PARAMETER ESTIMATION OF MULTIPLE PULSE TRAINS FOR ILLUMINATION SENSING

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ABSTRACT

We consider illumination sensing in a light emitting diode (LED) lighting system based on frequency division multiplexing (FDM). In the FDM scheme, LEDs render periodical illumination pulses at different frequencies with prescribed duty cycles. The purpose of illumination sensing is to identify the illumination contributions of different LEDs at a target location, within a limited response time. With the use of a photosensor at the target location, the problem of interest is to estimate the amplitude of the sensor signal component due to each LED. In this paper, we propose a successive estimation approach exploiting higher order harmonics of the sensor signal. We show that a larger number of LEDs can be supported using the proposed approach, as compared to our previous approach using only the fundamental frequency component, at the same estimation error.

Index Terms— Illumination sensing, LED lighting systems, frequency division multiplexing, successive estimation

1. INTRODUCTION

LED lighting systems are becoming prevalent, offering energy efficiency along with the ability to render colorful, dynamic and localized lighting effects [1]. This ability is due mainly to three features. First, LEDs are colored light sources by nature. Secondly, each LED can provide hundreds of different illumination levels through pulse width modulation (PWM) dimming [2]. Finally, an LED lighting system normally consists of a large number of spatially distributed LEDs with narrow light beams. Associated with these features is the challenge of controlling such lighting systems.

A solution to LED lighting control was presented in [3] using illumination sensing. Here, illumination pulses from different LEDs are modulated differently. A sensor is placed at the target location where a certain lighting effect is desired. The illumination contribution of each LED is in turn determined via sensor signal processing. A central controller can then determine the setting of the duty cycle for each individual LED to achieve the desired lighting effect. An alternate approach uses frequency division multiplexing (FDM) [4] and is attractive due to the low-cost driver circuits.

In this paper, we consider the FDM scheme, under which a typical optical signal received at the target location from the ith LED is illustrated in Fig. 1. The signal consists of a pulse train with frequency \( f_i \), that is set differently for different LEDs. The frequencies \( \{ f_i \} \) are usually chosen between 2 and 4 kHz [4], which is determined by the requirement of no visible flicker and by optical properties of the LEDs. The amplitude of the pulse train is called the illuminance (in lux), denoted by \( a_{i0} \), and the duty cycle is denoted by \( p_i \), where \( 0 \leq p_i \leq 1 \). The illumination contribution of the LED at the target location is given by the product \( a_{i0} p_i \). The duty cycle

\[
p_i \quad \text{is known from the controller. The amplitude } a_{i0} \text{, which is determined by the optical power of the ith LED and the free-space optical channel attenuation [3], is unknown. Hence, the key challenge for illumination sensing is to estimate } a_{i0} \text{ for each } i \text{ to determine the illumination contribution of the ith LED.}
\]

The optical signals from all the LEDs superimpose at the target location. It is difficult and expensive to distinguish different LEDs optically. Therefore, the optical signal is converted into electrical by using a photosensor, such as a photodiode. The amplitude of the electrical sensor signal is denoted by \( a_i \). The challenge of illumination sensing is in turn transformed into the estimation of \( a_i \).

Based on the FDM scheme, an estimator was proposed in [4], where only the fundamental frequency component of the sensor signal was used. The basic idea was to estimate \( a_i \) through the spectrum of the sensor signal at \( f_i \). Due to the limited response time for estimation (typically 0.1 s), there is induced interference between the sensor signal components from different LEDs. The frequency spacing between different \( f_i \) has, therefore, to be large enough to limit the induced interference. Given a fixed frequency range for the allocation of \( f_i \), the number of LEDs that can be supported is thus limited. Moreover, the estimation performance deteriorates when the power of the fundamental frequency component is small, e.g. when \( p_i \) is close to 0 or 1. Finally, the estimation performance also suffers from frequency offsets in \( f_i \). Due to these reasons, the number of LEDs that can be supported by this estimator is only about 100.

In many practical lighting applications, a larger number of LEDs need to be supported, e.g. [5]. To this end, we consider an estimation approach in this paper using higher order harmonics. This approach is attractive for two reasons. First, there is a larger frequency separation between the higher harmonics of two adjacent frequencies. Hence, it should be theoretically possible to pack a larger number of frequencies in the given frequency range. Secondly, we can utilize the power in the higher order harmonics in the sensor signal. This is especially meaningful when \( p_i \) is close to 0 or 1, in which case a larger portion of the signal power lies in higher order harmonics rather than the fundamental frequency component.

We note that previous literature on sinusoid estimation considered the case of parameter estimation with multiple sinusoids, e.g. [6, 7] and estimation using multiple harmonics from a single source, e.g. [8]. The problem setting and approach in this paper as such is fundamentally different from previous works.
2. PROBLEM DESCRIPTION

The sensor signal at the output of the photosensor is given by

\[ y(t) = \sum_{i=1}^{L} y_i(t) + v(t) = \sum_{i=1}^{L} a_i \sum_{n=-\infty}^{\infty} \text{rect} \left( \frac{t + \theta_i}{p_i} \right) f_i - n + v(t), \]

where \( L \) is the number of LEDs and is known from the controller. The signal \( y_i(t) \) is the sensor signal component due to the \( i \)th LED, where \( \text{rect}(t) = 1 \) when \( |t| \leq 1/2 \) and \( \text{rect}(t) = 0 \) elsewhere. Each \( y_i(t) \) thus consists of a rectangular pulse train with an amplitude \( a_i \), a frequency \( f_i \) and an initial phase shift \( \theta_i \). None of these three parameters is exactly known to the sensor. The amplitude \( a_i \) characterizes the illumination contribution of the \( i \)th LED, and is thus the primary parameter to be estimated.

The ideal frequency \( f_i \) is allocated between \( f_{\text{min}} = 2 \) kHz and \( f_{\text{max}} = 4 \) kHz, i.e. the considered bandwidth is \( W = f_{\text{max}} - f_{\text{min}} = 2 \) kHz. In [4], the \( \{ f_i \} \) are allocated uniformly between \( f_{\text{min}} \) and \( f_{\text{max}} \) with a frequency spacing \( \Delta f \) between adjacent frequencies. In this paper, however, as will be explained later, we divide the frequency range \( f_{\text{min}}, f_{\text{max}} \) into \( M \) sub-ranges. The ideal frequencies \( \{ f_i \} \) in each sub-range are still uniformly allocated with a frequency spacing \( \Delta f \), except that \( \Delta f \) decreases with the increase of \( m \). Nevertheless, the value of \( f_i \) is always known to the sensor as the identifier for the \( i \)th LED. Due to clock inaccuracies, however, there is an unknown frequency offset, \( \epsilon_i \), between \( f_i \) and the actual frequency \( f_i \), i.e. \( \epsilon_i = f_i - f_i \). The value of \( \theta_i \) can be anywhere between \( -\pi f_i / p_i \) and \( \pi f_i / p_i \). To obtain accurate estimate of \( a_i \), the values of \( f_i \) and \( \theta_i \) also need to be estimated. The noise term \( v(t) \), consisting of electronic and shot noise, is assumed to be additive white Gaussian noise with double-sided power spectrum density \( \frac{N_0}{2} \). The signal-to-noise ratio (SNR) is defined as \( \zeta_i = 10 \log_{10}(a_i^2/(N_0W)) \) [dB]. For a practical indoor environment [4], we have \( \max_i(\zeta_i) \geq 90 \).

To undertake the estimation of \( \{ a_i, f_i, \theta_i \} \), it is convenient to further write \( y_i(t) \) into the form of harmonics, i.e.

\[ y_i(t) = a_i \sum_{m=0}^{\infty} 2b_{i,m} \cos(2\pi mf_i t + m\phi_i), \]

where \( b_{i,m} \) is the magnitude of the \( m \)th harmonic. For a rectangular pulse with a known duty cycle \( p_i \), we have known \( b_{i,m} \) given by \( b_{i,m} \approx \frac{\sin(\pi m p_i)}{\pi m p_i} \). Note that, under practical protocols for PWM dimming control [4], we have \( p_{\text{min}} = 0.001 \leq p_i \leq p_{\text{max}} = 0.973 \). The phase term is \( \phi_i = 2\pi f_i p_i \). The estimation of \( \{ a_i, f_i, \theta_i \} \) is then transformed to the estimation of \( \{ a_i, f_i, \phi_i \} \). In [4], only the term \( m = 1 \) in (1) is used for the estimation of \( a_i \).

For the estimation of \( a_i \), the key requirements concern speed and accuracy. The first requirement is that the response time \( T \leq 0.1 \) s. The second requirement is that the estimation results should be accurate enough such that the estimation error is invisible to human eyes. More specifically, as long as the cost function [4]

\[ \xi_i = 10 \log_{10} \left( \frac{|\hat{a}_i - a_i| p_i}{(\sum_{m=1}^{L} a_{i,m} p_m)} \right) \leq -20 \text{dB}, \]

where \( \hat{a}_i \) denotes the estimated value for \( a_i \), the estimation error is considered acceptable.

With the above requirements on speed and accuracy being satisfied, the key challenge is to design an estimator so as to accommodate more LEDs, compared to that in [4], by allowing a smaller spacing between adjacent frequencies. To do this, we shall exploit multiple harmonics.

3. SUCCESSIVE ESTIMATOR

3.1. Frequency Domain Perspective

We describe the proposed estimator from a frequency domain perspective. Due to the limited response time \( T \), the sensor signal \( y(t) \) is multiplied with a windowing function \( g(t) \), whose support is \( T \). In the Fourier domain, we have

\[ Y(f) = \sum_{i=1}^{L} Y_i(f) + V(f), \]

where

\[ Y_i(f) = \sum_{m=-\infty}^{\infty} Y_{i,m}(f) = \sum_{m=-\infty}^{\infty} a_i b_{i,m} e^{i m \phi_i} G(f - m f_i). \]

Here, \( Y_i(f) \) is the Fourier transform of the windowed signal from the \( i \)th LED, i.e. \( Y_i(f) = \int_{-\infty}^{\infty} y(t) g(t) e^{-j 2\pi f t} dt \). The \( m \)th harmonic component in \( Y_i(f) \) and \( G(f) \) is the Fourier transform of \( g(t) \). Without loss of generality, we let \( G(0) = 1 \). The Fourier transform of the windowed noise term is denoted by \( V(f) \).

In order to utilize multiple harmonics for the estimation of \( \{ a_i, f_i, \phi_i \} \), we first look at the frequency ranges for different \( m \), as illustrated in Fig. 2, where \( m = 1 \) to 4. It can be seen that the frequency ranges for different \( m \) overlap each other. This overlap indicates that there is mutual interference between different harmonics from different LEDs. Hence, it is not straightforward to use the \( m \)th harmonic and support \( m \) times more LEDs.

3.2. Successive Estimation Procedure

A closer inspection of Fig. 2 indicates that there is no frequency overlap in the frequency range between 4 kHz to 6 kHz in the second harmonic range. Hence, there is no interference from other harmonics. An estimator can thus be built based on this frequency range to obtain estimates, \( \{ \hat{a}_i, \hat{f}_i, \hat{\phi}_i \} \), for the LEDs with \( 4 \) kHz < \( f_i < 6 \) kHz.

Let us name this estimator as the Component Estimator, as it is a component of the successive estimation process described later in this section.

Before describing such component estimators in further detail, the following frequency spacing criterion applies from [4]: As long as the frequency spacing between two adjacent \( m \)th order harmonics is \( 2/T \), the estimates \( \{ \hat{a}_i, \hat{f}_i, \hat{\phi}_i \} \) are sufficiently accurate in the sense of (2), under response time \( T \). The above criterion applies under no interference from other harmonics. For \( m = 2 \), the corresponding spacing between two adjacent fundamental frequencies is only \( 1/T \). Hence, the frequencies \( \{ f_i \} \) can be more closely packed by a factor of two, in comparison to that in [4]. The above criterion however suggests that a larger number of LEDs can be supported using even higher order harmonics while maintaining the error estimation performance.

3.2.1. Successive Procedure

Now, instead of taking the frequency range between 4 kHz to 6 kHz, let us only consider the range from \( 2f_{\text{min}} \) to \( f_{\text{max}} \), where we know...
Fig. 3. Illustration of the successive estimator, where the dark regions correspond to the frequency ranges of the LEDs in Group 1.

Table 1. Frequency range and number of LEDs of each group.

<table>
<thead>
<tr>
<th>Group</th>
<th>W_m/W</th>
<th>harmonic</th>
<th>Δ_f, m</th>
<th>L_m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1/3</td>
<td>2nd</td>
<td>Δ_f</td>
<td>2WT</td>
</tr>
<tr>
<td>m &lt; M</td>
<td>(m+1)/m</td>
<td>(m+1)th</td>
<td>Δ_f</td>
<td>2WT</td>
</tr>
<tr>
<td>M</td>
<td>Mth</td>
<td></td>
<td>Δ_f</td>
<td>2WT</td>
</tr>
</tbody>
</table>

3.3. The Component Parameter Estimator

In this section, we present a component parameter estimator that is used in the successive estimation procedure presented earlier in Section 3.2. This component parameter is applied once to each of the M groups. The aim of this estimator is to obtain an estimate \( \hat{Y}_i, \hat{f}_i, \hat{\phi}_i \) for each \( i \) in every group.

For Group \( m \leq 1 \), the LEDs indexed are \( i = L_{m-1}+1 \) to \( L_{m-1} \), where \( L_{m-1} = \sum_{k=1}^{m-1} L_k \). The input of such an estimator is denoted by \( Y_m(f) \), where \( Y_m(f) = Y(f) - \sum_{i=1}^{m-2} Y_i(f) \). Moreover, we focus on the \( m \)th harmonic frequency range for this group, i.e. between \( (m-1)f_{\max} \) and \( mf_{\max}/(m+1) \). Due to the successive estimation procedure, this is an overlap-free frequency range. Hence, we only need to consider

\[
Y_m(f) \approx \sum_{i=L_{m-2}+1}^{L_{m-1}} Y_{i,m}(f) = \sum_{i=L_{m-2}+1}^{L_{m-1}} \alpha_i b_{i,m} e^{j m \phi_i} G(f - m \tilde{f}_i).
\]

As shown in [4], we can design \( G(f) \) such that \( G(m \tilde{f}_j - m \tilde{f}_i) = 0 \), for \( i \neq j \), so that ideally we can use \( Y_m(m \tilde{f}_i) \) to estimate \( \alpha_i \) and \( m \phi_i \). In practice, however, due to the existence of frequency offsets, we should in fact use \( \hat{Y}_m(f) \), instead of \( Y_m(m \tilde{f}_i) \). Moreover, there may be induced interference from \( Y_{i,m}(f) \) to the value \( \hat{Y}_m(m \tilde{f}_i) \), since \( m \tilde{f}_j - m \tilde{f}_i \) no longer lies on the zeros of \( G(f) \).

The resulting estimation error due to these effects of frequency offset is not tolerable, especially because of error propagation in the successive estimation procedure. Thus, due to the induced interference between \( Y_{i,m}(f) \) and \( Y_{j,m}(f) \), we subtract the interfering \( Y_{j,m}(f) \) from \( \hat{Y}_m(f) \) for the parameter estimation of the \( i \)th LED. Further, a more accurate estimation of \( f_i \), instead of simply using \( \hat{f}_i \), is desirable to arrive at better estimation of \( \alpha_i \) and \( \phi_i \). To this end, we propose an iterative estimator as given in Algorithm 1.

The initial value of \( \tilde{f}_i \) for each \( i \) is set to be equal to the ideal frequency \( \tilde{f}_i \). The initial values of \( \hat{\alpha}_i \) is then obtained based on the magnitude of \( \hat{Y}_m(f) \). The phase of the \( m \)th harmonic is denoted by \( \tilde{\phi}_i, m = [m \phi_i, m] \), where the operation \([·]\) makes \( -\pi \leq \tilde{\phi}_i, m \leq \pi \), such that \( \tilde{\phi}_i, m - m \phi_i \) is a multiple of \( 2\pi \). The initial estimate for the phase, denoted by \( \tilde{\phi}_i, m \), is obtained to be the phase of \( \hat{Y}_m(f) \). We can also then obtain the initial estimated \( m \)th harmonic component \( \hat{Y}_{i,m}(f) \) for each \( i \).

In each of the \( N_{\text{iter}} \) iterations, for the \( i \)th LED, we subtract the component \( \hat{Y}_{i,m}(f) \) of the neighboring LEDs from \( \hat{Y}_m(f) \), where \( |j - i| < L_{\text{neighbor}} \), since these LEDs give the most significant interference to \( \hat{Y}_{i,m}(f) \). In practice, it suffices to have \( N_{\text{iter}} \leq 5 \) and \( L_{\text{neighbor}} \leq 10 \). The result of this subtraction is considered to be an updated \( \hat{Y}_{i,m}(f) \). Then \( \tilde{f}_i \) is obtained by locating the peak of \( |\hat{Y}_{i,m}(f)| \) and \( \tilde{\phi}_i \) and \( \tilde{\phi}_i \) can in turn be obtained based on \( \hat{Y}_{i,m}(f) \).
Algorithm 1 An iterative parameter estimator

1: for $i = L_{m-2} + 1$ to $L_{m-1}$ do
2: \[ \hat{f}_i \leftarrow \bar{f}_i, \hat{a}_i \leftarrow |Y_{m}(m \hat{f}_i)/b_{i,m}| \]
3: \[ \hat{\phi}_{i,m} \leftarrow \text{angle}(Y_m(m \hat{f}_i)/b_{i,m}) \]
4: \[ Y_{i,m}(f) = \hat{a}_i b_{i,m} G(f - m \hat{f}_i) \exp(j \hat{\phi}_{i,m}) \]
5: end for
6: for $N_{i}$ iterations do
7: \[ Y_{i,m}(f) = Y_m(f) - \sum_{j} Y_{j,m}(f), \text{when } |j - i| < L_{\text{neighbor}} \]
8: \[ \hat{f}_i \leftarrow \arg_{j} \max |Y_{i,m}(f)|, \text{when } |f - \hat{f}_i| < \frac{m \Delta f_{m-1}}{2} \]
9: \[ \hat{a}_i \leftarrow |Y_{i,m}(m \hat{f}_i)/b_{i,m}| \]
10: \[ \hat{\phi}_{i,m} \leftarrow \text{angle}(Y_{i,m}(m \hat{f}_i)/b_{i,m}) \]
11: \[ Y_{i,m}(f) = \hat{a}_i b_{i,m} G(f - m \hat{f}_i) \exp(j \hat{\phi}_{i,m}) \]
12: end for
13: end for
14: end

In the result of Algorithm 1, besides $\hat{a}_i$ and $\hat{f}_i$, we can obtain $\hat{\phi}_{i,m}$, which could correspond to $m$ possible $\phi_i$, denoted by $\psi_{i,k}$ for $k = 1$ to $m$, such that $e^{j \psi_{i,k}} = e^{j \phi_i}$. This is due to phase ambiguity. This phase ambiguity has to be resolved for the successive estimation procedure since $\hat{\phi}_{i,m+1}$ to $\hat{\phi}_{i,m}$ will be later used for the subtraction steps. To this end, we refer to the $(m - 1)$th harmonic range of the LEDs in the $(m - 1)$th group. Specifically, we consider

\[ Y_{m-1}(f) \approx \sum_{i=1}^{L_{m-2}+1} a_i b_{i,m-1} e^{j(m-1)\phi_i} G((f - (m-1)\hat{f}_i)). \tag{7} \]

Theoretically, for every possible $\psi_{i,k}$, we can reconstruct $\bar{Y}_{i,m-1}(f)$. Among these, the one that makes $\bar{Y}_{i,m-1}(f)$ match best with the $Y_{m-1}(f)$ at $f = (m - 1)\hat{f}_i$ is taken as $\hat{\phi}_i$. In practice, due to the induced interference from the neighboring LEDs, we also consider the $(i - 1)$th and $(i + 1)$th LEDs jointly with the $i$th LED. Specifically, there are, in total $m^3$ different combinations of $\{\psi_{i-1,k_1}, \psi_{i,k_2}, \psi_{i+1,k_3}\}$, where $k_1, k_2, k_3 \in \{1, 2, \ldots, m\}$.

Let $k = [k_1, k_2, k_3]$. For every possible $k$, we can regenerate $\bar{Y}_{i,m-1}(f)$, for $l = \{i-1, i, i+1\}$. The optimal $k^* = [k_1^*, k_2^*, k_3^*]$ is given by

\[ k^* = \arg_{k} \min \left| Y_{m-1}((m - 1)\hat{f}_i) - \sum_{l=1}^{i+1} \bar{Y}_{l,m-1}((m - 1)\hat{f}_i) \right|, \]

and the final estimate is obtained as $\hat{\phi}_i = \psi_{i,k^*}$. The phase ambiguity is as such resolved.

Finally, note that the $m$th and $(m - 1)$th harmonics of every LED in the $(m - 1)$th group should exist for the above described component estimator to work effectively. This gives a minor constraint on the cycle times. In particular, it is required that each $p_i$ in the $(m - 1)$th group has to satisfy that both $|b_{i,m}|$ and $|b_{i-1,m}|$ are larger than $\delta$, where $\delta$ is small (e.g., $\delta = 0.001$ in chosen in the numerical results presented next).

4. NUMERICAL RESULTS

Due to a large number of combinations of $\{p_i, a_i, f_i, \phi_i\}$, it is not possible to show the performance for each parameter set. By way of illustration, we show the case when $p_i = p_{\text{min}}$ for every $i$, where there is significant signal power in the higher harmonics. Further, we take $a_i = a_k$ for every $i \neq k$, such that every LED receives significant induced interference from other LEDs. The frequency offsets $\epsilon_i$ and $\phi_i$ are generated randomly, based on uniform distributions, according to 100 ppm clock inaccuracy and $-\pi \leq \phi_i \leq \pi$, respectively.

Results are shown for $M = 11$, $L = 500$, and $C = 90$ dB. Specifically, the estimation error $\max_i(\epsilon_i)$ for the LEDs in each group is depicted in Fig. 5. Here, the simulations were performed 100 times and the worst case was selected for each $\max_i(\epsilon_i)$ among the 100 simulation instances. It can be seen that there tends to be a larger error in the later groups than the earlier groups, attributed to error propagation and larger frequency offsets. Nevertheless, the estimation error is well below $-20$ dB for every LED, as required.

5. CONCLUSIONS

We considered the use of multiple harmonics for parameter estimation in illumination sensing for FDM based LED lighting systems. A successive estimation approach was presented. With this approach, the number of LEDs that can be supported scales logarithmically with the number of harmonics considered. Simulation results indicate that we can support at least five times the number of LEDs in comparison to the method previously described in [4].

6. REFERENCES