Adaptive Energy Saving Technique with Saturation Avoidance for Outdoor VLC

Antonio Costanzo, Valeria Loscrì

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Antonio Costanzo* *IEEE Member*, Valeria Loscri* *IEEE Senior Member*

***Abstract*—Saturation of optical receivers, caused by sunlight, represents a major issue in outdoor VLC system design for vehicular applications. This effect reduces maximum communication range, causing performance degradation when transmitter and receiver are in strict proximity. In addition, when saturation phenomena occur, only a fraction of total transmitted power is really exploited by the receiver, resulting in a significant waste of energy. The aim of this work, is to provide a novel analytical perspective, properly validated by experimental tests, in which the effects of saturation are related to the performance of outdoor VLC systems, in terms of signal to noise ratio (SNR). This analysis is further exploited for proposing an adaptive energy saving approach, which decreases the amplitude of transmitting power when saturation phenomena are detected by the receiver. A use case evaluation shows a reduction of 30% on average energy per bit transmitted, without any significant degradation of signal to noise ratio. Conversely, the adaptive control significantly improves SNR when transmitter and receiver are in close proximity and the system is fully approaching saturation.**

Keywords:VLC, Outdoor, SNR, Energy Saving

I. Introduction

A. Generalities, issues and related works

Visible Light Communication (VLC) [1] exploits Light Emitting Diodes (LED), normally employed in lighting infrastructures, also for data communication purposes. Most of the interest in VLC technology has been for indoor applications, where LED lights are ubiquitously available in buildings, commercial areas and public transports. Conversely, outdoor VLC architectures suffer sunlight interference and saturation of optical receivers. Sunlight hugely interferes with the useful signal, it saturates the photo-detector and can completely preventing, in many potential application, the use use this paradigm. Several works deal with the effects of sunlight on VLC systems [2], [3] and some noise reduction techniques have been described [4]–[6].

Saturation in optical system has been faced very few times in current literature. Maximum linear photo-current in silicon photo-detectors has been derived in [7], while an upper bound for the optical power flowing in a photo-diode before saturation occurs, has been computed in [8]. These works deal with general optical receivers, without considering the effects on a communication system. Anyway, the big concern about the saturation of optical receivers in VLC outdoor systems, is still an open issue. The waste of energy caused by saturation is another critical problem. During saturation phenomena, indeed, an increment of transmitting power does not contribute to improve SNR. In contrast, reducing power level during saturation, allows to reduce overall consumption, increase battery time and life time of optical and electrical components of the system. Even if several techniques for saving transmitted power in wireless communication system using adaptive modulation are proposed in current literature [11], [12], few works are focused on VLC. An exhaustive power consumption evaluation in High Speed VLC Systems has been provided in [13], while an interesting adaptive model, controlling input waveform of LED lamps for achieving efficient brightness and reduce power consumption, is provided in [14]. Anyway, to the best of our knowledge, our paper is the first one focusing on the relation between saturation avoidance and power consumption reduction.

Antonio Costanzo, Valeria Loscri are with Inria Lille - Nord Europe

B. Contributions

The main contributions can be summarized as follows:

- A closed form of Signal to Noise Ratio (SNR) is provided and tested using Pulse Position Modulation (PPM) signals, considering saturation effects in real scenarios.
- A novel adaptive energy saving technique, integrating a saturation avoidance mechanism, which controls power levels at each transmission has been proposed.
- An experimental setup, based on a Software Defined Paradigm, has been designed and employed for validating the model . Furthermore, an evaluation of proposed Adaptive Energy Saving technique, considering a simple use case and evaluating both energy consumption and system performance, has been provided.

The paper is organized as follows. In section II, we analytically describe the problem of saturation, and its effect on the performance of VLC outdoor communication, according to channel estimation, modulation control and detection. Furthermore, we describe our approach for reducing energy consumption. An experimental validation of the saturation is described in section III, as well as the evaluation of proposed energy saving technique. Finally, we conclude the work in section IV.

II. System Model

A. Saturation in VLC systems

In our analysis, we consider a basic point-to-point VLC communication between a transmitter, i.e. a LED and a receiver, i.e. a photodiode. A typical outdoor application is represented by two vehicles communicating by the means of a VLC-based paradigm, as depicted in Fig. 1.

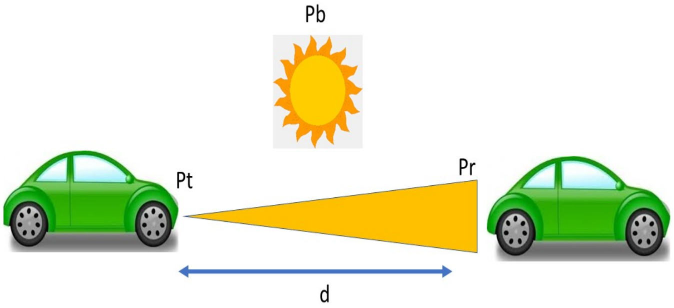

Fig. 1. An outdoor communication setup: VLC vehicular communication.

The ratio between the optical radiated power P_T, and the received optical power at a distance d is modeled by considering the LED as a Lambertian source. In automotive application, low-beam and high-beam headlamps with asymmetrical intensity distributions should be considered. However, independently by the pattern distribution, the highest effect of saturation occurs in the direction of maximum optical power. Since our work is focused on saturation effects, transmitter and receiver have been aligned and a simple model has been employed in order to facilitate the analysis without loss of generality. Assuming -3dB beam width of the LED equal to θ_{-3dB}, received power can be calculated as follows [15]:

$$P_R = P_T \frac{(m+1)A}{2\pi d^2} cos^m(\theta) cos(\psi) TG \quad (1)$$

being A the effective area of the photodiode, d the distance between transmitter and receiver, θ the angle of irradiance with respect to the axis normal to the transmitter surface and ψ the one referred to the receiver surface,T the gain of optical filter, G the receiver optical concentrator gain and m the order of the Lambertian Radiation. Lambertian order is calculated as follows

$$m = \frac{ln2}{ln(cos(\theta_{-3dB}))} \quad (2)$$

while the gain of the optical concentrator can be calculated, starting by its refraction index η and by the field of view of the receiver ψ_0, as follows:

$$G = \frac{\eta^2}{sin^2(\psi_0)} \quad (3)$$

Once the light strikes to the photo-diode, the optical power is converted into an electrical current, I_{ph}, proportional to the responsivity S of the photo-diode. However, when the total optical power, P increases, the photo-diode current tends to saturate to a constant value I_s, given by [7]. Total power P is given by the optical received power, due to the transmitting led, and the background light power P_B, mainly due to sunlight and other external light source, namely $P = P_R + P_B$.

$$I_{ph} = I_s(1 - e^{-\frac{I_s}{SPTG}}) \quad (4)$$

where, I_s depends by the applied voltage at photodiode terminals, V_a, the load resistor R_L , which depends of the the further electrical stages of the receiver, and the built in voltage V_b, related to the potential across the depletion region in thermal equilibrium of the diode [8].

$$I_s = \frac{V_b - V_a}{R_L} \quad (5)$$

When input optical power is low, photo-diode works in a linear region and power-current characteristic curve is represented by a straight line with slope STG, but rapidly approaches to Is when it increases [9]. The ratio between output current and saturation current $\alpha = \frac{I_{ph}}{I_s}$ is chosen according to the tolerance of the system to non linearity. If we indicate $I_x = S(P_B + P_R)TG$, eq. (4) becomes:

$$I_{ph} = I_s(1 - e^{-\frac{I_s}{I_x}}) \quad (6)$$

We consider a limit value $\alpha_0 = 0.9$, which typically guarantees linearity in dynamic range studies [7], and $I_x^\star$, that is its corresponding I_x value. Manipulating eq. (6), we obtain

$$\frac{I_{ph}}{I_s} = 1 - e^{-\frac{I_s}{I_x^\star}}, I_x^\star = -\frac{I_s}{\ln(1-\alpha)} \quad (7)$$

Assuming that for $I_x \leq I_x^\star$ the photo-diode works in a linear region, we apply the principle of superposition for calculating the Signal to Noise Ratio in output to the photo-diode. According to (4), let us consider $I_R = I_{ph}(P = P_R)$ the current induced by the transmitting LED, $I_B = I_{ph}(P = P_B)$, the one induced by the background sunlight. Shot noise [15], equal to $P_{shot} = \frac{I_{shot}}{S}$, and the thermal noise, $P_{th} = \frac{I_{th}}{S}$, cause an additive current equal to:

$$I_{shot} = \sqrt{2qS(P_R + P_B)B}, \quad (8)$$

and

$$I_{th} = \sqrt{kT_{env}B} \quad (9)$$

where q is the electron charge, k is Boltzmann constant, B the bandwidth of the system and T_{env} the temperature of the environment. Most of outdoor VLC systems provide a minimum optical power $P_{Tmin} = QP_T$, for illumination purpose even when the communication system is not active, so we consider a further term $P_{Rmin} = QP_R$, corresponding to the received power corresponding to this quota, and $I_{Rmin} = I_{ph}(P = P_{Rmin})$ the related current. In the linear region, SNR can be rewritten as:

$$SNR = \frac{P_R - P_{Rmin}}{P_B + P_{shot} + P_{th}} = (\frac{I_R - I_{Rmin}}{I_B + I_{shot} + I_{th}})^2 \quad (10)$$

which becomes:

$$SNR = (\frac{e^{-\frac{I_s}{SP_RTG}} - e^{-\frac{I_s}{SP_RQTG}}}{1 - e^{-\frac{I_s}{SP_BTG}} + I_{shot} + I_{th}})^2 \quad (11)$$

for $I_x \leq I_x^\star$.

When the photodiode behavior approaches saturation, the upper level of the current passing in the photodiode is clipped to the value I_s, namely:

$$SNR = \left(\frac{I_s - e^{-\frac{I_s}{SP_R TG}}}{1 - e^{-\frac{I_s}{SP_B TG}} + I_{shot} + I_{th}}\right)^2 \qquad (12)$$

for $I_x \geq I_x^\star$.

B. Energy saving technique based on saturation avoidance

As asserted before, when the transmitter and the receiver are too close, or a high level of background interference affects the optical channel, saturation phenomena prevent the receiver to completely exploit the power provided by the transmitter, resulting in waste of energy. In these conditions an increasing of optical power does not produce an enhancement of Signal to Noise Ratio. Converters, filters and all other active components of transmitting and receiving contribute to energy consumption [13], too. However, in our algorithm we only consider the power consumption of the transmitting lamp, since it represents the most effective parameter to control in order to achieve a significant energy reduction. We propose an adaptive mechanism for controlling transmitted power, when the receiver detects saturation effect. The receiver measures the current I_{ph} produced by the photo-diode, which is compared to the threshold current $I_x{}^*$, in order to detect saturation phenomena. If saturation occurs, the receiver sends to the transmitter an alert message, in a dedicated time slot, otherwise, no feedback messages are sent. This time slot has been added after the synchronization frame, according to the technique we proposed in [10] for VLC full duplex communication. When the transmitter receives a feedback containing an alert message, transmitting power is reduced by a decreasing factor β, potentially reaching a minimum power value P_{min} when successive saturation phenomena are detected. In contrast, transmitting power is gradually increased by a factor γ when no saturation occurs, up to the maximum LED power P_{max}. Main operations are described in algorithm 1 and 2.

Algorithm 1 TX operation

```
Initialize Power level P_new = P_max
while TRUE
    Transmit data with P_new
    Read alert message
     if (Alert is not empty)
            Decrease Power Level P_new = max(P_min, P_new * β)
     else
            Increase Power Level P_new = min(P_max, P_new * γ)
```

Algorithm 2 RX operation

```
while TRUE
    Receive data
    Evaluate I_ph
     if (I_ph ≥ I_x*)
            Send alert message
```

III. Performance Evaluation

In this Section we validate the correctness of proposed model, providing a basic performance analysis of an outdoor Visible Light Communication link, based on 2, 4, 8 and 16 PPM modulations. Furthermore, we evaluate system performance, in terms of signal to noise ratio and energy per bit, implementing energy saving algorithm, proposed in Section II. It is worth to notice that the aim of this work is not to show a complete operative architecture, integrated in a real outdoor VLC application (for instance automotive), but, rather, to provide a useful mathematical analysis for considering saturation problems that can highly impact a VLC system. Indeed, the design, the components and the location of the experiments, have been maintained as simple as possible to avoid that other aspects, that are not addressed in the proposed model, which could affect the model and prevent a fair comparison between theoretical results and experimental tests.

A. Experimental validation of saturation effects on system performance

A Software Defined Architecture, has been employed for the validation. Two NI USRP 2920 and two low frequency daughterboards have been mounted in the devices in order to manage PPM signals in the correct frequency range. All the signal processing operations have been managed using ad hoc Lab-View routines, working on two different PCs, one in receiver and one in transmitting path, connected via Gigabit Ethernet with the corresponding front ends. The transmitting LED driver is composed by bias tee circuit, allowing to increase or decrease the DC component of the light signal, a single transistor for allowing ON-OFF operations and other passive elements (capacitor, resistance, etc.). In the receiver path, in order to evaluate saturation effects due only to the photodiode, a completely passive circuit has been employed. No optical filters or beam concentrators have been used, so $G = T = 1$. We measured system performance outside the window of our office room, as shown in Fig. 2, in a heavy cloudy afternoon (illuminance up to 1000 lux). Optical receiver is equipped by a CENTRONIC OSD15-5T photodiode, with 0.20 A/W responsivity and 120 degrees field of view. Optical transmitter is equipped by a CREE MKRAWT-02-0000-0D00J2051 LED, showing 45 degrees field of view and fed with a maximum electrical power of 15W.

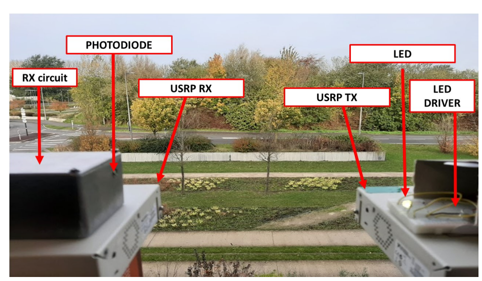

Fig. 2. Experimental Setup

According to the above setup, a series of measurements have been carried out, varying electrical led power from 1W to 15W. In Fig. 3, Signal to Noise Ratio (SNR) has been theoretically and experimentally evaluated for 2,4,8 and 16 PPM, considering a pulse duration equal to 500ns for each modulation and a distance between transmitter and receiver equal to 1m. A

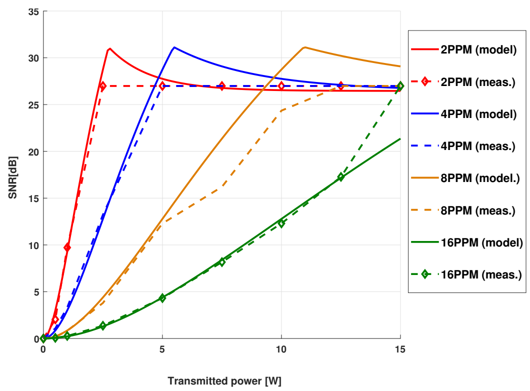

Fig. 3. Transmitted power vs Signal to Noise Ratio

good agreement between experimental results and theoretical data is found. We notice that when saturation level is reached, exceeded power does not result in an improvement in system performance, especially for lower modulation index. In fact, For 2 PPM modulation, we notice how an increasing of feeding power from 5W to 15 W does not improve significantly Signal to Noise Ratio. This aspect could be interesting to be further analyzed in those systems where low energy consumption is a hard constraint.

At the same way, for 16PPM, a power increasing implies only a marginal SNR improvement after a certain value. These considerations could also be taken into account in order to exploit an adaptive system, changing the maximum irradiated power and the order of modulation scheme on the basis of measured performance on the receiver. Several channel parameters (external light interference, reciprocal position between transmitter and receiver, etc.) are involved and several system parameters (bias voltage, optical filter transmittance, etc.) can be setup for improving the system. For this reason, an intelligent system, learning from the environment and accordingly set the parameters in order to avoid saturation and waste of power can be implemented based on this theoretical model. When power level increases too much, system performances degrade, especially when transmitter and receiver are in proximity.

B. *Evaluation of energy saving algorithm*

A simple use case has been considered In order to evaluate the performance of proposed energy saving technique. The transmitted is located in a reference position and has not been moved during the evaluation. The initial position of the receiver is 3m away, and it moves toward the transmitter. Each step measures 10cm and the receiver transmits a frame of duration equal to 1s in each step. A maximum transmitting power of 15W and a minimum power of 1.5W have been considered. According to this scenario, we have compared the performance of VLC system without and with the energy saving approach in Figures 4. Total transmitting power, signal to noise ratio and energy per received bit have been considered for each frame, while eventual power control messages are transmitted only at the end of the frame. We computed bit energy according to the analysis provided in [10] and considering 16PPM modulation with 1Mbit/s data rate.

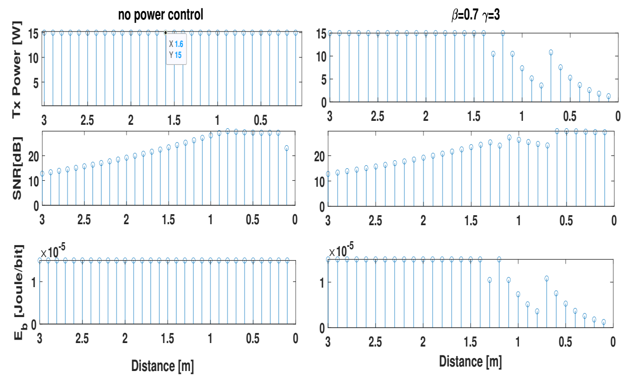

Fig. 4. Use case: performance evaluation if no algorithm is applied (left). Performance evaluation applying saving energy algorithm (right). Transmitting power, Signal to Noise Ratio, and energy per bit.

No saturation phenomena are detected when the receiver is further than 1.4m from the transmitter. In this case, the algorithm does not produce any changes in transmitting power, and consequently, no changes in system performance are observed. When the distance decreases, the receiver approaches to saturation and the algorithm reduces total transmitting power in order to save energy. The overall reduction on transmitting energy, considering the entire path, is around 30%, while no significant reduction in SNR have been noticed. In addition, when the transmitter and the receiver are in proximity (less than 20cm), the algorithm produces a 10dB improvement on SNR, since power control avoids the compression of signal dynamic caused by saturation. The right choice of β and γ is important to achieve real benefits on system performance. An aggressive power reduction strategy (both β and γ low) could cause a fast convergence on minimum energy point, with a significant reduction of SNR, while, a conservative approach (both β and γ high), could not cause significant effects in terms neither of power reduction, nor in SNR improvement in case TX and RX are the immediate vicinity. In order to analyse these effects on system performance, the average SNR and the average Energy per bit in the overall path have been evaluated, considering the same scenario, but different values of β and γ for each evaluation (Fig. 5).

We notice how, in this scenario, best performance are achieved when $\beta \approx 0.6$ and $\gamma \geq 2$ are set, with a significant reduction of average energy per bit, without an sensible degradation of SNR, in comparison with the case when no algorithm is applied (red markers in Fig 5). Further considerations on the optimization of β andγ, as well as a

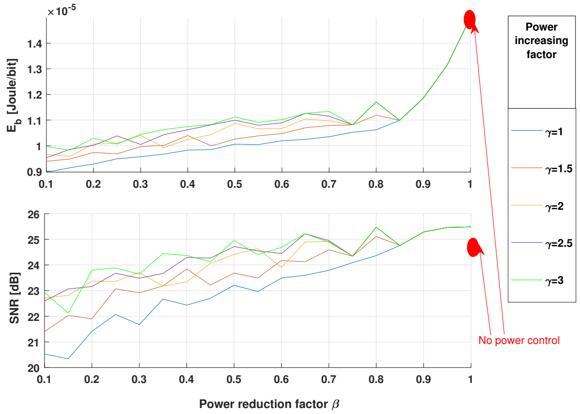

Fig. 5. Use case: Average SNR and Energy per bit, using different values of reduction factor β and increasing factor γ

different implementation of the algorithm, considering also precedent states of saturation, will be deeper taken into account in a future extension of this work. Since saturation phenomena also depend by the external sunlight interference, a comparison between system performance with and without the application of the power adaptive algorithm, are shown in fig. 6. We considered the same use case of previous evaluation. We notice

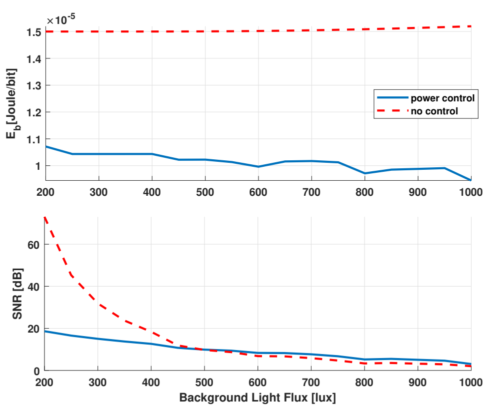

Fig. 6. Energy saving technique performance with different levels of background optical noise

how, the amount of average energy per bit, saved using the algorithm, is not significantly affected by external sunlight, while SNR slightly diverges only for very low values of external background noise, but no significant difference are noticed for higher values of interference, which could be critical for the right behavior of the system.

IV. Conclusion

In this paper we have considered saturation effects on a VLC system based on a transmitter/LED and a receiver/photo-diode. In particular, we have derived a theoretical model accounting for this effect when both transmission and background (e.g. sunlight noise) power are considered. The model has been validated by the means of experimental results based on a test-bed implementing a Software Defined approach. Such a kind of model is paramount for outdoor VLC applications, since we have been able to demonstrate that the increasing of the power not only does not improve the performance of the system but after certain values it impacts negatively on SNR, by uselessly wasting power. Based on this analysis, we have proposed an adaptive technique for mitigating saturation effects, and, consequently, saving energy during transmission. In particular, a use case evaluation, showing a significant reduction of energy per transmitted bit has been presented, for different levels of external sunlight interference, with no negative effects on Signal to Noise Ratio.

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