TAMPEREEN TEKNILLINEN YLIOPISTO
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VERIFICATION OF CAMERA MODULE CONDUCTED IMMUNITY

Master of Science Thesis

Examiner: Professor Karri Palovuori
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ABSTRACT

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Cameras are nowadays important part of mobile devices like smart phones, mobile phones and tablets. Nokia is concentrating on camera development, and good cameras are one way how Nokia is differentiating from its competitors.

During camera development there are many kinds of tests that need to be done to verify the performance of a camera module. Testing can be time-consuming for Nokia and camera suppliers. Automated tests are a good way to reduce the time needed for testing and the workload of test operators. Automating usually also improves test repeatability which makes it safer to count on camera suppliers' measurements. With repeatable test systems, more testing can be moved to camera suppliers and hence problems are found in earlier phases of camera development. Purpose of this thesis was to develop an automated conducted immunity test for camera modules.

The conducted immunity test is a part of electromagnetic compatibility (EMC) tests, and it tests how well the camera module can tolerate fluctuations on power supply lines. Power supply fluctuations can cause row noise to an image, which lowers the image quality. Noise on power supply lines can come from inside or outside of the camera module. On a smart phone camera, there are possible noise sources inside the small camera module like an autofocus (AF) and an optical image stabilizer (OIS). Therefore it is important to pay attention to camera module immunity against power supply fluctuations.

The automated test replaced an old manually done conducted immunity test. Biggest problems with the manual test were that it took too much time to do the test, it was not repeatable enough, and it did not find all problem frequencies. The automated test eliminated these problems. Test results shows what are the problem frequencies and how much the image has row noise at those frequencies. This gives understanding of camera module immunity and also gives guidance what sensitive frequencies should be avoided if there is possibility to affect to noise signal frequencies. The automated test has already been taken into use at Nokia and camera suppliers.

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Kamerat ovat nykyään tärkeä osa mobiililaitteita, kuten älypuhelimia, matkapuhelimia ja tabletteja. Nokia keskittyy kameroiden kehittämiseen ja hyvät kamerat ovat yksi Nokian tapa erottautua kilpailijoistaan.

Kameroille tehdään paljon erilaisia testejä niiden kehityskaaren aikana. Testit voivat vaatia paljon aikaa Nokialta ja kamerantoimittajilta. Testien automatisointi on hyvä keino vähentää testeihin kuluvaa aikaa ja se myös vähentää testihenkilöiden työkuormaa. Testien automatisointi myös yleensä parantaa testien toistettavuutta, jolloin Nokia voi luottaa enemmän kamerantoimittajien mittaustuloksiin. Näin ollen testausvastuuta voidaan siirtää enemmän kamerantoimittajille, jolloin ongelmat tulevat aiemmin ilmi. Tämän diplomityön tarkoituksena on tutkia ja määritellä automaattinen testi kameramoduulin johtuvan immuniteetin testaamiseen.

Johtuvan immuniteetin testaus on osa kameramoduulin EMC testejä ja se kertoo kuinka hyvin kamera sietää käyttöjännitteiden vaihtelua. Käyttöjännitteiden vaihtelu voi aiheuttaa kuvaan rivikohinaa, joka huonontaa kuvanlaatua. Käyttöjännitteiden häiriö voi olla peräisin kameran sisältä tai ulkopuolelta. Mobiililaitteen pienen kameramoduulin sisällä on häiriön aiheuttajia, kuten optinen kuvanvakain. Niinpä on tärkeää huomioida kameramoduulin immuniteetti käyttöjännitteiden häiriöitä vastaan.

Automaattinen testi korvasi vanhan manuaalisesti tehtävän testin. Vanhan testin suurimpina ongelmina oli, että testi vei paljon aikaa, se ei ollut tarpeeksi toistettava ja se ei löytänyt kaikkia ongelmataajuuksia. Automaattinen testi poisti nämä ongelmat. Testitulokset kertovat millä taajuuksilla kamera häiriintyy ja paljonko näillä taajuuksilla esiintyy rivikohinaa. Tulokset antavat tietoa kameramoduulin immuniteetista ja antavat mahdollisuuden välttää näitä herkkiä taajuuksia, jos häiriösignaalin taajuuteen on mahdollista vaikuttaa. Automaattinen testi on jo otettu käyttöön sekä Nokialla että kamerantoimittajilla.

PREFACE

I would like to thank Pentti Väänänen who was my supervisor at Nokia and also Ossi Pirinen and Ville Sipinen who both helped me developing the automated conducted immunity test by doing programming needed for the test system.

I would also like to thank Professor Karri Palovuori who was the examiner of my thesis work.

Tampere 8.4.2014

Jussi Mikkonen

CONTENTS

SYMBOLS AND ABBREVIATIONS

ADC	Analog to Digital Converter
AF	Autofocus
EMC	Electromagnetic Compatibility
CFA	Color Filter Array
CI	Conducted Immunity
CSI-2	Camera Serial Interface
CMOS	Complementary Metal Oxide Semiconductor
FF	Fill Factor
FFT	Fast Fourier Transform
FPC	Flexible Printed Circuit
FPN	Fixed Pattern Noise
ILC	Inter Laboratory Comparison
MIPI	Mobile Industry Processor Interface
OIS	Optical Image Stabilizer
PWM	Pulse Width Modulation
SH	Sample and Hold circuit
STD	Standard Deviation
Vana	Analogue Voltage
Vbat	Battery Voltage
Vdig	Digital Voltage

1 INTRODUCTION

Cameras are nowadays an important part of mobile devices like smart phones, mobile phones and tablets. Nokia is concentrating on camera development, and good cameras are one way how Nokia is differentiating from its competitors.

During camera development there are many kinds of tests that need to be done to verify camera module performance. Testing can be time-consuming for Nokia and camera suppliers. Automated tests are a good way to reduce the time needed for tests and the workload of test operators. Automating usually also improves test repeatability, which makes it safer to count on camera suppliers' measurements. With repeatable test systems more testing can be moved to camera suppliers and hence problems are found in earlier phases of camera development. The purpose of this thesis was to develop the automated conducted immunity test for camera modules.

The conducted immunity test is a part of EMC tests, and it tests how well the camera module can tolerate fluctuations on power supply lines. Power supply fluctuations can cause row noise to the image, which lowers the image quality. Noise on power supply lines can come from inside or outside of the camera module. On the smart phone camera there are noise sources inside the small camera module like the autofocus (AF) and the optical image stabilizer (OIS). Therefore it is important to pay attention to camera module immunity to power supply fluctuations.

Nokia already have the conducted immunity test which is done manually. This thesis introduces improved automated conducted immunity test to replace the old manual test. Test results shows what are problem frequencies and how much the image has row noise at those frequencies. Developing the automated test required some programming, which was done in and outside Nokia, but not by undersigned. Programming for this test was needed on signal generator controlling, row noise calculating and test results reporting.

This thesis includes four main chapters in addition to introduction. Chapter 2 introduces the basic structure of a CMOS image sensor. Chapter also introduces row noise phenomena, which is caused by fluctuations on power supply voltages.

Chapter 3 shows measured noise on mobile phone camera power supply lines.

Chapter 4 introduces the new automated conducted immunity test and compares it to the old manual conducted immunity test.

Chapter 5 compares inter-laboratory comparison (ILC) test results measured by the old test and the new test. This comparison shows how the repeatability of the conducted immunity test is improved after the automated conducted immunity test is been taken to use.

2 BACKGROUND INFORMATION

2.1 Camera module on a mobile device

This chapter explains the basic structure of the digital camera module. Sensor structure and function is described more closely, because good knowledge of them is needed to understand why row noise appears due fluctuations of the power supply.

2.1.1 Imaging process

Figure 2-1 shows the simple structure of logical blocks of the digital camera. Lens purpose is to gather and focus incoming light to the image sensor. The camera module can have one or more lens elements. Usually lenses on mobile devices are made from plastic, but also glass is used.

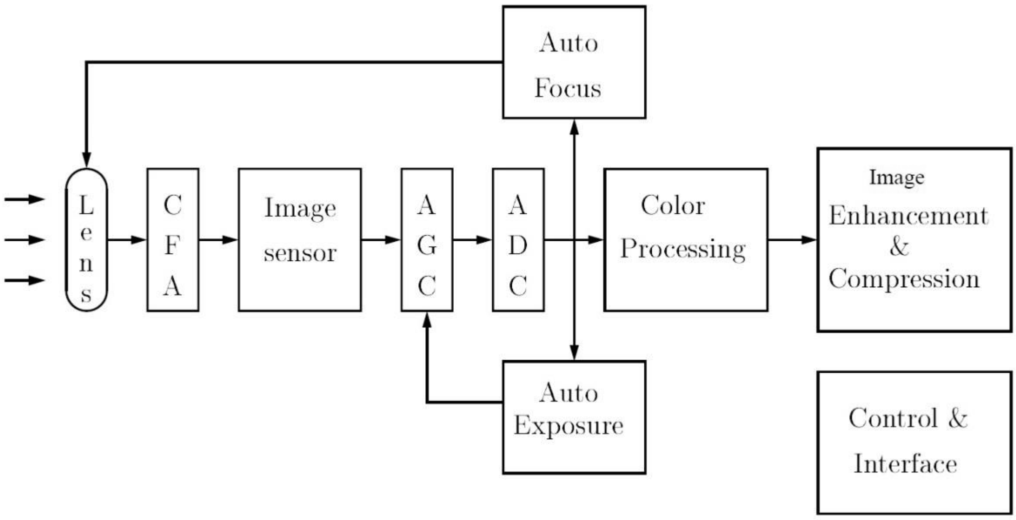


Figure 2-1: Image capturing process [1].

The image sensor converts light signal to electrical signal. Above the image sensor there is a color filter array (CFA) which filters light so that every pixel will be illuminated by light with only certain wavelengths.

Pixel values are gained in analog form and after that pixel values are converted to digital form. Analog amplifiers (AGC) and analog to digital converters (ADC) can be placed inside the CMOS image sensor.

Auto exposure controls exposure by changing an exposure time and an analog gain. Auto focus moves lenses so that the image appears sharp on the image sensor.

After analog to digital conversion the image is converted from RAW-format to some viewable format like a RGB-image. On this part color filter array interpolation needs to be done. Many enhancements are also done to the image, like white balance correction and shading correction.

2.1.2 Electrical interface

Usually the camera module needs three power supply voltages; analogue voltage (Vana), digital voltage (Vdig) and battery voltage (Vbat). Control and data interfaces between the camera module and the host system are standardized by Mobile Industry Processor Interface alliance (MIPI). A commonly used standard is the CSI-2 standard, which includes four data lanes for data transfer. In addition to data lanes the CSI-2 interface includes also clock signal for data transfer and the I2C-interface for controlling the camera. A CSI-2 interface is shown on figure 2-2. [2]

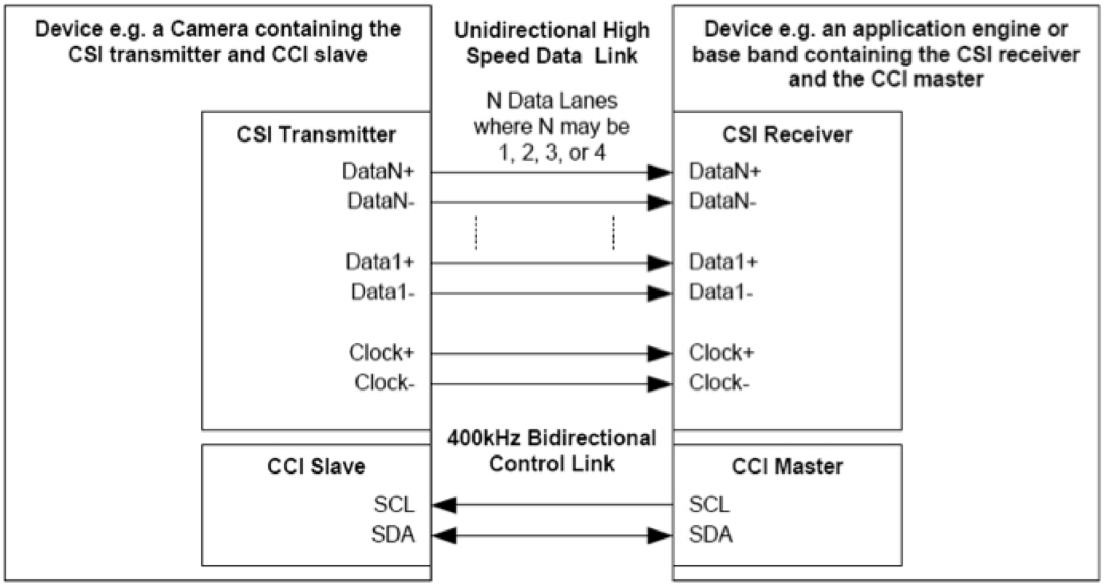


Figure 2-2: The CSI-2 interface. [2]

2.1.3 CMOS sensor

This chapter explains the structure of the CMOS sensor on a pixel level and on a sensor level. Three different types of pixel structures and three types of readout techniques are presented.

2.1.3.1 Sensing the light

The photosensitive component of the pixel is a photodiode. A connection of the photodiode is presented on figure 2-3. The p -region of the photodiode is grounded and the n -region is first connected to positive voltage during pixel reset. Therefore the photodiode is reverse biased and after unconnected from positive voltage the photodiode remains on reverse biased condition and becomes electrically floating. Incoming light excites electrons on a photodiode depletion region if the energy of a photon is larger than the band gap energy of semiconductor. The excitation of the electron produces a pair of mobile charge carries –electrons and holes. This process is called photogeneration. The energy of the photon is determined by its wavelength. Sufficient wavelength for exciting electrons can be calculated by equation 1.

$$E_{photon} = h \times f = \frac{h \times c}{\lambda} \geq E_g, \tag{1}$$

where E_{photon} is the energy of the photon, f is the frequency of light, h is Planck's constant, c is the speed of light, λ is the wavelength of light and E_g is the band gap energy of semiconductor.

The band cap energy of silicon is 1.1 eV, so light with wavelength shorter than 1100 nm can excite electrons. Consequently the image sensor cannot detect light with wavelength longer than 1100nm. Excited electrons accumulate at the positively charged n –region and holes at the negatively charged p –region. This causes current called a photocurrent. The photocurrent reduces the potential of the n -region and so incoming light signal has changed to electrical signal. Figure 2-4 shows how the integration affects to the voltage of the photodiode. Vbias on figure means pixel voltage after reset. T_0 is time when the integration starts and t_{int} is time when the integration ends. Plots show the difference on pixel voltage on low light and high light. [3, 4, 5]

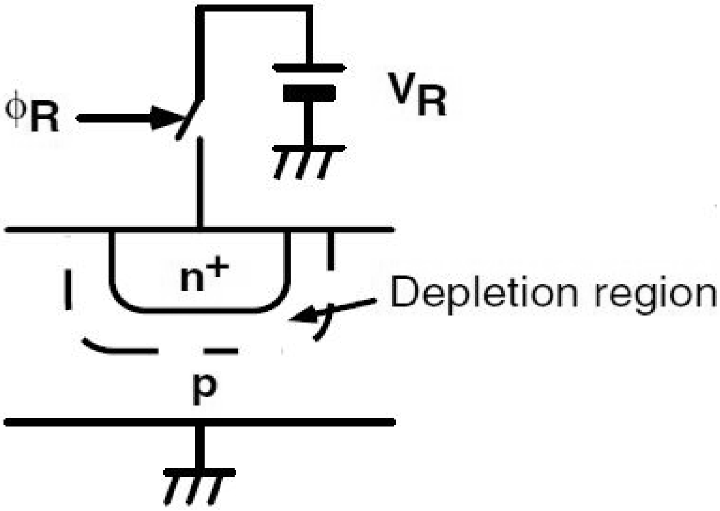


Figure 2-3: The connection of the photodiode. [5]

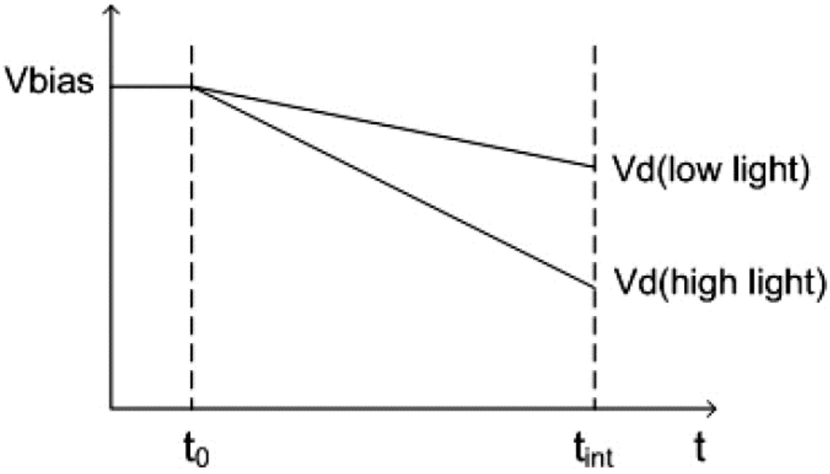


Figure 2-4: Changes on pixel voltage during the integration on low light and high light. [4]

2.1.3.2 Passive pixel

Figure 2-5 shows the structure of a passive pixel. The passive pixel includes only the photodiode and one transistor. The transistor is used to transfer a pixel value from the photodiode to a column line. The passive pixel has the high fill factor (FF) as it has only few components inside the pixel. The fill factor is the ratio of the pixel photosensitive area to the total pixel area and can be calculated by equation 2. Higher fill factor means higher sensitivity to light.

$$FF = \frac{A_{ps}}{A_{pix}} \times 100\%, \tag{2}$$

where FF is the fill factor, A_{ps} is the photosensitive area of the pixel and A_{pix} is the total pixel area.

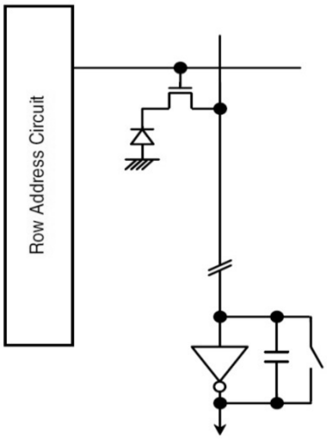


Figure 2-5: The structure of the passive pixel. [5]

As a drawback on the passive pixel signal is more sensitive to noise between the pixel and an amplifier as the pixel value is not amplified inside the pixel. Noise problem gets worse as the pixel array goes bigger, so the passive pixel is not preferred to use with large sensors. [5]

2.1.3.3 Three transistor active pixel

Figure 2.6 shows the basic structure of a three transistor active pixel. There are the photodiode (PD), a reset transistor (Mrs), a select transistor (Msel) and a source follower transistor (Mrd) inside the active pixel. Cpix is a capacitance of a storage node inside the pixel. The reset transistor is used to connect the photodiode to the power supply as reverse biased before the integration time. The source follower transistor buffers the pixel voltage and select transistor transfers the pixel voltage to the column line. [5]

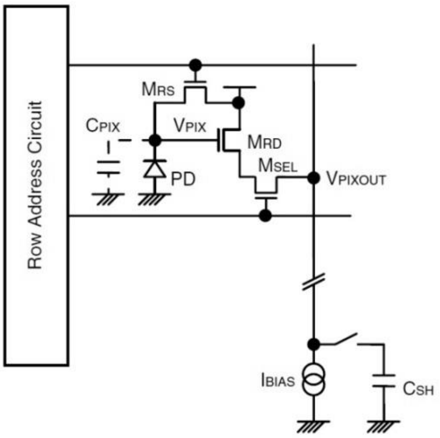


Figure 2-6: The structure of the 3 transistor active pixel. [5]

2.1.3.4 Four transistor active pixel (Pinned photodiode)

Mostly used pixel structure nowadays is a four transistor active pixel which uses a pinned photodiode. In addition to the structure of the three transistor active pixel there are a transfer gate (TX) and a floating diffusion node (FD). The structure of the four transistor active pixel is shown on figure 2-7. Before the integration period the floating diffusion node is reseted to the power supply voltage and right after that voltage on the floating diffusion node is read. This way an offset voltage and reset noise can be read and those unwanted signals can be reduced from the pixel value. An actual pixel value can be read when the transfer gate is activated. [4, 5]

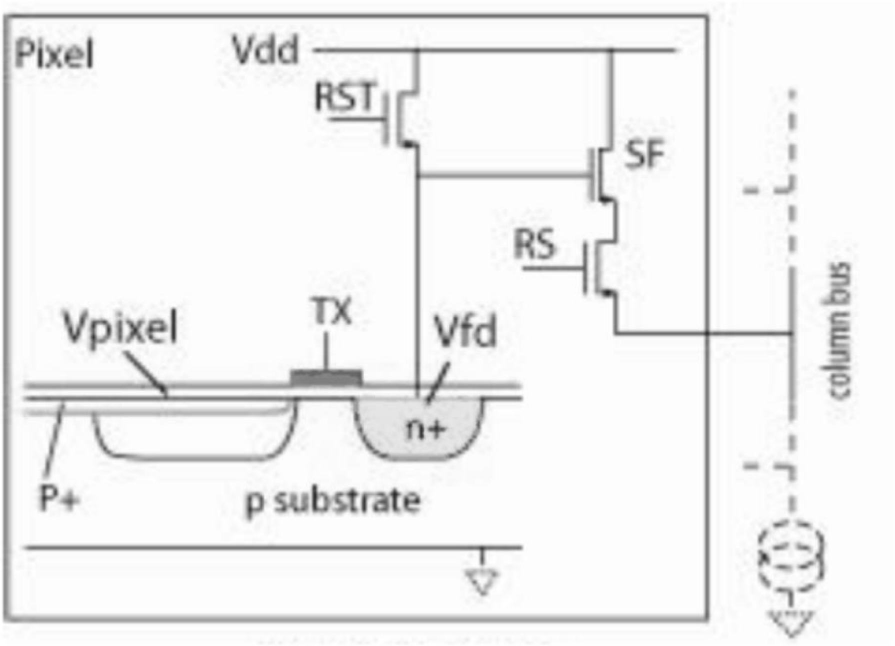


Figure 2-7: The structure of the 4 transistor active pixel. [4]

2.1.3.5 Pixel readout

There are three different pixel readout architectures. Architectures differ from others by the way how analog processing is done. Exposure is done similar on all architectures. First pixels are reseted before the integration period. This is done by applying a reset pulse to pixels usually one row at a time. Applying the reset pulse to a reset transistor gate the photodiode comes reverse biased and its junction capacitance is loaded to the supply voltage. The exposure period starts after the reset pulse and the photodiode starts to collect charge as explained on chapter 2.1.3.1. The exposure period ends when the select pulse is applied to the select transistor gate. The pixel voltage is buffered by the source follower and the voltage is transferred to the column signal line. Analog processing can be implemented before or after transferring signal to the column signal line. [5]

Analog processing of the image can be implemented either on a chip level, a column level or a pixel level. Analog processing includes the programmable gain amplifier (PGA) and the analog to digital converter (ADC). Camera ISO speed is controlled by the programmable gain amplifier. On chip level processing every pixel value of one row is first moved to a sample and hold circuit (SH). Then pixel values are one by one amplified with the programmable gain amplifier and then converted to digital form. After that, next row is read for processing. This processing technology is simple and offers good uniformity to the image as all pixel values are processed with same amplifiers and analog to digital converters. Low speed is a drawback of this technology as there is no parallel amplifying or analog to digital converting for pixels.

Therefore this is not very suitable processing technique on high megapixel image sensors if decent framerate is needed. Also noise can be a problem as analog signals have to be transferred at longer distances than on column level or pixel level processing. Structures of chip level and column level analog processing is shown on figure 2-8. [4, 5]

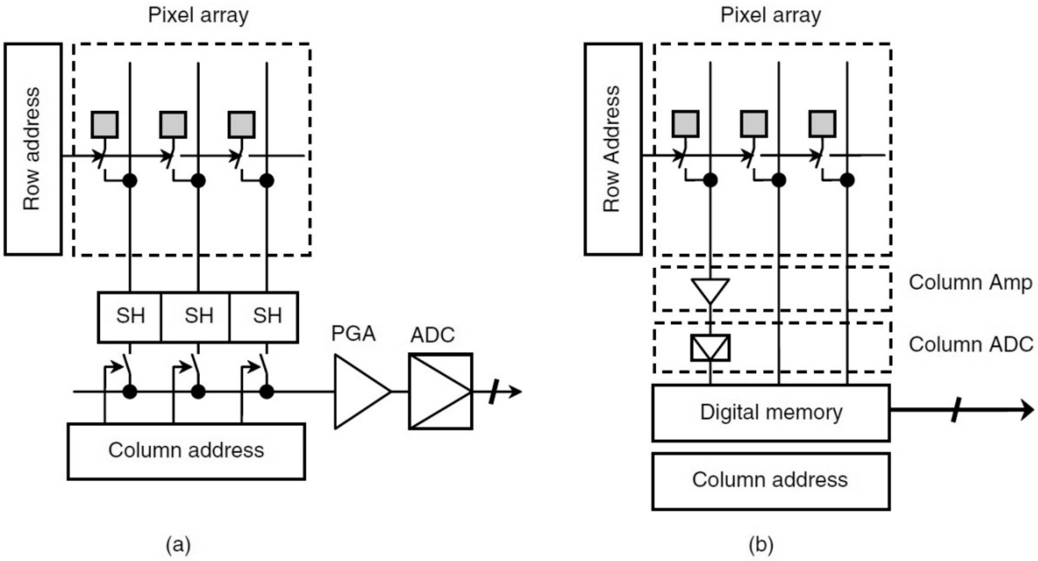


Figure 2-8: a) Chip level and b) Column level analog processing. [5]

Column level processing uses separate amplifier and analog to digital converter for each column. Processing for each pixel on the same row is made parallel and after that pixel values are moved to a digital memory. Column level processing can operate on higher speed compared to chip level processing. Although an offset and a gain mismatch on analog to digital converters and amplifiers can cause column fixed pattern noise (FPN) because every column has the separate amplifier and the analog to digital converter. Also the area of the sensor needs to be increased as more amplifiers and analog to digital converters are needed. [4, 5]

On pixel level processing analog amplifiers and analog to digital converters are located inside pixels. This allows very high speed processing as every pixel can be processed parallel but as a drawback pixel size have to be very big or else the fill factor of the pixel becomes low because the amplifier and the analog to digital converter are located inside the pixel. Figure 2-9 shows the structure of pixel level analog processing. [4, 5]

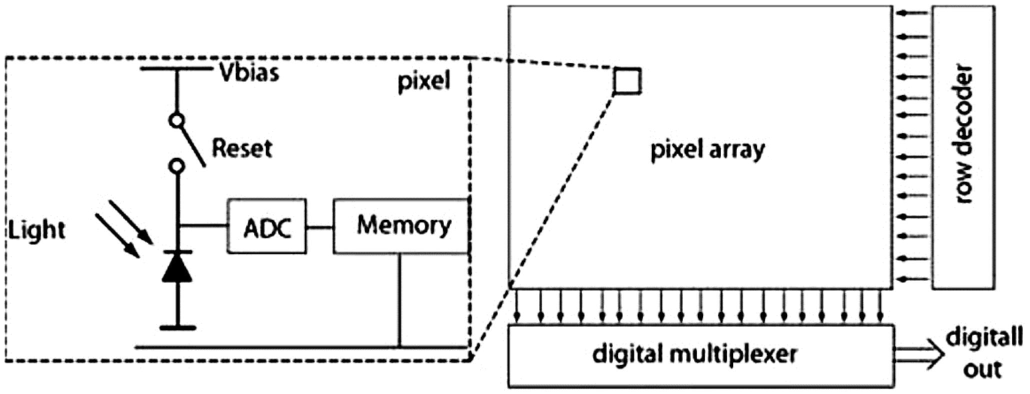


Figure 2-9: The structure of pixel level analog processing. [4]

2.1.3.6 Bayern filter

Every pixel on the image sensor has same electrical structure and the pixel itself cannot electrically separate different colors. Color separating is done by adding the color filter array over the image sensor. The color filter array include different color filters that each passes through only one color so every pixel receive only certain wavelengths of light. Afterwards some algorithm is used to create a full color image from these different color pixels. [6]

The most commonly used color filter array is a Bayern filter. The Bayern filter includes red, green and blue filters and those are arranged as an array shown on figure 2-10. The Bayern filter includes twice as many green pixels as red or blue pixels. The Bayern filter has more green pixels because human eye is more sensitive to green light than red or blue light. [6]

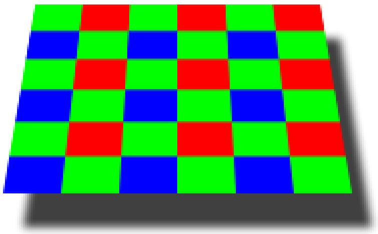


Figure 2-10: The Bayern filter [8].

The final full color image is created from the raw image using a demosaicing algorithm. The demosaicing algorithm calculates value for red, green and blue component for every pixel. The simplest way to create a RGB pixel is to take each color value from nearest pixel with same color. This algorithm is called nearest neighbor interpolation. Other simple technique is bilinear interpolation which calculates mean value of two or four nearest pixel with same color. [6]

2.1.4 Row noise

As column parallel readout architecture is usually used on the CMOS image sensors it allows row noise to be formed into the image. Fluctuations on power supply lines can cause row noise to the image for example during pixel reset, amplification and analog to digital conversion. Because every pixel in one row is reset and read at the same time, fluctuations on power supplies affect same way for every pixel in the same row. In addition different rows are reset and read sequentially so fluctuation on power supplies are resulting as row noise on the image. An example image where row noise is visible is seen on figure 2-11.

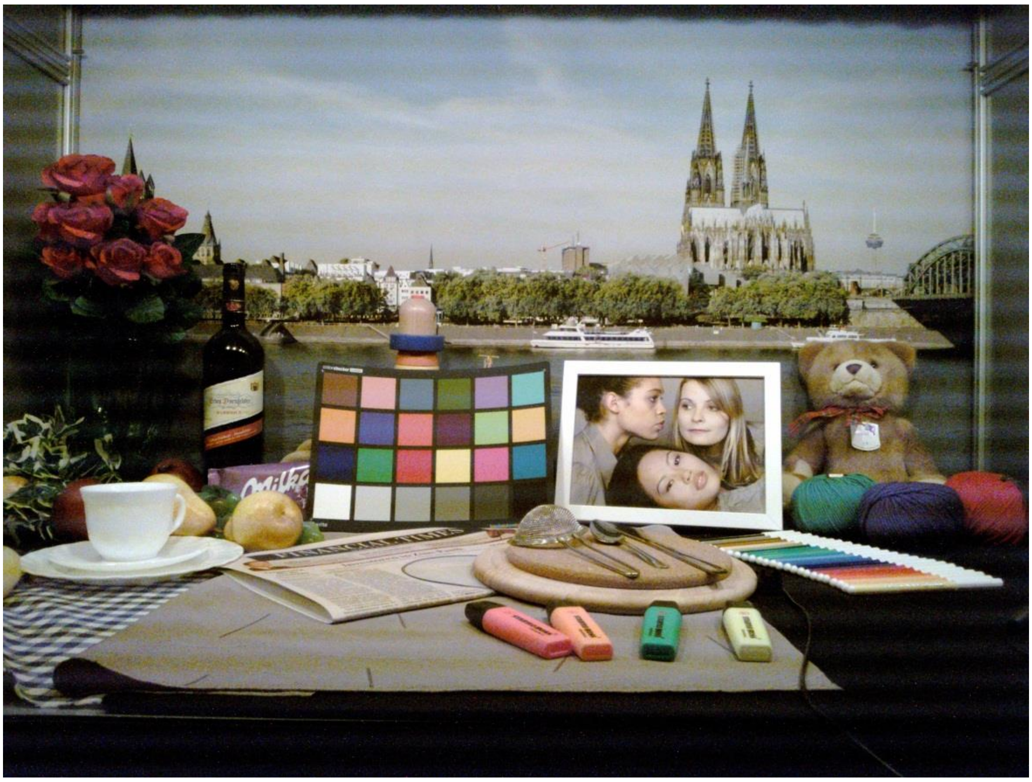


Figure 2-11: The image with row noise.

Row noise form is dependent on noise signal frequency and image line frequency. Line frequency means how many lines are read per second. Line frequency can be calculated by equation 3.

$$Line\ frequency = fps \times frame\ length, \tag{3}$$

where fps is frames per second.

If noise signal frequency is exactly the same as line frequency or line frequency harmonics there is no row noise on the image, but noise still affects the overall brightness of the image. On that case the image does not include row noise because the noise signal is on same phase on every row. For example if the noise signal is at maximum during first row pixel reset, it is also maximum during every row pixel reset. Figure 2-12 demonstrates a situation where the frequency of the noise signal is equal to line frequency harmonics. The situation is simplified so that noise is critical only on one exact moment during line reading. Figure includes the noise signal, which has twice as high frequency as line frequency and vertical lines represents critical moment of currently read row. Figure shows that the noise signal is at the same level during each row critical moment.

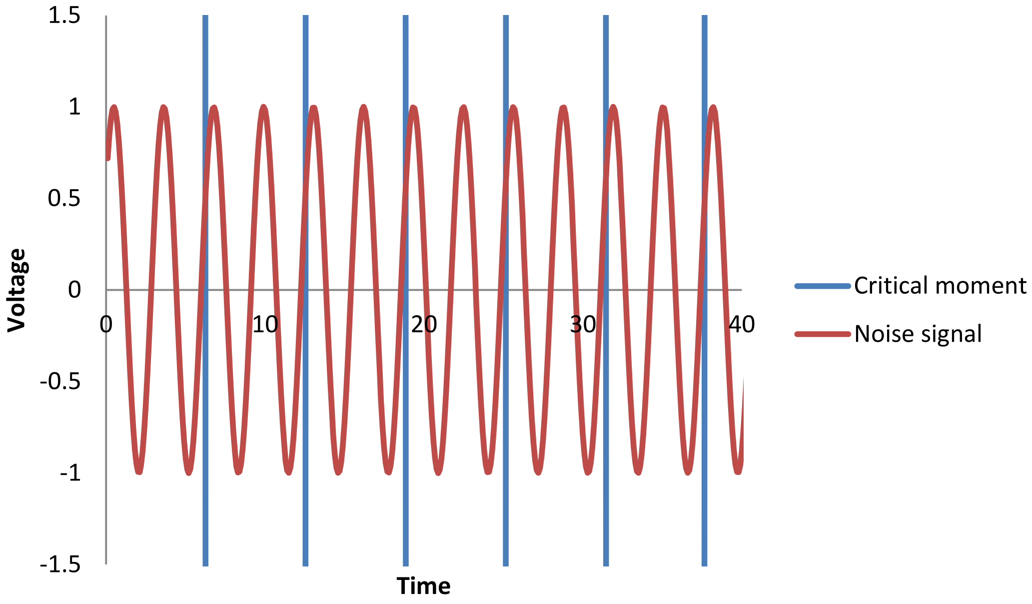


Figure 2-12: Situation where noise signal frequency is equal to line frequency harmonics.

If the frequency of the noise signal is a little different than line frequency harmonic, row noise appears as wide bands on the image. The more noise signal frequency differs from line frequency harmonics, the narrower bands row noise has. If noise signal frequency is in the middle of two line frequency harmonics, row noise appear as a one pixel high lines because then on every two rows noise signal is on same phase. Figure 2-13 demonstrates a situation where noise signal frequency is in the middle of two line frequency harmonics. Figure shows that the noise signal alternates between two different levels on sequential rows.

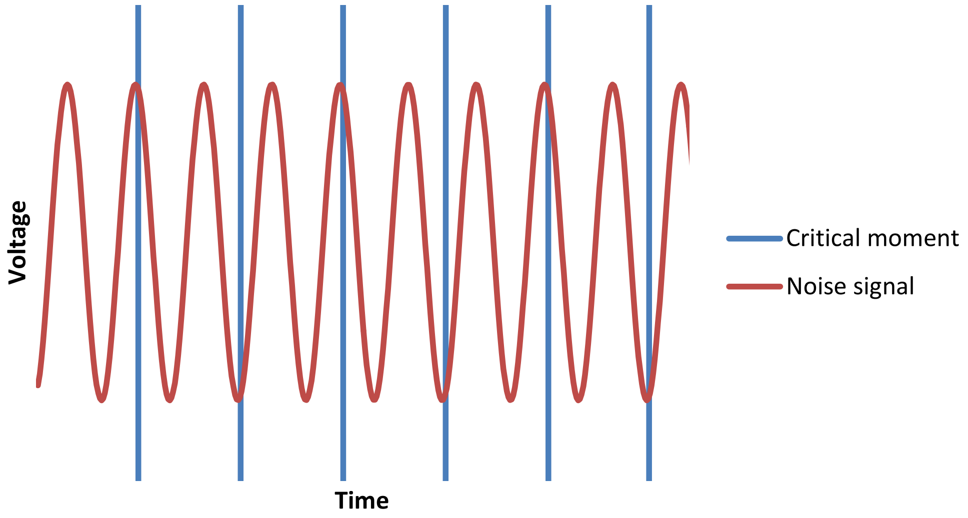


Figure 2-13: Situation where noise signal frequency is in the middle of two line frequency harmonics.

With red and blue pixels situation is different because Bayern filter include red and blue pixels only on each two rows. So line frequency for red and blue pixels is half of the actual line frequency. So when considering about red and blue content, line frequency has to be halved when trying to simulate row noise visualization.

Row noise seems to be strongest when the noise signal is near one of the line frequency harmonics. Figure 2-14 shows measured row noise and vertical lines show line frequency harmonics. Row noise is calculated with an algorithm introduced on chapter 4.2.5.

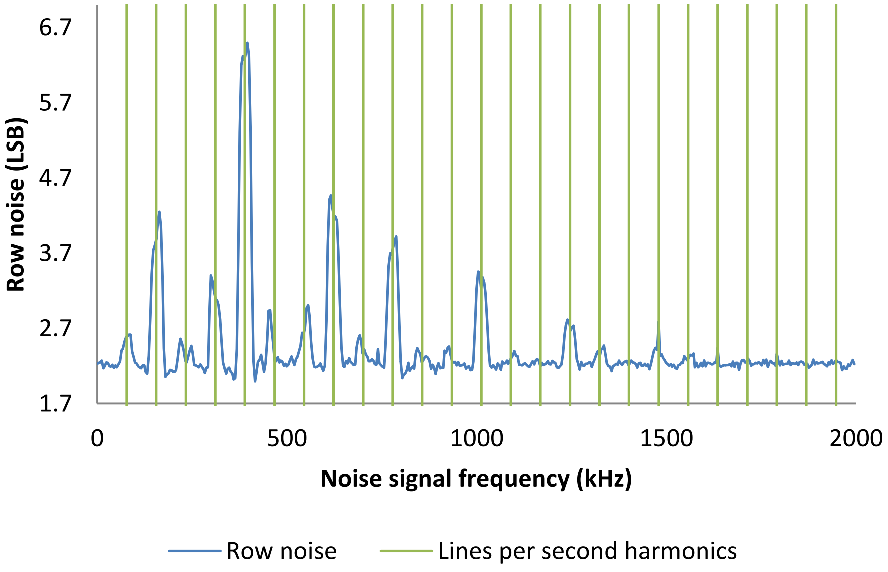


Figure 2-14: Row noise and line frequency harmonics.

2.1.5 Reducing row noise

Different kind of approaches can be used to reduce row noise. Different approaches are removing the noise signal, matching frequencies so that the noise signal does not affect to the image and removing row noise from the image afterwards.

The noise signal can be decreased by using filtering capacitors. Capacitors should be attached to power supply lines so that sensor power supply voltages will be more stable. Capacitors decrease the noise signal well on high frequencies but good performance on low frequencies would require physically big capacitors, which are not really suitable for mobile devices. Figure 2-15 demonstrate how the amount of row noise decreases when 100 nF, 1 µF and 27 pF capacitors are attached to power supply lines on a camera carrier board. Row noise is calculated with the algorithm introduced on chapter 4.2.5. According to this test the impact of capacitors becomes visible with higher than 750 kHz noise signal.

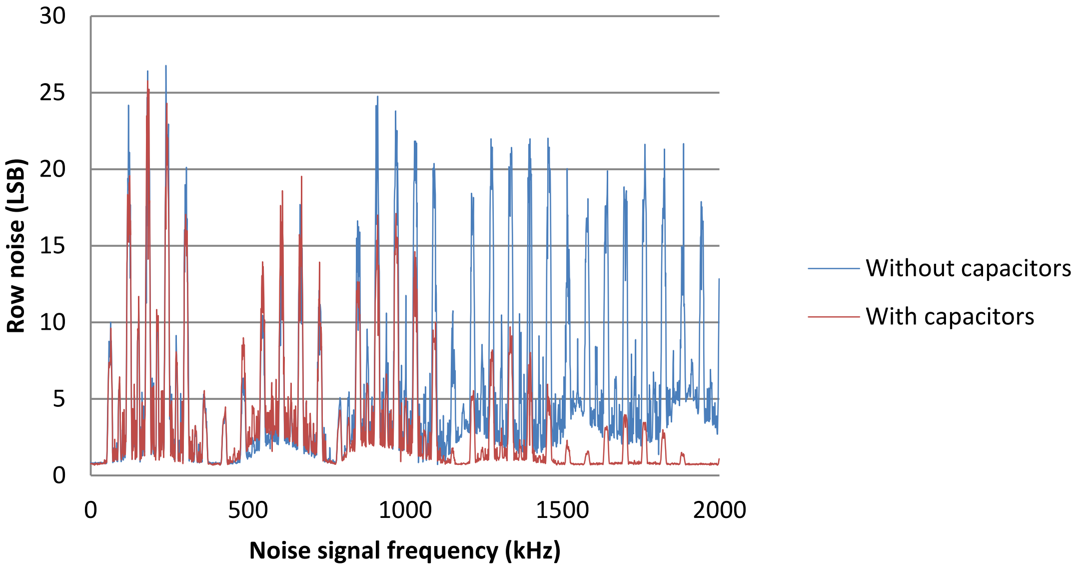


Figure 2-15: The impact of capacitors on power supply lines.

Frequency matching can be used if the power supply has noise on some known frequencies. If some of these noise frequencies are close to harmonics of line frequency, camera settings can be changed so that line frequency harmonics will not match anymore with noise frequencies. On some cases noise frequency can also be shifted. For example if actuator driver pulse width modulation (PWM) frequency is close to harmonics of line frequency, it can cause row noise. On that case it could be easier to change actuator PWM frequency than sensor line frequency.

Several methods are invented to reduce row noise after the exposure. One technique uses dark reference pixels to estimate the amount of row noise. Every row has dark reference pixels which structures are same as other pixels but they are not sensitive to light. This can be obtained by covering pixels with non-transparent material or attaching the photodiode to the power supply. These dark pixels are affected by supply voltage changes the same way as other pixels on the same row. Estimated row noise can be calculated from these reference pixels by averaging their value. This estimated row noise can then be subtracted from other pixels on the same row. Subtracting is done in digital form after analog to digital conversion. A problem with this technique is that random noise on dark reference pixels appears as row noise on the corresponding row after correction. The effect of random noise can be reduced by increasing the number of dark reference pixels. Increasing dark reference pixels means that the speed of amplifying and analog to digital conversion needs to be increased in order to keep frame rate the same. Also warm and hot reference pixels increase error on calculating row noise. Warm pixel refers to the pixel which appears a little brighter and hot pixel to the pixel which appears bright when they are supposed to be completely dark. There is also a possibility that light can get under the non-transparent cover and in that way illuminate dark reference pixels. [7, 8]

Other way to reduce row noise is to examine several rows above and below the current row. The offset of the row is determined by collecting statistic of surrounding rows and this offset is then subtracted of every pixel on the current row. Also on this technique errors on estimating row noise will add row noise to the image. [9]

3 NOISE ON MOBILE PHONE POWER SUPPLY LINE

Noise measurement on the mobile phone power supply line is presented on this chapter. The idea was to see what frequencies could be seen on power supply noise.

3.1 Measurement setup

Measurement was done with Nokia Lumia smartphone. Power supply noise was measured on Vana-line close to a camera flexible printed circuit (FPC) connector. Noise was measured on frequency domain with a spectrum analyzer. Measured bandwidth was the same which is specified on Camera module EMC tests specification 5.0 with a conducted emissions test [10.] Measurements were done when the camera was turned on and off.

3.2 Results

Figure 3-1 shows measured power supply noise on bandwidth from 0 Hz to 2.8 MHz. A blue curve is measured noise when the camera is powered on and a red curve is noise when the camera is not powered on. Results show that there are no high noise peaks after 1.5 MHz.

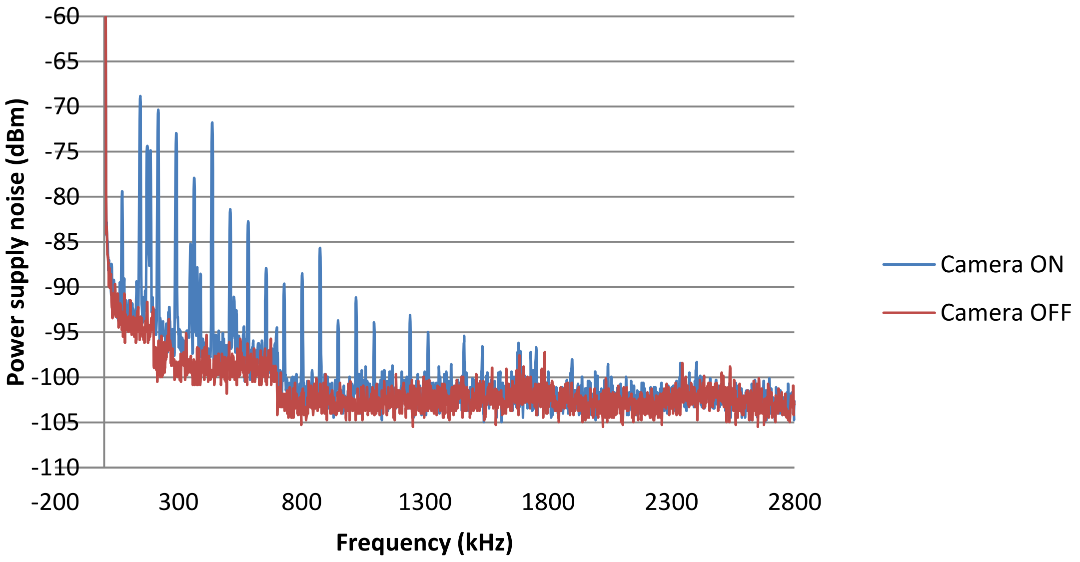


Figure 3-1: Measured power supply line spectrum with bandwidth 0-2.8 MHz.

Figure 3-2 shows measured power supply noise on bandwidth from 0 Hz to 1 MHz. A blue curve is measured noise when the camera is powered on and a red curve is noise when camera is not powered on. Camera line frequency and its harmonics can be seen on noise measurements, and the most of noise peaks can be explained by that. Line frequency is about 72 kHz. There are also some other noise peaks for example near 172 kHz and 350 kHz frequencies.

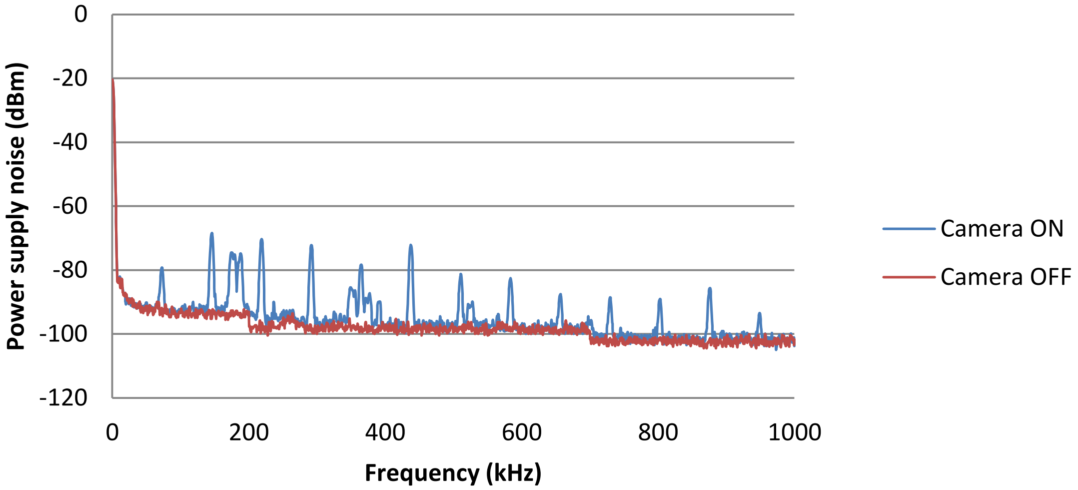


Figure 3-2: Measured power supply line spectrum with bandwidth 0-1 MHz.

4 CONDUCTED IMMUNITY TEST

On this chapter the old manual and the new automated conducted immunity tests are introduced. The idea of the conducted immunity test is that the noise signal is added to power supply lines and then it is monitored how immune the camera is for these power supply fluctuations. On the old manual test immunity is examined by testing how small noise signal amplitude causes visible row noise to the image. On the new automated test immunity is examined by testing how much row noise 200mV$_{p-p}$ noise signal causes to the image. Chapter 4.1 shows the old conducted immunity test specification and considers what problems there are on the old test. The new automated conducted immunity test is introduced on chapter 4.2.

4.1 Manual test

4.1.1 Test setup

On the conducted immunity test Scooby2 is a device which is used to control the camera and export the image from the camera to a computer. Scooby2 is a test platform for MIPI and SMIA compliant image sensors. Scooby2 features include for example MIPI and SMIA receivers (Virtex 5 FPGA core), possibility to use external or programmable internal power sources and 2GB DDR image buffer. [11]

EBox is a device which is used on camera EMC tests. On the conducted immunity test ebox is used to add the noise signal from a signal generator to power supply lines. [12]

A light source is needed to illuminate the camera. Light level is low and light should be diffused. [12]

A DC power supply powers the camera and the eBox.

Software which is used to control the camera is called Mobile Imaging Playground (MIP). It is developed by Nokia and it can be used for example to control cameras, process images and control other test devices like signal generators.

4.1.2 Test procedure

Instructions below are copied from the old Camera module EMC tests specification [12.]

H.F. Conducted Immunity measurement method. (50Hz to 30 MHz)

- In the frequency range specified above Conducted Immunity will be restricted to noise injected on the Vana and Vdig supply rails and any other supply rails for Non-SMIA modules.
- As previously, the camera module shall be initially set up in a low ambient light level from a diffuse source. For SMIA modules the analogue_gain_code_global (registers 0x0204 and 0x0205) shall be set to the maximum allowed by analogue_gain_code_max (0x0086 and 0x0087).
- The coarse_integration_time (0x0202 and 0x0203) may then be varied between the limits defined by coarse_integration_time_min (0x1004 and 0x1005) and coarse_integration time max_margin (0x1006 and 0x1007) to give approximately 50% FSD codes average on an output image.
- The CCI lines shall be set up so that the 8 specified CCI registers are continuously being read by the test hardware at the highest rate commensurate with the system clock speed.
- Note that the CCI registers must not be rewritten during testing. They may only be read by the software.
- The d.c. supplies will be set to the nominal operating values, and the interfering signal amplitude will be set to 100mV peak to peak at the lowest frequency specified and the frequency will be stepped in 1/12 octave increments and an assessment made of the S+N / N ratio degradation at each frequency. The amplitude of the interfering signal shall be 3dB down at 1.0MHz from it's low frequency value, and thereafter the applied amplitude will fall at 6dB / octave to the highest specified frequency. The interfering signal amplitude can be monitored with a high frequency probe. The amplitude of the interfering signal must be rolled off above 1.0MHz due to possible thermal effects on any internal decoupling components in the module.
- The standard sensor decoupling will be used.
- Requirement : For SMIA modules there shall be no interference patterns on the reconstructed image when visually assessed in Low-light as above. An alternative method of measuring the Signal to noise ratio may be used if preferred. In this case the numerical limit must be shown to meet the empirical criteria above

Non-SMIA A/F & zoom modules,

- The module should be focused on an image and this image should be checked for lack of focus during testing to check there is no interference with the motor operation. For these modules the motor supply rail should be checked as well in the same way.
- Requirement : Any interference with the normal focusing ability of the camera will be regarded as a failure.

4.1.3 Problems

The old test has many problems and biggest problems are that it is so laborious and because of increasing frequency step it does not find nearly any of problem frequencies when frequency is high enough.

On the old test you have to measure 254 different frequencies. Every time when changing frequency, you also have to adjust the noise signal so that the measured noise signal on an oscilloscope shows 100mV$_{p\text{-}p}$. On every frequency operator must inspect a computer monitor to check if there is any interference pattern on the image. Looking the bright image could be very tiring and uncomfortable for eyes as one test case takes several hours.

The specification says that the frequency range is from 50 Hz to 30 MHz. A frequency step is 1/12 octave. A problem here is that even on relatively low frequencies steps increases so much that you find problem frequencies only if you are lucky and problem frequencies just happens to occur on measurement points. Figure 4.1 demonstrates this problem. A blue curve is measurement results with the automated test and vertical red lines shows where test points are according to the old test specification. On this example, almost every problem frequencies are between measurement points so they would not be seen on the old manual test. A frequency band on figure 4.1 is from 0 Hz to 2 MHz, which is the frequency band on the automated test. As the frequency band on the manual test is from 50 Hz to 30 MHz, steps will get even bigger than figure 4-1 shows.

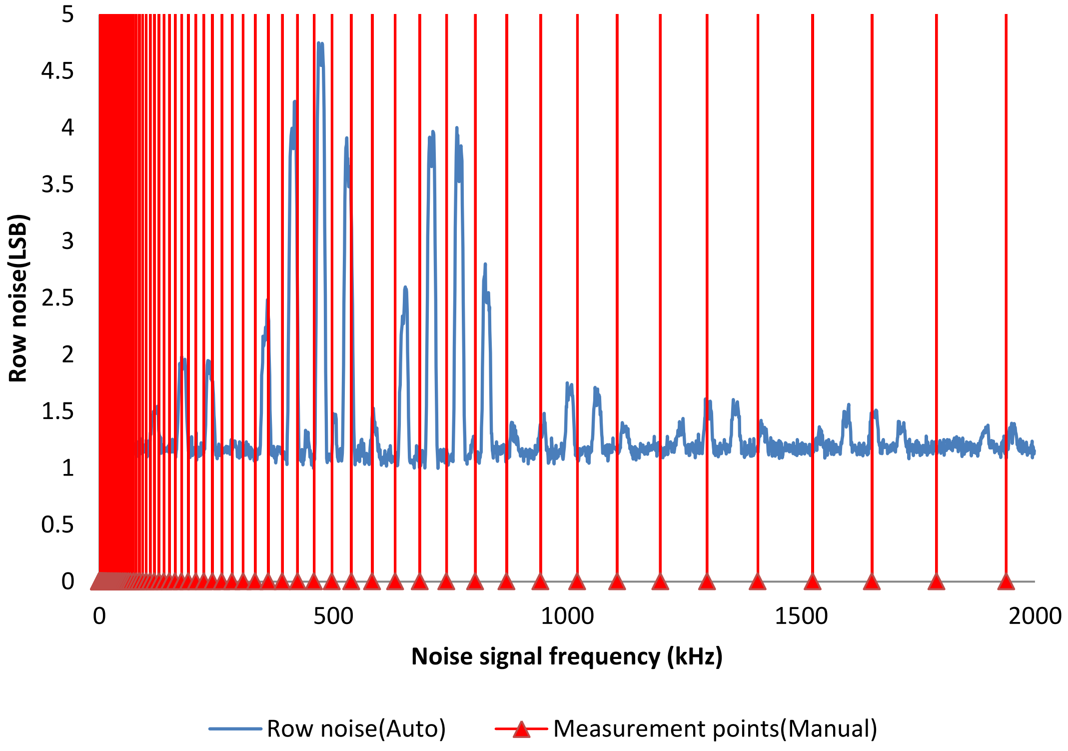


Figure 4-1: Demonstration of problem with manual test frequency steps.

Partly because the manual test takes so much time there is only one case of setting to be measured. Although it would good to do measurements with different settings changing for example external clock frequency or image data format.

Results are also pretty subjective, because judging is made based on human's visual aids. Different persons have different opinions when there is visible row noise on the image and it is also dependent on for example what display is used to watch images.

About illumination the specification says only that low ambient light level from a diffuse source is used. This is a pretty loose definition, which is not good because illumination has an effect on how visible row noise is.

As we see there are many reasons why the old test has no good repeatability. Results vary between different test persons and even between same person's different measurements. Inadequate repeatability of the test means that it is risky to rely only on camera suppliers' measurements. That increases workload because all important tests need to be done also by Nokia.

4.2 Automated test

4.2.1 Test setup

Equipment for the new test are same as on the old test but the new test requires that the signal generator can be controlled via computer and the needed frequency range is only from 50 Hz to 2 MHz. The light source is also not needed on the automated test. Figure 4-2 shows a test setup for the automated conducted immunity test.

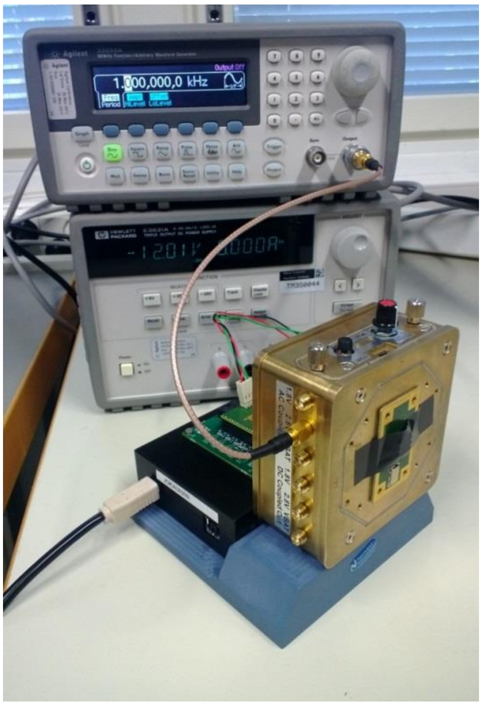


Figure 4-2: Conducted immunity test setup.

4.2.2 MIP playground

Figure 4-3 shows a MIP playground which is used to measure conducted immunity. There are two loop structures on the playground. Smaller, right-hand loop is used first to set the camera to stream with right settings. It is good to check on this loop that the camera is streaming proper images before starting the test.

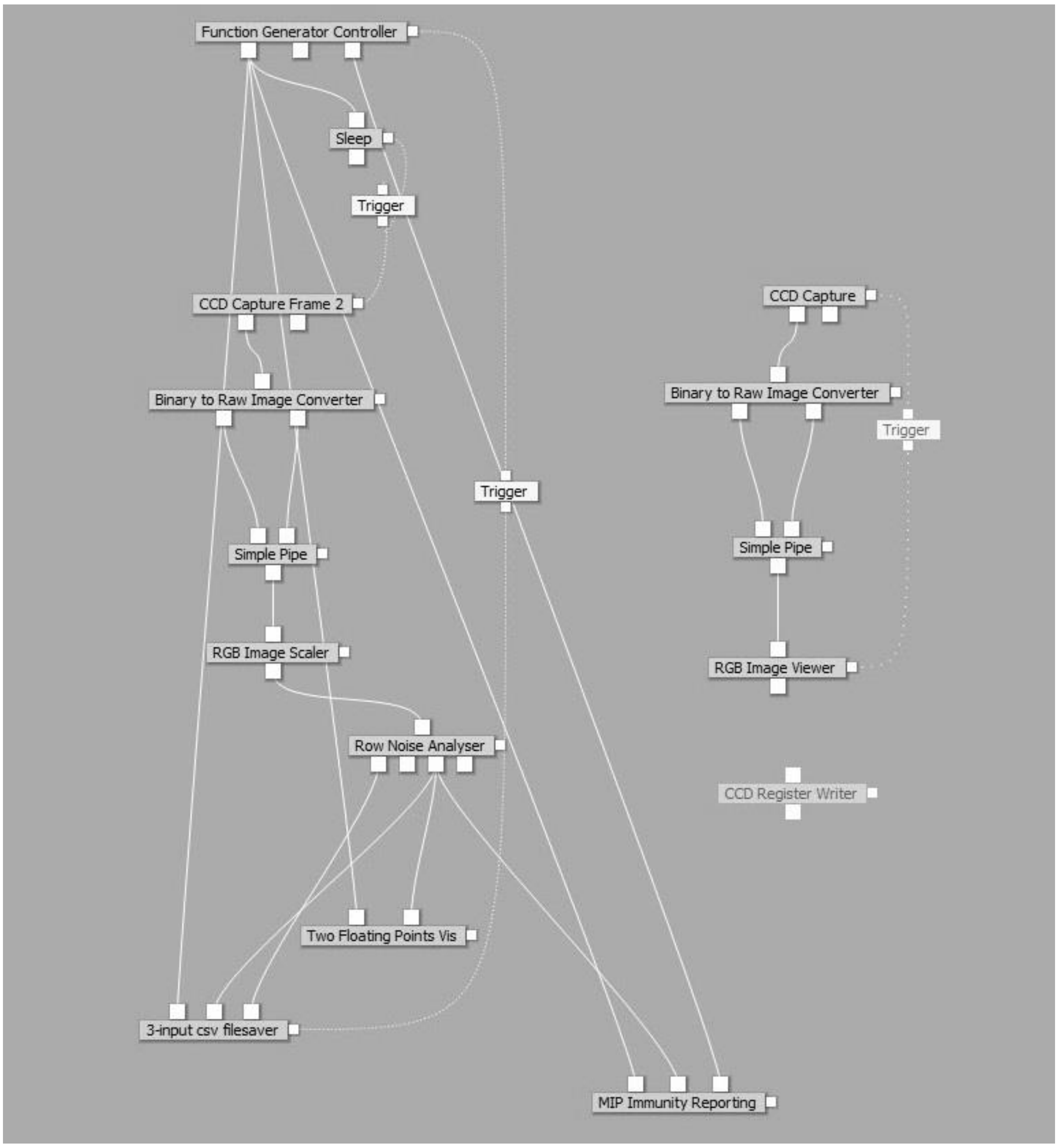
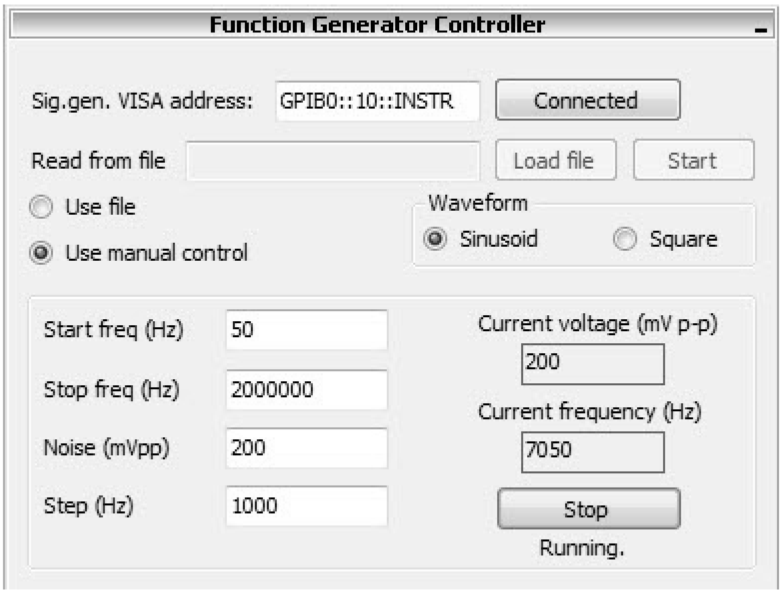


Figure 4-3: Conducted immunity test playground on MIP.

Function Generator Controller –plugin controls the function generator and outputs current frequency. On every loop, plugin changes frequency by one frequency step. Function Generator Controller can be initialized manually or by a file. User interface of Function Generator Controller –plugin is shown on figure 4-4. Sweep parameters can be determined manually on Function Generator Controller-plugin or they can be read from the control file. With manual control sweep is defined by start frequency, stop frequency, noise signal amplitude, sweep step size and noise signal waveform. If file control is used, different amplitude can be used on different frequency steps. This is useful feature if an user wants take a circuit frequency response into account.



Sig.gen. VISA address: GPIB0::10::INSTR
Read from file
○ Use file
● Use manual control
Waveform
● Sinusoid
○ Square
Start freq (Hz) 50
Stop freq (Hz) 2000000
Noise (mVpp) 200
Step (Hz) 1000
Current voltage (mV p-p) 200
Current frequency (Hz) 7050
Running.

Figure 4-4: Function Generator Controller -plugin user interface.

CCD Capture Frame takes a current frame from the camera and passes it forward to be analyzed. Binary to Raw Converter passes the raw image to Simple Pipe, which process the image and converts it to the RGB image.

RGB Image Scaler scales the image size down. Image scaling is used to reduce random noise so row noise comes more dominant. This makes row noise calculation easier and phenomenon comes clearer. Figure 4-5 demonstrates the impact of image scaling to results. Scaling also reduces the impact of very narrow lines on the image. Very narrow lines are not so disturbing as wider bands, so it is good that wider bands have become more clearly shown on results. Figure 4-6 compares results with and without image scaler to manual measurements, which bases on human visual aid. From this figure it is easy to see how much the scaler improves test result correlation to human visual opinion.

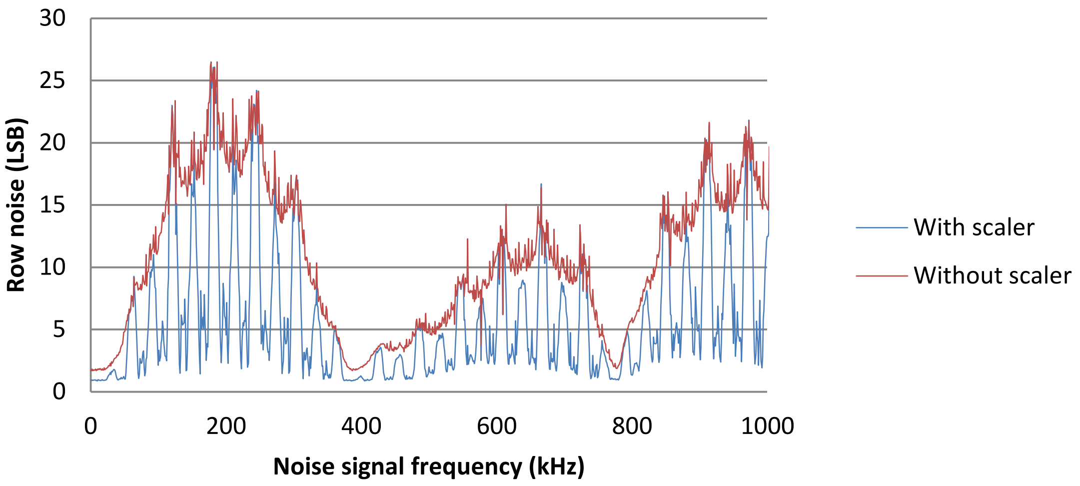


Figure 4-5: The impact of the scaler.

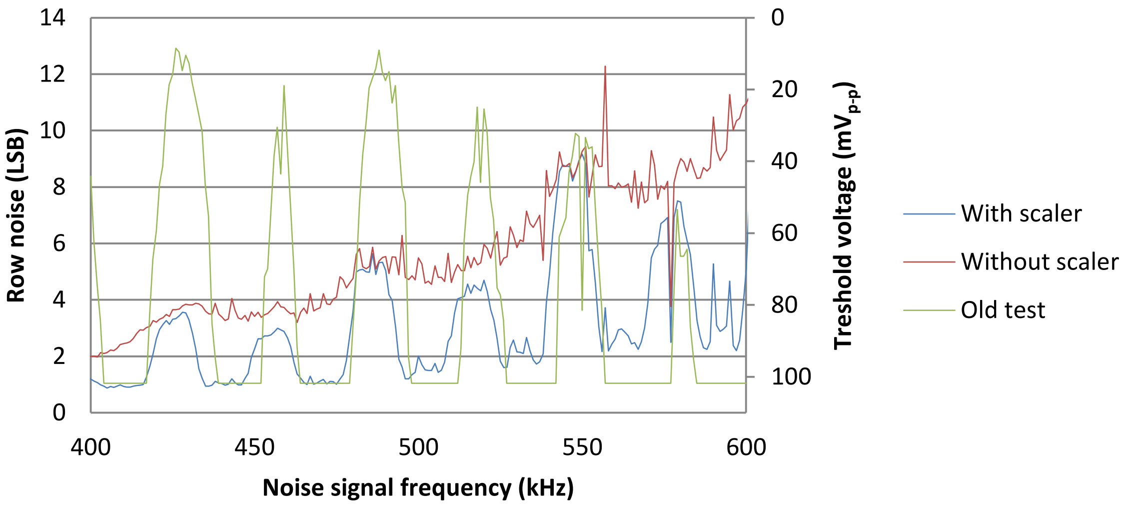


Figure 4-6: Comparison of the old test and the new test with and without the scaler.

Row Noise Analyzer calculates row noise from the RGB image and outputs row noise value and row noise frequency. Row noise calculation method is explained on chapter 4.2.5.

Two Floating Point Vis shows a plot of row noise against noise signal frequency. The user can use this plugin to monitor row noise during the test but precise analysis cannot be done from this plot, as precise frequencies cannot be read from it.

3-input csv filesaver -plugin stores all measurement data to a csv –file which can be determined by the user. MIP Immunity reporting-plugin creates a pdf –document which includes test information and row noise –figures for every power supply –ports. Usually this pdf –report is enough, but sometimes it is needed to look results more closely and see exact frequencies and on those cases the csv –file is useful. The test is done with small frequency –steps, so very precise plots with smaller frequency range can be drawn from the csv –file.

4.2.3 Settings

Table 4-1 shows camera settings which are used on the conducted immunity test.

Table 4-1: Camera settings for the conducted immunity test. [10]

Exposure time	100 us, or shortest possible.
Illumination level	0 lux. Cover the camera with non-transparent optical material.
Analog gain	Max to be used
Digital gain	1x.
Ext Clk (MHz)	9.6, 13.0 and 19.2
Data format	Raw10 and Raw8Dpcm
Resolution	Maximum used.
Interface speed (CCP2 CSI2)	Maximum used.
Configuration->Camera config	Use DCC-file provided by Nokia.
AF/OIS	Turn off if possible.

Exposure time is very short because then there are as little as possible noises caused by other sources than power supply fluctuation. Longer exposure time causes more random noise to the image so row noise, which is caused by power supply fluctuation, becomes less visible.

Illumination is 0 lux so that row noise is better seen and especially calculated because the image is more uniform than what it is when the image is illuminated with the light source. This also makes test repeatability better because there are no differences on light sources. Figures 4-7 and 4-8 show the difference between illuminated and dark images.

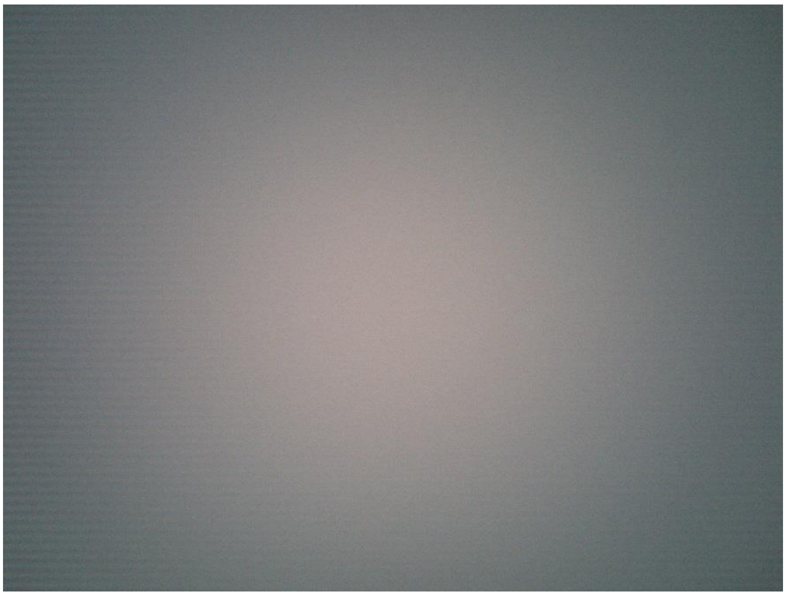


Figure 4-7: Row noise on the illuminated image.

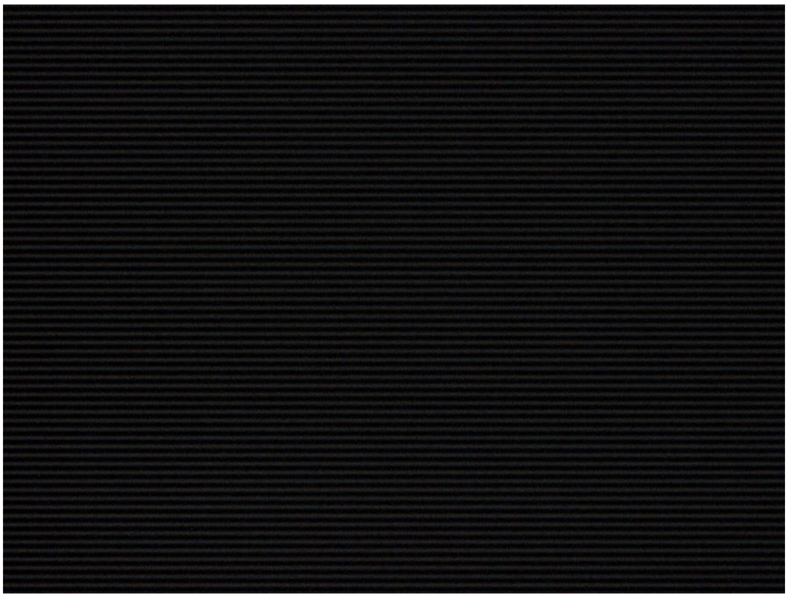


Figure 4-8: Row noise on the dark image.

The analog gain is maximum which is used on a product. Increasing the analog gain makes row noise more visible so by using maximum gain it can be ensured that camera immunity is good enough with every analog gain. From figure 4-9 it can be seen that row noise gets much higher values when the analog gain is eight instead of one. The difference is so big that when the analog gain is one, the test does not even find every problem frequencies.

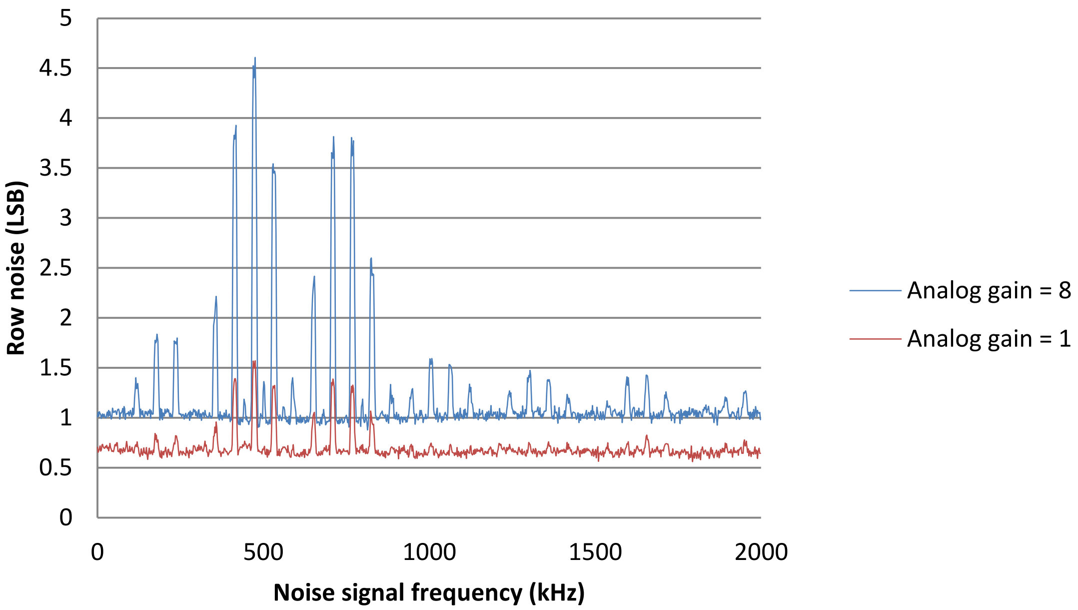


Figure 4-9: The impact of different gains.

Table 4-2 shows settings for the signal generator. The frequency range is from 50 Hz to 2 MHz. The frequency range is limited to 2 MHz instead of 30 MHz because capacitors reduce noise heavily at high frequencies. Figure 4-10 shows the example of a frequency response measured from an eBox output connector when noise is added to an eBox input connector. Noise signal with 200mV$_{p-p}$ amplitude was added and output noise was measured on Vana -line and the camera was attached and running. Already on 2 MHz, noise signal amplitude has fallen from 200 mV$_{p-p}$ to 8 mV$_{p-p}$, so probably it is not meaningful to measure higher frequencies than 2 MHz. Measurements in section 3.2 also showed that there are not much emissions at frequencies over 1.5 MHz on phone power supply lines.

Table 4-2: Settings for the signal generator. [10]

Frequency range	**Frequency step**	**Amplitude**	**Waveform**
50 Hz – 2 MHz	1 kHz	200 mVp-p	Sinusoid

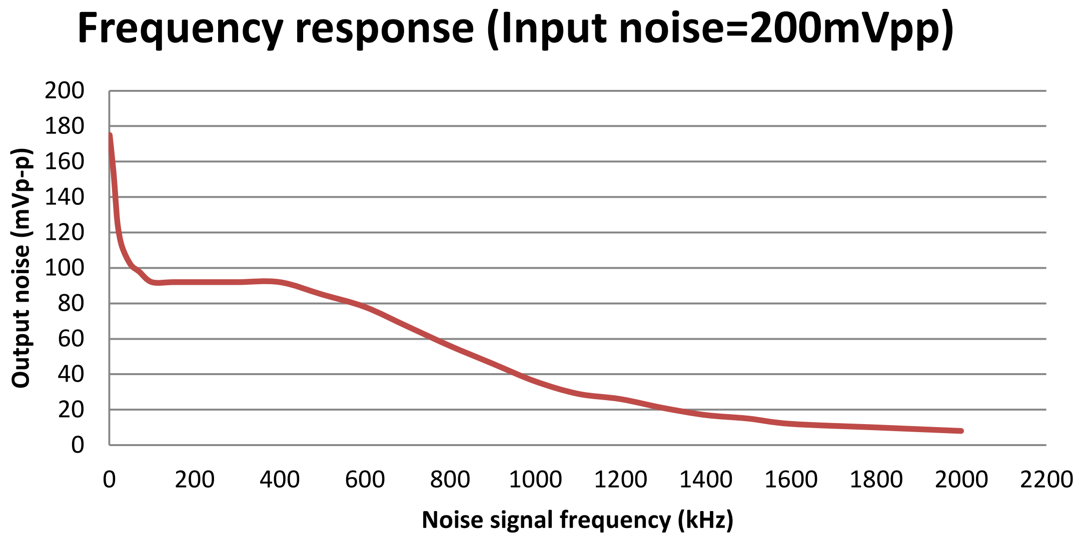


Figure 4-10: The frequency response of eBox.

The frequency step is 1 kHz so there are 2000 measurement points. With the old test method there are only 134 measurement points between 50 Hz and 2 MHz. The automated test gives an option to change the frequency range and the frequency step if you for example want to measure some narrow band more precisely. Choosing the frequency step for the test specification was about to find a good balance between test time and result resolution. Decreasing the frequency step gives more accurate results but on the other hand it increases test time. Figure 4-11 demonstrates the impact of the frequency step size to measurements results. Frequency step size does not seem to make such a big difference to results, at least when it is between 500 Hz and 4 kHz. It could be useful to increase step size from 1 kHz for example to 3 kHz when using the camera with very high number of megapixels. High megapixel count makes the test significantly slower as image transferring and processing comes slower.

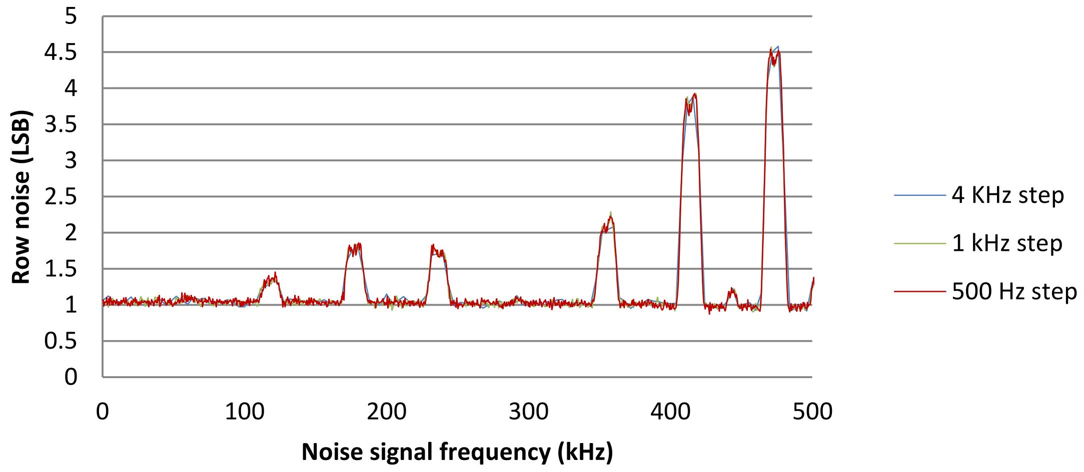


Figure 4-11: The impact of frequency step size.

Noise signal amplitude is 200 mV_{p-p}, and it is not corrected during the measurement. On the old specification noise signal amplitude is 100 mV_{p-p}, and it needs to be corrected during the test. Noise correction was removed from the test to make it easier to do and because there are also capacitors on the mobile phone which reduces fluctuation of power supply voltage.

4.2.4 Test procedure

Instructions below show how the conducted immunity test is done. Instructions are from the Camera module EMC tests specification 5.0 [10].

1. Connect the coaxial cable from the function generator to the eBox first SMA power supply input port to be measured.
2. Open My Playgrounds/VUP/EMC_CI_Test.MIP playground from MIP tool.
3. Configure the CCD Capture plugin as instructed in chapter 5.3 and start the device. Press capture.
4. Open 3-input csv filesaver and select path where to store the test results. Name re-sult file according following example:
CI_<Power supply>_<Resolution>_<Data format>_<Ext Clk>_<Module name>_<Module version>_<Camera module sample number>_<DCC-file>_<Amplitude>._<Waveform>csv.
Example:
CI_Vbat_2600x2400_Raw10_9.6MHz_Ahven_es1.0_1_10101010_200mVp-p_SIN.csv
5. Open Function Generator Controller plugin and connect the generator to relevant VISA address (For example GPIB0::10::INSTR). You can check the instrument address using National Instruments Measurement & Automation Explorer SW. Install IVI drivers for the device if you don’t see the device. After selecting the instrument press “Use manual control” radio button.
6. Configure function generator frequency and amplitude settings according to table 5.4 and press START button to start the test.
7. Fill test information to the pop up -window. If you are measuring different Ext Clk or Data format or you are changing some other parameter write those to Additional info –section.
8. Wait until the test ends. You can monitor row noise plot during the test with Two Floating Point Vis plugin. Press clear before starting new test.
9. Repeat steps 4-7 until you have measured all relevant ports (Vana, Vdig, and Vbat).
10. Open MIP Immunity Reporting plugin. To create PDF report, select Camera Module, ModuleID and Additional Info. Then press Report button.
11. Fill all sections on pop up -window and press OK.

12. Name result file according following example:
CI_<Resolution>_<Data format>_<Ext Clk>_<Module name>_<Module version>_<Camera module sample number>_<DCC-file>_<Amplitude>._<Waveform>.pdf
Example: CI_2600x2400_Raw10_9.6MHz_Ahven_es1.0_1_10101010_200mVp-p_SIN.pdf
13. Change data format or Ext Clk and repeat steps 3-11 until all combinations of data format and Ext Clk are measured.

4.2.5 Row noise calculation

Three different algorithms were tested for row noise calculation. Currently used algorithm calculates first mean of each row and then calculates standard deviation of those mean values. This is done separately for each color channel of the RGB-image. Row noise value is mean of those different color channel standard deviations. Calculation is expressed on Matlab code below:

```
means = mean( image, 2 )
STD = std( means )
rowNoise = ( STD(1) + STD(2) + STD(3) ) / 3
```

Other tested algorithm calculated FFT from row means. On this calculation row noise value is the amplitude of the frequency component which has the biggest amplitude. Results with these two algorithms are quite similar, but tests show that STD-calculation detects smaller row noise than FFT-calculation. Figure 4-12 shows the difference between STD- and FFT-calculations results. The difference can be clearly seen between 400 kHz and 800 kHz. STD –calculation detects small problems better.

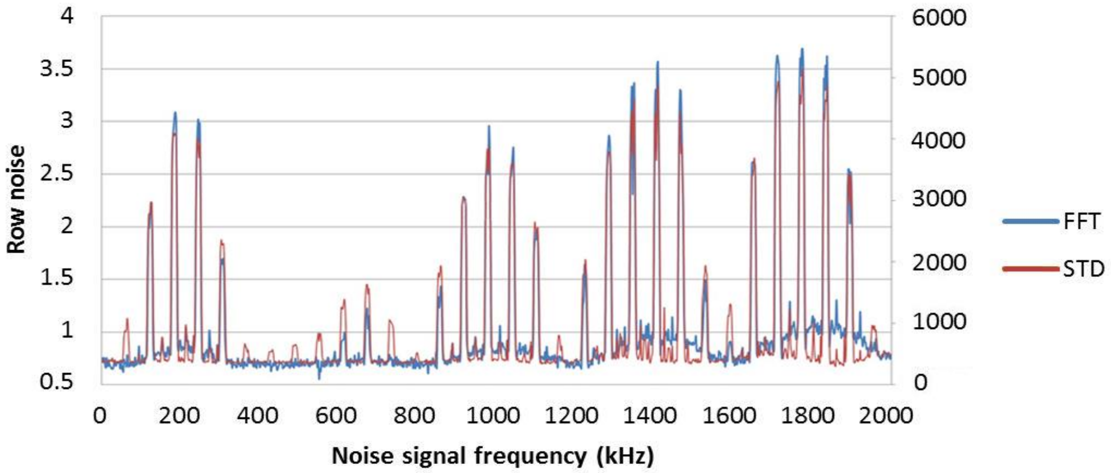


Figure 4-12: FFT- vs STD -calculation.

Third option for an algorithm calculates ratio of random noise and row noise. Row noise is here calculated from the raw –image. STD –calculation seems to correlate better with the old manual test where evaluation is done based on test person opinion of row noise.

4.2.6 Repeatability

A repeatability test was done by measuring conducted immunity from the same camera module five times. Test sequence was planned so that the impact of assembling the test setup and warming of the camera and other test setup came studied. The repeatability test was done following instructions below:

1. Assemble test setup
2. Run test 1
3. Run test 2
4. Disassemble and assemble test setup
5. Run test 3
6. Disassemble and assemble test setup
7. Run test 4
8. Run test 5

Figure 4-13 shows repeatability test results. Figure 4-14 shows results more closely with the frequency band from 1 MHz to 1.5 MHz. Test results show that repeatability is very good at least when same person makes tests with same devices. Also camera module warming does not affect to the results according to this test. Repeatability between different test operator and different devices are examined on next chapter where ILC test results are presented.

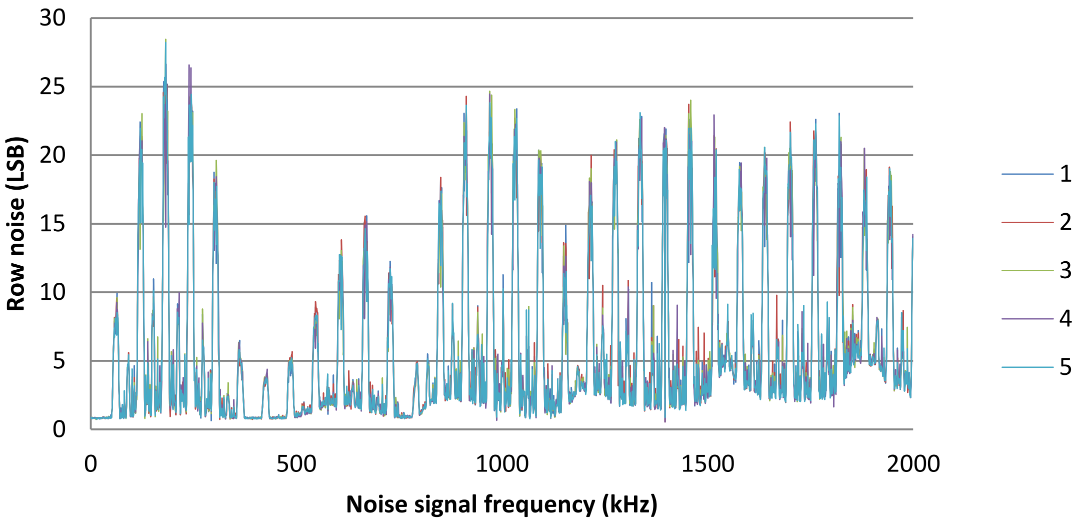


Figure 4-13: Repeatability test results. Frequency band 0-2 MHz.

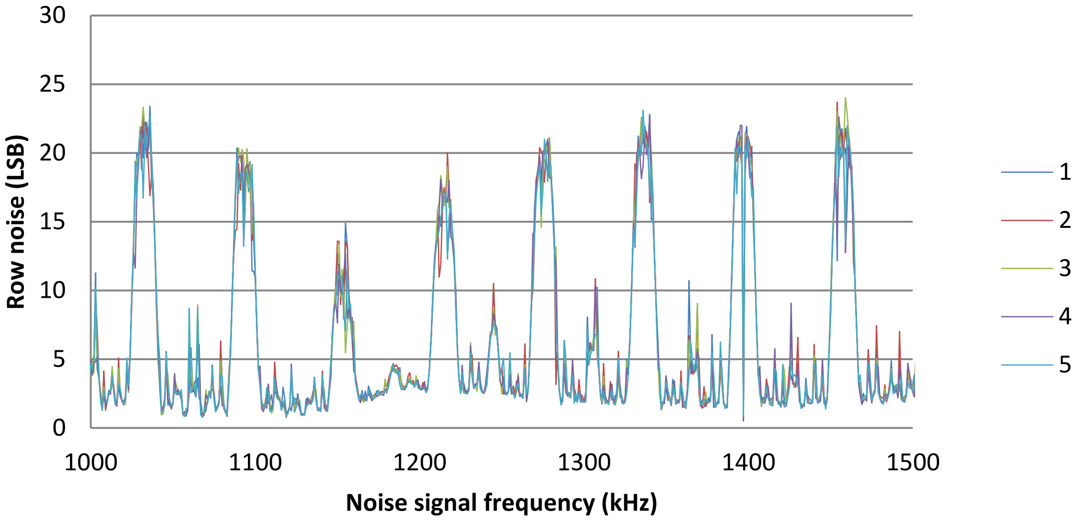


Figure 4-14: Repeatability test results. Frequency band 1 MHz-1.5 MHz.

5 ILC

ILC is inter-laboratory comparison. On ILC Nokia and Nokia’s camera suppliers performed same measurements with same camera modules. Measurement results can be used to confirm that every supplier and Nokia gets same results. Differences on results can be caused by for example operator’s mistakes or uncalibrated measurement devices. ILC for the conducted immunity test was executed 2012 with the old manual test and 2013 with the new automated test. These two ILC gave understanding how much the repeatability of the conducted immunity test has changed after the automated test was taken to use.

5.1 ILC with manual test

On ILC 2012 Nokia and four camera suppliers did the manual conducted immunity test with same three camera modules (same camera, three samples). Immunity was tested on all power supply ports (Vana, Vdig, Vbat). The test was done a little different way than what the EMC test specification clarified. Tested band was only from 400 kHz to 600 kHz and the frequency step was 1 kHz. Figures 5-1, 5-2 and 5-3 show four companies’, including Nokia’s, results for measured conducted immunity for all power supply ports. Figures show results only for a module 1.

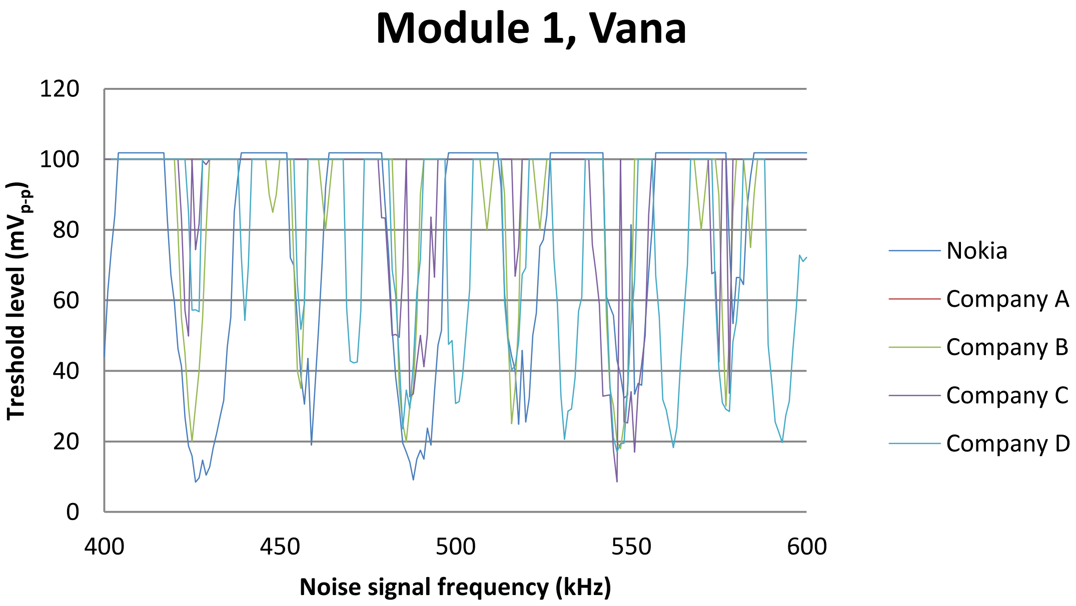


Figure 5-1: ILC 2012 results for the module 1 Vana. [13]

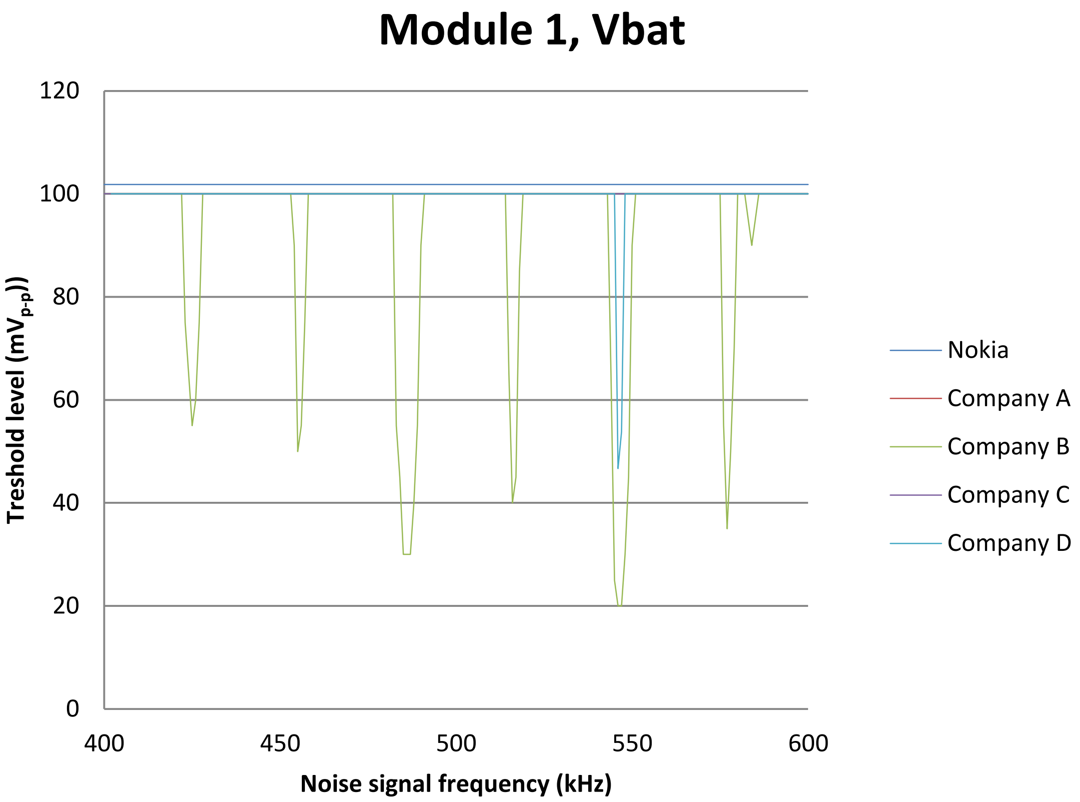


Figure 5-2: ILC 2012 results for the module 1 Vbat. [13]

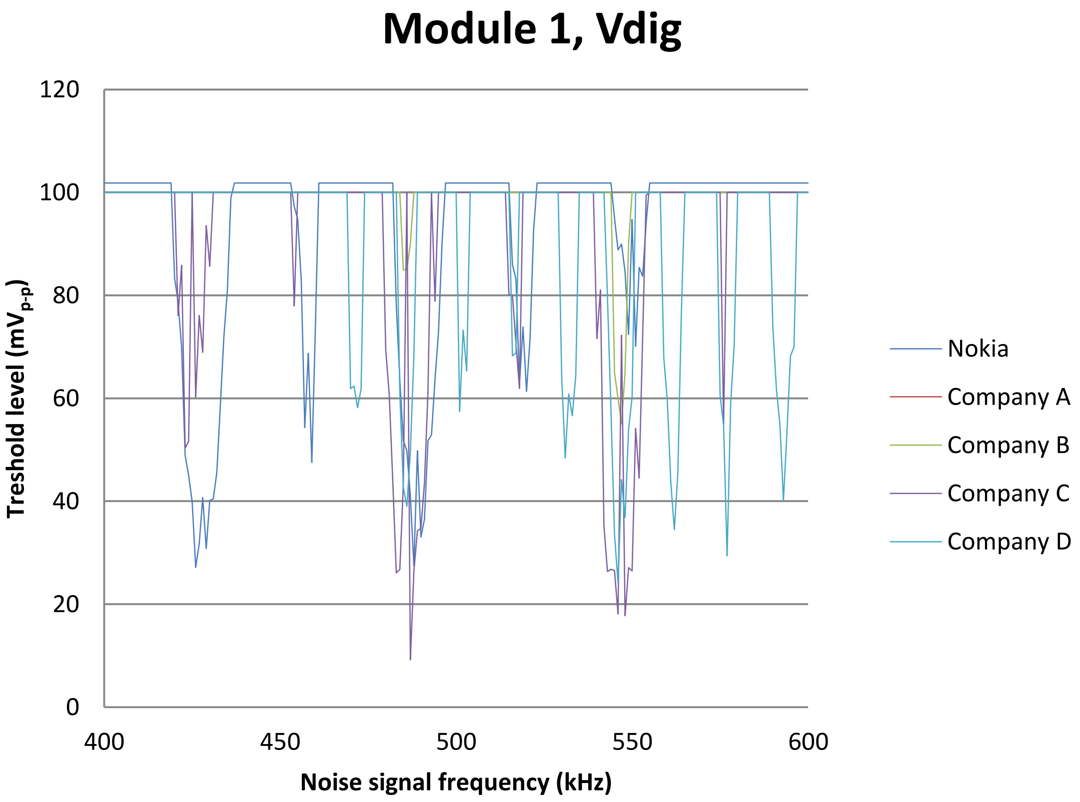


Figure 5-3: ILC 2012 results for the module 1 Vdig. [13]

The main point was that all companies should find all problem frequencies. Problem frequencies were pretty much similar with all except company D’s results. Company D found much more problem frequencies than others. Also Nokia, Company A and Company B have differences on problem frequencies width. For example on figure 5-1 the first spike is about 22 kHz wide on Nokia’s result and about 8 kHz wide on Company B’s results. So Nokia found row noise on about three times wider frequency band, which is quite big difference. When noise signal frequency is near line frequency harmonics row noise appears as wide bands and when frequency is changed further from the line frequency harmonics, bands get narrower. When bands are narrower they get more difficult to see and observation comes even more difficult if the image is not viewed with full resolution. That could explain why problem frequencies are on narrower band on some companies’ results.

Bigger differences are with treshold level. If we watch figure 5-1 and the first problem spike, we see that highest treshold level is about 57 mV (Company C) and lowest is about 8 mV (Nokia). So Company C needed about seven times higher noise signal amplitude to see row noise on the image than Nokia. This shows that measuring treshold level this way is very unreliable. As results vary this much between Nokia’s and suppliers’ results, it can be very risky to rely on suppliers’ measurements and meaning of pass limits are pretty pointless.

5.2 ILC with automated test

On ILC 2013 Nokia and four camera suppliers did the new automated conducted immunity test. Intention was that same three camera modules are used as on ILC 2012 but one module went broke before all companies had made measurements and the broken camera module was replaced by a new one. Immunity was tested on all three power supply ports and the frequency band was 0-2MHz.

Camera supplier’s results was very close to Nokia’s results so according to this comparison test repeatability has increased clearly as the new automated test has being taken to use. Figures 5-4, 5-5 and 5-6 show camera supplier’s and Nokia’s measured conducted immunity from all power supply ports. Figures show results only for the module 1. Although the test was done on the frequency band from 0 Hz to 2 MHz, figures show plots only on the frequency band from 400 kHz to 600 kHz. This way results are easier to compare with ILC 2012. During ILC 2013 we did not yet had the current version of the row noise algorithm. The only difference was that an old algorithm calculated row noise only from green color channel. Thus it did not find every second problem frequency spikes because row noise at those frequencies do not include green component. But test repeatability should be the same with the new algorithm.

As can be seen from figures 5-4, 5-5 and 5-6 all problem frequencies are same on every companies’ measurements. Also amplitude of row noise is quite identical on every companies’ results except on Vbat –measurements. Nokia and Company D had lower values there than other companies on every module. This could indicate to problem with the eBox calibration. Recently done calibrations have improved the frequency response of eBoxes. Uncalibrated eBoxes usually shows on lower row noise value on results because real noise signal amplitude is lower on camera power supply lines. Used eBoxes were calibrated, but probably eBoxes cause these differences somehow. This conclusion can be made as differences are on the same power supply with every camera module.

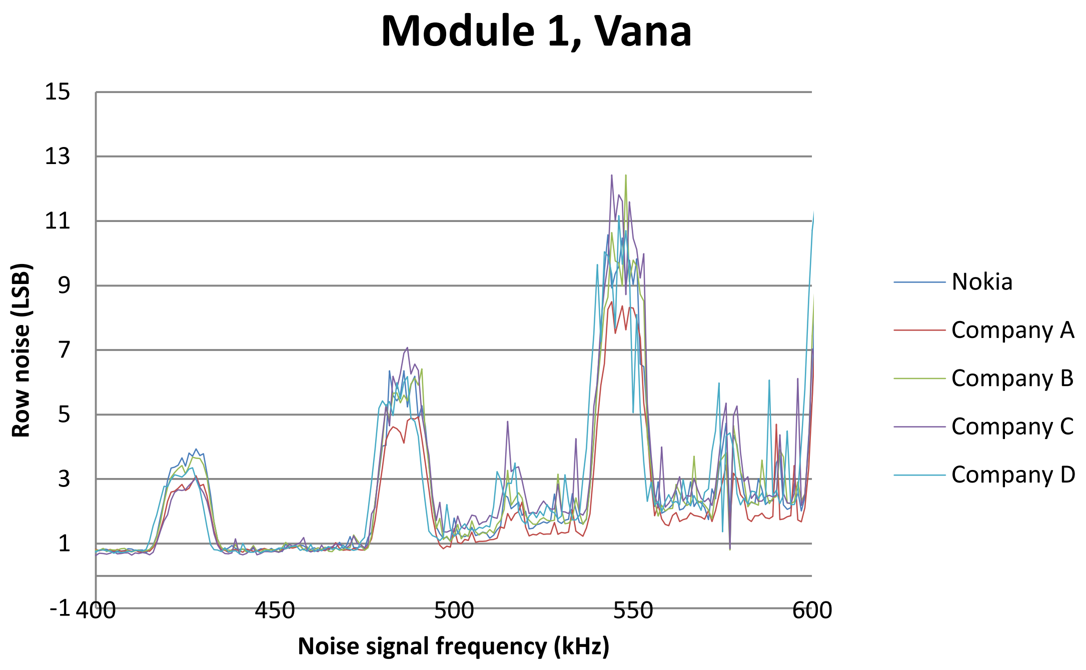


Figure 5-4: ILC 2013 results for the module 1 Vana. [14]

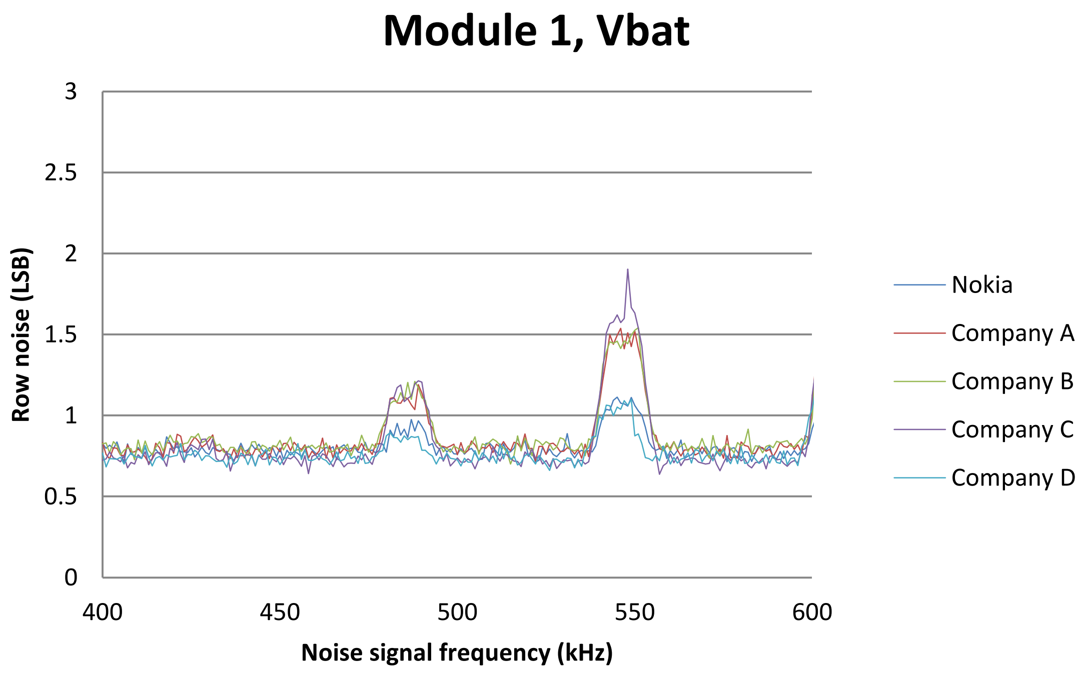


Figure 5-5: ILC 2013 results for the module 1 Vbat. [14]

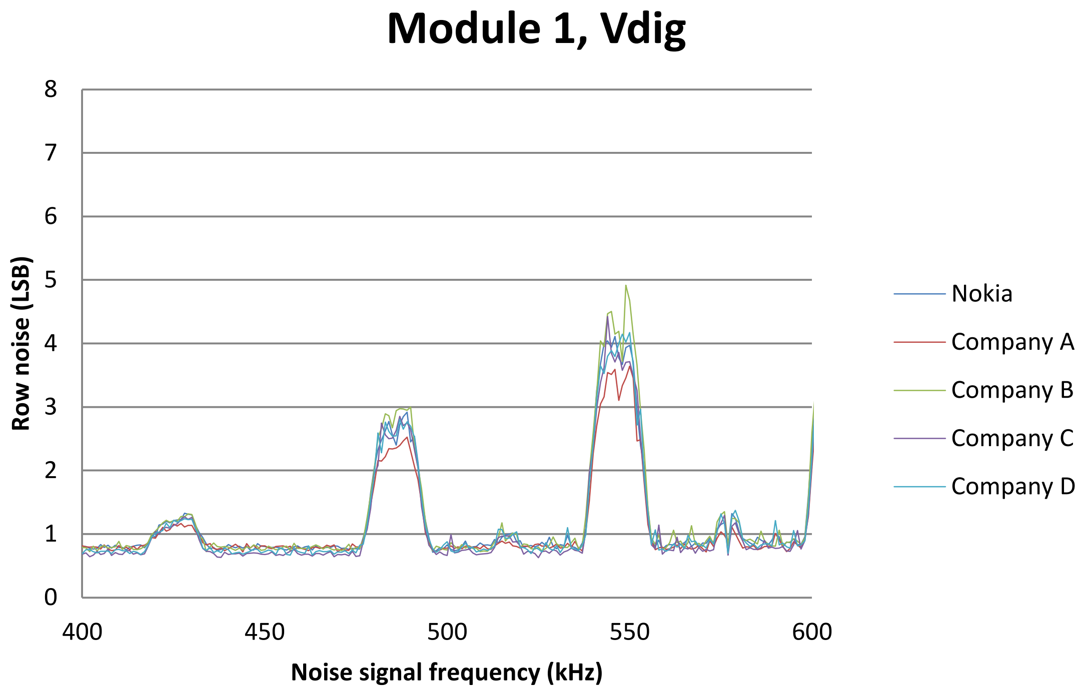


Figure 5-6: ILC 2013 results for the module 1 Vdig. [14]

ILC results show that correlation between Nokia's and camera suppliers' measurements has improved clearly. With the automated test eBox calibration also becomes more essential as we are not making amplitude correction anymore to the noise signal.

6 CONCLUSIONS

The aim of this thesis was to develop the automated conducted immunity test to replace the old manual conducted immunity test. Biggest problems with the old test were that it was so laborious to do and it did not find all problem frequencies. The manual test was done so that test operator changed noise signal frequency and then determined how small noise signal amplitude caused row noise to the image. Same measurement was done on 254 different frequencies. This was very slow and also boring task to do. Still there should have been more frequencies to be measured so that every problem frequencies could have been found.

The automated test is done so that a computer controls the signal generator and the amount of row noise is automatically calculated from the image on every tested frequency. The automated test has 2000 measurement points so basically there is no chance that problem frequencies are not found because row noise would be visible only between measurement points. The automated test is also much faster and it requires very little work from the test operator. Repeatability of the new automated test is much better than the old manual test. The new test method was also taught to Nokia’s camera suppliers.

The automated conducted immunity test seems to be a big improvement compared to the old manual test. The test is already in use at Nokia and camera suppliers and the repeatability of the automated test was proved on ILC test.

For the future work, it would be good to determine a pass limit for the test. One possible way to do this would be first to run the immunity test according to the EMC tests specification or with noise signal amplitude sweeps on few different frequencies. The next step would be to take test images on a stable scene with these same settings on the camera and noise signal. Then several people could rate when row noise is distracting or visible on images. Finally it should be compared how high row noise values the automated test gave with these same setting on the camera and noise signal. That value could be the pass limit for the test.

Also one possible addition to the test specification could be that after the test is finished, a test operator selects for example two frequencies where row noise has biggest values and does some manual testing with those frequencies. It could test that what is the noise signal amplitude when row noise disappears from the image and it also may be useful to save images at those frequencies. The test could also automatically save images during the test if row noise value exceeds some threshold value.

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