Coding for Uncoordinated Multiple Access in Visible Light Positioning Systems

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***Abstract*—To avoid interference among the signals from different transmitters in a visible light positioning (VLP) system, central unit is usually used. This resists us to simply deploy a VLP system on the existing lighting infrastructure. This paper proposes an uncoordinated multiple access scheme for VLP systems without the need for central unit. A unique codeword is allocated to each transmitter equipped with a light emitting diodes (LED). The transmitters send the codewords in an asynchronous manner. A receiver can eliminate the interference among the LEDs by using Fast Fourier Transform (FFT) to estimate the average received powers from each LED. Then the estimated power is used for position estimation. The required FFT size and the scheme delay, i.e., the minimum received signal duration needed by the receiver to estimate the average received powers from the LEDs, grow linearly with the number of LEDs. The proposed scheme is compared with the existing schemes in literature. Simulation results show that the proposed scheme outperforms the existing schemes in terms of receiver complexity, scheme delay and system performance. The average 3-dimensional position error of 3 cm is achievable for average transmitting optical flux of 500 lm. Our proposed scheme can be applied to a system with a large number of LEDs. The potential of the proposed scheme for data communication is discussed.**

***Index Terms*—Uncoordinated Multiple Access Scheme; Large Scale Indoor Positioning Systems; Visible Light Communications.**

I. INTRODUCTION

Visible light communication (VLC) is getting a lot of attention recently due to its promising features such as license-free spectrum, high security and energy efficiency [1–3]. In VLC systems, light emitting diodes (LEDs) and photodiodes (PDs) are used as transmitters and receivers, respectively. These systems provide not only illumination but also communication and positioning [4].

Recently, indoor positioning systems based on visible light (see e.g., [5–9]) are reported in literature. These systems estimate receiver's position based on the received light intensity from each LED, and require a central unit to coordinate the transmission of the LEDs. This is called *system-level synchronisation* due to the need of the central unit. The systems proposed in [7, 8] are based on Time Division Multiple Access (TDMA). However, TDMA is only suitable for systems with a small number of LEDs as explained below. Consider a TDMA system with N LEDs where each LED transmits for a duty cycle of $\frac{1}{N}$. If the required average transmitting optical power from each LED is Φ_i, then each LED needs to transmit optical power of $N\Phi_i$ that may become impractical for large N.

Philips has deployed an indoor positioning system using VLC. In their patent [10], a central unit allocates one or more coded light components (CLC) to each light source. These CLC are used to modulate the signal. The CLC may be a sinusoidal (a single tone in the frequency domain), rectangular wave or other waveform. Each CLC has a unique switching frequency used as an identifier of the light source. Instead of using PDs, receivers use camera(s) to detect the received light. Since the exposure time of a camera causes selective frequency response, some frequency components cannot be detected. To mitigate this problem, the central unit first collects information about the exposure times of the cameras of all active users, which can be done through a radio frequency channel, and then optimizes the assigned switching frequencies of the CLC such that it avoids allocating undetectable switching frequencies. When the number of users increases, the central unit may not be able to avoid allocating all the undetectable switching frequencies. Therefore, it divides the users into groups and serves each group at different times that degrades the system accuracy.

It is important to develop a multiple access scheme that can get rid of the need of central units so that the complexity and the cost of the system can be reduced. Recently, some VLC-based positioning systems [11–15] are proposed which do not use central units. In [11], a unique codeword is assigned to each LED, however the codeword length grows exponentially with the number of LEDs. Each LED can randomly start its transmission. At the receiver, the received power from each LED is estimated by perfectly eliminating the interference from other LEDs, which is commonly called multiple access interference (MAI). Because of the exponential increase of the codeword length, the scheme delay, i.e., the minimum received signal duration needed by the receiver to estimate the average received powers from the LEDs, grows exponentially with the number of LEDs. Moreover, the system proposed in [11] is based on an assumption that the delays in the transmission among the LEDs are integer multiple of chip time. We call this *chip-level synchronisation*.

In [12–15], LEDs start transmitting at any time, and no chip-level synchronisation is required. This setting is considered as the *asynchronous case*. Random access protocol termed as basic frame slotted ALOHA (BFSA) is proposed for VLC-based indoor positioning systems in [12]. In BFSA, each LED randomly selects time to transmit data. However, to reduce the probability of collision among LEDs, the total number of slots in a frame should be much larger than the number of LEDs and each LED uses one slot only during a frame. It is shown in [12] that achieving probability of successful transmission equal to 0.95 requires 150 time slots per frame for a system with 4 LEDs, which significantly increases the scheme delay. Moreover, to satisfy the required illumination level, the transmitters need to transmit much higher optical powers because each LED transmits only once in the frame. In [13, 14], Frequency Division Multiple Access (FDMA) with square waves for VLC-based positioning are proposed. In [13], a square wave with a unique switching frequency is allocated to each LED. These switching frequencies are chosen between 2 kHz and 4 kHz and each switching frequency is different from others by at least 0.5 kHz. Then the receiver applies Fast Fourier Transform (FFT) to estimate the average received powers from the LEDs. However, the accuracy of the estimates degrades dramatically due to MAI. In [14], each LED is assigned a square wave with a unique switching frequency, but these switching frequencies grow exponentially with the number of LEDs. At the receiver, the FFT of the received signal is calculated and the average received powers from the LEDs are estimated. Due to the exponential increase of the switching frequencies, the FFT size and the scheme delay grow exponentially with the number of LEDs. Also, the estimated average received powers are impacted by MAI. Although it is possible to reduce the effect of MAI by increasing the sampling rate of the received signal, the needed FFT size increases and consequently the receiver complexity grows. Similarly, in [15], the effect of MAI severely degrades the estimated received power, where asynchronous optical code division multiple access (A-OCDMA) is applied for VLC-based positioning systems.

In this paper, we propose an uncoordinated multiple access (UMA) scheme for the *asynchronous case* where LEDs can start transmitting at different times without the need for a central unit. In this scheme, a unique codeword is allocated to each LED. By applying FFT, these codewords enable the receiver to estimate the average received powers from the LEDs without any MAI impact. Then the receiver uses the estimated powers for positioning. Instead of using camera, PD is used to simplify the receiver design. The FFT size and the scheme delay grow linearly with the number of LEDs. The codewords are defined in an alphabet with only $N+1$ values for N LEDs. Moreover, the average transmitting optical power can be tuned easily to satisfy the required illumination level. The proposed scheme is compared with the FDMA scheme in [14] in terms of receiver complexity, scheme delay and system performance.

This paper is organized as follows. Section II gives the overview of the visible light channel model and explains the problem formulation. The proposed multiple access scheme is detailed in Section III. Simulation results are presented in Section IV. Finally, discussion and conclusion are given in Section IV and Section V, respectively.

II. Channel Model and Problem Formulation

A. Channel Model

Suppose the distance between LED i in a transmitter and a PD in a receiver is d_i for $1 \leq i \leq N$. If ϕ_i is the irradiance angle with respect to the LED i's normal and ψ is the incidence angle with respect to the PD's normal, then the channel gain of a LoS optical wireless channel [16] between Transmitter i and a PD is given by

$$h_i = \frac{(l+1)A}{2\pi d_i^2} \cos^l(\phi_i) T(\psi) g(\psi) \cos^f(\psi), \qquad (1)$$

where the parameters are explained as follows. The Lambertian parameters of the LED and PD are given by $l = \frac{-\log 2}{\log(\cos(\phi_{1/2}))}$ and $f = \frac{-\log 2}{\log(\cos(\psi_{1/2}))}$, where $\phi_{1/2}$ is the half-power angle of irradiance of an LED and $\psi_{1/2}$ is the half-power angle of incidence of a PD. The effective area of the PD at the receiver is given by A. The filter gain and concentrator gain are represented by $T(\psi)$ and $g(\psi)$, respectively. When the average transmitting optical flux of LED i is Φ_i (in lumens), the average received optical power† of the PD is given by $P_i = \Phi_i h_i$ (in lux$\cdot$ m^2). In our system, we do not use filter and concentrator at the receiver (i.e., $T(\psi) = g(\psi) = 1$). In this setting, we assume without loss of generality that the optical power incident on the PD from LED i is given by

$$P_i = \frac{\Phi_i (l+1)A}{2\pi d_i^2} \cos^l(\phi_i) \cos^f(\psi). \qquad (2)$$

An uncoordinated indoor positioning system using visible light is depicted in Fig. 1. In this system, assume that N LEDs are installed in a space. All LEDs transmit simultaneously and they may interfere with one another. The receiver is a mobile device equipped with a PD and an accelerometer. To estimate the receiver's position, the positioning algorithm [8] is applied that requires the average received power from at least 2 LEDs and accelerometer measurements as inputs. Assume that the receiver starts receiving signals from N LEDs at time $t = 0$. Denote the transmitted signal from LED i at time t as $x_i(t)$. Suppose that LED i starts transmitting at $t = -\tau_i$. Since LEDs may be switched on at different times, τ_i may be different from one LED to another. The superposition of signals from all LEDs is received together with the background light intensity Φ_0 at the receiver. Here, we assume that h_i and Φ_0 are constant over a short period of time. This is justified by that it is common to achieve a transmission rate over 10^6 symbol/ second in VLC [17]. If the receiver's displacement and the change in the background light intensity are negligible within 10^{-3} seconds, h_i and Φ_0 can be seen as invariant for more than 10^3 symbols. Without loss of generality, assume that R_p, the responsivity of the PD, is equal to 1. So the received signal is modelled as

$$y(t) = \sum_{i=1}^{N} x_i(t) h_i + \Phi_0 + w(t), \qquad (3)$$

†Here, we use the photometric unit lux$\cdot$m^2 for power. Physical units lux$\cdot$m^2 and Watts are interchangeable and the constant for conversion depends on the device.

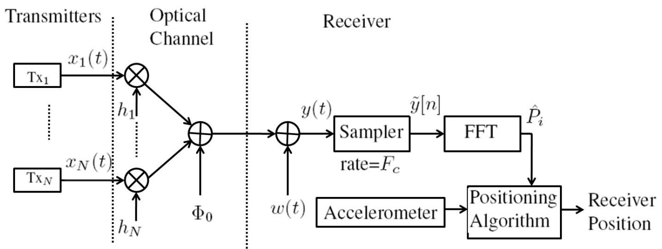


Fig. 1: Hierarchy of indoor positioning system using visible light. (a) Transmitter side. (b) Receiver side.

where $w(t)$ consists of both shot noise and thermal noise. At the receiver, the signal $y(t)$ is sampled at a finite rate F_c before the FFT is applied to estimate the average received powers from the LEDs. Then the estimated average received powers and the accelerometer measurements are used to estimate receiver's position.

B. Problem Formulation

Since the LEDs transmit simultaneously, $y(t)$ is the sum of the received powers from different LEDs. Furthermore, the receiver has no idea how long a transmitter has transmitted. Therefore, we need to cleverly design $x_i(t)$ such that the receiver can distinguish the average received power from LED i denoted by P_i.

III. Proposed System

In our proposed multiple access scheme, we assign a unique codeword to each LED, which controls the generation of $x_i(t)$. These codewords are generated by means of sinusoidal signals. By using these codewords, the average received power from each LED can be estimated precisely in the frequency domain and then used for positioning.

A. Transmitter Design

Suppose N independent LEDs are installed in a space with $N \geq 2$. A unique codeword of length $2N$ chips is allocated to each LED. Define T_c as the chip duration so that the codeword duration is $2NT_c$. Let $\mathbf{C}_i$ be the codeword assigned to LED i. The codewords are generated according to the following definition.

Definition 1. *Let $C_{i,j}$ be the amplitude of the j-th chip in the codeword $\mathbf{C}_i$. For $0 \leq j \leq 2N-1$, define*

$$C_{i,j} = cos\left(\frac{2\pi ij}{2N}\right) + 1, \tag{4}$$

and

$$\mathbf{C}_i = (C_{i,j}) \qquad for \quad 0 \leq j \leq 2N-1. \tag{5}$$

Also, $\mathbf{C}_i$ satisfies that $\frac{1}{2N}\sum_{j=0}^{2N-1} C_{i,j} = 1$.

The codeword $\mathbf{C}_i$ is repeatedly transmitted by LED i so that the transmitted signal from LED i is determined by $\mathbf{C}_i$ according to

$$x_i(t) = \Phi_i \sum_{\rho=0}^{\infty} \sum_{j=0}^{2N-1} C_{i,j}\ \mathrm{rect}(t - jT_c - \rho 2NT_c + \tau_i), \tag{6}$$

where Φ_i is the average transmitting optical flux per chip from LED i and

$$\mathrm{rect}(t) = \begin{cases} 1 & 0 \leq t < T_c, \\ 0 & \text{otherwise}. \end{cases} \tag{7}$$

Note that the codewords are defined in an alphabet with $N+1$ values, which is different from [14] that requires only two values.

B. Receiver Design

The receiver instantaneously receives the superposition of received signals from the LEDs that are within its field of view (FOV). Assume that the receiver knows which codeword is assigned to each LED. The received signal $y(t)$ is sampled at a rate of $\frac{1}{T_c}$. Define a *frame* as a received vector of length $2N$ samples. For $0 \leq n \leq 2N-1$,

$$\begin{aligned} \tilde{\mathbf{y}}[n] &= y(nT_c) \\ &= \sum_{i=1}^{N} h_i x_i(nT_c) + \Phi_0 + w(nT_c). \end{aligned} \tag{8}$$

For $\mu = 0, \ldots, 2N-1$, let $\mathbf{Y}[\mu]$, $\mathbf{R}[\mu]$ and $\mathbf{W}[\mu]$ be the Discrete Fourier Transform (DFT) of $\tilde{\mathbf{y}}[n]$, $\sum_{i=1}^{N} h_i x_i(nT_c) + \Phi_0$ and $w(nT_c)$, respectively. Then the estimated average received power from LED i is given by

$$\hat{P}_i = \begin{cases} \frac{|\mathbf{Y}[i]|}{N} = \frac{|\mathbf{R}[i]+\mathbf{W}[i]|}{N} & i = 1, \ldots, N-1, \\ \frac{|\mathbf{Y}[i]|}{2N} = \frac{|\mathbf{R}[i]+\mathbf{W}[i]|}{2N} & i = N. \end{cases} \tag{9}$$

Theorem 1. *(Complete elimination of MAI): For all i, the estimated average received power from LED i, $\hat{P}_i$, is equal to*

$$\hat{P}_i = \begin{cases} \frac{|\mathbf{R}[i]+\mathbf{W}[i]|}{N} & i = 1, \ldots, N-1, \\ \frac{|\mathbf{R}[i]+\mathbf{W}[i]|}{2N} & i = N. \end{cases} \tag{10}$$

where

$$P_i = \begin{cases} \frac{|\mathbf{R}[i]|}{N} & i = 1, \ldots, N-1, \\ \frac{|\mathbf{R}[i]|}{2N} & i = N. \end{cases} \tag{11}$$

and $\mathbf{W}[i]$ is the i-th element in the DFT of $w(nT_c)$ for $0 \leq n \leq 2N-1$. Therefore, $\hat{P}_i$ is only affected by the additive noise $w(t)$ but not P_j for $j \neq i$. Hence, MAI is totally eliminated.

Theorem 1 tells that it is possible to estimate the average received power from LED i without MAI effect. This can be done by applying FFT of size $2N$ on one frame. After estimating the average received powers from the LEDs, positioning algorithms (e.g., [8]) can be applied to estimate user's position.

Example 1. *Consider $N = 2$, frequency modulation of the LEDs $= 2$ MHz and $T_c = \frac{1}{2\times10^6} = 5 \times 10^{-7}$ s so that the frame duration $2NT_c = 2 \times 10^{-6}$ s, $\tau_1 = 0$, $\tau_2 = 3.5T_c$, $\Phi_0 = w(t) = 0$, $\Phi_1 = \Phi_2 = 1$, $h_1 = 1$ and $h_2 = 2$ so that the average received power from LED 1 $P_1 = h_1\Phi_1 = 1$ and the average received power from LED 2 $P_2 = h_2\Phi_2 = 2$. The transmitted signals of LED 1 $x_1(t)$ and LED 2 $x_2(t)$ are shown in Fig. 2(a) and (b), respectively. These signals are based on two cosine waves with different frequencies which*

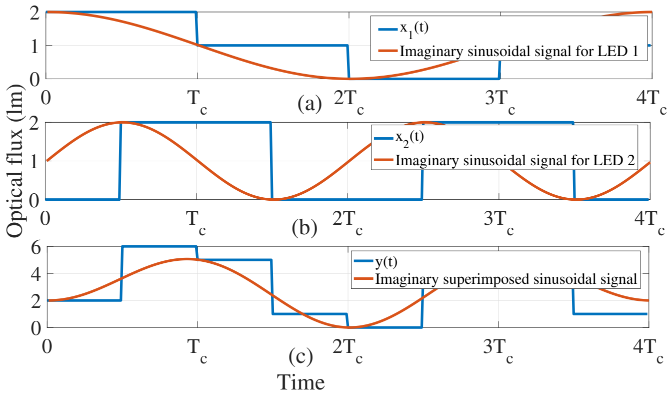


Fig. 2: The codewords and their corresponding imaginary analog sinusoidal signals at (a) LED 1 (b) LED 2 (c) receiver.

TABLE I: Simulation Parameters.

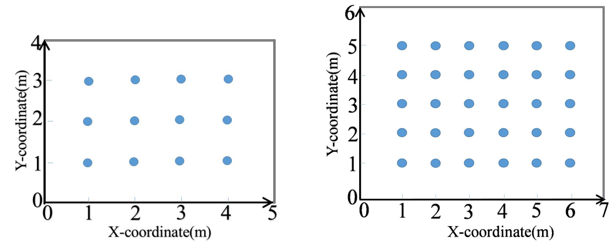
Transmitter configuration	**Values**
LED half power-angle $\phi_{1/2}$	$\frac{\pi}{3}$ rad
Background noise current	$51\mu A$
τ_i	random
Receiver configuration	**Values**
Number of PD	1
PD's Lambertian parameter f	1.4
PD's FOV	$\frac{\pi}{2}$ rad
PD's responsivity R_p	22 nA/lux
Receiver's area A	15 mm^2
Mean current generated by PD due to light emitted by LED i	$\frac{R_p P_i}{A}$
$\sigma^2_{\texttt{noise}} = \sigma^2_{\texttt{thermal}} + \sigma^2_{\texttt{shot}}$	$8.0185 \times 10^{-18} + 1.869 \times 10^{-11} \mu_{I_{Ri}}$ [7]
Accelerometer noise variance	$10^{-5}(m/s^2)^2$

are indicated in the figure as imaginary sinusoidal signals. Note that $x_1(t)$ and $x_2(t)$ complete one and two cycles, respectively, during one frame duration so that the human eye cannot sense such fast light intensity fluctuation. The received signal $y(t)$ and its corresponding imaginary sinusoidal signal are illustrated in Fig. 2(c). In this example, the frame length $2N = 4$ so that the received signal $y(t)$ is sampled at $t = nT_c$ for $0 \leq n \leq 3$ to obtain $\tilde{\mathbf{y}}[n] = \{2 \ \ 5 \ \ 0 \ \ 5\}$. By applying FFT on $\tilde{\mathbf{y}}[n]$, we have $|Y[\mu]| = \{12 \ \ 2 \ \ 8 \ \ 2\}$. Then we apply (9) to have $\hat{P}_1 = \frac{|Y[1]|}{2} = 1 = P_1$ and $\hat{P}_2 = \frac{|Y[2]|}{4} = 2 = P_2$, which demonstrates that the estimated average received powers from the LEDs are free of MAI.

IV. Simulation Results

A. Simulation Setup

In this section, we compare UMA with FDMA [14] in terms of system performance, receiver complexity and scheme delay. Moreover, we present and discuss the numerical results for UMA in systems with large number of LEDs. We use Monte Carlo simulation to evaluate the performance of UMA and FDMA. We assume that each LED transmits the same average optical flux per chip. The receiver is equipped with a PD and an accelerometer. LEDs start transmitting at random times and then continue transmitting. The parameters of the transmitters and the receiver configuration are listed in Table I. Figure 3



(a) Setup 1: length = 5 m, width = 4 m, height = 5 m and $N = 12$.

(b) Setup 2: length = 7 m, width = 6 m, height = 5 m and $N = 30$.

Fig. 3: Space dimensions and LEDs configuration

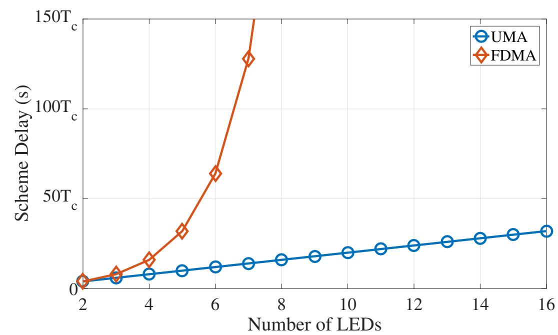


Fig. 4: The scheme delays of UMA and FDMA vs the number of LEDs.

shows two considered setups for space dimensions and LED configurations. In these two setups, the LEDs are regularly placed over the space and separated by a distance of 1 m from their closest LEDs.

B. Comparison of UMA with FDMA

We first compare the scheme delay and the receiver complexity of both schemes. We define the scheme delay as the minimum received signal duration needed by the receiver in order to estimate the average received powers of the LEDs. For UMA, the scheme delay is equal to the frame duration $2NT_c$. However, for FDMA, the scheme delay is $2^N T_c$ which is equal to the time duration needed for the square wave with the lowest switching frequency to complete one cycle.

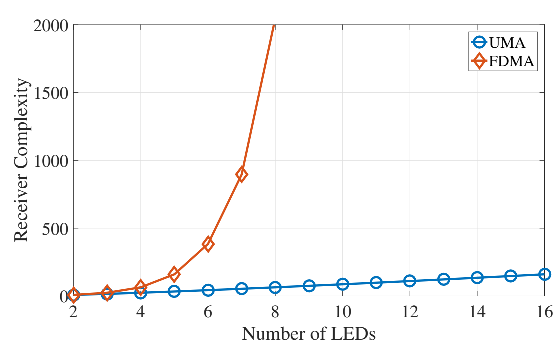


Fig. 5: The receiver complexity of UMA and FDMA vs the number of LEDs.

We now consider the receiver complexity, which is defined as the total number of real additions and multiplications at the receiver. For both multiple access schemes, the receiver complexity is associated with the FFT complexity. We consider the complexity of an M-point FFT operations as $\mathcal{O}(M \log_2 M)$ [18]. For a fair comparison, we here consider equal sampling rate $\frac{1}{T_c}$ for both schemes. Thus, the FFT sizes of UMA and FDMA are $2N$ and 2^N, respectively. Figure 4 and Fig. 5 illustrate the scheme delay and receiver complexity of both schemes vs the number of LEDs, respectively. For $N = 16$, the scheme delay of FDMA is $65536T_c$, while the scheme delay of UMA is $32T_c$. For the same N, the receiver complexities of UMA and FDMA are 160 and 1048576, respectively. Note that this significant difference in the scheme delay and receiver complexity between both schemes is due to the fact that both scheme delay and the FFT size of UMA and FDMA grow linearly and exponentially with the number of LEDs, respectively. A short scheme delay is critical for a positioning system to track fast moving objects. In our proposed scheme, the receiver can estimate its position after every received frame whose time duration is $2NT_c$.

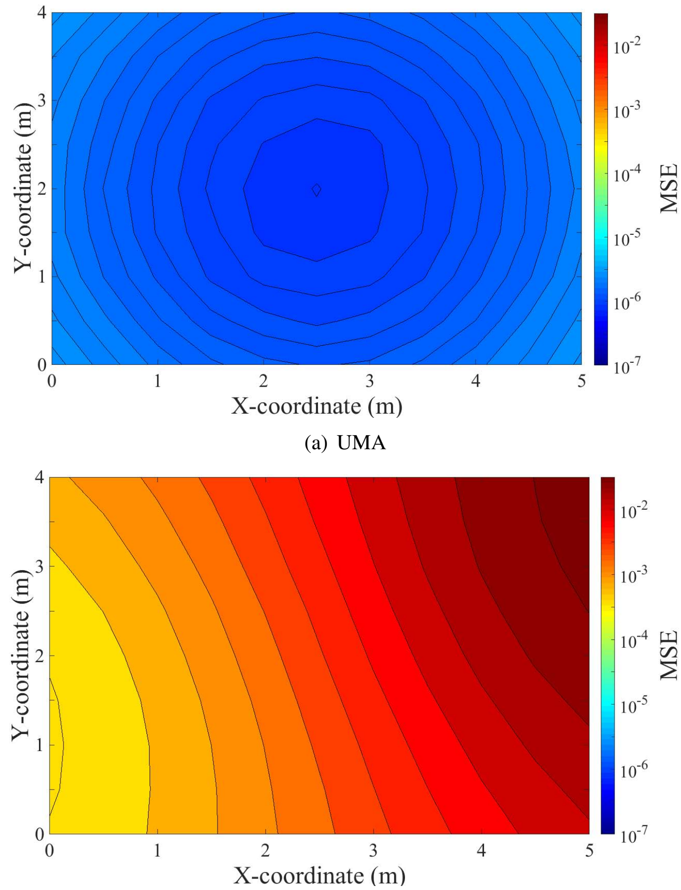
We now compare the system performance of both schemes. Here, we consider Setup 1 for space dimensions and LEDs configuration, shown in Fig. 3(a), where number of LEDs is 12. Both the frequencies of the codewords of UMA and the switching frequencies of the square waves of FDMA allocated to the LEDs grow with the LED position from the lower left corner to the upper right corner in Setup 1. The frame durations of UMA and FDMA are $(2 \times 12)T_c$ and $2^{12}T_c$, respectively, where the frame duration is considered to be equal to the scheme delay. To make a fair comparison, the same average transmitting optical flux per chip $\Phi_i = 500$ lm and the same time resources are allocated to both schemes. Hence, the receiver of UMA collects 170 frames, whose total time durations are equivalent to the time duration of one FDMA frame, and takes the average of these 170 frames to have one frame. Then UMA applies FFT on this frame to estimate the average received powers from the LEDs. It is noted that the estimated average received powers of UMA are independent of the background light intensity as long as it is constant for each frame duration.

Since UMA is applicable to any positioning algorithm based on the received signal strength (RSS), we evaluate the accuracy of the estimated average received powers through the mean square error (MSE) which is defined as

$$\text{MSE} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{P_i - \hat{P}_i}{P_i}\right|^2. \tag{12}$$

The MSE offers a performance benchmark of our proposed scheme that is meaningful for any positioning algorithm based on the RSS.

In simulation, the receiver position varies over the space given in Fig. 3(a) with an increment of 0.5 m and a fixed height of 1 m from the ground. The MSE is calculated at each receiver position. The MSEs vs the receiver position of UMA and FDMA are shown in Fig. 6. Note that the average MSEs of UMA and FDMA are 1.5×10^{-6} and 9.9×10^{-3}, respectively. Moreover, the MSE of UMA is consistent over the whole space, since UMA eliminates MAI entirely and is only impacted by noise so that $\lim_{SNR\to\infty} MSE = 0$ as predicted by Theorem 1. However, FDMA suffers from MAI impact due to the fact that the harmonic frequency components of the square waves interfere with the fundamental frequency components after sampling the received signal and consequently they cause MAI. It is also noted that the higher frequency components suffer from MAI more than the lower frequency components which explains the increase in the MSE from the lower left corner to the upper right corner in Fig. 6(b). Note that it is possible to reduce MAI of FDMA by increasing the sampling rate of the received signal, but the required FFT size increases and consequently the receiver complexity grows.

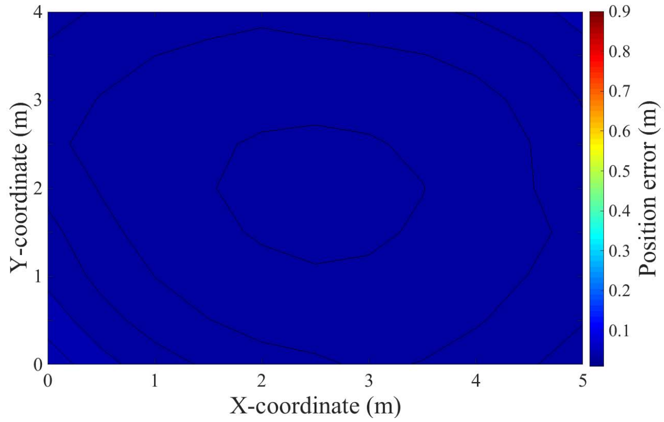


(a) UMA

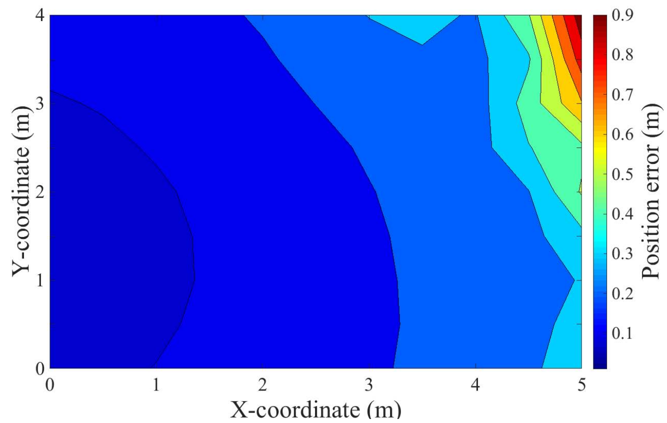
(b) FDMA

Fig. 6: MSEs of UMA and FDMA vs receiver position in Setup 1.

Figure 7 shows the position errors of UMA and FDMA vs the receiver position. In this paper, we consider 3-dimensional position error. The position is estimated by applying the positioning algorithm in [8]. The average position errors of UMA and FDMA are 3 cm and 21.5 cm, respectively. Note that the position errors of both schemes follow their MSEs, i.e., they reduce with improving MSEs and vice versa.



(a) UMA



(b) FDMA

Fig. 7: Position errors of UMA and FDMA vs receiver position in Setup 1.

C. Systems with Large number of LEDs

Unlike FDMA, the scheme delay and the FFT size of UMA grow linearly with the number of LEDs. Moreover, the estimated average received powers of UMA are free of MAI. Therefore, UMA can be considered as a potential multiple access scheme for systems with large number of LEDs, and when reusing codes is either difficult or not possible, e.g., in supermarkets where many light sources are installed close to one another. So we consider Setup 2 for the space dimensions and the LEDs configuration, shown in Fig. 3(b), where $N = 30$. The considered receiver position is $(3.5, 3, 1)$.

Figure 8 illustrates the position error for different average transmitting optical flux per chip vs the number of the considered LEDs for position estimation, i.e., we here consider the subset of LEDs with the greatest estimated average received powers for position estimation. It is noted that by increasing the optical flux, the received signal-to-noise ratio (SNR) increases, and consequently position accuracy improves. Figure 8 also reveals that the position accuracy improves with increasing the number of the considered LEDs for position estimation.

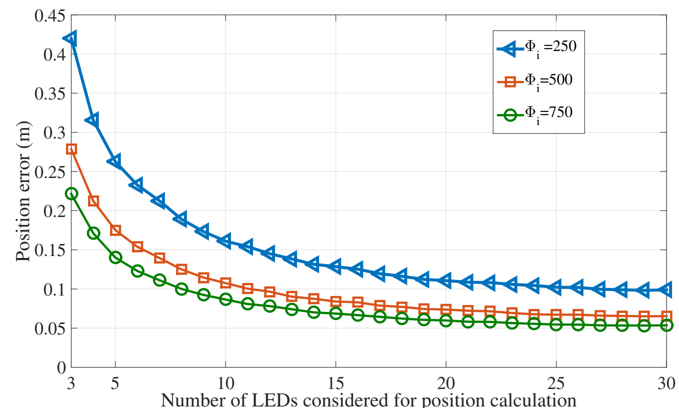


Fig. 8: Position error verses the number of LEDs considered for position calculation, in the space dimensions and LEDs configuration in Setup 2 shown in Fig. 3(b).

V. Discussion

The LED's are modulated using piecewise constant modulation, rather than continuously variable. There are two main advantages: 1) it is simpler to design the transmitter circuit to realise this output; 2) it is possible to show that our proposed codewords achieve the same performance of the continuously variable waveform but with less computational power.

In this paper, we have focused on the applications in position estimation. However, the proposed scheme is also useful for data communications. Since our proposed scheme enables the receiver to estimate the received power from each LED, the scheme supports modulation scheme like pulse amplitude modulation (PAM). On the other hand, we can assign more than one codewords to the LEDs so that the system can implement a scheme like frequency shift keying (FSK). The data rate of such a system is limited by the codeword duration LT_c, which depends on N, and the number of distinct codewords. How to optimize these parameters to find an efficient modulation scheme on top of our proposed multiple access scheme is an interesting research question. This question is reserved as a future research direction from this work.

VI. Conclusion

We have proposed an uncoordinated multiple access scheme for positioning systems where no central unit is required to control the transmission of LEDs. By applying FFT, the receiver can estimate the average received powers from the LEDs without any MAI. The scheme delay and the FFT size grow linearly with the number of LEDs so that our proposed scheme can support a large number of asynchronous transmitters. Simulation results showed that our proposed scheme outperforms the existing schemes in terms of the scheme delay, receiver complexity, the MSE of the estimated average received powers and the position error. Moreover, for transmitting optical flux of 500 lm, the obtained average MSE of the estimated average received powers and the average position error are 1.5×10^{-6} and 3 cm, respectively. Our proposed scheme can be extended to support data communications for multiple transmitters.

REFERENCES

[1] R. Zhang , J. Wang, Z. Wang, Z. Xu, C. Zhao and L. Hanzo, “Visible light communications in heterogeneous networks: Paving the way for user-centric design,” *IEEE Wireless Communications,* vol. 22, no. 2, pp. 8–16, April. 2015.

[2] A. A. Saed, S.-W. Ho and C. W. Sung, “Adaptive Modulation for Two users in VLC,” *IEEE GlobeCom Workshop*, Dec. 2015.

[3] Q. Gao , C. Gong, S. Li, and Z. Xu, “DD-informative modulation for visible light communications under lighting constraints,” *IEEE Wireless Communications,* vol. 22, no. 2, pp. 54–60, April. 2015.

[4] S. Wu , H. Wang, and C.-H. Youn, “Visible light communications for 5G wireless networking systems: from fixed to mobile communications,” *IEEE Network,* vol. 28, no. 6, pp. 41–45, Dec. 2014.

[5] S.-H. Yang, H.-S. Kim, Y.-H. Son, and S.-K. Han, “Three-Dimensional Visible Light Indoor Localization Using AOA and RSS With Multiple Optical Receivers," *Journal of Lightwave Technology*, vol. 32, no. 14, pp. 2480–2485, Jul. 2014.

[6] L. Jaechan, “Ubiquitous 3D Positioning Systems BY LED-Based Visible Light Communications," *IEEE Wireless Communications*, April. 2015.

[7] M. Yasir, S.-W. Ho and B. N. Vellambi, “Indoor positioning system using visible light and accelerometer,” *IEEE/OSA Journal of Lightwave Technology,* vol. 32, no. 19, pp. 3306–3316, Oct. 2014.

[8] M. Yasir, S.-W. Ho and B. N. Vellambi, “Indoor positioning tracking using multiple optical receivers,” *IEEE/OSA Journal of Lightwave Technology,* Feb. 2016.

[9] M. Biagi, S. Pergoloni, A. M. Vegni, “LAST: a Framework to Localize, Access, Schedule and Transmit in Indoor VLC Systems,” *IEEE Journal of Lightwave Technology,* vol.33, no.9, pp.1872-1887, 1 May 2015.

[10] B. De, G. Lokhoff, S. Nijssen, and C. Baggen, “Detection of Coded Light," European Patent Application Number: PCT/EP2015/059436, Nov 19, 2015.

[11] M. Yasir, A. A. Saed and S.-W. Ho, “Uncoordinated Multiple Access Scheme for VLC Systems with Positioning Capability,” *Australian Communication Theory Workshop*, Jan. 2016.

[12] W. Zhang, M.I.S. Chowdhury and M. Kavehrad, “Asynchronous indoor positioning system based on visible light communications,” *Journal of Optical Engineering*, vol. 53, no. 4, March. 2014.

[13] U. Nadeem, N.U. Hassan, M.A. Pasha and C. Yuen, “Indoor positioning system designs using visible LED lights: performance comparison of TDM and FDM protocols,” *IEEE Electronics Letters*, vol. 51, no. 1, Jan. 2015.

[14] S. D. Lausnay, L. D. Strycker, J. P. Goemaere, N. Stevens and B. Nauwelaers, "A Visible Light Positioning System using Frequency Division Multiple Access with Square Waves," Signal Processing and Communication Systems (ICSPCS), 2015 9th International Conference on, Cairns, QLD, 2015.

[15] S. D. Lausnay, L. D. Strycker, J. P. Goemaere, N. Stevens and B. Nauwelaers, “Optical CDMA codes for an indoor localization system using VLC,” *International Workshop in Optical Wireless Communications*, Sep. 2014.

[16] J. Kahn and J. Barry, “Wireless infrared communications,” *IEEE Proceedings*, vol. 85, no. 2, pp. 265–298, Feb. 1997.

[17] S. Rajagopal, R. D. Roberts and S.-K. Lim, “IEEE 802.15.7 visible light communication: modulation schemes and dimming support,” *in IEEE Communications Magazine,* vol. 50, no. 3, pp. 72–82, Mar. 2012.

[18] P. Duhamel and M. Vetterli, “Fast Fourier transforms: A tutorial review and a state of the art,” *Signal Process*, vol. 19, pp. 259–299, 1990.