LAT Indoor MIMO-VLC
—Localize, Access and Transmit— *

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Abstract–Visible Light Communications (VLC) is an innovative technology that uses the visible spectrum for high-speed data communications. In this paper we investigate the use of MIMO in the design of luminaires supporting VLC and, specifically, in enabling localization and high data rate services. Localization and transmission appear as two different problems in the communication system; however, the former is helpful to understand which is the diversity degree that the system can adopt, in order to achieve the required performance in terms of BER and data rate. Finally, we consider also how different users can access the Internet by means of a TDMA-like access scheme

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1 Introduction

Visible Light Communications (VLC) has received much recent attention through manifestations as LiFi and IEEE $802.15.4$. As a "smart lighting" paradigm, it has received significant interest by the scientific community since this new paradigm may be used for sensing, localization and data transmission, in addition to the common illumination application [1–4]. The main feature of VLC is its potential for "dual-use", providing both illumination and high-speed data access. This aspect brings to several advantages that make VLC a great complement to Radio-Frequency (RF) communications. Indeed, while exploiting the free use of the visible light spectrum, VLC uses the directional of optical transmissions, and can provide secure transmissions.

VLC systems can adopt Multiple Input Multiple Output (MIMO) techniques through the use of multiple contributing light sources. Several authors have been investigating this technique, *e.g.* in [5], the authors consider a MIMO-LED scheme based on imaging with 4 LEDs and 4 photodiodes. Among the main advantages, MIMO-VLC works easily, by deploying multiple LED devices. As a result, network performances are strongly enhanced.

As the title of this paper suggests, the proposed solution, namely *LAT* (*L*ocalization, *A*ccess and *T*ransmission), considers the following pillars: (*i*) an indoor localization technique based on a power measurements database, (*ii*) a MIMO-LED architecture for adaptive Pulse Position Modulation (PPM), and (*iii*) a TDMA approach, suitable for VLC connectivity links.

The remainder of the paper is organized as follows. In Section 2 we present the indoor localization method, which exploits a database collecting power measurements. Section 3 investigates a novel coding technique for multiuser access based on the MIMO-LED system with a Space-Time Block Coding. This method considers a PPM modulation, and shows an increase in transmission rates, with no additional signal degradation. Moreover, we briefly describe the VLC TDMA approach, and highlight how the transmission performances are increased for a single user. Numerical results, showing the effectiveness of LAT solution for nominal use cases, are in Section 4. Finally, conclusions are drawn at the end of this paper.

2 Database-like Localization

The localization procedure can be performed according to real-time measures by cross checking them with already available statistics present in a geographical database. It is assumed to collect several—power—measurements, which can be compared with realtime acquisitions. Let us consider the case with a single LED in an area (*e.g.*, a room) designed as a $N_x \times N_y$ grid, where

$$N_x = \frac{L_x}{\Delta x} \quad \text{and} \quad N_y = \frac{L_y}{\Delta y}, \tag{1}$$

being L_x and L_y the lengths on two orthogonal directions, and Δ_x and Δ_y the paces (assumed identical). By using only one LED, ambiguity can occur since, usually, the same energy level is detected over a circle *i.e.*, the base section of a cone, as similar as for each cellular system, where localization is performed with only one base station. Analytically, this is the situation where in different positions the *energy* measurements are almost the same, such as

$$E_{x_i,y_i} \cong E_{x_j,y_j} \quad \text{with } x_i \neq x_j, \text{ and/or } y_i \neq y_j. \tag{2}$$

One solution to reduce ambiguity issue is to use several LED devices, accordingly displaced in order to provide a statistical independence of measurements w.r.t the LEDs. As an instance, if we consider a number of LEDs equal to M opportunely displaced over the ceiling of a room, we can gather M real-time measurements corresponding to the set of (x_i, y_i) positions in the room. For M energy measurements, $E_{x_i,y_i}(k)$ collected in corresponding to each (x_i, y_i) position, we obtain a discrete d.d.p., whose mean value for each LED is

$$\mathbb{E}\left\{E_{x_i,y_i}(k)\right\} = \sum_{k=1}^{M} E_{x_i,y_i}(k)\, p\left(E_{x_i,y_i}\right), \tag{3}$$

where $\mathbb{E}\{\cdot\}$ represents the mean value operator and $p\left(E_{x_i,y_i}\right)$ can be obtained by performing a histogram approximation. In order to estimate the unknown position, the Maximum Likelihood (ML) criterion can be applied, so that the estimation is obtained by solving the following problem

$$(\hat{x}_i, \hat{y}_i) = \arg\max_{x_i,y_i} p\left(\mathbf{r}\,|\mathbf{m}\right), \tag{4}$$

where $\mathbf{r}$ is the measurements vector w.r.t the LEDs, while $\mathbf{m}$ is the vector of mean values of measurements. In the simple case of a Gaussian distributed energy collection, the problem in (4) reduces to the following

$$(\hat{x}_i, \hat{y}_i) = \arg\min_{x_i,y_i} \left\|\mathbf{r} - \mathbf{m}\right\|^2. \tag{5}$$

This approach is very effective although we need, in practice, at least $M = 3$ in order to considerably reduce the effect of ambiguity.

3 Adaptive PPM Space-Time Coding

The MIMO-LEDs scheme can be represented via the use of vectors and matrices under the assumption of using PPM. This modulation format is sufficiently simple to implement; it allows the space-time matrix to have some interesting properties and helps localization task since information is carried on delay, that is, range.

Let us start from a model where the channel is close to be flat w.r.t the frequency response (*i.e.*, a LOS scenario). In principle with NLOS channels it is possible to have delay spread and so, Inter Pulse Interference or Inter Symbol Interference. The way to avoid those effects is to increase the signaling time since the consequent rate reduction may be counterbalanced by spatial diversity.

We pose n_T and n_R as the number of LEDs and photodiodes at the transmitter and the receiver sides, respectively. The received signal can be written in the following way

$$\mathbf{Y} = \mathbf{X}\mathbf{H} + \mathbf{W}, \tag{6}$$

where (*i*) $\mathbf{Y}$ is the $L \times n_R$ matrix collecting the L-PPM symbols received by the n_R photodiodes, (*ii*) $\mathbf{H}$ is a $n_T \times n_R$ matrix, where each element in the position (l, m) is the channel path between the l-th transmitting LED and the m-th receiving photodiode, (*iii*) $\mathbf{W}$ is a $L \times n_R$ matrix, describing the whole disturbance, expressed in terms of thermal and ambient noise, and (*iv*) $\mathbf{X}$ is the PPM Space-Time Block Code (STBC) $L \times n_T$ matrix that carries information according to the cardinality of

PPM and the number of transmitting LEDs. The matrix **X** logically describes the presence of a pulse among the time axis and on the space.

By assuming a $(L = 2)$-PPM performed over $(n_T = 2)$ LEDs, the matrix dimension is then 2×2. The maximum allowed number of matrix is Ln_T, under the constraint of transmitting only one signal per slot by each slot in matrix form this means to have a sole 1 on each matrix column, such as

$$\begin{aligned} \mathbf{C}_1 &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \mathbf{C}_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \\ \mathbf{C}_3 &= \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix}, \mathbf{C}_4 = \begin{bmatrix} 0 & 0 \\ 1 & 1 \end{bmatrix}. \end{aligned} \tag{7}$$

Considering the matrix $\mathbf{C}_1$ in the 2×2 model, since the generic l-th column represents the signal emitted by the l-th LED, the first column refers to the signal emitted by the first LED while the second column refers to the second LED. By assuming the pulse duration equal to T_p and a guard time T_g, the time length of each column is $L(T_p + T_g)$. Thus, the total rate is

$$R = \frac{1}{L\left(T_p + T_g\right)} \log_2 L^{\min\{n_R, n_T\}}. \tag{8}$$

Leveraging (8), we can state that the achievement of high rate values is due to both the possibility of having several LEDs/photodiodes that can be installed also in small rooms, and the LED ability to quickly operate the electrical-to-optical conversion.

In the case of four LEDs serving U users, one goal is to displace among the timeline the devices, so to improve energy efficiency by considering user position. It is not assured, in general, that each user needs to be served by all LEDs since it depends on single-user rate requirement, evaluable as

$$R_u = \frac{1}{UL_u\left(T_p + T_g\right)} \log_2 L_u^{\min\left\{n_R^u, n_T^u\right\}}, \tag{9}$$

where $L_u = L$ for the u-th user, with $u = \{1, 2, \cdots, n\}$, so that $L_{u(i)} \neq L_{u(j)}$ with $(i, j) \leq n$. It follows that (8) is the sum over n of single R_u.

4 Numerical Results

The effectiveness of the proposed MIMO-VLC system has been proven in a use case depicting a room, as shown in Figure 1, representing a 10 m $\times 9$ m $\times 3$ m open office at the Department of Applied Electronics of Roma Tre University. This scenario, comprised of 4 workspaces with several chairs, has been designed via Candles software [6]. The wall reflectivity is 80% while for the workspaces it is 50%, typical for wooden tables. Under each workspace, there is a chest whose reflectivity has been assumed equal to 70%. No reflectivity factor has been assumed for the chairs. Along the south wall, there is a huge window covering almost the room length, with a reflectivity factor of 0%; while along the north wall, we assume a bookcase with 80% of reflectivity. In the whole room, a noise level of 5.8 W/cm^2/nm has been considered.

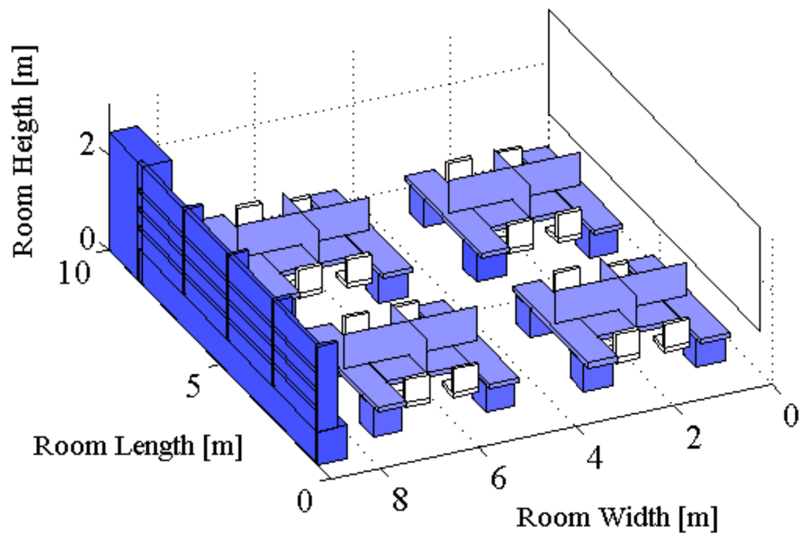

Figure 1: Description of the "Room" at the Department of Applied Electronics of Roma Tre University, where measures took place.

The receiver is based on channel inversion (or spatial pseudo inversion in case of $n_T \neq n_R$) so the measure operated by the LEDs in the localization step is fundamental both for localization and channel estimation.

The following results provide a viable solution for the deployment of a set of transmitters in the room, accordingly to BER requirements. In Figure 2 a map reporting the active LEDs needed for achieving a target BER of 10^{-5} is shown. In the middle area, that is, at the center of the room, only 1 LED may be used to achieve the target BER; 2 LEDs are needed in the most part of the positions in the room, while 3 and 4 LEDs have been considered in positions close to the boundaries of the room.

By changing the required BER till to achieve the value of 10^{-7} the number of required LEDs increases, as depicted in Figure 3. This is due since the performance improvement can be obtained only via higher diversity order w.r.t. the case of BER $= 10^{-5}$. Note that only few zones (close to the middle of the room) require only 1 or 2 LEDs, while on different positions, not necessary on the borders, 3 or 4 LEDs are required to achieve the target performance.

Last in Figure 4 the effect of the number of users, averaged on different room positions, has been reported by considering a target BER of 10^{-5}. The total rate of the system does not change considerably by increasing the number of users, while the rate per user obviously decreases according to the TDMA policy till to achieve rate of the order of Mb/s.

5 Conclusions

This paper investigates a MIMO approach for VLC indoor system. The main aim of proposed method is to evaluate the position of the users and use this information to optimize performance by serving devices with one or more LEDs in dependence of a target BER and data rate requirement.

Future work will be addressed to extensive simulations, to validate the indoor MIMO-VLC

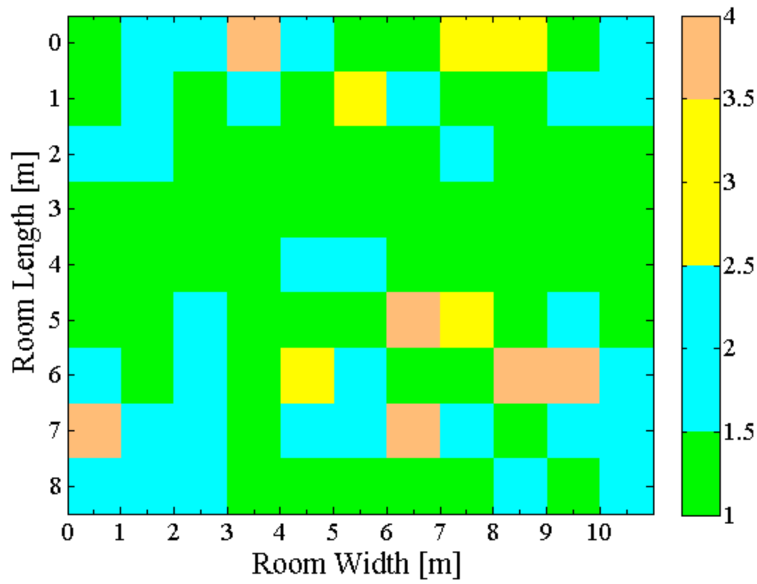

Figure 2: Number of active LEDs required at BER $= 10^{-5}$.

system in terms of position accuracy and Dilution of Precision.

References

[1] D. O'Brien, H. Le Minh, L. Zeng, G. Faulkner, K. Lee, D. Jung, Y. Oh, and E. T. Won, "Indoor visible light communications: challenges and prospects," in *Proc. of SPIE*, vol. 7091, 2008.

[2] M. Kavehrad, "Sustainable Energy-Efficient Wireless Applications using Light," *IEEE Communications Magazine*, pp. 66–73, December 2010.

[3] T. Borogovac, M. Rahaim, and J. B. Carruthers, "Spotlighting for Visible Light Communications and Illumination," in *Proc. on the First IEEE Workshop on Optical Wireless Communications, GLOBECOM*, Miami, FL USA, December 2010.

[4] F. Szczot, "Safety problems in free space optical transmission," in *Proc. of SPIE*, vol. 6159, 2006.

[5] L. Zeng, D. O'Brien, H. Minh, G. Faulkner, K. Lee, D. Jung, Y. Oh, and E. T. Won, "High data rate multiple input multiple output (MIMO) optical wireless communications using white led lighting," *Selected Areas in Communications, IEEE Journal on*, vol. 27, no. 9, pp. 1654 –1662, December 2009.

[6] M. Rahaim, T. Borogovac, and J. B. Carruthers, "CandLES: Communications and Lighting Emulation Software," in *Proc. on the 5-th ACM Intl. Workshop on Wireless Network Testbeds, Experimental Evaluation and Characterization, ACM*, 2010.

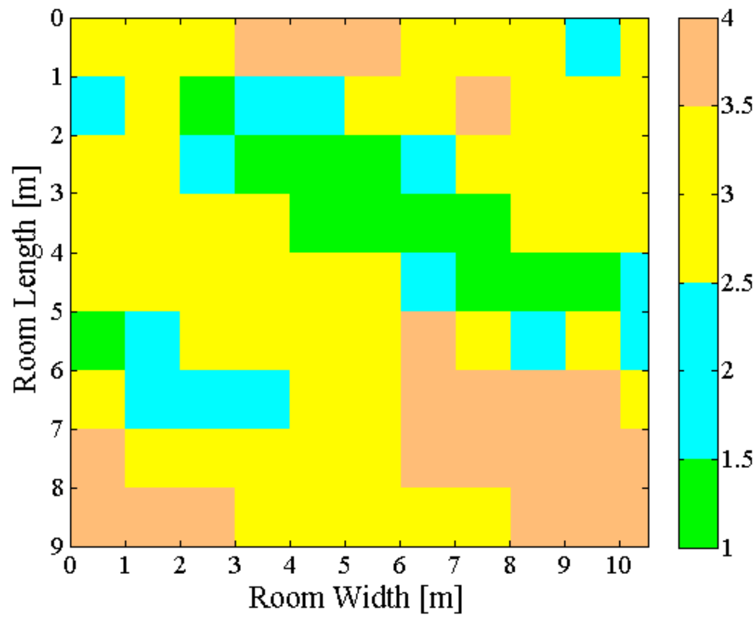

Figure 3: Number of active LEDs required at BER $= 10^{-7}$.

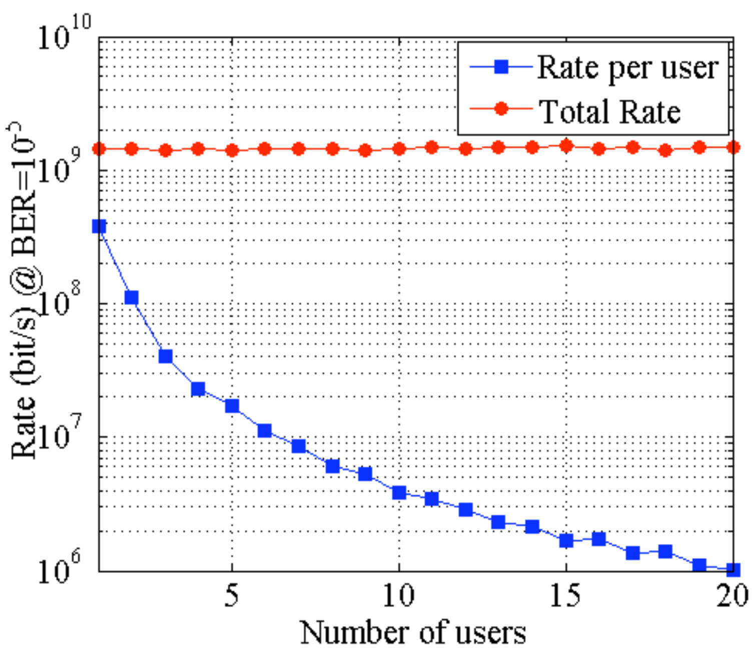

Figure 4: Total rate sustained by the network (*red*), and rate per user (*blue*) at BER $= 10^{-5}$, vs. different numbers of users.