On overcoming photodetector saturation due to background illumination while maintaining high sensitivity by means of a tailored CMOS pixel

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***Abstract*—Visible Light Communication is a good candidate to substitute, or at least to work along with Wi-Fi at indoor environments. Nonetheless, it still faces several challenges, like the necessity of receivers with high sensitivity and Dynamic Range. This follows from the large DC level of the high brightness LED and the intense levels of background illumination. We present in this paper a review of an integrated circuit topology, the *Bouncing Pixel*, that avoids signal saturation, achieving both High Dynamic Range and high sensitivity, suited to be implemented on a chip. The Pixel has the potential to be a good candidate for Li-Fi applications at the receiver node, especially for IoT applications.**

***Index Terms*—Receiver, pixel, photodetector, Li-Fi, background illumination, CMOS, high dynamic range.**

I. INTRODUCTION

Wireless connectivity never ceased to grow and is expected to keep growing at an increasing rate. As the majority of devices with wireless connection works at the radio frequency (RF) spectrum, the related channels may suffer from overcrowded bands in the near future. This problem is compounded by the advent of the Internet of Things (IoT), forecasting an amount of 10 billion new devices to be connected to the Internet by 2019 [1]. An alternative to RF-based communication is the operation in the visible range, as a shift towards a much wider and less populated spectral band, coined as the Visible Light Communication (VLC), or Light Fidelity (Li-Fi) in case of higher data rates ($> 10\,Mbps$) [2].

Li-Fi communication systems use LEDs as transmitters, which may serve a twofold purpose: as illumination and Access Point (AP) [3]. These systems take advantage of using Orthogonal Frequency-Division Multiplexing (OFDM) modulation that is robust against multipath effects, and thus, being ideal for monitoring several IoT devices [4], encoding information symbols with intensity modulation (IM). The OFDM modulation is considered to be a disadvantage for RF transmission, since it has an inherently high Crest Factor, i.e. a high peak-to-average-power ratio (PAPR). Consequently, RF transmissions would require a considerable high-power transmission, resulting in high costs in terms of energy [4]. For LED transmitters, however, there is already a DC level due to the illumination purpose. Thus, signals can be encoded around this DC operating point, turning the high PAPR of the OFDM modulation into an advantage [4]. In addition, a high PAPR and the DC bias applied to the signal in Direct Current Optical OFDM (DCO-OFDM) [5], means that transmitters and receivers should feature a High Dynamic Range (HDR), in order to avoid signal distortion [6]. This distortion occurs due to saturation and nonlinearities in these components. For instance, a difficulty faced by the receiver is the high level of background illumination from ambient light, which may saturate the receiver, preventing the information to be read. Additionally, it is also convenient to detect signals in a linear fashion, in order to diminish detected signal distortions, and therefore, reducing the Bit Error Rate (BER).

Another desirable feature of the receiver circuit is a high Sensitivity (S), corresponding to how easily it can distinguish between very close photocurrents. This feature is recommended, since very weak optical power signals, embedded in rather small power variations, could be more easily detected. In an IoT world, where power consumption will be of major concern, to reduce the optical power transmitted by each ”thing”, and still being able to detect these signals, are a major advantage. Finally, IoT transmitted signals will be very small if compared to ambient background illumination. If not properly designed, the ambient light itself may lead to detector saturation. On the other hand, if the receiver is designed to sense larger optical intensities, it may not have acceptable sensitivity, in order to detect the small signals received.

On a real IoT application, the detector and its readout amplifier might be implemented on a discrete circuit, or in an integrated circuit (a chip). The latter is a better choice for IoT, since it is more reliable, smaller, easier to replace, consumes less power, has less parasitic components, and is cheaper in larger production scales. This is true for both the detector to be placed on the IoT device, and at the Access Point. Therefore, the aim of this paper is to review a circuit topology, the Bouncing Pixel [7], that achieves both HDR and high Sensitivity, integrated to CMOS, making it a good candidate for VLC applications to be working with IoT.

II. RECEIVER CIRCUITRY AND MODULATION

A. Modulation

Orthogonal Frequency-Division Multiplexing (OFDM) is distinguishing itself as the strongest modulation candidate to be employed in Li-Fi. This is mostly due to its robustness to multipath effects, which are largely observed for indoors VLC systems.

For nonoptical OFDM, information is encoded in the electric field, and therefore can be bipolar (negative or positive) while transmitting. Its corresponding receiver has a local oscillator, allowing coherent detection to be employed [6]. For optical wireless OFDM, however, signals are modulated as the intensity of a light beam, and is directly sensed by a photodetector, leading to the conventional Intensity-Modulated Direct-Detection (IM/DD) optical system [5]. Since information is encoded as intensities, they must be, therefore, real and positive, in contrast with the bipolar signal used in nonoptical OFDM. Nonetheless, baseband OFDM signals before transmission are complex and bipolar.

The common method for ensuring that the baseband OFDM signal becomes real, is to enforce Hermitian symmetry at the input of the Inverse Fast Fourier Transform (IFFT), that is used for modulation and multiplexing, at the transmitter [6]. There are many methods in order to obtain a positive signal in the time domain, that can be intensity-encoded and transmitted [8]. The two main ones are the DCO-OFDM and the Asymmetrically clipped optical OFDM (ACO-OFDM) [9]. The first method is based on the addition of a DC bias, in order to ensure that most of the signal is kept positive. In fact, for a large number of subcarriers (> 64), the time-domain OFDM signal, at the output of the IFFT, can be considered to have a Gaussian distribution [5]. Therefore, due to the large PAPR, the smaller the DC bias, the larger the number of negative peaks that would still remain negative. When this happens, these peaks are clipped, resulting in distortions that limit performance, and increase the BER. In contrast, the ACO-OFDM uses only the odd subcarriers for transmission of data, while the remaining even subcarriers are set to zero. Then, all the clipping noise falls on the even subcarriers, and data is not affected.

The second method is more energy efficient, since only a small DC bias is required, and there are less clipping distortions. Nonetheless, it features half of the spectral efficiency, if compared to the DCO-OFDM, since half of the subcarriers are unused. It must be noticed, however, that in VLC systems, the DC bias is generally employed for Illumination purposes, besides the positive signal constraint [10]. In this case, the DCO-OFDM seems to be more suitable, and will be considered in this paper.

B. Receiver Figures of Merit

As mentioned earlier, in order to decrease the BER, the minimum number of distortions sources should be included during modulation, like avoiding nonlinearities and clipping noise to happen. This means that the clipping noise of the DCO-OFDM modulation should be minimized. This can be done by adding a scaling factor (α) to the time-domain OFDM signal ($x[k]$), and with a proper DC bias (B_{DC}) [11], [12], as shown in equation (1).

$$x_t[k] = \alpha\, x[k] + B_{DC} \tag{1}$$

where $x_t[k]$ stands for the transformed signal, and k refers for the k^{th} subcarrier.

By choosing proper scaling factor and bias, it is possible to keep the OFDM signal inside the dynamic range of both the transmitter amplifier and the LED, which we assume here. Moreover, $x_t[k]$ can be downscaled even further, while maintaining B_{DC} at a proper level, in which way that clipping noise is kept to a minimum. In addition, these factors could be employed for providing dimming capability [12], or to fix a certain electrical transmitted power [12], [13], that is essential for power saving in IoT devices.

Reducing the amount of transmitted power is clearly beneficial for the transmitter, especially for IoT applications, where application-specific integrated circuits (ASICs), in which they will be implemented, should feature low power operation. However, reduced power transmission means less power being detected, and it has its consequences at the receiver side, in terms of the detector Signal-to-Noise Ratio (SNR) [5]. First, because the SNR is proportional to the square of the received power, which therefore, may limit the distance in a communication link, due to path loss. Second, due to background illumination, that may degrade performance by both its added photon shot noise, and by saturating the detector.

Regarding that, two figures of merit are of great relevance for the receiver: the Dynamic Range (DR) and the Sensitivity (S), as previously mentioned. Usually, the detection circuit is composed by a photodetector that is directly connected to a transimpedance amplifier. This amplifier converts the input photocurrent (I_{DC}) into an output voltage (V_{sig}). The measure of how far apart lie the maximum and minimum photocurrents detectable by the receiver amplifier is the DR. It is defined in a logarithmic scale, as shown in equation (2), by the ratio between the maximum and minimum readable currents.

$$DR = 20\, log\left(\frac{I_{max}}{I_{min}}\right) \tag{2}$$

The HDR feature is required, in order to avoid detected signal saturation, and to enhance the SNR. A very attractive feature of a HDR detector circuit, is the ability to provide a good SNR at its output for larger input currents, since its input-referred noise is reduced, due to the usually large gain of the detector circuit.

Meanwhile, the sensitivity S quantifies the ability of the circuit to differentiate between similar light intensities and is defined by a derivative of an output voltage (V_{sig}) and the input photocurrent (I_{DC}), as shown in equation (3) [14].

$$S = \frac{\partial V_{sig}}{\partial I_{DC}} \tag{3}$$

The sensitivity may also be viewed as the transimpedance gain, and therefore, the larger its value, the smaller will be the input-referred noise. A large sensitivity is also required in order to sense small variations coming from the transmitter, either by its reduced transmitting power, or due to path loss.

The combination of both HDR and large sensitivity for the detector is ideal for the IoT scenario, since even with a reduced transmitted power embedded in a large background illumination, information could still be recovered. Concerning ASICs, however, it is not an easy task to devise an integrated circuit to interface with the detector, that is able to feature

HDR and large sensitivity, with linear response, mainly due to the usually low voltage supply on chip.

C. Detection Methods

A well designed receiver circuit allows for a more robust signal detection, and might be the bottleneck for low-power IoT applications. Therefore, designing a circuitry for transducing light into electrical signals, among the many that exist, is an important task. For optical OFDM, IM/DD is usually employed. However, it suffers from loss of sensitivity and high susceptibility to noise effects, depending on the channel conditions. An amplifier circuit that alleviate these issues is of foremost importance. Furthermore, the designed circuit should be compatible with Complementary Metal-Oxide Semiconductor (CMOS) technology. This way, it can be integrated on an ASIC chip.

In the literature, generally a shunt-shunt transimpedance amplifier is used, and is followed by an Analog to Digital Converter (ADC), in order to convert signals to the digital domain for further demultiplexing and demodulation [2]. The usual amplifiers use an operational amplifier coupled along with resistances and/or capacitances. Such amplifiers are not well suited for integrated circuits, since they tend to be large, consume a lot of power, and introduce many noise sources, such as the use of resistances. These are well-known issues in the *Image Sensor* community. On their context, the transimpedance amplifier is one type of *Pixel Circuit*, a generally smaller circuit, that uses no resistances and a couple of MOS transistors [15].

A Pixel Circuit works as an integrator, sampling the current through an integration capacitance C, during a time interval ΔT. The integrated voltage after the integration time ΔT is the sampled value read by the pixel, which in turn is directly related to the light intensity [15]. The maximum photocurrent that can be detected is termed the saturation current (I_{sat}). For light signals that result in currents larger than I_{sat} the pixel is said to be saturated and, therefore, unable to convey any information for these values. The saturation current is given by $I_{sat} = C\, V_{DD}/\Delta T$, where V_{DD} is the chip voltage supply. On the other hand, the Sensitivity (S) of the pixel circuit is generally given by $S = \Delta T/C$ [15]. There is an inverse relationship between S and I_{sat}, as can be seen in equation (4). Therefore, if a large saturation current is required, for High Dynamic Range, the Sensitivity consequently decreases. This trade-off is limited mainly due to the fixed low chip voltage supply V_{DD}.

$$I_{sat} = \frac{V_{DD}}{S} \tag{4}$$

Although traditional pixel circuits found in the Image Sensor literature do not solve this constraint, they are more suitable to VLC applications, if compared to a simple transimpedance amplifier. As pixel circuits also perform a process of integration of the photocurrent, they intrinsically act as to reduce noise. At the same time, they may even amplify the signal, dismissing the necessity for off-chip processing, with discrete components. The ADC that is required in both solutions, also can be implemented on the same chip. Therefore, this receiver circuitry may be combined with other circuits to form a single ASIC that is able to demultiplex and demodulate an OFDM based signal, from detection through digital processing, reducing costs and power consumption.

The most commonly used topology for pixel circuit is the Active Pixel Sensor (APS) [16], which however, does not feature HDR, requiring some adaptations to achieve higher values of this figure of merit. The various methods for HDR can be classified in seven different categories: logarithmic, multimode, clipping, frequency based, time to saturation (TTS), global and autonomous control over time integration sensors [15]. In these approaches, the increase in DR is exchanged by a lower sensitivity on higher light intensities. This is due to the fact that, to be able to measure photocurrent values above those of I_{sat}, the aforementioned approaches tend to change the integration time, integrating capacitance, condense the signal span in a logarithmic fashion or perform further signal processing. However, all of these processes diminish the sensitivity, also losing linearity for the pixel response.

Nonetheless, it must be noticed that exactly in higher light intensities is where sensitivity should be enhanced, since the small OFDM signals coming from low power IoT transmissions will be embedded on intense background illumination. Furthermore, if low power is not a concern for transmission, and a large DC is employed for solving the high PAPR problem and for illumination, with or without a scaling factor α, the sensitivity should still be larger at the highlights.

III. THE *Bouncing Pixel*

One other way of achieving a higher dynamic range is to increase the circuit supply voltage. However, this solution is not feasible, since the downscaling of CMOS technology nodes also limit the maximum value of V_{DD}. Regarding that, a pixel circuit that virtually enhances the operational voltage has been proposed. Named the *Bouncing Pixel*, it is capable of circumventing the constraints of featuring High Dynamic Range, high sensitivity and linear operation at the same time [7]. The basic idea of this pixel is to prevent the saturation of the voltage signal such that it keeps integrating until the end of the time interval ΔT, as shown in Fig. 1. In order to prevent saturation, the pixel changes the direction of the integrating signal when it reaches an upper (V_{max}) or lower (V_{min}) reference voltage, and thus, limiting the signal to an arbitrary range ($\Delta V = V_{max} V_{min}$). At the end of the integration time, the voltage signal in the integrating capacitor (V_{cap}) is sampled. This value, together with the number of times the signal bounced (N) enables the total reconstruction of the HDR signal of interest (V_R) that emulates a higher V_{DD} [7].

The recovery of the signal of interest is easily done with one of the two following expressions, being equation (5) with respect to N odd and equation (6) to N even.

$$V_R = N\,\Delta V + (V_{cap} - V_{min}) \tag{5}$$

$$V_R = N\,\Delta V + (V_{max} - V_{cap}) \tag{6}$$

Since any of the voltage swing, the value read at the capacitor and both upper and lower thresholds are limited by V_{DD}, the maximum pseudo voltage achievable ($V_{R_{max}}$) with this pixel topology is, theoretically, only limited by the number of bits (b_c) at its digital counter (responsible for counting the number of bounces), that is $N_{max} = 2^{b_c - 1}$. Then, the saturation current of the *Bouncing Pixel* can be described by the counter overflow, that occurs when the counting changes to $N = 2^{b_c}$. From equation (7):

$$I_{sat} = \frac{V_{R_{max}}}{S} = \frac{\Delta V\, 2^{b_c}}{S} \tag{7}$$

This relation proves that high values of I_{sat}, and therefore HDR, are achievable without diminishing S, given a large enough number of bits for the digital counter. For a regular 8-bit counter and $\Delta V = 1\ V$, pseudo-voltages of up to $V_{R_{max}} = 256\,V$, could be achieved on a chip.

To assert the expected characteristics of this topology on a commercial CMOS technology, simulations were made in the Analog Mixed-Signal (AMS) Designer simulator within the Cadence® Virtuoso® suite. A TSMC CMOS $180nm$ technology node was used, enabling a $1.8V$ operational voltage while featuring one polysilicon and up to six metal layers, both P and N wells and MIM capacitors. Moreover, noise due to electronic components was simulated with the built-in models from the foundry and the noise from the photodiode was added by using the characteristics of commercial components. Also, the digital counter in the pixel was simulated with $b_c = 8\ bits$. The simulations were performed for photocurrents varying from $400\mu A$ up to $4mA$, where the smaller current is emulated to be limited by the background illumination that a VLC system may face with room illumination or natural lighting. Both shot and thermal noise were introduced, and considered to be additive white Gaussian noise (AWGN).

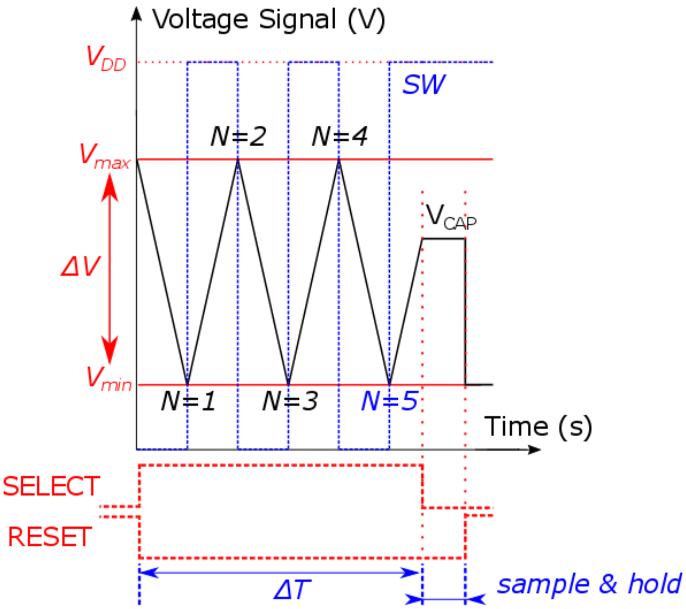

Fig. 1. *Bouncing Pixel* operation.

Fig. 2 provides the data plot of the average reconstructed voltage (V_R) by the *Bouncing Pixel*, from equations (5) and (6), relative to the input current coming from the photodetector. It can be seen that pseudo-voltages larger than $200\ V$ were achieved. Also, a large sensitivity, or transimpedance gain, of $49.80 mV/\mu A$ were achieved, regarding the slope of the curve. This means that a $1\ \mu A$ current variation at the photodetector would produce a voltage variation at the output of the pixel of $49.80\ mV$. Moreover, the response is quite linear for the whole dynamic range.

Each point in the solid line curve of Fig. 2 presents the average reconstructed voltage for 30 different simulations. Each one of these has a different seed for the noise simulations. From the standard deviation obtained from the output voltage simulations, it is possible to obtain the input-referred noise, by dividing the voltage noise by the sensitivity of the circuit. This input-referred noise is the minimum current readable by the circuit (I_{min}), and was find to be $23.84\ nA$ for the chosen photodetector. From equation (2), we can calculate the DR, by using the minimum current calculated before, and the maximum current (I_{max}) given by $4\ mA$, from Fig. 2. This leads to a high DR equal to $105\ dB$.

It must be noticed that the voltage at the capacitor V_{cap} must be converted to the digital domain by an ADC. Although the pseudo-voltages are as large as $200\,V$, the actual voltages converted by the ADC are lower than $V_{DD} = 1.8\ V$, and therefore, the constraints for number of bits for the ADC are less strict. The combination of the digital value from the ADC and the counter gives the final reconstructed voltage V_R, that has HDR, large sensitivity and good linearity.

For the minimum noise current of $23.84nA$, and a sensitivity of $49.80\ mV/\mu A$, the smallest readable voltage at the output of the pixel circuit is $1.19\,mV$. This imposes that an ADC of, at least, $11\ bits$ should be employed, for a reference voltage of $1.8\,V$. Because of the way that the *Bouncing Pixel* is built, it can be designed to provide even larger sensitivities. In this case, for the same minimum input current, it would provide a larger voltage difference at its output, and therefore, a lesser number of bits for the ADC could be used.

Furthermore, it is worth noting that the pixel operational frequency must be higher than the OFDM modulated signal. However, this is less problematic for IoT applications, which require reduced data rates [17]. An additional noteworthy feature of the *Bouncing Pixel* is its ability to work with LEDs with low brightness in the related transmission nodes, since the pixel can detect very small amplitude variations around the large DC intensity. This allows diminishing the output power of the LEDs, a major advantage for IoT applications with low and ultra-low energy budget.

IV. CONCLUSION

The conditions of strong background illumination and low intensity signals that were simulated, suggest that the *Bouncing*

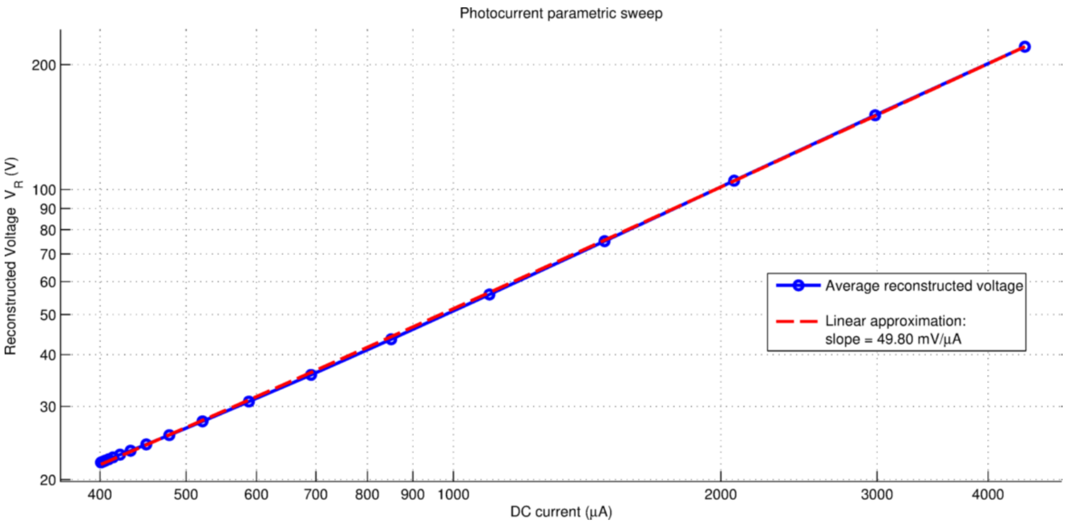

Fig. 2. Average reconstructed voltage from $400\,\mu A$ up to $4.4\,mA$, with $\Delta T = 256\,\mu s$.

Pixel is able to handle the hard task of transducing light signals from IoT devices transmitting with low power LEDs, even where background illumination is abundant. This conclusion comes from the HDR of $105\,dB$, and high sensitivity of $49.80\,mV/\mu A$, that keep input-referred noise to a minimum. In contrast with other integrated pixel topologies, such high sensitivity is kept for a wide range of input currents for this pixel, even at high background illuminations, since it is able to avoid saturation. Furthermore, the response is linear, which does not introduce distortions in signal demodulation. Moreover, Fig. 2 shows that pseudo-voltages up to $200\,V$ can be achieved, with an 8-bit counter, even with a chip supply of only $1.8\,V$.

All these features suggest that the Bouncing Pixel is a good candidate for the receiver node, either at the AP or at an IoT device, where low power processing and transmission are required, and still being able to recover small signal variations embedded on intense background illumination.

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