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Characterization of Light-To-Frequency Converter for Visible Light Communication Systems

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Abstract: PIN (positive intrinsic negative) photodiodes and analog-to-digital converters (ADC) are commonly used on visible light communication (VLC) receivers in order to retrieve the data on detected signals. In this paper, a visible light communication receiver based on a light to frequency converter (LTF) is proposed. We characterized the LTF and derived an equation for signal-to-noise ratio (SNR) estimation in terms of its input optical power, and the frequency of the output periodic signal. The experiments show that the periodic signal of the LTF converter has a maximum output frequency of 600 kHz at a distance of 6.2 cm. In this setup, measured SNR reached 18.75 dB, while the lowest obtained SNR with 1.1 m length was roughly -35.1 dB. The results obtained suggest that a bit rate of 150 kbps can be achieved with an on-off keying (OOK) modulation format. We analyzed the results and discuss the advantages and limitations of the LTF converter for optical wireless communication purposes.

Keywords: visible light communication; light to frequency converter; white-light LED; optical wireless communication

1. Introduction

In optical wireless communication (OWC), it is common to find optical receivers conformed by positive intrinsic negative (PIN) photodiodes or avalanche photodiode (APD) and analog-to-digital converters (ADC) [1–6], as proposed by the IEEE 802.15.7 standard [7] for visible light communication (VLC) systems. Among these, the PIN photodiodes (PD) are presented more often in VLC systems, because they have better immunity to noise and low parasitic capacitance, and can be used to speed up the transmission (ultrafast PIN-PD), which is a milestone in VLC works [2,6]. This is a result of the intrinsic material between the p–n junction, which leads to a reduction of the time constant, and thus better bandwidth [2,8]. In fact, the PIN-type photodiodes adapted to the red-green-blue (RGB) sensors have been studied for applications in VLC systems [9], the authors characterized these sensors and determined its frequency response. Furthermore, PIN photodiodes are being adapted to other systems, to perceive intensity levels of light and turn over periodic electrical signals with frequencies that correspond to the incident power in the photodetector [10]. These devices are known as light-to-frequency (LTF) converters, and are internally comprised of PIN-type photodiodes and a module that transforms the photocurrent to frequency. The mentioned module employs a voltage-controlled oscillator (VCO), which reduces and simplifies the conditioning circuit of

the photodiode, allowing its adaptation with embedded low-cost systems that do not require ADC [10–16]. Therefore, the LTF converters are exposed as an attractive solution for the detection of communication signals in the visible range of the electromagnetic spectrum because of the reduction of the system complexity [10]. Recently, LTF converters have been investigated, for example, in optical communication systems for the design of portable transceivers [11] and in health applications to detect levels of oxygen in the blood [12], among others.

In this paper, we propose the use of a light-to-frequency converter as an alternative to design the receiver of a VLC system. In this scheme, the characterization and performance evaluation of LTF converter as a receiver in a VLC system, based on on-off keying (OOK) modulation, is presented. The main contribution of this article is summarized as follows: initially, the characterization of an LTF converter is presented, and an equation is derived based on both the incident optical power and the frequency generated in the LTF, in order to estimate the system's SNR value. The second contribution is the evaluation of the LTF by using a periodic optical signal, which reveals the advantages and disadvantages regarding its use as a receiver in a VLC system.

The rest of the paper is organized as follows: Section 2 shows the model of the VLC system and the LTF converter. The characterization of the LTF converter for a VLC system is presented in Section 3. The results and discussions are presented in Section 4. Finally, we summarize the main conclusions.

2. VLC and LTF System Model

2.1. VLC System Model

VLC systems are based on intensity modulation and direct detection (IM/DD), which is the most used method to implement optical wireless communications [1,2,7]. A typical VLC system is depicted in Figure 1.

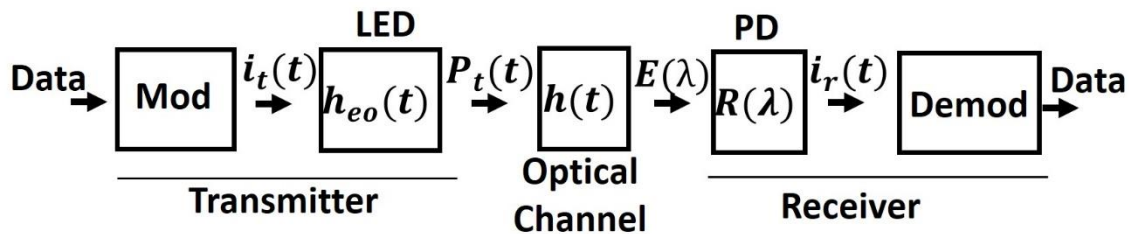


Figure 1. Block diagram of a visible light communication (VLC) system. LED—light-emitting-diode; PD—photodiode.

Once the photodiode (PD) detects an incident optical power or irradiance $E(\lambda)$ on its photosensitive surface, it will generate a photocurrent $i_r(t)$ proportional to device responsivity $R(\lambda)$ and $E(\lambda)$, which is corrupted by noise $n(t)$. Such relation is illustrated in Equation (1):

$$i_r(t) = R(\lambda)E(\lambda) + n(t) \quad (1)$$

If emitted optical signal degradation effects due to communication channel are considered, the model in the work of [1] can be described through the expressions in Equation (2):

$$\begin{aligned} i_r(t) &= R(\lambda)P_t(t) \otimes h(t) + n(t), \\ P_t(t) &= i_t(t) \otimes h_{eo}(t), \end{aligned} \quad (2)$$

where $i_t(t)$ is the bias current of light-emitting-diode (LED); $h_{eo}(t)$ is the impulse response of LED; $P_t(t)$ is the emitted instantaneous optical power by the LED; $h(t)$ represents the channel impulse response; $i_r(t)$ is the sensor generated photocurrent; $R(\lambda)$ is the photodiode responsivity; $\otimes$ denotes the convolution operator; and $n(t)$ is the system noise, which is modeled as additive white gaussian

noise (AWGN). The radiated optical power is always positive $P_t(t) \geq 0$; moreover, it is important take into account that the required illumination in a space in which people are dwelling needs to be below a certain limit of the average total emitted optical power, in order to mitigate the possible harmful effects on the eyes [2]. The average optical power of the source can be estimated with Equation (3):

$$P_{avg} = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T P_t(t) dt \quad (3)$$

VLC systems usually have two main threats: thermal noise and shot noise, both of which distort the signal of interest. The source of shot noise is the randomness in the photon absorption process and the electron-hole pair recombination within PD, whereas thermal noise depends on the environment temperature that perturbs enough the electrons in the receiver discrete devices [8]. The noise is a random process, thus it is characterized by a total variance. In the model described in the literature [8], the overall variance σ^2 is equal to the sum of the shot noise variance σ_{shot}^2 and the thermal noise variance $\sigma_{thermal}^2$ as shown in Equation (4):

$$\begin{aligned} \sigma^2 &= \sigma_{shot}^2 + \sigma_{thermal}^2, \\ \sigma^2 &= 2qR(\lambda)(P_r + P_n)B_w + i_{amp}^2 B_{amp}, \\ B_n &= \beta B_r, \end{aligned} \quad (4)$$

where:

- q , is the electron charge (1602×10^{-19} coulomb),
- $R(\lambda)$, is the PD responsivity,
- P_r is the signal power received,
- P_n is the noise power generated by external light sources,
- B_w is the channel equivalent noise bandwidth,
- i_{amp} is the parasitic current of the amplifier,
- B_{amp} is the bandwidth of the amplifier,
- β is the Bandwidth factor, and
- B_r is the signal bit rate.

A commonly used figure of merit in telecommunications is the SNR, which is a ratio between the signal power and the power contributed by the noise described by σ^2 [17–23]. In the case of a VLC system, the electrical SNR can be estimated with (5):

$$\begin{aligned} P_{in}(t) &= E(\lambda)Ar, \\ SNR &= \frac{(R(\lambda)P_{in}(t))^2}{\sigma^2} \end{aligned} \quad (5)$$

where:

- $P_{in}(t)$ is the incident optical power,
- $E(\lambda)$ is the irradiance, and
- Ar , is the PD area.

2.2. Light-To-Frequency Model

An LTF reduces and simplifies the signal acquisition process coming from a light source because its output can be sent directly to be processed to a microcontroller for data processing [10]. As a result, traditional systems using ADCs can be seen as an additional option on the list. In some low-cost cases, complex ADCs are not a good choice as they can be oversized for low speed applications, and this is the result of all the related subsystems inside of an ADC-like antialiasing filter, sampler, quantization, and encoder. The LTF in data processing quantifies light intensity variations in terms of frequency, through a current-to-frequency (CTF) converter [11,15].

An LTF generates a train of pulses with a constant duty cycle (50%) and a frequency that is a function of the irradiance incident light signal:

$$f_0 = f_D + (R_e)(E(\lambda)) \quad (6)$$

From Equation (6), it can be observed that the output frequency of the LTF f_0 is proportional to the irradiance of the perceived light $E(\lambda)$, and when no power is detected, the LTF has a constant frequency f_D , which is called dark frequency. R_e is the LTF responsivity in a certain wavelength λ and the associated units are $\text{Hz}/(\mu\text{W}/\text{cm}^2)$. The irradiance is related to the surface area A_r of the LTF converter through the expression $E(\lambda) = \frac{P_{in}}{A_r}$ measured in $\mu\text{W}/\text{cm}^2$ [1,11].

The dark frequency value, f_D , results from the leak current produced by the semiconductor material and is affected by the overall system temperature [13,14].

Given that LTF output corresponds with a pulse train with variable frequency, it is important to keep in mind the different available techniques to measure it; therefore, a selection criterion of the technique will depend on the resolution and speed of the electronic interface used [14]. Thus, if a high resolution embedded system is required and time response is not too demanding, frequency counting or an accumulation of pulses can be used; if frequency is high and a high speed electronic interface is needed for measurement, given the rapid change of the light intensity, the period measurement technique is the more suitable solution [14,15]. The period measurement demands a reference clock signal with a frequency greater than the signal of interest. In the case of the TCS3200 LTF sensor, the output signal possesses frequencies between 10 Hz and 780 kHz; hence, this guides the choice of a low-cost embedded system, because almost every single chip on the market has an equipped timer with a reference signal in the order of MHz [16]. As quoted, the period measurement technique for the scenario of optical wireless communications is properly considered, given that these systems call for online processing to decrease the overall link latency.

3. Characterization of the LTF for a VLC System

In this section, we present the characterization of the LTF converter and the analysis of the proposed VLC.

In particular, an EMC 3030 HV white light LED, Tektronix TDS 3034C oscilloscope, THORLABS PM100D instrument and an LTF TCS3200 were used for the experimental setup, as shown in Figure 2. In the TCS3200, the light-to-frequency converter reads an array of 8×8 photodiodes with 16 photodiodes with blue filters, 16 with red filters, 16 with green filters, and the remaining 16 photodiodes are clear with no filters. For this experimental setup, the TCS3200 device was configured for its maximum output frequency and only the blue channel was used for the VLC system as the blue component of a white LED lighting has the highest bandwidth [18–20]. Given the nature of the proposed experiment, it is necessary to bear in mind that the central wavelength of the blue filter in the LTF is $\lambda_c = 470 \text{ nm}$ and the total area of the photodiodes is $A_r = 0.1936 \text{ cm}^2$ [14].

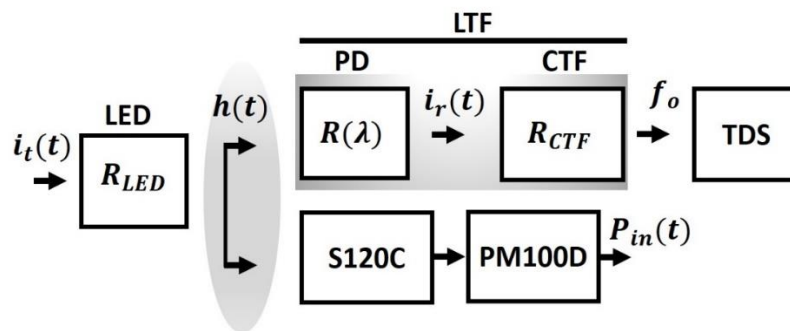


Figure 2. Experimental setup for the characterization of the LTF converter.

The schematic diagram of the experimental characterization for the LTF converter is shown in Figure 2. It consists of an optical transmitter based on a white light LED and a LTF converter acting as VLC receiver. For convenience, the LTF converter is represented as a two connected subsystems block: a photodiode and a CTF converter.

In order to analyze the performance of the LTF converter, it is necessary to derive a mathematical expression for the signal-to-noise ratio at the VLC receiver output. In this way, using Equation (1) to represent the output current of the photodiode $i_r(t)$ within the LTF block, the output signal of the CTF subsystem, f_0 , can be estimated using the following expression:

$$f_0 = R_{CTF}R(\lambda)E(\lambda) + R_{CTF}n(t) \quad (7)$$

where R_{CTF} is the CTF responsivity. Now, it is important to remark that the expression for f_0 , given by Equation (7), does not alter the LTF model as an analogy could be made between the terms of Equations (6) and (7), that is, $R_{CTF}R(\lambda)$ with $R_e(\lambda)$ and $R_{CTF}n(t)$ with f_D . The aforementioned statement can be demonstrated by considering an analysis of the units for each variable. The term R_{CTF} denotes a conversion factor between the input current in amperes (A) and output frequency in Hertz (Hz) of the CTF subsystem; therefore, the units of R_{CTF} are Hz/A. Next, $R(\lambda)$ is the conversion factor between the optical irradiance and the photocurrent output then its units are $\frac{A}{\mu W/cm^2}$. Thus, the term $R_{CTF}R(\lambda)$ will be given in the units of Hz/($\mu W/cm^2$), which is equivalent to the units of $R_e(\lambda)$ in Equation (6). Conducting a similar analysis for the term $R_{CTF}n(t)$, it can be shown that it has the same units as that of the dark frequency f_D . It is also important to note that the noise variance is scaled by the factor R_{CTF} , such that $\sigma_{f_0}^2 = R_{CTF}^2\sigma^2$, of the stochastic process $R_{CTF}n(t) = f_D$.

Once we have obtained an expression for the dark frequency f_D , the SNR value in Equation (5) can be estimated as a function of the incident irradiance and the frequency of the LTF, that is,

$$SNR = \frac{(R_{CTF}R(\lambda)E(\lambda))^2}{\sigma_{f_0}^2} = \frac{(f_0 - f_D)^2}{\sigma_{f_0}^2} \quad (8)$$

where

$$E(\lambda) = \frac{Ar}{P_{in}(t)} \quad (9)$$

3.1. Evaluation of the LTF Converter

The evaluation process for the LTF has been broken down into the following three steps:

1. constant current signal, $i_t(t)$, is applied to the transmitter LED.
2. Using the Tektronix TDS 3034C oscilloscope, the output frequency f_0 and dark frequency f_D are measured for different distance cases between the transmitter LED and the LTF.
3. Next, the incident optical power, $P_{in}(t)$, is recorded for each case using the optical sensor S120C with aperture diameter 9.5 mm, which is coupled with the THORLABS PM100D instrument. This meter console can deliver measurements of luminous flux and incident irradiance. It is not recommended to use the irradiance measurement as the PM100D instrument considers the area of the sensor S120C rather than the area of the photodiodes integrated into the LTF TCS3200 [21]. Therefore, the useful information of this experiment is the incident optical power flow $P_{in}(t)$, considering the Ar of the sensor S120C.

3.2. LTF Response to an Optical Periodic Signal

For this evaluation process, the objective is to observe the response of the LTF converter when it is excited by a periodic signal. Using this type of signal is helpful to observe the advantages and disadvantages of using the LTF as a receiver in a VLC system. For this case, the arbitrary waveform generator (AWG) RLGOL DG4162 was used to generate the modulated signal, applied to the base

of the 2N3904 NPN transistor, configured in saturation mode, and acting as the driver of the LED. A frequency sweep is then carried out for the modulating signal f_{OOK} from 1 kHz until reaching the saturation frequency of the LTF. For each frequency, the separation distance of the link between the transmitter LED and the LTF was changed, from 0 cm up to the distance where the LTF output frequency was greater than or equal to the frequency of the modulating signal, that is, $f_o \geq f_{OOK}$. This limit makes sense from the viewpoint of the frequency generated by the LTF, that is, f_o reaches its maximum value during the half-period in which the modulated signal is in a high state (presence of the optical signal).

4. Results and Discussion

In this section, LTF characterization and the proposed VLC system performance analysis are evaluated, considering the input optical signal $P_{in}(t)$, variation of the link distance, LTF output frequency f_o , and SNR. We assume that the VLC channel is corrupted by AWGN. First, the LTF performance was evaluated in function of the input constant optical signal, and we proceeded with the distance variation between the transmitter LED and the LTF receiver. Figure 3 depicts LTF output frequency and optical input power versus link distance. It can be seen in Figure 3a that LTF output maximum frequency was 780 kHz (LTF saturation frequency) at the 5 mW optical input power, with 5 cm minimum link distance. On the other hand, we can see in Figure 3b that when the power input is 10 μ W, the link distance that achieves the minimum output LTF frequency 1.6 kHz is 110 cm. This result is consistent with the inverse-square law, as the LED is a Lambertian source [16].

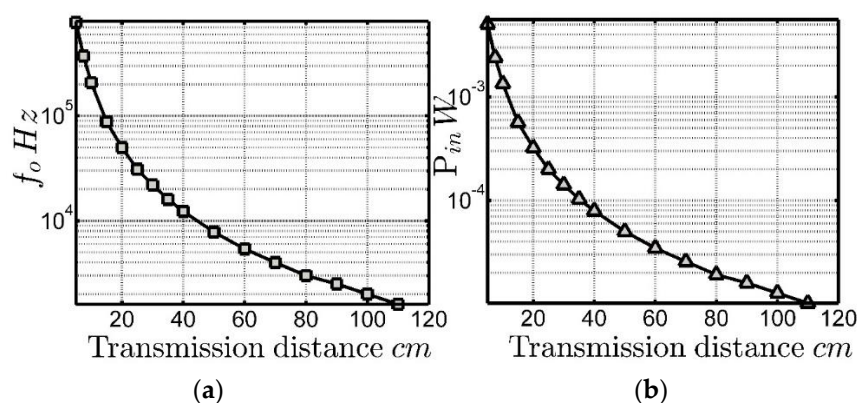


Figure 3. Experimental setup. Estimated f_o and optical power under various link distance: (a) LTF output frequency versus link distance; (b) optical input power versus link distance.

The estimated LTF responsivity value during the experiment was $R_e = 30.34 \text{ MHz}/(\mu\text{W}/\text{cm}^2)$. This result enables the LTF to detect optical power levels of the order of nW. However, in this paper, the minimum optical power reference was limited to 10 μ W, which generates a respective frequency $f_o = 2 \text{ kHz}$. This configuration was important for us to experiment with a minimum frequency in the modulating signal OOK.

Additionally, based on the data presented in Figure 4, the LTF conversion factor R_e will positively affect the SNR of the system. Therefore, to generate an LTF output frequency f_o approximate to saturation, a measured SNR equal to 18.75 dB with link distance of 5 cm was found in the experiment, as illustrated in Figure 4a; for the case of less frequency $f_o = 1.6 \text{ kHz}$, the SNR was around -35.15 dB , with maximum link distance of 110 cm, as illustrated in Figure 4b. The parameters estimated for the LTF are significantly different from those of the data sheet [15], because the experiment was performed under specific physical conditions and a white light LED was used.

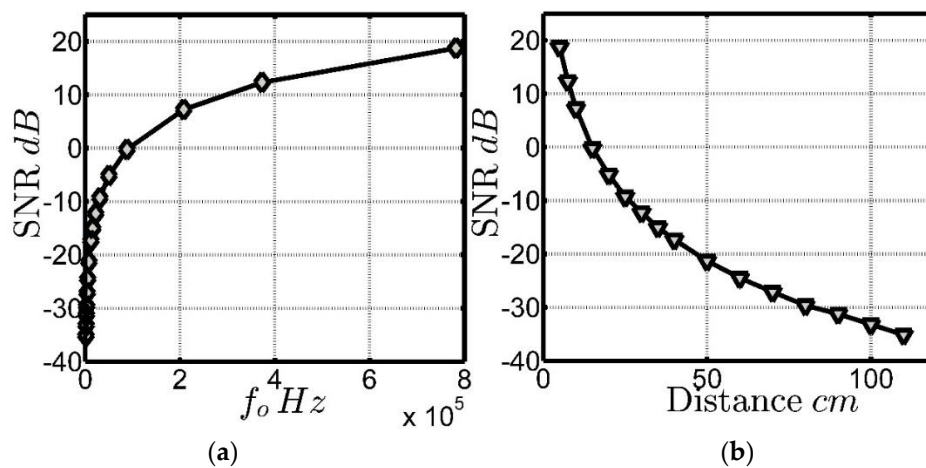


Figure 4. Model description: (a) signal-to-noise ratio (SNR) versus LTF output frequency; (b) SNR versus link distance.

The relationship $f_o = f_D$ is the dark condition (without optical power). Figure 5 summarizes the results for the dark frequency f_D versus link distance. We can see that when link distance ranges from 20 cm to 40 cm, the condition $f_D < 35$ Hz is reached, which indicates the presence of external optical sources, that is, oscilloscope, AWG, and power supplies. With this approach, it is important to mention that in the experimental setup, we do not consider focusing optical power on the LTF sensor.

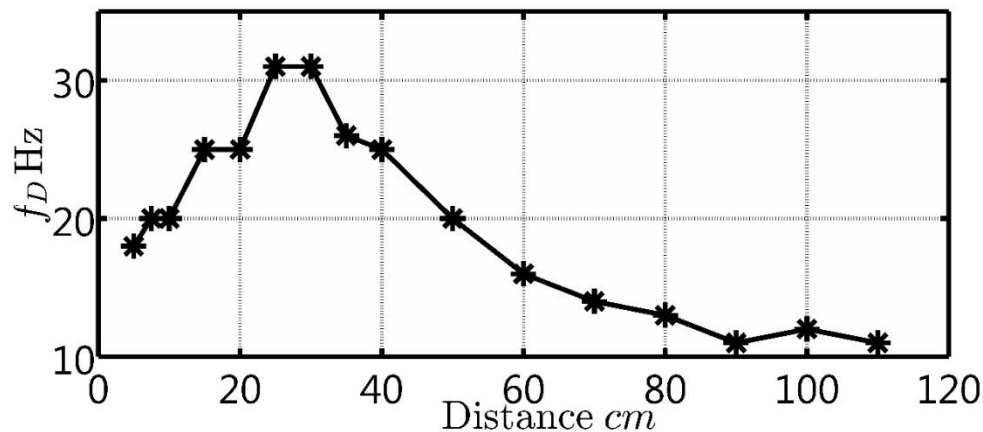


Figure 5. Dark frequency versus link distance.

The result in Figure 6 clearly shows the LTF output frequency response to light intensity variations on photodiode. At the transmitter side, the electrical OOK signal is applied to modulate the white light LED with a modulating frequency $f_{OOK} = 1$ kHz and 50% of duty cycle, as shown in Figure 6a. After free space optical transmission, the OOK signal is detected by an LTF receiver and generates an electrical signal. Then, the electrical OOK signal is converted to frequency by a current-to-frequency converter, as shown in Figure 6b.

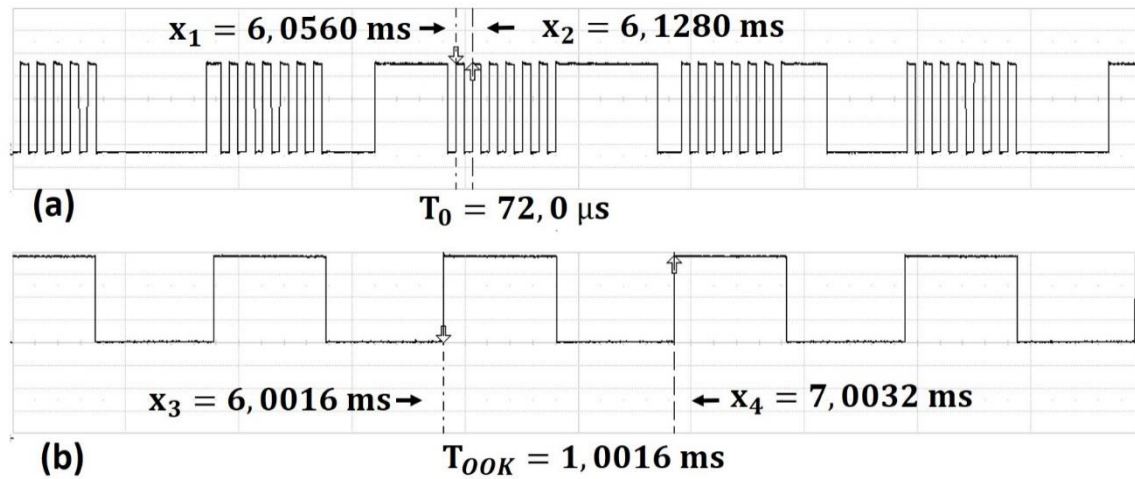


Figure 6. Transmitter with on-off keying (OOK) modulator signal and LTF as receiver signal: (a) optical power transmission; (b) LTF output frequency.

LTF converter generates a frequency around the $f_o = 13.88 \text{ kHz}$ when the LED transmit optical power when duty cycle is one, and, if duty cycle is zero, the LTF output frequency is $f_o = f_D$, with $f_D < 35 \text{ Hz}$. The $f_D \ll f_{OOK}$; therefore, for LTF frequency estimation, it was necessary that we use the period measurement technique, for maximum data-acquisition rate (this data-acquisition rate depends on the resolution of the timer) [14,15]. However, for the VLC system, such high accuracy measurement is not necessary, because in these systems, time boundaries are wide enough to determine if a symbol is in the on-off state.

We experiment with different frequency values f_{OOK} . One thing to note, however, is the LTF frequency estimation for symbol decoding. It is necessary that the condition $f_o \geq f_{OOK}$ should be fulfilled; thus, given the unknown oscillator state of the LTF, when intensity fluctuations occur, there exists a possibility that high state of the square output signal will not be completed. Therefore, we recommend that the LTF output frequency meet the following condition $f_o \geq 4f_{OOK}$, in order to mitigate the frequency estimation problem due to the deviations generated by the LTF output.

Regarding the experiment, for each frequency f_{OOK} value, we can see the link distance between the LED and the LTF converter, which would allow finding an LTF output frequency $f_o \geq 4f_{OOK}$. Figure 7 depicts an experimental estimation of the LTF output frequency f_o versus link distance, for the different values f_{OOK} . We can see that the maximum frequency f_{OOK} of modulating signal is limited by transmission length, because the light intensity on the LTF is also a function of distance. The minimal link distance was 6.2 cm for a maximum frequency $f_{OOK} = 600 \text{ kHz}$, without the LTF output frequency operates in saturation mode. Such maximum frequency could be achieved at a greater distance ($>6.2 \text{ cm}$), if we consider an optical concentrator in the receiver. For the case of less frequency $f_{OOK} = 1 \text{ kHz}$, the maximum distance was the 100 cm.

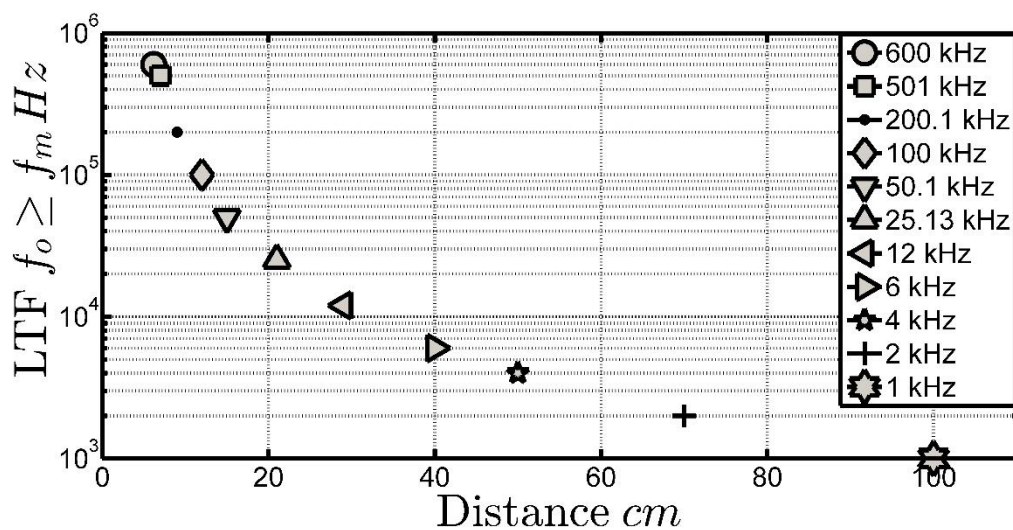


Figure 7. LTF frequency estimation for the different f_{OOK} value and variation link distance.

In Figure 4, we can appreciate the sensibility of the LTF converter to incident light. For slight variations of transmission reach, a considerable change in output frequency is observed. Nevertheless, we consider that having a receiver with high responsivity could limit the visible light communication system, if the application scenarios have light sources different to LED transmitters. Such stimulations may cause a frequency deviation of that mapped in the color-shift keying (CSK) constellation space [23].

5. Conclusions

This paper proposed a novel receiver for visible light communication system using a LTF converter as the detector. The LTF can convert the modulated light into periodic square signal with a frequency proportional to light intensity. Under this scheme, the frequency estimation can be performed with the period measurement technique, without the need of ADC modules in the receiver side. In this system, the characterization of LTF converter was presented in terms of SNR, its input optical power, and the frequency of its output squares signal. The main objective of this characterization is to identify the parameters that determine the performance of the LTF converter as a receiver in a VLC system. Among the measured parameters of the LTF detector, responsivity R_e was big enough to make the device too sensitive to light intensity variations. However, such a characteristic could affect the overall SNR of the communication, as the detector is also sensitive to power related to outside optical sources. Experimental results showed that the LTF output signal has a maximum output frequency of 600 kHz at a distance of 6.2 cm. In this setup, measured SNR reached 18.75 dB, while the lowest obtained SNR with 1.1 m length was roughly −35.1 dB. Therefore, we conclude that it is possible to use the LTF converter as a receiver in a VLC system, considering a minimum SNR value that guarantees the $f_o \geq 4f_{OOK}$ inequality. Given the condition that $f_o \geq 4f_{OOK}$, a theoretical bit rate can be achieved and would be less than or equal to 150 kbps; however, we must be aware that no bit error rate measurement was made, because the electronic elements used are noisy and under the mentioned conditions, we obtained an SNR of 18.75 dB. This could have an impact on the speed of the system, but we consider that it could be a functional VLC system, because the main application is in low data rate sceneries, so the bit rate is not critical. The $f_o \geq 4f_{OOK}$ is necessary for the identification of the LTF output frequency with the measurement system used in the receiver. Additionally, it must be ensured that the application scenario has a reduced number of non-transmitting lighting sources, in order to mitigate the negative effects of noise on the VLC receiver, and then the frequency shift in the LTF output.

The main advantage of using the LTF converter as a detector in a VLC system lies in the low complexity to convert light intensity to an electrical signal, which can be directly processed in a digital

device such as a microcontroller, a field-programmer gate array (FPGA), or an embedded system equipped with a fast reference clock [14,15].

This way of detection is suggested for low data rate sceneries (indoor location, sensor networks, VLC-ID systems) because of limited bandwidth of the LTF, which is less than 800 kHz. Hence, higher data speed can be improved with an increased order of the CSK modulation format, at the cost of a penalty in transmission reach [23].

Future works include evaluation of multilevel modulation techniques like CSK [22,23] and pulse-width modulation (PWM) [24,25], which allows one to maximize the low bandwidth of the LTF converter.

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