings

Numerous different factors influence the measured luminance level like display type, measuring device or viewer's head position. In this paper we have focused on two factors. The first one is the luminance coded within the range 0 to 255 for the left view l_l and the right view l_r. The luminance is uniform across the whole display area. The second factor is a display type denoted by D. The luminance measured by us (the output parameter) is called display luminance and denoted by L. We measure it in specific conditions: through glasses parallel to the display, in the right-eye position and in the middle of the screen. It means that the presented luminance curves are measured through the right glass.

The measured display luminance function is denoted as:

$$L(t, S_i, D) \tag{6}$$

where t is time in seconds, S_i is an input sequence of particular l_l and l_r values and D denotes a display type. A sequence is defined as particular series of l_l and l_r values displayed at time t. In case when the display type is irrelevant $L(t, S_i)$ notation is used. In some cases we are interested in a time averaged display luminance:

$$L^*(S_i(n), D) = \int_n^{n+1} L(t, S_i, D)dt \tag{7}$$

Parameter D represents four different investigated displays (for convenience the display abbreviation is specified in brackets):

- Samsung TV UE40C8000 (TV),
- BENQ LCD XL2410T (LCD1),
- Samsung LCD 2233RZ (LCD2),
- HYUNDAI LCD W240S (LCD3).

Considered technologies were polarized (LCD3) and shutter glasses (TV, LCD1, LCD2). In case of shutter glasses a TV set with its own shutter glasses system (TV) and two different monitors with NVIDIA 3DVision system (LCD1 and LCD2) were used.

C. Measuring Sequences

In order to analyze performance of 3D displays three different luminance sequences S_1, S_2 and S_3 were prepared. For all sequences the right view luminance l_r increases from 0 to 255 stepwise. Since a constant value of luminance lasts for one second instead of t we are using n which is both the time starting from 0 and the l_r luminance level. The left view sequence l_l is different for each sequence S_1, S_2, S_3 given by:

$$S_1(n) = \begin{cases} l_l=0 \\ l_r=n \end{cases}, S_2(n) = \begin{cases} l_l=128 \\ l_r=n \end{cases}, S_3(n) = \begin{cases} l_l=n \\ l_r=n \end{cases}$$

where $n = 0, 1, ..., 255$.

For a no crosstalk display the same luminance level should be measured for corresponding n for each sequence i.e. $L^*(S_i(n), \text{no crosstalk}) = L^*(S_j(n), \text{no crosstalk})$ for any $i, j = 1, 2, 3$. Real displays cannot achieve such a precision because of technical limitations. Based on the classical crosstalk explanation (see Eq. (3)-(5)) observed pattern should be similar to the pattern plotted in Fig. 2. The vertical distance between the solid S_1 and the dotted S_3 lines is constant (even if it does not seem to be).

The theoretical pattern comes from the following assumption. If $l_l = 0$ then the luminance is the smallest since nothing leaks into the right view. In case of $l_l = 128$ the measured values are $L^*(S_1(n)) + A = L^*(S_2(n))$, for any n i.e. we should measure the same pattern as for $S_1(n)$ sequence with additional constant shift (denoted as A). Observed shift is caused by leaking of the left 128 luminance level. In the last sequence $S_3(n)$ increasing luminance level should

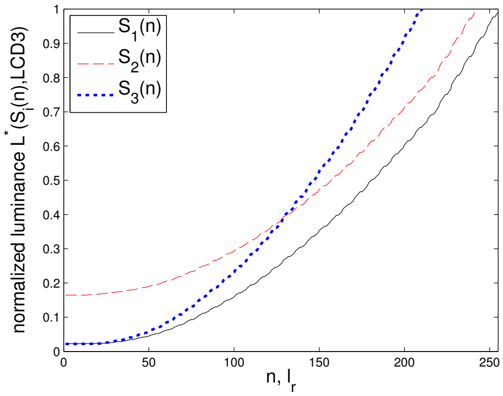

Figure 3. Crosstalk pattern for LCD3 - polarized display.

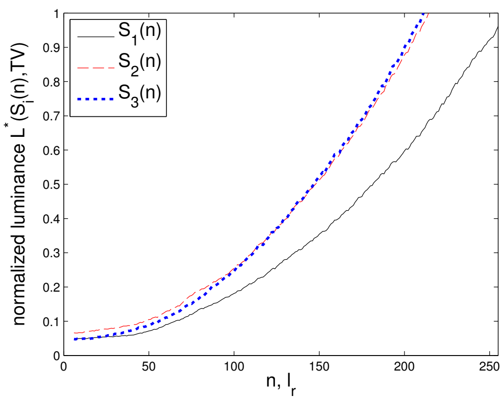

Figure 4. Crosstalk pattern for TV - shutter glasses display.

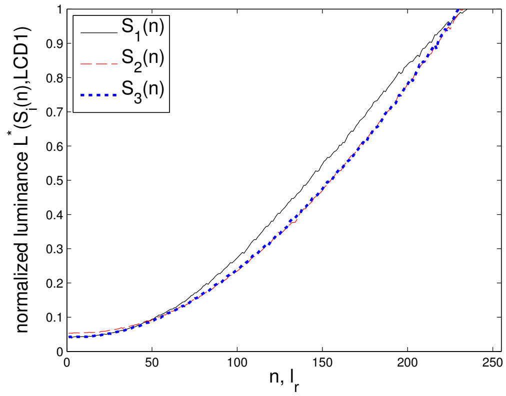

Figure 5. Crosstalk pattern for LCD1 - shutter glasses display.

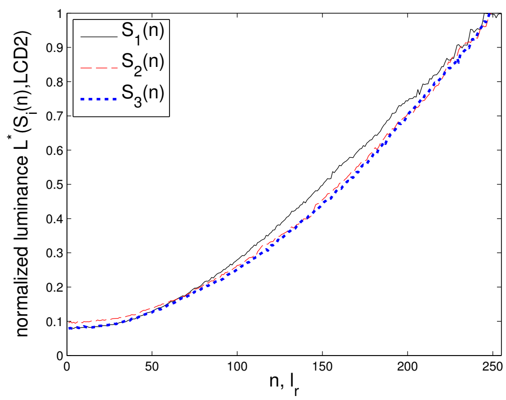

Figure 6. Crosstalk pattern for LCD2 - shutter glasses display.

be observed as well. Moreover, $L^*(S_3(n)) > L^*(S_1(n))$ for $n = 1, 2, ..., 255$ and $L^*(S_3(n)) > L^*(S_2(n))$ for $n = 129, 130, ..., 255$ since in theory, luminance increase is caused by luminance leaking from l_l component.

IV. The Obtained Results

Plots of $L^*(S_i(n), D)$ obtained for all tested displays are presented in Fig. 3 to Fig. 6.

One can observe the difference between measured curves and the theoretical one. Only the polarized display LCD3 reveals a pattern predicted by the theory (see Fig. 3). In this case term "leaking" fits well since the measured effect is caused by imperfection of separation in polarized glasses.

$L^*(S_i(n), \mathrm{TV})$ plot presented in Fig. 4 is different from expected results. "Leaking" is not the single observed effect since the vertical distance between $L^*(S_1(n), \mathrm{TV})$ and $L^*(S_2(n), \mathrm{TV})$ depends on l_r value also. It means that Eq. (3)-(5) are not fulfilled. We observe more distortion in a brighter image than in a darker one. On the other hand, plots $L^*(S_2(n), \mathrm{TV})$ and $L^*(S_3(n), \mathrm{TV})$ are much closer to each other. It shows that the effect observed for $l_l = 0$ is different from this observed for higher l_l values.

Results for LCD1 and LCD2 displays are consistent to each other (Fig. 5 and Fig. 6 respectively). Both displays make use of NVIDIA shutter glasses. For these devices crosstalk is small since all obtained lines are close to each other. In this case, however, the Eq. (3)-(5) are not fulfilled because the following relation $L^*(S_1(128), \mathrm{LCD1}) > L^*(S_2(128), \mathrm{LCD1})$ is observed. In other words, when one observes or measures the average display luminance L^* in the right-eye position and increases brightness of "left" view from $l_l = 0$ to $l_l = 128$, the average luminance L^* of the right view decreases. It means that the measured crosstalk is in some sense contrary to the "leaking" and has to be caused by different phenomenon than in case of polarized glasses.

In order to understand why such $L^*(S_i(n))$ patterns are observed an analysis of temporal changes of a display luminance level is presented in the following section.

V. Analysis of Temporal Changes of a Display Luminance

The shutter glasses technology faces different problems than the passive one. In case of polarized glasses the greatest contribution to crosstalk is caused by imperfection of glasses

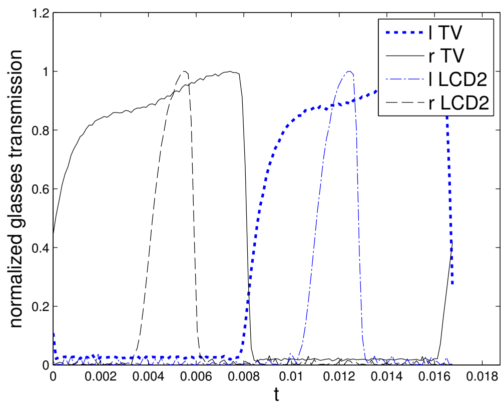

Figure 7. Shutter glasses characteristics for TV and LCD2 device. Time relation between left and right channels are preserved.

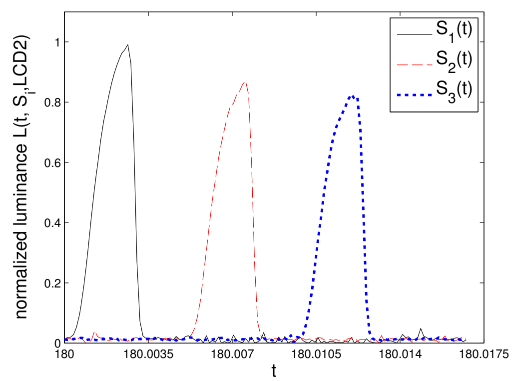

Figure 9. Luminance level measured in a right-eye position for crosstalk patterns and LCD2. Parameter $n = 180$ for sequences S_1, S_2, S_3 have been chosen.

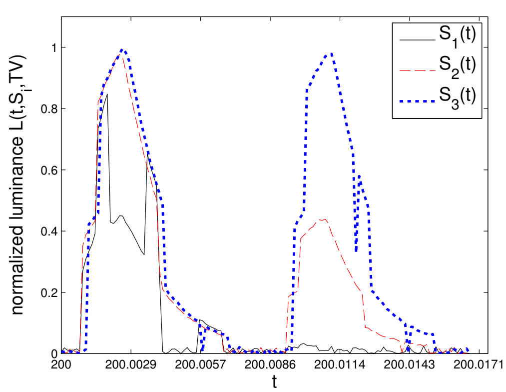

Figure 8. Luminance level measured without glasses for TV set. Parameter $n = 200$ for sequences S_1, S_2, S_3 have been chosen.

attenuation or perspective (parallax) distortion [10]. On the other hand, in case of shutter glasses the most demanding challenge is the fast switching between left and right views. In order to generate such fast switching each display has to run a specific procedure which influences the luminance pattern.

A shutter glasses display has to generate a particular luminance in a short time. Moreover, it has to synchronize it with the shutter glasses. In particular, we have identified two different shutter glasses technologies. Opening times for both of them are presented in Fig. 7. They differ by means of the duration of the "open" state i.e. a time period they are transparent. First solution used in the TV set opens shutter glasses for half of cycle. The correct amount of light is presented just in the middle of the opening time period. The second solution used in LCD1 and LCD2 opens shutter glasses for an over 3 times shorter period of time when compared to the first solution. In this case the display algorithms can do whatever to achieve the correct luminance outside of the opening time interval.

In Fig. 8 time plots of luminance of the TV set $L(t, S_i, \text{TV})$ for $n = 200$ are presented. The left half of plots (up to $t = 200.0086$) corresponds to a right-eye position, while the right one to a left position. Screen luminance in the left half of plots should not change for all sequences $S_i(n)$ because the only one difference is in the part which is displayed in the right half of the figure (for a left-eye position). It seems that the different luminance level displayed in the left-eye position influences the way the right-eye position is displayed. We do not know why such an effect exists since the luminance level for any sequence is fading to zero between each view. This in turn means that TV set is fast enough to change luminance level from minimum to maximum during one cycle.

Shutter glasses with short opening time interval are used in case of LCD1 and LCD2 . Time plots of luminance of LCD2 for $n = 180$ and for different sequences are presented in Fig. 9. This time, measured patterns are very similar. Nevertheless, $L(t, S_i, D)$ measured without glasses (see Fig. 10) is significantly different for each sequence. For example focusing at the first left half of Fig. 10 (up to $t = 180.0086$) which corresponds to the right view one can see that:

- In the case of $S_1(n)$ the value of luminance related to 180 has to be reached from 0 since a previously displayed value for the left view is 0.
- In the case of sequence $S_3(n)$ luminance is not changed at all since both left and right views are set to the same value of 180.

In order to reach high luminance level the display is overdriving the luminance. If the shutter glasses open when the luminance is overdriven, then the measured luminance is higher than in the case when luminance is constant. That is why $L^*(S_1(n)) > L^*(S_3(n))$ even if the "leaking" of the left view is much higher for $S_3(n)$ than for $S_1(n)$.

Based on our observation we propose a new crosstalk

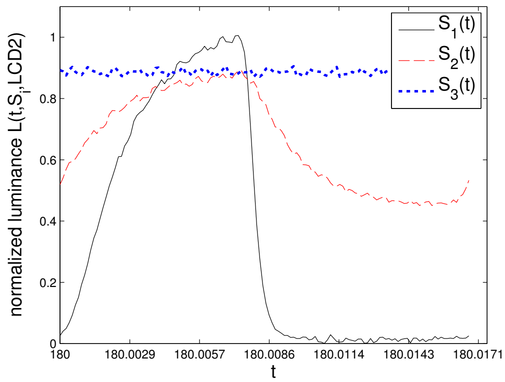

Figure 10. Luminance level measured without glasses for LCD2. Parameter $n = 180$ for sequences S_1, S_2, S_3 have been chosen.

objective metric. It is based on two assumptions. The first one is that the reference signal should be a 2D sequence i.e. a signal where $l_l = l_r$. The second assumption is that subjects observe a relative difference. Those two assumptions result in a crosstalk objective metric (for the right-eye position) for a sequence S_i

$$C(S_i, D) = \frac{|L^*(S_i, D) - L^*(S_3, D)|}{L^*(S_3, D)} \tag{8}$$

where

$$S_i = \begin{cases} l_l = x \\ l_r = y \end{cases} \text{ and } S_3 = \begin{cases} l_l = y \\ l_r = y \end{cases} \tag{9}$$

Note that for left-eye position measurement S_3 will change to $l_l = x$ and $l_r = x$.

The proposed definition is much more display technology independent since each 3D display can process 2D signal as well.

VI. Conclusions and further work

The paper shows that objective crosstalk metrics such as these proposed in [2], [4] perform well in case of a polarized technology. These definitions are based on the assumption that one view "leaks" into the other view. Nevertheless, "leaking" paradigm is not relevant in case of a shutter glasses technology.

The detailed temporal analysis shows that the luminance level depends on both l_l and l_r values but their relation is not linear. Therefore, an intuitive definition such as proposed in [5] and given by Eq. (2) is also not applicable. Luminance of a particular point can be incorrect (comparing to the original luminance) even if the leaking of the other view is close to zero.

The paper shows that for both types of tested shutter glasses results of luminance measurements cannot be explained by methods proposed in literature. Section V presents the detailed discussion of the difference between both shutter glasses and polarized technologies. For this purpose an analysis of temporal changes of a screen luminance has been performed.

Our future plan is to run subjective experiments and validate the proposed objective metric. The validation will be made first for shutter glasses displays and then for other technologies.

Acknowledgment

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