Hybrid Visible Light Communications in Intelligent Transportation Systems with Position Based Services

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***Abstract*—This paper proposes a hybrid communication system for Intelligent Transportation System (ITS) utilizing visible light and radio communications for position-based services. The directionality of light communication is used to distribute position-based keys to vehicles such that they can extract information related only to their desired lanes. The extended coverage of radio communication is used to provide stable data communication complementing the visible light communications (VLC) systems. This paper provides system models and important parameters for designing a hybrid ITS system. The system performance is evaluated by simulation, and the results demonstrate a considerable increase of the effective communication area and receivable information using the proposed hybrid ITS system compared with a VLC system.**

I. Introduction

Intelligent Transportation Systems (ITS) has been motivated by the need for reducing traffic congestion and offering better user experience in navigation and location-specific services. In general, ITS can be combined with data transmission technology, real-time control technology, and data-mining technology for providing efficient traffic and data communication simultaneously. By reducing the average travel distance and waiting time of each vehicle, hence their carbon emission, ITS also helps prevent the global warming [1]-[2].

Recently, visible light communication (VLC) has drawn a lot of attention. ITS is one of its most important applications. The use of VLC in ITS has several advantages over the conventional use of radio-frequency (RF) communication. First, light-emitting diodes (LED), which have been widely deployed in traffic lights, can be used as VLC transmitters. Second, VLC allows more precise positioning of the vehicles because light travels in a straight line [3]. In addition to these two advantages, there is a third advantage which has received less attention in the literature: lane-specific communication. VLC can combine the features of positioning and data transmission, in the sense that the receiver can detect not only the data, but also the physical position of the source transmitting the data. In ITS, this allows the receiver at the vehicle to decode and to display to the driver only that traffic information which is relevant to the lane which the vehicle is in. Then the driver will not be bothered with traffic information irrelevant to him (e.g. those only relevant to neighboring lanes) and the user experience is improved. In this work, we consider the feature of lane-specific communication as a necessary requirement.

Nevertheless, it is well known that VLC cannot compete with radio frequency (RF) systems when it comes to long-distance transmission. This is an important concern in ITS [4], as the distance between consecutive traffic lights in a lane can easily exceed the coverage of current practical VLC transmitters. The limitation of VLC in coverage becomes even more important, if the demand for bit rate increases. This is possible in ITS if more sophisticated or detailed traffic information, or the provision of comfort applications is required in the future. In particular, comfort applications are drawing attention in industry and academia [5], as they can provide entertainment, tourist information, and up-to-date contextual information to drivers and passengers. As a result, the prevalence of VLC systems may be hindered in the future ITS.

In this paper, a novel hybrid system that makes use of VLC and RF communication is introduced to solve the above problem. Other hybrid VLC-RF systems that have been proposed in the literature applied VLC and RF communication in links of different directions (e.g. VLC in forward link and RF in reverse link). Unlike these systems, the hybrid system proposed in this work applies VLC and RF communication in the same direction. The transmitted information is divided between the VLC channel and the RF channel. By sending only a small amount of information over the VLC channel and sending most of the information over the RF channel, long-distance transmission is possible, while maintaining the positioning capability of VLC. We propose such a hybrid system for the application in ITS, in which lane-specific communication is supported.

II. System model

The proposed system is a combination of VLC and RF communication. Good directionality is a vital characteristic of optical communication. However, the optical channel suffers from weather conditions and interference from ambient lights and the optical link breaks off when obstacles appear. On the other hand, radio waves have a high reliability but do not propagate only in the desired direction. In many situations, vehicle drivers want to have the information related to their lane only. Figure 1 shows a practical scenario illustrating the heterogeneous requirements in ITS. If an accident has happened in another lane, a vehicle which has already passed by does not need this information anymore. On the other hand, this vehicle may need some information related to vehicle parking. In many situations, a position based intelligent transmission system is desired. At the same time, vehicles want to have good connection all the time. In this paper, a hybrid system for ITS is proposed.

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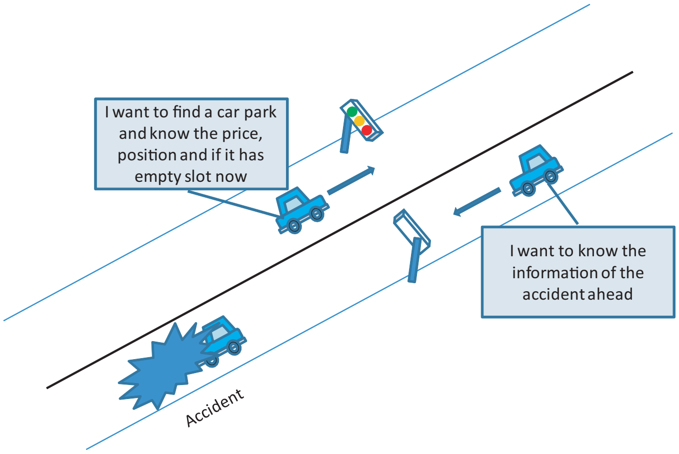

Fig. 1. Different information is desired for different lanes.

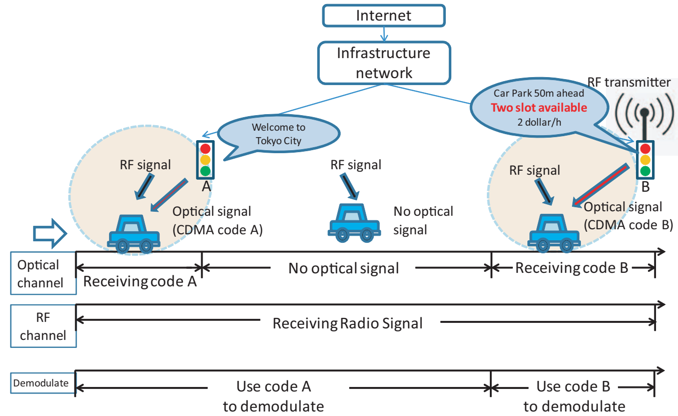

Fig. 2. Proposed hybrid system model.

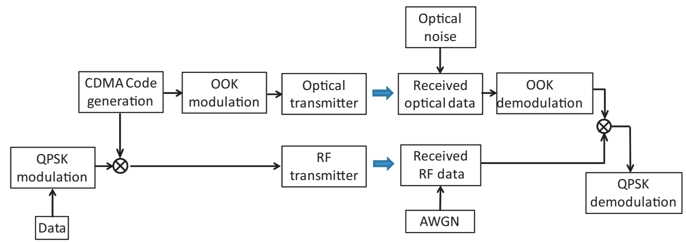

Fig. 3. Block diagram for the hybrid CDMA system.

The proposed hybrid system is shown in Figure 2. First of all, the proposed system utilizes code division multiple access (CDMA) for multiple access. The CDMA data and the CDMA spreading code are transmitted by different communication technologies, cf. Figure 3. In particular, the LED traffic light acts as the transmitter of optical communication which transmits the CDMA spreading code. There are two possible receiver designs. The first one is using a photodiode (PD). Due to the limited field of view (FOV) of PDs, the signal from the traffic light on a vehicle's lane significantly dominates over that of the neighboring lane. The second one uses high-speed camera as receiver. This allows parallel reception of multiple LED transmitters, including traffic lights of different lanes, traffic signs, etc [6]. Both kinds of receivers can determine which traffic light is the transmitter for the vehicle's lane and, hence, can acquire the correct traffic light ID (also the CDMA spreading code ID). In this paper, we will assume the first kind of design.

Each traffic light has a VLC transmitter serving only the lane it belongs to. And among a cluster of neighboring traffic lights, one of them also has a RF transmitter. The RF channel has a higher coverage so that it covers all lanes of the cluster of traffic lights. Only the ID of the traffic light is sent over the VLC channel. The traffic information and other payload data will be sent over the RF channel, using CDMA to resolve the RF interference among the neighboring traffic lights. The receiver will use the spreading code corresponding to that ID acquired in the VLC channel to despread the signal in the RF channel, and acquire the data of the lane which the traffic light corresponds to with that ID. As a result, the vehicles in each lane can only decode the information that is relevant to themselves and improve the transmission efficiency with a high bit rate.

The traffic light sends the optical CDMA spreading code repeatedly. When the vehicle cannot receive any optical code, the previously received and stored CDMA spreading code will be used to demodulate the radio signal. When the vehicle receives a new optical code, this new optical code will be used instead to decode the radio signal. In other words, the decoding process will not be changed until the vehicle receives a new CDMA code (i.e., when the vehicle is near another traffic light).

The features of the proposed system can be summarized as follows:

1) Hybrid deployment and utilization of two different communication technologies with complementary features.
2) Utilization of the directionality of conventional VLC systems to provide position based communication, and utilization of the reliability of radio communication to provide robust communication.
3) Applicable to not only ITS, but also other situations such as museums, shopping malls, and restaurants, etc.

III. Performance Analysis

In this work, we adopt a channel model similar to that in [7].

TABLE I
SIMULATION PARAMETERS

Symbol	Quantity	Value
Length of Traffic Arm	L	$2.0(m)$
Height of Traffic Light	H_l	$5.3(m)$
Height of Receiver	H_r	$1.0(m)$
Difference between H_l and H_r	z	$4.3(m)$
Half-power Semiangle	$\phi_{1/2}$	15°
Detector Physical Area of APD	A	$0.79(cm^2)$
Gain of Optical Filter	$T_s(\psi)$	$300(K)$
Refractive Index	n	1.7
Width of Lane		$7(m)$
Width of Vehicle		$1.8(m)$
Transmit power	P_t	$314(mW)$

A. Optical Channel

The assumed optical channel scenario is shown in Figure 4. Here, d represents the distance between the optical receiver and the transmitter, which is given by

$$d = \sqrt{x^2 + y^2 + z^2}, \tag{1}$$

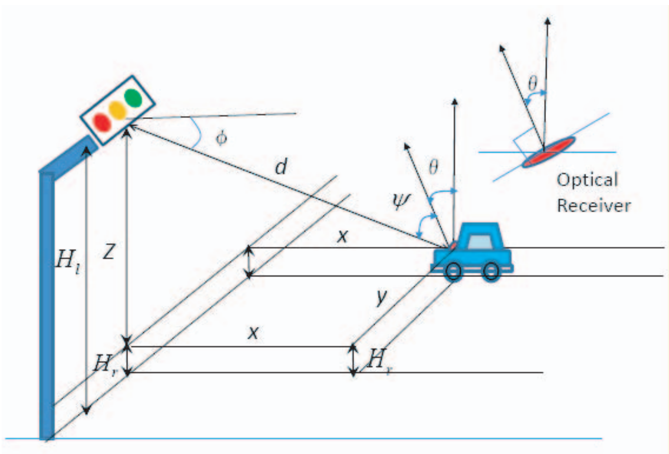

Fig. 4. Configuration of transmitter and receiver.

where x and y are the horizontal and vertical distance between the traffic light and receiver, respectively. H_l is the height of traffic light, H_r is the height of receiver. $z = H_l - H_r$. θ is the inclination angle of the receiver. The size of traffic light and the distance between LEDs in the traffic light is ignored. ϕ is the irradiance angle, Ψ is the incidence angle. The value of these parameters are shown in Table I[7]. In the proposed system, angle ϕ and Ψ are calculated as

$$\phi = \arccos(\frac{x}{d}), \tag{2}$$

$$\psi = \arccos\left(\frac{\sin(\theta + \arctan(\frac{z}{x}))\sqrt{(x)^2 + z^2}}{d}\right). \tag{3}$$

The channel direct current (DC) gain is given by

$$H(0) = \begin{cases} \frac{(m+1)A}{2\pi d^2}\cos^m(\phi)T_s(\psi)g(\psi)\cos(\psi), 0 \leq \psi \leq \psi_c \\ 0, \psi \geq \psi_c, \end{cases} \tag{4}$$

where A is the detector physical area of the photodiode, $T_s(\psi)$ is filter transmission in the receiver and $g(\psi)$ is the concentrator (lens) gain in the receiver. An idealized non-imaging concentrator having an internal refractive index n achieves a gain

$$g(\psi) = \begin{cases} \frac{n^2}{\sin^2 \psi_c}, 0 \leq \psi \leq \psi_c \\ 0, \psi > \psi_c. \end{cases} \tag{5}$$

The order m is related to $\phi_{1/2}$ by

$$m = -\frac{\ln 2}{\ln \cos \phi_{1/2}}. \tag{6}$$

The optical noise power N_{op} at the optical receiver includes both shot noise and thermal noise, which are modeled as additive white Gaussian noise (AWGN) with a double-sided power spectral density. The expression of the noise variance is given by [8]-[10]

$$N_{op} = \delta^2_{shot} + \delta^2_{th}, \tag{7}$$

$$\delta^2_{shot} = 2qrP_aB + 2qrP_{bg}\Delta\lambda A I_2 B, \tag{8}$$

$$\delta^2_{th} = \frac{8\pi k T_A}{G}\eta A I_2 B^2 + \frac{16\pi^2 k T_A \Gamma}{g_m}\eta^2 A^2 I_3 B^3, \tag{9}$$

where δ^2_{shot} is the variance of the shot noise. The first term of (7) is the variance of the shot noise from signal and the second term of (7) is the variance of the ambient shot noise. δ^2_{th} is the variance of the thermal noise. P_a is the average received optical signal power. r is the optical-to-electrical (O/E) conversion efficiency. B is the desired bandwidth. The other parameters are defined in Table II.

TABLE II
SIMULATION PARAMETERS

Symbol	Quantity	Value
Noise-bandwith factor	$\Delta\lambda_{nb}$	$10\ (nm)$
Electron charge	q	$1.6 \times 10^{-19}(C)$
O/E conversion efficiency	r	0.35 (A/W)
Background irradiance per unit bandwidth	P_{bg}	$5.8(\mu W/cm^2 \cdot nm)$
Boltzmann's constant	k	$1.380662 \times 10^{-23}(J/K)$
Temperature	T_A	$300(K)$
Fixed capacitance of photodetector per unit area	η	$112(pF/cm^2)$
FET channel noise factor	Γ	1.5
FET transconductance	G_m	$30mS$
Noise bandwidth factor for white noise	I_2	0.562
Noise bandwidth factor for f_2 noise	I_3	0.868
Open-loop voltage gain	G	10

If P_{opt} is defined as the optical transmit power, the received electric signal power is given by

$$P_{ops} = (rP_{opt}H(0))^2. \tag{10}$$

The signal-to-noise ratio (SNR) of the optical system is

$$SNR_{OP} = \frac{P_{ops}}{N_{op}}. \tag{11}$$

In the proposed system, intensity modulation (IM) and ON-OFF keying (OOK) modulation is assumed. It is "ON" during a bit "one" and "OFF" during a bit "zero". The bit error rate (BER) of the system using OOK modulation is given by

$$BER_{OP} = Q\left(\sqrt{SNR_{OP}}\right), \tag{12}$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-y^2/2}dy \tag{13}$$

is the the Q-function which calculates the tail probability of the standard normal distribution.

B. Radio Channel

The RF channel is used to transmit CDMA information signal. Here we assume the RF signal is transmitting through a line-of-sight (LOS) channel and the transmit power of the transmitted signal is P_{RFt}. The received power of the RF signal can be expressed as

$$P_{RFs} = P_{RFt}\left(\frac{\sqrt{G_l}c/f_{RF}}{4\pi d_{RF}}\right)^2. \tag{14}$$

Here, $\sqrt{G_l}$ is a product of the transmit and receive antenna field radiation pattern, $c = 3.0 \times 10^8$ is the light speed. f_{RF} is the radio frequency, and d_{RF} is the distance between RF transmitter and receiver. On the other hand, we assume omni-directional transmit antennas and the RF carrier frequency is $f_{RF} = 2.4$ GHz. Then, the SNR of the radio channel is

$$SNR_{RF} = \frac{P_{RFS}}{B_{RF}kT_A}, \quad (15)$$

where $B_{RF}kT_A$ is the thermal noise power and B_{RF} is the channel bandwidth.

Each traffic light sends a different CDMA spreading code which can be used to decode the CDMA information related to its lane. Assume each RF transmitter sends information of K lanes for traffic lights. Then, The signal-to-interference-plus-noise ratio (SINR) of radio channel can be written as [11]

$$SINR_{RF} = (\frac{B_{RF}kT_A}{P_{RFs}} + \frac{K-1}{G_{RF}})^{-1}, \quad (16)$$

where G_{RF} is the processing gain.

In this paper, binary phase shift keying (BPSK) modulation is used and the BER of the radio system is [11]

$$BER_{RF} = Q\Big(\sqrt{2SINR_{RF}}\Big). \quad (17)$$

C. Performance of the Hybrid System and Pure VLC System

In this work, the optical channel is used to send lane ID and the radio channel is used to send the information signal. We define an error event as where the lane ID is incorrectly detected, or the frame error occurred when decoding the Traffic Information. Mathematically, the probability of such error event can be written as

$$P_{Error} = P_{IDE} + (1 - P_{IDE})P_{DATAE}, \quad (18)$$

$$P_{IDE} = 1 - (1 - BER_{OP})^{L_{ID}}, \quad (19)$$

$$P_{DATAE} = 1 - (1 - BER_{RF})^{L_{DATA}}, \quad (20)$$

where P_{IDE} is the probability of the detection error of the lane ID and P_{DATAE} is the probability of the detection error of the traffic information, L_{ID} is the number of information bit of the ID frame, and L_{DATA} is the number of information bit of the data frame.

For a conventional pure VLC system, the optical signal is used to transmit the data signal and no code signal is needed. The probability of detection error of the VLC system is

$$P'_{Error} = 1 - (1 - BER_{OP})^{L_{DATA}}. \quad (21)$$

D. Receivable Information

The amount of information received within a service area with can provide a reliable communication is expressed as

$$M_p = R_b L_{SA}/v, \quad (22)$$

where M_p is receivable information, R_b is transmission bit rate, v is the car speed, and L_{SA} is the length of service area.

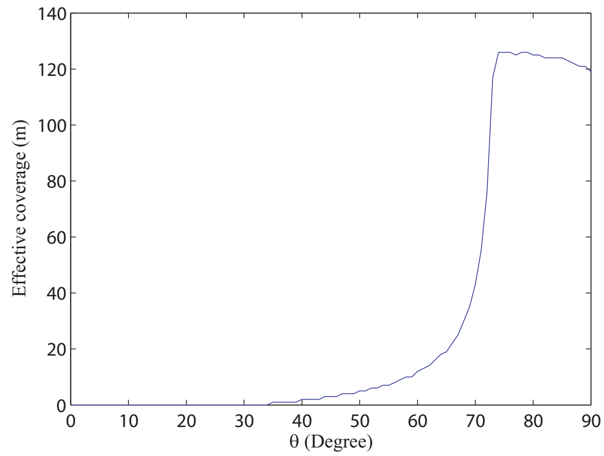

Fig. 5. The effective coverage with different values of θ (Desired SNR=13.6dB)

IV. Simulation Results

A. The Angle of Optical Receiver and SNR of VLC system

The optical channel scenario shown in Figure 4 is used for our simulation. For optical communication using OOK modulation, a minimum SNR of $13.6dB$ (or a BER of 10^{-6}) is required to maintain a reliable communication link. The range of an area which can guarantee a reliable communication link is defined as effective coverage. From Figure 4, it can be observed that the inclination angle of the receiver θ is an important parameter for the proposed system. The receiver is horizontal when $\theta = 0$ and vertical when $\theta = 90°$. Figure 5 shows the effective coverage area which can provide a communication link with a required SNR of $13.6dB$. It can be seen that when θ is smaller than 34°, the effective coverage area is almost zero. As θ increases, the effective coverage area increases first before it decrease again. It is because the optical receiver has a limited FOV. If θ is well chosen, the possibility that the optical signal is in the FOV of the receiver can be higher. Here, when θ is 74°, the effective coverage area reaches the maximum value.

The SNRs of the VLC system with different x and y are calculated when $\theta = 74°$. The result is shown in Figure 6. The SNR is very low when the vehicle is too close to the traffic light. The SNR first increases due to the increases of visibility and then decreases when the pass loss becomes the dominating factor. When $x = 14$ meters, the SNR reaches its maximum value.

B. Performance of Proposed Hybrid System and Pure VLC System

In the proposed system, VLC is used to transmit code signal and radio communication is used to transmit data signal. For a conventional pure VLC system, the optical signal is used to transmit the data signal and no code signal is needed. For a better understanding, we assume that one RF transmitter is set at the same place as one of the traffic lights, such as traffic light B in Figure 2. The RF receiver is assumed to be set at the same place of light receiver on the vehicle. The probability of error event P_{Error} and P'_{Error} (refer to (18) and (21)) are calculated. x (refer to Figure 4) is the horizontal distance of the transmitter to the receiver for both light channel and radio channel.

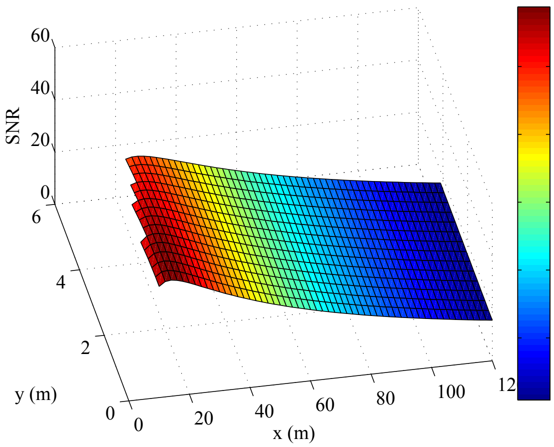

Fig. 6. SNR versus x and y ($\theta = 74°$)

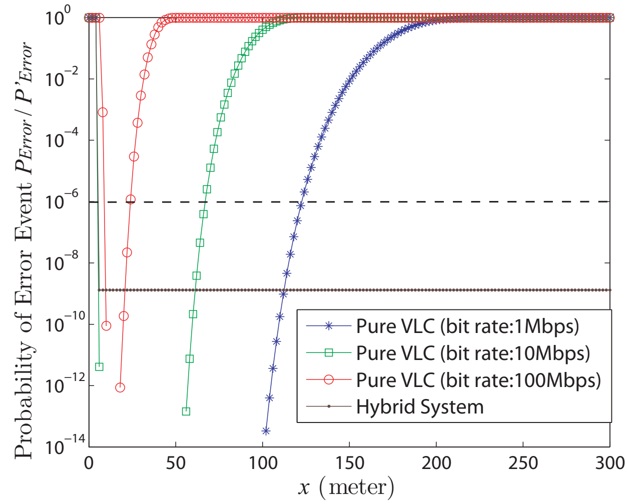

Fig. 7. Probability of error event of the proposed hybrid system and VLC system

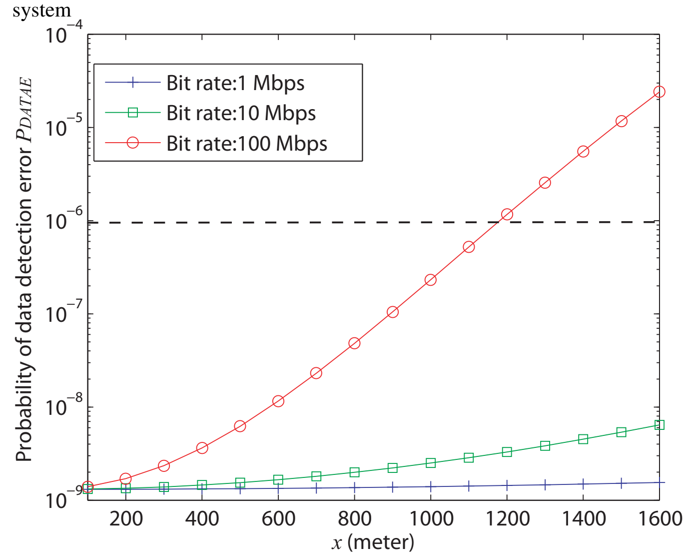

Fig. 8. Probability of data detection error of the radio channel for proposed hybrid system.

Figure 7 shows P'_{Error} of the pure VLC system and P_{Error} of the hybrid system with user number $K = 10$, $G_{RF} = 200$ (refer to (16)), $L_{DATA} = 100$ bits, $y = 0$. For the hybrid system, $L_{ID} = 10$ bits (refer to (19)); For the pure VLC system, code signal is not used. P'_{Error} is calculated for different bit rates: $1Mbps$, $10Mbps$, $100Mbps$; The bit rate of the hybrid system for optical channel and radio channel are assumed to be $100Kbps$ and $100Mbps$ respectively. If the received ID signal is from the same traffic light, we only need to decode the ID signal once. From this result, for the pure VLC system, each of 3 curves is broken at some small x, it is because smaller x results in smaller path loss of optical channel but bigger incidence angle Ψ. When the optical transmitter is out of the receiver's FOV, the light signal can not be received. It can be noticed that the effective coverage decreases with the bit rate. If the required probability of error in the proposed system is less than 10^{-6}, the effective coverage is 117 meters, 61 meters, and 15 meters when bit rate is 1 Mbps, 10 Mbps, 100 Mbps, respectively, for pure VLC system. The effective coverage is increased by using proposed hybrid system.

Figure 8 shows the probability of data detection error P_{DATAE} of the radio channel for proposed hybrid system. From this figure, we can see the effective coverage (P_{DATAE} is less than 10^{-6}) of radio system is larger than light system when using the same transmit power. For example, the effective coverage is around 1200 meters when the bit rate is 100 Mbps. In this radio effective coverage, the vehicle can always receive data signal.

C. Receivable Information

The receivable information, refer to (22), of a pure VLC system and the proposed hybrid system is calculated for the scenario shown in Figure 2. Assume the speed of vehicle is 60 km/h, the distance between two traffic lights located in the same lane is 300 meters (e.g. traffic light A and B). The receivable information from A to B is calculated for different bit rates, as shown in Figure 9. Assume that the vehicle can receive the CDMA spreading code from traffic light A, the CDMA spreading code can be used for decoding the data signal before the vehicle receives another CDMA spreading code from traffic light B. From A to B, the information can always be decoded. From this figure, it can be observed when the bit rate is more than $10kbps$, the proposed system can receive more information than a pure VLC system. It is worth mentioning that this result was calculated without considering any obstacles between the vehicle and traffic light. For the real situation, when the road is congested, the continuous transmission time by optical link may be very short. Once the optical link is broken, the information has to be transmitted again. Here, much less receivable information can be received by the pure VLC system. In the proposed system, the information is broadcasted utilizing radio channel and obviously, the receivable information will be increased.

V. Conclusion

This paper proposed a hybrid ITS system which improves the broadcasting downlink efficiency of current traffic broadcast system. The proposed system offers position based communication services with high bit rate by using both visible light and radio communication system. The light channel is used to send the CDMA spreading code and the radio channel is used to send the CDMA data signal. It resolves the limitation of pure VLC system in coverage, while maintaining its capability of position based communication. Simulation results showed that the effective communication area and the

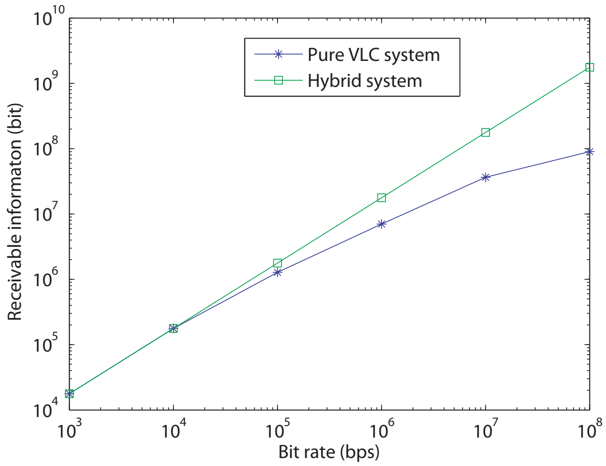

Fig. 9. Receivable information versus bit rate

receivable information can be increased by using the proposed system compared with a pure VLC system. The application of the proposed hybrid system is not limited to ITS, and will be further studied in the future.

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