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Abstract. Many techniques using polarizers, differential detectors, and electrical filters are used to overcome the penalty induced by artificial light interference and are analyzed. These techniques are used to reduce noise current or remove it by using an electrical filter or a polarizer or both of them together. We are going to display the effect of noise voltage, flicker voltage of a tungsten lamp, and signal-to-noise ratio (SNR) of the systems by changing each parameter to reach the best solution for reducing the effect of noise on free space optics. This paper will show that the best SNR is obtained with the differential detector with a two orthogonal polarizer system and that the worst one is with the system of a single photodetector. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.OE.53.5.055109]

Keywords: optical wireless system; ambient noise; flicker voltage; noise voltage signal-to-noise ratio; differential detector with single polarizer; differential detector with orthogonal polarizers.

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1 Introduction

Optical wireless systems have an abundance of bandwidth and the advantages of being immune to radio-frequency interference, eliminating cables between systems, and confining data to the place of origination. However, in optical wireless systems, photodetectors may be exposed to strong ambient light, thereby introducing additional noise to the receiver. Incandescent light, daylight, and fluorescent lamps are the common ambient-noise light sources.^{1,2} Optical filtering or electrical filtering is usually adopted in order to suppress the effects of ambient noise light, and subcarrier modulation is also used so that the baseband signal waveform is translated to a carrier frequency away from the baseband interference.

In mobile telemetry systems, a limited transmitter complexity and small power consumption are of utmost importance. In such cases, digital pulse position modulation (PPM), based on intensity modulation and direct detection, is a very suitable modulation scheme because it combines the advantages of digital transmission (easy multiplexing of sensor signals, the possibility for data compression and error correction) and small duty-cycle pulse transmission (low-power transmitter).³ The PPM scheme and a maximum likelihood integrate-and-dump (I&D) demodulator are described in Ref. 4. A similar idea was briefly suggested by Barry,⁵ but no analysis was provided to support the benefits of the technique, described in Ref. 6, using the equation of an optical filter. Here, we use the same idea of using a differential detector with a single optical filter with polarizer equations⁷ and an electrical filter equation.⁸

2 Mathematical Model

2.1 Using Single Photodetector

The SNR for the time-varying signal in a single photodiode is defined as⁷

$$\text{SNR}_0 = 10 \log \left[\frac{i_s^2(t)}{i_{\text{amb}}^2(t) + i_{\text{shot},0}^2(t)} \right] \text{dB}, \quad (1)$$

where $i_{\text{shot},0}$ is the shot noise due to the dc current in a single photodiode without a polarizer, and $i_s(t)$ and $i_{\text{amb}}(t)$ are the time-varying currents due to the signal and the photodiode quiescent current due to ambient radiation, respectively.⁷

2.2 Using Single Photodetector and Polarizer

This system depends on the idea that the polarizer blocks all light of perpendicular polarization and passes some but not all of the light of one polarization. The receiver is composed of a photodiode (PD) and a linear polarizer (PL). If a linear polarizer is placed in a linearly polarized beam, the transmittance $T(\theta)$ will vary between a maximum value T_{max} and a minimum value T_{min} according to Malus's law.⁷

$$T(\theta) = (T_{\text{max}} - T_{\text{min}})\cos^2 \theta + T_{\text{min}}, \quad (2)$$

where θ is the tilt angle between the transmission axis of a polarizer and the electric vector of the incident beam. For $\theta = 0$ deg the SNR for the time-varying signal in a single photodiode with polarizer can be defined as

$$\text{SNR}_{\text{SD-SP}} = 10 \log \left[\frac{T_{\text{max}}^2 i_s^2(t)}{T_n^2 i_{\text{amb}}^2(t) + i_{\text{shot},1}^2(t)} \right] \text{dB}, \quad (3)$$

where $i_{\text{shot},1}(t)$ is the shot noise due to the average dc photocurrent in single detector single polarizer (SD-SP) and T_n is the constant transmittance of polarizer for ambient noise light. Also, the improved SNR_{SD-SP} over SNR of a single photodetector (SNR₀) can be defined as

$$\Delta \text{SNR}_{\text{SD-SP}} = \text{SNR}_{\text{SD-SP}} - \text{SNR}_0. \quad (4)$$

From this equation, one can see that the improvement in SNR depends mainly on the transmittance of the polarizer.

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2.3 Using a Differential Detector with a Single Polarizer

In this section, a different technique to combat the effects of the artificial light interference is analyzed. A similar solution was described in Ref. 6, using an equation of optical filter. Here, we used the same idea with the polarizer equations described in Ref. 7. The lower front-end in Fig. 1 receives the transmitted signal with much higher interference amplitude since no polarizer is used. The result is that the interference-to-signal ratio is much higher at the output of the lower front-end than at the upper front-end. If the output of the lower front-end is attenuated so that the amplitude of the interference received by the two stages is equal and the two outputs of the lower and upper front-ends are subtracted, the interference is totally cancelled while the transmitted signal is only partially attenuated. The output current is obtained as

$$i_{out}(t) = [T_s \cdot T_n][i_s(t) + I_{so}] + i_{shot,0}(t) + T_n \cdot i_{shot,1}(t), \quad (5)$$

where T_s is the transmittance of the polarizer due to the signal and I_{so} is the dc current due to the signal. The signal-to-noise ratio, SNR_{DD-SP} , in a differential detector is obtained as

$$SNR_{DD-SP} = 10 \log \left[\frac{(T_s - T_n)^2 \cdot i_s^2(t)}{i_{shot,1}^2 + T_n^2 \cdot i_{shot,0}^2} \right] dB. \quad (6)$$

2.4 Using a Differential Detector with Two Polarizers

Another efficient method to eliminate the interference from ambient noise light is the differential detection, in which two photodetectors (PD1 and PD2) and two linear polarizers (PL1 and PL2) are used.⁷ For orthogonal polarizers, PL1 is copolarized ($\theta_1 = 0$ deg) and PL2 is cross-polarized ($\theta_2 = 90$ deg) to the transmitted signal; the transmittance of PL1 for the signal is T_{max} and that of PL2 is T_{min} , as in the transmittance equation. The differential output current is the difference between the two photocurrents⁷ and SNR_{DD-OP} is⁷

$$SNR_{DD-OP} = 10 \cdot \log \left[\frac{\Delta T^2 \cdot i_s^2(t)}{i_{shot,1}^2(t) + i_{shot,2}^2(t)} \right] dB, \quad (7)$$

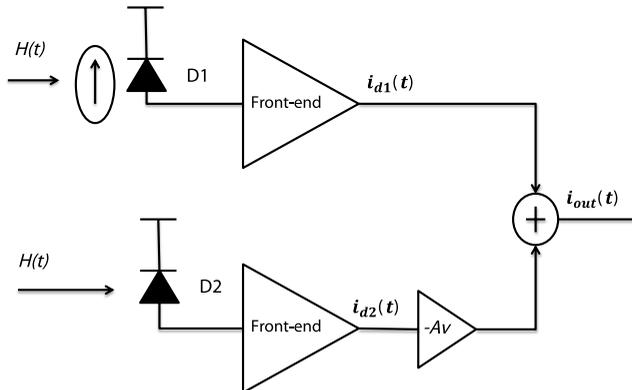


Fig. 1 Optical receiver using a single polarizer.

where $i_{shot,2}$ is the shot noise from the second branch.⁷ For nonorthogonal polarizers, the transmittance of PL1 for the signal is $T(\theta_1)$ and that of PL2 is $T(\theta_2)$. The transmittance difference is obtained in the form

$$\Delta T = (T_{max} - T_{min})(\cos^2 \theta_1 - \cos^2 \theta_2). \quad (8)$$

The SNR in a differential detector with nonorthogonal polarizers (DD-non-OP) is derived in the form

$$SNR_{DD-non-OP} = 10 \cdot \log \left\{ \frac{(T_{max} - T_{min})(\cos^2 \theta_1 - \cos^2 \theta_2)[i_s^2(t)]}{i_{shot,1}^2(t) + i_{shot,2}^2(t)} \right\} dB. \quad (9)$$

2.5 Using L-PPM Modulation and I&D Demodulation Filter

The demodulator in our study is assumed to be a maximum likelihood I&D demodulator. The influence of flicker and other intensity variations can be modeled after considering the demodulation in Ref. 8. One can define the flicker voltage $\Delta_i(V)$ and the noise voltage $\sigma_n(V)$ as follows:⁸

$$\Delta_i(V) = \frac{(L-1)T_{frame} T_{pulse}}{L C} \left[\frac{dI_{amb}}{dt} \right]_{max} (V) \quad (10)$$

and

$$\sigma_n(V) = \frac{1}{C} \sqrt{N_{amb} T_{pulse}} (V). \quad (11)$$

In these expressions, C is the value of the capacitor in I&D filter, L is the number of slots for L-PPM, $[(dI_{amb})/(dt)]_{max}$ is the maximum slope of the ambient noise current,⁸ and N_{amb} is the noise caused by ambient radiation with double-sided spectral density, where $N_{amb} = e \cdot I_{amb}$. The frame with duration T_{frame} is divided into L slots with duration T_{pulse} ; only one of these slots contains an optical pulse. For $L = 4$ we can use the following equations⁸

$$T_{pulse} = \frac{T_{frame}}{2L} \quad \text{and} \quad I_{amb} \leq \frac{eL}{2\pi^2 m_i^2 f_i^2 T_{frame}^3}, \quad (12)$$

where f_i is the interfering frequency. We will use the previous systems explained in Sec. 2 with L-PPM modulation and I&D demodulation filter. The polarizer will affect the value of the noise current (ambient current) where it will multiply by T_n which will reduce the ambient current noise by T_n to

$$I_{amb} \leq \frac{T_n \cdot e \cdot L}{\pi^2 m_i^2 f_i^2 T_{frame}^3}. \quad (13)$$

This means a reduction in the value of noise voltage and flicker voltage. The SNR equations will be the same for all systems. If the I&D demodulator filter and half pulse L-PPM are used in the previous techniques, described in Sec. 2, the design of the differential detector shows the cancellation of ambient current noise for the tungsten lamp to be zero, but the noise due to the photodetectors will increase, which

makes the value of flicker and noise voltage (noise voltage due to ambient radiation) equal to zero.

3 Results and Discussion

In our calculation, we used avalanche photodiodes (APDs). The current responsivity of the APD is equal to 30 A/W at 800 nm. An incandescent lamp is used for a noise light source. The transmittance of the noise light T_n through the polarizer is ~ 0.5 and the transmittance of the transmitted signal $T_{\max} = 1$ and $T_{\min} = 0$, i.e., the signal will totally be polarized. The amplitude is $\sim 1/20$ times the dc noise current.

3.1 Comparison Between Δ SNR for the Different Systems

From Fig. 2, one can observe that Δ SNR_{SD-SP} increased suddenly from 0 dB at $I_n = 0$ mA to 6 dB at $I_n = 0.1$ mA; then, the value will remain constant at 6 dB until $I_n = 1$ mA. The reason for this is the effect of the polarizer on the value of noise current. It is multiplied by a fraction equal to T_n , which caused this improvement, and it will saturate because the polarizer will remove the noise current by the same factor that fixes the value of Δ SNR_{SD-SP}. Also it is noticed that increasing the noise current leads to an increase in Δ SNR_{DD-SP}, where its level changes from -6.99 dB at a noise current equal to 0 mA to 28.33 dB at a noise current equal to 1 mA. The reason for this observation is as follows: at zero noise current, there will be no improvement, but the value of Δ SNR_{DD-SP} in this case will be worse than the value of Δ SNR_{SD-SP} because the amplitude of the current signal will be decreased by a factor equal to $(T_{\max} - T_n)$, which decreases SNR_{DD-SP}. For $i_{\text{amb}} > 0$ the systems that used DD-OP and DD-SP will remove this current to improve SNR. It is clear that the best Δ SNR is obtained in the differential detector with a two orthogonal polarizers system because it has the highest value addition; Δ SNR_{DD-OP} is

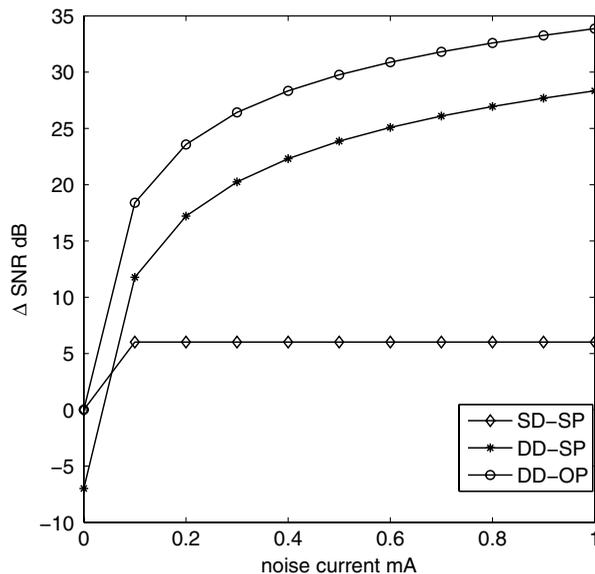


Fig. 2 Comparison between Δ SNR for different systems.

equal to zero at zero current noise, which means that the SNR of a single photodetector will be equal to SNR_{DD-OP}.

3.2 Effect of Using a Differential Detector with Two Nonorthogonal Polarizers

In Fig. 3, the SNR has three different values at θ equal to 0, 60, and 90 deg and the value of SNR is better in the case of $\theta_2 = 90$ deg. This is because when $\theta_2 = 0$ deg, the transmission axes of PL1 and PL2 will be in the same direction of the transmitted signal, which yields a zero value for the amplitude of the transmitted signal at the output of the differential detector.

3.3 Effect of Detector Parameters on Δ SNR

For the receiver bandwidth, Fig. 4 shows its effect on the SNR_{DD-OP}. It can be seen that an increase in the detector bandwidth (BW) decreases the values of SNR_{DD-OP} and SNR_{SD}. But the change is too small (it is nearly constant) in SNR_{SD} compared to SNR_{DD-OP} due to the existence of the two photodetectors, which leads to a decrease in the level of Δ SNR as described in Table 1. This can be explained by the wide bandwidth of the receiver, which leads to a high concentration of noise that produces a decrease in SNR_{DD-SP}. We are here referring to shot noise not ambient current noise, because an increase in ambient current noise will increase SNR_{DD-SP}. But increasing the shot noise current will decrease SNR_{DD-SP} due to existence of the two photodetectors.

It is also found that an increase in the excess noise factor in Fig. 5(a) and the current gain of the detector in Fig. 5(b) will lead to a decrease in Δ SNR_{SD-OP} due to the two photodetectors. This is because a higher excess noise factor and bigger current gain lead to a high concentration of noise. Table 1 indicates that Δ SNR_{SD-SP} is constant. This is because the change in photodetector parameters will not affect the system that uses only a single detector.

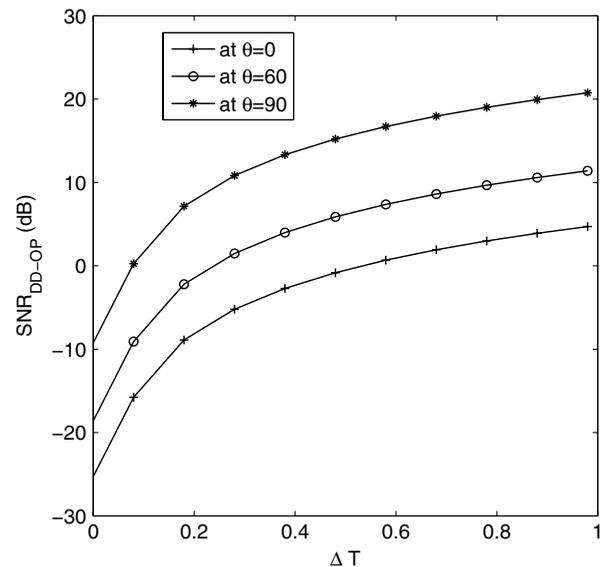
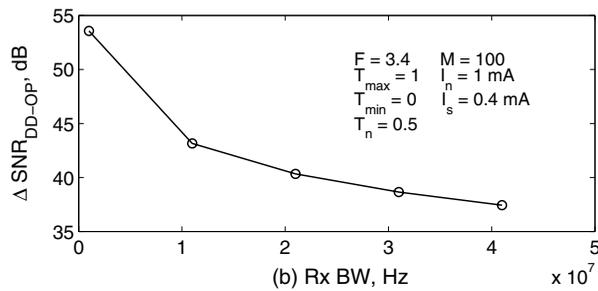
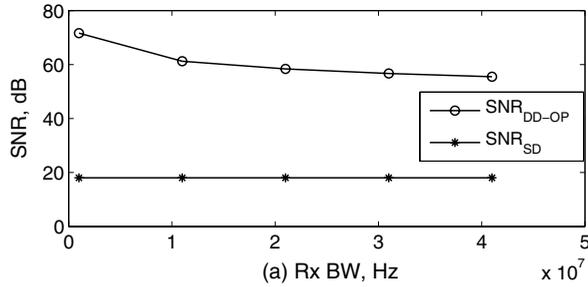
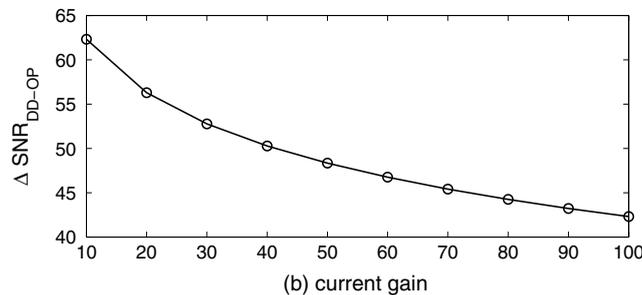
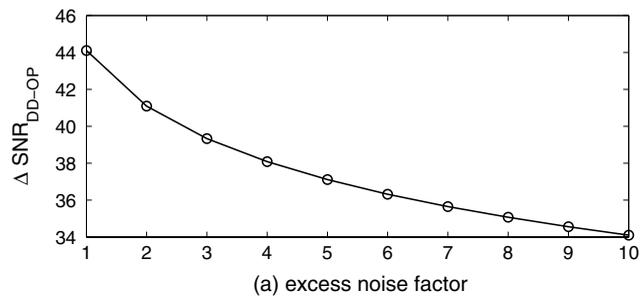
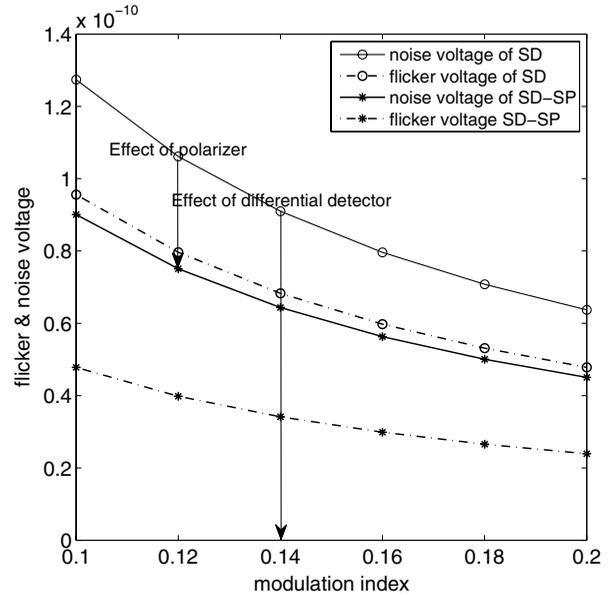


Fig. 3 Effect of the angle between the two polarizers and the transmittance difference on SNR_{non-DD-OP}.

Table 1 Comparison between the values of ΔSNR with the changing photodetector parameters on ΔSNR .

Parameters	$\Delta\text{SNR}_{\text{SD-SP}}$ (dB)	$\Delta\text{SNR}_{\text{DD-SP}}$ (dB)	$\Delta\text{SNR}_{\text{DD-OP}}$ (dB)
Δf (10 : 50 MHz)	Cost at 6	46.77 : 29.78	53.56 : 36.57
F (1 : 10)	Cost at 6	37.31 : 27.31	44.10 : 36.10
M (10 : 100)	Cost at 6	55.52 : 35.52	62.30 : 36.31


Fig. 4 Effect of receiver bandwidth on (a) SNR_{SD} and $\text{SNR}_{\text{DD-OP}}$ and (b) $\Delta\text{SNR}_{\text{DD-OP}}$.

Fig. 5 Effect of receiver parameters on (a) excess noise factor (b) current gain on $\Delta\text{SNR}_{\text{DD-OP}}$.

Fig. 6 Effect of modulation index of L-PPM and integrate-and-dump (I&D) filter on $\Delta_i(V)$ and $\sigma_n(V)$.

3.4 Using L-PPM and I&D Filter

3.4.1 Effect of L-PPM and I&D filter parameters on $\Delta_i(V)$ and $\sigma_n(V)$

As one can observe from Fig. 6, increasing the modulation index (by changing lamp type or manufacturer) decreases the level of flicker voltage and noise voltage. The reason for that is mainly due to the level of IR radiation that produces noise that exceeds the effect of the very low modulation index (10%) with the low flicker operating frequency (100 Hz), which both control the level of flicker voltage. This is only valid in incandescent lighting. Also, we can see that the polarizer decreases the level of flicker voltage by a factor equal to T_n and the noise voltage by a factor equal to $\sqrt{T_n}$ (effect of polarizer). For both the differential systems, noise and flicker are zero because these systems canceled the effect of ambient noise (effect of DD). An increase in demodulator capacitance decreases the level of flicker voltage and noise voltage as shown in Fig. 7. This is because a large capacitance means a large capability of storing ambient radiation, including flicker. This can give a reason for the large change in the level of flicker and noise voltages seen at 1 and 100 μF . Also, the polarizer decreased those effects and this decrease is not constant because ambient noise current does not depend on capacitance.

Similar to the previous discussion, Fig. 7(b) indicates that decreasing the frame time from 20 to 1 μs will increase the level of flicker and noise voltage. This is mainly because decreasing the frame time in a low flicker frequency and low modulation index environment, like incandescent lighting, leads to a high concentration of noise and flicker levels in a short period of data time. Using a maximum-likelihood I&D demodulator capacitance will lead to a sudden increase in the shot noise generated (especially at 1 μs) and, hence, increases both flicker and noise voltages.

Now, the effect of number of slots per frame is investigated. Figure 8 shows that increasing the number of slots per frame increases the level of flicker interfering voltage, but the level of noise voltage remains constant. Increasing

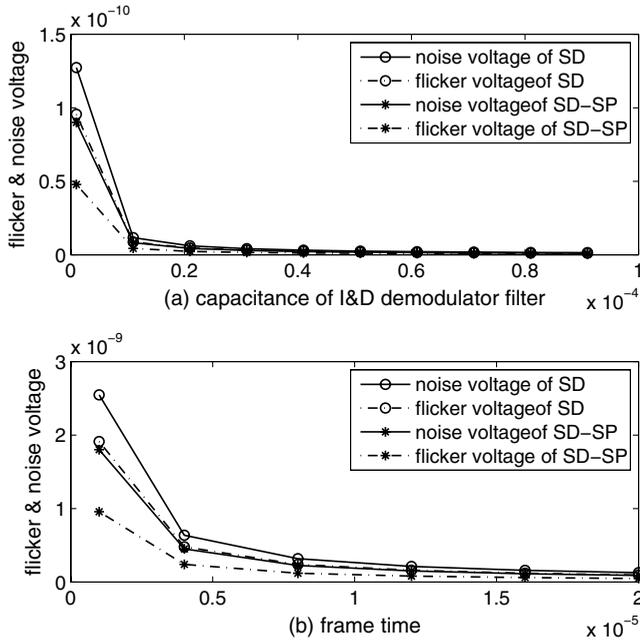


Fig. 7 (a) Effect of capacitance of I&D filter on $\Delta_i(V)$ and $\sigma_n(V)$. (b) Effect of frame time on $\Delta_i(V)$ and $\sigma_n(V)$.

the number of slots per frame will make the capacitor charge several times to get data slots with noise and flicker. Hence, this increases their levels, noting that the frame time is constant.

3.4.2 Effect of L-PPM and I&D filter parameters on ΔSNR for different systems

Figure 9(a) shows that an increase in the modulation index decreases ΔSNR_{DD-OP} with a very small change. This can be explained as follows: an increase in the modulation index leads to a decrease in the ambient noise current. Using a DD-OP, which removes the ambient current noise,

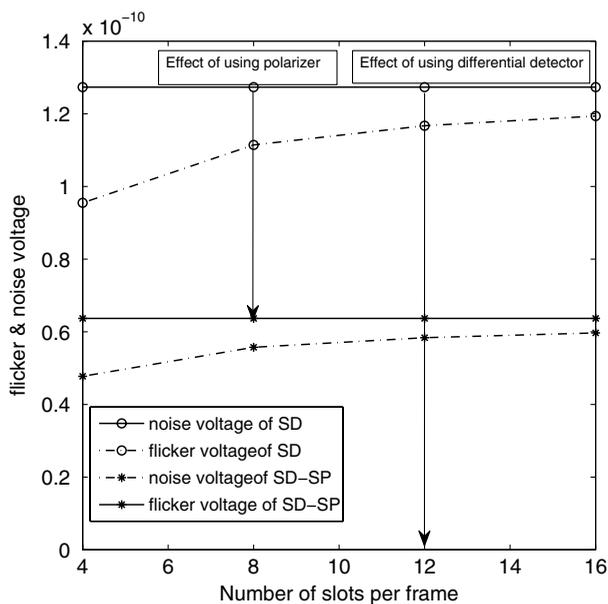


Fig. 8 Effect of number of slots per frame on noise and flicker voltages.

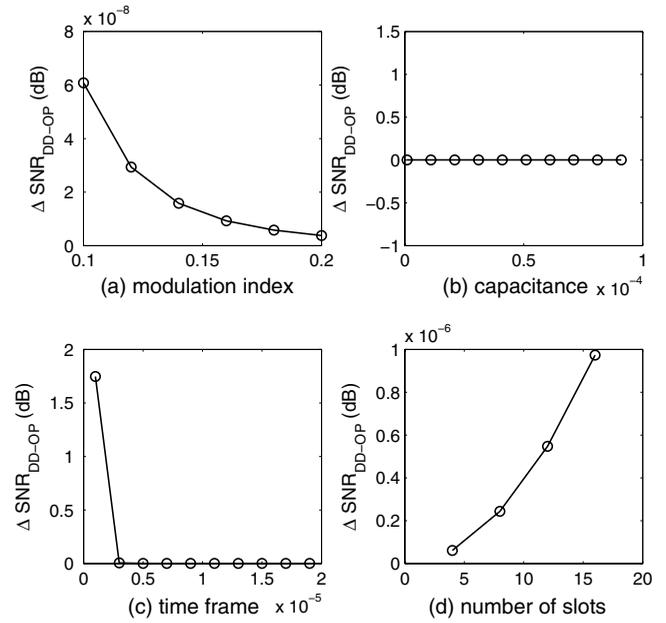


Fig. 9 Effect of (a) modulation index, (b) capacitance, (c) time frame, and (d) number of slots on ΔSNR_{DD-OP} .

makes its effect very small on ΔSNR_{DD-OP} . But it affects only the shot noise current of the two photodetectors, which is very small. For Fig. 9(b), an increase or decrease in the value of the capacitance has no effect on both differential ΔSNR_{DD-OP} and ΔSNR_{DD-OP} . This is because the capacitance has no effect on the ambient current noise equation, and also, it will not affect both ΔSNR_{DD-OP} and ΔSNR_{DD-OP} . Increasing T_{frame} in Fig. 9(c) will increase SNR_{DD-OP} and decrease ΔSNR_{DD-OP} . This is because increasing the frame time leads to a decrease in the ambient noise current and the shot noise current, which affects SNR_{DD-OP} . It is clear from Fig. 9(d) that an increase in L decreases SNR_{DD-OP} and increases ΔSNR_{DD-OP} . This is because an increase in L increases the ambient noise current and the shot noise current, which affects SNR_{DD-OP} and ΔSNR_{DD-OP} .

One can notice from Table 2 that the variation of ΔSNR_{SD-SP} and ΔSNR_{DD-OP} is very low because the noise current is very low, as the analysis considered that the noise source is not very closed. The level of ΔSNR_{DD-SP} is negative because the noise current is very low and this system decreases the value of the transmitted signal. The whole result can be summarized in Figs. 10 and 11; it is seen that the SD system just adds a noise signal

Table 2 Effect of L-PPM and I&D demodulation filter parameters on ΔSNR for different systems.

Parameters	SD-SP	DD-SP
m_i (10% : 20%)	$4.56 \times 10^{-8} : 2.85 \times 10^{-9}$	-6.9895 : -6.9897
C (1 μf : 100 μf)	Const at 4.56×10^{-8}	Const at -6.9895
T_{frame} (1:20) μs	1.5: ≈ 0	-5.8400 : -6.9895
L (4:20)	$(0.0046 : 0.1140) \times 10^{-5}$	-6.9895 : -6.9888

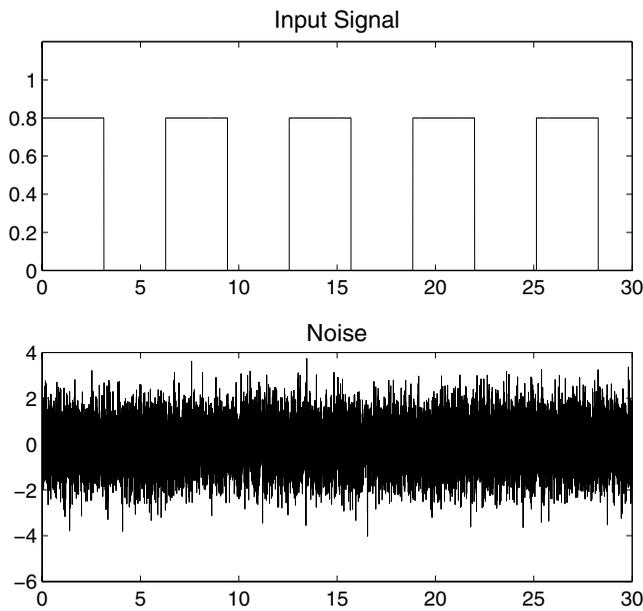


Fig. 10 Input signal and noise in the systems described in Sec. 2.

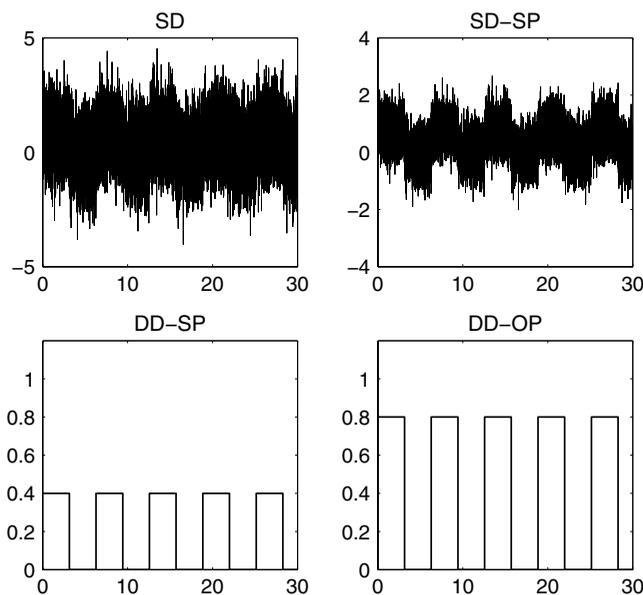


Fig. 11 Output signal from different systems.

to the input signal, the SD-SP system decreases the noise signal by a factor equal to T_n , the DD-SP system removes noise but it decreases input signal by a factor equal to $(T_s - T_n)$, and the DD-OP system removes noise without decreasing the value of input signal.

4 Conclusion

This paper studied the effect of ambient noise current caused by a tungsten lamp and of receiver components on the noise voltage, flicker voltage, and SNR. The different techniques used to reduce the effect of this noise are studied and analyzed. From the results and discussions that have been obtained in this study, the following conclusions are pointed out:

1. The best SNR is obtained in the differential detector with a two orthogonal polarizers system and the worst one is in the system of a single photodetector where $\Delta\text{SNR}_{\text{DD-OP}}$ achieved the highest value of 18.3937 dB at a noise current equal to 1 mA.
2. Changing photodetector parameters will have no effect on the improved SNR of the system that uses only a single detector; rather it will have an effect on the improved SNR of the system that uses a differential detector, where the effect of parameters will be doubled due to the use of two photodetectors.
3. Changing modulation index m , time frame t_f , interfering frequency f_i , and number of slots per frame L (L-PPM and I&D filter parameters) affects ΔSNR depending on the increase or decrease of these parameters, but is still constant when changing capacitance.
4. Noise and flicker voltages due to ambient noise current in both systems that use the differential method are zero, where the differential method removed the noise current.

References

1. S. Arnon, "Optical wireless communications," in *Encyclopedia of Optical Engineering*, R. G. Driggers, Ed., pp. 1866–1886, Marcel Dekker Inc., Ben-Gurion University of the Negev, Beer-Sheva, Israel (2003).
2. S. Mariellucci and M. Saniarsiero, *Free and Guided Optical Beams*, World Scientific Publishing Co., Singapore (2004).
3. S. Hranilovic, *Wireless Optical Communication Systems*, Springer Science, Boston (2005).
4. H. Willebrand and B. S. Ghuman, *Free-Space Optics: Enabling Optical Connectivity in Today's Networks*, Sams Publishing, Indianapolis, Indiana (2002).
5. J. R. Barry, "Wireless communication using non-directed infrared radiation," PhD Dissertation, University of California at Berkeley (1992).
6. A. J. C. Moreira, R. T. Valadas, and A. M. de Oliveira, "Characterization and modeling of artificial light interference in optical wireless communication systems," in *Proc. of the 6th IEEE Int. Symp. on Personal, Indoor and Mobile Radio Communications*, pp. 1–6 (1995).
7. S. H. Lee, "Reducing the effects of ambient noise light in an indoor optical wireless system using polarizer," *Microw. Opt. Technol. Lett.* **40**(3), 228–231 (2004).
8. R. Otte, L. P. de Jong, and A. H. M. van Roermund, "Wireless optical PPM telemetry and the influence of lighting flicker," *IEEE Trans. Instrum. Meas.* **47**(1), 51–55 (1998).

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