Visible Light Communication System Based on Direct Sequence Spread Spectrum

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Abstract A direct sequence spread spectrum scheme for visible light communication system is proposed. The spread spectrum scheme is based on the Shannon theorem in information theory. Theoretical analysis result demonstrates that spread spectrum technology can mitigate the effect of multipath and improve the security in visible light communication system. The simulation results show that the performance of direct sequence spread spectrum based system is improved comparing with the directly detecting system without spread spectrum. Spread spectrum is a practical approach to improve the reliability of the visible light communication system.

Key words optical communications; visible light communication; spread spectrum; direct sequence spread spectrum

OCIS codes 060.4510; 060.2605; 200.3050

基于直接序列扩频的可见光通信系统

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摘要 提出了一种基于直接序列扩频的可见光通信系统，扩频通信的方法以香农信息论作为理论基础，对可见光通信系统中扩频通信理论进行了分析，理论分析结果表明扩频通信方法可以缓解可见光通信系统的多径损耗，并且提高可见光通信系统安全性。对基于直接序列扩频的可见光通信系统进行了仿真，仿真结果表明系统性能相比直接检测系统有一定提高，扩频通信技术对提高可见光通信系统可靠性具有实际的意义。

关键词 光通信；可见光通信；扩频；直接序列扩频

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1 Introduction

Over the past few years, visible light communication technology has attracted more and more attention. The visible light communication is a novel kind of optical wireless communication utilizing white LEDs, which has high-speed response[1-2]. Visible light communication is more advantageous than radio and infrared communications in terms of ubiquitousness and transmission at ultra high speed and harmlessness for human body and electronic devices[3]. So the visible light communication system will expect as indoor wireless communication of next generation and also draw much attention[4-5]. In indoor environment, the received signal arrives as an unpredictable set of reflections and/or direct lights which are with its own degree of attenuation and delay. This is the effect of multipath. Multipath results from the fact that the propagation channel consists of several obstacles and reflectors. Multipath causes interference of the received signal[6-9].

In this paper, a direct sequence spread spectrum (DSSS) scheme for visible light communication system is proposed. The principle of direct sequence spread spectrum is depicted. Theoretical analysis result illustrates that the multipath is suppressed by the spectrum dispreading. The simulation results show that the performance of direct sequence spread spectrum based system is improved comparing with the directly detecting system without spread spectrum. Consequently, direct sequence spread spectrum is an

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attractive approach to improve the reliability of the visible light communication system.

2 Spread spectrum principle

In information theory, the Shannon formula defines the theoretical maximum channel capacity is[10]

$$C = B\,\mathrm{lb}(1 + S/N),\tag{1}$$

where C is the channel capacity in bits per second, B is the bandwidth of the channel, S is the average received signal power over the bandwidth and N is the average noise or interference power over the bandwidth. S/N is the signal-to-noise ratio (SNR) of the communication signal to the Gaussian noise interference.

The Shannon theorem tells the maximum rate at which information can be transmitted over a communication channel of a specified bandwidth in the presence of noises. Based on the Shannon formula, it can be concluded that the increase of the channel bandwidth reduces the requirement of the SNR in the receiver when the channel capacity is constant. This is the theoretical basis of spread spectrum communication.

Visible light communication system is considered as a digital modulation communication system. In visible-light communication systems, non-return-to-zero (NRZ) on-off keying (OOK) modulation based on intensity modulation/direct detection (IM/DD) is a very suitable modulation owing to its simple implementation[11]. The transmitted digital information sequence is $\{b_m\}$, where $b_m \in \{0,1\}$, m is bit interval. This sequence is transmitted over a wireless channel and the received sequence is

$$r_m = Eb_m + w_m,\tag{2}$$

where E ($E > 0$) is the average energy of the pulse representing each bit and w_m is zero-mean additive white Gaussian noise (AWGN) sequence. The power spectral density of AWGN is $N_0/2$. The autocovariance of w_m is

$$E[w_m w_{m+l}] = \sigma^2\delta(l) = \frac{N_0}{2}E\delta(l),\tag{3}$$

where δ is unit impulse function, σ^2 is mean variance, l is delay. An optimal correlation receiver is employed. The receiver makes its decision based on a decision variable y_m, which is a certain function of the received signal r_m. It is assumed throughout that the information source produces 0 and 1 with equal probability. The simplest possible receiver is obtained, where $y_m = r_m$. Its statistics determine the performance of the receiver. From elementary detection theory, the average probability of bit error is

$$P_e = Q\left(\sqrt{\frac{E}{N_0}}\right) = Q\left(\frac{E}{\sqrt{2}\sigma}\right),\tag{4}$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty}\exp\left(-\frac{z^2}{2}\right)\mathrm{d}z.\tag{5}$$

It is easy to see that the performance of the system is determined by the ratio of E/σ.

In spread spectrum communication, instead of one pulse for each information bit, a sequence of N pulses is transmitted. N pulses are sent to represent the bit of information. The duration of the data bits is partitioned into N subintervals. Only one transmitted bit is considered. Thus the transmitted signal for the information bit is expressed as

$$s_n = E_c b c_n,\quad n = 0,\cdots,N-1\tag{6}$$

where $E_c = E/N$ is the average energy of one pulse, b is the information bit, $\{c_n\}$ is defined for all n and has the period of N. The autocorrelation is given by

$$\frac{1}{N}\sum_{n=0}^{N-1}c_n c_{n+i} \approx \begin{cases}1, & i = 0\\ 0, & 0 < i < N\end{cases}.\tag{7}$$

The received sequence is

$$r_n = E_c b c_n + w_n,\quad n = 0,\cdots,N-1.\tag{8}$$

In correlation receiver for the spread spectrum signal, the decision variable of the optimal correlation receiver is

$$y = \sum_{n=0}^{N-1}r_n c_n = \sum_{n=0}^{N-1}(E_c b c_n + w_n)c_n.\tag{9}$$

Substituting Eq. (7) into Eq. (9) and assuming $c_n = 1$, it is obtained that

$$y = NE_c b + \sum_{n=0}^{N-1}w_n c_n = Eb + w.\tag{10}$$

Again the performance is determined by E/σ. Comparing with the non-spread spectrum system, the performance is not improved in ideal AWGN channel. This is because the independent noise contributes the same power in the channel. The power of spread spectrum signal in the receiver comes from interference, multipath, or signals from other transmitters in the network employing spreading signals.

Considering a simple multipath channel, with a direct path with strength α and a reflected path arrived at a delay l with strength β, the received chips during the m bit interval are

$$r_n = \begin{cases}\alpha b_m c_n + \beta b_{m-1}c_{N-l+n}, \\ \quad n = 0,\cdots,l-1 \\ \alpha b_m c_n + \beta b_m c_{n-l}, \\ \quad n = l,\cdots,N-1\end{cases},\tag{11}$$

where $0 < l < N$, the delay is less than one bit duration. The decision variable is expressed as

$$y_m = N\alpha b_m + \beta b_{m-1}\sum_{n=0}^{l-1}c_{N-l+n}c_n + \beta b_m\sum_{n=l}^{N-1}c_{n-l}c_n + \sum_{n=0}^{N-1}w_n c_n.\tag{12}$$

According to Eq.(7), it becomes

$$y_m = N\alpha b_m + 0 + 0 + \sum_{n=0}^{N-1} w_n c_n. \qquad (13)$$

The multipath signal is suppressed by the dispreading. Hence spread spectrum technology can be used to mitigate the effect of multipath in visible light communication.

3 Simulation and results

Figure 1 presents the employed simulation architecture of visible light communication system with direct sequence spread spectrum. The transmitted digital information sequence is spreaded by the Pseudo noise (PN) code and the spread spectrum signal is generated. The Gold sequence generated by two m sequences is employed as PN code in the simulation system. It has random-like properties with low crosscorrelations and high autocorrelation. A LED with the wavelength of 450 nm is directly modulated by the spread spectrum signal. Then, the visible light signal is launched into the indoor channel. In the receiver, a PIN is used to convert the light signal to electric signal. The power of the received signal comes from interference, multipath and the noise. The received signal is de-spreading by the PN code which is the same as the PN code in the transmitter. The transmitted data are recovered after the low pass filter (LPF).

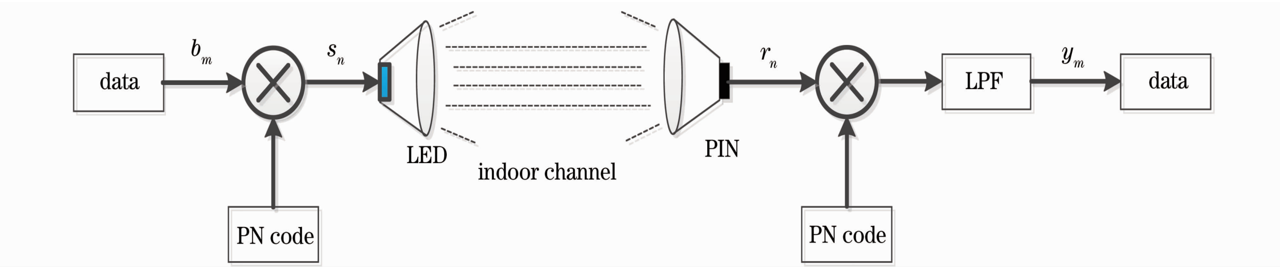

Fig.1 Simulation architecture of visible light communication system with DSSS

The indoor multipath channel model is shown in Fig.2. The dimensions of the room model are 5 m × 5 m × 3 m. The reflection type is mirror/specular and the reflection coefficent is 0.8. The number of maximum reflections is 3. The LED is a point Lambertian source and the number of the LED is one. The receiver is a PIN. The receiver area is 1 cm^2 and the field of view (FOV) is 85°. The photon tracing algorithm (PTA) is employed for calculation of impulse response of the channel[12].

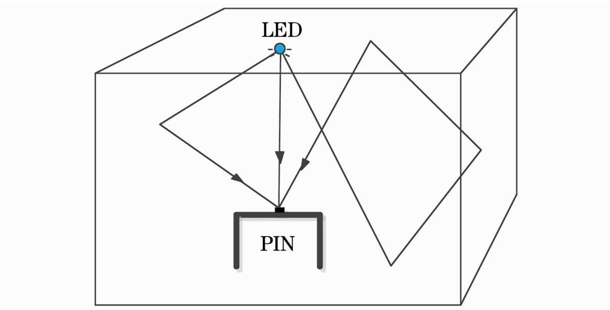

Fig.2 Indoor multipath channel model

The signal spectrum in the simulation system is shown in Fig.3. The red curve in Fig.3(a) denotes the spectrum of the transmitted signal. It is a narrow bandwidth signal. Fig.3(b) shows the spectrum of the spreading signal. The spectrum is much wider compared with the original transmitted signal. The power spectral density is extremely low. After propagating in the indoor channel, the signal in the receiver is composed of the spreading signal, the multipath interference signal and the AWGN signal. The spectrum of the received signal is shown in Fig. 3(c). The red curve is the spreading signal. The green curve denotes the multipath interference signal, and the blue curve is the AWGN signal. It can be seen that the spectrum of the multipath interference signal is similar with that of the spreading signal though its power spectral density is lower than that of the spreading signal. The power spectral densities of the spreading signal and the multipath interference signal are lower than that of the AWGN signal. The SNR of the received signal is negative. The spectrum of the de-spreading signal after LPF is shown in Fig. 3(d). The original transmitted signal is recovered and the multipath interference signal is suppressed.

Bit error ratio (BER, R_{BE}) performances of visible light communication system with spread spectrum are shown in Fig. 4. The results indicate that information bit can be correctly transmitted employed spread spectrum, although the transmitted signal is buried in the noise environment. This characteristic can be applied to secure visible light communication. As the decrease of the received SNR, the BER of the system will increase. BER performances can be affected by different spreading gains G. In the same BER condition, the SNR requirement of received signal is lower with the increase of the spreading gain.

In spread spectrum communication, the SNR is the ratio of the average energy of the spreading signal and the noise. The SNR of the information bit signal is not reduced comparing with the non-spread spectrum system. Though the performance is not considerately improved, the effect of multipath is mitigated.

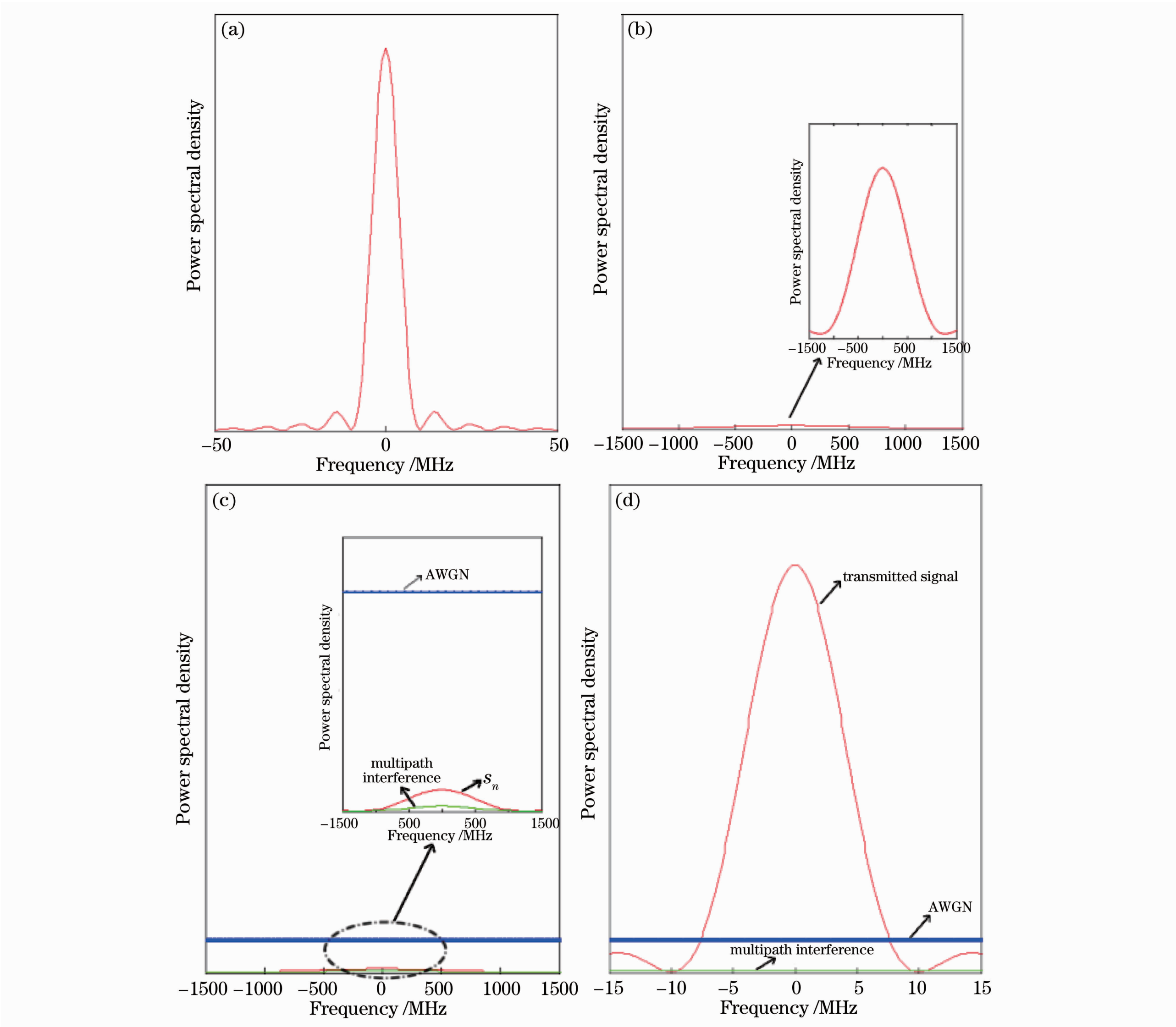

Fig. 3 Signal spectra in the simulation system. (a) Transmitted signal; (b) spreading signal; (c) received signal; (d) recovered signal

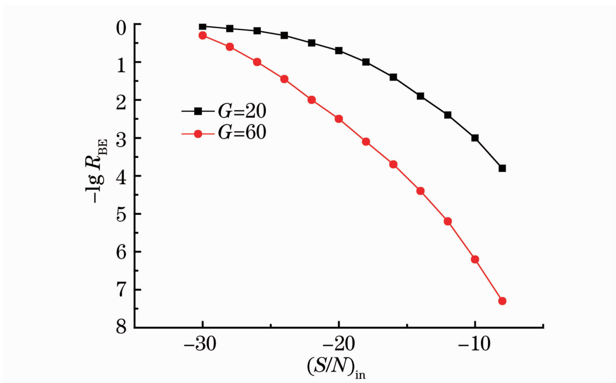

Fig. 4 BER performance of visible light communication system

4 Conclusion

A direct sequence spread spectrum scheme for visible light communication system is proposed. The spread spectrum communication is based on the Shannon theorem in information theory. When the channel capacity is constant, the increasing of the channel bandwidth reduces the requirement of the SNR in the receiver. Spread spectrum technology can mitigate the effect of multipath in visible light communication system. The information can be correctly transmitted under the condition of negative SNR. The security of the visible light communication system is improved. Spread spectrum is a practical approach to improve the reliability of the visible light communication system.

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