Optical OFDM spatial diversity system in lognormal fading UVLC channels

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Abstract: Underwater visible light communication (UVLC) is an attractive solution to achieve high-speed and large-data transmission but challenging due to the impairments induced by absorption, scattering and turbulence. To combat effects of multipath and fading for the UVLC system over turbulence channels, optical orthogonal frequency division multiplexing (O-OFDM) schemes with the transceiver spatial diversity were proposed, which employed equal gain combining (EGC) at the receiver side. Underwater path loss was calculated by a generalized Lambertian formula, and the fading induced by weak turbulence was modelled as a lognormal-distribution random variable. Based on the channel model and Monte Carlo (MC) simulation, the bit error ratio (BER) performance for quadrature-amplitude modulation (QAM) asymmetrically clipped optical OFDM (ACO-OFDM) and DC-biased optical OFDM (DCO-OFDM) systems in the channel with and without turbulence was evaluated. Furthermore, the diversity gain was estimated for different diversity orders and scintillation indexes. The results demonstrate that the diversity scheme with EGC is an effective measure to reduce the effect of turbulence and could be useful for designing, predicting, and evaluating the performance of O-OFDM UVLC system in a weak oceanic turbulence condition.

Key words: UVLC; fading; lognormal distribution; spatial diversity; OFDM

CLC number: TN929.1 **Document code:** A **DOI**: 10.3788/IRLA202049.0203008

对数正态分布衰落下的光 OFDM 水下可见光通信空间分集系统

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收稿日期:2019-10-11; **修订日期:**2019-11-21

基金项目:国家自然科学基金地区项目(61661016,61761014);广西重点研发计划项目(Guike AB18126030);广西无线宽带通信与信号处理重点实验室主任基金(CXKL06180101);桂林电子科技大学研究生出国(境)研修项目(GDYX2018002)

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摘 要: 水下可见光通信(UVLC)是实现高速宽带信息传输的有效方案,但由于受到信道中吸收、散射和湍流的不利影响而面临着许多困难。针对水下湍流信道中多径和衰落带来的影响,提出了一种光正交频分复用(O-OFDM)等增益合并的分集方案,根据广义的朗伯定律得到信道增益,通过对数正态分布模拟信号衰落。采用蒙特卡洛方法对正交幅度调制(QAM)的非对称削波光正交频分复用(ACO-OFDM)和直流偏置光正交频分复用(DCO-OFDM) 两种分集系统进行建模仿真,分析高斯信道和弱湍流信道下系统的误比特率,探讨不同分集数目和闪烁系数情况下的分集增益。研究结果验证了分集是降低湍流影响的有效手段,有利于改善水下信息传输性能,为弱湍流信道下正交频分复用可见光通信系统的设计、预测和评估提供参考。

关键词: 水下可见光通信; 衰落; 对数正态分布; 空间分集; 正交频分复用

0 Introduction

A large number of underwater applications ranging from environmental monitoring, resource exploration, data collection to port security and tactical surveillance have spurred continuous growth in underwater communication demand [1]. Wired systems can achieve stable and high-rate data transmission. However, it is costly, inflexible and difficult to maintain, thus limiting implementation in practice. Wireless communication is a preferable alternative in underwater communication. In general, acoustic communication is considered as a reliable solution for long-range underwater communication up to several kilometers with a low data rate of kilo-bits per second (Kbps). Complementing the acoustic communication, UVLC using the wavelength of 450-550 nm (i.e. blue/green spectral range) is an attractive alternative for high-speed short-range communication. The optical spectrum offers a large bandwidth compared to the acoustic frequency and a data rate in the range of Gbps is achievable. However, optical signals suffer absorption, scattering and turbulence in the underwater environment, which result in power loss, multipath propagation leading to inter-symbol interference (ISI) and turbulence-induced fading. In order to combat these degrading effects, UVLC system adopts channel coder [2], spectrally efficient modulation schemes such as orthogonal frequency division multiplexing (OFDM) [3], equalization schemes [4] and diversity/multiplexing technologies (e.g. cooperative diversity, multiple-input-multiple-output (MIMO) schemes [5-6]). The study shows that the selection of modulation scheme and MIMO is an effective method to reduce the effect of turbulence-induced fading. Though O-OFDM has been applied for high-speed UVLC, to the best knowledge of authors, there is no prior work to evaluate the performance of O-OFDM spatial diversity scheme in turbulence-induced fading channel. Hence, in this paper, we propose a UVLC O-OFDM with diversity scheme to mitigate the turbulence effect in weak oceanic turbulence. The UVLC oceanic channel is modelled as a lognormal distribution and the BER performance of the O-OFDM is evaluated for various diversity orders and turbulence strengths. The popular O-OFDM schemes namely ACO-OFDM and DCO-OFDM system are considered. The study shows that the diversity scheme is effective in mitigating the turbulence effect.

1 UVLC system description

1.1 O-OFDM with spatial diversity

We consider an $M\times N$ MIMO-OFDM system with M transmitters and N receivers as shown in Fig.1. OFDM has been extensively utilized in optical communication systems as a special subcarrier modulation because of its resistance to ISI and high spectral efficiency compared to baseband modulation such as On-Off Keying (OOK). The traditional OFDM, however, cannot be directly applied to intensity modulation/ direct detection (IM/DD) optical communication as IM/DD system requires a real-value and positive signal. The traditional OFDM is modified to output real and non-negative signal, thus making it suitable for IM/DD optical systems. DCO-OFDM and ACO-OFDM are the popular variations of OFDM that have been adopted in this paper. Detail of these modulation schemes are given in Ref.[7] and hence not repeated here.

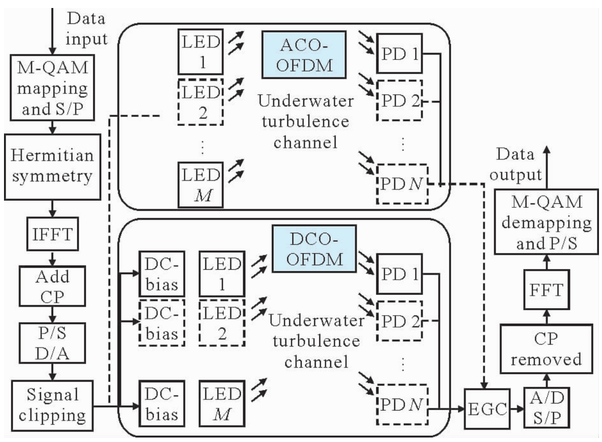

Fig.1 Block diagram of MIMO ACO and DCO-OFDM schemes for UVLC

The block diagram of the proposed system is shown in Fig.1. The input bit streams are first mapped to quadrature amplitude modulation (QAM) constellations followed by a serial to parallel (S/P) converter. To generate a real signal, Hermitian symmetry is imposed before the inverse fast Fourier transform (IFFT) operation, which is at the cost of half of the spectral efficiency. A cyclic prefix (CP) is added to eliminate both ISI and inter-carrier interference (ICI). The OFDM symbols are then serialized using parallel-to-serial (P/S), followed by conversion to analog signals using a digital-to-analog converter (DAC) and a filter[8-9]. The real signal is further converted to unipolar signal to drive a linear optical modulator by clipping or combination of clipping and DC-bias addition.

In DCO-OFDM, the output of the IFFT is hard-clipped and a DC-bias is applied. The DC-bias I_{DC} is given as[7,10]:

$$I_{DC}=g\sqrt{E_S} \tag{1}$$

where g is the normalized bias and E_S is the energy per symbol. The signal is clipped at a bottom level of $-I_{DC}$. Generally, $10\log(g^2+1)$ is defined as a bias level in dB[7].

In ACO-OFDM, the signal is clipped at zero level without DC-bias. It assigns QAM symbols only to odd subcarriers and sets zeros on even subcarriers. So, the noise from asymmetrical clipping below the zero level only falls into even subcarriers, and odd subcarriers are not impaired. In ACO-OFDM, although there is no need for a DC-bias, the scheme only achieves half of the spectral efficiency of DCO-OFDM for the same QAM constellation level[11].

At the transmitters with spatial diversity, the repetition coding (RC) is used i.e. all the transmitters send the same signal. It is assumed that the power per transmitter is P_S/M so that the total transmitted optical power is a constant P_S irrespective of M. Similarly, the receiver aperture for the diversity scheme is D/N, so that total collection area is D irrespective of N. The output photocurrents at the receiver are then linearly summed using equal gain combining (EGC), followed by OFDM decoding process. We followed the standard OFDM decoding for both ACO and DCO-OFDM as detailed in Ref.[8]. The received instantaneous electrical signal for ECG can be expressed as[12]:

$$y(t)=\frac{\eta kDP_S}{MN}x(t)\sum_{m=1}^{M}\sum_{n=1}^{N}\alpha_{mn}h_{mn}+n(t) \tag{2}$$

where η denotes the photodiode (PD) responsivity, k is the modulation index, $x(t)$ represents the OFDM signal, $|kx(t)|\leqslant 1$, α_{mn} and h_{mn} respectively represent the fading coefficient and channel path loss (or DC gain) from the m^{th} transmitter to the n^{th} receiver and $n(t)$ is the additive white Gaussian noise (AWGN) signal. Using EGC, the electrical signal-to-noise ratio (SNR) γ_{EGC} can be derived as:

$$\gamma_{EGC}=\left(\frac{\eta kDP_S}{MN}\right)^2\frac{E[x^2(t)]}{\sigma^2}\left(\sum_{m=1}^{M}\sum_{n=1}^{N}\alpha_{mn}h_{mn}\right)^2 \tag{3}$$

where $E[\cdot]$ stands for the expectation operator and σ^2 is the total AWGN variance.

1.2 UVLC channel

The UVLC channel is characterized by the path loss and turbulence-induced fading coefficient. For a generalized Lambertian source, the path loss h_{mn} from the m^{th} transmitter to the n^{th} receiver is given as[13]:

$$h_{mn}=\begin{cases}\dfrac{(m_l+1)A_{PD}\cos^{m_l}(\phi)\cos(\varphi)\mathrm{e}^{-c(\lambda)d}}{2\pi d^2} & 0\leqslant\varphi\leqslant\dfrac{FOV}{2}\\ 0 & \varphi\geqslant\dfrac{FOV}{2}\end{cases} \tag{4}$$

where $m_l=\ln(2)/\ln(\cos(\theta_{1/2}))$ is the order of Lambertian emission with the half-power angle $\theta_{1/2}$ of the LED, A_{PD} is the detector area, ϕ is the irradiance angle, φ is the incidence angle, FOV is the field of view of the receiver, d is the distance between transmitter and receiver and $c(\lambda)$ is the extinction coefficient at the optical wavelength λ.

The fading introduced by the random fluctuation of salinity, density and temperature of water follows the lognormal distribution for weak turbulence and is given as[14-15]:

$$f(\alpha)=\frac{1}{2\alpha\sqrt{2\pi\sigma_\rho^2}}\exp\left(-\frac{(\ln(\alpha)-2\mu_\rho)^2}{8\sigma_\rho^2}\right) \tag{5}$$

where μ_ρ and σ_ρ^2 denote the mean and variance of the Gaussian-distributed variable ρ, respectively, α is the fading coefficient, and $\rho=0.5\ln(\alpha)$ is known as the fading log-amplitude. In order to ensure no energy loss or gain during the turbulence-induced fading process, the fading amplitude is normalized, i.e. $E[\alpha]=1$, leading to:

$$\sigma_I^2=\frac{E[I^2]-E^2[I]}{E^2[I]}=\frac{E[\alpha^2]-E^2[\alpha]}{E^2[\alpha]} \tag{6}$$

In order to take int o account turbulence effects, the channel impulse response is multiplied by a multiplicative fading coefficient $\alpha=\exp(2\rho)$[14].

Under the turbulence effect, the average BER P_{MIMO} can be obtained by[12]:

$$P_{MIMO}=\int_\alpha P_e(\gamma_{EGC})f_\alpha(\alpha)\mathrm{d}\alpha \tag{7}$$

where $P_e(\gamma_{EGC})$ is the conditional error probability of the received electrical signal-to-noise ratio (SNR), $\alpha=\{\alpha_{mn}, n=1, \cdots, N, m=1, \cdots, M\}$ is the fading matrix and $f_\alpha(\alpha)$ is the joint probability density function. So, Eq.(7) is an MN-dimensional integration and a closed-form expression is difficult to obtain. Hence, to calculate the average BER, analytical simplification of Eq.(7) by some approximations or MC simulations is used. In this paper, we employ the MC method to analyze the BER performance of the OFDM system in the lognormal fading channel.

2 Results and discussion

We con sider a short-range UVLC system in the clear ocean with an extinction coefficient of 0.150 m^{-1} [16]. The transmitter is with a half-power angle of 10° (half) and receiver has an optical system with FOV of 30° and the aperture of 10 cm in radius. The transmitter/receiver separation is 30 cm and the communication range is 6 m. The channel matrixes for different diversity orders are obtained using Eq.(4). Using these parameters, we simulated the performance of ACO and DCO-OFDM in the UVLC turbulence channel assuming a quasi-static block fading channel i.e. the fading coefficient is unchanged over an OFDM symbol duration[17].

Figure 2 presents the BER against electrical energy-per-bit to single-sided noise power spectral density E_b/N_0 of 4-QAM and 16-QAM single-input-single-output (SISO) scheme for ACO and DCO-OFDM systems without turbulence. We employ a bias level of 7 dB for the DCO-OFDM system to be consistent with the literature [11]. As expected, to obtain an identical BER, ACO-OFDM scheme requires lower E_b/N_0 than DCO-OFDM. For the higher constellation size, the E_b/N_0 requirements are also increased. Also, the BER performance of 16-QAM ACO-OFDM is very close to that of 4-QAM DCO-OFDM. It should be noted that the spectral efficiency of 16-QAM ACO-OFDM is same as that of 4-QAM DCO-OFDM but the required E_b/N_0 levels are not necessarily identical due to the chosen bias level.

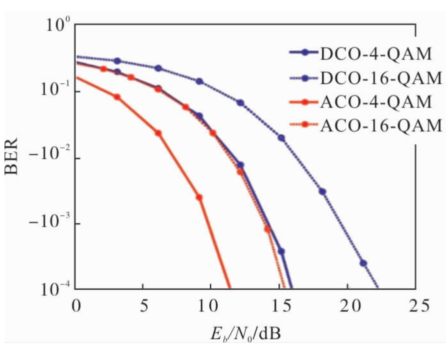

Fig.2 BER of OFDM SISO scheme in an AWGN channel without turbulence, ACO-OFDM vs. DCO-OFDM, 4-QAM vs. 16-QAM

We also evaluate the BER performance of optical OFDM in a turbulence channel, as shown in Fig.3. Compared to that of the AWGN channel, at the BER of 10^{-4}, power penalties of 8.3 dB and 8.1 dB are observed for 4-QAM-ACO-OFDM and 4-QAM-DCO-OFDM schemes, respectively, at σ_I^2=0.2. In addition, spatial diversity can be used due to its obvious effect on turbulence mitigation. As the constellation size increases, the system is more sensitive to clipping noise and turbulence. Hence, for the 16-QAM, the BER of the SISO optical OFDM system is poor and plateaus with the increasing E_b/N_0. Hence, increasing the

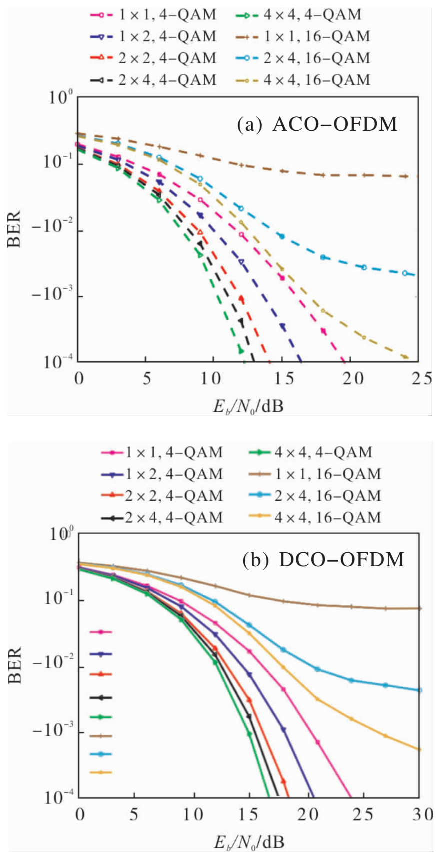

Fig.3 BER for the optical OFDM 4-QAM and 16-QAM constellations in a turbulence channel with σ_I^2=0.2

transmitted power can't combat the turbulence effect in SISO optical OFDM 16-QAM system. The BER performance improves with diversity order but even the spatial diversity of 2×4 has a BER floor of 10^{-2}. For the spatial diversity of 4×4, the BER less than the FEC limit of 3.8×10^{-3} is achieved at a relatively high E_b/N_0. This suggests that the diversity on its own is not sufficient to mitigate the turbulence effect for higher constellation size. The performance can be further improved using error correction coding and equalization in combination with spatial diversity.

Furthermore, EGC diversity gain of optical OFDM 4-QAM constellation is given in Fig. 4 for different diversity orders and scintillation indexes. Note that the diversity gain is the difference in E_b/N_0 (dB) required to achieve a BER of 10^{-4} for the systems with and without diversity. From Fig.3, we can observe that the EGC diversity gains are almost same for the ACO-OFDM and DCO-OFDM. Figure 4 illustrates that the diversity gain increases with the increased turbulence strength, and the gain slope becomes flat as the diversity order increases. In a weak turbulence channel, a low-order spatial diversity is enough to compensate for the turbulence effect, because high-order spatial diversity will not give any extra diversity gain. For example, in the turbulence channel with σ_I^2=0.1, the diversity order of 4 is adequate.

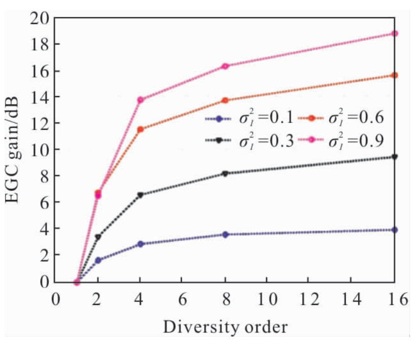

Fig.4 EGC diversity gain in a log-normal oceanic turbulence channel against the diversity order at BER=10^{-4} for 4-QAM O-OFDM

3 Conclusion

In this paper, we have studied the performance of spatial diversity UVLC system with equal gain combining for O-OFDM scheme. The path loss and fading of the weak oceanic turbulence channel is calculated by a generalized Lambertian formula and modelled as a multiplicative lognormal-distribution random variable, respectively. We employed Monte Carlo simulations to evaluate the BER performance of 4 & 16-QAM ACO-OFDM and DCO-OFDM for various SNR values in the channel with and without turbulence. It was observed that the turbulence significantly impairs the BER performance and a power penalty of ~8 dB is incurred at the BER of 10^{-4} for 4-QAM-O-OFDM without diversity at a scintillation index of 0.2. Higher order modulation shows further power penalty. It is verified that spatial diversity can effectively mitigate turbulence, however increasing diversity order saturates diversity gain. The diversity order of 4 is adequate for a scintillation index of 0.1 while a diversity order of 8 is required for the scintillation index of 0.3. Thus, spatial diversity order should increase with increasing turbulence strength and constellation size. The analysis and results provide a basis for the design and evaluation of the IM/DD O-OFDM UVLC system over weak turbulence channels.

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