



An efficient hybrid visible light communication/radio frequency system for vehicular applications

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Received: 23 June 2019 / Accepted: 17 October 2019 / Published online: 29 October 2019
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Abstract

This paper focuses on improving the traffic system for Intelligent Transportation System (ITS) by using an imaging receiver instead of photodiode as a single receiver. Here, two simple traffic models have been proposed and analyzed in order to optimize the design characteristics such as signal to noise ratio, required power, received information, bit error rate, and modulation technique. First, a standalone visible light communication (VLC) with different modulation techniques is considered. The On–OFF Keying, L-Pulse Position Modulation (L-PPM), and Inverse L-Pulse Position Modulation (I-L-PPM) are investigated. Then, a hybrid communication system utilizing VLC and radio frequency (RF) is proposed for position-based services. The VLC/RF system combines the benefits of both systems and offers long distance transmission which is an important concern in ITS and in order to improve the link reliability in infrastructure to vehicle communications. This means that the probability of having a communication link between the transmitter and receiver is maintained without interruption. Then, the performance is finally evaluated. The obtained simulation results show a considerable increase in the received information using the proposed hybrid VLC/RF system compared to a VLC system.

Keywords Traffic system · Vehicular applications · Radio frequency (RF) · Visible light communications (VLC) · Code division multiple access (CDMA)

1 Introduction

The number of vehicles that use the transportation infrastructure is increasing every year. For this reason, it is mandatory to continuously improve both the safety and efficiency of the transportation system. Connecting vehicles using Visible Light Communication (VLC) technology can significantly enhance efficiency of travel, reduce traffic accidents, improve safety, and alleviate the impact of overcrowding (Ndjiongue and Ferreira 2018). The Intelligent Transportation System (ITS) technology combines

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intelligent vehicles and infrastructure, working simultaneously to increase the safety and efficiency of the transportation system (Papadimitratos et al. 2009).

Vehicle Information and Communication System (VICS) has been introduced into practice since 1996. This system depends on infrared (IR) optical beacons to detect vehicles on the road, control the traffic and supply real-time traffic information. However, this system is not flexible because it is only capable of transmitting a small amount of information (Che Wook et al. 2006).

Nowadays, VLC is becoming an alternative communication source to be used in many applications; both indoor as well as outdoor.

The vehicular VLC system uses light emitting diodes (LEDs). The new LEDs that are used in VLC play a dual role in providing both illumination and data transmission. A new LED-based traffic light, based on automobile brake lights and even head lights approaches, was invented and has already been used, in many parts of the world (Ndjiongue and Ferreira 2018).

Currently, global positioning system (GPS) is widely used for tracking vehicles. However, GPS system is costly, insecure, and cannot provide services in areas where the RF signal is weak or unavailable like, tunnels or underground. Moreover, GPS system utilizes RF and this makes its signal suffers from many problems such as, multipath and radio interference errors. Hence, it is difficult to be used in vehicular applications, like, positioning or controlling and estimating the traffic flow. Thus, a new VLC/RF wireless system can provide a good complementary option to the GPS system (Zhuang et al. 2018).

Most of VLC systems depend on line-of-sight (LoS) transmission, which is a better advantage over RF, that facilitates directionality property and enables positioning applications such as sending the lane ID from LEDs traffic light to the vehicle. But unfortunately, LoS propagation cannot be always guaranteed, especially in the outdoor environment with many potential obstacles that break down the optical link; such as random movements of birds, vehicles, or trucks. Moreover, interferences from the surrounding ambient lights, small coverage and different weather conditions; like fog and rain are all considered as challenges when working with VLC channel. Also, in one lane, the VLC transmitters cannot cover the distance between consecutive traffic lights. However, VLC cannot cover long distances, while RF system can cover long distances, but sends broadcast data that is not directed. Accordingly, the idea of constructing hybrid systems was investigated (Basnayaka and Haas 2017; Chowdhury and Katz 2014; Basnayaka and Haas 2015; Kashef et al. 2016; Wang et al. 2015) to overcome the limitations of both VLC and conventional RF systems, providing the benefits of both systems that offer long distance transmission which is an important concern in ITS and improving the link reliability in infrastructure to vehicle communications. This means that the probability of having a communication link between the transmitter and receiver is maintained without interruption. It is important to know that VLC does not interfere with the RF technology which means that both technologies can coexist and collocate without any design constraints.

Namdar et al. (2018) analyzed the outage and bit error rate (BER) performances of the indoor relay-assisted hybrid radio VLC/RF systems, while A. Dushyantha and H. Haas studied how to improve the user data rate performance of VLC indoor systems using hybrid VLC/RF system in Basnayaka and Haas (2015), and then at 2017 he proposed a new system for design and analysis the hybrid VLC/RF system (Basnayaka and Haas 2017).

For outdoor applications, H. Kazemi proposed a system model for soft switching between the FSO and RF channels in different weather conditions by a finite-state Markov chain process, then he analyzed the outage probability of the system (Kazemi et al. 2014).

In this paper, first, a new structure of VLC vehicular system is constructed using different modulation techniques suitable for VLC outdoor applications. The standalone VLC system performance is examined by solving the signal to noise ratio, power required and BER for each modulation technique used. Second, a novel hybrid system that makes use of VLC and RF communication is introduced to overcome the VLC standalone system challenges.

The OOK, L-PPM and I-LPPM modulation techniques are investigated to depict the best modulation technique for I2 V applications. Then, we evaluated system parameters, including the BER, the required power for each modulation technique, and the effect of vehicle speed on the received information at different data rates.

Although RF is superior in many applications, but, still some challenges could not be overcome. RF cannot be used effectively in tunnels and underground applications. Also, for secure or hazardous places, RF is not suitable. This leads to a good alternative, which is the VLC, for these specific applications. VLC does not need expensive costs for building its infrastructure, and can send secure high data for short ranges, which is our case in traffic. So, VLC can be used in concurrent with RF to take the advantages and overcome the challenges for each system when used alone.

The proposed hybrid system performance is evaluated by calculating the probability of detecting error data at different bit rates and also, by solving the information received for several vehicle velocities. Most of the previous hybrid VLC/RF systems that have been proposed in the literature applied VLC for downlink and RF for uplink. The hybrid system is proposed to achieve a long-distance transmission, and, at the same time, the positioning ability of VLC is maintained. The transmitted information is divided between both of the RF and VLC channels by sending only a small amount of information over the VLC channel and the majority over the RF channel. This ensures that the data is sent from the traffic light, which can cover wider service area to the vehicles for long distances. In our proposed system, we considered each benefit of the previous work and tried to use them all in I2 V system. One of the problems that faces the proposed system is the usage of a single photodiode receiver which is not suitable for our system, while 32×32 pixels imaging receiver is found more suitable practically for a communication distance up to 100 m from the traffic lights. However, using 64×64 , 128×128 , 256×256 , or 1024×1024 pixels will raise the system cost while achieving approximately the same SNR as 32×32 pixels imaging receiver for the same needed communication coverage area.

The remainder of this paper is organized as follows. Section 2 introduces the system model and numerical analysis of the proposed system including all equations used to evaluate the system performance. Section 3 displays and discusses the simulation results. Finally, Sect. 4 is devoted to the main conclusions of this work.

2 System model and analysis

A real scenario that explains the idea of using hybrid VLC/RF system in vehicular communications is shown in Fig. 1. The RF has a wider and longer coverage than that from VLC coverage. If car number 1 needs information about an accident that happened to car number 6 in the same lane, the traffic light can only send the lane number to the car, while all detailed information can be sent by RF. If there are other vehicles that have already passed by the accident, then, they do not need this information anymore. At the same time,

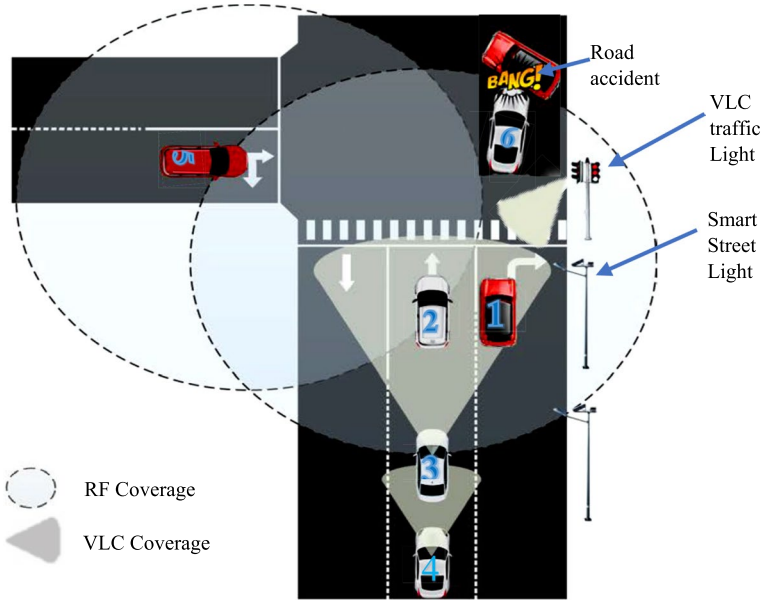


Fig. 1 Transmitting information using hybrid VLC/RF system

a vehicle may need some information related to places available for parking. In all situations, a position based hybrid VLC/RF system is desired to offer good connection all the time.

The proposed system is shown in Fig. 2. It is considered that, there are no heavy vehicles area fixed receiver on a vehicle mounted outside vehicle in front of the windshield with θ vertical inclination and ψ_c field of view (FOV). Wider FOV angles provide larger service areas, but lead to a degradation in the performance because of receiving much more undesired light signals.

The optical signals are intensity modulated (IM) in every color. Working on an actual LED traffic light, the half-power semi angle, $\theta_{1/2}$, of LED takes the value of 15° . The position of a vehicle is identified by the distance in the lane direction, x , and the distance in the width direction, y as shown in Fig. 3. A vehicle is on the first lane, where there is an LED

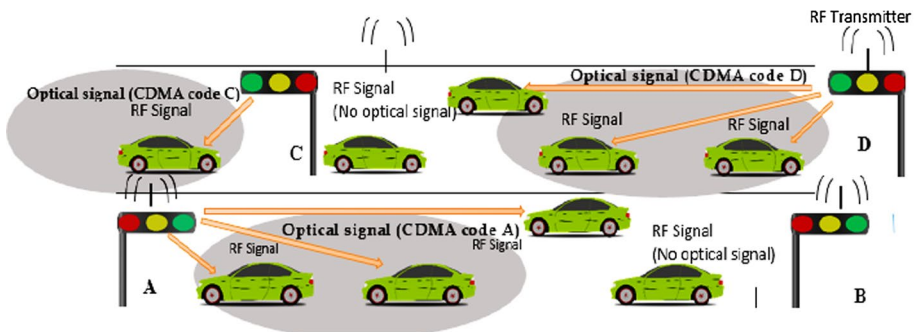


Fig. 2 The proposed hybrid VLC/RF system

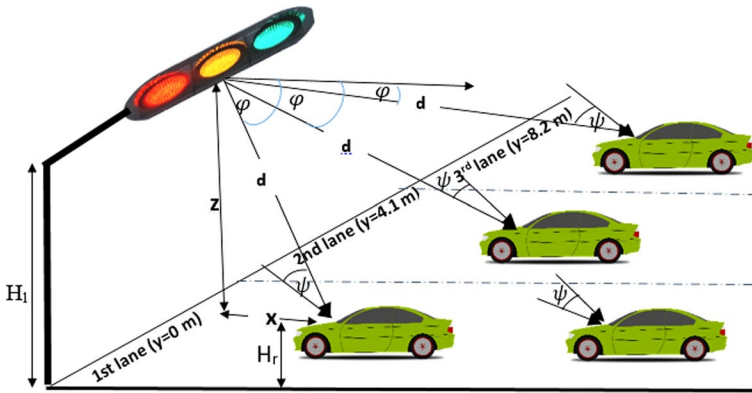


Fig. 3 Propagation model between traffic light and vehicle

traffic light is in position $y=0$ m. Supposing that the width of a lane is 3.5 m and the width of a vehicle is 1.8 m, $H_l=5.3$ m represents the height of traffic light, $H_r=1$ m represents the height of the receiver itself from the road, and z is the height difference between H_l and H_r , as used in Che Wook et al. (2006).

2.1 Transmitter and optical channel

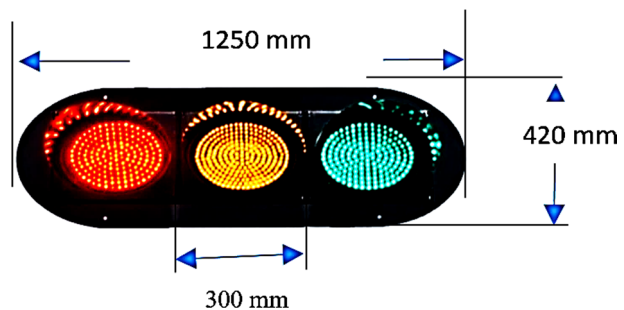
The LEDs traffic light consists of a set of LEDs closely wired to fit into the standard traffic light dimension of 200 mm or 300 mm. In the proposed model, we use 300 mm as used in Che Wook et al. (2006). The scales of the used traffic light model are shown in Fig. 4.

Each LED emitter is ideally modeled using a generalized Lambertian radiation pattern. So, the transmitted power from LED transmitters is calculated as Barry (1994), Kahn and Barry (1997) and Gfeller and Bapst (1979)

$$P_{tr}(\varphi) = \left[\frac{m+1}{2\pi} \right] P_t \cos^{m+1}(\varphi) \tag{1}$$

where P_t is the time average transmission optical power, it is supposed that $P_t=314$ mW as used in Akanegawa et al. (2001), φ refers to the angle of irradiance which characterizes the transmitter and m is an order related to half-power semiangle $\theta_{1/2}$, and can be obtained as Che Wook et al. (2006)

Fig. 4 The scales of used traffic light model



$$m = \left[\frac{\ln 2}{\ln (\cos (\phi_{1/2}))} \right] \tag{2}$$

Each light signal in a traffic light (red, yellow, green) consists of several LEDs. So, the resulting radiation pattern consists of the superposition of several Lambertian radiation patterns; one for each single LED in the transmitter. For any closely placed array of LEDs, the radiation pattern can be modeled as an equivalent Lambertian distribution.

In optical wireless communication channel, the direct current (DC) gain is given by Akanegawa et al. (2001)

$$H(0) = \begin{cases} \left[\frac{(m+1)A}{2\pi d^2} \right] \cos^m(\varphi) T_f(\psi) T_{c,i}(\psi) \cos(\psi), & 0 \leq \psi < \psi_c \\ 0, & \psi \geq \psi_c \end{cases} \tag{3}$$

where A is the detector physical area, ψ is the angle of incidence, φ is the angle of irradiance, $T_f(\psi)$ is the filter transmission constant and $T_{c,i}(\psi)$ is the fraction of image size on i th pixel, and is given by Kahn and Barry (1997)

$$T_{c,i}(\psi) = -0.1982\psi^2 + 0.0425\psi + 0.8778 \tag{4}$$

The LoS path, d , Fig. 3, between the LED traffic light and the receiver is easily given as

$$d = \sqrt{x^2 + y^2 + z^2} \tag{5}$$

Both angle of irradiance, φ , and angle of incidence, ψ , are calculated from Fig. 3 as

$$\varphi = \cos^{-1} \left(\frac{x}{d} \right) \tag{6}$$

$$\psi = \cos^{-1} \left(\frac{\sin \left(\theta + \tan^{-1} \left(\frac{z}{x} \right) \sqrt{x^2 + z^2} \right)}{d} \right) \tag{7}$$

The proposed system here is working on small distances and therefore, the weather conditions do not affect the performance. Therefore, it is assumed that we are working in a clear air channel model.

2.2 VLC receiver model

First, following Akanegawa et al. (2001) analysis, which utilized a conventional APD receiver, it appears that all of the signals are detected and processed simultaneously, and the processed signal may contain undesired signals, ambient noise, etc. Therefore, the desired signals will degrade the system performance. Accordingly, to avoid device complexity and, at the same time, reduce the effect of undesired signals, a 2-dimensional image sensor is used instead of the APD (Che Wook et al. 2006). When using a 2-dimensional image sensor as a receiver, each pixel will have its own independent FOV. Hence, most of the undesired signals can be reduced.

The desired power in a pixel can be obtained as Che Wook et al. (2006)

$$P_{rx,i}(t) = P_{tr}(\varphi)H(0) \tag{8}$$

The total received signal, including noise, is given by Che Wook et al. (2006)

$$P_t = P_{rx,i}(t) + Noise(t) \tag{9}$$

Following the analysis of Personick and Smith in computing the receiver noise (Personick 1973; Smith and Personick 1980) the noise variance referred to the input of the *i*th pixel is given approximately by

$$\sigma_{tot,i}^2 \approx 2qrI_2(P_{b,i} + P_{rx,i})B + \frac{8\pi k_B T}{G} \eta \hat{A} I_2 B^2 + \frac{16\pi^2 k_B T \Gamma}{G_m} \eta^2 \hat{A} I_3 B^3 \tag{10}$$

The first term is the shot noise which is considered the dominant noise source in wireless optical communications (Kahn and Barry 1997), *q* is the electronic charge, *r* is the detector responsivity, *P_{b,i}* is the ambient light power detected by the *i*th pixel, *I₂* and *I₃* are constants referring to the noise bandwidth factor for noise, and *B* is the required bandwidth, depending on the bit rate and modulation method of interest.

The second term represents the thermal noise from the feedback resistor; *k_B* is Boltzmann constant, *η* is the capacitance per unit area, *G* is the open-loop voltage gain, *T* is the absolute temperature, and *ĤA* is the detector effective area, which can be calculated as Chowdhury and Katz (2014)

$$\hat{A} = \begin{cases} A \cos(\varphi), & \varphi < FOV \\ 0, & \geq FOV \end{cases} \tag{11}$$

In the third term, which describes the thermal noise from the field-effect transistor (FET) channel resistance, *Γ* is the FET channel noise factor, and *G_m* is the FET conductance.

The use of imaging sensor with many small pixels will reduce all the three terms in noise equation, as compared to a single-element receiver. The first term is reduced because the small FOV associated with a small pixel size diminishes the received ambient light power, while the second and third terms are reduced because a small pixel size reduces the preamplifier input capacitance.

A smaller pixel will have a smaller FOV. Hence, the first term is reduced because *P_{b,i}* becomes smaller as follows

$$P_{b,i} \approx 4\pi A B_{sky} \Delta\lambda T_f T_{c,i} \times \cos(\psi_i) \sin^2\left(\frac{\psi_{a,i}}{2}\right) \tag{12}$$

where *ψ_{a,i}* is the pixel FOV, *A* is the light detector area, *B_{sky}* is the power spectral density (PSD) of skylight and *Δλ* is the filter bandwidth. The second and third terms are reduced because the input capacitance decreases as the pixel size decreases. While the received power depends on FOV of the detectors, it is essential to get an expression for the FOV. Following Jungnickel et al. (2003) analysis, it is shown that the FOV angle is changed according to the size of the entire detector, i.e. the image sensor itself and the focal length of interest.

2.3 VLC analysis

To reduce cost and implementation complexity, intensity modulation with direct detection (IM/DD) is used in most VLC systems (Barry 1994). In IM/DD, the intensity of the LED is modulated by the input signal. In DD, a photodetector produces a current proportional to the received instantaneous power.

The choice of modulation technique in the design of VLC systems remains one of the most important technical issues. In our analysis, we used various modulation techniques, OOK (which forms the basic standard for evaluation), L-Pulse Position Modulation (L-PPM) and Inverse L-PPM (I-L-PPM) (where L is equal to 2^n , and n is an integer = 1, 2, 3, ...). Most wireless communication systems can be modeled as having an output signal Y(t) and an input signal X(t). The output signal can be calculated as Cailean et al. (2014)

$$Y(t) = X(t) \otimes rH(t) + N(t) \tag{13}$$

where \otimes denotes convolution, H(t) is the channel impulse response and N(t) is additive noise.

Recalling that the objective of this paper is to minimize the transmitted power required to attain a certain probability of BER. Using the select best (SB) technique, the SNR is obtained as Che Wook et al. (2006)

$$SNR = \frac{r^2 P_{rx,i}^2(t)}{\sigma_{tot,i}^2} \tag{14}$$

The BER for OOK scheme is actually calculated by the same equation as in 2-PPM case (Che Wook et al. 2006), which is given by

$$BER_{OOK} = Q(\sqrt{SNR}) = Q\left(\frac{rP_{rx,i}(t)}{\sqrt{\sigma_{tot,i}^2}}\right) \tag{15}$$

where

$$Q(x) = (2\pi)^{-1/2} \int_x^\infty \exp(-z^2/2) dz = \frac{1}{2} \operatorname{erfc}\left(\frac{x}{\sqrt{2}}\right) \tag{16}$$

Another important factor for checking the system quality is the BER. So, we compare the BER performance for OOK, I-L-PPM and L-PPM which can be obtained as Wada et al. (2005)

$$BER_{L-PPM} = Q\left(\sqrt{\frac{L \log_2 L}{2}} \sqrt{SNR}\right) \tag{17}$$

$$BER_{I-L-PPM} = Q\left(\frac{1}{L-1} \sqrt{\frac{L \log_2 L}{2}} \sqrt{SNR}\right) \tag{18}$$

2.4 RF analysis

To accommodate multiple users at the same time without interfering with each other, a multiple access technique should be used. Here, the proposed system utilizes code division multiple access (CDMA), where a set of orthogonal spreading codes is applied to the information bits from different users, and binary phase shift keying (BPSK) modulation is used.

Here, the RF signal is transmitted through a LoS channel and the transmitted signal power is P_{RFtx} . The RF signal can receive a power which is expressed as Goldsmith (2005)

$$P_{req,OOK} = \frac{1}{r} \sqrt{\sigma_{tot,i}^2} Q^{-1}(BER) \tag{19}$$

The path loss, P_l , can be defined as the ratio between transmitted and received power. It can be extracted from (10) as

$$P_l = \frac{P_{RFtx}}{P_{RFrx}} \tag{20}$$

$$P_l(dB) = -10 \log_{10} \left(\frac{\sqrt{G_t} \lambda}{4\pi d_{RF}} \right)^2 \tag{21}$$

where $\sqrt{G_t}$ is the product of the transmit and receive antenna field radiation pattern in the LoS direction, λ is the signal wavelength, and d_{RF} is the distance between transmitter and receiver in the RF system.

The path gain is the opposite of the path loss and can be obtained as

$$P_G = -P_l = 10 \log_{10} \left(\frac{\sqrt{G_t} \lambda}{4\pi d_{RF}} \right)^2 \tag{22}$$

The ratio of the received signal power, P_{RFrx} , to the noise power within the bandwidth of the transmitted signal, B_{RF} , can be used to calculate the received SNR as

$$SNR_{RF} = \frac{P_{RFtx}}{NoisePower} = \frac{P_{RFtx}}{B_{RF} k_B T} \tag{23}$$

From Eqs. (20) and (23), one can get a relationship between SNR_{RF} and the path loss as follows

$$SNR_{RF}(dB) = P_{RFtx}(dB) - P_l(dB) - NoisePower(dB) \tag{24}$$

From (19) and (22), the SNR can be obtained

$$SNR_{RF} = P_{RFtx} \left(\frac{\sqrt{G_t} \lambda}{4\pi d_{RF} \sqrt{B_{RF} k_B T}} \right)^2 \tag{25}$$

Now, it is observed that the SNR is inversely proportional to the square of covered distance between the RF transmitter and receiver, which means that as the distance from the traffic light to the vehicle increases, the SNR decreases. The SNR is also proportional

to the square of the signal wavelength, and as the carrier frequency increases, the SNR decreases.

The BER in RF system is calculated based on the signal-to-interference-plus noise ratio (SINR) instead of SNR (Goldsmith 2005). P_I is the interference power after spreading the CDMA code. In our proposed system, a different CDMA spreading code is sent by each traffic light in a lane and can be used to decode the CDMA information at the same lane. The SINR of RF channel can be obtained as Goldsmith (2005)

$$SINR = \frac{P_{RFrx}}{B_{RF}k_B T + P_I} = \left(\frac{B_{RF}k_B T}{P_{RFrx}} + \frac{j-1}{G_{RF}} \right)^{-1} \tag{26}$$

where G_{RF} is the processing gain and j is the number of users.

The BER for RF can be obtained as Goldsmith (2005)

$$BER_{RF} = Q\sqrt{2SINR} \tag{27}$$

2.5 Hybrid system and pure VLC system performance

As mentioned before, the VLC channel here is used to send the lane number while the RF channel is used to send the information signal (i.e. nearest places available for parking, accident in the road,...). The VLC channel is modeled as a linear optical additive white Gaussian noise (AWGN) channel. The probability of error when receiving wrong lane ID (P_{eVLC}) and the probability of error when receiving a frame error occurring when decoding the traffic information (P_{eRF}) are given by Liu et al. (2012)

$$P_{eHybrid} = P_{eVLC} + (1 - P_{eVLC-OK})P_{eRF} \tag{28}$$

$$P_{eVLC-OK} = 1 - (1 - BER_{OP})^\gamma \tag{29}$$

$$P_{eRF} = 1 - (1 - BER_{RF})^\zeta \tag{30}$$

where γ is the number of information bits of the ID frame and ζ is the number of information bits of the data frame.

When changing the VLC modulation technique used (OOK) to L-PPM and I-L-PPM, one can get the probability of error by substituting from (17) and (18) in (29) as

$$P_{eVLC-LPPM} = 1 - \left(1 - Q\left(\sqrt{\frac{L \log_2 L}{2}} \sqrt{SNR} \right) \right)^\gamma \tag{31}$$

$$P_{eVLC-I-LPPM} = 1 - \left(1 - Q\left(\frac{1}{L-1} \sqrt{\frac{L \log_2 L}{2}} \sqrt{SNR} \right) \right)^\gamma \tag{32}$$

For a standalone VLC system, the data signal is transmitted by the light signal. Therefore, no code signal is needed. The probability of detecting an error of a VLC system is calculated as Liu et al. (2012)

$$P_{e_{vLC}} = 1 - (1 - BER_{OP})^\zeta \tag{33}$$

Table 1 shows the BER of the lane ID in case of using L-PPM modulation $P_{e_{VLC-PPM}}$ or I-L-PPM modulation $P_{e_{VLC-I-PPM}}$ when using $L=4, 8$ and 16 and substituting in (31) and (32).

From Eq. (15), one can get the power required for OOK as

$$P_{req,OOK} = \frac{1}{r} \sqrt{\sigma_{tot,i}^2} Q^{-1}(BER) \tag{34}$$

This power will be used as a guide to compare the performance of the other modulation schemes.

From Eq. (17), the required power for L-PPM can be obtained as

$$P_{req,L-PPM} = \frac{\sqrt{\sigma_{tot,i}^2} Q^{-1}(BER)}{r \sqrt{\frac{L \log_2 L}{2}}} = \frac{P_{req,OOK}}{\sqrt{\frac{L \log_2 L}{2}}} \tag{35}$$

Using Eq. (18), the required power for I-L-PPM can be obtained as

$$P_{req,I-L-PPM} = (L - 1) \frac{\sqrt{\sigma_{tot,i}^2} Q^{-1}(BER)}{r \sqrt{\frac{L \log_2 L}{2}}} = (L - 1) \frac{P_{req,OOK}}{\sqrt{\frac{L \log_2 L}{2}}} \tag{36}$$

2.6 Received data

The received data is one of the most important parameters to examine the performance of the system used. Here, the amount of data that can be received within a particular service area is expressed as follows Ndjiongue and Ferreira (2018)

$$Received\ data[bit] = \frac{Transmission\ rate \left[\frac{bits}{sec} \right] \times Service\ area[m]}{velocity\ of\ vehicle[kmph]} \tag{37}$$

Table 1 The probability of error for the lane ID in case of L-PPM and I-L-PPM

L	$P_{e_{VLC-L-PPM}}$	$P_{e_{VLC-I-L-PPM}}$
4	$1 - (1 - Q(2\sqrt{SNR}))^\gamma$	$1 - (1 - Q(\frac{2}{3}\sqrt{SNR}))^\gamma$
8	$1 - (1 - Q(2\sqrt{3SNR}))^\gamma$	$1 - (1 - Q(\frac{2}{7}\sqrt{3SNR}))^\gamma$
16	$1 - (1 - Q(4\sqrt{2SNR}))^\gamma$	$1 - (1 - Q(\frac{4}{15}\sqrt{2SNR}))^\gamma$

Table 2 Minimum SNR corresponding to minimum BER = 10^{-6}

Modulation technique	Minimum SNR (dB)
OOK	13.6
4-PPM	7.52
8-PPM	2.75
I-4-PPM	17.062
I-8-PPM	19.65
I-16-PPM	22.01

Table 3 Numerical analysis parameters

Parameter	Symbol	Value
Boltzmann constant	k_B	1.3811×10^{-23} J/K
Transmission power	P_t	314 mW
Absolute temperature	T	300 K
Detector responsivity	r	0.35 A/W
Light detector area	A	0.79 cm ²
Electron charge	q	1.602×10^{-19} C
Voltage gain	G	10
FET transconductance	G_m	30 ms
FET channel noise factor	Γ	1.5
Bandwidth of filter	$\Delta \lambda$	10 nm
Radio frequency	f	2.4 GHz
PSD of skylight	B_{sky}	43.0 mW/m ² sr-nm
Capacitance per unit area	η	112.0 pF/cm ²
Receiver FOV	$\Psi_{1/2}$	26°
Vertical inclination	θ	74°
Data rate in pure VLC	R_b	1 Mbps, 10 Mbps and 100 Mbps
Data rate in hybrid system	R_b	100 kbps for VLC and 100 Mbps for RF system
Vehicle velocity	v_m	60 km/h
Number of user	j	10
Processing gain	G_{RF}	200
Number of information bit of data frame	ζ	100 bits
Number of information bit of ID frame	γ	bits
Noise bandwidth factor for white noise	I_2	0.562
Noise bandwidth factor	I_3	0.868

3 Simulation results and discussion

3.1 The VLC system

In order to accomplish a reliable data communication, the BER must be above 10^{-6} . Therefore, using the Q function table, we determined that at least SNR = 13.6 dB in OOK modulation is

required. Taking $L=4, 8,$ and $16,$ we evaluate the minimum SNR for each modulation technique as shown in Table 2.

The parameters being used in our simulation, as used in Liu et al. (2012), are shown in Table 3.

In order to achieve the ultimate area of reception, we follow H. Wook et al. assumption (Che Wook et al. 2006)

$$\theta + \Psi_{c,\max} \leq 90^\circ \tag{37}$$

From Eq. (14) the results displayed in Fig. 5 are obtained, which show the SNR against the coverage distance at different number of pixels from 1×1 to 1024×1024 pixels in the first lane at data rate = 1 Mbps, showing the minimum SNR corresponding to minimum BER = 10^{-6} for different modulation techniques. Here, it is clear that OOK has the moderate value between I-L-PPM and L-PPM. The I-L-PPM achieves the better SNR while the L-PPM achieves the widest coverage area. The single photodiode is not preferable here. As the number of pixels increases, the received SNR and the coverage area increase, too. After 20 m, the SNR slope is drooped but when using I-16-PPM the traffic light can send data tends to 80 m and the vehicle can receive it with SNR = 22.01 dB which is considered a more suitable value, modulation technique, and coverage when compared to all other investigated modulation techniques.

When using 100 Mbps OOK for VLC system as used in Liu et al. (2012), it appears that for a single photodiode, the maximum value that can be received for SNR = 42.8 dB, while in case of using imaging receiver, the maximum, 57 dB, value can be achieved when using $32 \times 32, 64 \times 64, 128 \times 128, 256 \times 256,$ or 1024×1024 pixels.

Figure 6 shows the SNR against the coverage distance at different number of pixels from 1×1 to 1024×1024 pixels in the second lane. Here, the SNR is lower than that in lane 1 which is expected because the vehicle is far from the traffic light than in lane 1, but the traffic light can still cover the second lane. The maximum SNR received using imaging receiver and single photodiode is 52.67 dB and 35.86 dB, respectively.

Figures 7, 8, 9 and 10 show the SNR against the coverage distance in the first and second lanes at 10 and 100 Mbps bit rate, respectively. It is clear that when the bit rate increases,

Fig. 5 SNR lane1 at bit rate = 1 Mbps

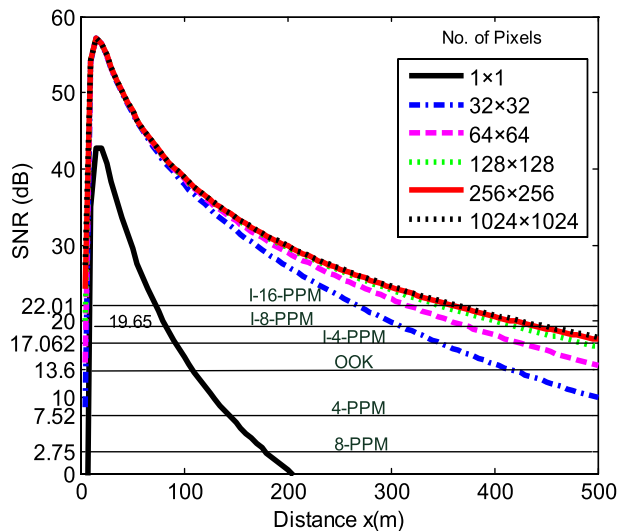


Fig. 6 SNR lane 2 at bit rate = 1 Mbps

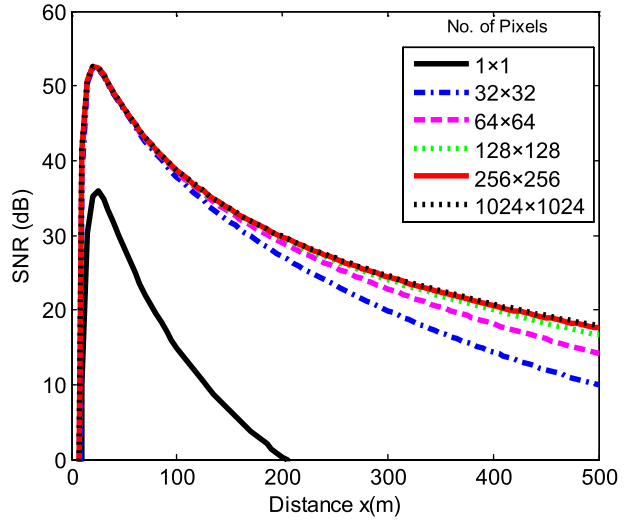
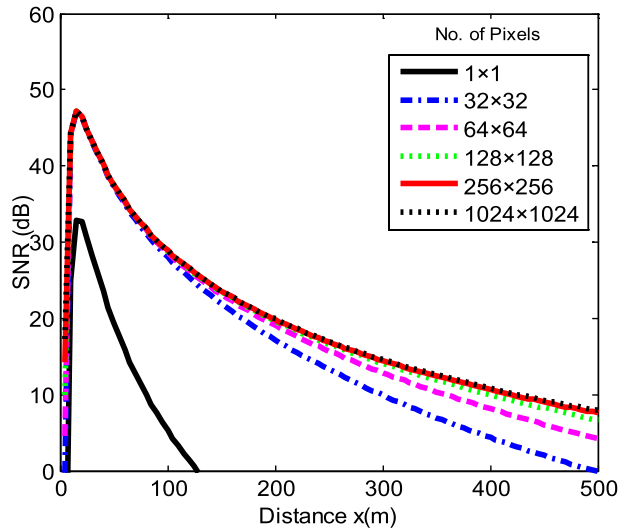


Fig. 7 SNR lane1 at bit rate = 10 Mbps



the SNR decreases. At 100 Mbps, the I-L-PPM is not a good choice for single photodiode case because a small signal will be received by the vehicle and after $L=16$, no signal will be further received. At the same parameters' value, it is much better using 32×32 pixels which gives approximately the same SNR to cover a distance ~ 100 m between the traffic light and the vehicle. This will reduce both the cost and complexity.

At first, in Figs. 5, 6, 7, 8, 9 and 10, we can see that the SNR increases after few meters, because when the vehicle is near to the traffic light the visibility is not clear so much. This occurs when the size of projected image is larger than the size of one pixel and $T_{c,i}$ becomes very small. Thus, for communication concentrating on distance between 5 to 20 m from the traffic lights, we have found that the best number of pixels is 32×32 . At a distance of 20 m from traffic light, we get the higher value of receiving data, i.e. the peak value of SNR.

Fig. 8 SNR lane 2 at bit rate = 10 Mbps

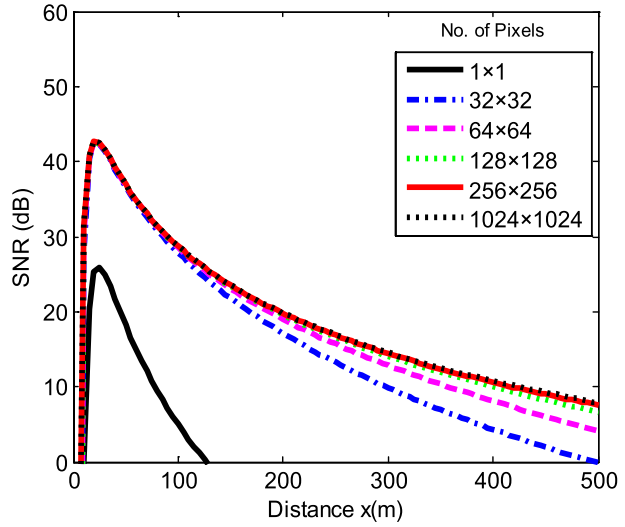
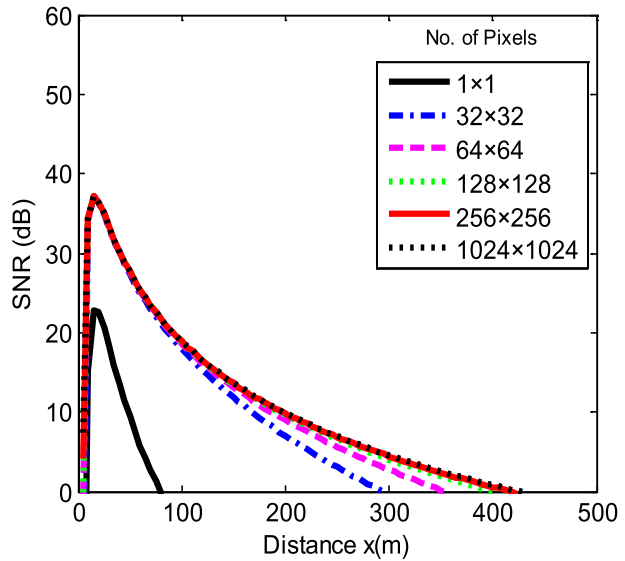


Fig. 9 SNR Lane 1 at bit rate = 100 Mbps



After that, when the distance between the traffic light and the vehicle increases, the SNR degrades.

Figures 11 and 12 display the required power and the corresponding BER for various modulation techniques for the VLC system. From Fig. 11, it is observed that the I-L-PPM requires more power than OOK and L-PPM. As long as L increases, the PPM requires less power but I-L-PPM requires more power. As shown in Fig. 12, the BER is less in case of L-PPM modulation than I-L-PPM while OOK is considered as a moderate modulation technique.

The 3-PPM is slightly better than 2-PPM in terms of bandwidth and power efficiency, but its implementation is more complicated because $\log_2 3$ is not an integer. It

Fig. 10 SNR Lane 2 at bit rate = 100 Mbps

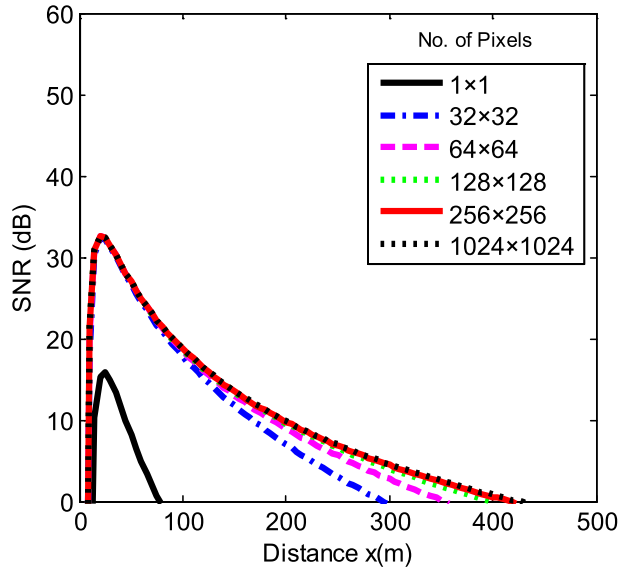
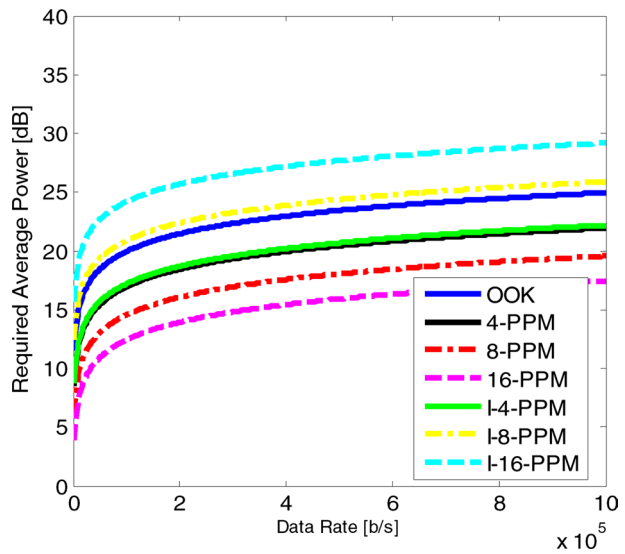


Fig. 11 Required average power needed for OOK, 4-PPM, 8-PPM, 16-PPM, 4-I-PPM, 8-I-PPM, 16-I-PPM



is apparent that, the 4-PPM is particularly attractive because it has the same bandwidth requirement as 2-PPM and requires 3.8 dB less optical power. Therefore, from the point of view of bandwidth and power efficiency, the 4-PPM is always preferable over 2-PPM. As L increases from 4 to 16, the bandwidth requirement increases from $2R_b$ to $4R_b$, while the sensitivity increases from 3 to 7.5 dB better than OOK.

Fig. 12 BER against SNR for OOK, 4-PPM, 8-PPM, 16-PPM, I-4-PPM, I-8-PPM and I-16-PPM

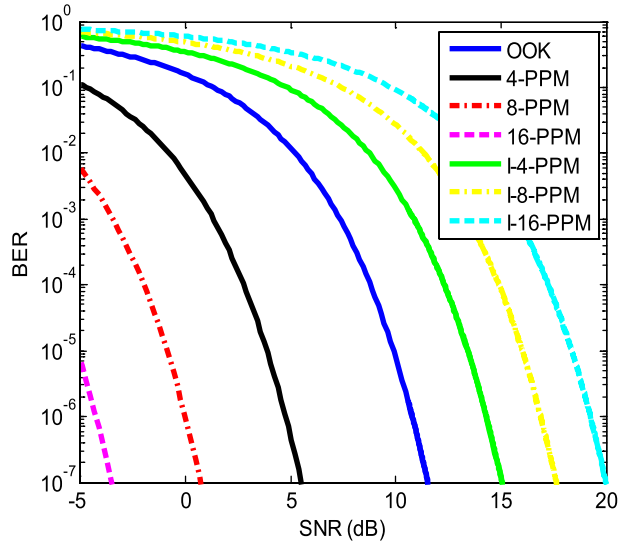
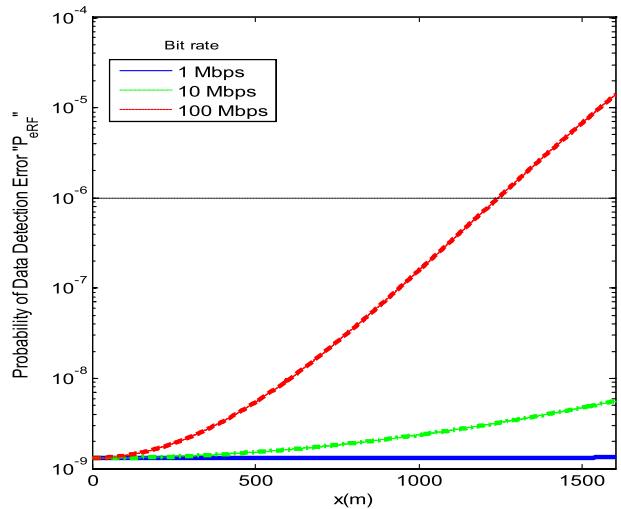


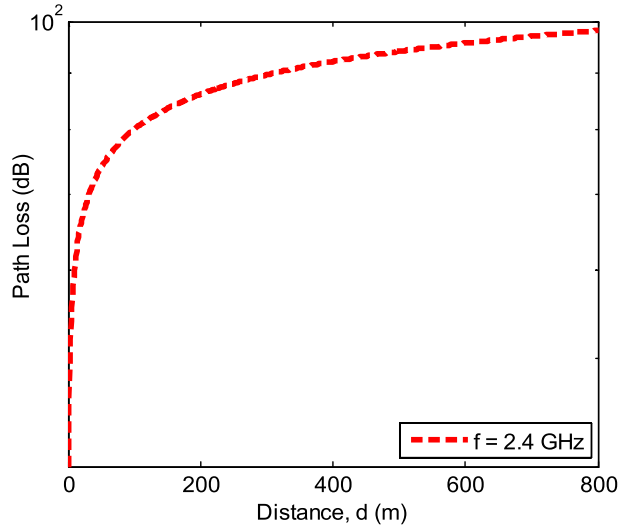
Fig. 13 Probability of data detection error of the RF channel for the proposed hybrid system (Liu et al. (2012))



3.2 Hybrid system evaluation

Using the same parameters in Table 3, it is possible to compare the pure VLC system with the hybrid VLC/RF system showing which one achieves better performance. We assume that the RF transmitter is set at the same place as the traffic light one. Also, the RF receiver is assumed to be set at the same place of light receiver on the vehicle. Figure 13 shows the probability of detecting error of the RF channel for the proposed hybrid system (Liu et al. 2012). The results displayed in Fig. 13 show that, when using the same transmitted power, bandwidth and modulation technique, the effective coverage of the RF system at P_{erF} less than 10^{-6} is larger than the standalone VLC even when using a receiver with

Fig. 14 Path loss for RF system



higher number of pixels as shown in Fig. 5. For example, at 100 Mbps bit rate, the effective coverage is around 1200 m while when using pure VLC system, the maximum coverage at the same bit rate and BER, will not exceed 50 m when using APD receiver, and 150 m when using an imaging receiver. This means that the vehicle can always receive data signal from the traffic light when using a hybrid VLC/RF system.

Referring to Eq. (21), the path loss for the RF system can be obtained and simulated as shown in Fig. 14. As much as the vehicle is away from the traffic light, the path loss increases.

Figure 15 shows the probability of error for both VLC and hybrid systems in the first lane using the parameters in Table 3. For the VLC system using OOK modulation technique, P_{eVLC} is calculated at different bit rates: 1–10–100 Mbps. While for solving

Fig. 15 Probability of error of the proposed hybrid system and standalone VLC system (OOK used)

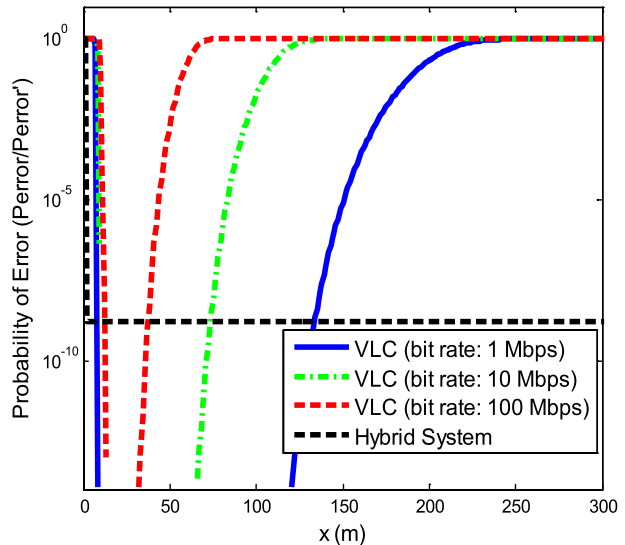


Fig. 16 Probability of error of the proposed hybrid system and standalone VLC system (4-PPM used)

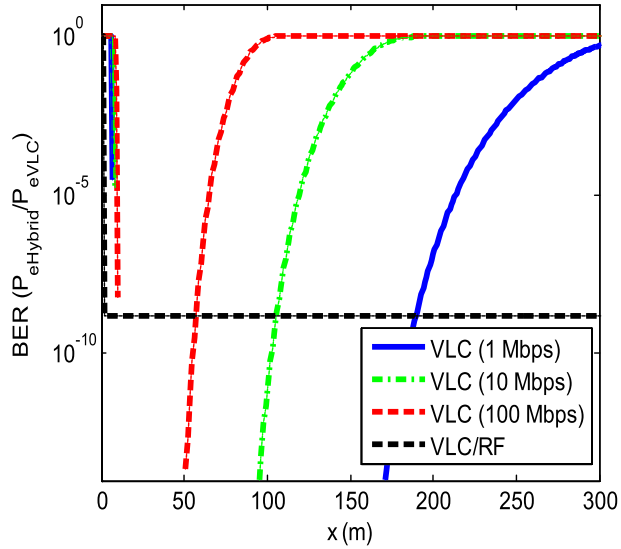
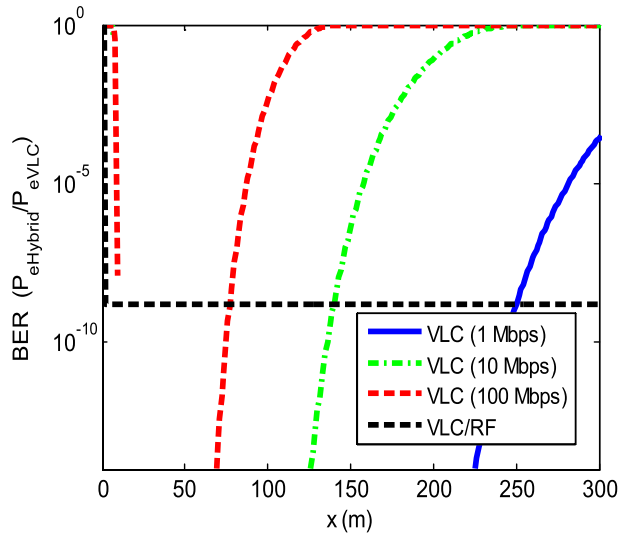


Fig. 17 Probability of error of the proposed hybrid system and standalone VLC system (8-PPM used)



$P_{eHybrid}$, the bit rate used for VLC and RF channels are assumed to be 100 kbps and 100 Mbps, respectively.

From Fig. 15, it is obvious that the coverage distance decreases when the bit rate increases. For example, at 10^{-6} probability of error, the effective coverage distances for bit rates 1, 10 and 100 Mbps are 134, 74 and 38 m, respectively, for the VLC system. The three curves are broken at very small distances. This is because smaller distances lead to a smaller path loss for VLC channel but with larger incidence angle. Therefore, the receiver FOV cannot catch the transmitted light signal and so it cannot be received. If the vehicle receives ID signal from the same traffic light at the same lane, it is only

Fig. 18 Probability of error of the proposed hybrid system and standalone VLC system (16-PPM used)

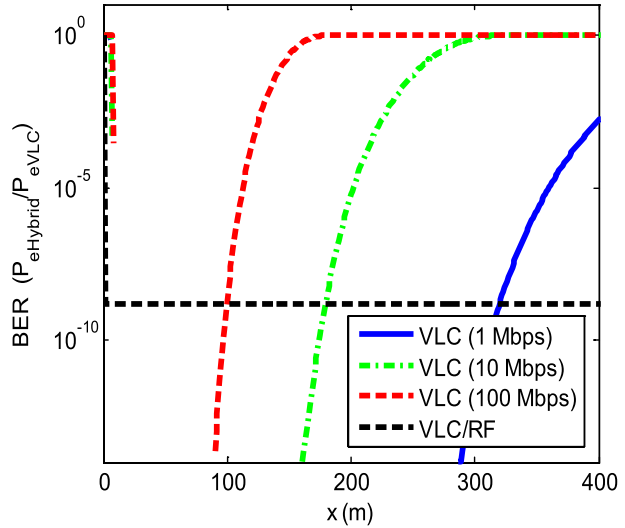
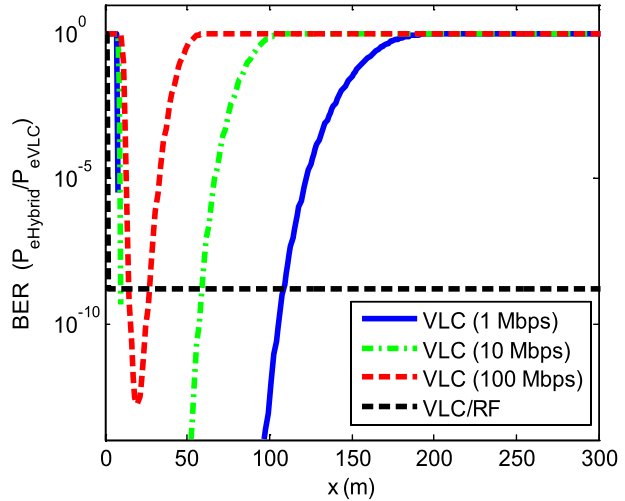


Fig. 19 Probability of error of the proposed hybrid system and standalone VLC system (4-I-PPM used)



needed to decode the ID signal once. By using a combination of VLC/RF system the effective coverage will increase. Moreover, using different L-PPM modulation techniques with VLC system tends to increase coverage distances, while L-I-PPM requires more power and so it achieves higher bit error rate, as shown in Figs. 16, 17, 18, 19, 20 and 21.

Fig. 20 Probability of error of the proposed hybrid system and standalone VLC system (8-I-PPM used)

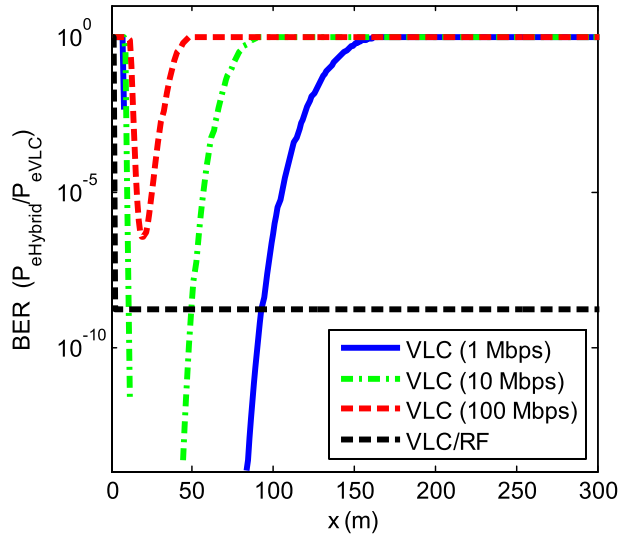
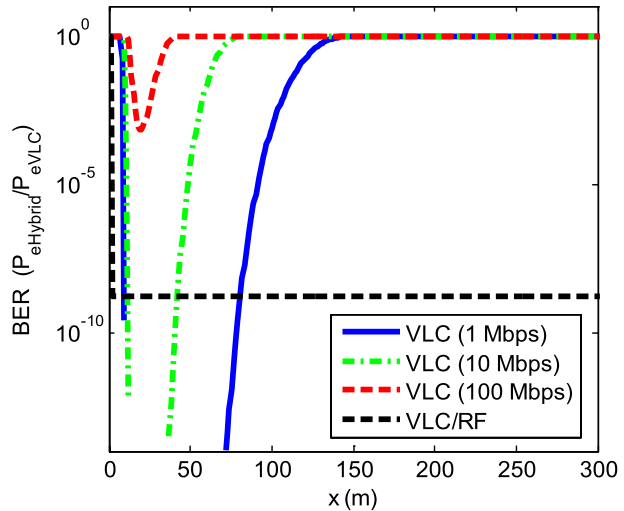


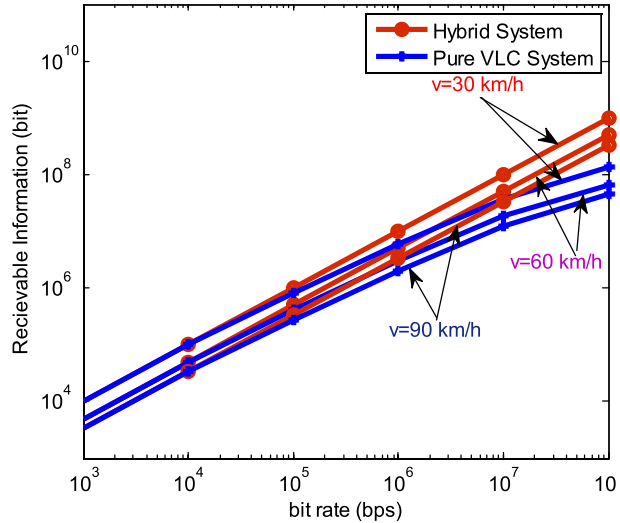
Fig. 21 Probability of error of the proposed hybrid system and standalone VLC system (16-I-PPM used)



3.3 Received information

According to Eq. (36), the amount of received information for a pure VLC system and the proposed hybrid system is calculated and is shown in Fig. 22. First, we take the speed of vehicle 60 km/h as in Liu et al. (2012), then, the vehicle speed is changed to 30 km/h and 90 km/h. The distance between two traffic lights (for example the distance between traffic light A and B in first road way or C and D in second road way as shown in Fig. 2) located in the same lane is 300 m. Figure 22 shows the received information against bit rate in the distance between two cascaded traffic lights. It is observed that when the bit rate is greater than 10 kbps, the proposed hybrid VLC/RF system can receive more information than the standalone VLC system.

Fig. 22 Received information versus bit rate at $v = 20, 40, 60$ km/h



Also, when the vehicle speed is decreased, the corresponding received information increases. In the first lane, if the CDMA spreading code can be received from traffic light A by the vehicle, this code can be used for decoding the data signal, before the vehicle receives another CDMA spreading code from traffic light B.

4 Conclusion

This work discusses the implementation of pure VLC system model, showing the replacement of single element photodiode receivers by an imaging receiver. This led to an improvement of SNR and a reduction of both the required transmitter power and BER.

Comparing with the simplest OOK technique, it is noted that, in the absence of multipath distortion, the required power for 2-PPM is identical to that of OOK. Assuming $L = 4, 8,$ and 16 , for L-PPM, the average power required decreases steadily with increasing L , but, at the expense of the used bandwidth. On the other hand, I-LPPM is suitable for the scenario, where power is not a required constraint for illumination to remain in place. In each case, the proposed system performance has been evaluated by its SNR, BER, service area and the received information depending on the velocity of the vehicle.

The 32×32 pixels is found more practically suitable for a communication distance up to 100 m from the traffic lights. For achieving $\text{BER} = 10^{-6}$, the SNR for all the mentioned modulation techniques is calculated, and standing for OOK, the SNR = 13.6 dB. In this case, the required power is calculated showing that L-PPM technique requires less power than OOK and I-L-PPM, and the 16-PPM requires 10 dB less power than 16-I-PPM requires.

Comparing with previous work in literature (Akanegawa et al. 2001; Che Wook et al. 2006; Liu et al. 2012), we noticed that mostly used the simplest OOK modulation technique. In our work, we considered another modulation techniques and studied their effect on the received data using imaging receiver. The obtained results in different modulation techniques assured the superiority of imaging receiver. Also, we compared many constellations of pixels and studied the most cost effective case that gave higher SNR and wider

coverage to facilitate receiving the data for long distances, which is not considered before in literatures.

After that, a hybrid VLC/RF model is proposed to provide the benefits of both systems when working together. The obtained results proved that VLC/RF system offers higher coverage area (up to 1200 m at bit rate 100 Mbps) than pure VLC system, and improves the downlink broadcast efficiency in infrastructure to vehicle communications. The proposed hybrid VLC/RF system can receive more information than a pure VLC system which is increased by decreasing the vehicle speed.

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