Comparison of Three Receiver Designs for Optical Wireless Communications using White LEDs

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***Abstract*—Three visible light optical wireless communication systems using asymmetrically clipped optical orthogonal frequency division multiplexing (ACO-OFDM) and white light emitting diodes (LEDs) are compared. The LEDs considered have a larger modulation bandwidth for the blue optical frequencies than for the rest of the transmitted optical spectrum. It is shown that for typical parameter values, a novel diversity combining receiver has slightly greater capacity than a system optimized for reception of blue light only, and that both have greater capacity than a system designed to receive the entire visible light spectrum.**

***Index Terms*—Visible light communications, OFDM, diversity reception, optical wireless, ACO-OFDM.**

I. Introduction

SOLID state lighting will increasingly replace conventional incandescent and fluorescent lighting because of its energy efficiency. A number of recent papers have shown that the white light emitting diodes (LEDs) designed for illumination can also be used to transmit very high speed data [1, 2]. As a result visible light communications (VLC) is a rapidly growing research area [3].

Early papers, considered devices which used a combination of red, green and blue LEDs [4]. However most recent systems use single chip white LEDs which consist of a single blue LED and a phosphor coating which produces light with a broad spectrum in the green-yellow-red (GYR) visible range. When white LEDs of this type are used for communication, the modulation bandwidth of the blue component is much larger than that of the GYR component. Grubor et al. [1] measured one commercially available white LED and found that the blue light had a 3 dB modulation bandwidth of around 20 MHz, compared with only 2 MHz for the blue plus GYR component. In their experiments they used a blue optical filter at the receiver to minimize shot noise. As a result, only a fraction of the received optical power was available for data recovery. Zeng *et al.* [2] instead used no blue filter but equalized the received electrical signal to compensate for the low pass characteristic caused by the limited modulation bandwidth. While this maximizes the received signal power, it also increases the noise.

In this paper we compare the two approaches at a fundamental level by calculating the capacity of the systems when asymmetrically clipped optical OFDM (ACO-OFDM) is used as the modulation scheme. ACO-OFDM is chosen for the comparison because it is compatible with intensity modulation (IM), is efficient in terms of optical power [5], and the channel capacity can be calculated [6, 7]. We also describe a new diversity combining technique where the receiver has two paths, one optimized to receive the blue component and the other optimized to receive all of the transmitted optical spectrum. This technique is particularly well suited to OFDM as the different frequency components can be separately demodulated and simple selection diversity can be used. For each OFDM subcarrier the path with the greatest signal-to-noise ratio (SNR) is used for data detection.

II. System Description

All of the systems analyzed use ACO-OFDM as the modulation technique. Calculations are made for transmitters using two different white LEDs. Three different receiver configurations are considered.

The ACO-OFDM system considered uses a conventional transmitter, so only the odd frequency subcarriers are used to carry data, while the even subcarriers form a bias signal which ensures the non-negativity requirement of IM. It can be shown that in the ACO-OFDM transmitter half of the electrical power is on the odd subcarriers and half on the even. For a system with a total single-sided modulation bandwidth, M, and fast Fourier transform (FFT)/inverse FFT size of N, the bandwidth of each subcarrier is $2M/N$. Taking into account the Hermitian symmetry required to achieve a real output, there are a total of $N/4$ independent data-carrying odd frequency inputs [6].

The systems analyzed use the white LEDs designed for lighting described in [8]. White LEDs with a range of spectral characteristics are available. By using different proportions of blue, 'cool', 'neutral' or 'warm' white light can be created [8]. Fig. 1 shows the relative optical spectral power distribution for three LEDs. Each distribution has two peaks, one in the blue range and one in the GYR range. The cool light has the highest proportion of blue, while the warm light has the highest proportion in the GYR range. Note that each graph is normalized to the peak power for *that* LED. This means that care has to be taken in interpreting the graphs. Although the cold and the neutral have maximum values in the blue range, the *proportion* of the power in the blue range is much

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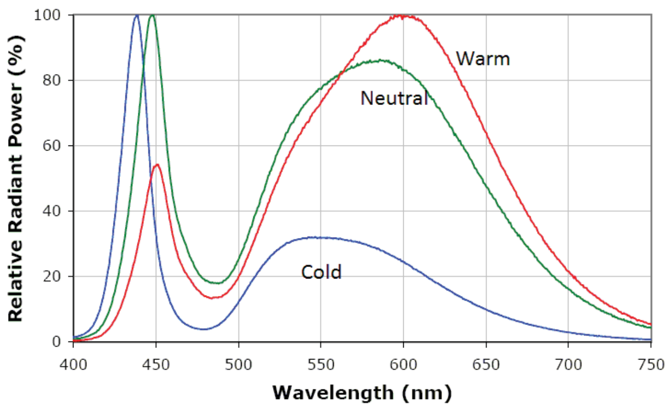
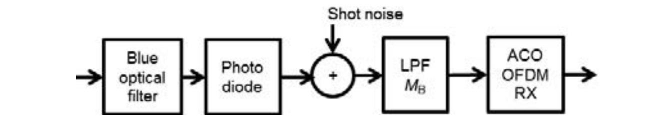


Fig. 1: Relative radiant optical power of Cree Xlamp XR-C LEDs (Graph image is the property of, and is used by permission of Cree, Inc).



(a) Receiver optimized for blue light

(b) Receiver optimized for visible light spectrum

(c) Two branch diversity combining receiver

Fig. 2: Block diagrams of the three receivers

greater for the cold LED than the neutral one. In this paper transmitters using the cold and warm LEDs are analyzed.

The three receiver designs which are compared are shown in Fig. 2. In each receiver an optical filter precedes the photodiode. This limits the optical signal to the desired optical frequencies, for example for the receiver in Fig. 2(a), which is optimized for blue frequencies, only the blue range is included and other optical frequencies are excluded. The electrical current output from the photodiode depends on the light reaching the photodiode. We assume that the main source of noise is shot noise. This is modeled as additive white Gaussian noise (AWGN) added in the electrical domain [9]. The power spectral density of the shot noise depends on the light reaching the photodiode [9]. The electrical signal at the output from the photodiode is low pass filtered so that all of the wanted signal is passed, but out-of-band shot noise is excluded. This maximizes the SNR. The resulting signal is demodulated in a conventional ACO-OFDM receiver.

The first receiver, shown in Fig. 2(a), is designed to receive only the blue component of the light. This, like the system in [1], takes advantage of the larger modulation bandwidth of the blue component. In this case it is assumed that the ACO-OFDM transmitter allocates power over the odd frequency data-carrying subcarriers up to frequency M_B, where M_B is the modulation bandwidth of the blue component. In this receiver a blue optical filter is used to limit the light reaching the photodiode to the blue range, and exclude light in the GYR range. The electrical signal at the output of the photodiode is low-pass filtered using a filter with bandwidth M_B to prevent aliasing of any out-of-band shot noise into the demodulated signal.

The receiver in Fig. 2(b) is designed to make use of all of the transmitted visible light, so the optical filter includes this range. This means that all of the useful received optical power is used in signal detection. The system has two disadvantages. Firstly the wider bandwidth optical filter means that because the power of the optical signal reaching the photodiode is greater and so the shot noise power also increases. Secondly the GYR signal has a lower modulation bandwidth so the modulation bandwidth is limited to M_{GYR}, where M_{GYR} is the modulation bandwidth of the GYR component. Because the modulation bandwidth is M_{GYR}, a low pass filter (LPF) of this bandwidth is chosen.

Fig. 2(c) shows the novel diversity combining receiver. In this case it is assumed that the ACO-OFDM transmitter allocates power over the odd frequency data-carrying subcarriers up to frequency M_B . The top branch is optimized for the blue light component and the lower branch for all of the transmitted visible light. Selection combining is then used to select the odd frequency OFDM subcarriers with the higher SNR. This will in general be the lower branch for modulation frequencies up to M_{GYR} and the upper (blue) branch for higher modulation frequencies. In this way the receiver combines the advantages of the two previous systems. It uses the wider modulation bandwidth of the blue component while also using all of received signal power in the GYR component.

III. Analysis

In this section we calculate the capacity of the first two systems and a lower bound on the new diversity system. First consider a *single* odd frequency subcarrier subject to a constraint on transmitted *electrical power*. This forms an average power-limited, bandwidth-limited system with additive white Gaussian noise (AWGN) [6, 7], so the well-known Shannon formula can be applied [10] and the capacity of the k-th subcarrier is given by

$$C_k = \frac{2M}{N} \log_2 \left(1 + \mathrm{SNR}\,(k)\right), \quad k \text{ odd}. \tag{1}$$

In this analysis we will assume that the channel is flat across a modulation bandwidth of M_B and that the only noise is AWGN due to shot noise. It is also assumed that the transmitter knows what type of receiver is being used so that the appropriate modulation bandwidth can be selected. For the receiver optimized for the entire visible light spectrum the smaller modulation bandwidth of M_{GYR} should be used, while for either of the other receivers a modulation bandwidth of M_B should be chosen. To achieve capacity, in the first two systems the transmitter should allocate electrical power equally across the odd subcarriers, and the overall capacity, assuming all of the available odd frequency subcarriers are used, is the sum of the capacities of the individual subcarriers,

$$C_{total} = \frac{2M}{N}\sum_{k=1,3}^{N/2-1}\log_2(1+\mathrm{SNR}(k)). \quad (2)$$

which for equal power distribution and a flat channel simplifies to

$$C_{total} = \frac{M}{2}\log_2(1+\mathrm{SNR}). \quad (3)$$

For the diversity receiver, capacity is achieved by allocating more power to the lower frequency subcarriers which are received with a greater SNR. The actual distribution depends on the SNR so instead we calculate a lower bound assuming even distribution up to a modulation bandwidth of M_B.

To calculate the capacity we must determine the SNR of each subcarrier. First consider the 'blue' receiver in Fig 2.(a). Using the properties of photodetectors [9], the current in the photodetector due to the wanted signal is given by

$$i_{S,B} = \int_{\lambda_1}^{\lambda_2} A p_S(\lambda) R(\lambda) f_B(\lambda)\,d\lambda. \quad (4)$$

where the subscripts S and B denote 'signal' and 'blue' respectively so $i_{S,B}$ is the current in this photodetector due to the *signal* component of the received light using the *blue* filter, A is the area of the photodetector, $p_S(\lambda)$ is the optical power per unit area of the signal component at wavelength, λ, $R(\lambda)$ is the responsivity of the photodetector and $f_B(\lambda)$ is the normalized filter response of the blue filter. λ_1 and λ_2 are the lower and upper wavelengths of the blue filter. So the average received electrical signal power of each odd subcarrier normalized to 1 Ω is $2i_{S,B}^2/N$.

In general the transmitter LED will not be the only source of light reaching the photodiode. For example, light due to sunlight from windows, or light from other unmodulated lights may result in significant ambient light. In a similar way current in this photodetector due to this ambient light is given by

$$i_{amb,B} = \int_{\lambda_1}^{\lambda_2} A p_{amb}(\lambda) R(\lambda) f_B(\lambda)\,d\lambda. \quad (5)$$

where the subscript 'amb' in a variable denotes the component due to the ambient light.

So the single-sided shot noise electrical power spectral density in this detector, normalized to 1 Ω, is given by [9]

$$\begin{aligned} S_{shot,B} &= 2q(i_{S,B}+i_{amb,B}). \\ &= 2q\int_{\lambda_1}^{\lambda_2} A(p_S(\lambda)+p_{amb}(\lambda))R(\lambda)f_B(\lambda)\,d\lambda, \end{aligned} \quad (6)$$

where q is the charge on an electron. The bandwidth of each subcarrier in this case is $2M_B/N$ so the shot noise power for each subcarrier $2M_B S_{shot,B}/N$.

So the SNR for each of the $N/4$ independent ACO-OFDM data carrying subcarriers is

$$\mathrm{SNR}_B = \frac{A\left(\int_{\lambda_1}^{\lambda_2} p_S(\lambda)R(\lambda)f_B(\lambda)\,d\lambda\right)^2}{qM_B\int_{\lambda_1}^{\lambda_2}(p_S(\lambda)+p_{amb}(\lambda))R(\lambda)f_B(\lambda)\,d\lambda}. \quad (7)$$

If the ambient light has the same spectral characteristics as the signal then $p_{amb}(\lambda) = Cp_S(\lambda)$ where C is a constant, and (7) simplifies to

$$\mathrm{SNR}_B = \frac{A\left(\int_{\lambda_1}^{\lambda_2} p_S(\lambda)R(\lambda)f_B(\lambda)\,d\lambda\right)}{qM_B(1+C)}. \quad (8)$$

Similarly, for the second receiver, because the transmitted modulation bandwidth is limited to M_{GYR} , then assuming the same photodetector area A in all cases.

$$i_{S,vis} = \int_{\lambda_1}^{\lambda_3} A p_S(\lambda) R(\lambda) f_{vis}(\lambda)\,d\lambda, \quad (9)$$

and

$$\mathrm{SNR}_{vis} = \frac{A\left(\int_{\lambda_1}^{\lambda_3} p_S(\lambda)R(\lambda)f_{vis}(\lambda)\,d\lambda\right)}{qM_{GYR}(1+C)}, \quad (10)$$

where λ_3 is the upper wavelength of the visible light and the subscript 'vis' is used for optical frequencies comprising all of the visible spectrum from λ_1 to λ_3. So combining (4), (8), (9) and (10),

$$\mathrm{SNR}_{vis}/\mathrm{SNR}_B = i_{S,vis}M_B/i_{S,B}M_{GYR}. \quad (11)$$

And for the branch of the new diversity combining receiver optimized for GYR modulation bandwidth

$$\mathrm{SNR}_{GYR} = \frac{A\left(\int_{\lambda_1}^{\lambda_3} p_S(\lambda)R(\lambda)f_{vis}(\lambda)\,d\lambda\right)}{qM_B(1+C)}, \quad (12)$$

Note that (12) depends on M_B not M_{GYR} because in this case the modulation bandwidth is M_B. So for the third receiver

$$\mathrm{SNR}_{GYR}/\mathrm{SNR}_B = i_{S,vis}/i_{S,B}. \quad (13)$$

IV. Results

To determine the relative capacities for the different cases, the ratios $i_{S,vis}/i_{S,B}$ for the cold and warm LEDs with the characteristics in Fig. 1 were calculated using numerical integration, assuming a silicon photodetector and values of $\lambda_1 = 400$ nm, $\lambda_2 = 480$ nm, and $\lambda_3 = 750$ nm. A silicon photodetector has a responsivity $R(\lambda)$ which increases relatively linearly over the visible range, and typically peaks at around 900 nm, falling rapidly to zero above the cutoff wavelength of 980 nm. The responsivity is usually in the range 0.2 at 400 nm up to around 0.6 A/W at the peak. The results are shown in Table 1.

To calculate the relative SNRs in the first two receivers, the modulation bandwidth must be considered. The table shows results for the two different combinations of M_B and M_{GYR} given in [2] and [1]. The relative SNRs shown in Table 1 range from 6 dB to 22 dB depending on the parameters used, with the greatest difference occurring for the warm LED and for larger difference between M_B and M_{GYR}.

To show the overall implications for channel capacity, the values of capacity given by (2) were calculated for three cases;

TABLE I: Parameter Values

Parameter	Cold	Warm
$i_{S,vis}/i_{S,B}$	3.87	14.7
SNR_{vis}/SNR_B for [2] M_B = 14 MHz and M_{GYR} = 2.5 MHz	13 dB	19 dB
SNR_{vis}/SNR_B for [1] M_B = 20 MHz and M_{GYR} = 2 MHz	16 dB	22 dB
SNR_{GYR}/SNR_B	6 dB	12 dB

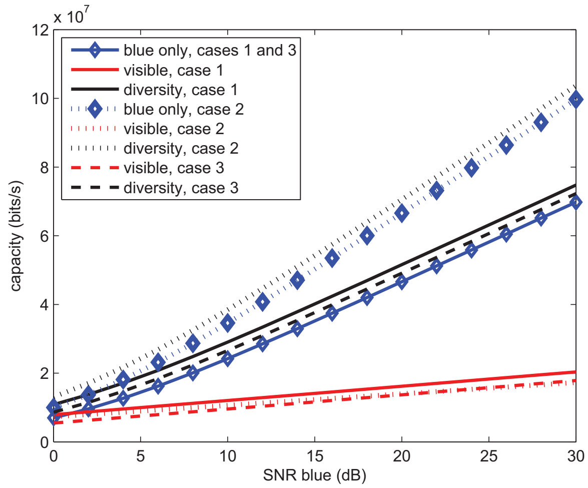


Fig. 3: Channel capacity for three receivers versus received SNR blue.

Case 1: warm white LED, M_B = 20 MHz , M_{GYR} = 2 MHz , Case 2: warm white LED, M_B = 14 MHz , M_{GYR} = 2.5 MHz Case 3: cold white LED, M_B = 20 MHz , M_{GYR} = 2 MHz . The results are plotted in Fig. 3. To make clear the relative performances of the three different receiver configurations, for a given LED, the capacity is plotted as a function of the SNR of the received blue component. In all cases the best performance is given by the new diversity configuration and the worst performance for a (non-diversity) receiver designed to receive all of the light transmitted by the LED. The difference between diversity and blue only is relatively small and in most cases would not warrant the increased receiver complexity. Thus the best option in practice is to design a system optimized to use the blue light component for data transmission as the gain from the increased modulation bandwidth outweighs the loss in received signal power. For a given optical channel and total optical transmit power, a system using a cold white LED will have the largest capacity, as it has a greater proportion of light in the blue range than neutral or warm.

V. Conclusions

Three receiver designs for visible light communications using white LEDs are compared in systems where ACO-OFDM is used to modulate the LEDs. Analytical expressions are derived for the capacity of systems in terms of the received SNR and optical and electrical bandwidths. Calculations are presented which use the parameters of commercially available white LEDs and typical silicon photodiodes. It is shown that for all cases considered a novel diversity combining receiver gives a slight increase in capacity relative to the one designed to receive only the blue component of light, and that both result in significantly greater capacity than the receiver designed to receive light over all of the transmitted spectrum. However the small increase in performance of the diversity receiver relative to the blue receiver comes at the cost of increased receiver complexity.

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