Optical Wireless CDMA Employing Solid State Lighting LEDs

Tim C. W. Schenk, Lorenzo Feri, Hongming Yang, Jean-Paul M. G. Linnartz
Philips Research Laboratories, High Tech Campus 37, 5656 AE Eindhoven, The Netherlands,
Tel. +31 40 27 49764, Fax. +31 40 27 46276, tim.schenk@philips.com

***Abstract*— We show that optical wireless CDMA can successfully be applied for visible light communication with power LEDs. We detail how it meets the requirements of multiple access communication, particularly for positioning and illumination sensing.**

I. Introduction

Solid state lighting is considered to become the dominant illumination technology in future. The advantages of the application of high-brightness light-emitting diodes (LEDs) for lighting include superior longevity, high radiative efficiency, and limited heat generation [1].

One of the additional advantageous properties of lighting LEDs is that these have sufficient bandwidth to allow for fast modulation of their light output. The light sources, in parallel to their illumination function, can invisibly embed data in their light output. This means that these LEDs can be used as the basis for wireless optical communication, often referred to as visible light communication (VLC). Consequently, in the future every light source can potentially be a communication source. Hence, VLC enables new application categories of lighting systems. The most important ones are data communication [2], positioning [3], and lighting control [4].

For data communication, experimental tests have shown that data rates of up to 100 Mbps are feasible [2], [5]. Most of the works on this subject, however, do not address the topic of multiple access (MA). When we consider a system with multiple distributed light sources that all transmit different streams, MA shows to be essential for a robust solution. This is especially true for future lighting systems, where we expect a high density of LEDs [6].

Illumination sensing is a key enabler for localized control of lighting effects in lighting systems with a large number of LEDs. In such systems, consisting of numerous dimmable and color controllable LED light sources, the complexity of controlling each source individually is too high for users. To ease user control, we proposed a control system for rendering light effects at a target location in [4]. This rendering is based on the estimation of the individual illumination contributions of different light sources, named *illumination sensing*. VLC-based transmission of unique identifiers per light source enables this sensing.

Thus it is essential to solve the MA issue for the considered applications. In the following we discuss suitable optical code division multiple access (OCDMA) solutions.

II. Key requirements

The key requirements for MA-based VLC solutions are:
a) **Independent data and illumination**: The main function of the LEDs is illumination, thus the data modulation should not affect the short-term average light output of the light sources.
b) **Imperceivable**: The data modulation of the LEDs should not create visible flickering. This can be achieved by minimizing the energy in low frequency components (approximately below 100 Hz) due to the modulation in the light output.
c) **Efficient LED operation**: The proposed MA and modulation techniques should preferably be compatible with the typically applied pulse-width modulation (PWM) dimming of LED light output. Such binary on-off switching allows one to drive the LEDs at their nominal current, which results in energy efficient operation and prevents color aberrations.
d) **Number of LEDs**: A large number of LEDs should be supported in the system, typically more than 100.
e) **Application performance**: The VLC solution should meet the application requirements. For data communication these are expressed in terms of bit-error rate (BER), for positioning in terms of detection probability, and for illumination sensing in terms of estimation error.

III. Synchronous CDMA solution

To meet the requirements a) and c), we consider PWM-based embedding of data in the light output. This is achieved by selecting the duty cycle of the signal based on the required illumination level and then embedding the data by modulating the width of the pulses. In this section we consider a synchronous CDMA technique as a solution to the MA problem. An example of the resulting driving signal for the lth LED is given in Fig. 1.

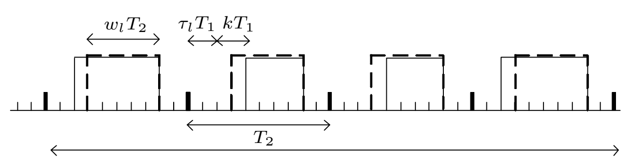

Fig. 1. Example of the PWM pulse train for one frame for an LED, modulated (solid) and unmodulated (dashed). The embedded code is $[-1, 1, 1, -1]$.

It shows the transmission of CDMA code $[-1, 1, 1, -1]$ and bit $b = 1$, where one chip is embedded per block of length T_2 and one bit is transmitted per frame of length T_3. T_1 is the resolution at which the LEDs can be modulated. The unmodulated pulses are given by the dashed line for a dimming level of w_l = 50%. The starting point counter of the modulated pulse is defined by τ_l and the modulation depth by k.

As spreading code we consider Walsh-Hadamard (WH) codes, of which we apply all except the "all ones" code word. The remaining code words are DC-free and contain a small amount of low frequency components. The latter results in suppressed visibility of the embedded data. The code length determines the number of LEDs that can be uniquely identified and that can transmit data in the system, i.e. for a code length N the system supports $N-1$ LEDs. The chip detection can be based on the average light power over a T_2 block or on the on-off pattern on a T_1 level. Advantageously, the first approach requires a receiver bandwidth of $1/T_2$ instead of $1/T_1$.

To support more lamps in the system, LEDs can additionally be identified by the start of the pulse in a block τ_l. The resulting scheme is a hybrid code and time division multiple access (CTDMA) solution. The number of pulse start positions equals $N_{\mathrm{s}} = T_2/T_1$, where $1/T_1$ typically is in the order of 1 MHz and N_{s} will be larger than 2^{10}. As a result, the number of uniquely addressable LEDs is $N_{\mathrm{s}}N/k$. Typically this is larger than 10,000, thereby fulfilling requirement d). We note that CTDMA requires a receiver bandwidth of $1/T_1$.

After propagation through the channel, the individual light intensity from the lth LED at the sensor location is given by g_l. The resulting electrical signal, received with a photodetector (PD) with a responsivity of ε, is input to a receiver. After matched filtering the incoming signal, this receiver correlates it with the WH codebook. The resulting signal-to-noise ratio (SNR), after despreading, equals

$$\mathrm{SNR}_l = Nkg_l^2\varepsilon^2/(4\sigma_{\mathrm{n}}^2), \tag{1}$$

where σ_{n}^2 is the variance of the sum of shot and thermal noise. For a threshold detector this results in a BER of

$$\mathrm{BER}_l = (1/2)\mathrm{erfc}(\sqrt{\mathrm{SNR}_l/2}), \tag{2}$$

and a mean squared error (MSE) in estimation of the illumination contribution g_l using the least-squares estimator of

$$\sigma_{\mathrm{LSE}}^2 = g_l^2/\mathrm{SNR}_l. \tag{3}$$

Figure 2 illustrates the BER and MSE results for the CTDMA-PWM modulation for three color lighting LEDs, in a system with 10,000 LEDs spaced regularly on the ceiling, see [7]. We can observe that the communication link is almost errorless up to a range r_l of 10.7, 9.3 and 8.1 m for the red, green, and blue LEDs, respectively. A normalized MSE (N-MSE) of 10^{-2} is achieved for distances up to 12.5, 10.7 and 9.3 m, respectively. Beyond these ranges, the sensor moves away from the center of the LED light beam and performance decreases fast. The variation in performance for the different color LEDs can be attributed to the difference in LED light output power and the color dependence of the PD responsivity.

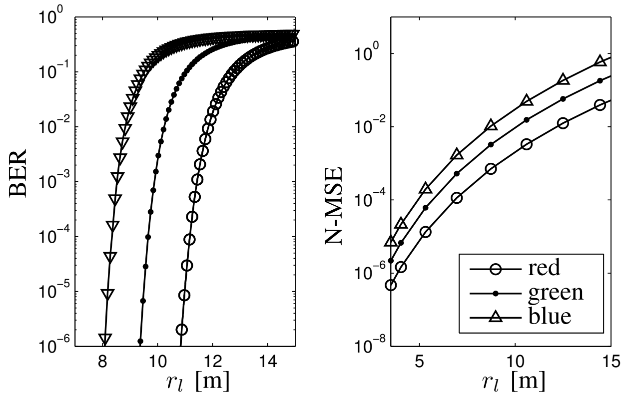

Fig. 2. BER (left) and MSE (right) performance vs. LED-PD propagation distance for red, green and blue LEDs. Ceiling height h = 3.5 m.

IV. Asynchronous CDMA solution

When applying the solution of Section III, the different LEDs in the system require synchronization, which forms a clear disadvantage. Loss of synchronization severely affects system performance. Since synchronization may not be available for every system, we also developed an asynchronous VLC CDMA solution. This solution is reviewed here.

Different types of pseudonoise (PN) codes can be applied to encode and decode data in VLC. In contrast to the codes in Section III, these codes are not perfectly orthogonal, however, they have a low crosscorrelation for all possible timing offsets. The latter makes them specifically suitable for asynchronous operation. Also here the codes are embedded with the PWM method illustrated in Fig. 1, meeting requirements a) and c).

The main disadvantage of this MA solution is that it has to deal with multiple access interference (MAI), i.e. the contributions from other light sources are not fully suppressed. This will result in a decreased SNIR, given by

$$\mathrm{SNIR}_l = \frac{Nkg_l^2\varepsilon^2}{4(\sigma_{\mathrm{n}}^2 + \varepsilon^2\sum_{m\neq l} g_m^2\rho_{ml}^2)}, \tag{4}$$

where ρ_{ml} denotes the correlation between the mth and lth code. This decreased SNIR results in an increased BER and MSE, using (2) and (3). We can conclude from (4) that a PN code needs to be much longer than a synchronous code, to match the performance of a synchronous solution. This is especially true since, according to requirement d), many LEDs need to be allocated. The resulting increased detection time and lower data rate, make such solution unsuitable for several applications. Moreover, to meet requirement b), additional constraints are imposed on the set of PN codes, to avoid low frequency components in the illumination signals.

V. Conclusions

We showed how CDMA can be applied for MA in VLC using PWM modulation, and how both proposed solutions meet the key system requirements. We foresee that extensions in asynchronous CDMA will enable more VLC applications.

References

[1] E. F. Schubert, et al., *Science*, vol. 308, May 2005.
[2] J. Grubor, et al., in *Proc. ECOC 2007*, Sept. 2007.
[3] G. Pang, et al., in *Proc. World Congr. Intell. Transport Syst.*, 1998.
[4] J.-P. M. G. Linnartz, et al., in *Proc. ICC*, May 2008.
[5] T. Komine, et al., *IEEE Trans. on Cons. Elect.*, vol. 50, Feb. 2004.
[6] H. Yang, et al., *IEEE Trans. on Sig. Proc.*, vol. 57, Mar. 2009.
[7] J.-P. M. G. Linnartz, et al., under rev. *IEEE Trans. on Sig. Proc.*, 2009.