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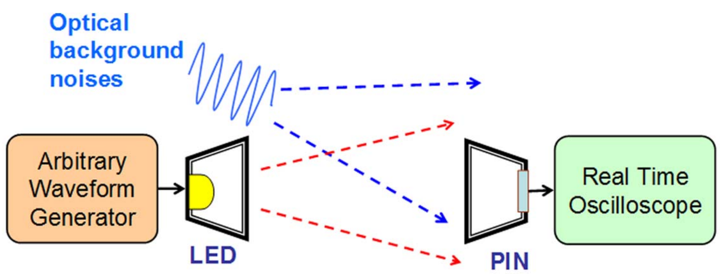

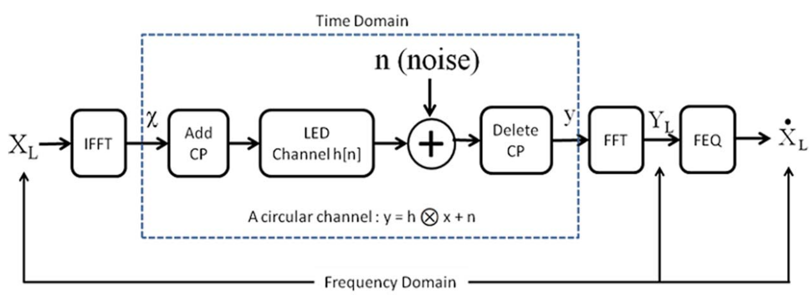

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Background Optical Noises Circumvention in LED Optical Wireless Systems Using OFDM

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Abstract: Background optical noises generated by the conventional fluorescent light sources or AC-power light-emitting diode (LED) can significantly affect the performance of the LED optical wireless communication and produce challenges to implementation. We demonstrate using orthogonal frequency division multiplexing (OFDM) to effectively circumvent the optical background noises. Besides, by using simple equalization at the receiver side, the transmission capacity can be extended from 1 Mb/s to 12 Mb/s. The theory and analysis of the equalization are presented. Experiments at different data rates and different OFDM subcarriers are preformed, and results show that, by adjusting the number of OFDM subcarriers, the influence of the background optical noises can be significantly circumvented.

Index Terms: Free space communication, optical communications, light-emitting diode (LED), noise mitigation.

1. Introduction

Light-emitting diode (LED) lighting has many attractive features over the conventional lighting sources, such as long lifetime and high power efficiency. Besides, LED lighting can be applicable to optical wireless communication. As the LED is deployed for the primary function of lighting, the value-added communication function can be implemented at very little extra cost. The optical wireless communication provides many advantages [1]–[5], such as being license-free, high directional channel, and electromagnetic interference (EMI) free. The immunity to EMI allows the optical wireless system to be deployed in many different radio-frequency (RF) prohibited areas, such as hospitals and airplanes. Recently, different approaches have been proposed to increase the direct modulation speed of phosphor-based LED, which has the modulation bandwidth of only $\sim$1 MHz [6]. These include the use of pre- or post-distortion [6]–[8], or advanced modulations [9]. Advanced modulation, such as orthogonal frequency division multiplexing (OFDM), provides high spectral efficiency, hence allowing high-data-rate transmission in the bandwidth-limited LED communication.

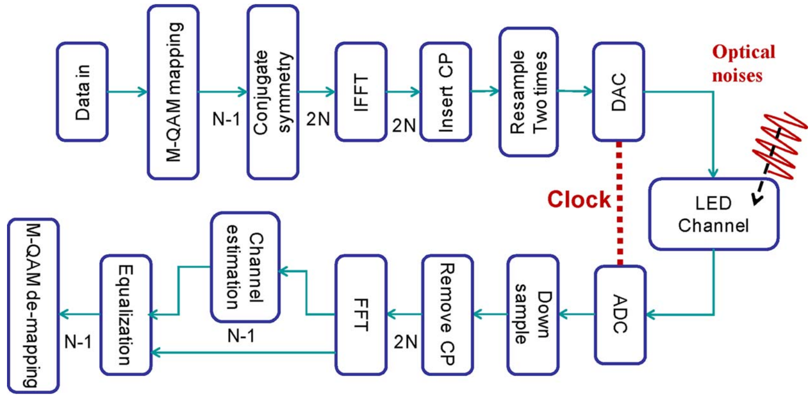

Fig. 1. Diagram of the OFDM LED wireless optical communication experiment.

Background optical noises can significantly affect the performance of the optical wireless communication link. Scenarios could happen when the LED lamps and conventional fluorescent lamps or AC-LED lamps coexist in the same place. Approach of using adaptive filtering [9] has been proposed; however, no quantitative measurement results are presented. Wavelength filtering has also been proposed [10] to reduce the optical interference; however, red–green–blue (RGB) LED and optimized planning of illumination coverage are needed. Manchester coding can mitigate the low-frequency background noise; however, it requires twice the modulation bandwidth of nonreturn-to-zero (NRZ) and limits the data rate of optical wireless system [11].

In this paper, we first analyze the degradation by background optical noises to the OFDM-based wireless optical link. The theory and analysis of the equalization are presented. Experiments using different transmission data rates (5 Mb/s and 12 Mb/s) at free space transmission distance of > 1 m using different numbers of OFDM subcarriers (32 and 64 OFDM subcarriers) are preformed. We also analyze and demonstrate that, by adjusting different OFDM subcarriers, the influence of the background optical noises can be significantly circumvented.

2. Optical Wireless System Experiment

Fig. 1 shows the logic flow diagram of the OFDM LED wireless optical communication experiment. At the transmitter (Tx), the pseudorandom binary sequence (PRBS) data is first mapped to 4-quadrature amplitude modulation (QAM) [also called quadrature phase shift keying (QPSK)]. Then, the data is serial-to-parallel converted, render to $N-1$ symbol streams and modulate $N-1$ OFDM subcarriers (note that the DC subcarrier was unmodulated). To produce real-value signal for the inverse fast Fourier transform (IFFT), conjugate symmetry is needed. By performing the conjugate symmetry conversion, $X_0 = X_N = 0$, and $X_n^* = X_{2N-n}$, where X and X^* are the input symbol and its conjugate symmetry, respectively. Hence, at the output, 2N OFDM symbols are obtained. After the IFFT, the cyclic prefix (CP), depending on the channel frequency response, is inserted. After the CP insertion, the OFDM symbols are resampled two times. Then, the OFDM data are applied to the LED via a digital-to-analog converter (DAC), which is an arbitrary waveform generator (AWG).

Fig. 2 shows a detail experimental setup, including the photograph of the LED transmitter (Tx), which consists of LEDs for lighting and communication, and LEDs for lighting purpose only. All the LEDs are phosphor-based. The AWG used has a bandwidth and resolution of 20 MHz and 14 bits, respectively. The sampling rate is 50 MSa/s. It is commercially available for general lighting. It has a 3-dB direct modulation bandwidth of 1.2 MHz. The LED is DC biased at 2 V, and the peak-to-peak voltage of the applied OFDM signal is 1 V. The free space transmission distance between the LED Tx and the PIN receiver (Rx) is $>$ 1 m. This is a line-of-sight (LOS) channel. According to the optical wireless channel analysis in the standard room (5 m $\times$ 5 m $\times$ 3 m), the intersymbol interference (ISI) generated by the multiple optical path fading only has large influence on performance when

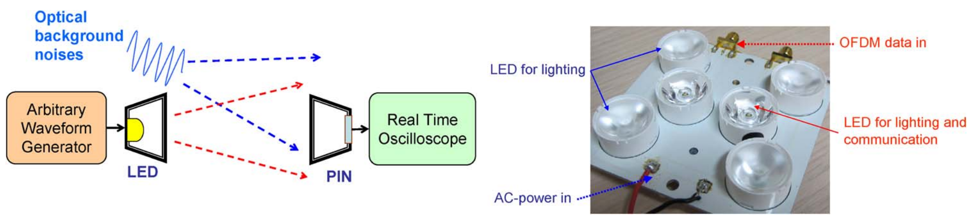

Fig. 2. (Left) Experimental setup of the LED wireless communication. (Right) Photograph of the LED transmitter.

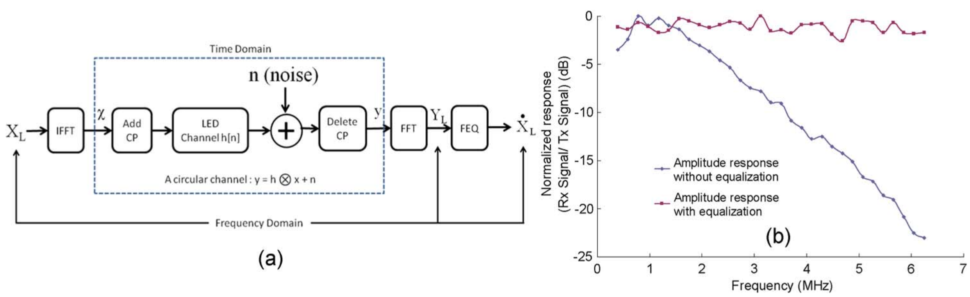

Fig. 3. (a) The OFDM system block diagram used in wireless optical with frequency domain equalization. (b) Measured amplitude response without equalization and with equalization.

the data rates are $>$ 100 Mb/s [12]. As the data rate in this experiment is below 100 Mb/s, the ISI generated by the multiple optical path fading is negligible. No optical blue filter is used. After the signal is received by the Rx, it is captured by a real-time oscilloscope (RTO). The PIN Rx is silicon-based, having the detection wavelength range of 350–1100 nm. It has a bandwidth of 17 MHz and the root mean square (RMS) noise of 530 μV. The RTO has the bandwidth of 100 MHz, with vertical resolution of 9 bits and sample rate of 1.25 GSa/s. First, we study the performance of the OFDM wireless optical link under the influence of AC-power LED. The AC-power LED is operated at 60 Hz. Second, we study the performance of the OFDM wireless optical link under the influence of fluorescent light. A conventional fluorescent light from a desk lamp is purposely placed near the Rx. It is used to generate the optical interference noises. The fluorescent lamp was placed at different distances away from the Rx to produce different optical interference noise powers.

The received wireless optical signal is captured by a RTO, which is an analog-to-digital converter (ADC), shown in Fig. 1. The digital signal is then downsampled, CP removed, and FFT. The channel estimation is implemented at the Rx side to perform the one-tap equalization for enhancing the channel capacity. The detail of this process will be described in next section. After the channel estimation and equalization, the 4-QAM demapping and decoding are performed. Then, the average signal-to-noise ratio (SNR) is calculated by averaging the SNRs of all the subcarriers, and the bit error rate (BER) is calculated based on the average SNR.

3. Equalization Process

We first discuss the equalization process to enhance the capacity of the bandwidth-limited LED channel. As shown in Fig. 3(a), the signal is demodulated using FFT. If the system is modeled as a linear-time invariant (LTI) system with finite impulse response, the relation between input and output can be expressed in a mathematical form of circular convolution in time domain and multiplication in frequency domain. The expression in frequency domain is $Y_L = H_L X_L + N_L$, where X_L, Y_L, and N_L are the input signal, output signal, and additive noise, respectively. H_L represents the frequency response of the channel, and L is the subcarrier index.

Since the wireless optical communication system can be approximated as a LTI system, when the frequency response of amplitude and phase can be estimated, we can easily recover the original signal. The calculation is made as the following:

a) The received signal Y_L can be approximated by $H_{L-\text{estimated}}\ X_L$. By sending training pattern (a known X_L), the channel response is estimated as $H_{L-\text{estimated}}$.
b) The original signal is obtained by dividing the estimated frequency response coefficient

$$\begin{aligned} Y_L &= H_{L-estimated}X_L = H_L X_L + N_L \\ \Rightarrow \dot{X}_L &= Y_L/H_{L-estimated} = (H_L/H_{L-estimated})X_L + (N_L/H_{L-estimated}). \end{aligned} \tag{1}$$

If the $H_{L-\text{estimated}}$ is well estimated, then

$$\dot{X}_L \sim X_L + (N_L/H_{L-estimated}) \tag{2}$$

where X_L is the output after the equalizer, as shown in Fig. 3(a). By using one training symbol, we can estimate the channel response H_L (estimated as $H_{L-\text{estimated}}$, the N_L term makes some error in the estimation). From (2), $N_L/H_{L-\text{estimated}}$ should be small enough for X_L to be approximate equal to X_L. The method used here is called zero-forcing equalization. This solves the issue of ISI. If the additive noise is too large, the zero-forcing equalization *cannot recover* the signal to an acceptable level.

Fig. 3(b) shows the experimental amplitude response before and after the equalization. In this example, 32 OFDM subcarriers are used, occupying a total bandwidth of 6.25 MHz. Each OFDM subcarrier carries 4-QAM signal. The detail parameters will be given in next section. The diamond (blue) curve is the transfer function before the equalization

$$H_1 = Y_L/X_L = H_L + (N_L/X_L) \tag{3}$$

the square (purple) curve is the transfer function after equalization

$$H_2 = \dot{X}_L/X_L = (H_L/H_{L-estimated}) + [N_L/(H_{L-estimated}X_L)]. \tag{4}$$

We can observe from Fig. 3(b) that the channel response is significantly extended and equalized. The original 3-dB response can be increased to above 6 MHz. As 4-QAM is used, hence, the total capacity of 12 Mb/s can be achieved. The small fluctuation in the purple curve (after equalization) is due to the imperfect estimation of channel response and additive noise.

4. Results and Discussion

Here, we report the experimental results of the background noise mitigation by using 2 data rates: 5 Mb/s and 12 Mb/s applying to the LED. In each data rate, 32 and 64 OFDM subcarriers are used, respectively, and 4-QAM (also called QPSK) is used in each OFDM subcarrier. In the case of 5 Mb/s transmission, the bandwidth used is 2.5 MHz; the OFDM carrier spacings are 78.13 kHz (using 32 subcarriers) and 39.06 kHz (using 64 subcarriers). The CP used is $(1/8) \cdot 2N$, where N is the number of subcarriers. In the case of 12 Mb/s transmission, the bandwidth used is 6.25 MHz; the OFDM carrier spacings are 195.31 kHz (using 32 subcarriers) and 97.66 kHz (using 64 subcarriers). The CP used is also $(1/8) \cdot 2N$, where N is the number of subcarriers. The fluorescent lamp is used to produce different optical interference noise powers.

For the performance of the OFDM wireless optical link under the influence of AC-power LED, as the AC-power LED is operated at 60 Hz, it produces negligible effect to the wireless optical link in the experiment. This is because the first OFDM subcarrier is located at 78.13 kHz (5 Mb/s using 32 subcarriers) and 39.06 kHz (5 Mb/s using 64 subcarriers), and 195.31 kHz (12 Mb/s using 32 subcarriers) and 97.66 kHz (12 Mb/s using 64 subcarriers). Hence, the spectral overlap between the 60-Hz noise source with the OFDM signal is minimum.

Then, we study the spectral characteristics of the optical background noise caused by fluorescent lamps. It is worth to mention that all gas discharge lamps, such as the fluorescent lamps, require a

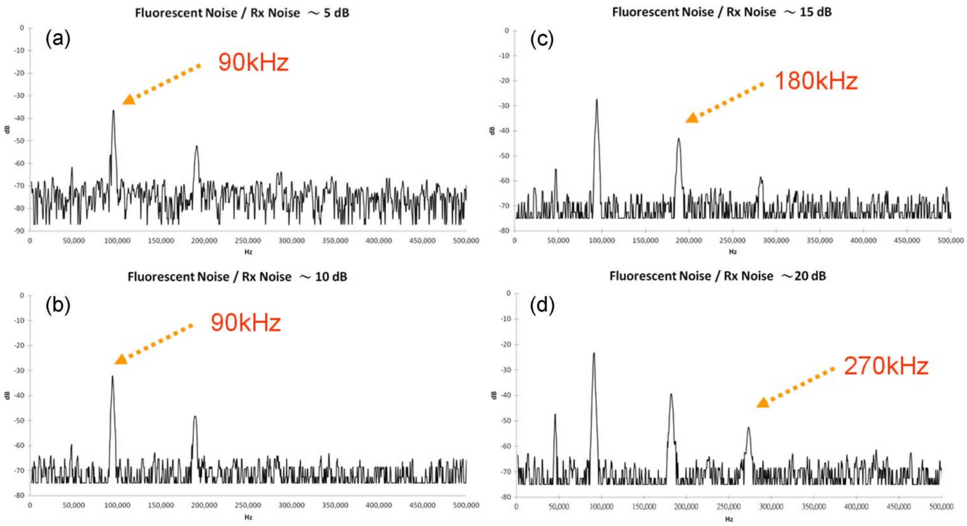

Fig. 4. Measured RF spectra of the fluorescent light at noise powers of (a) 5 dB, (b) 10 dB, (c) 15 dB, and (d) 20 dB.

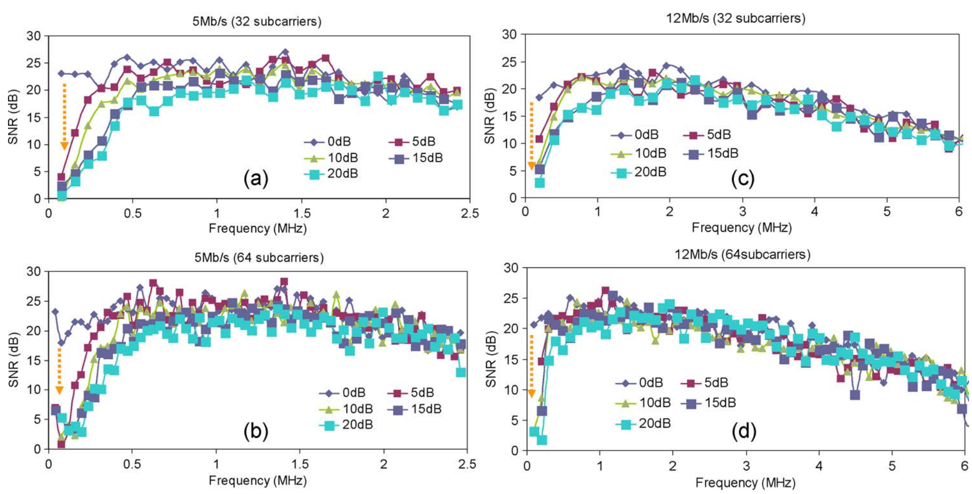

Fig. 5. Measured SNR of each OFDM subcarrier at data rate of (a) 5 Mb/s using 32 subcarriers, (b) 5 Mb/s using 64 subcarriers, (c) 12 Mb/s using 32 subcarriers, and (d) 12 Mb/s using 64 OFDM subcarriers.

ballast to operate. The ballast offers a high initial voltage to start the gas discharge process. Besides, the ballast converts the main supply 60-Hz frequency to higher frequency in order to operate the fluorescent lamps more efficiently. The spectral characteristics of the fluorescent light by measuring the RF spectra are shown in Fig. 4(a)–(d). The fluorescent lamp has a dominant tone at 90 kHz and harmonic tones at 180 kHz and 270 kHz. Due to the weaker power of the 270-kHz harmonic, it can only be detected at the Rx when the noise powers are $>$ 15 dB. The fluorescent noise power is defined as the ratio of the fluorescent noise with respect to the Rx thermal noise level. The thermal noise power of the Rx is measured when all light sources (LED and fluorescent light) are turned off.

Fig. 5(a)–(d) shows the measured SNR of each OFDM subcarrier at the data rate of 5 Mb/s and 12 Mb/s, when using 32 and 64 subcarriers, respectively. Different fluorescent noise powers (5 dB,

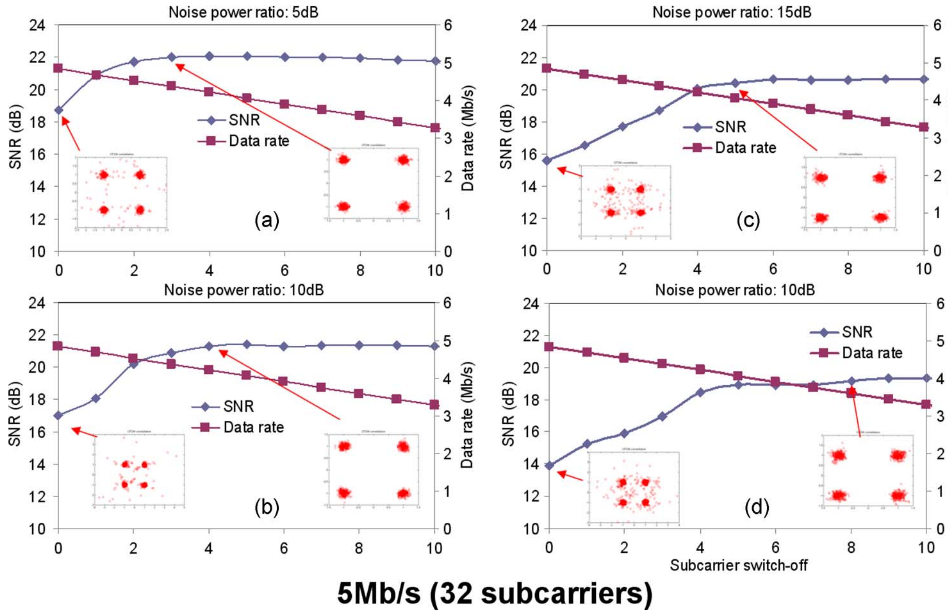

Fig. 6. Measured SNR when different subcarriers are switched off (in the case of 5 Mb/s, 32 subcarriers) when the fluorescent noises are (a) 5 dB, (b) 10 dB, (c) 15 dB, and (d) 20 dB.

10 dB, 15 dB, and 20 dB) are introduced. We can observe that, when the fluorescent noises are introduced, the SNR at lower frequency OFDM subcarriers are highly affected. This is because the fluorescent noise is operated at low frequency (the dominant tone at 90 kHz) and corrupted the lower frequency subcarriers. When the optical wireless link is operated at 5 Mb/s, the SNRs of subcarriers > 0.5 MHz is relatively constant, while in the case of 12 Mb/s operation, the SNRs of higher frequency subcarriers (> 2.5 MHz) decrease. This is due to the zero-forcing equalization cannot recover the signal well at the high frequency (discussed in Section 3). It is also worth to mention that the original frequency response of the LED channel without equalization is only about 1 MHz.

Then, the performance of the OFDM wireless optical link under the influence of fluorescent light is performed. The mitigation of the fluorescent noise can be dynamically controlled by adjusting the number of OFDM subcarriers. This can be easily achieved in the Tx side by not applying the data onto these subcarriers or neglecting these subcarriers at the Rx side. In the case of 5 Mb/s using 32 subcarriers, Fig. 6 shows the SNR improvement when different numbers of OFDM subcarriers are switched off. The subcarriers are switched off from low frequency, and the SNR shown in Fig. 6 is the average SNR of each OFDM subcarrier measured in Fig. 5. For example, in Fig. 6(a), when the fluorescent noise of 5 dB is introduced, the SNR degrades to 18 dB. By switching off 3 OFDM subcarriers (the first, second, and third subcarriers excluding the DC), the average SNR of the wireless optical communication channel can be restored to 22 dB, which corresponds to a BER of 1.6×10^{-11}. However, using less OFDM subcarrier reduces the total capacity of the communication link, and the data rate reduces from 4.84 Mb/s to 4.38 Mb/s [shown in the box curve in Fig. 6(a)]. The insets of 4-QAM constellation diagrams also show the signal improvement when 3 subcarriers are unused, showing the constellation becomes more concentrated. Fig. 6(b) shows that the communication channel can also be restored to 22 dB when the fluorescent noise level is increased to 10 dB. However, when the fluorescent noise powers are increased to high level of 15 dB and 20 dB, as shown in Fig. 6(c) and (d), respectively, the SNR cannot be restored back to 22 dB. In these cases, it can only be improved to 20 dB (corresponding to BER of 1×10^{-10}) and 19 dB (corresponding to BER of 3×10^{-10}), respectively. This is because, at higher noise powers, other higher frequency harmonics of the fluorescent light can be detected by the Rx, and they degrade the signal.

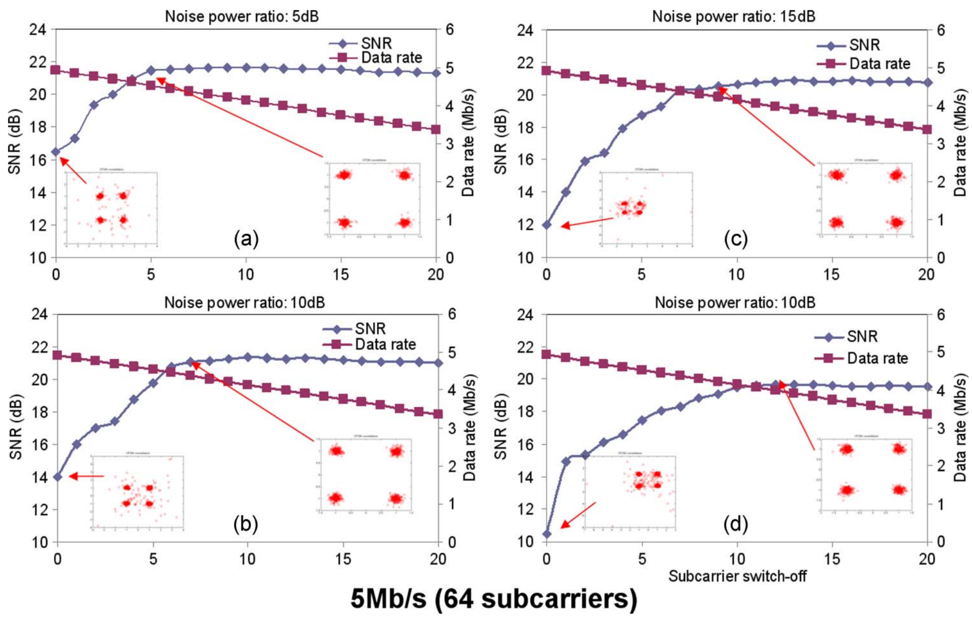

Fig. 7. Measured SNR when different subcarriers are switched off (in the case of 5 Mb/s, 64 subcarriers) when the fluorescent noises are (a) 5 dB, (b) 10 dB, (c) 15 dB, and (d) 20 dB.

Besides, 64 subcarriers are also evaluated. Hence, the total capacity is finely divided into more parallel data, and each subcarrier carries less data rate. In Fig. 7(a), when the fluorescent noise of 5 dB is introduced, the SNR degrades to 16.5 dB. By switching off 5 OFDM subcarriers, the average SNR of the communication channel can be restored back to 22 dB. The behaviors shown in Fig. 7(a)–(d) under different noise powers are similar to that in Fig. 6(a)–(d). We can observe one advantage by using more subcarriers, that is, for example, in Fig. 7(a), only 5 subcarriers (in the case of using 64 subcarriers) are needed to be switched off to restore the SNR back to 22 dB, while 3 subcarriers [in the case of using 32 subcarriers, shown in Fig. 6(a)] are needed to be switched off. Hence, less capacity is sacrificed in the case of using 64 subcarriers (total capacity is 4.53 Mb/s) when compared with the case of using 32 subcarriers (total capacity is 4.38 Mb/s).

We also measure the SNR against different numbers of switched-off OFDM subcarriers at 12 Mb/s using 32 and 64 subcarriers, respectively. In order to shorten the paper, only the noise powers at 5 dB and 15 dB are included in Fig. 8. Fig. 8(a) and (b) shows the SNR performance when using 32 OFDM subcarriers when the fluorescent noise powers are 5 dB and 15 dB, respectively. In Fig. 8(a), as the first subcarrier is at 195.31 kHz (using 32 subcarriers), while the dominated fluorescent noise is at 90 kHz; hence, negligible degradation is observed in the wireless optical communication link without and with switching off the first subcarrier. The SNR is at 16 dB. When the fluorescent noise power is increased to 15 dB [see Fig. 8(b)], other harmonics at 180 kHz can be detected by the Rx. Hence, switching off the first subcarrier can restore the wireless optical communication channel. When using 64 subcarriers, as shown in Fig. 8(c) and (d), the first subcarrier is at 97.66 kHz; hence, the first subcarrier should be switched off in order to restore the wireless optical communication channel. In this case, the total capacity is decreased from 12.3 Mb/s to 12.1 Mb/s. When studying the results shown in Fig. 8(a) (using only 32 OFDM subcarriers), we can observe that no OFDM subcarrier is required to be switched off since the first subcarrier is at 195.31 kHz, and the dominated fluorescent noise at 90 kHz does not directly overlap onto the first subcarrier. As a result, no data rate is sacrificed in this case. However, when the noise power is high, using higher number of OFDM subcarriers may allow more flexibility for noise mitigation with less data-rate scarification. The actual number of OFDM subcarrier used and the number of switched-off OFDM subcarrier depend on the real system architecture.

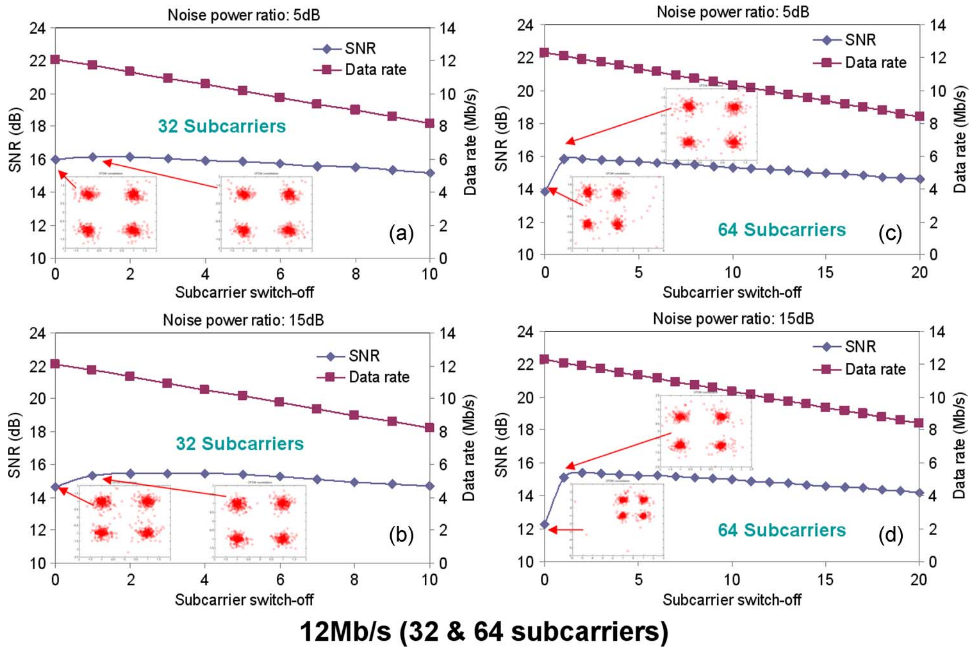

Fig. 8. Measured SNR when different subcarriers are switched off (in the case of 12 Mb/s) when the fluorescent noises are (a) 5 dB (using 32 subcarriers), (b) 15 dB (using 32 subcarriers), (c) 5 dB (using 64 subcarriers), and (d) 15 dB (using 64 subcarriers).

5. Conclusion

Background optical noises produced by the AC-power LED or the conventional fluorescent light sources can significantly affect the performance of the optical wireless communications. Here, we have demonstrated using OFDM coding for the LED optical wireless communication to mitigate the optical background noises. The theory and analysis of using equalization in OFDM to enhance the capacity of the bandwidth-limited LED optical wireless communication link have been presented. We have reported the experimental results of the background noise reduction by using 5 Mb/s and 12 Mb/s applying to the 1-MHz modulation bandwidth phosphor-based white LED. In each data rate, 32 and 64 OFDM subcarriers have been used, respectively, and 4-QAM (QPSK) has been used in each OFDM subcarrier. Experimental results have shown that the background optical noise produced by AC-power LED has negligible effect to the optical wireless transmission if OFDM is used (since the first subcarrier at DC is not used). Results have also shown that the fluorescent noise can be effectively removed by using different number of OFDM subcarriers.

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