Experimental Assessment of the Accuracy of Modulated and Unmodulated Visible Light Positioning

1st Sander Bastiaens
WAVES, INTEC
Ghent University/imec
Ghent, Belgium
Sander.Bastiaens@UGent.be

2nd Kenneth Deprez
WAVES, INTEC
Ghent University/imec
Ghent, Belgium
Kenneth.Deprez@UGent.be

3rd Luc Martens
WAVES, INTEC
Ghent University/imec
Ghent, Belgium
Luc1.Martens@UGent.be

4th Wout Joseph
WAVES, INTEC
Ghent University/imec
Ghent, Belgium
Wout.Joseph@UGent.be

5th David Plets
WAVES, INTEC
Ghent University/imec
Ghent, Belgium
David.Plets@UGent.be

Abstract—To feature a Light-Emitting Diode (LED) illumination infrastructure as a received signal strength (RSS)-based Visible Light Positioning (VLP) system’s beacons, each LED’s driver currently needs to be retrofitted. As a consequence of the intensity modulation (IM) retrofit, the LEDs’ average radiant flux decreases. To remain adherent to the required illuminance levels, additional LED sources are required, which significantly raises the roll-out cost. The goal of unmodulated VLP (uVLP) is to refrain from modulating the LEDs by exploiting an inherent characteristic of the LEDs’ light signals, namely the *characteristic frequency* (CF). This paper shows the aptitude of using the spectral magnitude at the CF to infer accurate positioning in photodiode (PD)-based RSS uVLP. Compared to regular VLP, uVLP displays a limited increase in median and 90th percentile root-mean-square error of 3.52 cm (8.72 cm vs. 5.20 cm) and 7.54 cm (16.96 cm vs. 9.42 cm) respectively, during trilateration in a 4 m by 4 m lab setup. This shows uVLP’s potential as an indoor localisation system.

Index Terms—Unmodulated Visible Light Positioning, uVLP, Visible Light Positioning, VLP, Light Signals Of Opportunity, Characteristic Frequency, Received Signal Strength (RSS), LED, Localisation, Positioning

I. INTRODUCTION

Visible Light Communication (VLC) is being researched for application in next-generation broadcasting networks. The *Internet of Radio Light* (IoRL) framework [1], [2], for instance, integrates VLC into a 5G network for wireless and mobile connectivity in homes, businesses [3], museums [4] and supermarkets [5]. Several (immersive) broadcasting applications suitable for VLC, depend on a form of location-awareness [6], e.g. wireless augmented and virtual reality [7]. Visible Light Positioning (VLP), as a subdomain of VLC, strives to deliver this required, accurate geographic data.

Typical VLP (and thus VLC) systems employ intensity modulated LED lamps that are frequently part of a pre-existing illumination infrastructure. This reuse of the lighting may be categorised as VLP’s main economic driver. However, VLP-enabling LED lamps not only entails a LED driver retrofit, it also inadvertently decreases the LEDs’ average radiant flux. The result is an elevated roll-out cost as more lamps will be needed to meet the stringent illumination requirements.

Unmodulated VLP (uVLP) hopes to cope with these challenges by leaving the LEDs *unmodulated* and by utilising the LEDs’ light signals of opportunity (LSOOP) to infer (accurate) positioning estimates. Two uVLP approaches can be distinguished, depending on whether (1) the total illuminance or irradiance measured at the receiver is used as localisation input, or (2) de LSOOP signals are first separated into individual LED contributions. In [8], Amsters et al. evaluated the performance of the former by running an iterated extended Kalman filter on the total photovoltage and on encoder values to navigate a photodiode (PD)-equipped mobile robot inside a 10 m x 10 m area with 4 Lambertian LEDs placed in a square. A simulation experiment showed positioning errors exceeding 50 cm, even with multiple PDs. This and other *total illuminance* methods run into difficulties in the absence of an illuminance gradient, which frequently occurs in practice as a uniform illuminance distribution is strived for. Zhang et al. in [9] demonstrate that the inherent *characteristic frequency* (CF) of fluorescent lights (FLs) can be exploited to demultiplex the different FLs’ contributions. With a smartphone, a 37 cm accurate positioning in a 23.7 m by 6.4 m by 3.1 m area can be obtained.

With the illumination market transitioning to LED technology i.e. the *solid-state lighting (r)evolution*, (u)VLP also turns to LEDs rather than FLs. In this paper, it is shown that although high-power LED deployments differ extensively from their FL counterparts, their constant current drivers induce resonance frequencies as well. Moreover, the identifiable *characteristic frequency (CF)* can serve as a discriminative feature in PD-based received signal strength (RSS) uVLP. Based on 2 large datasets collected in a 4 m by 4 m lab setup, the trilateration-based positioning root-mean-square error (RMSE) of both uVLP and regular VLP is experimentally compared.

II. SYSTEM DESCRIPTION

A. LEDs' Characteristic Frequency

LED lamps vary both in their bare LED light sources and their LED driver topologies and complexity, depending on the contemplated market segment and application [10]. The constant current driver found in most LED systems induces resonance frequencies that are noticeable in the LED's electrical output signal. The sole or most prominent of the resonance frequencies is dubbed the *characteristic frequency (CF)*. As is the case for fluorescent lights (FLs), a substantial variation in the LEDs' emitted electrical spectrum is present, allowing the discerning of a unique *CF* per LED, even for LEDs of the same type. Exploiting the set of *CF*s, permits the application of the VLP positioning principles without having to modulate the LEDs.

B. (Positioning) Measurement Setup

This paper considers *BXRE-35E2000-C-73*¹ Chip on board (COB) LEDs. COB LEDs are favoured in VLP as they are exhibiting approximately Lambertian radiating point source behaviour, and hence allow an easy localisation [11]. The COBs' *CF*s and associated unmodulated VLP positioning performance is recorded in a dedicated 4 m by 4 m VLP lab (Fig. 1) that is surrounded by black cloths to minimise reflections [11].

There, $K = 4$ *BXRE* LEDs are placed in a quasi-square, 2.25 m above the receiver plane. To ensure a fair comparison between both uVLP and dedicated VLP, the COB LEDs are driven by an identical LED driver, the LTM8005 Demo Board², in DC and AC regime respectively. In AC regime, the LTM8005 driver's frequency $f_{c,i} = 2^{i-1}f_0$, ($f_0 = 0.5$ kHz, $i = 1..K$) is set via the WiFi-enabled Adafruit Feather M0 WIFI w/ATWINC1500³ module in accordance with the square wave modulation scheme of [12].

At the receiving end, the transmitted signals are found encoded in the total photovoltage signal $V_{PD,i}(t)$ generated by the Thorlabs PDA36A2⁴ module (with a transimpedance gain of $1.51 \cdot 10^3$ V/A [11]). Placed on a slider system, $V_{PD,i}(t)$ is measured on a uniform 2.5 cm grid, yielding 24649 measure-

Fig. 1. Illustration of the COB (u)VLP lab environment

ment locations in total. The subsequent receiver chain blocks consist of the National Instrument USB-6212 DAQ device and a MATLAB® backend to both sample $V_{PD,i}(t)$ (during 1 s at a rate $f_S = 256$ kHz) and employ it as input for the demodulation and localisation engine.

To determine the LEDs' *CF*s, $V_{PD,i}(t)$ is first measured, with $N = 51.2$ kS samples, directly underneath each LED whilst the other LEDs are switched off. 100 *CF* measurements are averaged to obtain the final *CF*.

C. Positioning Approach

1) *Demodulation*: From $V_{PD,i}(t)$, the set of the individual LED photovoltage magnitude contributions $\{V_{PD,i}\}$ at frequencies $\{f_{c,i}\}$ is demultiplexed via the fast Fourier transform (FFT) amplitude spectrum-based identification method of [12]. $f_{c,i}$ is either the first harmonic frequency in regular VLP [12] or the characteristic frequency in uVLP. To improve demodulation (and positioning) robustness, instead of taking the spectral magnitude found at $f_{c,i}$, a peak detection is opted for. The neighbourhood $2\Delta f$ of the nominal $f_{c,i}$ i.e. $[f_{c,i} - \Delta f, f_{c,i} + \Delta f]$ is considered (see Section III-B).

Prior to demodulation, the $V_{PD,i}(t)$ time signal, spanning 1 s, is subdivided in *AVG* segments to average $\{V_{PD,i}\}$. Two *averaging* methods are discerned: (1) the complex FFT spectrum is averaged prior to peak detection of $\{V_{PD,i}\}$ on the amplitude spectrum, and (2) the peak detected $\{V_{PD,i}\}$ of each of the segments is averaged. Methods (1) and (2) are respectively denoted by *SPECT* (with abbreviation *s*) and *PEAK* (with abbreviation *p*)

The positioning method of the following Section II-C2 employs the set of per LED received radiant powers $\{P_{R,i}\}$, $i = 1..K$ as RSS values, rather than their photovoltage variants $\{V_{PD,i}\}$. The individual power contributions $\{P_{R,i}\}$ are derived from $\{V_{PD,i}\}$ after division by subsequently the transimpedance gain (leading to the photocurrent magnitudes $\{I_{PD,i}\}$) and the receiver responsivity [11].

¹https://www.bridgelux.com/sites/default/files/resource_media/Bridgelux%20DS101%20Gen%207%20V13%20Array%20Data%20Sheet%2020190930%20Rev%20N.pdf

²<https://www.analog.com/en/products/lm8005.html#product-overview>

³<https://www.adafruit.com/product/3010>

⁴<https://www.thorlabs.com/thorproduct.cfm?partnumber=PDA36A2>

Fig. 2. Distribution of $I_{PD,3}$ obtained via FFT-based demodulation with $AVG = 16$ over 157^2 grid points for uVLP (a) *PEAK* and (b) *SPECT*, and for VLP (c) *PEAK* and (d) *SPECT*. $2\Delta f$ equals 10 Hz and 100 Hz for VLP and uVLP respectively. uVLP's $I_{PD,i}$ is similarly demodulated as VLP's.

2) *Trilateration Positioning*: Given the LEDs' coordinates $(x_{S,i}, y_{S,i}, z_{S,i})$ and $\{P_{R,i}\}$, *trilateration*-based RSS first estimates the LED-PD distances d_i by inverting a VLP channel model before computing a location estimate via least-squares minimisation of the linear system relating d_i to $(x_{S,i}, y_{S,i}, z_{S,i})$ (see [13] for details). The positioning performance is evaluated in terms of the root-mean-square error (rmse), i.e. the Euclidean distance between the actual location and the estimated position.

3) *Propagation Model*: The employed VLP channel models are, as found in literature [14], the IR-propagation models of Kahn et al. [15]. The description of Kahn's models is the same as in previous work [11]. A cosine receiver angular acceptance is assumed.

4) *Calibration*: The LED coordinates $(x_{S,i}, y_{S,i}, z_{S,i})$, $i = 1..K$ equal $x_{S,i} = [-1.13, -1.12, 1.17, 1.15]$ (m), $y_{S,i} = [-1.41, 1.44, -1.43, 1.4]$ (m) and $z_{S,i} = [2.26, 2.26, 2.25, 2.26]$ (m).

Besides accurately knowing $(x_{S,i}, y_{S,i}, z_{S,i})$, also $\{P_{t,i}\}$ and $\{f_{c,i}\}$ need to be a priori known. $\{f_{c,i}\}$ is determined with a single measurement per LED (see section II-B). $P_{t,i}$ generally is too [16]. However, a more robust method entails taking the mean of $P_{t,i} \cdot (d_i/z_{S,i})^3$ for all grid points within a 10 cm radius of LED _{i} 's projection.

III. EXPERIMENTAL RESULTS

A. Measuring the Characteristic Frequency

Fig. 3 depicts the Multiple Signal Classification (MUSIC) [17] pseudospectrum of subspace order 20 of the total photovoltage time domain signal $V_{PD,i}(t)$ for each of the 4 COBs. The LEDs' *CF*s are identified via peak detection to be 76.57 kHz, 81.82 kHz, 83.49 kHz and 86.09 kHz. The minimal LED spread is 1.67 kHz, which in turn dictates a minimal N (with N the number of $V_{PD,i}(t)$ samples). These BXRE measurements allow concluding that the *CF* is dependent on the individual LED lamp's characteristics, and that the *CF*s are prominent enough to use as a basis for positioning. With the *CF*s up to and exceeding 80 kHz, uVLP dictates a sufficiently high f_S or necessitates the use of the *CF* aliases. For the former, f_S should exceed 2 times the maximum *CF*, provided the absence of higher frequency components that could alias into the *CF* range.

Fig. 3. MUSIC pseudospectrum versus frequency on a logarithmic scale of the 4 BXRE-35E2000-C-73 COB LEDs

B. Measuring the $I_{PD,i}$ Propagation

Given $f_{c,i}$, the photocurrent contributions $I_{PD,i}$ are demodulated with $AVG = 2^4 = 16$. $AVG = 16$, also the FFT resolution in Hertz, is chosen as to discern between $f_{c,i}$ frequencies spread at least 16 – 20 Hz apart. A contour plot of the $I_{PD,i}$ distribution appertaining to LED 3 is shown in Fig. 2 for uVLP (a) *PEAK* and (b) *SPECT*, and for VLP (c) *PEAK* and (d) *SPECT*.

Fig. 2 (a) and (b) demonstrate that the uVLP *PEAK* $I_{PD,i}$ distribution exhibits less noisy, i.e. capricious behaviour than *SPECT*'s. This is due to the instability of the (instantaneous) *CF*. During VLP on the other hand, *PEAK* and *SPECT* effectuate the same $I_{PD,i}$ as $f_{c,i}$ is stable. As *SPECT* is of lower complexity, it is the designated demodulation technique for VLP. Finally, comparing Fig. 2 (a)/(b) with (c)/(d) permits concluding that uVLP's $I_{PD,i}$ is 2 orders of magnitude smaller than VLP's.

As the variance on $I_{PD,i}$ is correlated with the localisation precision, it is interesting to plot the spatial distribution of the standard deviation on the VLP *PEAK* $I_{PD,4}$ of LED 4 (in Fig. 4). This standard deviation is computed based on the $I_{PD,i}$ of each of the $AVG = 16$ segments.

Fig. 4 shows that the standard deviation profile on $I_{PD,i}$ shows a significant contribution of the neighbouring (both in space and frequency) LEDs i.e. LED interference (mostly of LED 3 located at the bottom right). This extra contribution

Fig. 4. Per grid point standard deviation of the $AVG = 16$ segments' $I_{PD,4}$ ($I_{PD,i}$ for LED 4) measurement for VLP *Peak*

can be attributed to the real $f_{c,i}$ not being exact multiples of the ground frequency f_0 . For uVLP, LED interference is not the dominant factor. There, the standard deviation has a strongly proportional component to the $I_{PD,i}$ magnitude. Also noticeable is that VLP's deviation's magnitude is two orders of magnitude smaller than the signal's. A final side note is that, for the setup under consideration, the deviation's amplitude is comparable to uVLP's $I_{PD,i}$.

C. Positioning Results

The cumulative distribution functions (CDFs) of the rMSE found during trilateration with the ($AVG = 16$) $I_{PD,i}/P_{R,i}$ obtained in uVLP/VLP localisation with *PEAK/SPECT* demodulation, are shown in Fig. 5.

Fig. 5. CDF of the (u)VLP positioning rMSE with *PEAK* (*p*) and *SPECT* (*s*) demodulation. The *PEAK* and *SPECT* curve related to VLP overlap.

As expected (Section III-B), *PEAK* outscores *SPECT* when unmodulated LEDs are used. The p_{50} , p_{75} and p_{90} percentile rMSE improve respectively by 10.36 cm (54.3%), 13.94 cm (52.5%) and 17.4 cm (50.6%). The more than 50% positioning accuracy increase does come at the cost of additional complexity ($AVG - 1$ extra peak detects) and thus latency. The execution time rises 14 fold.

Fig. 6. Influence on the uVLP/VLP *PEAK/SPECT* p_{50} and p_{90} of averaging AVG segments

Fig. 5 also demonstrates the limited loss of positioning accuracy of uVLP *PEAK* systems compared to their regular VLP counterparts. While VLP displays a $p_{50} = 5.2$ cm, $p_{75} = 7.67$ cm and $p_{90} = 9.42$ cm, uVLP only augments the rMSE to 8.72 cm, 12.63 cm and 16.96 cm, respectively. Those values represent percentage increases of 67.8%, 64.7% and 80.1%.

1) *Positioning precision and accuracy*: Main accuracy decreasing factors are identified to be LED interference (certainly for VLP, see section III-B), the LED tilt present (i.e. due to the nonideal lab setup) [11], the cosine normalised responsivity assumed [11], and measurement errors.

To estimate the portion of the positioning error that can be attributed to the noise influence, i.e. the localisation precision, the $AVG = 16$ $I_{PD,i}$ values are reverted to. Per grid point, the standard deviation on both the localisation rMSE and the position estimate (i.e. Euclidean distance) of each segment, with respect to the mean $I_{PD,i}$'s rMSE and location, is computed. The 50th and 90th percentile deviation on the localisation error and the positioning estimate are denoted by $p_{50,err}/p_{90,err}$ and $p_{50,dist}/p_{90,dist}$.

For uVLP, $p_{50,err}$ and $p_{90,err}$ equal 15.6 cm and 21.06 cm, while $p_{50,dist}$ and $p_{90,dist}$ amount to 21.09 cm and 26.73 cm. For VLP, these values are 2.2 cm, 5.75 cm, 3.26 cm and 8.5 cm. However, the results of Fig. 5 are obtained with the averaged $I_{PD,i}$. Under assumptions (such as uncorrelatedness), the above numbers are reduced by a factor $\sqrt{AVG}$. From this approximate precision analysis, it can be concluded that a significant part of uVLP's loss of accuracy (compared to VLP) is due to its significantly lower signal-to-noise ratio (SNR). This loss of accuracy can be partly mitigated by averaging multiple $I_{PD,i}$ observations, at least as many as latency constraints allow. VLP's performance is mainly limited by consistent and bias inaccuracies, such as those listed in the beginning of this section.

2) *Positioning rMSE as a function of AVG*: Fig. 6 depicts the p_{50} and p_{90} positioning errors for the different (de)modulation combinations as a function of the number

TABLE I
COMPARISON OF uVLP AND 'REGULAR' VLP

Description	VLP	uVLP
Principle		
Typical frequency range	up to MHz	30-90 kHz
Modulation Index	50%	0%
Average LED current	50%	100%
Accuracy		
Experimental p_{50}	5.20 cm	8.72 cm
Cost		
Retrofitting effort	LED driver	None
New infrastructure	Additional lamps	None
Receiver-side Cost	Same	Same

of (*AVG*) segments' $I_{PD,i}$ is averaged for positioning. The segment length remains constant, while the number of averaged $I_{PD,i}$ samples increases from 1 to 16. Fig. 6 again shows the superior performance of *PEAK* over *SPECT* in uVLP. The latter being plagued by the $f_{c,i}$ time variation mismatch. At $AVG = 16$, uVLP's p_{50} and p_{90} have not yet converged, meaning that uVLP's performance can still be ameliorated by increasing *AVG*. However, as the associated positioning update rates drop below 1 Hz, such systems are deemed impractical for most real-time applications. A use case is still found in the tracking of slow-moving objects (and in non-real-time situations).

For VLP, $AVG = 5$ seems to be the convergence start point. p_{50} and p_{90} only decrease by approximately 9.2% and 4.02% when averaging $I_{PD,i}$ 11 times more. Stopping at $AVG = 5$, allows to increase the update rate (more than) threefold.

3) *Discussion of Results:* Table I lists the principles and differences of both uVLP and regular VLP. FFT-based RSS uVLP exhibits p_{90} positioning errors no longer contained in the subdecimetre range, effectively ruling uVLP systems out for highly-accurate applications such as the tracking of indoor unmanned robots. However, an accuracy below 30 cm does suffice for many other (broadcasting) applications. Certainly, as due to uVLP not requiring a dedicated infrastructure, lighting that is furthermore omnipresent, the roll-out costs are minimal. Only the tracked object needs to be equipped with a VLP-enabled receiver, which in itself is not of large cost.

IV. CONCLUSION AND FUTURE WORK

In this manuscript, it is shown that COB LEDs exhibit a *characteristic frequency (CF)*, which helps identifying and demultiplexing the LEDs' individual photovoltage contributions to be used in photodiode (PD)-based received signal strength (RSS) uVLP. In combination with trilateration and FFT-based demodulation in a 4 m by 4 m lab setup, uVLP increases respectively the p_{50} and p_{90} rMSE from 5.2 cm to 8.72 cm and from 9.42 cm to 16.96 cm compared with VLP.

This manuscript shows uVLP's potential for many localisation applications such as tracking hospital beds, office room laptops (equipped with a PD), virtual and augmented reality.

Boasting the uVLP positioning performance via improved demodulation and positioning methods for both point source-like and non-point source LEDs encompasses the future work. uVLP's aptitude in industrial settings should also be examined.

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