

Assessment of Camera Phone Distortion and Implications for Watermarking

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1. INTRODUCTION

In this paper, the distortion introduced by cameras of smart phones such as iPhone 3G and iPhone 3GS is measured and quantified. In particular, the spatial frequency response (SFR) of a mobile camera phone is measured [1]. A new robustness metric that relates camera phone quality to watermark robustness is defined. Experiments were conducted using watermarked images to verify the predictions made by the robustness metric. The main advantage of defining a robustness metric based on camera quality distortion is that it enables fast and effective modeling of watermark detector performance for a wide range of mobile phones. This is important because ideally the watermarked printed image should be readable by a variety of consumer smart phones. By simulating the watermark detector behavior for a range of mobile devices, important feedback can be provided to the chrominance watermark embedding process. In particular, the SFR-based robustness model provides information on the expected performance of watermark detector for images marked with different watermark density and strengths. Thus, the use of robustness models saves time and cost by reducing the need for several watermarked print runs before finding the optimal balance between watermark visibility and robustness to distortion. In addition, new devices can be quickly qualified for their use in watermark applications.

1.1 Chrominance Watermarking for Print

Chrominance watermarking facilitates imperceptible watermarking of images at lower spatial frequencies in comparison to luminance watermarking [2]. This makes it ideal for smart phone applications of watermarking. Prior to embedding, the watermark signal may be scaled by a strength factor determined by the visibility and robustness trade-off. Of the two component signals of chrominance watermarking - message and synchronization signals - the synchronization signal plays a dominant role in influencing both watermark visibility and robustness to distortion. The synchronization signal allows the watermark to be read after printing over a wide range of scale and angle. Detection of the synchronization signal is prerequisite for decoding the message signal. Hence the analysis in this paper is restricted to the synchronization signal.

For watermarking, the number of watermark bits per inch (WPI) is an important factor influencing both visibility and robustness. Typically, higher WPI results in improved visibility. The spatial frequencies spanned by the synchronization signal range from $1/4^{\text{th}}$ to $3/4^{\text{th}}$ of the spatial frequency corresponding to the given WPI.

For a mobile phone application, the following are the main factors influencing the robustness of chrominance watermarking of printed images.

- Watermark bits per inch (WPI)
- Image content
- Print quality
- Camera capabilities of a mobile phone

Any variation in quality and distortion introduced during the printing process is beyond the scope of this paper. The specific content of an image is outside the scope of watermarking. Watermark pixel density and resolution influence both visibility and watermark robustness. In smart phone applications, limitations of a camera's resolution and focal length usually reduce the watermark robustness for higher WPI. Camera distortion and WPI are used for defining the robustness metric in the following section.

2. CAMERA QUALITY MEASUREMENT FOR WATERMARKING

Test procedures for the measurement of the quality of images produced by digital cameras are well established. However, standardized test methods for the evaluation of camera phones are still lacking. The recently established camera phone image quality (CPIQ) initiative by the International Imaging Industry Association (I3A) aims to develop standards for evaluating camera phone image quality [3]. The main attributes of image quality are resolution, sharpness, noise, and color reproduction [3].

Watermark detection is most influenced by the information conveyed by SFR [4]. Hence, in this work, the mobile phone image quality metric for watermark robustness assessment is restricted to SFR. SFR is a method to gauge the contrast loss of a device when it captures the varying frequency content of a scene. The SFR curve represents the relative efficiency of the camera in terms of capturing the contrast from print to digital image [5]. The work used the slanted-edge SFR measurement implemented by the ISA SFREdge (v.5) software [6]. Alternative measurements, such as the sine-wave SFR (S-SFR) are also of interest but have not been evaluated.

The ISO 12233 test chart was used for slanted-edge SFR measurement. A robot was used to capture low-resolution preview images of the slanted edge target (ISO 12233 test chart) by positioning cell phones at a specified distance. The images were captured in the presence of cool white fluorescent light. Note that, in this application, preview frames are used instead of high-resolution photographs. This is because the preview frames are quick to capture and provide the desired user experience.

The SFR measurements for iPhone 3G and iPhone 3GS cameras at target distances of 3, 5, and 7 inches were obtained as shown in Figure 1. The SFR characteristics of iPhone 3GS are indicated by dotted lines and SFR curves of iPhone 3G are indicated by solid lines. As expected, the SFR of iPhone 3GS is much better than that of iPhone 3G at all distances. Due to the fixed focal length of iPhone 3G, the SFR response does not deteriorate rapidly as a function of distance. The SFR curves of the individual red, green and blue channels are usually within a narrow margin around the curve for luminance SFR. Hence for the experiments in this paper (including Figure 1), only the luminance channel is used for representing the SFR of a particular capture device.

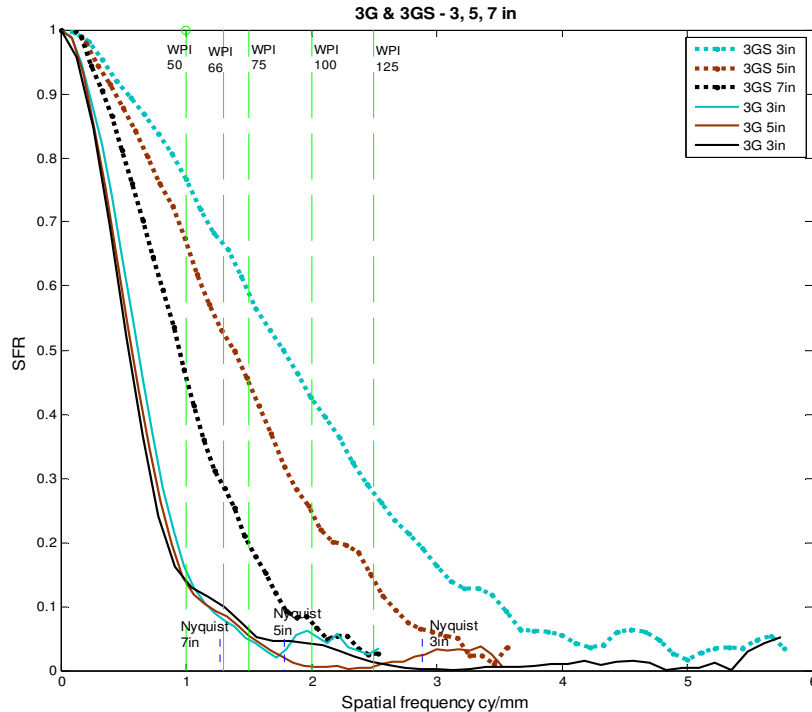


Figure 1: SFR characteristics for iPhone 3G and iPhone 3GS for distances 3, 5, and 7 inches

The dotted blue lines indicate the Nyquist frequency of the image captured at different distances. The Nyquist frequency is determined by the resolution of preview capture at a given distance. For example, preview frames captured at a distance of 3 inches were measured to have a resolution of 146 pixels per inch (ppi), preview frames captured at 5 inches had a resolution of 90 ppi, and preview frames at 7 inches had a resolution of 64 ppi. Any image content consisting of spatial frequencies above the sampling frequency is aliased in accordance with a scaling factor determined by the SFR. The aliased content interferes with the image content at lower spatial frequencies. The dotted green lines in Figure 1 show various WPI options available during the watermark embedding process. For example, 100 WPI corresponds to 50 cycles per inch. For a printed image watermarked at a resolution of 100 WPI, the synchronization signal is present in the spatial frequencies ranging from 12.5 cycles per inch to 37.5 cycles per inch. Hence, by projecting the WPI onto the SFR characteristics, the SFR of a capture device is obtained for the spatial frequencies spanned by the synchronization signal.

3. SFR-BASED WATERMARK ROBUSTNESS METRIC

The SFR as a function of spatial frequency is a good measure of the image quality distortion due to the camera. By including the spatial frequency corresponding to a particular WPI, the impact of camera distortion on watermark synchronization signal can be deduced. A measure of watermark robustness based on the SFR is derived by computing the area under the SFR curve for the range of spatial frequencies in which the synchronization signal exists and subtracting the area under the SFR curve due to aliasing. The SFR-based robustness metric λ at a given target distance is obtained as follows.

$$\lambda = \rho_{synch} - \rho_{alias} \tag{1}$$

where ρ_{synch} is the area under the SFR curve in the region of the synchronization signal and ρ_{alias} is the area under the SFR curve due to spatial frequencies aliasing with the synchronization signal. The area under the SFR curve is computed using the trapezoidal rule over small intervals of spatial frequencies.

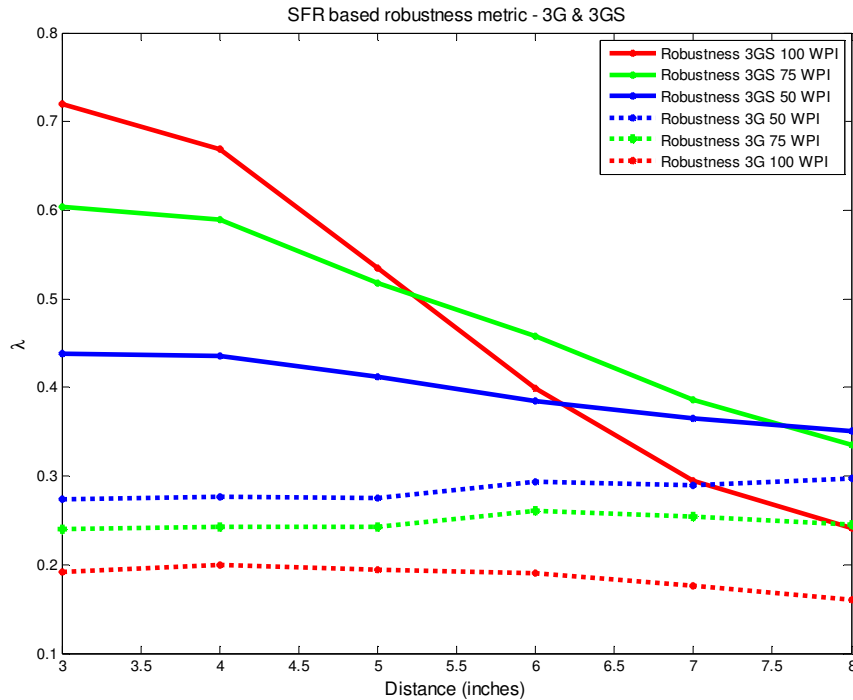


Figure 2: SFR-based robustness metric for iPhone 3G and iPhone 3GS

The SFR-based robustness metric was computed for iPhone 3G and iPhone 3GS for different WPI values at target distances ranging from 3 to 8 inches (see Figure 2). According to Figure 2, the watermark decoding performance for images captured by iPhone 3GS is better than that for iPhone 3G for all WPI and for all target distances below 7 inches. In general, similar detector behavior was observed when large-scale experiments were conducted using iPhone 3G and iPhone 3GS as capture devices for real watermarked printed images. The following section discusses the relationship between SFR-based watermark robustness and actual watermark detector behavior for iPhone 3GS.

4. SFR-BASED ROBUSTNESS AND WATERMARK DETECTOR PERFORMANCE

In order to verify the accuracy of the robustness model based on the SFR-robustness metric, several experiments were conducted using actual smart images [1]. For the experiments discussed in this section, a set of 4 newsprint images with diverse content was used. The images were watermarked with different watermark strength values (3 and 4) and WPI (75 and 100) resulting in multiple sets of watermarked images. The iPhone 3GS was used to capture the preview frames of each watermarked image over a range of distances of 3 inches to 7 inches in the presence of cool white fluorescent illumination at a light level of 50 lux. The light level was selected to be at the lowest value in common use in an office or home environment. For each of the 4 prints a set of 35 preview images were captured at each position, separated by 0.3 inches from 2.9 inches to 7.1 inches. The captured images were then input to the watermark detector. Thus each point on the actual watermark robustness curve (for example, see Figure 3) represents the average of 280 image captures. The captures were degraded by Gaussian noise with a standard deviation of 20% before watermark reading to avoid saturation of the robustness at low distances.

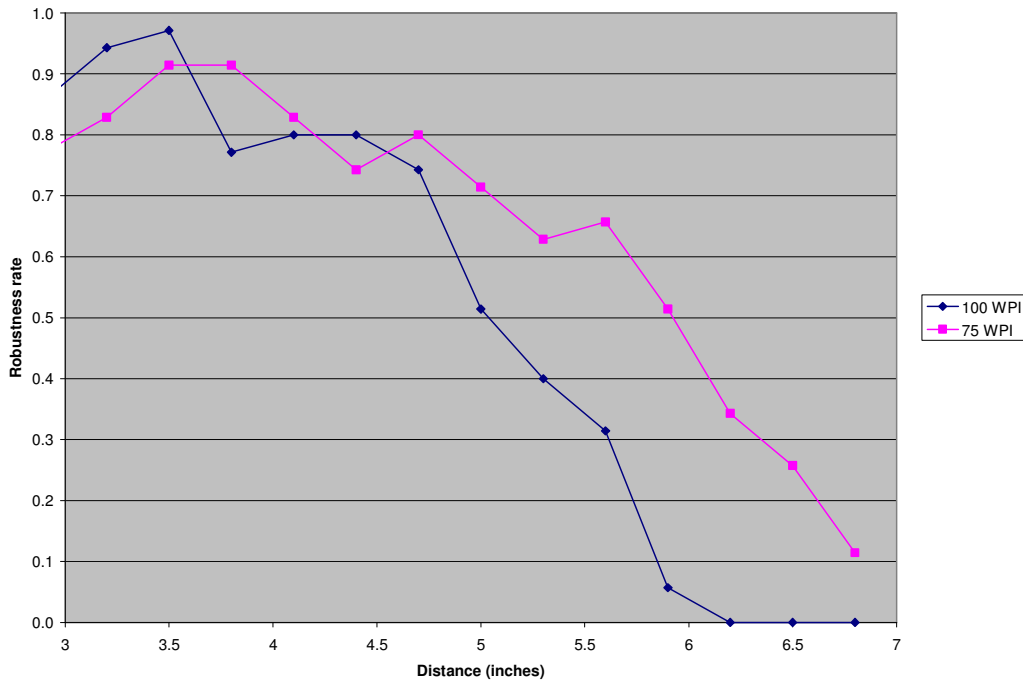


Figure 3: Average watermark robustness for WPI 75 and 100 as a function of distance

The watermark detection results of captured images which were watermarked at strength 4 and WPI 100 and 75 are shown in Figure 3. The magenta curve is for WPI 75 and the blue curve is for WPI 100. The detection rate at each distance is the average for 280 image captures. Figure 4 shows the robustness measurement predicted by the SFR-based robustness metric for WPI 75 and WPI 100 images captured by iPhone 3GS. By comparing Figures 3 and 4, it can be observed that the SFR-based robustness metric provides a fairly accurate estimate of the watermark detector performance for different WPI. For example, in Figure 3, the cross-over point of the two curves occurs at a distance of

4.7 inches while the SFR-robustness measurements predict a cross-over point at a distance of 5.2 inches. The SFR-robustness model predicts that watermarking at WPI 100 results in better robustness over shorter target distances (below 5 inches) and watermarking at WPI 75 results in better robustness over longer target distances (greater than 5 inches). This prediction was verified by the actual watermark detector results as shown in Figure 3.

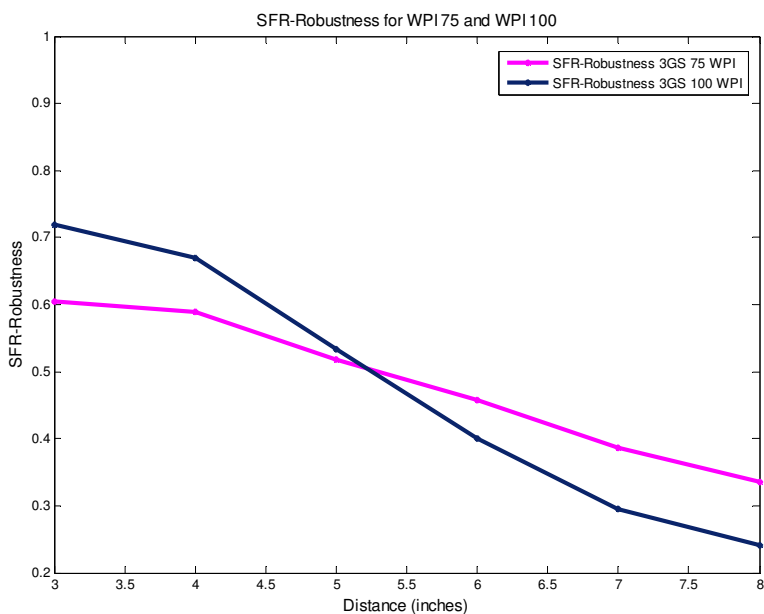


Figure 4: Watermark robustness predicted by SFR-robustness metric for WPI 75 and 100 as a function of distance

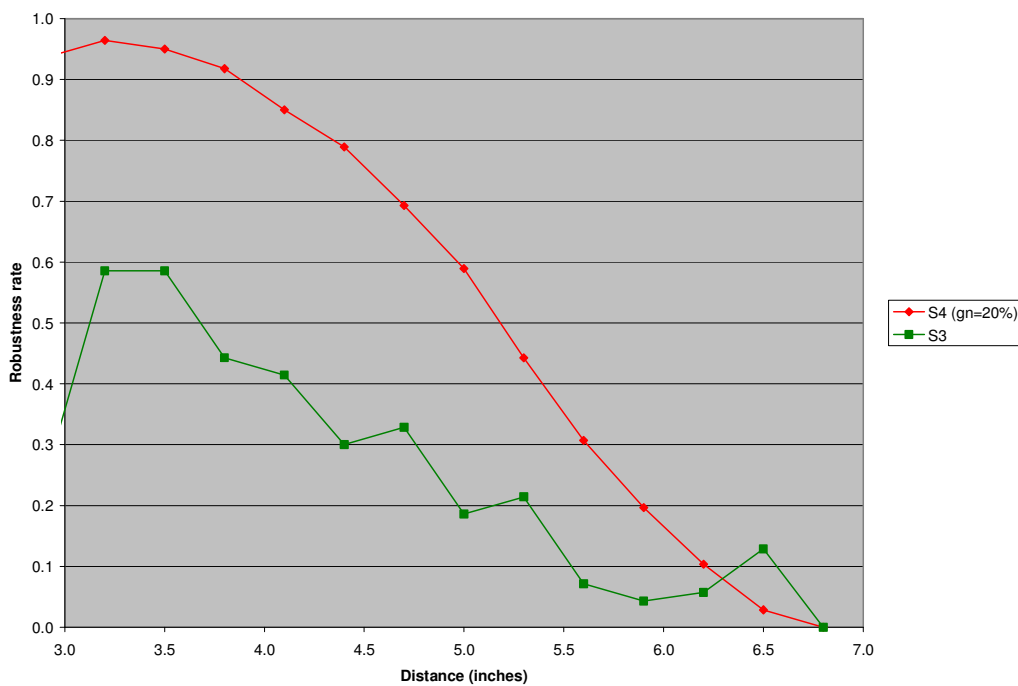


Figure 5: Average watermark robustness for WPI 75 at strength values of 3 and 4 as a function of distance

In addition to WPI, the watermark robustness model can also include the strength information. Images watermarked with different WPI result in watermark detection plots with different slopes and shapes. While images watermarked at the same WPI, but different strengths result in watermark detection plots which are scaled versions of each other at least in the near-field (less than 6 inches). The actual watermark detector results for images marked at strengths 3 and 4 at WPI 75 are as plotted in Figure 5. The SFR-robustness plot for WPI 75 as shown in Figure 4 was interpolated using a 4th order polynomial to collect data at intermediate distances ranging from 2.9 inches to 6.8 inches, in increments of 0.3 inches. The resulting SFR-robustness data was plotted against watermark robustness data for strengths 3 and 4 at WPI 75 (indicated by markers in Figure 6).

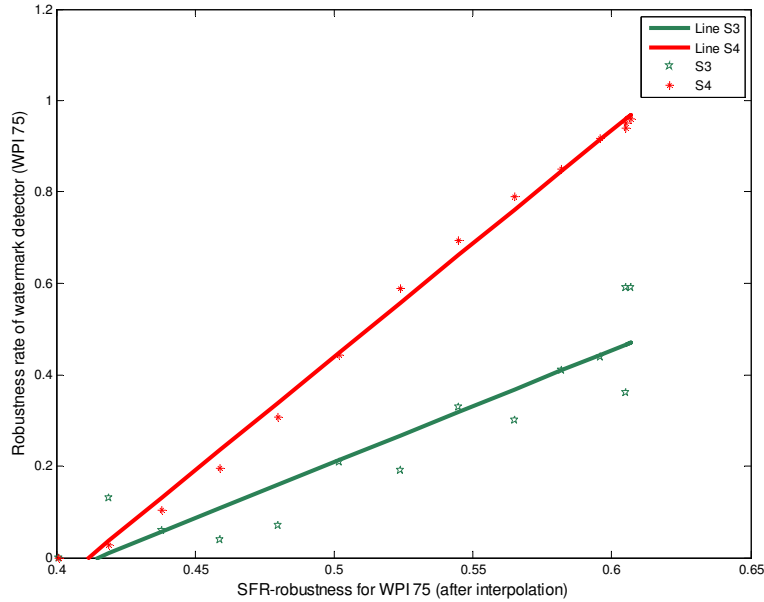


Figure 6: Comparison of SFR-robustness (interpolated) with watermark robustness at strength values of 3 and 4 (all for WPI 75)

The lines are the result of least squares fitting to the data for strengths 3 and 4. The linear least squares solutions (y_{S3} and y_{S4}) for strength 3 and strength 4 data are governed by the following equations.

$$y_{S3} = 2.4499\lambda - 1.0166 \tag{2}$$

$$y_{S4} = 4.959\lambda - 2.0409 \tag{3}$$

The mean squared error (MSE) between y_{S4} and watermark robustness data for strength 4 is 6.77×10^{-4} . The MSE for y_{S3} and watermark detector results for strength 3 is 0.0057. The y_{S3} data is associated with a higher MSE because the watermark robustness results were based on fewer (35 compared to 280) image captures. Due to the linear relationship between the SFR-robustness data and watermark detector results at different strength values, a constant scaling factor can account for watermark strength variations in the SFR-robustness results. Experimental results in the final paper will include the SFR-robustness results for a number of strength values.

The SFR-robustness model provides a fast and effective method to evaluate the impact of a given smart phone on the detection of smart images marked using different WPI and strength values. The model can be used to evaluate and

compare the impact of various smart phones on watermark detection without having to conduct time-consuming experiments using real images and their captures. Additionally, the SFR-robustness model provides feedback to the watermarking embedding process about the effect of embedding parameters such as WPI and strength on watermark detection without having to conduct expensive print-runs of images in newspapers and magazines.

5. CONCLUSIONS

An SFR-based watermark robustness model is presented for smart phone applications of watermarking. The robustness model was effective in predicting the relative watermark detector performance for different densities or WPI. The robustness model was able to predict the relative impact of different watermark strength parameters on watermark detection. The SFR-based robustness model provides an effective method to qualify smart phones for use in watermark applications. The SFR-based robustness can provide feedback to the watermark embedding process in finding a reasonable trade-off between visibility and robustness while averting the need for expensive and time-consuming print runs. Future work will involve combining the noise model of the capture device with the SFR-robustness model.

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