Image Sensors and Image Quality in Mobile Phones

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Abstract

This paper considers image sensors and image quality in camera phones. A method to estimate the image quality and performance of an image sensor using its key parameters is presented. Subjective image quality and mapping camera technical parameters to its subjective image quality are discussed. The developed performance metrics are used to optimize sensor performance for best possible image quality in camera phones. Finally, the future technology and technology trends are discussed. The main development trend for images sensors is gradually changing from pixel size reduction to performance improvement within the same pixel size. About 30% performance improvement is observed between generations if the pixel size is kept the same. Image sensor is also the key component to offer new features to the user in the future.

1. Introduction

Camera phones offer great benefits to the users by enabling photography, video recording, and content sharing always and everywhere. Besides the camera, modern mobile phones offer an extensive set of features, which require relatively large number of components. This sets tough limits for the size and cost of an individual component. Size and cost are also one of the main challenges in cameras in mobile phones. On the other hand, the very high volumes enable, e.g., using advanced silicon process technology.

There is a wide range of camera phone products (more or less camera driven), and a wide variety of possible camera technologies. Careful product planning and managing technologies are required to map the right technologies and cameras to right products. This paper considers image sensor performance metrics, subjective image quality and sensor optimization. Finally the sensor performance trends and future sensors are discussed.

Image sensor is the key component to enable high image quality even in the challenging mobile phone environment. The performance of image sensors has improved enormously during the past few years. There are promising new technologies to enable similar development also in the future.

2. Performance metric

A reliable sensor performance metric is needed in order to have meaningful discussion on different sensor options, future sensor performance, and effects of different technologies. Comparison of individual technical parameters does not provide general view to the image quality and can be misleading. A more comprehensive performance metric based on low level technical parameters is developed as follows.

First, conversion from photometric units to radiometric units is needed. Irradiation E [W/m^2] is calculated as follows using illuminance E_v [lux], energy spectrum of the illuminant (any unit), and the standard luminosity function V.

Equation 1: Radiometric unit conversion

$$E = \frac{\int s(\lambda)d\lambda}{683\frac{lm}{W}\int s(\lambda)V(\lambda)d\lambda}E_v$$

The number of photons hitting the target can be calculated by multiplying illuminant spectrum per unit wavelength by the irradiance E and diving this by photon energy.

Equation 2: Number of photons.

$$N_{ph}(\lambda) = \frac{\frac{s(\lambda)}{\int s(\lambda)d\lambda}E}{\frac{hc}{\lambda}}$$

The number of electrons generated in each pixel is calculated using lens transmission T, F-number F, target reflectance R, pixel size p, IR cut filter transmittance C, integration time t, full well capacity W, and quantum efficiency Q for each channel c.

Equation 3: Number of signal electrons.

$$S(c) = \min\left(\frac{RT}{4F^2}p^2t\int N_{ph}(\lambda)C(\lambda)Q(\lambda,c)d\lambda, W\right)$$

The required analog gain is estimated using the green channel signal S(g), exposure target e and maximum analog gain G_m.

Equation 4: Analog gain.

$$G = \max\left(1, \min\left(G_m, \frac{e}{S(g)}\right)\right)$$

Finally, the noises are calculated for each channel using well-know formulas, where r is the readout noise [e], d is the average dark current generation at temperature T [e/s], P is the photo-response non-uniformity relative to the signal, and B is the number of ADC bit.

Equation 5: Main noise sources.

$$n_{ph}(c) = \sqrt{S(c)}$$
$$n_r(c) = r$$
$$n_d(c) = \sqrt{dt}$$
$$n_{prnu}(c) = PS(c)$$
$$n_{ADC}(c) = \frac{W}{2^B G\sqrt{12}}$$

The total noise level for each channel n(c) can be estimated by taking root of squares of each component. The sensor raw signal to noise ratio can be calculated using the presented formulas, but the raw SNR tells little about the achievable image quality of the sensor.

SNR after color matrix correlates better with the resulting image quality, i.e., the required color transform is part of the sensor performance. The color matrix can be derived using the sensor spectral response, e.g., [9].

Simple white balance is applied before the color matrix.

Equation 6: White balancing.

$$S_{WB}(c) = \max(S(c))$$
$$n_{WB}(c) = \frac{\max(S(c))}{S(c)} n(c)$$

The effect of color matrix is calculated as follows. This is only shown for red channel here.

Equation 7: Applying color matrix.

$$S_{CCM}(r) = S_{WB}(r)C_{rr} + S_{WB}(g)C_{rg} + S_{WB}(b)C_{rb}$$
$$n_{ccm}(r) = \sqrt{(S_{WB}(r)C_{rr})^2 + (S_{WB}(g)C_{rg})^2 + (S_{WB}(b)C_{rb})^2}$$

To understand which camera is better in a given condition, the separate channel SNRs are combined single overall SNR. A simple way to do this is to use the luminance coefficients L_r=0.299, L_g=0.587 L_b=0.114 and calculate the combined SNR as follows.

Equation 8: Combined SNR.

$$S = L_r S_{CCM}(r) + L_g S_{CCM}(g) + L_b S_{CCM}(b)$$
$$n = \sqrt{(L_r n_{CCM}(r))^2 + (L_g n_{CCM}(g))^2 + (L_b n_{CCM}(b))^2}$$

The illuminance where a given target SNR is reached is used as a one-number performance metric. SNR=10 commonly used as target SNR. The advantage of using such x value is that comparison of illumination is easier than comparison of SNRs.

The actual SNR in the final output image is obviously different from the calculated SNR, because the calculation does not include several steps of the image processing. This is not a problem since the metric is only used to compare the sensor performances.

There are many open issues in the performance metric and also several simplifications were made when it was derived. The areas for future work are as follows.

- All noise sources are not included. This causes inaccuracy especially in low light.
- All noise sources do not have such statistics that the resulting sum noise could be calculated using the simple formula presented in this paper. Especially dark current hot pixels and line noises cannot be included [1].
- Combining the SNRs as presented here is not exactly correct because the noise components after color matrix are correlated. Furthermore, the Bayer arrangement of the pixels is not taken into account.
- Relative illumination is not taken into account. A possibility include this would be to integrate QE over the whole image area.
- The achievable color accuracy is not taken into account; only the noise effect of the color matrix.
- The noise floor as a function of gain can have more complicated relationship than the simple quantization noise model used here.
- Sensors tend to have many problems that are not included in the metric, such as green imbalance and color shading.

Even with the given limitations, the presented method has been successfully used. Furthermore, when more accurate methods are developed, the accuracy of the input parameters also needs to be improved.

3. Subjective image quality

The ultimate quality measure of a camera is the overall user experience, which includes subjective image quality and usability.

In Nokia, subjective image quality is measured by capturing test images in standard conditions and asking a group of test people to grade the image quality. This way, mean opinion score (MOS) can be calculated for each camera in each condition.

When a future camera is specified, its target performance should include target mean opinion scores. To enable specifying and planning target mean opinion scores, a method to map the technical parameters to mean opinion score is needed. This mapping is extremely challenging since there are many components: flash, optics, image sensor, image processing. The subjective image quality depends on the quality of each component and how well they operate together.

Figure 1 represents a simple heuristic model for camera head mean opinion score estimation. The x-axis shows a sensor performance metric, such as the one developed in this paper, and the y-axis shows the estimated MOS. The curves link the sensor performance to the MOS for different resolutions of the camera system, including optics, sensor and processing.

The model has been derived based on measured mean opinion scores for various cameras. When the sensor output is noisy, MOS is mainly limited by the sensor performance, i.e., the camera system resolution and contrast do not significantly affect the results. On the other hand, when the sensor outputs clean noise-free image, MOS is mainly limited by the optics performance. This simple model assumes that the image processing platform is kept unchanged, so it needs to be separately tuned for different image processing platforms. Different color temperatures may also need separate tuning.

The main challenges and areas for the future development are as follows.

- Development of the fair sensor performance metric. The challenges listed in the previous section are also valid here. Optics performance estimation also needs similar approach; this is outside the scope of this paper.
- Including the image processing. Formal way of mapping image processing methods to subjective image quality is extremely challenging and may not be possible. Heuristic approach may be always needed.
- Accurate method for mapping the sensor resolution to the x-axis of the model. If the optics resolution and pixel-level SNR is kept unchanged but the resolution of the sensor is changed, how should it be mapped to the model? Image processing complicates calculating the resulting effective SNR.

Even tough there are still open items in the model, the key claim is that there must be link between the technology selections and the final product image quality. The camera development is like running blind, if there are no performance targets, no method to estimate the subjective image quality, or no means to map the technical parameters to the subjective image quality. Comparison of the early performance predictions to the final product performance is also very important channel for feedback and continuous improvement.

4. Image quality optimization

The low light performance is usually mentioned first, when image quality issues are discussed. Still, more important question than whether there is anything visible in 1 lux image is *what exposure is needed to capture the first acceptable image.*

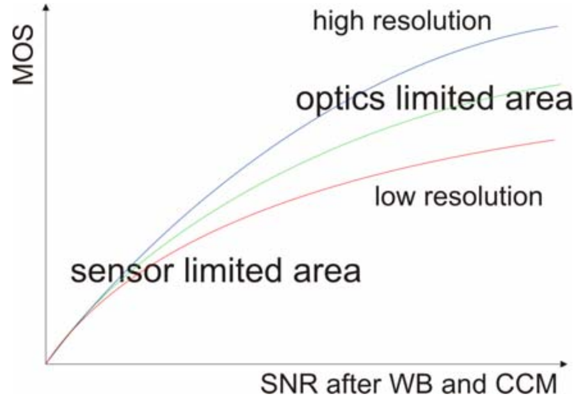

Figure 1: MOS estimation model.

SNR=10 after white balance and color matrix has proven to be a good approximate criteria for first acceptable image in subjective image quality tests. Similar conclusion has been done in ISO standard even though the SNR calculation method is different [3]. More accurate value is not needed, because "first acceptable" is very subjective item and depends also on other camera system parameters.

Optimizing a sensor for the first acceptable image is challenging. In conditions that yield SNR=10, the most dominant noise source is usually photon shot noise, when typical camera phone lens and exposure times are used. Therefore, the SNR can be significantly improved only by increasing quantum efficiency and reducing crosstalk (crosstalk is reduced to enable smaller CCM coefficients).

Readout noise and dark current are usually so low that further reduction of them would not significantly change the situation, e.g., [7]. Full well capacity does not either affect image quality in SNR=10 conditions. It is also interesting to notice that in most cases crosstalk has much more contribution to the maximum effective SNR than full well capacity or photo response non-uniformity.

An example of a 1.75u pixel optimization is shown in Figure 2. It shows the illumination level to reach SNR=10 for different 1.75u pixel optimizations: standard, 30% reduction of the readout noise, 10% increase of sensitivity (QE), and -0.1 smaller diagonal elements (and +0.05 +0.05 larger off-diagonal elements).

The most important parameters in addition to the basic SNR performance are angular response, line noise characteristics, dynamic range, and color accuracy. Especially angular response – shading and crosstalk performance – need special attention in mobile phones due to the low height camera module optics and resulting high chief ray angles in thin phones.

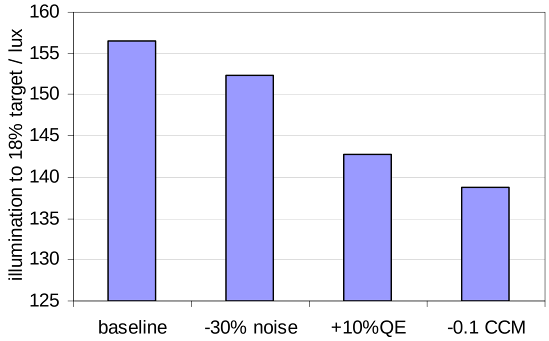

Figure 2: Illumination to reach SNR=10 after WB and CCM for different optimizations of a 1.75u pixel. Calculations use 3200K illuminant, F=2.8/Tr=0.8 lens, and 18% target reflectance.

5. Technology trends

As the contemporary pixel sizes enable large resolutions even in small camera modules, there are two options for the new sensor generations: 1. continue the pixel size reduction, or 2. performance optimization using the same pixel size. The performance comparison of larger and smaller pixel in the same optical format is not straightforward because the larger resolution makes noise less disturbing or enables more downscaling which increases SNR.

Based on historical data, if the pixel size is kept the same, *a new generation technology improves the SNR=10 metric about 30%*. There are already products on the market showing this: the sensor in Nokia N95 is about 30% better than the sensor in Nokia N80, based on the SNR=10 metric. Both products use the same pixel size, but N95 uses a newer pixel generation.

It will be very interesting to see how long the same performance improvement trend can be kept. There is a lot of room since the ideal sensor would have 100% QE and perfect colors with unity color matrix. When traditional technology is used, improving the optical path is very important for QE and angular response [7]. When the limits of the traditional approach are reached, promising new technologies, such as back-side illumination [4] (new in consumer applications), and organic film materials [6] can enable keeping the average trend longer time. Multiplying electrons, enabling effectively zero noise floor or photon-counter approach could be also one potential solution [5].

A very important trend in cameras is also offering new features to the user. Especially high dynamic range [1] and high frame rate technologies [8] are very promising. Still image stabilization would be also a wonderful feature. If backside illumination becomes practical, it will enable more digital processing integrated in to the sensor so that a lot of new digital features become possible for small pixels.

6. Conclusions

Sensor performance has been discussed using a proposed sensor performance metric. QE and crosstalk are currently the most important sensor parameters. A 30% yearly improvement of the proposed SNR metric has been observed. Future shows also very promising technologies for improving them. Image sensor is also the key component to offer new camera features in the future.

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