Analog Multiplex Bus Readout Method to Reduce Ghosting Image Artifact in CMOS Image Sensors

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***Abstract*— This paper presents an analog multiplex bus readout method for CMOS image sensors. This method reduces memory effect of analog bus resulting in ghost image artifact by self precharging the bus to the reset value separating any two pixel data on the bus. In this readout scheme pixel signal value from the column sample and hold capacitance is read first on to the multiplex bus followed by the reset value of the pixel. Since the reset value is almost constant, within the FPN levels, this level will be same for all the pixels. So every pixel data on the bus starts from the same value, which is equivalent to precharging the bus without actual pre-charge cycle. Another advantage of this readout is that the signal swing on the bus is proportional to the light captured by the pixel. The dark signal will have minimum swing and white signal will have maximum swing. So the settling error will be less for black pixel which is critical from noise point of view. For bright pixels photon shot noise dominates and hence more settling error can be tolerated.**

Index Terms*—Analog Multiplex Bus, CMOS Image Sensor, Ghosting, Image Artifact

I. Introduction

The demand for high speed CMOS image sensors is increasing every day. One of the major bottlenecks in the readout path of CMOS image sensors is the speed of analog multiplex bus which connects the columns to analog front end as shown in Figure 1. Generally the analog multiplexer bus extends for the entire width of the sensor. For sensors with horizontal width of the order of few tens of mm, the speed of the multiplex bus is limited by the RC of the metal bus wire. The analog multiplex bus with huge RC time constant creates memory effect (ghosting) in the image when operated at high speed beyond the limits. Figure 2 shows an illustration of ghost created by analog multiplex bus. When the image contains high intensity structures like bright spots in dark background or dark spots in white background, echo of high intensity structures is seen in the image captured, which repeats after the periodicity of the analog multiplexer. This artifact magnitude should be below the sensor noise level to be invisible in the image.

Figure 3 shows the column readout path. Data from column capacitors is read out through column buffers on to the multiplex bus. Reset and Signal are readout sequentially through the same amplifier so that both reset and signal contains same amplifier offset and flicker noise which will be removed later by subtracting reset and signal.

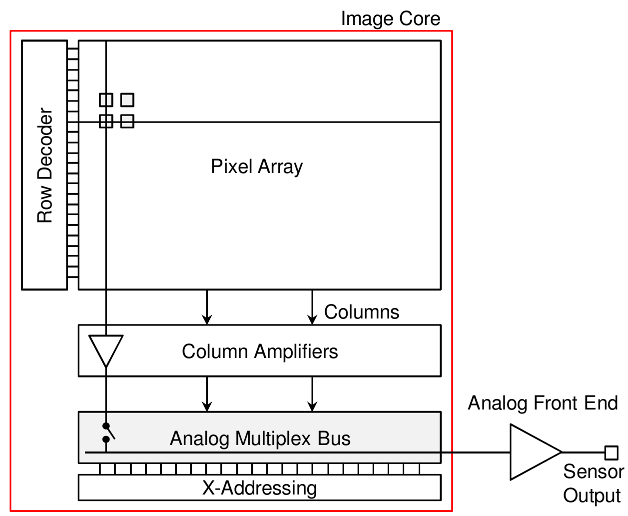
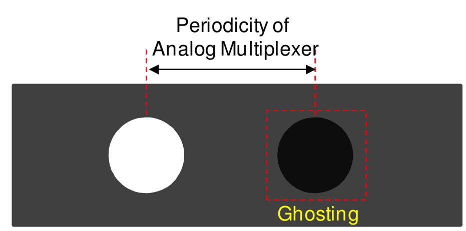


Figure 1: Architecture of a CMOS Image Sensor.

(a). Input scene to CMOS Image Sensor



(b). Output Image from Sensor showing Ghosting

Figure 2: Illustrative drawings explaining Ghosting image artifact from analog multiplex bus.

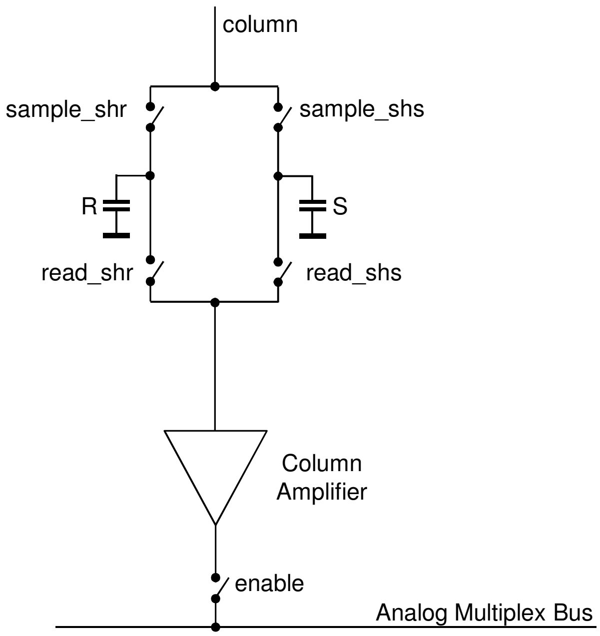


Figure 3: Architecture of column readout path.

II. RESET-SIGNAL (RS) READOUT OF ANALAOG MULTIPLEX BUS

Traditionally reset is read first followed by signal (*RS readout*) onto the analog multiplex bus. In this scenario two different pixels are separated by the signal value of the pixel which is image dependent and random, i.e. the starting point of any pixel reset on the bus is determined by the signal value of the previous pixel. Since the settling on the bus is not complete (only to accuracy of certain bits depending on the design), the final value of the reset in the available time will always depend on the previous value, creating a memory effect. Figure 4 shows the 'BWWBB' (B = Black, W = White) pattern waveforms on analog multiplex bus with RS readout. From this figure it is clear that 'B' followed by 'W' is different from 'B' followed by 'B'. Similarly 'W' followed by 'B' is different from 'W' followed by 'W'. Considering a first order settling, reset and signal on the bus are given by

$$V_{Rbus}[n] = V_R[n] + \{V_{Sbus}[n-1] - V_R[n]\} \times e^{-t/\tau} \tag{1}$$

$$V_{Sbus}[n] = V_S[n] + \{V_{Rbus}[n] - V_S[n]\} \times e^{-t/\tau} \tag{2}$$

Where V_R = Reset Value on the multiplex bus if allowed to settle for infinite time; V_S = Signal Value on the multiplex bus if allowed to settle for infinite time; V_{Rbus} = Reset Value on the multiplex bus after time *t;* V_{Sbus} = Signal Value on the multiplex bus after time *t*. Settling error component in the difference between reset and signal is

$$\begin{aligned}\Delta_{settling} &= \{V_S[n] - V_R[n]\} \times e^{-t/\tau} \\ &- \{V_{Rbus}[n] - V_{Sbus}[n-1]\} \times e^{-t/\tau}\end{aligned} \tag{3}$$

From equations (1) and (3) we can see that reset value on the always depends on the signal value of the previous pixel creating ghosting of magnitude given by

$$V_{Sbus}[n-1] \times e^{-t/\tau} \tag{4}$$

Where *Vsbus[n-1]* is the signal value of the previous pixel, *t* is the available time for settling and τ is the time constant of the analog multiplex bus. There are some other disadvantages of this readout apart from ghosting. Swing on the analog multiplex bus for a given light intensity is random depending on the previous pixel value which is image dependent. This creates random settling error for a given light intensity and increases noise. Analog multiplexer should be designed such that for worst case settling (full swing) on the bus, the settling error is less than sensor noise. This requires huge chip area to reduce the RC time constant of the analog multiplex bus which runs for the full-length of the pixel array (~30mm for 35mm sensor formats used in Digital Cinematography). Also it requires huge power to meet the high bandwidth requirements.

III. SIGNAL-RESET (SR) READOUT OF ANALAOG MULTIPLEX BUS

In the proposed readout method signal is readout first followed by reset value on to the analog multiplex bus called SR readout. In this scheme different pixels are separated by the reset value, which is always same irrespective of the pixel signal value and hence there will not be any ghosting with this readout (reduces significantly to invisible levels even for moderate bus settling). Figure 5 shows waveforms on the bus for 'BWWBB' pattern with SR readout. From this figure it is clear that value of 'Black' or 'White' is same all the time irrespective of the pattern. With this readout signal and reset voltages on the multiplex bus are given by

$$V_{Sbus}[n] = V_S[n] + \{V_{Rbus}[n-1] - V_S[n]\} \times e^{-t/\tau} \tag{5}$$

$$V_{Rbus}[n] = V_R[n] + \{V_{Sbus}[n] - V_R[n]\} \times e^{-t/\tau} \tag{6}$$

Settling error component in the difference between reset and signal is

$$\begin{aligned}\Delta_{settling} &= \{2V_S[n] - V_R[n] - V_R[n-1]\} \times e^{-t/\tau} \\ &+ \{2V_R[n-1] - V_S[n] - V_{Sbus}[n-1]\} \times e^{-2t/\tau} \\ &+ \{V_{Sbus}[n-1] - V_R[n-1]\} \times e^{-3t/\tau}\end{aligned} \tag{7}$$

From equation (7), we can see that ghosting reduces to second order effect with a magnitude given by.

$$V_{Sbus}[n-1] \times e^{-2t/\tau} \tag{8}$$

Table 1 compares the magnitude of ghosting with the RS and SR readout methods. To reduce the ghosting below 100µV, 14bit settling is required with old method, while new method requires only 7bit settling. Since the settling requirements are

TABLE 1: GHOSTING WITH RS AND SR READOUT METHODS FOR DIFFERENT SETTLING OF ANALOG MULTIPLEX BUS.

# of Bits Settling	t/tau (# of Time Constants)	Ghosting with RS Readout (mV)	Ghosting with SR Readout (mV)
5	3.47	3.13E+01	9.77E-01
6	4.16	1.56E+01	2.44E-01
7	4.85	7.81E+00	6.10E-02
8	5.55	3.91E+00	1.53E-02
9	6.24	1.95E+00	3.81E-03
10	6.93	9.77E-01	9.54E-04
11	7.62	4.88E-01	2.38E-04
12	8.32	2.44E-01	5.96E-05
13	9.01	1.22E-01	1.49E-05
14	9.70	6.10E-02	3.73E-06

relaxed, the area required for the bus and power can be reduced significantly.

Another advantage of the new method is that near dark signals will have small swing on the bus as shown in Figure 6. Dark signals are critical for noise performance, where the sensor readout noise dominates. Small swing on the bus favors the settling of near dark signals. For white pixels, photon shot noise dominates which increases with increase in light and hence more settling error can be tolerated.

This readout method is implemented in a high speed sensor. Silicon results demonstrated that the ghosting due to multiplex bus is eliminated, *i.e.* below the sensor noise levels with the proposed SR readout method.

IV. CONCLUSION

Ghost artifact from analog multiplex bus reduces to a second order effect with the proposed SR readout. With this readout analog multiplex bus settling accuracy requirement are reduced to meet the desired specifications of ghost artifact. This relaxed settling requirement helps in reducing power and area. Swing on the analog multiplex bus is proportional to the light intensity. Dark signals will have minimum swing and the hence small settling error which is critical for the noise performance of the sensor near dark.

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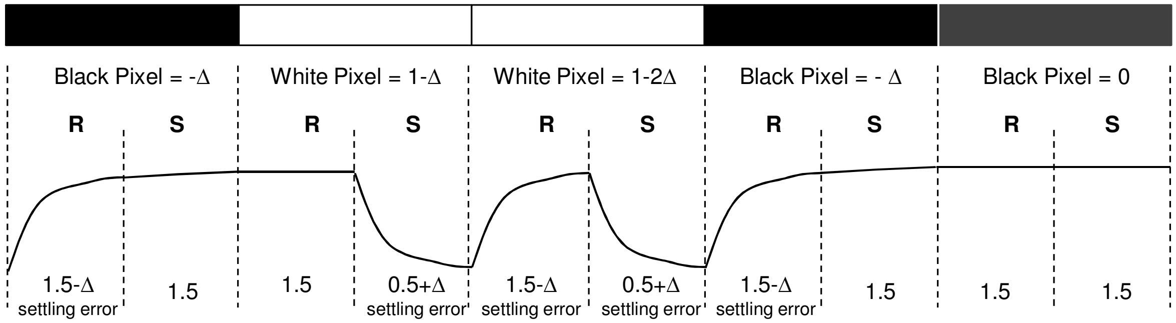

Figure 4: Voltage waveform on analog multiplex bus in standard readout method (RS readout) for a pattern 'BWWBB'.

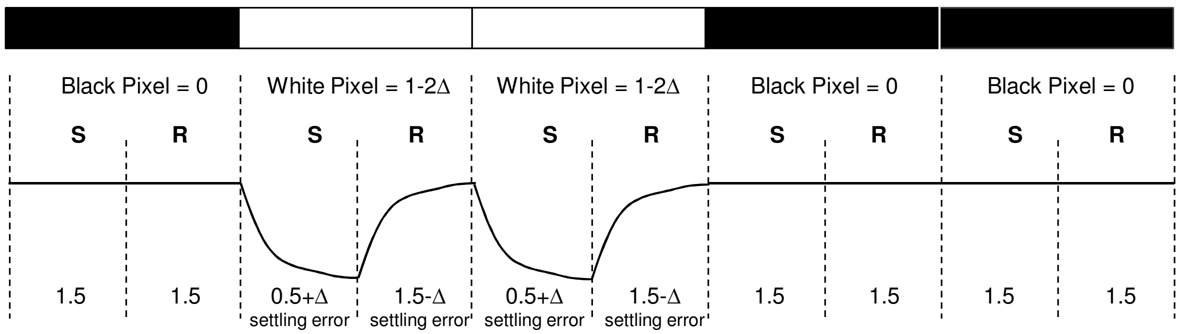

Figure 5: Voltage waveform on analog multiplex bus in new method (SR readout) for a pattern 'BWWBB'.

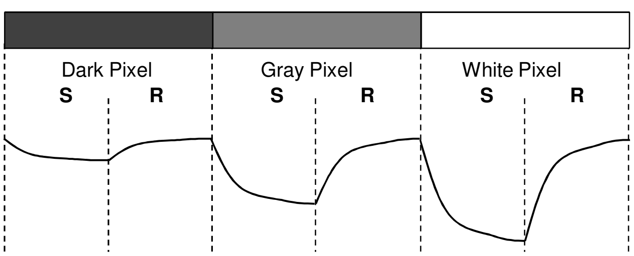

Figure 6: Voltage waveform on analog multiplex bus in new method (SR readout) for near dark, gray and white pixels.

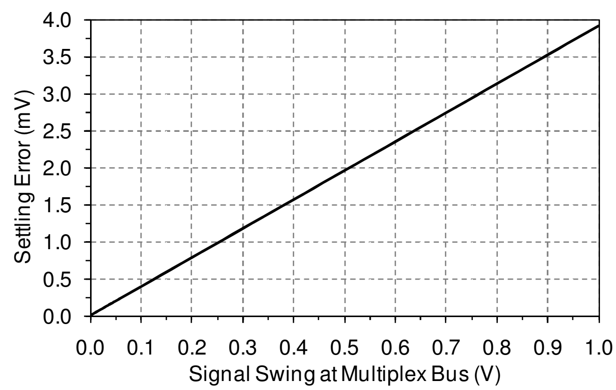

Figure 7: Settling error vs. pixel signal swing at analog multiplex bus. An *8-bit* settling of the bus is considered here. Near dark signals will have a small swing on the bus and hence will have small settling error compared to white signals. Due to inherent property of the image sensor signals (photon shot noise increases with increase in light) higher settling error can be tolerated for white pixels.