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Reading Analysis for Barcode Scanner With Interference from LED-Based Lighting

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ABSTRACT

This paper addresses reading failures of a barcode scanner interfered by light emitting diode (LED) lamps. It quantifies the reading performance in terms of timing signal-to-interference ratio (TSIR), in particular, as a function of modulation depth and frequency of the interference from modulated LED lighting. At the decision variable, the interference typically generated in the LED driver by a switched mode power supply (SMPS) is neither additive nor Gaussian. It has frequencies up to several MHz that can seriously affect the barcode reading performance. To calculate the signal and interference power for TSIR, the laser scanner physical channels are analyzed, including the laser beam path and the LED interference path. Since barcode scanners usually use peak or edge detection, the reading reliability is subject to the first and second derivatives of the LED inference, respectively. We validate the proposed TSIR for predicting scanner reading performance by experiments. For instance, we found that typical scanners reach a specified sensitivity at a TSIR value of around 50. We further investigate the reading performance under multi-frequency interference, e.g., interference from the harmonics of the SMPS control signal. In general, this paper presents a simple, yet realistic model to quantify the reading performance in terms of TSIR for barcode scanner subject to single-frequency LED interference, and it proposes an empirically verified flicker interference metric (FIM) for multi-frequency interference.

INDEX TERMS

Barcode, flicker, laser scanner, LED, TSIR, lamps, lighting.

I. INTRODUCTION

Barcode scanners play an essential role in the electronic data interchange where they are used extensively. They gave an electronic identity to objects, and have been a source of inspiration for the Internet of Things (IoT). Yet, in future they are likely to continue to play a role in asset tracking and inventory monitoring, even for passive object and components, not only for intelligent devices. Well-known examples are supermarkets, hospitals, express parcel tracking and industrial production statistics [1]. Meanwhile, as an emerging light source, the Light Emitting Diode (LED) has shown the promise for specialized and general lighting due to its high luminous efficiency, small size, easy control and long lifetime [2]. Nevertheless, this study has found that the rapid fluctuations in LED light output seriously interfere with the barcode scanner, thereby degrading the reading performance.

This motivates us to predict the effect of LED interference on a barcode scanner and, in particular, to understand its dependency on modulation intensity (depth) and the repetition frequency of the LED light output. Since both the modulation depth and frequency are controllable in lighting, they can be potentially optimized to ease risks on equipment that applies light as input signal. In lighting industry, an International Electrotechnical Commission (IEC) standard with new flicker metrics are still being refined to cover all types of light sources [3], including LEDs. This also justifies a study into the effect of the LED interference on light-based systems such as barcode scanners.

Because of the physical mechanisms behind the generation of light, fluorescent tubes generate more ripples than an LED driven by a perfectly constant DC current. LEDs lighting is now becoming such a mass market product that the electronics of the DC driver is under severe cost pressure. In some cases the visible flicker is only marginally suppressed while often Switched Mode Power Supply (SMPS)
oscillation artefacts remain present in the driver current. Moreover, Pulse-Width Modulation (PWM) modulation is sometimes directly applied to the LED current to allow dimming or to stabilize the current. This work was initially motivated by market complaints about failing barcode scanners after installing specific LED products. Premium design in the LED driver or bar code detector (or both) can resolve this, but we saw a need for quantifying the effects and for potential consideration in a standard to avoid Temporal Lighting Artefacts (TLA). We also foresee that the rising popularity of embedding data into the LED light, known as Visible Light Communications (VLC) [4], may require further insights in the need for compatibility in intensity modulated light spectrum. In joint illumination and communication systems, the light is intentionally modulated for data transmission without flicker perceptible to the human eye [5], [6]. In practice, the rapid fluctuations of light is mainly generated in the power-efficient SPMS for driving the LED. Although techniques such as the smoothing capacitor in the output of a Buck driver can mitigate the ripple, there is a tradeoff between efficiency and the ripple suppressing.

In scanning widely-used one-Dimensional (1D) barcode, the information is decoded from an acquired barcode signal with an accurate estimation of features such as the edges and peaks of the barcode patterns [7]. For instance, reported works dealt with signals for these features using signal filtering [1], [8], waveform analysis [9], deblurring [10], feature extraction [11] and other signal processing techniques such as Expectation-Maximization algorithm [12], [13] and Gauss-Newton algorithm [7]. However, for most of these techniques, the impact of LED interference was not yet addressed. In the scanner, Additive White Gaussian Noise (AWGN) causes a time shift to the zero crossings of a signal intersecting a threshold, experienced as a timing jitter [14], [14]. The timing signal-to-noise ratio determines the reading performance [15]. Nevertheless, the LED interference is neither additive nor Gaussian and thus its effect on the scanner reading performance needs to be further investigated. To the best of our knowledge, our work presents the first model of a barcode scanner system, subject to multiple LED interference sources.

Most reported work analyzed the performance of the barcode scanner based on a convolution of a laser beam over the barcode by considering the optical channel as constant gain [1], [10], [15]. However, this simplified channel model is inadequate to analyze the scanner reading performance in practical applications. For instance, the reading distance, which results in a certain channel gain, significantly affects the reading performance. Moreover, we found that the signal propagation channel differs from the high-frequency LED interference channel. Hence, we developed a channel model both for the signal and for interference.

In LED lighting, it is known that the fluctuating LED light potentially imposes risks on human flicker perception [16] and light-based electronic systems such as cameras [17] and barcode scanners [7]. Non-uniform illumination of the target can affect the barcode scanning, so a joint illumination estimation and deblurring algorithm was proposed [7]. In contrast to the non-uniform illumination, which changes very slowly compared to the barcode signal itself, we studied rapid fluctuations in LED light output [18]. Yet, these models did neither consider multiple interference sources nor was an experimental verification conducted.

This paper addresses reading failures of a barcode scanner that suffers from LED interference, and incorporates several new contributions. Firstly, we propose a new propagation channels for the barcode signal and LED interference separately. We argue that the LED interference power seen by scanner is constant under a required illumination level, regardless of it position w.r.t. the bar code. Secondly, the Timing Signal-to-Interference Ratio (TSIR) was proposed and verified for predicting the scanner reading performance under single frequency LED interference. Thirdly, for multi-frequency LED interference, we propose and verify a Flicker Interference Metric (FIM) in the form of P-norm with a weighted frequency-averaging. It indicates whether barcode reading is acceptably reliable. More specifically, we found that the TSIR for a single (strongest) frequency interference source was not adequate to model the scanner reading performance for multi-frequency LED interference. This is because multiple non-AWGN LED interferences results in a combined interference with a more complicated distribution than adding variances, as in AWGN.

To this end, commonly used principles for barcode reading approaches are reviewed and modeled. A system description is provided in section II. The scanner is modeled in more detail in section III. In section IV, a barcode signal and the impact of LED interference with an arbitrary waveform on barcode reading are analyzed. In Section V, we verify our model with measurements of single and multi-frequency LED interference.

II. SYSTEM DESCRIPTION OF BARCODE SCANNERS

Two classes of scanning technique are widely used in hand-held barcode scanners, in particular light reflection and image capturing. The light reflection scanning principle can further be classified into two subclasses, namely LED-pen scanners with manual scanning and 1D laser scanners with automatical sweeping of a laser spot across the barcode. The image capturing scanner either uses a camera with an predefined reading line in the image or read the barcode by using an array detector such as a Charge-Coupled Device (CCD).

This paper attempts to build a generic model for light reflection scanners such as 1D laser scanner. We model it as a communication system that consists of three parts as described in Fig. 1: 1) a transmitter, which is composed of a laser, lens and a rotary prism. 2) an optical path, which includes the reflection against the barcode that modulates the spatial code as amplitude time-variations of the beam, 3) and a receiver which includes an optical filter, a Photo
Diode (PD), an edge detector or a peak detector and a signal processing module.

The signal disturbances mainly originate from four sources: 1) interference from artificial light such as rapid fluctuations in LED light intensity, 2) thermal noise generated in the receiver circuitry such as the Low-Noise Amplifier (LNA), which is signal-independent, 3) shot noise, caused by the instantaneous quantum efficiency in the PD, which depends on the signal and on the background lighting including the DC light level, and 4) speckle noise generated randomly by a rough print of the barcode, which is also signal-dependent [14]. It has been well elaborated that thermal noise, shot noise and speckle noise may be considered as Gaussian noise [14], [19]. However, as non-Gaussian interference, the time-varying (flickering) light output of LED lamps can severely affect the scanner reading performance, especially when the frequency of interference is comparable to the scanning rate. Based on our measurement, the LED interference becomes dominant under LED lighting. This motivated us to focus on LED interference. For a model of the LED interference, as it occurs in LED drivers, we refer to [20], [21].

In particular, for a laser scanner to operate under ambient light as bright as sunlight, a narrow-band optical filter matching the laser wavelength is often desired [22]. Nonetheless, due to the wide spectrum of white light, some parts of the light still reach the photodetector as shown in Fig. 2. Moreover, for a certain illumination level, warm light yields more absolute power entering into the scanner than cool light, due to the higher relative power spectrum at the laser wavelength. Hence, warm light will more seriously affect the reading performance than cool light, which was confirmed in the experiment [23]. Although interference from LED could be mitigated by a narrow spectrum filter, a high-performance optical filter is prohibitively expensive and therefore hardly used. In this case, the LED interference even more seriously affects the scanning performance. Anyhow, more serious is the effect of a fluctuating LED output light.

In general, a barcode scanner with fast scan velocity and large depth of field of the view is desired. Yet, the scan velocity is constrained by the transmitted power which is limited by eye safety. The scan depth is mainly affected by the blurring that is caused by the convolution process of the laser spot over the barcode symbol. This work proposes a performance metric, i.e., TSIR, by taking into account the relevant parameters, such as the laser power, scan velocity and reading depth.

III. SYSTEM MODEL FOR LASER SCANNERS

In this section, the transmitter, channel and receiver of the laser scanner shown in Fig. 1 are discussed in detail. In particular, new channel models are proposed to calculate the received signal and interference power.

A. TRANSMITTER

As shown in Fig. 1, the laser is the signal source in the transmitter. The output laser beam is concentrated by an optical lens, then reflected by a rotary mirror, and at last it scans across the barcode. In particular, using the micro-electromechanical systems (MEMS), the laser beam can be steered without a mechanical motor in the transmitter [24], which leads to a compact and low-cost barcode reader. In such case, the traditional channel model for mechanical scanners is not applicable and thus new channel models are necessary.

B. CHANNEL

Unlike most communication systems using Light-of-Sight (LOS), the scanner detects information that is embedded in the barcode through a reflected path between the transmitter and the receiver.

1) GENERAL CHANNEL MODEL

The scanner uses a laser to illuminate a small area within the printed barcode. The detector collects the reflected light and sees a temporal waveform when the spot is scanned across the barcode. The propagation path is illustrated in Fig. 3. The effective area $A_e$ that the receiver can observe is usually designed to be larger than the laser spot size $A_L$ and also larger than the barcode, but preferably not too large, to avoid the collection of unwanted noise or interference.

From Fig. 3, the received optical power $P_s$ from the laser at the detector is expressed as

$$P_s = \int \lambda P_{laser}(\lambda) L_L - P R(\lambda)L_P - D F(\lambda)d\lambda,$$ (1)
where \( P_{\text{laser}}(\lambda) \), \( L_{L-P} \) and \( L_{P-D} \) are the output power spectrum of laser over the wavelength \( \lambda \), the loss from laser to paper and the propagation loss from paper to the detector, respectively. Since all laser power falls in the spot area, \( L_{L-P} = 1 \) and thus the optical power in the spot is independent of the distance \( d \) between the laser source and the barcode. The laser signal is reflected by the barcode with a reflection coefficient \( R(\lambda) \). Then it passes through the optical filter \( F(\lambda) \) and finally it is picked up by the PD.

The effect of distance is non-trivial. Even though the laser sees a reflection channel, we argue that its received power does not follow an \( d^{-4} \) law, as in radar but an \( d^{-2} \) attenuation. The interference level is largely distance-independent, because the scanner sees an illuminated paper, re-mitting light that is attenuated by \( d^{-2} \) but composed of light from an area that grows with \( d^{+2} \). In quantifying the SNR, one should also consider that the rate of seeing data from the barcode is proportional to the distance, as the laser sweeps with constant angular velocity over distance \( d \).

2) PROPAGATION CHANNEL OF THE LASER BEAM

The simplified channel model for laser signal is proposed in Fig. 4 (a). The laser beam is rotated by the MEMS micromirror that utilizes a magnetic actuation. Specifically, an electric current flowing through the mirror to generate an equivalent mechanical scans across the barcode. The scattered light is received and then focused by a compound lens onto the PD. The laser signal is attenuated by the optical path from paper to detector.

The optical configuration using a MEMS micromirror in the scanner typically has a large detection area, so it is sensitive to the noise and interference. The reflection from a paper surface is well approximated by Lambertian re-radiation [14]. We write the Lambertian reflection as

\[
R(\phi) = \frac{1}{2}\pi \cos^m(\phi), \quad \text{where} \quad \phi \text{ is the angle between the outgoing laser beam and the main lobe direction of the reflection pattern [25].}
\]

The order \( m \) can be calculated by

\[
m = \frac{-\ln 2}{\ln (\cos \Phi_{1/2})},
\]

where \( \Phi_{1/2} \) is the semi-angle at half power of the pattern. For instance, the measured semi-angle of the pattern for a cardboard is around 30° [14]. Thus the propagation loss from paper to the detector is

\[
L_{P-D} = \frac{A_d \cos \theta R(\phi)}{d^2} = \frac{A_d \cos \theta (m + 1) \cos^m(\phi)}{2\pi d^2}, \tag{2}
\]

where \( A_d \) is effective aperture of the PD considering the effect of compound lens. The angle \( \theta \) is the off-axis angle in the normal direction of the lens and in such case, \( \phi = 2\theta \). The lens is located in a distance \( d \) from the laser spot. After the lens, the received optical power by PD is converted into current \( I_{PD} \), expressed as

\[
I_{PD} = \frac{\epsilon P_{\text{laser}} R(\lambda) A_d (m + 1) \cos^m(\phi) \cos \theta}{2\pi d^2}, \tag{3}
\]

where \( \epsilon \) is the PD responsivity (A/W) and \( P_{\text{laser}} \) is the received power after the integration over wavelength \( \lambda \), with assumption that reflection coefficient \( R(\lambda) \) is independent of \( \lambda \). Since the electric power is proportional to the square of the current, the signal power declines according to the fourth power of distance \( d \). Except for the signal power loss, in section IV-A, we further investigate the signal dispersion that depends on the spot size and the scan distance (depth).

3) PROPAGATION PATH OF THE LED INTERFERENCE

Evidently, LED interference can also be caused by VLC that is being applied in various frequency bands, depending on the application. Systems optimized for camera detection typically modulate up to several kilohertz. Our results show that barcode scanners are relatively insensitive to modulation at these frequencies. For data communication, as for instance in the ITU G.vlc standard, modulation starts above a few MHz. Our results show that barcode scanners are mainly sensitive at lower frequencies. Nevertheless, the poorly filtered SMPS are more likely to interfere with barcode scanners than VLC would, particularly if the rms modulation depth of VLC is relatively low. Earlier we saw that LED interference generated by the SMPS as a self-influence can harm the Bit Error Rate (BER) performance in a low rate VLC [20]. The effect of VLC-modulation-related mutual interference on BER performance of nodes in a VLC network was also investigated [26]. In this paper, we consider the sinusoid LED interference which is mainly generated in the SMPS. The fluctuation of the LED output light becomes a cross-interference into other light-based systems, for instance, barcode scanners. In scanner systems, the propagation path of LED interference is quite different from that of the laser beam.

The barcode and its surrounding environment are simultaneously illuminated by the LED lighting. Specular reflection is less likely for the LED interference because the lighting
is typically designed to avoid glare. Thus the illumination is realistically modeled to be uniform. Hence, we model the reflected light interference from the paper as Lambertian radiation with a main lobe perpendicular to the paper surface, as shown in Fig. 4 (b). In particular, since the far field effect for the Lambertian radiation, the interference is represented by the accumulation of a large number of small radiation elements.

As illustrated in Fig. 4 (b), the interference power received from the LED light can be expressed as an integral over the effective area $A_{e}$ and the wavelengths. So, we have

$$n_{\text{LED}} = \int \int_{A_{e}} P_{\text{LED}}(\lambda)P_{\text{P-D}}(a,b)F(\lambda)rd\theta d\lambda,$$

(4)

where $P_{\text{LED}}(\lambda)$ is the Power Spectral Density (PSD) of LED output light. The power loss $P_{\text{P-D}}(a,b)$ is caused by the Lambertian re-radiation at $(a = r \cos \beta, b = r \sin \beta)$ for each small spot in the view area, thus

$$P_{\text{P-D}}(r \cos \beta, r \sin \beta) = \frac{A_{d} \cos \theta'(m + 1) \cos^m(\phi')}{2\pi(d_{0}^2 + r^2)},$$

(5)

where $d_{0}$ is the vertical distance from paper to the detector. Because the main lobe is perpendicular to the paper surface, we have $\phi' = \theta'$. If assume that all patterns have $m' = 1$, integrating over the whole area, the total received interference power $n_{\text{LED}}$ becomes

$$n_{\text{LED}} = \int_{0} P_{\text{LED}} \int_{0}^{\theta_{0}} A_{d} d_{0} \cos^2 \theta_{0} \int_{0}^{2\pi} d\beta$$

$$= P_{\text{LED}} A_{d} \tan^2 \theta_{0} \int_{0}^{2\pi} (1 + \tan^2 \theta_{0}),$$

(6)

where $\theta_{0}$ is the view angle of the barcode scanner. $P_{\text{LED}} = \int_{0} P_{\text{LED}}(\lambda)F(\lambda)\lambda d\lambda$ is the light density on the scanned area, expressed as $W/m^2$. From (6), it can be concluded that the interference from LED $n_{\text{LED}}$ is always constant given the view angle and illumination level. Note that the rotation of a barcode object only affects the effective light density at the reading plane $P_{\text{LED}}$ from the LED lighting and thus the received LED interference is still a constant.

We define electrical $SIR = \left(\varepsilon P_{l}/\varepsilon n_{\text{LED}}\right)^2$ as the signal to interference ratio. Based on (3) and (6), provided that only LED flicker interference is present, the $SIR$ also declines according to a fourth power of distance $d$ and it is expressed as

$$SIR = \left(\frac{P_{\text{laser}}R(m + 1) \cos^m(\phi) \cos \theta(1 + \tan^2 \theta_{0})}{2 P_{\text{LED}} A_{d} d^2 \tan^2 \theta_{0}}\right)^2.$$  

(7)

Note that the scanner reading performance is not solely determined by the SIR since it does not take into account the scan rate. Thus, a new metric in terms of TSIR is provided in Section IV.

C. RECEIVER

As mentioned before, there are two widely used detection algorithms for barcode scanning, namely edge detection and peak detection [1]. Both algorithms are also widely used in other applications such as image processing [27], [28].

![Fig. 5. Peak detection for laser scanners.](image1)

![Fig. 6. Edge detection for laser scanners.](image2)

1) PEAK DETECTION

Fig. 5 shows a peak detection implementation for barcode reading, using the 1st derivative [1]. The zero crossing of the 1st derivative of signal is used to find the peak or valley of the received signal, which corresponds to the midpoint of the modules (stripes and gaps) of the barcode. Note that, the 1st derivative is calculated after the low-pass filtering to suppress the wide-band noise. For deblurring the signal, a further scaled second derivative is needed, based on the inverse filter design. This method is mainly used for high density barcode, i.e., $\sigma_1 < T_b < 4\sigma_1$, where $\sigma_1$ is a quarter of the spot size of the laser beam in time and $T_b$ is the module duration of the smallest bar or space.

2) EDGE DETECTION

The zero crossing of the 2nd derivative of the received signal can indicate an edge in the barcode. The implementation of edge detection using the 2nd derivative is shown in Fig. 6. In this scheme, after the signal and noise passing through a enhancement filter, the second derivative is computed for edge locations while other signals are also involved to avoid false edges. The edge detection is usually used for a low density barcode, i.e., $4\sigma_1 < T_b$. More details can be found elsewhere [19].

IV. SIGNAL AND PERFORMANCE ANALYSIS FOR LASER SCANNERS

A. SIGNAL DESCRIPTION

Scanning at a velocity $v$ transfers the barcode from space domain to time domain [29]. Normally, the scanning process is modeled as a one-dimensional swipe along the $x$ direction, although the laser spot is 2D [8], [30], [31]. Accordingly, we model the scanning process as the convolution of the laser spot over the barcode with additive noise $n(t)$, so the received signal $r(t)$ is

$$r(t) = \varepsilon L_{P-D}X(t) \otimes h(t) + n(t),$$

(8)

where $X(t)$ is the reflectivity function of the barcode in time and $h(t)$ indicates the laser Point Spread Function (PSF) of
the optical system. \( h(t) \) is generally modeled by a Gaussian function to produce the edge response [8] [14], expressed as

\[
h(t) = A_p \frac{1}{\sqrt{2\pi} \sigma_f} \exp \left( -\frac{t^2}{2\sigma_f^2} \right),
\]

where \( A_p \) is the power of the laser beam and \( \sigma_f \) is the temporal spread expressed as \( \sigma_f = w/ (4v) \), where \( w \) is the diameter of the laser spot. As elaborated in studies [1], [32], the laser beam converges to a non-zero minimum waist \( w_0 \) and then spreads with a divergence angle \( \alpha = 4\lambda/\pi w_0 \) to the far-field region, typically \( \alpha < \pi/180 \) (1 degree). Since \( w_0 \) is very small, the beam diameter can be described as \( w = 2d\tan\alpha \). So the laser point spread and the corresponding parameter \( \sigma_f \) grows when the barcode is moved away from the scanner. To ensure proper decoding, the spot size preferably is quite small, we can use second or fourth-order polynomial to approximate the high-pass inverse filter as a series expansion

\[
H_f(\omega) = \exp(\omega^2 \sigma_f^2/2) = 1 + \omega^2 \sigma_f^2/2 + \omega^4 \sigma_f^4/8 + \cdots,
\]

where \( \sigma_f = \eta \sigma_l \) and usually the scaler \( \eta = 1 \). Since \( \sigma_f \) is quite small, we can use second or fourth-order polynomial to approximate the series in the relevant \( \omega \) range.

1) PEAK DETECTION
As shown in Fig. 5, the second-order polynomial \( \tilde{H}_f(\omega) = 1 + \omega^2 \sigma_f^2/2 \) is used to approximate the high-pass inverse filter in (11) and then \( \sigma_f \) is optimized to avoid excessive noise enhancement above certain frequency. For the LPF \( H_G(f) \) in Fig. 5, we further use a Gaussian LPF which has the same form as the laser spot [33], [34]. Thus, the transient response of \( H_G(f) \) is expressed as

\[
h_G(t) = \frac{1}{\sqrt{2\pi} \sigma_f} \exp \left( -\frac{t^2}{2\sigma_f^2} \right),
\]

with Fourier transform \( H_G(\omega) = \exp(-\omega^2 \sigma_f^2/2) \) and \( \sigma_f \) indicating its bandwidth which is optimally selected for a typical scan distance.

2) EDGE DETECTION
For edge detection, an edge-enhancement filter is proposed [8], which combines the noise limiting and deblurring in one filter design. This filter can be described by the ratio of two polynomials as

\[
H_{f2}(s) = B(s)/A(s),
\]

where the numerator of \( B(s) = 1-s^2 \sigma_f^2/2 + s^4 \sigma_f^4/8 \) is used to approximate the prototype of the inverse filter in (11) using \( s \) parameter. The sixth-order Bessel filter was used for the denominator since it has a low-pass property with a linear phase but no overshoot [8]. However the drawback of the Bessel filter is that its response is not as steep as the Gaussian low-pass filter. Thus for better comparison, the same low-pass Gaussian filter in (12) is applied for edge detection.

C. SIGNAL FOR PEAK AND EDGE DETECTION
This paper focuses on the analysis for peak detection using the first derivative. After the low-pass filter in Fig. 5, the barcode reader calculates the first derivative \( s(t) \) to digitalize the received signal \( r(t) \) [1], [19], [35] such that

\[
s(t) = \frac{G_S}{2} \sum_{i=0}^{n-1} (-1)^i \frac{1}{\sqrt{2\pi} \sigma_o} \exp \left( -\frac{(t-t_i)^2}{2\sigma_o^2} \right),
\]

where \( G_S = sL_p \cdot D A_p C \) indicates the signal channel gain. And \( \sigma_o^2 = \sigma_f^2 + \sigma_l^2 \) is the total blurring. Considering the effect of the inverse filter, the signal used for peak detection is

\[
\sigma_f(t) = s(t) - \sigma_f^2 s''(t)/2.
\]

In edge detection, the edge is mathematically determined by the second derivative of the received signal \( r(t) \). The detailed analysis for edge detection is omitted to avoid repetition since similar approach can be applied, but its results are depicted for comparison in Section V.

D. RECEIVED INTERFERENCE FROM LED
The interference of AC-driven LED often has a strong 100 Hz (or, in USA, 120 Hz) component, but it is less harmful to barcode scanner. However, LEDs are usually powered by SMPS in efficient lighting [36]. In such case, the SMPS injects a cyclostationary intensity modulation with a frequency of at least several kHz, but often above 20 kHz to avoid any risk of audible noise coming from inductors in the lamp. More seriously, the frequency can be several MHz by taking into account the harmonics.

1) INTERFERENCE IN SMPS
In this work, the SMPS is considered due to its high power efficiency and easy digital control. Depending on the application, the topology of SMPS could be based on basic buck,
boost and Cuk converter [37]. For instance, the buck-based SMPS works as a DC to DC converter for high to low voltage conversion. However, it incurs a triangular ripple whose frequency depends on the PWM control signal [20]. It is necessary to note that there is a tradeoff between efficiency and the ripple suppressing, in other words, a high efficiency SMPS has substantial ripple ripples.

Usually, an output capacitor is necessary for ripple suppression in SMPS. However, the capacitor still leaves the fundamental frequency and its harmonics. In barcode scanner system, low-frequency harmonics of LED interference affect the reading performance. Therefore we initially model the LED light output $p(t)$ with a sinusoid waveform and write for a single-frequency interference as

$$P_{\text{LED}}(t) = p(t) = p_{\text{DC}}[1 + \kappa \sin(\omega t)],$$

where $p$ is the scale factor that indicates the transformation from irradiance to optical power [38], $p_{\text{DC}}$ is the light level at the reading pane, typically with 500 lux, and $\omega$ is the frequency of the interference.

The modulation depth $\kappa$ ($0 < \kappa < 1$) in LED lamp is defined as the output light difference divided by the sum of the two light levels,

$$\kappa = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}}),$$

where $I_{\text{max}}, I_{\text{min}}$ are the highest and lowest illumination levels in Lux. Although in some cases the interference waveform does not exactly resemble a sinusoid, the following approach still applies after the Fourier transformation.

For peak detection, we detect the zero crossing of the first derivative. Based on (6) and (16), the interference $n_1(t)$ seen at the detector can be interpreted as a randomly phased periodic signal

$$n_1(t) = \frac{d}{dt} [e^{n_{\text{LED}}(t + \xi)} \otimes h_{\text{G}}(t) \otimes \tilde{h}_{\iota}(t)] = G_1 H_0(\omega) \kappa \omega \cos(\omega t + \xi),$$

where $G_1 = \xi A_{\text{LED}} p_{\text{DC}} \tan^2 \theta_0 / (1 + \tan^2 \theta_0)$ is the interference channel gain, $\xi$ describes the random phase offset of the LED flicker and $\tilde{h}_{\iota}(t)$ is the impulse response of the inverse filter. $H_0(\omega) = H_{\text{G}}(\omega) H_{\iota}(\omega)$ indicates the overall filter response.

2) STATISTICAL MODEL FOR SINUSOIDAL INTERFERENCE

The mean of $n_1(t)$ can be expressed as

$$\mu_{\text{LED}} = E[n_1(t)] = \int_0^T n_1(t)p(t)dt = 0,$$

where $p(\xi) = 1/T$ indicates the uniform distribution of the phase in one period. The variance of $n_1(t)$ can be expressed as

$$\sigma_{\text{LED}}^2 = E[n_1(t)^2] - E^2[n_1(t)] = [G_1 H_0(\omega) \kappa \omega]^2 / 2.$$  

For the sinusoidal interference, the probability density function of $n_1(t)$ can be expressed as [20]

$$f_{\text{LED}}(n_1) = \begin{cases} \frac{1}{\pi \sqrt{\rho_1^2 - n_1^2}}, & \text{for } |n_1| < \rho_{\text{LED}} \\ 0, & \text{elsewhere}, \end{cases}$$

where the electrical signal amplitude $\rho_{\text{LED}} = G_1 H_0(\omega) \kappa \omega$ linearly depends on the power loss of the interference. Exact calculation of the error probability (per peak detection) becomes complicated, but a binomial approximation will be considered, with

$$f_{\text{LED}}(n_1) = a_1 \delta (n_1 - \rho_1) + a_2 \delta (n_1 + \rho_2),$$

where $\rho_1 = \rho_2 = \rho_{\text{LED}}$ and $a_1 = a_2 = 1/2$.

In particular, most of SMPSs produce a triangular interference waveform. In such case, $a_1$ and $a_2$ become the fractions of time in the rising and falling ramp, respectively. In addition, $\rho_1$ and $\rho_2$ are the slope of the rising and falling ramps, respectively.

E. ERROR MODELS

This paper analyzes the effect of the LED interference for peak detection using the first derivative. The zero-crossing time of the first derivative becomes uncertain due to sinusoidal interference. In Fig. 7, without interference, the $i$th zero-crossing point at time $t_{ii} = (i + 0.5)T_b$ indicates the barcode midpoint. The time module is expressed as $T_b = S_M/v$, where $S_M$ is the size of barcode module. However the interference shifts the zero-crossing point to time $t_{ii} + \Delta$, where $\Delta$ is the amount of timing shift, namely timing jitter [15]. As illustrated in Fig. 7, the time shift $\Delta$ can be expressed as

$$\Delta = n_1(t_{ii}) / s_{\iota}'(t_{ii}),$$

where $n_1(t_{ii})$ is the LED interference and $s_{\iota}'(t_{ii})$ is the slope of the signal $s_{\iota}(t)$ at the same $i$th zero-crossing point $t_{ii}$.

For a single zero-crossing point, the error probability that the interference plus noise exceed a certain threshold $\varepsilon T_b$ ($\varepsilon = 0.5$) equals the (two-sided) probability that point is shifted into an erroneous quantization zone. Hence the error

\[\text{FIGURE 7. First derivative with zero crossing time and sinusoid interference.}\]
probability is expressed as the sum of two equal error probabilities

\[ P_{err_{-1}}(|\Delta| \geq \varepsilon T_b) = P_{err_{-1}}\left(|n_1(t_{ii})| \geq \varepsilon T_b s_f'(t_{ii})\right) = 2 \int_{\varepsilon T_b s_f'(t_{ii})}^{\infty} f_{LED}(n_1)dn_1. \]  \hspace{1cm} (24)

1) BINOMIAL APPROXIMATION
If we use the binomial approximation for \( f_{LED}(n_1) \) in (22), we get

\[ P_{err_{-1}} = \begin{cases} 1, & \text{if } |\rho_1| \geq \varepsilon T_b s_f'(t_{ii}) \\ 0, & \text{if } |\rho_1| < \varepsilon T_b s_f'(t_{ii}), \end{cases} \]  \hspace{1cm} (25)

which means that, once the timing jitter exceeds the threshold, the scanner fails to read the barcode information. Thus when multi-frequency interference are present, the reading performance is mainly determined by the strongest component.

2) GAUSSIAN APPROXIMATION
If we make additive and Gaussian approximation for the LED interference, (24) becomes,

\[ P_{err_{-1}} = \frac{2}{\sqrt{2\pi} \sigma_{LED}} \int_{\varepsilon T_b s_f'(t_{ii})}^{\infty} \exp\left(-\frac{n_1^2}{2\sigma_{LED}^2}\right)dn_1 \]

\[ = \text{erfc}\left(\sqrt{\text{TSIR}}/(2\sqrt{2})\right), \]  \hspace{1cm} (26)

where \( \text{erfc}(.) \) is the complementary error function and we define \( \text{TSIR} \) as

\[ \text{TSIR} = \left[ T_b s_f'(t_{ii}) \right]^2 / \sigma_{LED}^2. \]  \hspace{1cm} (27)

In fact, the additive and Gaussian approximation suggest that the impact of multi-frequency interference is determined by the weighted summation of the power in each frequency component. Yet, later, in Fig. 12 we will very experimentally to what extend this is accurate.

3) ERROR BOUND AND TSIR
More generally, for any probability density function of \( n_1(t) \), Chebyshev’s inequality gives us the upper bound

\[ P_{err_{-1}}(|\Delta - \mu_\Delta| \geq \varepsilon T_b) \leq \frac{\sigma^2_\Delta}{(\varepsilon T_b)^2} = \frac{1}{\varepsilon^2 \text{TSIR}}, \]  \hspace{1cm} (28)

where the mean of timing jitter \( \mu_\Delta = 0 \) and its variance \( \sigma^2_\Delta \) can be calculated from (20) and (23). (28) suggests that the upper bound only depends on the value of \( \text{TSIR} \). For single-frequency interference, it is expected that the probability of a barcode scanner error depends on the \( \text{TSIR} \). Thus, we use \( \text{TSIR} \) as a reading performance metric for scanner under single-frequency interference.

Based on (14), (15), (20) and (27), we calculate the \( \text{TSIR} \) at \( t_{ii} = (t_i + t_{i+1})/2 \). For simplifying the calculation, we start with the first midpoint at \( t_00 = (t_0 + t_1)/2 \). From (15), the first part of \( s_f'(t_{00}) \)

\[ s_f'(t_{00}) = \frac{G_S}{2} \left[ \sum_{i=0}^{n-1} (-1)^i \frac{(t_{00} - t_i)}{\sqrt{2\pi} \sigma_0^2} \exp\left(-\frac{(t_{00} - t_i)^2}{2\sigma_0^2}\right) \right] \]

\[ \approx -\frac{G_S T_b}{2\sqrt{2\pi} \sigma_0^3} \exp\left(-\frac{(T_b)^2}{8\sigma_0^2}\right), \]  \hspace{1cm} (29)

where we assume \( \sigma_0 < T_b < 4\sigma_0 \) for the high density barcode and thus the effect of \( t_{ii+2} \) on \( s_f'(t_{00}) \) is negligible. Similarly, we get the second part of \( s_f'(t_{00}) \).

\[ s_f'(t_i) = s_f'(t_{00}) - \frac{3\sigma_0^2}{2} s''_f(t_i) \]

\[ \approx \frac{G_S}{2} \exp\left(-\frac{(T_b)^2}{8\sigma_0^2}\right) \]

\[ \times \left\{ -\frac{T_b}{\sqrt{2\pi} \sigma_0^3} - \frac{3\sigma_0^2}{2} \left[ \frac{3T_b}{\sqrt{2\pi} \sigma_0^3} - \frac{(T_b)^3}{4}\right] \right\}, \]  \hspace{1cm} (30)

where the approximation is reasonable since the third order of \( T_b \) is very small. Exploring the relation between scan rate \( R_s \) and module time \( T_b \), i.e., \( T_b = S_M/(2\eta_0 R_s \tan(\theta_0)) \), the \( \text{TSIR} \) becomes

\[ \text{TSIR} \approx \left[ \frac{G_S S_M^3}{16 \sqrt{\pi} G_I \eta_0 \tan^3(\theta_0) \sigma_0^2} \right]^2 \left[ \frac{\exp\left(-\frac{D}{4\eta_0^2}\right)}{4\eta_0 \kappa \omega H_0(\omega)} \right]^2, \]  \hspace{1cm} (31)

where \( D = (2\eta_0 S_M \cos \theta / \tan \alpha)^2 / 8 \). From (31), the \( \text{TSIR} \) decreases with the frequency \( \omega \) and modulation depth \( \kappa \) of interference from the LEDs. Especially, the total blurring \( \sigma_0^2 \) is independent with distance \( d_0 \). Compared to the \( \text{SIR} \) in (7), we can easily find that the \( \text{TSIR} \) declines approaching to a sixth power of distance \( d_0 \), which is different from communication channels.

V. NUMERICAL EVALUATION AND EXPERIMENTAL VALIDATION
In this section, we present numerical results of the proposed \( \text{TSIR} \) with different distance, frequency and modulation index of the LED interference. Moreover, for a required detection error probability with a given \( \text{TSIR} \) value, the tolerable modulation depth (sensitivity) under single-frequency LED interference is calculated and validated by experiments. Finally, since the LED interference is non-additive and non-Gaussian, a new metric in terms of Flicker Interference Metric (FIM) is proposed and verified to estimate the effect of the multi-frequency LED interference.

We measure the sensitivity of a barcode scanner in a room illuminated only by LED lighting. The experimental setup includes LED lamps, a barcode laser scanner, a signal generator, an amplifier, a lux meter and a photo detector connected to an oscilloscope, as shown in Fig. 8. A sinusoidal signal is initially generated and amplified. Along with a DC power supply, the DC-biased sinusoid signal feeds the LED lamps. The lux meter measures the LED light level that reaches the barcode, and the oscilloscope with the photo detector
measures the light waveform and modulation depth of the LED interference. In particular, to improve the reliability of the experiment, eight Universal Product Code (UPC) barcodes are placed on a turntable which has a constant speed. Using this turntable, the scanner reads the barcodes with the same scan time for each barcode. In the initial stage of our experiment, the scanner reads the barcode on the running turntable without reading error when there is no LED interference. Note that the turntable speed is very slow compared to the scanning rate (100 c/s in the scanner), and thus its effect on module time $T_b$ is negligible. Then we add the LED interference by controlling the frequency and modulation depth, and the scanner starts to have failures. When the turntable rotates for a round and two of the eight barcodes fail to be recognized, the scan error probability is 25% and the corresponding modulation depth is considered as the sensitivity. Unless otherwise stated, the related parameters used for the calculation and setup are listed in Table 1.

### A. TSIR

Fig. 9 shows the numerical results of $TSIR$ versus distance and compares the $TSIR$ with its approximation using the 4th and 6th power of $d_0$ in the denominator of (31). As we can see, at a short scanning distance, the $TSIR$ is quite small due to the dominant effect of the exponential term in (31). When increasing the scan distance, there is an optimal distance around 20 cm with the largest $TSIR$ and many barcode scanners are designed for this distance. After that, the $TSIR$ declines approaching to the inverse of the sixth power of distance other than the fourth power. Our theoretical results explain that the scanner fails to read when the barcode is too close or too far away in our measurement, and the optimal reading distance around 20 cm is used for our setup in Table 1.

Based on (31), we can express $TSIR$ in terms of other parameters that we are interested in, e.g., the frequency and modulation depth of the LED interference. As expected, the scanner system has a larger $TSIR$ value with a smaller modulation depth $\kappa$ [18]. For $TSIR$ versus frequency, we notice there is a valley around 150 kHz caused by the electronic low-pass filter. To be specific, below 150 KHz, the $TSIR$ decreases with increasing the interference frequency. This is because the low frequency interference can pass through the electronic filter and affects the system. But after that, the low-pass filter attenuates the high-frequency component gradually, so the system becomes immune to high-frequency interference.

### B. SENSITIVITY VERSUS FREQUENCY

Given a required detection error probability, the tolerable modulation depth, i.e., the sensitivity to single-frequency LED interference is measured by gradually increasing the frequency and changing its modulation depth. For an error probability of 25%, the measured tolerable modulation depth $\kappa$ is shown in Fig. 10, where the $x$-axis is the interference frequency and $y$-axis is the tolerable modulation depth. Since the scan error probability is determined by the $TSIR$, the predicted sensitivities for different $TSIR$ values are also depicted in Fig. 10. As we can see, the predicted sensitivity for peak detection with $TSIR = 50$ agrees well with the measurement.

For $TSIR = 50$, peak detection starts to be affected by the LED interference around 1 kHz. Further increasing the interference frequency to 150 kHz, the tolerable modulation depth decreases, that is, the scanner is more sensitive to high frequency interference. After a most sensitive point around 150 kHz, the scanner gradually becomes immune to higher
The proposed in (26) suggests that we may sum up the powers of the individual components. Nevertheless, such assumption is unrealistic for the LED interference which is non-additive and non-Gaussian. On the other hand, our binomial approximation for a sinusoidal or triangular interference, which contains multiple harmonics of a fundamental frequency, would suggest that only the largest power of the individual components matters.

Experimentally, the sensitivity to multi-frequency interference is investigated by using two frequencies, one of 2 kHz plus one of 10 kHz. These two frequencies with an odd-harmonic relation are inspired by the harmonics in typical SMPS, which belongs to the Fourier series expansion of a triangular waveform. In the measurement, the signals at these two frequencies are synchronized at the beginning, which results into a worst case of the potential peak modulation depth. Thus, it provides a bound for other random phases. With a predefined modulation depth of the 2 kHz light, the modulation depth of the 10 kHz light is gradually changed until the mixed light reaches the sensitivity point for the scanner. Then the modulation depth is recorded. The measured results and numerical results for a mixture of the two lights are shown in Fig. 12, where the x and y axes are normalized by their single-frequency sensitivity, respectively.

From this figure, the ratios of the two lights approximately fulfil $n_{11} + n_{12} = 1$, where the ratio $n_{11}, n_{12}$ are defined as the ratio of actual modulation depth $k_f$ over the tolerable modulation depth for each frequency $k_f, k_f, k_f, k_f$ (see Fig. 10). For example, $n_{2kHz} = k_{2kHz}/k_{2kHz}$. In particular, we found that it is a generic relation since it holds for other given TSIR values. Thus when different types of LED lamps have the same illumination level (white light) or equally one lamp has multi-frequency flicker components, the effect of multiple-frequency interference is captured in a generic formula and thus a new Flicker Interference Metric (FIM) is proposed as

$$FIM = \sqrt{\sum_{m=1}^{\infty} \left( \frac{K_{fm}}{K_{fm,th}} \right)^p}$$

where $K_{fm}$ is the modulation depth for a specific frequency, $K_{fm,th}$ is the tolerable modulation depth for the same frequency, and $p$ is a parameter that determines the significance of the effect. The values of $p$ are as follows:

- $p < 1$: not influential
- $p = 1$: just influential
- $p > 1$: influential

The threshold TSIR for the measured results is further shown in Fig. 11. The threshold TSIR is expected to be a constant but it fluctuates between 27.5 and 146.5 in the measurement, which is caused by the limited resolution of the test. In worst case, the threshold TSIR should be at least 146.5 for a required scan error probability. Based on this value, the required modulation depth in the lighting is then determined.

C. SENSITIVITY TO MULTI-FREQUENCY INTERFERENCE

It is important to verify the sensitivity under multi-frequency LED interference because the light fluctuation due to a SMPS typically contains multiple harmonics. Moreover, the lighting system usually has different types of LED lamps and thus the LED interference can have different frequency components.

The error probability (24) suggests that we need to investigate the probability density function of the multi-frequency LED interference, which however usually becomes intractable. On one hand, the Gaussian approximation proposed in (26) suggests that we may sum up the powers of the individual components.
where $p$ is the norm factor and $m$ indicates the $n$th frequency component. The sensitivity for $\text{FIM} = 1$ with different $p$ are shown in Fig. 12. As we can see, if the LED interference is best described by an AWGN approximation related to the peak-to-peak amplitude of the interference, an appropriate choice would be $p = 1$ (45 degree line); if the rms value of the ripple is mostly relevant, $p = 2$ (circle); and if only the largest ripple component is relevant based on the bimodal approximation, $x$ approaches infinity (enclosing box). We conclude that linear weighing factor ($p = 1$) underestimates the distance by LED interference and the rms weighted amplitude overestimates it. However based on the measured results, $p = 1.5$ would be a reasonable, empirical weighting factor. In particular, interference contributions with random phases should be expected in the range between $p = 1$ to $p = 1.5$.

VI. CONCLUSION

This work analyzed the reading performance of barcode scanners subject to LED interference, in terms of a Timing Signal-to-Interference Ratio (TSIR) instead of a Signal-to-Interference Ratio (SIR), since the SIR does not take into account the scanning rate. To this end, this paper initially separately investigated the different propagation channels for the signal and interference in barcode scanners. Then based on the decoding algorithm, we derived the TSIR, which approximately is inversely proportional to the 6th power of the reading distance. Moreover, for a given illumination level in lightning, the amount of light interference falling into the scanner was constant and there appears to be an optimal distance around 20 cm for barcode reading. Besides, as expected, the reading performance highly depends on the modulation depth and frequency of the LED interference. For multi-frequency interference, we proposed a new metric $\text{FIM}$ with $1 \leq p \leq 1.5$ to enable scanner reading. The results can be also used to improve the algorithms for reading barcodes. This work lays a foundation to quantify the interference from the ubiquitous LEDs for light-based systems even the human eyes with flicker perception.

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