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# Watermarking of HDR Images in the Spatial Domain With HVS-Imperceptibility

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**ABSTRACT** This paper presents a watermarking method in the spatial domain with HVS-imperceptibility for High Dynamic Range (HDR) images. The proposed method combines the content readability afforded by invisible watermarking with the visual ownership identification afforded by visible watermarking. The HVS-imperceptibility is guaranteed thanks to a Luma Variation Tolerance (LVT) curve, which is associated with the transfer function (TF) used for HDR encoding and provides the information needed to embed an imperceptible watermark in the spatial domain. The LVT curve is based on the inaccuracies between the non-linear digital representation of the linear luminance acquired by an HDR sensor and the brightness perceived by the Human Visual System (HVS) from the linear luminance displayed on an HDR screen. The embedded watermarks remain imperceptible to the HVS as long as the TF is not altered or the normal calibration and colorimetry conditions of the HDR screen remain unchanged. Extensive qualitative and quantitative evaluations on several HDR images encoded by two widely-used TFs confirm the strong HVS-imperceptibility capabilities of the method, as well as the robustness of the embedded watermarks to tone mapping, lossy compression, and common signal processing operations.

**INDEX TERMS** HDR, invisible watermarking, visible watermarking, LVT curve, HVS-imperceptibility.

## I. INTRODUCTION

HDR images are characterized by a wide range of visible luminance values that can accurately represent the radiance of the scene, ranging from direct sunlight to faint starlight. Thanks to its floating-point representation, this type of imaging data can depict more colors and cover a wider range of intensity values than its Standard Dynamic Range (SDR) counterpart. Acquiring, storing, and displaying HDR images is possible thanks to the use of Transfer Functions (TFs), which perform the mapping from the linear light components of the scene, to a non-linear digital signal, and eventually to a linear luminance signal to be radiated by an HDR screen. TFs can then emulate the Human Visual System (HVS) by using non-linear operations to quantize the values representing the visible luminance with minimal subjective distortions.

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As HDR images become widespread, their vulnerability to piracy, unauthorized distribution, modifications, and illegal copying is expected to increase. HDR imaging piracy may result in significant losses to the economy, harming content production firms and distribution companies. In the U.S. alone, a recent study estimates that global online piracy costs the economy at least \$29.2 billion in lost revenue each year [1].

Watermarking is an effective tool not only for media ownership identification but also for auxiliary information delivery. The watermark, or auxiliary information, is usually embedded in the cover media as barcodes, Quick Response (QR) codes, logos, or copyright patterns. This embedded information may be visible or invisible depending on the watermarking process. It is well-known that invisible watermarking does not seriously degrade the visual quality of the cover media by performing the embedding process after a transformation, e.g., in the frequency domain. However, this type of watermarking usually requires the exchange of private keys or extra information about the embedding process to retrieve the watermark. Conversely, visible watermarking allows to visually assert the media's ownership without the need for such keys or extra information. This is usually achieved by performing the embedding process in the spatial domain; e.g., by altering pixel values. Visible watermarking is desirable when the copyrighted material is disseminated over channels where piracy control is not possible, e.g., the Internet, as the visible watermark can make the final user immediately aware of the media's ownership. However, this type of watermarking inevitably degrades the visual quality of the cover media.

To leverage the advantages of visible and invisible watermarking for HDR imaging, we propose a watermarking method in the spatial domain with HVS-imperceptibility capabilities. Our method, hereinafter called High Dynamic Range - Imperceptible Watermarking, (HDR-IW) provides an easy way to recognize the media's ownership without the need for exchanging keys or any extra information about the embedding process, while minimizing the visual distortion that can be perceived by the HVS. The proposed method is based on the Unseen Visible Watermarking (UVW) technique [2], [3] and extends our work in [4]. Differently from the UVW technique, which embeds copyright information in the spatial domain of SDR regions with low visibility, the HDR-IW method embeds imperceptible watermarks in the spatial domain by exploiting the inaccuracies among the non-linear digital representation of the linear luminance acquired by an HDR sensor, the linear luminance radiated by an HDR screen by means of a TF, and the brightness perceived by the HVS from the displayed luminance. The latter is achieved by using the information provided by a Luma Variation Tolerance (LVT) curve [4]. This paper extends and complements [4] as follows:

- The technical details and computation of the LVT curve are explained in detail for the two TFs widely-used to encode HDR images. The LVT is a core component to determine the maximum variations in luma codes that a pixel can suffer before the changes can be perceived by the HVS according to the TF used for encoding.
- An embedding region (ER) selection process is introduced to find the region with the highest tolerance to luma code variations according to the corresponding LVT curve.
- 3) A novel embedding payload metric is introduced to measure the embedding payload of the HDR-IW method by accounting for the characteristics of the HDR image and the corresponding LVT curve and TF.

The watermarks embedded by the HDR-IW method in the spatial domain are imperceptible to the HVS as long as the TF is not altered or the normal calibration and colorimetry conditions of the HDR screen remain unchanged. Hence, these watermarks can be easily identified without the need for private keys or any additional information about the embedding process.

We evaluate the proposed HDR-IW method for the embedding of binary watermarks in terms of embedding payload, imperceptibility (qualitatively and quantitatively), robustness to tone-mapping operations (TMOs), which are widely used to display HDR images on SDR screens, lossy compression [5]–[7] and other common signal processing operations. To the best of our knowledge, there are no other watermarking methods for HDR images that also embed information in the spatial domain in an imperceptible manner. However, we compare the imperceptibility capabilities and robustness of the HDR-IW method with those of two invisible watermarking methods that operate in the frequency domain, [8], [9].

The rest of the paper is organized as follows, Section II reviews comparable watermarking methods for HDR images that embed invisible watermarks after transforming the cover media. Section III briefly describes the HDR acquisition and encoding process. Section IV explains in detail the HDR-IW method. Section V presents and discusses the performance evaluation results. Finally, Section VI concludes this work.

#### **II. RELATED WORK**

Although SDR watermarking is a mature area that has been extensively explored both in the spatial and frequency domains, HDR watermarking is still in the early stages. In the last few years, however, important watermarking methods for HDR imaging that embed invisible watermarks after transforming the cover media have been proposed. These methods can be classified into two main groups. The first group includes methods that embed the watermark after applying a frequency transformation. For example, Bakhsh and Moghaddam [8] employ an artificial bee colony algorithm to find the best region to embed a binary watermark in the first-level approximation sub-band of the Discrete Wavelet Transform (DWT). Maiorana and Campisi [9] present a blinddetectable multi-bit watermarking method that uses the DWT of the Just Noticeable Difference (JND)-scaled representation of the HDR image for embedding purposes, as well as a contrast sensitivity function to modulate the watermark intensity in each DWT sub-band according to its scale and orientation. Guerrini et al. [10] present a blind-detectable one-bit watermarking method that uses the approximation sub-band of the DWT of the LogLUV color space. Autrusseau and Goudia [11] propose a non-linear hybrid method that combines additive and multiplicative watermarking. The embedding process is done in the DWT domain of the RGB radiances of an RGBe-encoded HDR image. The work in [12] exploits the properties of the Radon-Discrete Cosine Transform (R-DCT) to derive an image representation whose coefficients can be watermarked with an insignificant effect on the visual quality. In [13], the authors propose a watermarking method robust to TMOs by successively performing a non-subsampled contourlet transform and singular value decomposition to extract the structural information that is invariant to tone-mapping.

The second group of HDR watermarking methods includes those that embed the watermark after applying a color decomposition or filtering process. The work in [14] proposes a method based on feature map extraction by means of the Tucker decomposition. This method divides an HDR RGB color image into the three color channels so that three feature maps are extracted. The method then embeds a watermark in the feature map that contains most of the image's energy. In [15], the authors decompose an HDR image into multiple SDR images by means of a bracketing process. Each SDR image is watermarked with a random key before being merged to produce the final watermarked HDR image. In [16], the authors propose a blind-detectable watermarking method that uses bilateral filtering to extract the small scale and texture parts of the HDR image, also known as the blue component of the detail layer. The watermark is embedded in this blue component to minimize quality degradations.

In summary, the previous watermarking methods have been shown to achieve strong performance. However, they may require the deployment of specific watermark detection and extraction modules. For example, the methods in [8], [16], and [10] require an explicit exchange of private keys to detect and extract the watermark. Although embedding watermarks in the spatial domain eliminates the trouble of deploying an extraction module, such an embedding technique is seldom explored because the embedded watermarks are visible and hence defeat the goal of providing a highquality and realistic visual experience through HDR imaging. To the best of our knowledge, no watermarking method in the spatial domain with HVS-imperceptibility for HDR imaging has been previously proposed. Such methods have only been proposed for SDR images. For example, [17] and [18] propose to exploit the cover media's color histogram to embed the watermark in the spatial domain with HVSimperceptibility. The method in [19], on the other hand, uses a JND criterion for embedding in the spatial domain, the DCT to share extraction parameters, and a binarization function for extraction. Although these watermarking methods have HVSimperceptibility capabilities, they are not suitable for HDR images because of the color and visibility ranges of SDR images differ from those of HDR images, which comes as a consequence of using distinct TFs to encode the luminance and color information [9].

## **III. HDR IMAGING**

The abbreviations and acronyms used in this work are defined in Table 1.

Acquiring luminance from a scene in the form of an HDR image requires to first map the scene's linear luminance to

 TABLE 1. List of Abbreviations and Acronyms.

Abbreviation	Description	Abbreviation	Description
HDR	High Dynamic Range	LVT	Luma Variation Tolerance
TF	Transfer Function	HVS	Human Visual System
SDR	Standard Dynamic Range	QR	Quick Response
HDR-IW	High Dynamic Range - Imperceptible Watermarking	UVW	Unseen Visible Watermarking
TMO	Tone Mapping Operation	CS	Contrast Sensitivity
OETF	Opto-Electronic Transfer Function	EOTF	Electro-Optical Transfer Function
PQ	Perceptual Quantization	HLG	Hybrid Log-Gamma
HDR-VDP-2	HDR Visual Difference Predictor	MOS	Mean Opinion Score
mPSNR	multi-exposure Peak Signal to Noise Ratio	MSE	Mean Square Error
OP	Quantization Parameter	BER	Bit Error Rate



**FIGURE 1.** Mapping of luma codes to display luminance by different EOTFs.

a non-linear digital signal in the form of code values. This mapping is done through an opto-electronic transfer function (OETF). To display HDR images, the code values are mapped back to a linear luminance signal to be radiated by an HDR screen by means of an electro-optical transfer function (EOTF).

Two TFs are currently used for HDR images: the Perceptual Quantization (PQ) EOTF and the Hybrid Log-Gamma (HLG) OETF. The PQ EOTF, also known as the SMPTE ST.2084 standard [20], maps 10-bit luma codes,  $luma_{code} \in [0, 2^{10} - 1]$ , to display luminance  $\mathcal{L}_d \in [10^{-4}, 10^4] cd/m^2$ . This EOTF is an absolute, display-referred TF, as the maximum possible  $\mathcal{L}_d$  value depends on the screen's display capabilities. However, this TF maps each luma code to the same absolute luminance value in every screen. HDR images encoded by the PQ EOTF are not directly backward compatible with SDR screens. Conversely, the HLG OETF preserves backward compatibility. This TF is a relative, scene-referred TF [21], since digital signals produced by this TF represent the intensity of the light relative to the peak output of the HDR sensor.

Ideally, a TF should be a reversible function. Unfortunately, TFs are not reversible and the mapping between linear light components and non-linear codes is lossy. Fig. 1 plots the mapping of 10-bit luma codes,  $luma_{code} \in [64, 940]$ , to display luminance by the two EOTFs previously discussed. For the case of the HLG TF, Fig. 1 plots the inverse of the OETF, i.e., OETF<sup>-1</sup>, as the EOTF. Note that each EOTF maps the same luma code to a slightly different display luminance value. This can be best appreciated in Fig. 2.

Contrast threshold curves are commonly used to study the HVS' ability to make contrast distinctions [22], [23]. Fig. 3 shows the contrast threshold curve proposed by Hecht *et al.* [22], where the luminance,  $\mathcal{L}$ , is plotted from very dark to very bright conditions against the JND perceived by the HVS ( $\Delta \mathcal{L}/\mathcal{L}$ ). The JND model in Fig. 3 shows the three regions used to describe the HVS' behaviour when detecting contrast. The *scotopic* region,  $\mathcal{L} \in [10^{-6}, 10^{-3}] \ cd/m^2$ , which follows the De Vries-Rose law. The *photopic* region,  $\mathcal{L} \in [10, 10^8] \ cd/m^2$ , which follows a relatively constant trend, i.e., the Weber-Fechner Law. And



**FIGURE 2.** Mapping of  $luma_{code} \in [64, 192]$  to display luminance by different EOTFs.



**FIGURE 3.** Hecht's curve modeling the HVS' relationship between contrast thresholds,  $JND = \Delta \mathcal{L}/\mathcal{L}$ , and luminance,  $\mathcal{L}$ .

the *mesopic* region,  $\mathcal{L} \in (10^{-3}, 10) \ cd/m^2$ , which combines the characteristics of the scotopic and photopic regions. JND models like the one in Fig. 3 are used to design TFs with smooth visual transitions between consecutive luma code values. This is achieved by establishing coding steps below the threshold of visibility [24].

#### **IV. PROPOSED HDR-IW METHOD**

The HDR-IW method embeds binary watermarks in the spatial domain of the Y-channel with HVS-imperceptibility. It comprises 4 main stages, as depicted in Fig. 4 and described next.

# A. LUMA VARIATION THRESHOLD CALCULATION

When an initial low luminance stimulus is given to the HVS, very large variations in such a stimulus are required for the HVS to perceive any changes, as shown in Fig. 3. Designing a TF that accurately models the HVS' response to any luminance stimulus is a challenging task. Current TFs represent a trade-off between computational complexity and accuracy of the code assignment process. This trade-off usually results in representing low luminance values with a wide range of luma codes in order to minimize visible contouring artifacts at such low luminance levels. For example, for 10-bit signals, the PQ EOTF employs 100 luma codes to represent display luminance values  $\mathcal{L}_d \in [0.0001, 0.75) cd/m^2$ , 64 luma codes

for  $\mathcal{L}_d \in [0.75, 2) \ cd/m^2$ , and only 22 luma codes for  $\mathcal{L}_d \in$ [2, 3)  $cd/m^2$ . Among the 100 luma codes used by this TF for  $\mathcal{L}_d \in [0.0001, 0.75) \ cd/m^2$ , there is some redundancy that results in a significant amount of bits being wasted to encode small contrast changes that the HVS may not be capable of perceiving at such low luminance levels. A similar situation occurs with the HLG  $OETF^{-1}$ . In other words, there is a mismatch between the HVS's capacity to perceive differences in display luminance and the modeling used by an EOTF to represent display luminance as luma codes. Consequently, luma codes used to represent low display luminance values can be appropriately modified to embed a watermark in the spatial domain so it is imperceptible to the HVS. The challenge here is to determine the regions that are most tolerant to luma code variations and the maximum variation that they can tolerate before these changes can be perceived by the HVS, i.e., their luma variation threshold, denoted by  $\xi$ . For a given EOTF, we propose to compute  $\xi$  for a luma code, *luma<sub>code</sub>*, based on the difference, or error, between the contrast sensitivity (CS) of the HVS and the CS modeling of an EOTF. To this end, we first determine how the luma code assignment of an EOTF changes as the display luminance,  $\mathcal{L}_d$ , increases linearly, and how the HVS' CS increases as  $\mathcal{L}_d$  increases linearly.

# 1) INCREASE IN $luma_{code}$ AS $\mathcal{L}_d$ INCREASES LINEARLY

Let us recall that the end-to-end mapping of the linear light components of a real-life scene to the linear luminance values displayed by an HDR screen involves a non-linear quantization in the form of a digital signal. This means that if the luminance values displayed by an HDR screen increase in a linear trend, the corresponding luma codes do not increase linearly. To illustrate this, let us first define the increase in luma codes,  $\Delta luma_{code}$ , when the display luminance,  $\mathcal{L}_d$ , increases linearly by 1  $cd/m^2$ , as follows:

$$\Delta luma_{code}(\mathcal{L}_d) = luma_{code}[\mathcal{L}_d + 1] - luma_{code}[\mathcal{L}_d], (1)$$

where  $luma_{code}[\mathcal{L}_d]$  is the luma code assigned to the display luminance value,  $\mathcal{L}_d$ .

Fig. 5 plots Eq. (1) for the two HDR EOTFs for  $\mathcal{L}_d \in [0.5, 1000] \ cd/m^2$ . It is evident that when the display luminance values increase linearly by  $1 \ cd/m^2$ , the luma codes do not increase linearly. Note that for the two EOTFs, Eq. (1) follows a trend similar to that shown in Fig. 3, especially for low display luminance values. In other words, there is a wide range of luma codes available to represent low  $\mathcal{L}_d$  values compared to the narrow range available for large  $\mathcal{L}_d$  values.

### 2) INCREASE IN THE HVS' CS as $\mathcal{L}_d$ INCREASES LINEARLY

Part of the HVS' ability to discern information is attributed to its capacity to perceive differences in luminance within a field of vision [25]. Changes in luminance create a pattern of contrast that conveys the majority of visual information to the viewer. The HVS' sensitivity to detect contrast is given by the reciprocal of the JND value. The CS derived from this reciprocal, i.e., CS = 1/JND, is indeed the minimum perceived brightness by the HVS associated with a contrast threshold,

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FIGURE 4. The four steps comprising the proposed HDR-IW method.



**FIGURE 5.**  $\Delta luma_{code}(\mathcal{L}_d)$  of different EOTFs.

 $\Delta \mathcal{L}/\mathcal{L}$  [26]. To appropriately compare the HVS' CS with the display luminance encoded as luma codes, we apply the same *N*-bit quantization used by an EOTF to the HVS' CS [27]. This *N*-bit quantization is given by:

$$CS_{N_{bit}} = \left[ \left( 219 \cdot \frac{1}{JND} + 16 \right) \cdot 2^{N-8} \right], \tag{2}$$

where [x] denotes the rounding operation on x.

The increase in the HVS' CS after *N*-bit quantization can then be measured as the increase in  $CS_{N_{bit}}$  values when the display luminance increases linearly by  $1 cd/m^2$ , as follows:

$$\Delta CS_{N_{bit}}(\mathcal{L}_d) = CS_{N_{bit}}[\mathcal{L}_d + 1] - CS_{N_{bit}}[\mathcal{L}_d], \qquad (3)$$

where  $CS_{N_{bit}}[\mathcal{L}_d]$  is the *N*-bit representation of the HVS's CS associated with the display luminance value,  $\mathcal{L}_d$ . Fig. 6 plots Eq. (3) for the case of 10-bit signals, i.e.,  $\Delta CS_{N_{bit}=10}(\mathcal{L}_d)$ . Note that for the two EOTFs, Eq. (3) follows a trend similar to that shown in Fig. 5. However, there are differences between the values given by  $\Delta CS_{10}(\mathcal{L}_d)$  and those given by  $\Delta luma_{code}(\mathcal{L}_d)$  for the same EOTF. These differences are exploited to modify luma codes in the spatial domain in an imperceptible manner, as explained next.

#### 3) LUMA VARIATION THRESHOLD AND THE LVT CURVE

Once the  $\Delta luma_{code}$  and  $\Delta CS_{N_{bit}}$  values are computed for a display luminance value,  $\mathcal{L}_d$ , we can define the luma variation threshold,  $\xi$ , for  $\mathcal{L}_d$  as the absolute difference, or absolute error, between these two values:

$$\xi(\mathcal{L}_d) = \left| \Delta CS_{N_{bit}}(\mathcal{L}_d) - \Delta luma_{code}(\mathcal{L}_d) \right|.$$
(4)



**FIGURE 6.**  $\Delta CS_{N_{10}}(\mathcal{L}_d)$  of different EOTFs.



FIGURE 7. LVT curves of different EOTFs.

Fig. 7 plots  $\xi(\mathcal{L}_d)$  for 10-bit signals. These curves are the LVT curves, one for each EOTF. Note that according to these LVT curves, low  $\mathcal{L}_d$  values can tolerate large variations before the HVS is capable of perceiving them. This tolerance is relatively constant for all other  $\mathcal{L}_d$  values. This is better appreciated in Fig. 8, which shows the LVT curves for the lowest  $\mathcal{L}_d$  values plotted in Fig. 7. In this figure, one can note that for  $\mathcal{L}_d$  values within the boundaries of the scotopic and mesopic regions, there exists an important discrepancy between the CS modeling used by a TF and the brightness perceived by the HVS, i.e., the HVS's CS. The greatest differences are found for  $\mathcal{L}_d < 2.5 \ cd/m^2$ , for both EOTFs.

It is important to note that the LVT curves in Fig. 7 can also be defined in terms of luma codes. Fig. 9 shows the LVT curves plotted as a function of *luma<sub>code</sub>*, i.e.,  $\xi(luma_{code})$ , for



**FIGURE 8.** LVT curves of different EOTFs for low  $\mathcal{L}_d$  values.



FIGURE 9. LVT curves of different EOTFs for 10-bit luma codes associated with low  $\mathcal{L}_d$  values.

10-bit signals. For a PQ compatible system, one can see that a  $luma_{code} = 100$  can be modified to any value  $\in [75, 125]$  without being perceived by the HVS, since  $\xi(100) = 50$ . In the case of an HLG compatible system, a  $luma_{code} = 100$  can be modified to any value  $\in [96, 104]$ , since  $\xi(100) = 8$  without being perceived by the HVS. For a given EOTF, there is then a target range of luma code values that are best suited to embed a watermark in the spatial domain without being perceived by the HVS. We denote this target range by  $luma_{target}$ .

#### **B. EMBEDDING REGION SELECTION**

To guarantee that the embedded watermark in the spatial domain is imperceptible to the HVS, the ER must be uniform with luma codes  $\in luma_{target}$ . Our approach to finding an ER that fulfils these criteria on the Y-channel is embodied in Algorithm 1.

In line 2 of Algorithm 1, function superpixelSeg is used to perform SLIC superpixel segmentation [28] on the Y-channel, which results in set SP with  $\eta$  superpixels (SPs). Superpixel segmentation divides the Y-channel into  $\eta$ homogeneous regions in terms of texture, color and visual semantics, which is a desirable property for watermarking [29]. In lines 4-5, the average luma code ( $luma_{SP_k}$ ) and area ( $area_{SP_k}$ ) of the  $k^{th} SP \in SP$  are computed, where  $luma_{code}[p]$  is the  $p^{th}$  luma code and P is the total number of pixels in the  $k^{th} SP$ . In line 8,  $luma_{SP_k}$  is normalized to [0,1], where 0 denotes the largest value in set SP and 1 the

Algorithm 1 ER Selection
Input: Y-channel
Output: ER
1: $SP = \emptyset; SP_{GS} = \emptyset$
2: $SP = \{SP_1, SP_2, \cdots, SP_\eta\} \leftarrow \text{superpixelSeg}(Y)$
3: for each $SP \in SP$ do
4: $luma_{SP_k} = \frac{1}{P} \sum_{p=1}^{P} luma_{code}[p]$
5: $area_{SP_k} = P$
6: <b>end</b>
7: for each $SP \in SP$ do
8: $luma_{SP_k} \leftarrow normalize(luma_{SP_k})$
9: $\widehat{area}_{SP_k} \leftarrow \operatorname{normalize}(area_{SP_k})$
10: $GS_{SP_k} = w_l \cdot luma_{SP_k} + w_a \cdot \widehat{area}_{SP_k}$
11: $S\mathcal{P}_{GS} \leftarrow S\mathcal{P}_{GS} \cup GS_{SP_k}$
12: <b>end</b>
13: $SP_{GS} \leftarrow rank(SP_{GS})$
14: $ER \leftarrow inscribe(SP_{GS_1})$

smallest value in the set. In line 9,  $area_{SP_k}$  is normalized to [0,1], where 0 denotes the smallest value in set SP and 1 the largest value in the set. In line 10, a global score,  $GS_{SP_k}$ , is computed for the  $k^{th}$  SP as a weighted average of  $\widehat{luma_{SP_k}}$ and  $\widehat{area}_{SP_k}$ , with weights  $w_l$  and  $w_a$ , where  $w_l > w_a$  and  $w_l + w_a = 1$ . In other words,  $GS_{SP_k}$  assigns higher importance to  $luma_{SP_k}$ , i.e., SPs with small luma code values are preferred over those with large areas (and possibly relatively large luma code values) to guarantee imperceptibility. In line 11, the  $GS_{SP_k}$  value is placed in set  $SP_{GS}$ . In line 13, function rank organizes the elements in  $SP_{GS}$  in descending order, where the first element,  $SP_{GS_1}$ , is the largest SP with the smallest  $luma_{SP_k}$  value. Finally, in line 14, the ER is defined as the largest inscribed region within  $SP_{GS_1}$  by means of function inscribe. Fig. 10 (rows 1-3) shows sample results of Algorithm 1 on the Y-channel of various HDR images.

#### C. WATERMARK EMBEDDING

The HDR-IW method embeds a binary watermark, BW, of size  $m \times n$  into the ER of size  $m \times n$  to produce a watermarked ER denoted by  $\overline{ER}$ :

$$\overline{ER}_{i,j} = \begin{cases} ER_{i,j} + \Xi_{HDR} & \text{if } BW_{i,j} = 0\\ ER_{i,j}, & \text{otherwise,} \end{cases}$$
(5)

where  $\overline{ER}_{i,j}$  and  $BW_{i,j}$  are the value of the watermarked ER and the binary watermark at pixel location (i, j), respectively, and  $\Xi_{HDR}$  is the embedding factor of the cover image. It is important to mention that the human visual attention and the HVS' response to contrast variations not only depend on the target region but also on its surrounding region [23], [24]. For this reason, the HDR-IW method accounts for the  $\mathcal{L}_d$ values of the region surrounding the ER when embedding the watermark. The embedding factor of the cover image,  $\Xi_{HDR}$ , is then computed as a weighted sum of the average luma variation threshold of the ER, denoted by  $\overline{\xi}_{ER}$ ; the average luma variation threshold of the region surrounding the ER,



FIGURE 10. (1<sup>st</sup> row) Superpixel segmentation on the Y-channel of various sample HDR images. (2<sup>nd</sup> row) Corresponding target superpixel. (3<sup>rd</sup> row) ER used to embed the watermark. (4<sup>th</sup> row) Watermarked images after adding the color channels in 4:2:0 YUV format.

denoted by  $\bar{\xi}_{SR}$ ; and the average luma variation threshold of the cover image, denoted by  $\bar{\xi}_{HDR}$ :

$$\Xi_{HDR} = \lceil w_0 \cdot \bar{\xi}_{ER} + w_1 \cdot \left( \bar{\xi}_{SR} + \bar{\xi}_{HDR} \right) - k \rceil, \qquad (6)$$

where  $w_0$  and  $w_1$  are weights that establish the impact of the terms, with  $w_0 + (2 \times w_1) = 1$ , and k is a strength factor. The average luma variation thresholds in Eq. (6) are computed by averaging the luma variation thresholds of all the pixel locations in the corresponding region. For example, for the  $m \times n \text{ ER}$ ,  $\xi_{ER}$  is computed as follows:

$$\bar{\xi}_{ER} = \frac{1}{m \cdot n} \sum_{i=1}^{m} \sum_{j=1}^{n} \xi_{i,j}(luma_{code}), \tag{7}$$

where  $\xi_{i,j}(luma_{code})$  is the luma variation threshold of pixel location (i, j) as given by the corresponding LVT curve (see Fig. 9). The region used to compute  $\bar{\xi}_{SR}$  comprises the 8 blocks of size  $m \times n$  surrounding the ER. To compute  $\bar{\xi}_{HDR}$ , all pixels locations of the cover image are used except for those in the ER and its surrounding region, as shown in Fig. 11.

Fig. 10 (4<sup>th</sup> row) shows sample watermarked images in the 4:2:0 YUV color format after embedding the binary watermark in Fig. 12 in the Y-channel. Fig. 13 graphically illustrates the complete embedding process.

## **D. DETECTION**

A watermark embedded as explained in Section IV-C remains imperceptible to the HVS as long as the TF is not altered or



**FIGURE 11.** Regions used to compute the luma variation thresholds. ER is the  $m \times n$  embedding region. SR comprises the eight  $m \times n$  blocks surrounding ER. HDR comprises all pixels locations except for those in ER and SR.



FIGURE 12. Binary watermark used in this work.

the normal calibration and colorimetry conditions of the HDR screen remain unchanged. To make the watermark perceptible to the HVS, i.e., to visually detect it, one of the following procedures must be applied:



FIGURE 13. Block diagram of the embedding process. Blocks in green, red and blue denote inputs, outputs and processes, respectively.

- Manual color calibration of the HDR screen. The EOTF, peak RGB gamut, luminance, black/white points, and greyscale settings of the HDR screen affect the screen's colorimetry. Therefore, manually modifying the HDR screen's colorimetry to display a brighter version of the watermarked HDR imaging highlights mid and bright tones, which enhances the current contrast. This contrast enhancement contributes to exaggerating the watermarked luma codes, thus making the watermark perceptible to the HVS. This is illustrated in Fig. 14 for the watermarked HDR images in Fig. 10 (4<sup>th</sup> row).
- 2) Applying a gamma TF to the tone-mapped version of the watermarked HDR image. This process consists in varying the gamma factor of the traditional gamma TF, which is typically set to  $\gamma = 2.2$ . Applying a lower  $\gamma$ factor produces a brighter version of the tone-mapped image, thus making the watermark visible to the HVS.
- 3) Printing out the watermarked HDR image. The EOTF used by most printers is the dot gain compensation curve (DGCC), which is a variant of the traditional gamma function used by SDR screens [30]. The DGCC corresponds to luminance being reproduced as a power function of a code, where the exponent value is set to 1.75, instead of the traditional 2.2 value used for displaying purposes. Printing the watermarked HDR image involves applying a TMO, which is similar to the second procedure.
- 4) Using special software to handle color grading. Color grading aims to enhance the color of visual content by applying color correction and artistic color effects. Specialized color grading software performs a TMO and color correction with the traditional gamma TF, where  $\gamma$  can be modified to make the watermark perceptible to the HVS. This procedure is analogous to procedures 2 and 3.

#### **V. EVALUATION RESULTS**

Five sets of experiments are conducted to evaluate the proposed watermarking method to embed imperceptible binary watermarks in the spatial domain. These experiments evaluate the method's embedding payload, imperceptibility, and robustness. A total of 51 HDR images are used for evaluation. These HDR images are frames from a large collection of real-life HDR video sequences captured in a wide variety of scenarios and lighting conditions, including indoor and outdoor scenes, natural scenes, sports scenes, urban scenes, daytime scenes, night scenes, and textured scenes. Each HDR image has a resolution of 1920 × 1080 and is coded using Rec.2020 + PQ EOTF<sup>-1</sup> or Rec.2020 + HLG OETF, as tabulated in the first four columns of Table 2 and illustrated in Fig. 15. The binary watermark in Fig. 12 is embedded in each test HDR image in all experiments.

In all evaluations, the weights to compute  $GS_{SP_k}$  in Algorithm 1 are set to  $w_l = 0.6$  and  $w_a = 0.4$ . The weights to compute  $\Xi_{HDR}$  in Eq. (6) are set to  $w_0 =$ 0.6,  $w_1 = 0.2$ . Based on our evaluations, these values provide the strongest HVS-imperceptibility capabilities. This is confirmed in Figs. 16 and 17, which show the relationship between  $w_1$  and  $w_0$ , respectively, and the imperceptibility of a watermark embedded in image Show-Girl2TeaserClip4000\_25\_12\_P3ct2020\_444i\_300 [31], as tabulated in Table 2. We quantitatively measure the imperceptibility of the embedded watermark in terms of the HDR Visual Difference Predictor (HDR-VDP-2) [37]. This metric measures the visibility and quality of a pair of HDR images. The visibility describes the probability that an observer can distinguish differences between the two images and the quality measures the degradation that the original image suffers after watermarking. Both parameters are given in terms of an  $u \times v$  probability map,  $p(u, v) \in [0, 1]$ , which is reduced to a single term by means of the Minkowsky distance:

HDR-VDP-2 = 
$$\left(\sum_{u}\sum_{v}p(u,v)^{\beta}\right)^{1/\beta}$$
, (8)

where  $\beta = 2.4$  is an adjusting factor, and *u* and *v* are coordinates for the current pixel location. To compare HDR-VDP-2 values with conventional metrics, Eq. (8) is converted to a dB scale [37]:

$$HDR-VDP-2_{dB} = 20 \cdot \log_{10} \left( \frac{HDR-VDP-2_{max}}{HDR-VDP-2} \right).$$
(9)

From Fig. 16, we can see that the imperceptibility is strongly affected for  $w_l < 0.6$ . Hence, to guarantee that an ER with the smallest luma code values is selected over others with large areas (and possibly relatively large luma code values), we use  $w_l = 0.6$  and  $w_a = 0.4$ . From Fig. 17, we can see that values  $w_0 < 0.6$  also decrease the imperceptibility. Therefore, we set  $w_0 = 0.6$  and  $w_1 = 0.2$ .

#### A. FIRST SET OF EXPERIMENTS: EMBEDDING CAPACITY

Table 2 tabulates the size of the ER, in percentage w.r.t. the size of the cover image, the average luma code value of the ER,  $luma_{ER}$ , and the embedding factor of the cover image,  $\Xi_{HDR}$ . From this table, one can note that  $luma_{ER}$  and  $\Xi_{HDR}$ 

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FIGURE 14. Watermarks (see Fig. 10) made visible after manual color calibration of the HDR screen.



FIGURE 15. Sample test HDR images encoded using Rec.2020 + PQ EOTF<sup>-1</sup> (rows 1-2) and Rec.2020 + HGL OETF (rows 3-4).

values depend on both, the image's content and the TF used. Namely, PQ-encoded images have positive  $\Xi_{HDR}$  values and lower *luma<sub>ER</sub>* values than HLG-encoded images, which have negative  $\Xi_{HDR}$  values. As shown in Fig. 1, the HLG TF uses a narrower range of codes than that used by the PQ TF to encode low luminance values. Therefore, low luminance regions of HGL-encoded images are then expected to have a larger average luma code value than that of PQ-encoded

#### TABLE 2. Performance evaluation of the HDR-IW method and two invisible HDR watermarking methods.

Construct         Description         51         12         Description         51         32	Source	Image name	ID	TE	$\mathbf{FR} \cdot (\%)$	Income a	Europ	ECupp	Proposed metho	od: HDR-IW	Method is	ı [8]	Method i	n [9]
BerefescheserChipe002.51.2         PSC000241.0         BerefescheserChip002.51.2         PSC002441.00         BF_00         PC         2.20         66.489         5         0.0113         64.350         5         0.0113         64.350         5         0.0113         64.350         5         0.0113         64.350         5         0.0113         64.310         5         0.0113         64.310         5         0.0113         64.310         5         0.0113         64.310         5         0.0113         64.310         5         0.0133         64.310         5         0.0133         64.310         5         0.0133         64.310         5         0.0356         44.438         51.660         44.312         54.3177         0.35.01         33.587         33.587         33.640         44.344         34.203         33.587         33.587         34.561         44.316         34.3293         33.6423         33.	Bource	inage name	ш		ERsize (10)	$uma_{ER}$	$\Box HDR$	LOHDR	HDR-VDP-2	mPSNR	HDR-VDP-2	mPSNR	HDR-VDP-2	mPSNR
BeerFerGaseClipHonQ 25, 12 PSc202444, 100         BE,000         PQ         0.57         64.395         5         0.011         55.361         84.055         84.1455         33.8215 </td <td></td> <td>BeerFestTeaserClip4000_25_12_P3ct2020_444i_000</td> <td>BF_000</td> <td>PQ</td> <td>7.26</td> <td>65.0617</td> <td>5</td> <td>0.0549</td> <td>47.5145</td> <td>44.0568</td> <td>43.0318</td> <td>35.4686</td> <td>37.2813</td> <td>34.9757</td>		BeerFestTeaserClip4000_25_12_P3ct2020_444i_000	BF_000	PQ	7.26	65.0617	5	0.0549	47.5145	44.0568	43.0318	35.4686	37.2813	34.9757
BeerFerGrameCTigen002.51.2 Pic2002.444.100         BP100         PQ         0.44         64.305         5         0.011         55.201         88.230         44.739         55.118         35.6443         35.5443         35.564           BeerFerGrameCTige002.51.2 Pic200.444.100         BP2.00         PQ         0.439         55.331         4.0078         4.1092         55.331         4.2038         35.374         35.643         35.794         35.643         35.794         35.643         35.794         35.643         35.794         35.643         35.794         35.795         85.633         44.0163         35.296         35.794         35.676         35.795         35.676         44.0163         35.794         35.678         35.795         35.676         36.787         35.676         36.787         35.678         44.0163         35.698         35.797         35.676         36.787         35.678         36.878         36.878         37.875         36.676         37.875         36.676         37.875         36.676         37.875         36.676         37.875         36.676         37.875         36.676         37.877         36.918         36.916         37.875         38.6761         37.377         38.6761         37.875         38.6761         37.875		BeerFestTeaserClip4000_25_12_P3ct2020_444i_080	BF_080	PQ	0.57	64.4399	5	0.0415	45.8169	56.9533	44.0156	34.1435	35.8215	33.5727
BeerfestReaceClipH002_51_2Pet200_444_00         PC_00         PQ         0.80         6.8057         4.1557         88.665         4.2008         8.51.87         35.8567         35.8676         35.86		BeerFestTeaserClip4000_25_12_P3ct2020_444i_160	BF_160	PQ	0.44	64.2936	5	0.0413	53.5611	58.5206	44.7339	35.1188	35.6443	34.5371
BeerfesticaseCTipHo02_51_2Px2002_441_200         PF_320         PC         0.87         95.27         15         0.0826         41.4588         51.9600         45.776         45.776         45.771		BeerFestTeaserClip4000_25_12_P3ct2020_444i_240	BF_240	PQ	0.44	64.8045	4	0.0372	41.5577	58.6405	42.0038	35.1347	35.8567	34.5676
FierplaceTeaseCT:         FierplaceTeaseCT:         ProcessCT:		BeerFestTeaserClip4000_25_12_P3ct2020_444i_320	BF_320	PQ	0.89	86.2572	15	0.0826	41.4588	51.9660	45.9726	34.1767	40.5611	33.5904
FirejacTeaseCT:pH000_24_12_Psc200_441_00         P1_000         P0_0         P0_0<		FireplaceTeaserClip4000 24 12 P3ct2020 444i 000	FP_000	PÕ	0.79	95.4833	6	0.0460	44.9442	56.6304	41.4614	34.2924	32,7942	33.6542
[31]       FireplaceTeaseCTpi000_24_12_Psc200_444_170       PP_170       PQ       5.71       87.7632       7       0.0999       49.649       47.2802       40.1855       4.10890       88.061       33.423         FireplaceTeaseCTpi000_51_12_Psc20_444_000       80.000       PQ       6.64       6.5731       5       0.0837       60.317       6.5011       44.254       41.511       43.244       33.632       31.725       33.048         ShowGin2TeaseCTpi000_51_12_Psc20_444_124       SG_240       PQ       8.88       64.782       5       0.0831       44.058       47.741       40.1115       33.048       33.745       33.048       33.2426         ShowGin2TeaseCTpi000_51_12_Psc20_444_1240       SG_230       PQ       5.19       85.6985       9       0.0438       45.5536       55.875       40.9823       33.76       73.088       32.2456         ShowGin2TeaseCTpi000_51_12_Psc20_444_134       bC_344       PQ       0.31       60.059       13       0.0318       45.358       63.434       39.601       33.055       42.377       73.22377       73.22377       73.22377       73.22421       33.918       73.977       73.2238       73.977       73.22437       33.44       41.73       33.460       33.976       73.977 <t< td=""><td></td><td>FireplaceTeaserClip4000_24_12_P3ct2020_444i_090</td><td>FP_090</td><td>PÒ</td><td>0.52</td><td>93,9832</td><td>14</td><td>0.0778</td><td>41.9927</td><td>54,9763</td><td>39.8397</td><td>34.3107</td><td>33,3617</td><td>33.6748</td></t<>		FireplaceTeaserClip4000_24_12_P3ct2020_444i_090	FP_090	PÒ	0.52	93,9832	14	0.0778	41.9927	54,9763	39.8397	34.3107	33,3617	33.6748
Bit         FrequerTeaseCT_pleX02_24_12_DC202_441_20         PP 20         PP 20         S19         S13795         S5         00050         49.8233         48.6361         43.4615         33.8003         36.4023         31.725         33.0043           ShowGin2TeaseCT_pleX02_51_2 P24202.441_145         SG_114         PQ         8.88         64.7842         5         0.0832         48.2324         45.1176         42.4254         33.0049         31.4254         33.0049           ShowGin2TeaseCT_pleX02_1441_240         SG_214         PQ         8.83         64.7842         5         0.0851         44.9058         57.471         40.1115         21.3193         38.1632         33.009         33.0291         33.0293         33.0291         33.0293         33.029         33.029         33.029         33.029         33.0293         33.0291         33.0293         33.0291         33.0293         33	[31]	FireplaceTeaserClip4000_24_12_P3ct2020_444i_170	FP 170	PO	5.71	87.7632	7	0.0599	49 6649	47,2802	40.1855	34 0890	38 6916	33 4235
ShowGurl2TesserCip4000_25_12_Per2020_444_104 SG_154 PQ 8.88 64.704 55 0.0337 50.3415 45.019 41.9311 33.6824 11.7275 33.0948 51.957 51.957.019 51.2Psr2020_4441_124 SG_154 PQ 8.88 64.7048 55 0.0352 44.224 45.1176 42.2243 33.696 31.6320 33.797 53.506.01727esscr21p400_25_12_Per2020_444_124 SG_154 PQ 8.88 64.7048 55 0.0052 44.2048 73.411113 32.8195 31.6320 33.797 53.506.01727esscr21p400_25_12_Per2020_444_20 SG_240 PQ 8.88 64.7048 50 0.0052 44.2048 73.41113 32.8195 31.6320 33.797 53.506.01727esscr21p400_25_12_Per2020_444_20 SG_240 PQ 8.88 64.7048 50 0.0052 44.2048 75.997 40.9393 31.297 57.0838 32.0597 53.507 40.9392 31.2976 57.941 40.938 31.2057 53.508 40.901 51.976 50.514 51.2057 51	(0.1)	FireplaceTeaserClip4000_24_12_P3ct2020_444i_230	FP 230	PÕ	5.19	87 3795	5	0.0508	49.8233	48 6361	43 4615	33 8603	36.0432	33 1753
Show Cirit Tesser Cipe 000, 25, 12, Perico20, 444, 124 Show Cirit Tesser Cipe 000, 25, 12, Perico20, 4441, 24 Show Cirit Tesser Cipe 000, 25, 12, Perico20, 4441, 24 SG, 240 Show Cirit Tesser Cipe 000, 25, 12, Perico20, 4441, 240 SG, 200 PQ 8, 83 SHOW B, 21, PS, 200, 21, PE, 200, 2444, 240 SG, 200 PQ 8, 83 SHOW B, 21, PS, 200, 21, PE, 200, 2444, 240 SG, 200 PQ 8, 83 SHOW B, 21, PS, 200, 21, PE, 200, 2444, 240 SG, 200 PQ 8, 83 SHOW B, 21, PS, 200, 21, PE, 200, 2444, 240 SG, 200 PQ 8, 83 SHOW B, 21, PS, 200, 21, PE, 200, 2444, 240 SG, 200 PQ 8, 10 SHOW B, 21, PE, 200, 2444, 240 SG, 200 PQ 8, 10 SHOW B, 21, PE, 200, 2444, 240 SG, 200 PQ 8, 10 SHOW B, 20, 25, PE, 200, 2444, 240 SG, 200 PQ 8, 10 SHOW B, 20, 25, PE, 200, 244, 25, 25, 25, 25, 24, 248 SHOW B, 21, PE, 200, 244, 25, 25, 25, 24, 248 SHOW B, 21, PE, 200, 244, 24, 25, 24, 268 SHOW B, 21, PE, 200, 244, 24, 25, 24, 268 SHOW B, 21, PE, 200, 244, 24, 25, 24, 248 SHOW B, 24, 24, 24, 24, 24, 24, 24, 24, 24, 24		ShowGirl2TeaserClip4000_25_12_P3ct2020_444i_000	SG_000	PO	6.64	66 5731	5	0.0537	50 3415	46 5019	41 9311	33 6824	31 7275	33.0048
Show Citri ZinsacrClip400(2-5): L2 2)s2020, 441, 20         SC, 154         PQ         8.83         64.7084         5         0.0582         48.9187         43.1384         40.1463         34.3560         31.7597           Show Citri ZinsacrClip400(2-5): L2 2)s2020, 441, 20         SG, 300         PQ         2.17         87.0180         5         0.0447         45.553         55.7334         41.0723         33.159         33.797           Show Citri ZinsacrClip400(2.5): L2 Pis2020, 441, 20         SG, 300         PQ         2.17         87.0180         5         0.0487         45.5536         55.7334         41.0723         33.159         33.797         33.1251           beerfex: Lightshow, 102644         hC 2844         PQ         0.31         66.0559         15         0.0788         53.3829         61.351         44.0040         33.805         33.207         33.2185           beerfex: Lightshow, 102600         th'.2668         PQ         0.32         69.0718         16.0818         43.922         55.5414         33.4161         33.0181         33.2175         33.2185         33.0181         43.2207         33.0184         33.0181         43.2016         33.0181         43.2016         33.846         33.846         33.846         33.846         33.940         33.2185		ShowGirl2TeaserClip4000_25_12_P3ct2020_444i_134	SG 134	PO	8.88	64 7842	5	0.0582	48 2245	45 1176	42 4254	33 6269	32 4126	32 9472
Show clinit2TusserClip4000_25_12_P3c202_441_200         SG_240         PQ         8.83         88.183         90         0.0581         44.0628         75.9471         40.1115         32.8169         93.7048         32.0957           Show clinit2TusserClip4000_25_12_P3c202_441_30         SG_338         PQ         5.19         85.6985         9         0.0508         55.8079         44.0024         33.2957         33.2805         33.0957         33.0857         33.0957         33.0857         33.0957         33.0857         33.0957         33.0857         33.0957         33.0857         33.0957         33.2376         73.2387         14.0014         33.055         33.0957         33.2387         73.2387         73.2387         73.2387         73.2387         73.2387         73.2387         73.2387         73.2387         73.2387         73.2387         73.2387         73.2387         73.2387         73.2387         73.2387         73.2387         73.7777         5         0.0857         44.483         33.816         33.1583         31.1533         31.1533         31.1533         31.1533         31.1533         31.1533         31.1533         31.1733         34.5694         73.238787         23.2875         23.2875         23.2875         23.2875         23.2875         23.2875		ShowGirl2TeaserClip4000_25_12_P3ct2020_444i_154	SG 154	PO	8.88	64 7048	5	0.0582	48.0187	43 1384	40.1463	34 3596	31.6520	33 7307
Silow Cill Drived: 2, 1, 2, 59, 200, 1+41, 30         SG, 200         PQ         6, 519         85, 6985         9         0.00, 17         15, 33, 32         32, 350         33, 3206         37, 338         32, 350           Silow Cill Transer(Liptoby, 10244         52, 12, 26, 2020, 44i, 338         50, 300         PQ         0, 31         60, 058         53, 3329         61, 3511         44, 0004         33, 805         33, 807         33, 807         33, 805         33, 807         77, 77         32, 2215           bestra: (pishbow, 102640         bf, 3600         PQ         0, 20         66, 0659         15         0,0788         63, 3389         61, 3511         44,0004         33,805		ShowGirl2TeaserClip4000_25_12_P3ct2020_444i_154	SC 240	rQ DO	0.00	04.7040	5	0.0582	40.9107	43.1304	40.1405	22.8150	28 7048	33.7397
Since Unit Present up and 2, 12, per 2, 202, 02, 444, 308         FC         5, 19         6, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,		ShowGirl2TeaserClip4000_25_12_P3ct2020_444i_240	SG_240	rQ po	0.03	00.1032	9	0.0381	44.0028	57.6471	40.1115	32.0139	26 5900	32.0397
SnowLiniz Lessent, Upbold, 21, 242, 024, 144, 158         Value         Status         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         41.952.5         53.80/9         43.9821         53.80/9         43.4812         53.80/9         33.80         33.233         33.83         53.81/9         44.483         53.81.6         44.448         33.81.6         44.448.3         33.80         33.83         53.83/9         53.83/9         33.83         53.83/9         33.83         53.83/9         33.83/2         23.237.85         53.83/9         54.85/9         55.80/9         44.863         33.83         33.83/2         33.83/2         33.83/2         33.83/2         33.83/2         33.83/2         33.83/2         33.83/2         33.83/2         33.83		ShowGirl2TeaserClip4000_25_12_P3ct2020_4441_300	SG_300	PQ	2.17	87.0180	3	0.0447	45.5550	55.7554	41.7723	33.1234	30.3800	32.4200
beerfest_gigitsbow_10/2844 (b) 2344 (c) 0.31 (c) 0.031 (c) 0.038 (c) 3.5.889 (c) 0.354 (c) 0.054 (c) 0.055		ShowGirl2TeaserClip4000_25_12_P3ct2020_4441_338	SG_338	PQ	5.19	85.6985	9	0.0508	50.8921	55.8079	40.9829	33.2976	37.0838	32.6051
beerfest_lightshow_10/3020 b) 6_3020 PQ 0.89 66.4205 15 0.0881 4_3588 6_4.494 39.0001 33.0051 4_2.5977 4_32.2887 bistro_090958 b) 0.988 PQ 1_2.3 70.0706 14 0.0865 4_4.4522 51.6464 38.1566 3.44452 37.1327 33.2887 bistro_090958 b) 0.9170 b) 1710 b) 1717 PQ 2.59 120.868 10 0.0941 4_4.5038 4_4.7984 5.551 33.213 2_3.5069 37.2925 32.6893 bistro_09170 b) bistro_09170 b) 1710 PQ 3.03 697.418 14 0.0958 4_4.7984 5.551 33.213 2_3.5095 33.4880 37.2925 32.6893 bistro_091780 0x5_90184 b) 1710 PQ 3.03 697.418 14 0.0958 4_4.7984 5.551 33.5154 33.4880 37.3922 32.6893 bistro_091780 0x5_90184 b) 1710 PQ 3.03 697.411 5 0.0066 5 0.0185 4_4.752 4.3085 43.31807 43.3180 33.4857 33.4180 37.3922 32.4579 carouseLinework_090184 b) 170 PQ 9.00 70.0666 5 0.01359 4.47367 43.4386 44.1722 33.907 43.1310 33.7857 carouseLinework_09040 c1 6.670 PQ 9.07 75 64.2982 5 0.0955 4.42614 4.69478 43.8492 33.0776 43.2459 carouseLinework_097400 c1 6.700 PQ 5.75 64.2982 5 0.0955 4.42614 4.69478 43.8492 33.0736 33.9975 32.42893 b) carouseLinework_09740 c1 7.400 PQ 5.75 64.2982 5 0.0959 53.6466 6.6422 45.04668 34.0613 32.9740 33.24693 b) carouseLinework_097400 c5.730 PQ 0.41 74.0759 15 0.0901 53.6666 5.6462 44.50468 34.0613 32.9740 33.3800 pokertraveling_slowmotion_03122 pp.3122 PQ 0.131 9 44.287 16 0.0072 49.0392 50.2825 47.9129 33.8515 39.2887 33.749 showgirt_01_23566 sg_556 PQ 0.699 4.4287 15 0.0668 57.0186 51.01975 38.219 33.0357 33.4748 32.2670 showgirt_01_235965 sg_556 PQ 0.909 1.34 64.287 15 0.0668 57.0186 51.01975 38.219 33.0357 33.4748 32.2670 showgirt_01_235965 sg_556 PQ 0.913 74.4178 515 0.0674 74.788 49.5097 41.9896 33.3428 33.797 32.2247 showgirt_01_235965 sg_556 PQ 0.913 74.4185 15 0.0675 47.5099 4.0806 4.48737 33.2484 4.4540 33.32970 4.32466 4.34371 b) curchAhditeics014HD100p,HDREX_04272 EBU_4272 PQ 0.73 64.124 15 0.0851 75.7599 4.0806 35.3337 44.2540 33.2486 33.3192 33.846 33.3192 33.8486 33.3192 33.8486 33.3192 33.8486 33.3192 33.8486 33.3192 33.8486 33.3192 33.8486 33.3192 33.8486 33.3192 33.8486 33.3192 33.8486 33.3192 33.8486 33.3192 33.848		beerfest_lightshow_102844	bf_2844	PQ	0.31	69.0381	15	0.0758	53.3829	61.3531	44.0004	33.805	33.9029	33.2215
berfsel.gipthow_103660 bb_3288 b_0988 b_0288 pQ 1.23 70.0706 14 0.0886 41.4252 51.54648 33.81366 34.4452 37.1282 33.2887 bistro_091470 b_1710 b_1710 pQ 2.59 120.88 10 0.0941 45.4038 55.6251 33.5132 32.3098 37.2952 32.6893 bistro_091710 b_1710 pQ 3.05 697.418 14 0.0958 44.4803 55.6251 33.5132 32.3098 37.2952 32.6893 bistro_091710 b_1700 pQ 3.05 697.418 14 0.09587 44.4863 53.8816 44.1473 33.4560 39.346 37.8305 32.7253 carouse_freworks_096144 cf_6184 pQ 3.09 79.0611 4 0.0957 44.4863 53.8816 44.1472 34.3907 40.3130 33.7857 carouse_freworks_096270 cf_6270 PQ 9.00 70.0666 5 0.1384 47.3657 43.3856 44.1722 34.3907 40.3130 33.7857 carouse_freworks_09640 cf_6400 PQ 5.75 64.2929 5 0.0955 44.2614 46.0478 43.886 34.1724 32.4504 40.2805 34.0350 carouse_freworks_097400 cf_3400 PQ 5.75 64.2929 5 0.0955 44.2614 46.0478 43.8862 33.0756 35.9975 32.4252 carouse_freworks_09740 cf_340 PQ 0.44 92.9170 15 0.0061 52.9046 65.5446 46.4327 33.1749 32.863 32.4483 pokerture-ling_stomation_033122 p_3577 PQ 0.41 74.0759 15 0.0069 52.0406 66.5421 44.9146 34.1051 32.0971 33.2407 33.840 32.9770 32.4259 molecular stomation_033122 p_3577 PQ 0.41 74.0759 15 0.0067 47.0186 51.9658 44.3648 34.3151 32.9770 33.34718 32.2707 37.418 32.2707 37.418 51.755 44.0608 34.9851 32.9770 32.719 33.8418 32.2707 33.9877 32.219 33.8418 32.2707 33.9987 32.2219 12.2356 35.9975 32.4252 35.00658 44.0513 32.9771 32.2199 33.8451 32.9770 33.3408 37.418 32.2707 33.999 53.3456 35.3456 34.3426 34.3451 32.9770 33.3408 37.34718 32.2707 37.418 32.2707 33.9998 53.44656 53.0153 44.4512 33.3579 44.451 33.2707 33.9997 33.3418 32.2707 33.9998 33.9998 33.9998 33.9998 33.9998 33.9998 33.9998 33.9998 33.9347 33.9478 32.2707 33.9418 33.2707 30.9410 33.9418 33.3779 34.4455 33.5799 33.9418 33.3797 34.4455 33.5799 33.9418 33.3797 34.4455 33.5799 33.9418 33.3797 34.4455 33.5799 33.9418 33.3199 34.4455 33.5799 34.4455 33.5799 34.4455 33.5799 34.4455 33.5799 34.4455 33.5799 34.4455 33.5799 34.4455 33.5799 34.4455 33.5799 34.4455 33.5799 34.4455 33.5799 34.4455 33.5799 34.4455 33.3999		beerfest_lightshow_103020	bf_3020	PQ	0.20	69.0659	13	0.0820	45.3588	63.4394	39.6001	33.0551	42.5977	32.5231
bistro_00958         b_0958         b_0170         PQ         1.23         70.076         14         0.0865         41,422         S1.648         38.1366         34.4452         37.152         33.7897           bistro_00170         b_170         PQ         2.05         67.7718         14         0.0958         41.7098         55.6251         33.512         23.2695         32.2765           carouse_fireworks_006184         cf_6184         PQ         1.30         77.2717         61         0.0957         42.2710         50.485         33.5957         33.4386         37.8302         32.2755           carouse_fireworks_006184         cf_6144         PQ         1.30         77.0716         4         0.0957         42.2710         50.4855         33.153         <		beerfest_lightshow_103660	bf_3660	PQ	0.89	68.4265	15	0.0818	43.9821	56.5541	32.4812	33.0182	37.3207	32.3887
bistro_091710 b_1710 PQ 2.59 12.0868 10 0.0941 454038 55.6251 33.5132 32.698 37.2952 32.695 bistro_091780 b_1710 PQ 3.05 69.7418 14 0.0958 41.7908 50.5472 39.5097 33.4386 37.2952 32.695 bistro_091780 b_1710 PQ 1.23 72.707 5 0.0857 44.4863 53.8816 40.1473 33.4500 39.561 32.2253 carousel_firevorks_096184 c_6184 PQ 3.09 79.6111 4 0.0967 42.2710 50.4985 44.1722 34.3907 40.3130 33.7857 carousel_firevorks_09640 c_6.640 PQ 8.90 64.0895 5 0.1384 47.3657 43.4386 44.1722 34.3907 40.3130 33.7857 carousel_firevorks_09640 c_7.6400 PQ 5.75 64.1892 5 0.0955 44.2614 46.9478 43.8492 33.0756 35.9975 32.4252 hdr_testimage_273.35 hdr_3.35 PQ 0.20 151108 10 0.0669 52.0405 65.4662 44.9416 43.41050 36.0693 33.715 poke_fulshot_043787 PQ 0.41 74.0759 15 0.0807 25.9466 55.4662 44.9416 43.41050 36.0693 33.715 poke_fulshot_043787 PQ 0.41 74.0759 15 0.0807 42.9170 135.0566 54.6622 45.0648 44.0513 33.2963 33.2480 abovgart_0_2.35966 s_42.052 47.9129 33.0556 54.6622 45.0648 44.0513 33.2074 43.3800 poketraveling_slowmotion_033122 pp.3122 PQ 3.19 64.2887 16 0.0872 49.092 50.2823 47.9129 33.8551 33.2483 33.718 32.2670 showgart_0_2.35966 sg_2.536 PQ 0.69 42.2887 15 0.0667 57.0146 51.9077 48.259 33.0552 33.1578 33.2784 33.178 poke_fulshot_043787 72 PQ 0.53 74.6423 15 0.00679 42.4778 49.5079 43.8459 33.0552 33.0552 33.178 32.25670 showgart_0_2.35966 sg_2.536 PQ 0.513 74.1423 15 0.0079 42.4778 49.5079 43.8459 33.2587 33.1748 32.2570 matrix_shokhetcs2014HD100p_HDREXR_04727 EBU 4727 PQ 0.53 746.4519 41.9806 34.4523 34.0453 33.0552 34.3405 matrix_shok_0412 33.9806 bbc_0.36 HLG 0.37 16.5923 -10 0.01501 44.3787 45.5088 44.3837 35.2584 34.3458 33.3718 32.2570 matrix_shoketcs2014HD100p_HDREXR_04727 EBU 4727 140 59.8582 -10 0.1471 51.453 67.924 43.1413 33.952 33.3552		bistro_090958	b_0958	PQ	1.23	70.0706	14	0.0865	41.4252	51.4648	38.1366	34.4452	37.1528	33.7897
bistro_091710         b_1710         PQ         3.05         69.748         14         40.0058         41.47008         50.5472         39.5097         33.456         37.8302         32.7253           carousel_fireworks_096184         cf_6184         PQ         3.09         79.011         4         0.00967         44.22710         50.4985         38.5956         33.1583         31.1773         32.4597           carousel_fireworks_096270         cf_670         PQ         9.00         70.0666         5         0.1359         44.67792         43.4384         43.3690         30.076         32.4597         33.12753         43.0764         0.22975         32.4252           carousel_fireworks_097400         cf_7400         PQ         5.75         0.0801         52.9946         55.0106         46.5217         33.1294         32.8563         32.4453           poker_fulbshot_045787         pl_5787         PQ         0.41         74.075         15         0.0066         57.0186         51.9018         30.076         33.22974         33.2493         33.3479         33.2474         33.4103           poker_fulbshot_045787         pf.5787         PQ         0.41         74.4785         15         0.0066         57.0186         51.9097         <		bistro_091470	b_1470	PQ	2.59	120.868	10	0.0941	45.4038	55.6251	33.5132	32.3698	37.2952	32.6893
bisro_091780 bitro_096184 cf. 6184 PQ 3.09 79.611 4 0.0857 44.4863 53.8816 40.1473 33.4500 39.261 32.2539 carouse] fneworks_096270 cf. 6240 PQ 8.90 70.00666 5 0.1384 47.3657 43.4386 44.1722 33.3907 40.1310 33.7857 carouse] fneworks_09640 cf. 7400 PQ 8.96 64.0895 5 0.1384 47.3657 43.4386 44.1722 33.3907 40.1310 33.7857 (arouse] fneworks_097400 cf. 7400 PQ 5.75 64.2982 5 0.0955 44.2614 46.9478 43.8492 33.076 35.24803 bitr_testimage_273335 bitr_3335 PQ 0.20 1510.18 10 0.0699 52.6005 66.5421 44.9146 34.1050 36.0963 33.24803 bitr_testimage_273335 bitr_3335 PQ 0.20 1510.18 10 0.0699 52.6005 66.5421 44.9146 34.1050 36.0963 33.24803 bitr_testimage_273335 bitr_5332 PQ 0.20 1510.18 10 0.0699 52.6005 66.5421 44.9146 34.1050 36.0963 33.24803 bitr_testimage_273335 bitr_5332 PQ 0.20 1510.18 10 0.0699 52.6005 66.5421 44.9146 34.1050 36.0963 33.24803 bitr_testimage_27335 bitr_5332 PQ 0.219 15 50.6068 57.0186 51.9075 38.2519 33.0357 33.2487 33.2490 bitr_01.235065 space 5.90 0.90 64.2887 15 0.00677 42.4738 49.507 34.8218 32.9704 33.3800 bitr_0.23506 space 5.90 0.90 64.2887 15 0.00677 42.4738 49.507 34.9218 33.425 35.0707 32.2610 space 5.90 0.91 0.35 64.541 51 0.00774 57.570 54.5508 44.260 38.2433 42.2600 space 5.90 0.91 0.35 64.541 54 1.55 0.0617 42.4738 54.9008 43.9387 33.4748 34.2466 43.9371 bitr_01.235965 space 5.90 0.91 0.35 64.5461 15 0.0615 44.3670 53.3337 44.2540 38.2483 42.7304 44.3470 53.3337 bitr_01.23596 34.9483 42.7304 44.3473 33.9400 33.3425 33.9402 33.3415 bitr_01.23596 bitr_0.2306 bi		bistro_091710	b_1710	PQ	3.05	69.7418	14	0.0958	41.7908	50.5472	39.5097	33.4386	37.8302	32.7635
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$		bistro_091780	b_1780	PQ	1.23	72.7077	5	0.0857	44.4863	53.8816	40.1473	33.4500	39.361	32.7253
[32]         carouse_Interworks_09620         cf_6200         PQ         9.00         70.0666         5         0.1384         47.3657         43.4386         44.1722         33.007         40.3130         33.7857           carouseI_Inteworks_097400         cf_7400         PQ         5.75         64.2982         5         0.0389         44.2614         46.9478         43.8492         33.0736         33.9975         32.4252           carouseI_Inteworks_097400         cf_5.2140         PQ         0.744         92.9170         15         0.0801         52.9005         66.5421         44.9146         34.090         40.3133         32.6973         33.2475           poker_tublisto_U152340         pf_5787         PQ         0.20         151.018         10         0.0691         52.6005         66.5421         44.9146         34.1050         33.6973         33.2473         33.2493         34.2673         33.1749         33.8041         33.2687         33.1749         33.8041         33.2887         33.1749         33.8441         33.2887         33.1749         33.8441         33.2887         33.1749         33.2887         33.1749         33.2887         33.1749         33.2887         33.1749         33.2887         33.1749         32.2744         44.9507<		carousel fireworks 096184	cf 6184	PO	3.09	79.6111	4	0.0967	42.2710	50.4985	38.5956	33.1583	31.1773	32.4579
[32]       carouse_fireworks_096640       cf_640       PQ       8.96       64.0895       5       0.1359       46.7792       43.0877       35.1474       34.5604       40.2895       34.0380         car_fulbhot_132340       cf_7400       PQ       5.75       64.2982       5       0.0955       44.2614       46.0478       43.8422       33.1078       35.9795       32.24803         hdr_testimage_273355       hdr_335       PQ       0.20       151.018       10       0.0699       52.6005       66.5421       44.9146       34.1050       36.6963       33.3174         poker_fulbabc_045787       PQ       0.41       74.0759       15       0.0921       53.6565       54.6822       45.0648       34.0513       32.9774       33.8109         poker_fulbabc_04576       sg_5.565       PQ       0.99       64.2887       15       0.0668       51.075       33.2519       33.0537       33.3471       32.2670         shorgif_01_235965       sg_5.565       PQ       1.93       74.4185       15       0.0668       51.025       34.0380       33.425       33.0537       33.3425       35.0197       32.243       34.0109         smith_hammering_252764       Pd       5.12       10.2376 <td< td=""><td></td><td>carousel fireworks 096270</td><td>cf 6270</td><td>PÒ</td><td>9.00</td><td>70.0666</td><td>5</td><td>0.1384</td><td>47.3657</td><td>43,4386</td><td>44,1722</td><td>34,3907</td><td>40.3130</td><td>33,7857</td></td<>		carousel fireworks 096270	cf 6270	PÒ	9.00	70.0666	5	0.1384	47.3657	43,4386	44,1722	34,3907	40.3130	33,7857
carouse_fireworks_097400         cr_7400         PQ         5.75         64.2982         5         0.0955         44.2614         46.3978         43.8492         33.0736         33.9975         32.4252           cars_fullshot_132340         cfs_2300         cfs_2300         pQ         0.44         92.9170         15         0.0801         52.9946         55.0406         46.3227         33.1294         32.5863         32.4912           poker_fullshot_045787         pf_5787         PQ         0.41         74.0759         15         0.0921         53.6566         54.0822         45.0648         34.0513         32.9704         33.815         39.2878         33.1709           showgirl_0_235965         sg_5056         PQ         0.99         64.2887         15         0.0668         57.0186         51.9075         38.2519         33.0537         33.4278         33.0509           smith_hammering_525764         sg_5056         PQ         5.10         0.133         47.6781         55.1725         41.6906         34.948         32.7324         34.40651           313         EBU_zorhoAhthetes2014HD100p_HDREXR_04272         EBU_4998         PQ         0.13         64.1212         15         0.01851         47.6887         55.0088         41.6431	[32]	carousel fireworks 096640	cf_6640	PO	8.96	64 0895	5	0.1359	46 7792	43 0837	35 1474	34 5604	40 2895	34 0380
car_fulshou_123240         cf_2,2400         PQ         0.44         92,9170         15         0.0801         52,9946         55,0406         46,3237         33,1294         33,2663         32,4833         33,4715           pdc=r_fulshou_045787         pf_5787         PQ         0.20         151,018         10         0.0921         53,6565         54,6822         45,048         34,0513         32,9704         33,3810           poker_fullshou_045787         pg_53122         PQ         3,19         64,2887         6         0.0872         49,0922         50,2825         47,9129         33,8513         39,2881         33,4718         33,2400           showgirl_01_235965         sg_5965         PQ         1,93         74,4185         15         0.0667         42,4738         49,5097         41,9989         33,424         35,0797         32,2734         34,6057           31         EBU_ZaricAxhtheires2014HD100p_HDREXR_04972         PQ         0.73         64,1212         15         0.0815         44,3670         53,3337         44,2540         32,3483         32,4763         33,3704           31         EBU_ZaricAxhtheires2014HD100p_HDREXR_04998         EBU_AricAxie         74,0815         45,6932         -10         0.1511         47,6857		carousel_fireworks_097400	cf_7400	PÔ	5.75	64 2982	5	0.0955	44 2614	46 9478	43 8492	33.0736	35 9975	32 4252
Larg_unstance_122=7335         Lig_unstance_122         Lig_Unstance_122 <thlig_unstance< td=""><td></td><td>care fullshot 132340</td><td>cfs 2340</td><td>PO</td><td>0.44</td><td>02.0170</td><td>15</td><td>0.0955</td><td>52 0046</td><td>55.0406</td><td>46 3237</td><td>33 1294</td><td>32 5863</td><td>32 4803</td></thlig_unstance<>		care fullshot 132340	cfs 2340	PO	0.44	02.0170	15	0.0955	52 0046	55.0406	46 3237	33 1294	32 5863	32 4803
Ind_lstr_fullsbc_10353         Ind_lstr_503         Ind_lstr_503 <thind_lstr_503< th="">         Ind_lstr_503         Ind_</thind_lstr_503<>		hdr tastimaga 272225	bdr 2225		0.74	151.018	10	0.0600	52,6005	66 5421	44.0146	34 1050	36 6063	32.4005
plote         plote <th< td=""><td></td><td>nut_testimage_275555</td><td>nui_5555</td><td></td><td>0.20</td><td>74.0750</td><td>15</td><td>0.0099</td><td>52.0005</td><td>54 6922</td><td>45.0649</td><td>34.1050</td><td>30.0903</td><td>22 2800</td></th<>		nut_testimage_275555	nui_5555		0.20	74.0750	15	0.0099	52.0005	54 6922	45.0649	34.1050	30.0903	22 2800
pokettravening_slowmin_01_23562         ps_112         PQ         3.19         64.2887         6         0.0872         49.092         50.285         47.9129         33.3537         33.2570           showgirl_01_235965         sg_5965         PQ         1.93         74.4185         15         0.0668         57.0186         51.9075         33.2570         33.0537         33.0537         33.2670           smith_hammering_52764         sh_2764         pQ         5.12         102.222         15         0.01339         47.6781         55.1725         41.6906         34.948         33.2347         34.4605           [33]         EBU_ZarichAthletics2014HD100p_HDREXR_04927         EBU_4272         PQ         0.73         64.1212         15         0.0815         44.3670         53.337         44.2540         38.2483         42.4166         34.9571           EBU_ZarichAthletics2014HD100p_HDREXR_06998         EBU_4998         PQ         0.13         64.5464         15         0.0754         47.6857         55.2008         41.6431         34.0652         36.4082         33.194           BC_1_bot_HLG_s030         bbcl_012         HLG         0.37         155.2959         10         0.1471         51.4153         67.9249         43.1472         33.9444		poker_tulishot_045787	pi_5/8/	PQ	0.41	74.0759	15	0.0921	33.0300	54.0822	45.0648	34.0515	32.9704	33.3800
showgril_0l_235636         sg_2565         PQ         0.09         64.2887         15         0.00678         51.9073         38.219         33.3425         33.425		pokertravelling_slowmotion_033122	ps_3122	PQ	3.19	64.2887	0	0.0872	49.0392	50.2825	47.9129	33.8515	39.2887	33.1749
showgr1_01_253965         sg_5965         PQ         1.93         74.4185         15         0.067/         42.47.38         49.3097         41.9896         33.4245         33.7324         34.4605           31         EBU_zurichAthletics2014HD100p_HDREXR_04927         EBU_472         PQ         0.73         64.1212         15         0.0815         44.3670         53.3337         44.2540         38.2483         42.4160         34.948         33.7324         34.4605           31         EBU_zurichAthletics2014HD100p_HDREXR_04927         EBU_472         PQ         0.73         64.1212         15         0.0815         44.3670         53.3337         44.2540         38.2483         42.4160         34.951         33.372           EBU_zurichAthletics2014HD100p_HDREXR_00998         EBU_6998         PQ         0.13         64.5464         15         0.0751         47.6857         55.2008         41.6431         34.0652         36.4082         33.118           BBC_1_bbc_HLG_s012         bbc1_012         HLG         0.37         165.2959         10         0.1471         51.4153         67.9249         43.1472         33.1944         39.9151         33.1909           BBC_1_bbc_HLG_s320         bbc1_306         HLG         0.37         165.2959		showgirl_01_235636	sg_5636	PQ	0.69	64.2887	15	0.0668	57.0186	51.9075	38.2519	33.0537	33.4718	32.2670
smith_hammering_252764         sh_2764         PQ         5.12         102.222         15         0.1339         47.6781         55.1725         41.6906         34.948         32.7324         34.4605           [33]         EBU_ZurichAthletics2014HD100p_HDREXR_04272         EBU_4972         FBU_6998         PQ         0.73         64.1212         15         0.0815         44.3670         55.3337         44.2540         38.2483         42.4166         34.9471           BUZ_urichAthletics2014HD100p_HDREXR_06998         EBU_6998         PQ         0.13         64.5464         15         0.0754         57.5099         60.8063         45.8793         37.2843         41.5918         34.3073           Werage over PQ-encoded images (PQ AV)         74.0591         8.66         0.0751         47.6887         55.2008         41.6431         34.062         36.4082         33.8041           BBC_1_bbc,HLG_s036         bbc1_012         HLG         0.37         165.2959         -10         0.1471         51.4153         67.9249         43.1472         33.9444         39.9151         33.7569           BBC_1_bbc,HLG_s306         bbc1_306         HLG         0.09         8.8327         -10         0.1478         53.8029         57.9253         44.4877         37.5390		showgirl_01_235965	sg_5965	PQ	1.93	74.4185	15	0.0677	42.4738	49.5097	41.9896	33.3425	35.0797	32.6219
BBU_ZurichAthletics2014HD100p_HDREXR_04927         EBU_4272         PQ         0.73         64.1212         15         0.0815         44.3670         53.337         44.2540         38.2483         42.4166         34.9571           Average over PQ-encoded images (PQ AV)         74.0591         8.66         0.0751         47.6857         55.2008         41.6431         34.0652         36.4082         33.318           BBC_1_bbc_HLG_s012         bbc1_012         HLG         0.36         105.9323         -10         0.1501         48.7965         56.1623         44.3152         33.1943         39.8490         33.1943		smith_hammering_252764	sh_2764	PQ	5.12	102.222	15	0.1339	47.6781	55.1725	41.6906	34.948	32.7324	34.4605
[59]         EBU_ZurichAthletics2014HD100p_HDREXR_06998         EBU_699         PQ         0.13         64.5464         15         0.0754         57.5099         60.8063         45.8793         37.2843         41.5918         33.318           Average over PQ-encoded images (PQ AV)         74.0591         8.66         0.0751         47.6857         55.2008         41.6431         34.0652         36.4082         33.8041           BBC_1_bbc_HLG_s012         bbcl_012         HLG         3.36         105.9323         -10         0.1501         48.7965         55.1623         41.4312         33.9072         39.8490         33.8041           BBC_1_bbc_HLG_s036         bbcl_036         HLG         2.09         117.8460         -111         0.1390         52.8173         55.9453         44.4887         33.7569           [34]         BBC_1_bbc_HLG_s435         bbcl_320         HLG         1.10         76.8822         -10         0.1478         53.8029         57.9233         47.5049         37.3789         45.309         32.2366           BBC_1_bbc_HLG_s435         bbcl_601         HLG         0.36         42.168         1.5         0.0982         64.2180         65.2878         49.8506         31.871         33.1892           BBC_1_	[33]	EBU_ZurichAthletics2014HD100p_HDREXR_04272	EBU_4272	PQ	0.73	64.1212	15	0.0815	44.3670	53.3337	44.2540	38.2483	42.4166	34.9571
Average over PQ-encoded images (PQ AV)         74.0851         8.66         0.0751         47.6857         55.208         41.6431         34.0652         36.4082         33.8041           BBC_1_bbc_HLG_s012         bbc1_012         HLG         0.3.36         105.9323         -10         0.1501         48.7965         56.1023         44.3152         33.8072         39.8490         33.8041           BBC_1_bbc_HLG_s036         bbc1_036         HLG         0.3.7         165.2959         -10         0.1471         51.4153         67.9249         44.31472         33.944         39.9151         33.1909           BBC_1_bbc_HLG_s320         bbc1_306         HLG         0.37         165.2959         -10         0.1471         51.4153         67.9249         44.31472         33.1944         39.9151         33.1909           BBC_1_bbc_HLG_s320         bbc1_306         HLG         0.075         7.8460         -11         0.1478         55.3028         57.9253         44.487         37.5390         45.7309         32.5366           BBC_1_bbc_HLG_s401         bbc1_601         HLG         0.59         85.827         -10         0.1478         53.029         57.8055         44.8187         37.1877         45.403         33.1842         33.1842	[33]	EBU_ZurichAthletics2014HD100p_HDREXR_06998	EBU_6998	PQ	0.13	64.5464	15	0.0754	57.5099	60.8063	45.8793	37.2843	41.5918	34.3373
BBC_1_bbc_HLG_s012         bbcl_012         HLG         3.3.6         105.9323         -10         0.1501         48.7965         56.1623         44.3152         33.8072         39.8490         33.8041           BBC_1_bbc,HLG_s036         bbcl_036         HLG         0.37         165.2959         -10         0.1471         51.4153         67.9249         43.1472         33.19072         39.8490         33.8041           BBC_1_bbc,HLG_s306         bbcl_306         HLG         2.09         117.8460         -11         0.1390         52.8173         55.9453         44.487         33.7584         34.4815         33.7569           BBC_1_bbc,HLG_s435         bbcl_320         HLG         0.59         85.8327         -10         0.1473         57.3028         61.0855         47.8049         37.5390         45.7309         32.5126           BBC_1_bbc,HLG_s435         bbcl_601         HLG         0.36         142.1681         -15         0.0982         64.2180         65.2878         49.8506         37.1877         45.4032         32.1842           BBC_1_bbc,HLG_s014         bbcl_601         HLG         0.60         93.2377         -20         0.0495         67.2617         53.3055         44.4728         38.4868         43.31189         <		Ave	rage over PQ-e	ncoded ir	nages (PQ AV)	74.0591	8.66	0.0751	47.6857	55.2008	41.6431	34.0652	36.4082	33.3118
BBCbbc_HLG_s036         bbc_136         HLG         0.37         165.2959         -10         0.1471         51.4153         67.9249         43.1472         33.1944         39.9151         33.1909           BBCbbc_HLG_s036         bbc_306         HLG         2.09         117.8460         -11         0.1390         52.8173         55.9453         44.487         33.7589         44.4817         33.7589         44.4817         33.7589         44.4817         33.7589         44.4817         33.7589         44.4817         33.7589         44.4817         33.7589         44.4817         33.7589         44.4817         33.7589         35.2566         32.5366           BBCbbc_HLG_s435         bbc_16.598         HLG         0.059         85.827         -10         0.1478         53.029         57.9253         47.8086         38.2134         47.1820         33.2112           BBC_bbc_HLG_s601         bbc1_601         HLG         0.60         93.2377         -20         0.0495         67.2617         53.3055         44.4728         38.4868         43.3119         33.4890           BBC_c1_bbcc_HLG_s004         bbcc_014         HLG         2.89         93.7985         -20         0.0518         51.519         47.2546         48.5442         3		BBC 1 bbc HLG s012	bbc1_012	HLG	3.36	105.9323	-10	0.1501	48,7965	56.1623	44.3152	33.8072	39.8490	33.8041
BBC_1_bbc_HLG_s306         bbcl_306         HLG         2.09         117.8460         -11         0.1390         52.8173         55.9453         44.487         33.7585         44.4815         33.7560           [34]         BBC_1_bbc_HLG_s320         bbcl_320         HLG         1.10         76.8822         -10         0.1473         55.9453         44.487         33.7585         44.4815         33.7560           BBC_1_bbc_HLG_s435         bbcl_320         HLG         0.10         76.8822         -10         0.1473         57.9233         47.5049         37.3590         45.7309         32.2112           BBC_1_bbc_HLG_s435         bbcl_998         HLG         0.056         142.1681         -15         0.0982         64.2180         65.2878         49.8506         37.1877         45.032         32.142           BBC_1_bbc_HLG_s601         bbcl_998         HLG         0.06         93.2377         -20         0.0495         67.2617         53.055         44.4783         33.1920         33.1895           BBC_1_bbc_HLG_s005         bbccl_905         bbccl_914         HLG         1.28         95.6598         -18         0.0697         50.6502         52.3055         44.4815         33.1895           BBC_C1_bbcc_HLG_s046 <t< td=""><td></td><td>BBC 1 bbc HLG s036</td><td>bbc1_036</td><td>HLG</td><td>0.37</td><td>165 2959</td><td>-10</td><td>0.1471</td><td>51 4153</td><td>67 9249</td><td>43 1472</td><td>33 1944</td><td>39 9151</td><td>33 1909</td></t<>		BBC 1 bbc HLG s036	bbc1_036	HLG	0.37	165 2959	-10	0.1471	51 4153	67 9249	43 1472	33 1944	39 9151	33 1909
134         BBC_1_bbc_HLG_s320         bbcl_320         HLG         1.00         76.8822         -10         0.1478         53.8029         57.9253         47.5049         37.5390         45.7309         32.5366           BBC_1_bbc_HLG_s435         bbcl_335         HLG         0.59         85.827         -10         0.1478         53.8029         57.9253         47.5049         37.5390         45.7309         32.5366           BBC_1_bbc_HLG_s435         bbcl_361         HLG         0.59         85.827         -10         0.1478         53.8029         57.9253         47.5049         32.2366         33.211           BBC_1_bbc_HLG_s598         bbcl_601         HLG         0.59         85.8327         -20         0.0495         67.2617         53.3055         44.471.82         38.4868         43.3119         33.1895           BBC_C1_bbcc_HLG_s014         bbcl_005         bbccl_004         HLG         2.89         83.7985         -20         0.0518         51.5319         47.2546         48.542         34.4151         44.453         34.125           BBC_C1_bbcc_HLG_s014         bbcc_064         bbcc_046         HLG         0.59         9.6077         -18         0.0691         54.5520         5.9652         51.338         51.6727		BBC 1 bbc HLG \$306	bbc1_306	HLG	2.09	117 8460	-11	0.1390	52 8173	55 9453	44 4887	33 7585	44 4815	33 7569
IDC_lbc_lbc_lbc_lbc_lbc_lbc_lbc_lbc_lbc_lbc	[24]	BBC_1_bbc_HLG_s300	bbc1_320	ULC	1.10	76 8822	10	0.1370	53 8020	57 0253	47.5049	37 5300	45 7300	32 5366
BBC_lbbc_HLG_s03         D0cl_133         HLG         0.33         83.027         10         0.147.3         0.108.33         47.0803         33.127         47.162         03.211         03.211         01         01.047.3         07.0833         47.0803         33.127         47.0803         33.127         47.0803         33.1874         47.162.03         33.1874         47.0803         33.1874         47.0803         33.1874         47.0803         33.1874         47.0803         33.1875           BBC_lbbc_HLG_s001         bbcl_601         HLG         0.60         93.2377         -20         0.0495         67.2617         53.3055         44.4728         38.4868         43.3192         43.2180         33.1895           BBC_C_Lbbcc_HLG_s014         bbcc_1005         bbcc_1014         HLG         2.89         83.7985         -20         0.0518         51.5319         47.2546         48.8916         33.1895         34.1285           BBC_C_Lbbcc_HLG_s048         bbcc1.064         HLG         0.97         -18         0.0691         54.5520         52.9652         51.4338         35.1299         38.3687         34.1285           BBC_C_Lbbcc_HLG_s046         bbcc2.064         HLG         0.97         108.8868         -20         0.0499	[.54]	PPC 1 bbs HI C s425	bbc1_320	ULC	0.50	95 9327	-10	0.1473	57 2029	61.0255	47.3049	28 2124	47.1820	32.3300
IBBC_1_bbc_HLG_536         Dbc_1_93         HLG         0.50         H2_1081         -13         0.0922         64.2160         01.218         04.2180         01.218         04.2180         01.218         04.2180         01.218         04.2180         01.218         04.2180         01.218         04.2180         01.218         04.2180         01.218         04.2180         01.218         04.2180         01.218         04.2180         01.218         04.2180         01.218         04.2180         01.218         04.2180         01.218 <td></td> <td>BBC_1_00C_HEG_8455</td> <td>bbc1_455</td> <td>ILC</td> <td>0.39</td> <td>142 1691</td> <td>-10</td> <td>0.1473</td> <td>64 2120</td> <td>65 2070</td> <td>40.8506</td> <td>27 1077</td> <td>47.1620</td> <td>33.2112</td>		BBC_1_00C_HEG_8455	bbc1_455	ILC	0.39	142 1691	-10	0.1473	64 2120	65 2070	40.8506	27 1077	47.1620	33.2112
BBC		BBC_1_00C_RLO_\$396	0001_398	HLG	0.50	142.1081	-15	0.0982	04.2160	52,2055	49.8500	37.1877	43.4032	32.1642
BBC_C_1_bbcc_1H.G_9005         bbcc_1905         HLG         1.25         95.6598         -18         0.0697         50.6502         52.305         48.3916         33.192         40.3850         33.1895           [35]         BBC_C_1_bbcc_1H.G_9014         bbcc_1014         HLG         2.89         98.37985         -20         0.0518         51.5319         47.2546         48.3842         34.4151         34.4153           BBC_C_1_bbcc_1H.G_9048         bbcc_1044         HLG         0.59         99.6077         -18         0.0691         54.5520         52.9652         51.4333         35.1299         38.3687         34.1253           BBC_C_1_bbcc_1H.G_9046         bbcc_1066         HLG         0.97         108.3368         -20         0.0499         51.4165         55.3831         50.627         38.4945         34.9068         34.9453           BBC_C_2_bbcc_2.HLG_018         bbcc_2.031         HLG         3.16         87.8270         -20         0.0521         47.8915         47.3141         47.8720         34.9953         46.8846         34.9976           BBC_C_2_bbcc_2.HLG_045         bbcc_2.045         HLG         1.62         91.4447         -18         0.0701         53.696         55.7790         34.7593         46.8846         3		BBC_1_bbc_HLG_s601	bbc1_601	HLG	0.60	93.2377	-20	0.0495	67.2617	53.3055	44.4728	38.4868	43.3119	33.4840
BBC_C_1_bbcc_1H.G_9014         bbcc_1014         HLG         2.89         83.7985         -20         0.0518         51.5319         47.2546         48.8842         34.4153           BBC_C_1_bbcc_1H.G_9048         bbcc_1048         HLG         0.59         99.6077         -18         0.0691         54.5520         52.9652         51.4338         35.1299         38.3687         34.1285           BBC_C_2_bbcc_1H.G_9066         bbcc1_066         HLG         0.97         108.8368         -20         0.0499         51.4165         55.3831         50.6727         38.4945         40.0680         33.4914           BBC_C_2_bbcc_2_HLG_9018         bbcc_2_018         HLG         3.33         99.1747         -20         0.0521         57.8916         47.8356         55.3290         39.6010         48.3933         34.6056           BBC_C_2_bbcc_2_HLG_9031         bbcc_2_031         HLG         3.16         91.4447         -18         0.0701         53.6596         51.7501         49.2053         46.5846         34.9976           BBC_C_2_bbcc_2_HLG_9092         bbcc2_092         HLG         0.37         102.2924         -18         0.0688         56.6664         56.7111         45.4685         37.5548         43.1919         35.5511           <		BBC_C1_bbcc1_HLG_s005	bbcc1_s005	HLG	1.25	95.6598	-18	0.0697	50.6502	52.3055	48.4916	33.1920	40.3850	33.1895
BBC_C1_bbcc1_HLG_9048         bbcc_1048         HLG         0.59         99.6077         -1.8         0.0691         54.552         52.9652         51.338         35.129         38.3687         34.1285           BBC_C1_bbcc1_HLG_9066         bbcc1_066         HLG         0.97         108.8368         -20         0.0499         51.4165         55.3831         50.6727         38.4945         40.0680         33.4914           BBC_C2_bbcc2_HLG_018         bbcc2_018         HLG         3.33         99.1747         -20         0.0521         47.8356         55.3290         39.6010         48.8933         34.6945           BBC_C2_bbcc2_HLG_031         bbcc2_018         HLG         3.16         87.8270         -20         0.0521         47.8915         47.73141         47.8720         34.9953         46.8846         34.9976           BBC_C2_bbcc2_HLG_901         bbcc2_045         HLG         1.62         91.4447         -18         0.0701         53.6596         51.7501         49.2053         46.8846         34.9976           BBC_C2_bbcc2_HLG_902         bbcc2_045         HLG         1.62         91.4447         -18         0.0701         53.6596         51.7501         49.2053         46.8846         34.9976           BBC_C2_bbcc2_H	[35]	BBC_C1_bbcc1_HLG_s014	bbcc1_014	HLG	2.89	83.7985	-20	0.0518	51.5319	47.2546	48.5842	34.4151	48.4451	34.4153
BBC_C2_bbcc2_HLG_066         bbcc1_066         HLG         0.97         108.8368         -20         0.0499         51.4165         55.3831         50.6727         38.4945         40.0680         33.4914           BBC_C2_bbcc2_HLG_018         bbcc2_018         HLG         3.33         99.1747         -20         0.0522         55.8084         47.8356         55.3290         39.6010         48.3933         34.6056           BBC_C2_bbcc2_HLG_031         bbcc2_031         HLG         3.16         87.8270         -20         0.0521         47.815         47.3141         47.8720         34.9953         46.6846         34.9976           BBC_C2_bbcc2_HLG_045         bbcc2_031         HLG         3.16         87.8270         -20         0.0521         47.815         47.3141         47.8720         34.9953         46.5846         34.9976           BBC_C2_bbcc2_HLG_045         bbcc2_045         HLG         0.16         91.4447         -18         0.0701         53.6596         51.7501         49.2053         46.5763         45.2401         34.7593           BBC_C2_bbcc2_HLG_095         bbcc2_095         HLG         0.37         102.4470         -18         0.0688         56.6664         55.7111         45.4685         37.5548         43.1919 <td>[20]</td> <td>BBC_C1_bbcc1_HLG_s048</td> <td>bbcc1_048</td> <td>HLG</td> <td>0.59</td> <td>99.6077</td> <td>-18</td> <td>0.0691</td> <td>54.5520</td> <td>52.9652</td> <td>51.4338</td> <td>35.1299</td> <td>38.3687</td> <td>34.1285</td>	[20]	BBC_C1_bbcc1_HLG_s048	bbcc1_048	HLG	0.59	99.6077	-18	0.0691	54.5520	52.9652	51.4338	35.1299	38.3687	34.1285
BBC_C2_bbcc2_HLG_018         bbcc2_s018         HLG         3.33         99.1747         -20         0.0522         55.8084         47.8356         55.3290         39.6010         48.3933         34.6056           BBC_C2_bbcc2_HLG_s011         bbcc2_031         HLG         3.16         87.8270         -20         0.0521         47.8915         47.8356         55.3290         39.6010         48.3933         34.6056           [36]         BBC_C2_bbcc2_HLG_s045         bbcc2_045         HLG         1.62         91.4447         -18         0.0701         53.6596         51.7501         49.2053         46.7563         45.2401         34.7593           BBC_C2_bbcc2_HLG_s092         bbcc2_095         bbcc2_092         HLG         0.37         102.2924         -18         0.0688         56.6664         55.7312         45.0468         37.7574         34.7696           BBC_C2_bbcc2_HLG_s095         bbcc2_095         HLG         0.74         104.4708         -15         0.0986         52.7796         56.7392         47.0326         36.8810         33.7699           Average over HGL-encoded images (HLG AV)         103.6442         -15.81         0.0913         54.4107         55.3788         47.326         36.8810         33.7599		BBC_C1_bbcc1_HLG_s066	bbcc1_066	HLG	0.97	108.8368	-20	0.0499	51.4165	55.3831	50.6727	38.4945	40.0680	33.4914
BBC_C2_bbcc2_HLG_s031         bbcc2_031         HLG         3.16         87.8270         -20         0.0521         47.815         47.3141         47.8720         34.9953         46.8840         34.9976           BBC_C2_bbcc2_HLG_s045         bbcc2_045         HLG         1.62         91.4447         -18         0.0701         53.6596         51.7501         49.2053         46.7563         45.2401         34.9976           BBC_C2_bbcc2_HLG_s092         bbcc2_092         bbcc2_092         116.6         0.37         102.2924         -18         0.0688         56.6664         55.5711         49.2053         46.7563         45.2401         34.5919         35.551           BBC_C2_bbcc2_HLG_s095         bbcc2_095         HLG         0.74         104.4708         -15         0.0986         52.7796         56.7392         45.0768         37.7707         42.9350         34.7696           Average over HGL-encoded images (HLG AV)         103.6442         -15.81         0.0913         54.4107         55.3708         47.326         36.8810         43.7366         33.7549           Average over HGL-encoded images (HLG AV)         103.6442         -15.81         0.0913         54.4107         55.3788         47.326         36.8810         33.7549         <		BBC_C2_bbcc2_HLG_018	bbcc2_s018	HLG	3.33	99.1747	-20	0.0522	55.8084	47.8356	55.3290	39.6010	48.3933	34.6056
[36]         BBC_C2_bbcc2_HLG_s045         bbcc2_045         HLG         1.62         91,4447         -18         0.0701         53,6596         51,7501         49,2033         46,7563         45,2043         34,7593           BBC_C2_bbcc2_HLG_s092         bbcc2_092         HLG         0.37         102,2924         -18         0.0688         56,6664         56,5711         45,4685         37,5548         43,1919         33,5531           BBC_C2_bbcc2_HLG_s095         bbcc2_095         HLG         0.74         104,4708         -15         0.0986         52,7796         56,7392         45,0768         37,707         42,9350         34,7696           Average over HGL-encoded images (HLG AV)         103,6442         -1581         0.0936         52,4796         55,3788         47,326         36,8810         43,7366         33,7594         33,7591         32,5231		BBC_C2_bbcc2_HLG_s031	bbcc2_031	HLG	3.16	87.8270	-20	0.0521	47.8915	47.3141	47.8720	34.9953	46.8846	34.9976
BBC_C2_bbcc2_HLG_s092         bbcc2_092         HLG         0.37         102.2924         -18         0.0688         56.6664         56.5711         45.4685         37.5548         43.1919         33.5531           BBC_C2_bbcc2_HLG_s095         bbcc2_095         HLG         0.74         104.4708         -15         0.0986         52.7796         56.7392         45.0768         37.7707         42.9350         34.7696           Average over HGL-encoded images (HLG AV)         103.6442         -15.81         0.0913         54.4107         55.3708         47.7326         36.8810         43.7366         33.7548         33.7549         33.7548         33.7549         33.7548         33.7549         33.7549         33.7549         33.7549         33.7549         33.7549	[36]	BBC_C2_bbcc2_HLG_s045	bbcc2_045	HLG	1.62	91.4447	-18	0.0701	53.6596	51.7501	49.2053	46.7563	45.2401	34.7593
BBC_C2_bbcc2_HLG_s095         bbcc2_095         HLG         0.74         104.4708         -15         0.0986         52.7796         56.7392         45.0768         37.770         42.9350         34.7696           Average over HGL-encoded images (HLG AV)         103.6442         -15.81         0.0913         54.4107         55.3708         47.7326         36.8810         43.7366         33.7547         42.9350         33.7547		BBC C2 bbcc2 HLG s092	bbcc2 092	HLG	0.37	102.2924	-18	0.0688	56.6664	56.5711	45,4685	37.5548	43,1919	33,5531
Average over HGL-encoded images (HLG AV)         103.6442         -15.81         0.0913         54.4107         55.3708         47.7326         36.8810         43.7366         33.7549		BBC C2 bbcc2 HLG s095	bbcc2 095	HLG	0.74	104.4708	-15	0.0986	52,7796	56.7392	45.0768	37,7707	42,9350	34,7696
Antinge of inductional images (inductive) 1000 110 2010 2010 2010 11/1200 200001 40/1200 2010 201700 20000000000		Auera	e over HGI -en	oded im	Tees (HLG AV)	103.6442	-15.81	0.0913	54.4107	55.3708	47.7326	36.8810	43,7366	33,7549
		AVC/48	e orer mon-end	oucu ma		100.0448	10.01	(011/)	51.0492	55.0050	44.6970	25.4521	40.0724	22,7247



**FIGURE 16.** Imperceptibility (HDR-VDP-2 dB) of a watermark embedded in the ER selected by Algorithm 1 for different  $w_i$  values.

images. To embed imperceptible watermarks in the spatial domain of HLG-encoded images, the  $\Xi_{HDR}$  value should be then negative, otherwise, the embedded information may be perceived by the HVS as medium tones. On the other hand, to embed imperceptible watermarks in the spatial domain of PQ-encoded images, the  $\Xi_{HDR}$  value should be positive. Based on our evaluations on the test images, such  $\Xi_{HDR}$  values are achieved by setting the strength factor, k, to {5, 25} for PQ-encoded and HLG-encoded images, respectively [see Eq. (6)]. Additionally, as shown in Table 2, absolute  $\Xi_{HDR}$  values of HLG-encoded images tend to be larger than those of PQ-encoded images. The HLG TF has a relatively low



**FIGURE 17.** Imperceptibility (HDR-VDP-2 dB) of a watermark embedded in the ER using an embedding factor computed by Eq. (6) for different  $w_0$  values.

granularity of luma codes for low luminance values. Consequently, there is more room to modify these codes aggressively before the changes can be perceived by the HVS. This particular TF uses large coding steps in low luminance regions to code large luminance variations. Consequently, if a luma code is modified by a value  $< \Xi_{HDR}$ , the HVS may not be able to perceive the embedded watermark even after the TF is altered or the normal calibration and colorimetry conditions of the HDR screen are changed. This is because the ER's watermarked luma codes may still be within the range of values of the surrounding region. On the other hand, the PQ TF has a high granularity of luma codes for low luminance values. Therefore, modifying these codes aggressively increases the risk that the HVS can perceive the changes.

Based on the previous discussions, one can conclude that, in general, HLG-coded images allow for larger imperceptible variations to low-valued luma codes than PQ-encoded images. Such variations, however, can only be applied if the ER has luma codes  $\in luma_{target}$ , i.e., the range of luma codes that are best suited to embed a watermark in the spatial domain that is imperceptible to the HVS.

Let us recall that the HDR-IW method combines the content readability afforded by invisible watermarking and the visual ownership identification afforded by visible watermarking. As with any other watermarking method in the spatial domain, determining the embedding payload is challenging, as watermarks may be embedded by altering the whole cover media or a small region of it. The embedding payload of a watermarking method in the spatial domain is then dependent on the content of the cover media and the level of distortion introduced by modifying pixel values. Since the HDR-IW method indeed combines aspects of visible watermarking and invisible watermarking, we propose a new metric to quantitatively compute its embedding payload. Our metric,  $EC_{HDR}$ , accounts for the contents of the cover media and the TF. Specifically, it accounts for the size of the ER and the  $\bar{\xi}$  values:

$$EC_{HDR} = w_2 \cdot ER_{size} + w_3 \cdot \frac{w_0 \cdot \bar{\xi}_{ER} + w_1 \cdot (\bar{\xi}_{SR} + \bar{\xi}_{HDR})}{\max(\xi[luma_{target}])} \in [0, 1],$$
(10)

where  $ER_{size} \in [0, 1]$ ,  $\max(\xi[luma_{target}])$  is the maximum  $\xi(luma_{code})$  value for the range  $luma_{target}$  (see Fig. 9),  $\{w_0, w_1\}$  are weights as defined before [see Eq. (6)], and  $\{w_2, w_3\}$  are weights that establish the importance of each constituent term of the  $EC_{HDR}$  metric, with  $w_2 + w_3 = 1$ . A value  $EC_{HDR} = 1$  denotes the highest embedding payload, e.g., when the ER spans the entire cover image and the second term of Eq. (10) = 1.

Column 8 of Table 2 tabulates  $EC_{HDR}$  values for the test images with { $w_2 = 0.2, w_3 = 0.8$ }, i.e., by giving more importance to the second term as ER regions are, in general, relatively small and unlikely to span the entire cover image. Note that the  $EC_{HDR}$  metric indeed accounts for the cover's content and the TF used. For example, image BF\_100 has an embedding payload  $EC_{HDR} = 0.0549$ , which is less than the embedding payload of image BF\_320 ( $EC_{HDR} = 0.0826$ ), despite the fact that image BF\_100 has a larger ER than that of image BF\_320. Image BF\_100 has, however, a lower  $\Xi_{HDR}$  value, hence, the embedding payload is expected to be relatively small. As expected, HLG-coded images have the largest embedding payloads with a maximum value of  $EC_{HDR} = 0.1501$  for the test images.

# B. SECOND SET OF EXPERIMENTS: IMPERCEPTIBILITY

Let us recall that the HDR-IW method operates in the spatial domain by modifying pixels values in the Y-channel. It is then expected that the visual quality, both quantitative and qualitative, of the cover media is disrupted. However, since the embedded watermarks cannot be perceived by the HVS, these disruptions are expected to be non-existent or minimal. To confirm that the embedded watermarks are imperceptible to the HVS, we use two quantitative metrics that measure imperceptibility: the HDR-VDP-2 metric and the multiexposure Peak Signal to Noise Ratio (mPSNR) [38].

The mPSNR measures the error in a watermarked HDR image by first computing a series of exposure levels, which are tone-mapped by a gamma curve after exposure compensation. The tone-mapped version of an HDR image, I, is given by:

$$T(I, e) = \left[255 \cdot \left(2^{e} \cdot I\right)^{1/\gamma}\right]_{0}^{255},$$
 (11)

where *e* is the current f-stop, which represents a variation in the aperture of a camera,  $\gamma = 2.2$ , and  $[\cdot]_0^{255}$  indicates clamping to the integer interval [0, 255]. The mPSNR is then computed by using the mean square error (MSE) over a total of *E* exposure levels:

$$mPSNR = 10 \cdot \log_{10} \left( \frac{3 \cdot 255^2}{MSE} \right), \qquad (12)$$
$$MSE = \frac{1}{E \cdot W \cdot H} \sum_{E} \sum_{x,y} \left( \Delta R_{xy}^2 + \Delta G_{xy}^2 + \Delta B_{xy}^2 \right), \qquad (13)$$

where  $\{W, H\}$  are the width and height of I, respectively, and  $\{\Delta R_{xy}, \Delta G_{xy}, \Delta B_{xy}\}$  are the errors in the R, G, and B components, respectively. For an f-stop, e, these errors are computed after computing  $T(I, e) - T(\tilde{I}, e)$ , where  $\tilde{I}$  is the watermarked image [38].

To the best of our knowledge, no watermarking method for HDR imaging in the spatial domain with HVSimperceptibility capabilities has been previously proposed. However, in this second set of experiments, we also evaluate the invisible watermarking methods in [8], [9], which are proposed for HDR images and operate in the frequency domain by applying the DWT.

HDR-VDP-2 and mPSNR values are tabulated in the last six columns of Table 2. For the HDR-IW method, images with large ERs, i.e.,  $ER_{size} > 2.5\%$ , tend to have the lowest HDR-VDR-2 values. Note also that PQ-encoded images tend to be more robust to degradations introduced by watermarking, as HDR-VDR-2 values for these images are, on average, higher than those of HGL-encoded images. mPSNR values do not tend to significantly vary according to the TF or the ER size for the HDR-IW method. For the majority of the test HDR images, both metrics are within an acceptable range, which confirms that the HDR-IW method can indeed embed watermarks in the spatial domain that are imperceptible to the HVS.

TABLE 3. Qualitatively evaluation of the HDR-IW method in terms of the	Э
MOS: percentage of watermarked HDR images assigned to each of the	
four scores.	

Source	TF	Score 1	Score 2	Score 3	Score 4	Disturbing (%)
[31]	PQ	0	0	4.89	95.11	5.55
[32]	PQ	0	0	5.18	94.81	5.55
[33]	PQ	0	0	0	100	0
PQ	AV	0	0	3.35	96.64	3.70
[34]	HLG	0	0	3.81	96.19	6.66
[35]	HLG	0	0	1.66	98.33	2.25
[36]	HLG	0	0	0	100	0
HLG	AV	0	0	1.82	98.17	2.97
OA	V	0	0	2.59	97.40	3.33

Overall, the HDR-IW method attains a higher imperceptibility, in terms of HDR-VDP-2 and mPSNR, than that of the methods in [8], [9]. The lower HDR-VDP-2 and mPSNR values attained by the methods in [8], [9] are due to the fact these methods do not account for the EOTFs needed to display HDR images on a screen.

To qualitatively measure the imperceptibility of the embedded watermarks, we use the Mean Opinion Score (MOS) as the metric. Specifically, fifteen observers with various experience levels in HDR imaging have visually inspected each watermarked image on a laptop built-in HDR screen of 17 inches wide with Windows 10 HDR advanced color settings enabled. The observers are asked to identify the watermark in a variety of lighting conditions and are given the opportunity to analyze the watermarked images from any distance and viewing angle. Results from this evaluation are collected using four scores ranging from 1 to 4, where 1 corresponds to full perceptibility and 4 to full imperceptibility. In cases where the observer is able to perceive the watermark (scores 1 - 3), the observer is asked to determine if the watermark is visually disturbing. The percentage of watermarked HDR images assigned to each of the four scores is tabulated in Tables 3 - 5 for the HDR-IW method and the methods in [8], [9], respectively.

Results in Tables 3 - 5 further confirm that the HDR-IW method can embed watermarks in the spatial domain that are imperceptible to the HVS. In the few cases where the watermark can be barely perceived (score 3), only a very small percentage of images is found to be visually disturbing. Note that the lower MOS values assigned to the images watermarked by the methods in [8], [9] also show the importance of accounting for the EOTF in the embedding process, as this TF is needed to display the HDR image on a screen. Hence, visual distortions may be introduced if this TF is not accounted for even if the watermark is embedded in the frequency domain.

It is worth further emphasizing the importance of the LVT curve in the computation of the luma variation threshold ( $\xi$ ) and the embedding factor ( $\Xi_{HDR}$ ) to guarantee both imperceptibility and detection of the watermark in the HDR-IW method. For instance, in Fig. 18, the binary watermark is embedded using an arbitrary embedding factor which leads to full perceptibility, even when the watermark is embedded in the ER selected by Algorithm 1. Similarly, if the binary

# TABLE 4. Qualitatively evaluation of method in [8] in terms of the MOS: percentage of watermarked HDR images assigned to each of the four scores.

Source	TF	Score 1	Score 2	Score 3	Score 4	Disturbing (%)
[31]	PQ	0	0	5.33	94.67	3.11
[32]	PQ	0	0	27.41	72.60	13.33
[33]	PQ	0	0	90	10	36.66
PQ.	ĀV	0	0	40.91	59.09	17.70
[34]	HLG	0	0	23.81	76.190	7.61
[35]	HLG	0	0	11.66	88.34	5.00
[36]	HLG	0	0	5.33	94.67	2.66
HLG	AV	0	0	13.6	86.40	5.09
OA	V	0	0	27.25	72.74	11.39

**TABLE 5.** Qualitatively evaluation of the method in [9] in terms of the MOS: percentage of watermarked HDR images assigned to each of the four scores.

Source	TF	Score 1	Score 2	Score 3	Score 4	Disturbing (%)
[31]	PQ	0	33.78	41.78	24.44	12.89
[32]	PQ	0	42.96	28.15	28.89	33.70
[33]	PQ	0	0	36.67	63.33	46.66
PQ .	AV	0	25.58	35.53	38.88	31.08
[34]	HLG	0	0	14.28	85.71	4.76
[35]	HLG	0	0	28.33	71.66	3.33
[36]	HLG	0	0	2.66	97.33	2.66
HLG	AV	0	0	15.09	84.9	3.58
OA	V	0	12.79	25.31	61.89	17.33



**FIGURE 18.** Watermarked HDR imaging using an arbitrary embedding factor,  $\Xi_{HDR}$ .



FIGURE 19. Wartermarked HDR imaging using an arbitrary ER.

watermark is embedded in a region different from the ER selected by Algorithm 1, but using the  $\Xi_{HDR}$  for the appropriate ER, the watermark is also fully perceptible, as shown in Fig. 19.

#### TABLE 6. Percentage of watermarked HDR images assigned a Score = 4 (MOS) after applying a TMO using several watermarking methods.

		TMC	a on the n	non-ood II	DD IW m	athod		TMOs		ad in [9]		TMOs on the method in [0]					
Source	TE		s on the p	roposed n	DR-IW III	ethod		TMOSC	on the met	iou m [8]			TMOS 0	n me meu	iou in [9]		
Source		C-TM	G-TM	H-TM	M-TM	R-TM	C-TM	G-TM	H-TM	M-TM	R-TM	C-TM	G-TM	H-TM	M-TM	R-TM	
[31]	PQ	93.33	85	90	91.66	90	54.22	87.11	82.66	80	76.00	45.33	46.66	51.55	51.11	52.44	
[32]	PQ	94.44	98.61	94.44	98.61	97.22	58.51	70.90	59.39	69.09	61.818	29.62	25.92	29.25	36.66	41.85	
[33]	PQ	100	100	100	100	100	0	0	0	0	0	6.66	10	3.33	6.66	6.66	
PQ AV		95.92	94.53	94.81	96.75	95.74	37.58	52.67	47.35	49.69	45.93	27.20	27.53	28.04	31.48	33.65	
[34]	HLG	96.42	96.42	100	96.42	92.85	39.04	50.47	50.47	52.38	40.95	50.47	84.76	72.38	71.42	67.61	
[35]	HIG	03 75	100	100	100	100	86.66	02.33	88.33	58 33	86.66	01.66	05	03 33	88.33	90	
	IILO	95.15	100	100	100	100	00.00	94.55	00.55	50.55	00.00	91.00	95	95.55	00.55	20	
[36]	HLG	100	100	100	100	95	70.66	78.66	77.33	76	81.33	96	98.66	94.66	89.33	93.33	
HLG AV		96.72	98.80	100	98.80	95.95	65.46	73.82	72.04	62.23	69.65	79.38	92.80	86.79	83.03	83.65	
OAV		96.32	96.67	97.40	97.78	95.84	51.52	63.24	59.70	55.96	957.79	53.29	60.17	57.42	57.25	58.65	

#### TABLE 7. BER values of the extracted binary watermarks after applying various TMOs.

Carries	ID	TE	TMO	Os on the p	roposed H	DR-IW me	thod		TMOs o	n the meth	od in [8]			TMOs o	n the meth	od in [9]	
Source	ID ID		C-TM	G-TM	H-TM	M-TM	R-TM	C-TM	G-TM	H-TM	M-TM	R-TM	C-TM	G-TM	H-TM	M-TM	R-TM
	BF_000	PQ	0.0236	0.0246	0.0150	0.2066	0.0236	0.2071	0.2072	0.2068	0.2067	0.2073	0.5034	0.5071	0.5527	0.5035	0.4978
[21]	FP_230	PQ	0.0976	0.1011	0.0487	0.0976	0.1031	0.2072	0.2073	0.2067	0.2072	0.2073	0.4426	0.4735	0.4769	0.4446	0.4484
[31]	SG_134	PQ	0.0260	0.0273	0.0126	0.0260	0.0278	0.2072	0.2073	0.2068	0.2072	0.2073	0.4769	0.5052	0.5004	0.4852	0.4834
	SG_154	PQ	0.0327	0.0335	0.0186	0.0327	0.0343	0.2071	0.2072	0.2069	0.2071	0.2072	0.5068	0.5245	0.5507	0.5123	0.5095
	bf_3660	PQ	0.0866	0.0875	0.0709	0.0866	0.0884	0.2076	0.2075	0.2072	0.2066	0.2075	0.4519	0.4955	0.4593	0.4605	0.4633
	cf_6640	PQ	0.0031	0.0031	0.0030	0.0046	0.0049	0.2070	0.2071	0.2070	0.2070	0.2070	0.5496	0.5451	0.6079	0.5518	0.5436
[32]	cf_7400	PQ	0.0034	0.0549	0.0032	0.0530	0.0034	0.2067	0.2067	0.2066	0.2067	0.2067	0.4566	0.4894	0.4831	0.4628	0.4640
	hdr_3335	PQ	0.1184	0.1060	0.1155	0.1184	0.1381	0.2070	0.2072	0.2068	0.2071	0.2073	0.4624	0.4586	0.4561	0.4572	0.4503
	sg_5636	PQ	0.0244	0.0247	0.0286	0.0244	0.0441	0.2072	0.2073	0.2069	0.2070	0.2072	0.5007	0.4660	0.4776	0.4973	0.4931
[33]	EBU_4272	PQ	0.0060	0.0060	0.0054	0.0054	0.0061	0.6122	0.6030	0.6171	0.6109	0.6099	0.4473	0.5603	0.4717	0.4828	0.4975
	PQ AV		0.0327	0.0360	0.0245	0.0359	0.0365	0.2475	0.2467	0.2478	0.2474	0.2473	0.4798	0.5025	0.5036	0.4858	0.4851
	bbc1_012	HLG	0.1569	0.1490	0.2070	0.1569	0.1330	0.2549	0.2371	0.2854	0.2245	0.2141	0.2695	0.2660	0.2713	0.2653	0.2643
[34]	bbc1_306	HLG	0.1203	0.1724	0.2417	0.1203	0.1740	0.4251	0.4559	0.5042	0.4245	0.4231	0.2831	0.2674	0.2692	0.2718	0.2716
	bbc1_435	HLG	0.0753	0.1853	0.0426	0.0753	0.1919	0.4058	0.3673	0.4460	0.3999	0.3851	0.2743	0.2593	0.2681	0.2687	0.2638
	bbcc1_005	HLG	0.0703	0.0705	0.1237	0.0703	0.0708	0.5619	0.3065	0.3327	0.4497	0.4018	0.3202	0.3175	0.3063	0.2998	0.2976
[35]	bbcc1_048	HLG	0.0756	0.0713	0.2421	0.0756	0.0682	0.3364	0.3256	0.4241	0.3328	0.3235	0.2803	0.2734	0.2928	0.2754	0.2792
	bbcc1_066	HLG	0.0903	0.0823	0.2007	0.0903	0.0804	0.2313	0.2402	0.3089	0.2314	0.2277	0.2611	0.2564	0.2560	0.2612	0.2544
	bbcc2_031	HLG	0.0634	0.0627	0.1097	0.0634	0.0625	0.4642	0.4647	0.5921	0.4637	0.4565	0.2723	0.2738	0.2811	0.2720	0.2694
[26]	bbcc2_045	HLG	0.1053	0.1013	0.1834	0.1053	0.1017	0.4707	0.4669	0.5960	0.4704	0.4622	0.2717	0.2719	0.2814	0.2717	0.2691
[30]	bbcc2_092	HLG	0.0743	0.0750	0.0650	0.0743	0.0749	0.2552	0.2533	0.3740	0.2539	0.2468	0.2789	0.2778	0.2787	0.2760	0.2722
	bbcc2_095	HLG	0.1585	0.1587	0.1324	0.1585	0.1587	0.3292	0.3182	0.4528	0.3250	0.3183	0.2663	0.2672	0.2752	0.2654	0.2647
	HLG AV		0.0989	0.1143	0.1653	0.0989	0.1130	0.3735	0.3436	0.4316	0.3576	0.3459	0.2778	0.2731	0.2780	0.2727	0.2706
	OAV		0.0658	0.0751	0.0949	0.0674	0.0747	0.3105	0.2951	0.3397	0.3025	0.2967	0.3788	0.3878	0.3908	0.3793	0.3779

TABLE 8. BER values of the extracted binary watermarks after applying HEVC lossy compression.

Source	ID	TE		Proposed HE	OR-IW method			Metho	od in [8]			Metho	od in [9]	
Source		11	QP = 0	QP = 10	QP = 20	QP = 40	QP = 0	QP = 10	QP = 20	QP = 40	QP = 0	QP = 10	QP = 20	QP = 40
	BF_000	PQ	0.0136	0.0186	0.0425	0.2043	0.2111	0.2107	0.2094	0.2114	0.3618	0.4113	0.6721	0.7244
[21]	FP_230	PQ	0.0430	0.0440	0.0564	0.1768	0.2072	0.2071	0.2077	0.2093	0.3298	0.3493	0.5092	0.7068
[31]	SG_134	PQ	0.0107	0.0132	0.0601	0.1993	0.2069	0.2041	0.2090	0.2087	0.3666	0.3877	0.5150	0.6680
	SG_154	PQ	0.0146	0.0181	0.0443	0.2051	0.2070	0.2071	0.2082	0.2090	0.3872	0.4037	0.5302	0.6817
	bf_3660	PQ	0.0653	0.0748	0.1748	0.2386	0.2111	0.2107	0.2094	0.2114	0.3593	0.3871	0.5921	0.2975
	cf_6640	PQ	0.0003	0.0082	0.0406	0.1801	0.2072	0.2074	0.2093	0.2096	0.4786	0.4891	0.5584	0.3891
[32]	cf_7400	PQ	0.0001	0.0048	0.0300	0.1750	0.2069	0.2071	0.2087	0.2109	0.3761	0.4078	0.6581	0.7208
	hdr_3335	PQ	0.1048	0.0999	0.0935	0.2443	0.2069	0.2071	0.2086	0.2094	0.3530	0.3795	0.6331	0.7246
	sg_5636	PQ	0.0222	0.0263	0.0671	0.2062	0.2076	0.2071	0.2077	0.2094	0.3842	0.4035	0.5281	0.3563
[33]	EBU_4272	PQ	0.0026	0.0129	0.0726	0.2118	0.6179	0.6221	0.6333	0.7236	0.3651	0.3899	0.3094	0.4852
	PQ AV		0.0205	0.0264	0.0682	0.2057	0.2485	0.2490	0.2506	0.2609	0.3762	0.4009	0.5506	0.5754
	bbc1_012	HLG	0.1135	0.1180	0.1026	0.2069	0.5062	0.2981	0.2579	0.2372	0.2972	0.3217	0.4282	0.4239
[34]	bbc1_306	HLG	0.0716	0.0776	0.1116	0.2057	0.5031	0.3266	0.2749	0.2475	0.3010	0.3285	0.4199	0.4653
	bbc1_435	HLG	0.0347	0.0415	0.1420	0.2065	0.3993	0.2800	0.2558	0.2411	0.2687	0.2976	0.4243	0.4193
	bbcc1_005	HLG	0.0585	0.0583	0.0807	0.1930	0.4985	0.4087	0.3026	0.2746	0.3070	0.3292	0.3948	0.4709
[35]	bbcc1_048	HLG	0.0591	0.0610	0.1162	0.2060	0.4953	0.3136	0.2685	0.2475	0.2907	0.3104	0.4125	0.4209
	bbcc1_066	HLG	0.0526	0.0564	0.0709	0.2840	0.5389	0.2840	0.2478	0.2346	0.2774	0.2952	0.3958	0.3719
	bbcc2_031	HLG	0.0513	0.0597	0.0694	0.1930	0.4637	0.3617	0.2977	0.2648	0.3147	0.3340	0.4036	0.4471
[26]	bbcc2_045	HLG	0.0885	0.0925	0.1378	0.1988	0.5047	0.3718	0.3052	0.2688	0.3081	0.3287	0.3966	0.4431
[30]	bbcc2_092	HLG	0.0533	0.0617	0.0810	0.2145	0.4788	0.3682	0.2927	0.2658	0.3088	0.3307	0.3977	0.4464
	bbcc2_095	HLG	0.1296	0.1359	0.1548	0.2049	0.5063	0.3451	0.2821	0.2591	0.3026	0.3241	0.4135	0.4483
	HLG AV		0.0660	0.0707	0.0989	0.2085	0.4895	0.3358	0.2785	0.2541	0.2976	0.3200	0.4087	0.4357
	OAV		0.0433	0.0485	0.0836	0.2071	0.3690	0.2924	0.2645	0.2575	0.3369	0.3605	0.4796	0.5056

#### C. THIRD SET OF EXPERIMENTS: ROBUSTNESS TO TMO

For this experiment, five TMOs are applied to the test HDR images watermarked by the HDR-IW method and the methods in [8], [9]. Namely, Clip (C-TM), Gamma (G-TM), Hable (G-TM), Mobius (M-TM) and Reinhard (R-TM) [39]. Let us recall that TMOs are designed to generate SDR images from HDR images by maintaining similar visual content. TMOs modify the contrast of an HDR image by modifying pixel values, including regions with low luma codes, which are

the regions where the HDR-IW method operates. Table 6 presents the percentage of watermarked images that are assigned a Score = 4 by the observers of Experiment 3 after applying a TMO. These results show that the HDR-IW method embeds watermarks that are more robust to TMOs than those embedded by the methods in [8], [9]. Tone mapping reduces the dynamic range of an HDR image by squishing down the entire capability of representing luminance by means of luma codes. It is then expected that the watermarked

Source	ID	тр	SPO o	n proposed	HDR-IW 1	nethod		SPO on me	thod in [8]			SPO on me	ethod in [9]	
Source	ID	11.	GN	BL	ROT	DS	GN	BL	ROT	DS	GN	BL	ROT	DS
	BF_000	PQ	0.0127	0.0057	0	0.0028	0.1013	0.0492	0.0466	0.0584	0.2094	0.2066	0.3640	0.2071
[21]	FP_230	PQ	0.0380	0.0049	0.0011	0.0055	0.0707	0.0280	0.0324	0.032	0.2105	0.2067	0.3636	0.2071
[31]	SG_134	PQ	0.0087	0.0198	0.0041	0.0167	0.1045	0.0460	0.0482	0.0589	0.2119	0.2067	0.3629	0.2072
	SG_154	PQ	0.0121	0.0041	0.0012	0.0022	0.1809	0.1192	0.0834	0.1374	0.2125	0.2067	0.3626	0.2071
	bf_3660	PQ	0.0643	0.0142	0.0030	0.0088	0.1554	0.1217	0.0713	0.1235	0.2081	0.2066	0.3643	0.2071
	cf_6640	PQ	0.0001	0.0049	0	0.0031	0.6539	0.6559	0.3009	0.6542	0.2116	0.2066	0.3628	0.2071
[32]	cf_7400	PQ	0	0.0212	0.0055	0.0298	0.186	0.1557	0.0855	0.1594	0.2086	0.2066	0.3640	0.2071
	hdr_3335	PQ	0.1037	0.0069	0	0.0044	0.0715	0.0325	0.0328	0.0361	0.2087	0.2066	0.3640	0.2072
	sg_5636	PQ	0.0211	0.0051	0.0008	0.0038	0.1445	0.1091	0.0664	0.1121	0.2092	0.2066	0.3638	0.2071
[33]	EBU_4272	PQ	0.0036	0.0238	0	0.0180	0.1980	0.2019	0.0911	0.202	0.4135	0.3431	0.1903	0.3616
PQ AV			0.0198	0.0133	0.0009	0.0107	0.1867	0.1519	0.0859	0.1574	0.2304	0.2203	0.3462	0.2226
	bbc1_012	HLG	0.1114	0.0045	0.0005	0.0045	0.066	0.0180	0.0304	0.0200	0.3767	0.3672	0.2872	0.3724
[34]	bbc1_306	HLG	0.0700	0.0144	0.0043	0.0171	0.0560	0.0047	0.0257	0.0074	0.3548	0.3344	0.2974	0.3437
	bbc1_435	HLG	0.0351	0.0092	0	0.0088	0.0641	0.0055	0.0294	0.0091	0.3243	0.3220	0.3114	0.3245
	bbcc1_005	HLG	0.0595	0.0377	0.0152	0.0457	0.0457	0.0034	0.021	0.0043	0.4096	0.3470	0.2720	0.3634
[35]	bbcc1_048	HLG	0.0575	0.0520	0.0226	0.0554	0.0700	0.0116	0.0323	0.0160	0.3134	0.2956	0.3165	0.3022
	bbcc1_066	HLG	0.0501	0.0176	0.0051	0.0196	0.0744	0.0068	0.0342	0.0127	0.4109	0.4086	0.2715	0.4108
	bbcc2_031	HLG	0.0502	0.0172	0.0064	0.0206	0.0646	0.0124	0.0297	0.0174	0.2533	0.2332	0.3442	0.2401
[26]	bbcc2_045	HLG	0.0867	0.0113	0.0030	0.0117	0.0776	0.0198	0.0357	0.0271	0.2575	0.2333	0.3423	0.2415
[30]	bbcc2_092	HLG	0.0520	0.1010	0.0439	0.1028	0.0538	0.0039	0.0247	0.0060	0.3530	0.3225	0.2981	0.3337
	bbcc2_095	HLG	0.1000	0.0701	0.0099	0.0659	0.0522	0.0039	0.0239	0.0055	0.2609	0.2435	0.3406	0.2500
	HLG AV		0.0674	0.0317	0.0106	0.0335	0.0624	0.0090	0.0287	0.0126	0.3314	0.3107	0.3081	0.3182
	OAV		0.0424	0.0225	0.0058	0.0221	0.1246	0.0805	0.0573	0.0850	0.2809	0.2655	0.3272	0.2704

TABLE 9. BER values of the extracted binary watermarks after applying several Signal Processing Operations (SPO).

images by the HDR-IW method with low  $luma_{ER}$  values be assigned the full imperceptibility score (4) after applying a TMO.

To quantitatively evaluate the robustness to TMOs, we use the Bit Error Rate between the original binary watermark, BW, and the tone-mapped binary watermark,  $\widehat{BW}$ :

$$BER = \frac{1}{m \cdot n} \sum_{i=1}^{m} \sum_{j=1}^{n} \left| BW_{i,j} - \widehat{BW}_{i,j} \right| \in [0, 1] \quad (14)$$

BER values are tabulated in Table 7 for 20 of the most representative test HDR images in terms of color distribution, texture, variety of lighting conditions, and dominant contrast proportions. These results show that the HDR-IW method is more robust to TMOs than the methods in [8], [9], as BER values attained by this method are the lowest for all TMOs. It is important to recall that the HDR-IW method embeds the watermark in low luminance regions, whose values are less susceptible to aggressive tone mapping. Note that the method in [9] is particularly susceptible to TMOs for PQ-encoded images, with an average BER as high as 0.5036.

Figure 20 shows sample binary watermarks extracted after applying a TMO to the HDR images watermarked by the HDR-IW method and the methods in [8], [9]. These visual results confirm the trend observed in the BER values tabulated in Table 7. Specifically, note that although the binary watermarks for the HDR-IW method have noticeable visual artifacts, they have a higher visual quality than those for the methods in [8], [9].

# D. FOURTH SET OF EXPERIMENTS: ROBUSTNESS TO LOSSY COMPRESSION

To evaluate the robustness to lossy compression, we use the HEVC compression standard reference software HM v.16.18  $\,$ 

[40], which supports HDR compression. We employ intraprediction coding with four different Quantization Parameters (QP), ranging from a low compression level, QP = 0, to a very high compression level, QP = 40.

Table 8 tabulates the BER values of the decoded binary watermarks w.r.t. the original binary watermark after lossy compression, using the proposed HDR-IW and the methods in [8], [9]. As expected, these results show that the robustness of all methods to lossy compression decreases as the compression is more aggressive. This is due to the fact that lossy compression mechanisms tend to compress more aggressively smooth regions, which are where watermarks are usually embedded in the pixel domain. When aggressive lossy compression is used, e.g., QP = 40, the maximum BER value for the HDR-IW method is 0.2840. Conversely, the maximum BER value for the methods in [8], [9] for QP = 40are 0.7236 and 0.7246, respectively. We acknowledge that the sensitivity to aggressive lossy compression is one aspect of the proposed HDR-IW that may limit its applicability for the distribution of HDR images in compressed format.

# E. FIFTH SET OF EXPERIMENTS: ROBUSTNESS TO COMMON SIGNAL PROCESSING OPERATIONS

Watermarks embedded in the spatial domain can be easily modified by applying common signal processing operations such as noise addition (GN), blurring (BL), rotation (ROT) and downscaling (DS). To measure the robustness to these common operations, we modify the test watermarked images, as follows:

- 1) GN: Gaussian white noise is added to the Y-channel with a variance = 0.01.
- 2) BL: Blurring effects are introduced by replicating the border pixel values.



FIGURE 20. Binary watermarks extracted from BF\_000 (Rec.2020 + PQ OETF) after applying various TMOs. (Left to right) TMO: C-TM, G-TM, H-TM, M-TM, R-TM. First row: proposed HDR-IW method. Second row: method in [8]. Third row: method in [9].

- 3) ROT: The image is rotated by 45° w.r.t the original position.
- 4) DS: The image is down-scaled by a factor of 0.5.

Table 9 shows the BER values of the binary watermarks w.r.t. the original binary watermark after applying the signal processing operations listed before. These results confirm that the HDR-IW method is very robust to such operations. The largest BER values are obtained after adding Gaussian white noise; however, the average BER value for this operation is below 0.05. The methods in [8], [9] tend to be, on average, also robust to these signal processing operations. However, in general, the BER values for these methods are larger than those for the proposed method.

We finish this section with some comments about the computational complexity of the proposed HDR-IW method. For the evaluated HDR images tabulated in Table 2, our method takes, on average, 12.26 seconds to watermark each image on a PC with an Intel Core i7-7500U @2.90GHz CPU and 16GB of RAM. The methods in [8], [9] take, on average, 734.54 and 84.90 seconds, respectively, to watermark each of these HDR images on the same computer. Such low average processing times make the proposed method very well-suited and applicable for real-life scenarios.

## **VI. CONCLUSION**

In this paper, we proposed the HDR-IW method to protect HDR images by embedding binary watermarks in the spatial domain that are imperceptible to the HVS. The HDR-IW method is based on a thorough analysis of the modelling used by an OETF to represent HDR images as a non-linear digital signal, the linear luminance radiated by an HDR screen by means of an EOTF, and the brightness perceived by the HVS from the HDR screen. To this end, the method uses an LVT curve to determine not only the most appropriate ER, but also the maximum variation that luma codes within the ER can tolerate before any changes can be perceived by the HVS. The watermarks embedded by the HDR-IW method in the spatial domain remain imperceptible to the HVS as long as the TF is not altered or the normal calibration and colorimetry conditions of the HDR screen remain unchanged. Our evaluations on a wide range of real-life HDR images encoded by the PO and HLG TFs confirmed the method's capacity to embed imperceptible watermarks and its robustness to various manipulations, including tone-mapping. The HDR-IW method is then an attractive option to merge the advantages of invisible and visible watermarking methods to protect HDR imaging. Our future work focuses on increasing the robustness of the HDR-IW method to very aggressive lossy compression.

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