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Efficient Transmission under Low Dimming Control Levels in Indoor Visible Light Communications

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***Abstract*—In indoor visible light communication (VLC) systems based on orthogonal frequency division multiplexing (OFDM), employing multi-pulse position modulation (MPPM) for dimming control will affect the receiver (Rx) sensitivity requirement particularly at low dimming levels (DLs), thus affecting the system bit error rate (BER) performance. In this paper, we propose a hybrid visible light (VL) and infrared (IR) link, where the IR is used for downlink when the DL for VLC is very low. The "off" periods of MPPM is utilized for data transmission without affecting the illumination level. This arrangement will ensure data transmission under all illumination and dark conditions. Numerical results show that by adopting the IR link, low level M-ary quadrature amplitude modulation can be always used. At low DLs, both the Rx sensitivity requirement of the VL signal and the required transmit power can be significantly alleviated while keeping a constant data rate at a BER < 10^{-3}.**

***Index Terms*—Visible light communications; dimming control; orthogonal frequency division multiplexing; multi-pulse position modulation; infrared downlink.**

I. Introduction

Recently, light-emitting diodes (LEDs) has been emerging as a promising technology to replace incandescent or fluorescent lamps due to its long lifetime, high efficiency and small size, etc. Meanwhile, the increasing demand for high speed indoor wireless communication has greatly motivated research work towards visible light communication (VLC) systems especially based on the white LED technology, which offers advantages including unregulated huge spectrum, immunity to radio frequency (RF) interference, security against eavesdropping, etc. [1], [2]. Therefore, futuristic indoor VLC systems will have dual functionality, i.e., illumination and data communication. In practical applications, the illumination of LEDs should be adjusted according to the environment and the need of people using it, as well as to save energy [3]. As a result, the dimming of VLC systems has received research interest in the last few years [3]−[8].

Pulse amplitude modulation (PAM) and pulse width modulation (PWM) have been adopted for dimming control [4]. PAM was used to control the LED brightness level but affecting its lifespan [5]. PWM with a varying duty cycle has also been adopted for dimming in VLC [4], [6]. In [7] the concept of PWM was used to control the illumination level of the on-off keying (OOK) and variable pulse position modulation (VPPM) signals. The latter suffers from the spectral efficiency problem. Optical orthogonal frequency division multiplexing (OFDM) has been adopted in indoor VLC systems to overcome the limited LED bandwidth and the multipath effects. Through parallel transmission, high data rate up to Gbps can be achieved by using high level M-ary quadrature amplitude modulation (M-QAM) [9], [10].

For dimming control OFDM combined with PWM was reported in [11] to increase the transmission efficiency at the cost of severe self-interference at slower PWM rates. In [12], a promising scheme combining variable M-QAM OFDM with PWM was proposed to reduce the symbol rate and the transmit LED power P_t compared with OOK. In this method, OFDM symbols are only transmitted during the "on" periods of PWM. Therefore, the required symbol rate under low dimming levels (DLs) will be significantly increased, which increases the required receiver (Rx) sensitivity. In order to further reduce the symbol rate and P_t, multi-pulse position modulation (MPPM) in combination with variable M-QAM OFDM was proposed in [13]. Although excess signal can be transmitted, the Rx sensitivity requirement is still extremely high under low DLs, thus making it hard and inefficient to achieve a reliable communication at a constant data rate. Reverse polarity optical-OFDM (RPO-OFDM) was proposed to utilize the entire PWM cycle for data transmission in [14]. However, this scheme only supports the unipolar form of OFDM signal such as the asymmetrically clipped optical OFDM (ACO-OFDM) and etc. This means basically sacrificing half of frequency spectral. In addition, the DL is limited within a certain range, e.g., from 7 − 93% for 8-QAM, and it is not consistent with the duty cycle D.

In this paper, we proposed a low-power infrared (IR) based downlink to complement the visible light (VL) system based on the system reported in [13], especially under low dimming (illumination) levels. Similar to VL, IR communication also offers the same key features as that of VLC compared to the RF technologies and has been widely reported in the literature [15], [16]. It is also a potential solution to the uplink issue in indoor VLC [17], [18]. In this proposed hybrid system with dimming both VL and IR signals are used at the same time. Since IR is invisible, then the DC-biased optical (DCO-) OFDM signal can be transmitted via this IR link during the

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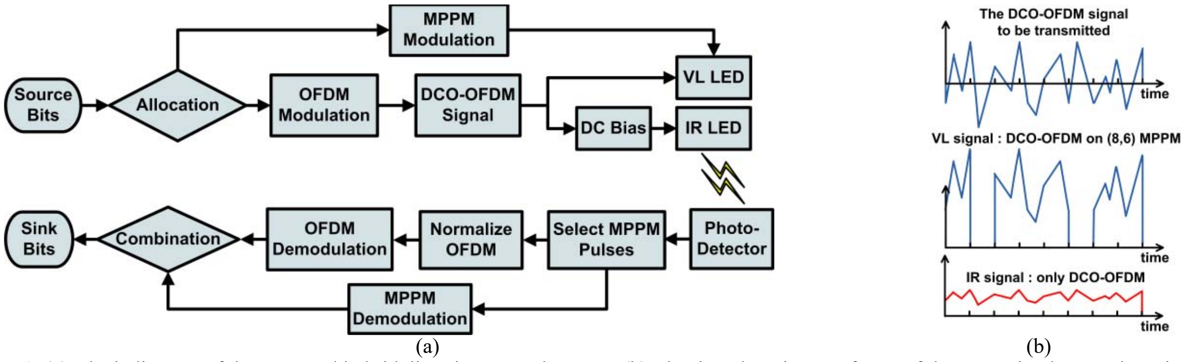

Figure 1. (a) Block diagram of the proposed hybrid dimming control system; (b) The time domain waveforms of the transmitted VL and IR signals.

entire MPPM cycle without affecting the brightness level. As a result, the M-QAM level is reduced, which is beneficial in maintaining a constant data rate. Simulation results show that with the IR link, both the Rx sensitivity requirement of the VL signal and the total required transmit power can be effectively reduced at low DLs while maintaining a constant data rate transmission at a bit error rate (BER) < 10^{-3}, thus being able to utilize the full dimming range (e.g., from 1 to 0) even under low P_t.

The rest of the paper is outlined as follow. The principle of the proposed method is presented in Section 2. Section 3 gives the performance analysis. Simulation results are shown in Section 4. Finally we provide a summary in Section 5.

II. Principle of the Proposed Method

For the conventional VLC dimming control systems based on PWM and MPPM, OFDM symbols are only transmitted during the "on" periods. In order to keep constant data rate, the required M-QAM symbol rate r_1 should be inversely-proportional to D, which can be described as

$$r_1 = r_0 / D, (0 \le D \le 1). \tag{1}$$

Here r_0 is the initial symbol rate at D of 1. Thus, reducing D will result in increased r_1. Consequently, the noise power in terms of r_1 is affected and the required Rx sensitivity will be significantly increased, making it hard and inefficient to achieve reliable communication at a constant rate. The key problem is that the "off" periods of dimming control pulses, which are not utilized, thus making the Rx sensitivity requirement highly dependent on D.

The block diagram of the proposed system is shown in Fig. 1(a). For the high values of DL, there is no need for dimming control and M-QAM OFDM at a constant rate can be simply transmitted on PWM signals with a full D. With dimming control, the bipolar data stream at the transmitter (Tx) is divided into two parts. One part is mapped into different MPPM dimming control patterns. For every MPPM symbol with p pulses of n-slot (denoted as (n, p) MPPM in this paper), the DL is controlled by D, which is equal to p/n. The other will be mapped into DCO-OFDM signals for simultaneous intensity modulation (IM) of both VL and IR LEDs. For the VL link, DCO-OFDM signals are combined with MPPM dimming control pulses, which basically is a superposition of the two signals. Only the DCO-OFDM signals during the "on" periods of MPPM patterns are transmitted for IM of the VL LED. Note that the "on" pulses of MPPM actually serve as the DC bias. The DCO-OFDM signals during the "off" periods of MPPM will not be used for IM of the VL LED. Therefore, no VL signal is transmitted during the "off" periods of dimming control. Unlike VL link, in the IR link, DCO-OFDM signals are always transmitted during both the "on" and "off" periods of MPPM. Note that for the IR link a relatively low DC bias is needed because of the eye safety and also for the convenience of MPPM demodulation at the Rx. The modulation index of the IR signal also needs to be adjusted to avoid clipping. Finally, all three signals of VL OFDM, VL MPPM and IR OFDM are transmitted simultaneously.

The time domain waveforms of the transmitted VL and IR signals are shown in Fig. 1(b). Notice that the "off" periods of a (8, 6) MPPM symbol are utilized to transmit OFDM without affecting the system brightness. Note the need for strict synchronization between VL OFDM, VL MPPM and IR OFDM to avoid multipath induced burst errors at the Rx. At the Rx, the hybrid signals consisting of VL OFDM, VL MPPM and IR OFDM are detected using a single photo-detector (PD), followed by a post amplifier and then separated and demodulated by further signal processing. During the "on" periods of MPPM, both VL and IR signals are received. During the "off" periods of MPPM, only the IR signal is received. Since the illumination intensity of the IR link is much lower compared with the VL link, we propose the following steps for demodulation: (i) integrate the received signal amplitudes over every time slots; (ii) select the maximum p values within each MPPM frame and decode the MPPM signal; (iii) remove the DC bias from the received OFDM signal according to the "on/off" state of MPPM obtained in (ii); (iv) use different normalization factors to normalize the received OFDM signal according to the "on/off" state of MPPM obtained in (ii); (v) perform fast Fourier transform (FFT) for the normalized OFDM time domain signal; and (vi) decode the M-QAM symbols and combine the recovered data stream from OFDM and MPPM signals in order to recover the original data stream. Note that, the received OFDM signal during the "on" and "off" periods can be processed separately for the procedure of normalization. The calculation of normalization factors in (iv) also needs the priori knowledge of the channel characteristic, the modulation index, the PD responsivity and P_t with no modulation for both VL and IR links, respectively, which will be revealed in Section 3.

III. Performance Analysis

There are generally two types of indoor propagation for both the VL and IR links: line of sight (LOS) and non-LOS [2],

[15]. The channel model reported in the literature can readily be adopted for both IR and VL based systems [19], [20]. The only small difference could be on the different surface reflections for different wavelengths. For the link with a LOS path, we have ignored the reflection from walls, etc. [2], [15]. However, in scenarios where the LOS path is not available or in the presence of strong multipath path it is essential to consider both LOS and non-LOS components, which is our future work. In this paper, we have also assumed that both VL and IR LED sources are Lambertian and the channel DC gain is given by [2]:

$$H_{VL/IR}(0) = (m+1)\cos^m(\phi) A\cos(\psi)/(2\pi d^2), \quad (2)$$

where m is the Lambert coefficient of Tx, A is the physical area of detector, d is the distance between Tx and Rx, ϕ is the angle of irradiance, and ψ is the angle of incidence. In the following, we use subscripts VL and IR to identify physical parameters for both VL and IR links, respectively.

For the proposed hybrid system, the received carrier power during the "on" periods of MPPM consists of both VL and IR components, which is given by:

$$P_{rON} = P_{rVL} + P_{rIR} = H_{VL}(0)P_{tVL} + H_{IR}(0)P_{tIR}, \quad (3)$$

where P_t is the LED transmit power with no modulation. Since the IR signal is low-power, we use κ to represent the intensity ratio between transmitted IR and VL signals, which is given as $\kappa = P_{tIR}/P_{tVL}$. Therefore, following filtering of the DC component, the electrical signal-to-noise ratio (SNR) at the output can be given as:

$$SNR_{ON} = \frac{(R_{VL}H_{VL}(0)M_{indexVL} + R_{IR}H_{IR}(0)\kappa M_{indexIR})^2 P_{tVL}{}^2 \overline{f(t)^2}}{\sigma_{ON}{}^2}, \quad (4)$$

where R is the responsivity of PD, M_{index} is the modulation index, $f(t)$ is the normalized signal, respectively. In the numerator, we can easily find the normalization factor used for OFDM demodulation during the "on" periods of MPPM. The noise variance $\sigma_{ON}{}^2$ consisting of both the shot and thermal noise sources can be seen as a function of the required r_1 for M-QAM and the received VL carrier power P_{rVL} [13], which is given as:

$$\begin{aligned}\sigma^2_{ON}(P_{rVL}, r_1) &= \sigma^2_{ON,shot}(P_{rVL}, r_1) + \sigma^2_{ON,thermal}(r_1) \\ &= 2q[R_{VL}P_{rVL}(1 + M_{indexVL}\overline{f(t)}) + \\ &R_{IR}P_{rVL}(1 + M_{indexIR}\overline{f(t)})H_{IR}(0)/(H_{VL}(0)\kappa) + I_{bg}I_2]r_1 \\ &+\sigma^2_{ON,thermal}(r_1),\end{aligned} \quad (5)$$

where I_{bg} is the background current and I_2 is the noise bandwidth factor. Note that the thermal noise is also a function of r_1. However, during the "off" periods of MPPM, there is no VL component. Therefore, SNR can be written as:

$$SNR_{OFF} = \frac{(R_{IR}H_{IR}(0)\kappa P_{tVL}M_{indexIR})^2 \overline{f(t)^2}}{\sigma_{OFF}{}^2}. \quad (6)$$

In the numerator, we can also easily find the normalization factor, which is needed for OFDM demodulation during the "off" periods of MPPM. The noise variance $\sigma_{OFF}{}^2$ can be represented by:

$$\begin{aligned}\sigma^2_{OFF}(P_{rVL}, r_1) &= \sigma^2_{OFF,shot}(P_{rVL}, r_1) + \sigma^2_{OFF,thermal}(r_1) \\ &= 2q[R_{IR}P_{rVL}(1 + M_{indexIR}\overline{f(t)})H_{IR}(0)/(H_{VL}(0)\kappa) \\ &+ I_{bg}I_2]r_1 + \sigma^2_{OFF,thermal}(r_1).\end{aligned} \quad (7)$$

According to [21], the BER upper bound of the variable M-QAM system can be given as:

$$BER \le 0.2\exp\left(\frac{-1.5SNR}{M_{QAM}-1}\right). \quad (8)$$

Thus, the BER upper bound of our proposed VLC system under dimming control conditions is given as:

$$BER \le 0.2D\exp\left(\frac{-1.5SNR_{ON}}{M_{QAM}-1}\right) + 0.2(1-D)\exp\left(\frac{-1.5SNR_{OFF}}{M_{QAM}-1}\right). \quad (9)$$

Here we have assumed that the DC bias of the MPPM is much higher than that of the IR signal, therefore both the additive Gaussian noise and the high peak in the time domain waveform of the OFDM signal can be ignored. Note that for the system with the forward error correction (FEC) code a BER of 10^{-3} is used as a bench mark [22]. Therefore to achieve this target BER the Rx sensitivity requirement of the VL link P_{sen} can be determined by solving the following:

$$10^{-3} = 0.2D\exp\left[\frac{-1.5SNR_{ON}(P_{sen}, r_1)}{M_{QAM}-1}\right] + 0.2(1-D)\exp\left[\frac{-1.5SNR_{OFF}(P_{sen}, r_1)}{M_{QAM}-1}\right]. \quad (10)$$

Note that both SNR_{ON} and SNR_{OFF} are function of r_1 and P_{sen}, respectively. From (10), we observe a constraint between the duty cycle, the required Rx sensitivity, the required M-QAM level and its symbol rate. This will be further discussed in Section 4. Compared with previous schemes, since the "off" periods are utilized, reducing D will have less impact on the Rx sensitivity requirement, especially under low DLs.

IV. Simulation and Discussions

In this section, the constant consolidate rate of the system is set at 50 Mbps. At first, DCO-OFDM symbols are transmitted via a 200 kHz PWM signal with D of 100%. Following the introduction of dimming control, each PWM period is divided into a 50-slot MPPM symbol. We have assumed that both VL and IR LED sources are installed at the same location with signals experiencing the same channel DC gain. Note that VL and IR LED sources can be installed at anywhere as long as their channel DC gains are known and the synchronization between the signals is maintained. The intensity ratio κ between the transmit power of IR and VL is assumed to be 0.1 except for Fig. 4. For the VL link, the responsivity of PD and the modulation index are assumed to be 0.5 and 0.2, respectively, while for the IR link, these parameter are kept the same as the VL link except for Figs. 5 and 6. Note that we have assumed the PD adopted in this paper has a wide spectral response, which covers both the VL and IR wavebands. However, using a single PD to cover both IR and VL bands will result in different responsivities, thus leading to variation in the received signal levels, which needs to be addressed. Additionally, considering the wavelength selectivity of a PD, optical band-pass filter could also be used to specifically select IR and VL bands where the PD responsivity is high in order to improve the link performance [2]. Alternatively, two PDs at specific wavelength bands could be used at the cost increased system complexity. For the purpose of comparison and evaluation, all other parameters are kept the same as in [12], [13, see Table 1]. For the VLC link at a constant data rate P_t should be minimized because of energy saving. Thus, the required variable M-QAM levels needs to be optimized for each duty cycle to achieve the minimum Rx

TABLE I
REQUIRED M-QAM LEVELS FOR CONSTANT DATA RATE TRANSMISSION

Duty cycle	PWM (case 1)	MPPM (case 2)	MPPM+IR (case 3)	MPPM+IR (case 4)
1	4	4	4	8
0.9	8	8	4	8
0.8	8	8	4	8
0.7	8	8	4	8
0.6	16	8	4	8
0.5	16	16	4	8
0.4	32	32	4	8
0.3	128	64	4	8
0.2	1024	512	4	8
0.1	1048576	524288	4	8
0	No solution	No solution	4	8

sensitivity requirement for the VL link. According to the constraint in (10), the optimized M-QAM levels, the corresponding Rx sensitivity requirement of the VL signal and the total required LED power are shown in Table 1, Figs. 2 and 3, respectively.

From Table 1, the required M-QAM level for both conventional PWM and MPPM increases with reduced DL. For example, at D of 0.1, the required M-QAM level is 1048576, which is too large and not practically available. Note that for D of 0 an additional data link would be required since there is no VL connectivity (i.e., switched-off). Thus, for the conventional PWM and MPPM methods the dimming control range is only limited from 1 to 0.2 or 0.3. However, with the proposed system, the required M-QAM levels can be significantly reduced. Both 4-QAM and 8-QAM can be always used for a full range of D, thus extending the dimming control range compared with previous methods. The constant M-QAM level can also avoid using the adaptive variable M-QAM method for a full range of D.

In Fig. 2, for the conventional PWM and MPPM methods, the required Rx sensitivity of the VL signal improves with DL. For example, at D of 0.9, the Rx sensitivity requirement is as low as −20.4 dBm. MPPM offers the lowest Rx sensitivity requirement for $0.3 \leq D \leq 1$. However, at low values of D the Rx sensitivity requirement increases drastically, which is not practically desirable. This is due to the increased M-QAM levels as in Table 1. Since the LED power should remain constant during the entire dimming control range to achieve a BER equal or lower than the target BER of 10^{-3}, then it is extremely hard and inefficient to realize the entire dimming control range from 1 to 0 by using conventional methods. However, the proposed hybrid system with 4- and 8-QAM based MPPM offers almost a flat Rx sensitivity response over the entire duty cycle. Note that for 4-QAM. The required Rx sensitivity is lower than 8-QAM, which is preferred because of energy saving.

Next, we compare the total transmit power P_{tTotal} as a function of the duty cycle as shown in Fig. 3. For the proposed system, $P_{tTotal} = P_{tIR} + P_{tVL}$. The plots shown follow the same pattern as in Fig. 2. As can be seen MPPM requires the minimum transmit power at $0.3 \leq D \leq 1$, therefore no need to use the IR link within this range. However, for $0 \leq D \leq 0.2$, P_{tTotal} increases sharply for the conventional schemes, thus making the VLC dimming control mechanism implementation inefficient. By adopting an additional IR link, the required transmit power can be drastically reduced under low DLs

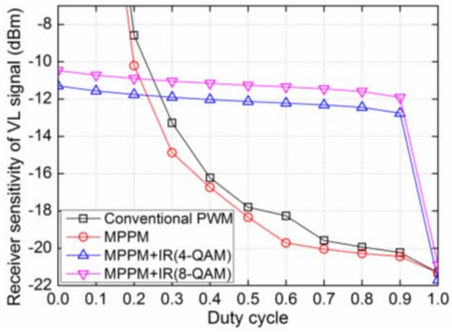

Figure 2. Comparison of the Rx sensitivity requirement of the VL signal.

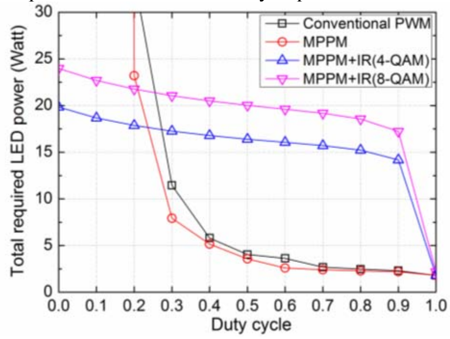

Figure 3. Comparison of the total required transmit power.

(more specifically, for $0 \leq D \leq 0.2$). For example, for 4-QAM P_{tTotal} is 17 W at D of 0.1. Actually, for D of 0, only the IR link is active with the transmit power of 1.64 W. Therefore, in order to achieve constant rate transmission at a BER < 10^{-3} over the entire DL range, P_{tTotal} should be 17 W for 4-QAM. Note that for the IR link, with the Lambertian LED source the eye safety is not critical, whereas with the IR light source with a narrow field of view the eye safety must be considered [23].

Fig. 4 depicts the required transmit power for the VL/IR link as a function of the duty cycle for a range of κ. For the VL link, P_t is lower for larger values of κ. However, larger κ also means performance degradation for both MPPM and OFDM. Therefore, there is a trade-off. On the other hand, for the IR link, κ makes no difference to P_t. In order to reduce P_t larger modulation index can be adopted for the IR signal or a PD with larger responsivity at the IR wavelength could be used, see Fig. 5.

Finally, Fig. 6 compares the maximum achievable data rate as a function of duty cycle for the limited P_t of 10 W. Here $M_{indexIR}$ is assumed to be 0.4 and 4-QAM is adopted for each D for all schemes. As can be seen data rates ≥ 50 Mbps are achieved for $0.2 \leq D \leq 1$ for all schemes, with the MPPM based schemes offering higher rates than PWM, reaching the maximum value of ~60 Mbps at D of 0.5. For $0 \leq D < 0.2$ the data rates of both conventional PWM and MPPM methods must compromise. However, with the proposed hybrid system a constant data rate of 50 Mbps at a BER < 10^{-3} can be always achieved within the entire dimming control range from 1 to 0.

V. CONCLUSION

For indoor VLC dimming control systems, we proposed a concept of using an additional low-power IR link to support the VL signal transmission. Compared with previous methods, improvement was achieved especially under low DLs. Numerical results show that by adopting the proposed method,

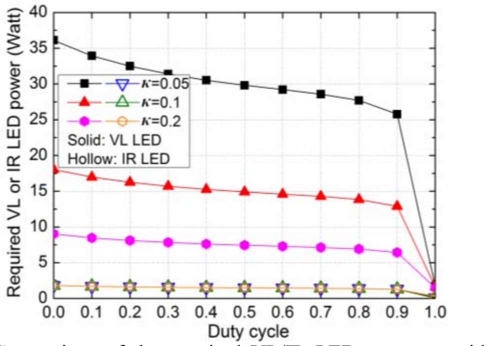

Figure 4. Comparison of the required VL/IR LED power considering the intensity ratio κ to be 0.05, 0.1 and 0.2, respectively.

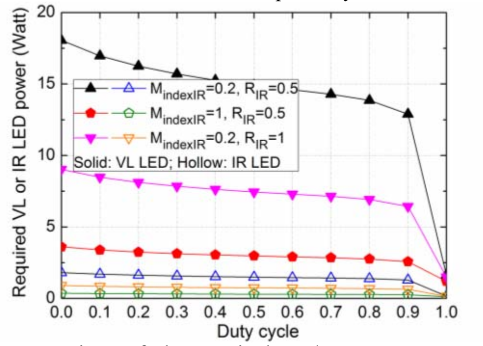

Figure 5. Comparison of the required VL/IR LED power considering different modulation indexes and photo-detector responsivities of the IR link.

both the required M-QAM level and the total required LED power can be significantly reduced under a constant data rate at a BER < 10^{-3}. This makes futuristic VLC systems more power-efficient to implement. Even when the transmit power is limited, reliable transmission at a constant data rate can be effectively achieved within the entire duty cycle between 1 and 0, thus extending the dimming control range compared with previous schemes.

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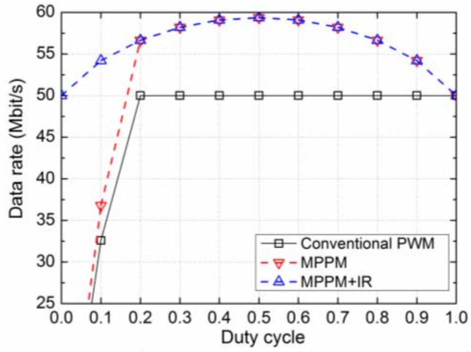

Figure 6. Comparison of the maximum achievable data rate for the limited transmit power of 10 W. Here the modulation index of the IR signal is assumed to be 0.4 and 4-QAM is adopted.

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