The Channel Impulse Response of SIMO Optical Wireless Communication based on Monte Carlo Simulation

Behnaz Majlesein[1], Asghar Gholami[1], Zabih Ghassemlooy[2]

[1] Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran

[2] OCRG, Mathematics, Physical and Electrical Engineering Department, Northumbria University, Newcastle upon Tyne, UK

Emails: b.majlesein@ec.iut.ac.ir; gholami@cc.iut.ac.ir; z.ghassemlooy@northumbria.ac.uk

***Abstract*— In underwater optical wireless communications (UOWC) the channel impulse response is essential in characterizing the link. In this paper we investigate the impulse response of the single input multiple output UOWC link using Monte Carlo simulation for different types of waters. We simulate the bit error rate (BER) performance for the proposed intensity modulation direct detection SIMO UOWC links for multiple receivers with a linear combining scheme by considering absorption, scattering, turbulence and all major noise sources. We show that, the clear, coastal and harbor waters display the best to the worth BER performance, respectively.**

Keywords—Underwater optical wireless communications (UOWC), impulse response, single-input multi-output, scattering, turbulence

I. Introduction

More than 66% of the earth surface is covered with water, which has been used for communications in a range of applications including submarines, pollution monitoring, off-shore oil industry, disaster detection and early warning, etc. In contrast to the terrestrial wireless radio frequency (RF) communications, the transmission medium in underwater communications is severally affected by a number factors including (*i*) marine environment – shallow coastal water to deep see or oceans; (*ii*) noise and ambient conditions; and (*iii*) limited bandwidth and power resources. These lead to severe attenuation, multipath and frequency induced dispersion, Doppler spread, etc. The dominant communications schemes used in under water have been based on the wireless technologies of RF, acoustic (sonar) and optical. The RF and acoustic waves suffer from high attenuations (3.5-5 dB/m and 0.1-4 dB/m for RF and acoustic, respectively) medium to low transmission data rates (Mbps and tens of kbps over short distances, respectively) as well as high latencies (in the order of second). Whereas, the underwater optical communications (UOWC) offers very high transmission data rates (i.e., > 200 Mbps over a transmission range of up to 100 m), low attenuation (at the blue-green 450-580 nm transmission window), low latency and enhanced security, which has become very attractive in recent years. However, UOWC link performance are affected by temperature fluctuations, scattering, dispersion and beam steering [2].

In previous studies it has shown that, absorption and scattering of the light beam will result in the energy loss and changes in the direction of photons [1]. The light scattering effect, which is shown using the impulse response (IR), illustrate the temporal behavior of UOWC and the main effect limiting the data rate [3]. The effect of scattering in the turbid seawater, which leads to inter symbol interference (ISI), degrades the system performance (i.e., the bit error rate (BER) and the needed channel bandwidth) [4]. As for the IR, a number of models have been reported for UOWC links. In [4], a line-of-sight (LOS) UOWC channel model was proposed in order to reduce the scattering effect by means of optimizing the aperture diameter and the FOV. In [5], a channel model based on Monte Carlo and Henyey-Greenstein (HG) for non-line-of-sight (NLOS) UOWC was proposed. A two-term HG model using a channel simulator for modeling of angle scattering was proposed, which was more accurate than HG model [6]. Also simulated was the IR for a single input and single output (SISO) UOWC link based on Monte Carlo for different water types and transmission link distances [6]. Tang considered a double gamma functions to model the channel IR, which fitted well with Monte Carlo simulation for coastal and harbor sea waters. The authors also designed a zero-forcing (ZF) equalization to overcome the ISI and improve the system performance [7]. In [8], the IR of the multiple input and single output (MISO) UOWC link based a weighted symmetric Gamma polynomial and adopting Monte Carlo simulation as well as a uniform circular array light sources was reported.

In order to combat the effects of atmospheric turbulence in optical wireless communications (in this case free space optics) space diversity techniques with multiple apertures at the transmitter (Tx) and/or at the receiver (Rx) can be effectively utilised to combat attenuation, but not phase distortion experienced by the propagating photons (i.e., optical beam front) as reported in [9], [10]. In [3], a multiple and input multiple output (MIMO) UOWC system using a weighted Gamma function polynomial to model the IR and considering the effects of absorption, non-scattering, single and multiple scattering was reported. In [11], based on the statistical simulation method the BER performance of SIMO UOWC using a light emitting diode (LED) and multiple detectors to mitigate deep fading was investigated. However, the authors did not consider the IR and all important noise sources (including the background light induced shot noise) for the proposed system.

However, to the best of authors' knowledge, no works have been reported on the IR based on Monte Carlo approach and on the BER performance of the SIMO UOWC link by considering all important noise sources. Note that, making an optical lens with an extremely large aperture size is challenging. Therefore, in this paper we consider the IR of intensity modulation/direct detection (IM-DD) SIMO UOWC system by using a combination of aperture averaging, spatial diversity and a linear combining schemes based on Monte Carlo for various types of waters, detectors' positions and link spans. To evaluate the link performance, the BER of the system considering absorption, scattering, turbulence and all noise sources is calculated.

The rest of this paper is organized as follows. In section II the system model for SIMO UOWC is presented, in section III simulation and numerical results are given and in section IV we conclude the paper.

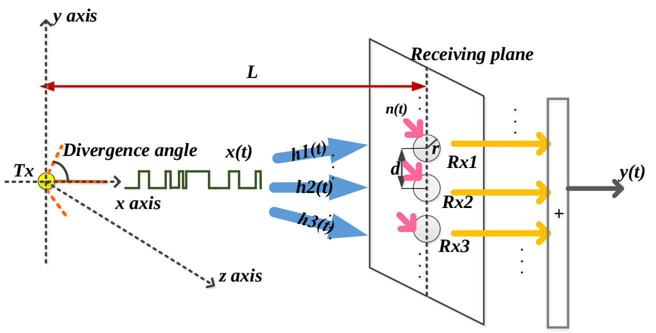


Fig. 1. System model

II. System Model

As shown in Fig. 1 we consider the IR of SIMO UOWC SIMO link, where each M^{th} free space link is equivalent to a SISO link. In Fig. 1, a light source as the Tx is centered at the x-axis and M photodetectors (PDs) are wrapped in linear arrays with d distance between each Rx and located on a plan at L distance from the center. The system is composed a single light source at a wavelength of 517 nm and a divergence angle of 0.5 radian as the Tx and M detectors of similar apertures size and field of views (FOVs) at the Rx. Considering the location of each PD, the IR is determined by means of Monte Carlo. In Monte Carlo approach N photons are transmitted simultaneously through 3 types of waters and each emitted photons are assigned with four basic features such as photon's positions, propagation time, transmission direction and the weight, which is also known as the intensity. Photons interacting with particles in the water will experience a change of direction and loss due to both scattering and absorption. At the Rx side a photon can be detected when its position and the arrival angle are within the Rx's aperture and FOV and its weight is higher than threshold level [12]. For the proposed link, the total IR can be computed as:

$$h_{total} = \sum_{N=1}^{M} h_1 + h_2 + \cdots + h_N \qquad (1)$$

where h_N is the channel IR from the Tx to the N^{th} Rx, N =1, 2…, M. Each IR is the temporal behavior of the SIMO UOWC link between a Tx and each Rx. In this work, the fading behavior of the free space channel is characterized using log-normal distribution for the line of sight propagation link. The strength of turbulence is best represented by the index-of-refraction structure parameterC_n^2, which its value ranges from 10^{-14} to $10^{-8}\ m^{-2/3}$ for underwater conditions as in [13].

The regenerated electrical signal at the M^{th} optical Rx, which is composed of a PIN photodetector and a transimpedance amplifier, is given as:

$$y_M(t) = x(t) \otimes h_M(t) + n_M(t) \qquad (2)$$

where $x(t)$ is the intensity modulated transmitted optical signal carrying the information data $a \in \{0, 1\}$, $h_M(t)$ is the channel transfer function between the Tx and the M^{th} Rx, $n_M(t)$ is the additive white Gaussian noise (AWGN) (i.e., representing background, dark current, thermal and signal shot noise sources) with zero mean and variance of $N_0/2$ (where N_0 is the noise spectral density) and $\otimes$ represents the convolution operation. Note, we have used a non-return to zero (NRZ) on off key (OOK) signal for IM of the light source (in this case a laser). Note that, we have used the system model given in [11], where all considered noise sources are described in detail. In this work, we consider the link performance under weak turbulence, which is modelled as lognormal distribution [14], [15].

The total received signal is given by:

$$y(t) = y_1(t) + y_2(t) + \cdots + y_M(t) \qquad (3)$$

III. Simulation Results

All the key system parameters adopted in the simulation of the proposed scheme are given in Table I, which are adopted from the current literature. Monte Carlo approach is used to determine the IR of the system. The simulation procedure is best explained with reference to the flow chart depicted in Fig. 2. Here we consider 1×3 and 1×5 configurations based on Fig. 1. Fig. 3 shows the IR for clear, costal and harbor waters for 1, 3 and 5 Rxs, respectively. As expected the clear water shows the best IR over a longer transmission range followed by the coastal water. Whereas, in the rich turbid environments such as the harbor water with a higher level of scattering the normalized power level is much lower than coastal and clear waters with higher levels of fluctuations. The IR for higher number of Rxs is improved due to increased number of captured scattered photons. Note that, for the IR the power is normalized to the transmit power.

Figs. 4 shows the BER performance as a function of the transmit power for three types of waters for M = 1, 3 and 5. From Fig. 3 we observe the followings: (i) links with higher number of Rxs (i.e., M = 5 in this case) offer the best BER performance for all three cases due to being able to capture higher number of photons and combating multipath (scattering) induced channel fading; (ii) the clear water displays the best performance over longer transmission spans; and (iii) the harbor water shows the worst case scenario with a higher power level requirement compared to Figs. (a) and (b). For example, at a BER of 10^{-3} which is below the forward error correction limit of 3.8×10^{-3}, the power penalties are 0.5 and 4 dBm for coastal and harbor waters, respectively compared to the clear water for M = 5. For the clear water the additional transmit power required for 3 and 1 Rxs are 0.3 dBm and 1.5 dBm, respectively compared to the 5 Rxs, whereas for the harbor water the additional power requirements are marginally higher by 0.8 and 2.5 dBm for 3 and 1 Rxs, respectively compared to 5 Rxs.

Table I- System parameters

Parameter	**Value**
Laser wavelength (λ)	517 nm
Laser beam divergence	0.5 rad
Data rate	100 Mbps
Low pass filter bandwidth (*B*)	$Data\ rate/_2$ =50 MHz
Photodetector responsivity	0.34 A/W
ATransimpedance amplifier gain	10 dB
$C_n{}^2$	$10^{-13}\ m^{-2}/_3$
Attenuation coefficient for harbor	$2.19\ m^{-1}$
Attenuation coefficient for coastal	$0.398\ m^{-1}$
Attenuation coefficient for clear	$0.151\ m^{-1}$
Albedo ($w_0 = \frac{b}{c}$, $b =$ scattering coefficient) for harbor	0.83
Albedo for coastal	0.55
Albedo for clear	0.245
The spacing between Rxs *(d)*	2 m
Rx's FOV	100°
Radius size of aperture (*r*)	0.2 m

Table II- The BER values for SIMO links for three types of water and a range transmission spans for a transmit power of 28.45dBm

Water type	**Distance (m)**	**BER for 3-Rx**	**BER for 5-Rx**
Clear	23	3.94×10^{-7}	7.15×10^{-8}
Coastal	15	2.41×10^{-5}	3.38×10^{-6}
Harbor	10	0.040373425	0.005191226

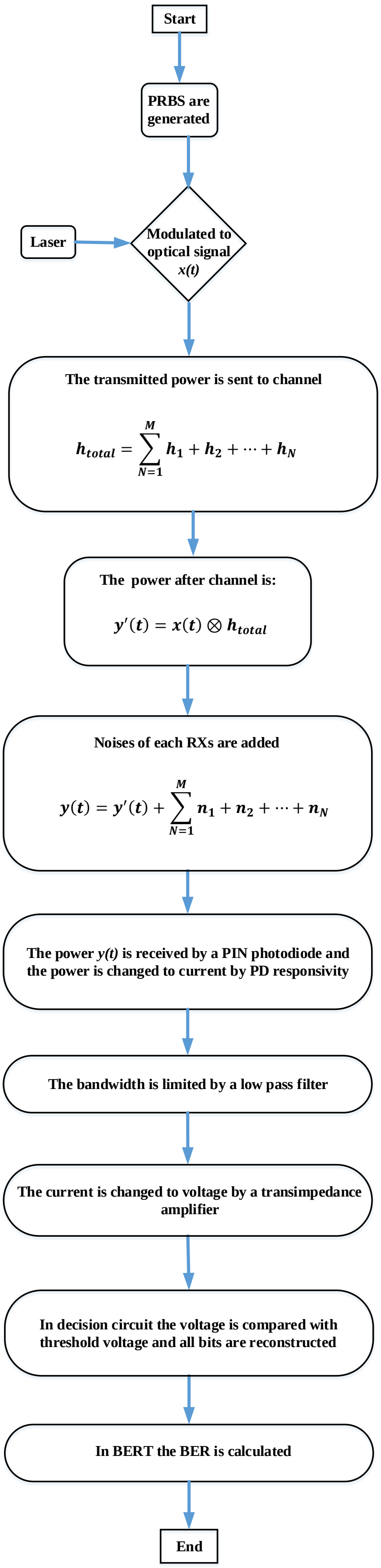
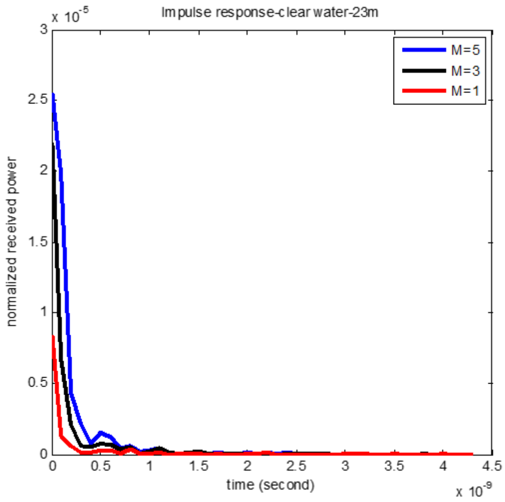
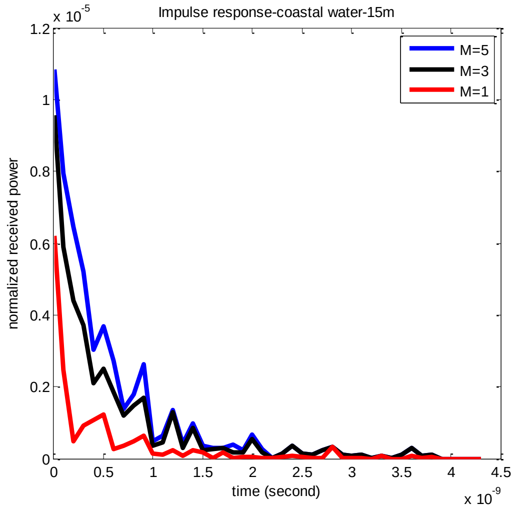


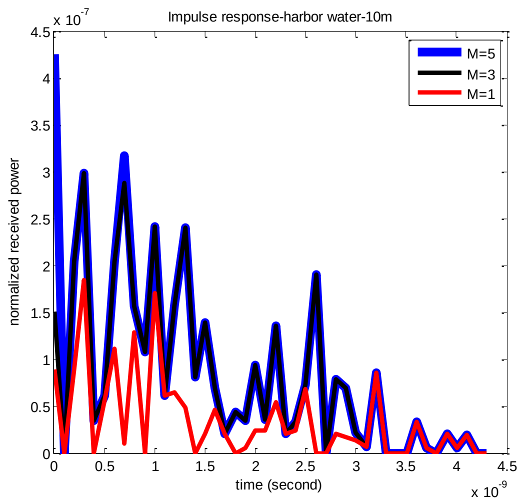
Fig. 2: The flow chart of the proposed model.



(a)

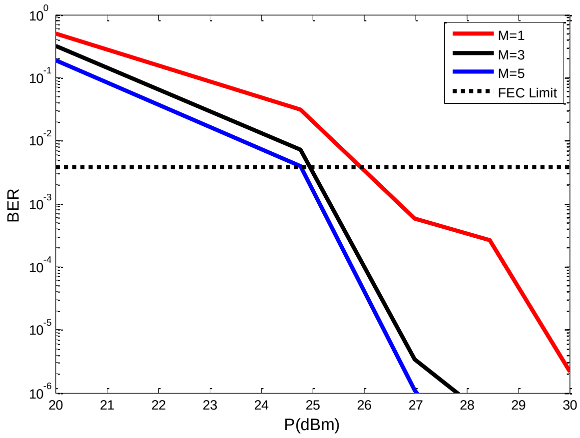


(b)

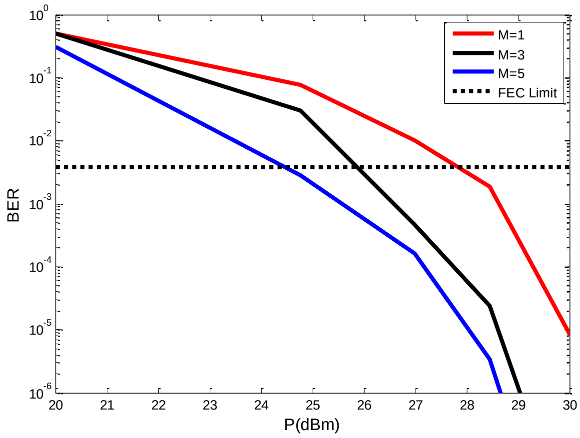


(c)

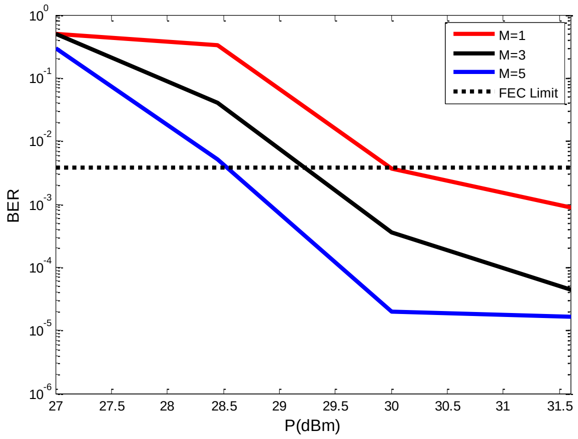
Fig. 3: The impulse responses for SIMO for: (a) clear water with L = 23 m, (b) coastal water with L = 15 m, and (c) harbor water with L=10 m.



(a)



(b)



(c)

Fig. 4: The BER performance against the transmission span for SIMO for: (a) for clear water with L=23, (b) coastal water with L = 15, and (c) harbor water with L = 10.

IV. CONCLUSIONS

In this paper, we presented the impulse response for UOWC SIMO link with receiver diversity for 3 types of water based on Monte Carlo simulation. In the simulation of the impulse response and the BER performance for the proposed link for clear, coastal and harbor waters considered absorption, scattering, turbulence, and all the key noise sources. We showed that, for the UOWC SIMO link with 5 receivers the BER performance is enhanced compared with 3 and 1 receivers due to capturing more scattered photons. The clear water of coursed offered the best performance since the propagating optical beam experience lower levels of channel fading compared with the coastal and harbor waters.

REFRENCES

[1] Z. Zeng, S. Fu, H. Zhang, Y. Dong, and J. Cheng, "A survey of underwater optical wireless communications," IEEE Communications Surveys & Tutorials, vol. 19, pp. 204-238, 2017.

[2] H. Kaushal and G. Kaddoum, "Underwater optical wireless communication," IEEE access, vol. 4, pp. 1518-1547, 2016.

[3] H. Zhang and Y. Dong, "Impulse response modeling for general underwater wireless optical MIMO links," IEEE Communications Magazine, vol. 54, pp. 56-61, 2016.

[4] R. Qadar, M. K. Kasi, and F. A. Kakar, "Monte Carlo based estimation and performance evaluation of temporal channel behavior of UWOC under multiple scattering," in OCEANS 2017-Anchorage, 2017, pp. 1-7.

[5] V. Jagadeesh, A. Choudhary, F. M. Bui, and P. Muthuchidambaranathan, "Characterization of channel impulse responses for nlos underwater wireless optical communications," in 2014 Fourth International Conference on Advances in Computing and Communications, 2014, pp. 77-79.

[6] C. Gabriel, M.-A. Khalighi, S. Bourennane, P. Léon, and V. Rigaud, "Monte-Carlo-based channel characterization for underwater optical communication systems," Journal of Optical Communications and Networking, vol. 5, pp. 1-12, 2013.

[7] S. Tang, X. Zhang, and Y. Dong, "On impulse response for underwater wireless optical links," in 2013 MTS/IEEE OCEANS-Bergen, 2013, pp. 1-4.

[8] Y. Dong, J. Liu, and S. Qian, "On impulse response of underwater optical wireless MISO links with a UCA of sources," in OCEANS 2016-Shanghai, 2016, pp. 1-4.

[9] M. R. Bhatnagar and Z. Ghassemlooy, "Performance analysis of gamma–gamma fading FSO MIMO links with pointing errors," Journal of Lightwave technology, vol. 34, pp. 2158-2169, 2016.

[10] M. Uysal, C. Capsoni, Z. Ghassemlooy, A. Boucouvalas, and E. Udvary, Optical wireless communications: an emerging technology: Springer, 2016.

[11] W. Liu, Z. Xu, and L. Yang, "SIMO detection schemes for underwater optical wireless communication under turbulence," Photonics Research, vol. 3, pp. 48-53, 2015.

[12] W. Cox. (2012). *Photonator*. [Online]. Available: https://github.com/gallamine/Photonator

[13] B. Majlesein, A. Gholami, and Z. Ghassemlooy, "A Complete Model for Underwater Optical Wireless Communications System," in 2018 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP), 2018, pp. 1-5.

[14] F. S. Vetelino, C. Young, L. Andrews, and J. Recolons, "Aperture averaging effects on the probability density of irradiance fluctuations in moderate-to-strong turbulence," Applied Optics, vol. 46, pp. 2099-2108, 2007.

[15] Z. Vali, A. Gholami, Z. Ghassemlooy, D. G. Michelson, M. Omoomi, and H. Noori, "Modeling turbulence in underwater wireless optical communications based on Monte Carlo simulation," JOSA A, vol. 34, pp. 1187-1193, 2017.