View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Warwick Research Archives Portal Repository

Original citation:
Jasman, Faezah, Green, Roger and Leeson, Mark S.. (2017) Impact of receiver field of view on underwater optical wireless communications. Microwave and Optical Technology Letters, 59 (4). pp. 837-840.

Permanent WRAP URL:
http://wrap.warwick.ac.uk/89854

Copyright and reuse:
The Warwick Research Archive Portal (WRAP) makes this work by researchers of the University of Warwick available open access under the following conditions. Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRAP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Publisher's statement:
This is the peer reviewed version of the following article: Jasman, F., Green, R. J. and Leeson, M. S. (2017), Impact of receiver field of view on underwater optical wireless communications. Microw. Opt. Technol. Lett., 59: 837–840. doi:10.1002/mop.30410, which has been published in final form at https://doi.org/10.1002/mop.30410 . This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Self-Archiving.

A note on versions:
The version presented here may differ from the published version or, version of record, if you wish to cite this item you are advised to consult the publisher's version. Please see the 'permanent WRAP url' above for details on accessing the published version and note that access may require a subscription.

For more information, please contact the WRAP Team at: wrap@warwick.ac.uk

warwick.ac.uk/lib-publications

Impact of Receiver Field of View on Underwater Optical Wireless Communications

Faezah Jasman, Roger J. Green and Mark S. Leeson

***Abstract*—This paper discusses the effect of receiver field-of-view (FOV) on the power distribution and bandwidth performance of short-range diffuse line-of-sight (LOS) links. Monte Carlo simulation is used to investigate the performance of the links for the on-axis and off-axis scenarios in clear, coastal and turbid water. In both clear and coastal water, the receiver FOV has little influence on the on-axis power reception but has a significant effect on the off-axis power reception where there is an approximately 30 dB gain (off-axis) when the receiver FOV is increased from 10° to 180°. However, in turbid water receiver FOV significantly affects the power received both on-axis and off-axis, with gains of 15-18 dB for the same change in receiver FOV. In terms of bandwidth performance, the FOV only affects the on-axis bandwidth in clear and coastal water but not in turbid water.**

***Index Terms*—underwater optical wireless communications, Monte Carlo simulation, power distribution, frequency response, bandwidth, diffuse sources, receiver field-of-view.**

I. INTRODUCTION

Optical wireless communication (OWC) technologies have progressed greatly over the last few years with continued advances in component technologies. Due to its promising performance for high data rate communication in terrestrial applications, OWC is now a potential candidate for application in underwater communication. Specifically wavelengths in the blue/green region are used as they experience the lowest attenuation underwater [1]. Recent work has reported data transmission well into the Gbps range [2]; this is much higher than its acoustic counterpart, which is limited by low bandwidth, multipath propagation and high delay [3].

A significant amount of work has been completed to understand and develop underwater OWC (UOWC) in various areas such as system design and development, channel modeling and characterization, and network technology. Several researchers have contributed to understanding the underwater environment by using Monte Carlo simulation [4-6]. Apart from that, work on designing high bandwidth systems in the Gbps range is still ongoing since the first report of such a data rate by Hanson and Radic using a laser beam [7]. The recent work by Oubei et al. demonstrated that 4.8 Gbps can be achieved at a distance of 5.4 m using QAM-OFDM [2]. Despite the high data rates achieved by those links, they face a considerable challenge to maintain accurate pointing and tracking since laser beams are highly collimated. Thus, several efforts to develop diffuse systems based on LED to ease the strict pointing requirements have been reported. An experiment using an omnidirectional transmitter has been conducted by Baiden et al. who successfully developed and tested an omnidirectional transmitter operating over 10 m at 40 Mbps [8]. Pontbriand et al. also conducted an experiment using an omnidirectional transmitter and receiver achieving transmission at 5 Mbps over 200 m [9]. In both of these papers, no analysis of the channel characteristics such as power and bandwidth was conducted. Hence, this paper will focus on the characterization and modeling of the diffuse channel, particularly its power and bandwidth performance. Particular attention is paid to the impact of receiver field-of-view (FOV) on the performance. In this case, the receiver FOV is defined as the maximum angle at which the incoming light can be accepted by the receiver. It should be noted that this paper concentrates on the limitations imposed by the channel only and thus does not consider bandwidth constraints from the LED source, the photodetector or from other system elements. Here, the source is diffuse in contrast to the work on the effect of FOV on the received power using a collimated source that has been reported in [4].

The remainder of this paper is organized as follows. In Section II we briefly present underwater optical properties and the underwater channel model. In section III we describe the system under study via Monte Carlo simulation. Next, we present numerical results to study power distribution and frequency response of line-of-sight (LOS) links in Section IV. Finally, Section V concludes the work.

II. BACKGROUND

A. *Optical properties*

The main optical properties that affect the attenuation of light in water are absorption and scattering. The former occurs when a photon loses energy as a result of the interaction between photons and other molecules or particles. The latter happens when a photon's initial direction is changed to another direction due to the interaction with other particles. Both of these effects are wavelength dependent and are generally represented by the absorption coefficient *a*, scattering coefficient *b,* and the attenuation coefficient *c*. Values of the coefficients have been established in the literature and are shown in Table 1 [10,11].

F. Jasman, R. J. Green and M. S. Leeson are with the School of Engineering, University of Warwick, Coventry CV4 7AL, UK.
(e-mail: F.Jasman@warwick.ac.uk).

Scattering is more dominant in turbid water and causes the light beam to spread away from its initial direction. The effect of scattering on communication can be understood in two ways [12]. The first of these is spatial dispersions caused by the spreading of the beam due to the multi-scattering process and consequently causing the photon density to decrease at the receiver position. For a diffuse beam, photons that arrive at the receiver are spatially dispersed due to the initial beam distribution and also due to the environment. The second mechanism is temporal dispersion that results when the light beam reaches the receiver at different times. Due to this, there will be a path difference and time delay which can limit the bandwidth. Published work has shown that temporal dispersion is only significant for high data rate links (>1GHz) and in highly turbid water [5]. Experimental results also show that temporal dispersion is not observed because it is not significant for short distances where multi-scattering is not severe [2,7].

In spite of the fact that scattering will limit the bandwidth, it can be useful to create a communication link when accurate pointing and tracking are difficult to achieve. Simulations of the performance of collimated beam and diffuse beam in turbid water show that a zone of communication can be established by both links with comparable performance [13].

B. *Channel Model*

The power received can be calculated by using the Beer-Lambert (BL) Law as [14]

$$P = P_o \exp(-c(\lambda)z) \tag{1}$$

where P_O is the transmitted power , z is the path length and $c(\lambda)$ is the beam attenuation coefficient. The beam attenuation coefficient, $c(\lambda)$ is calculated using

$$c(\lambda) = a(\lambda) + b(\lambda) \tag{2}$$

where $a(\lambda)$ is the absorption coefficient and $b(\lambda)$ is the scattering coefficient. It can be seen from eq. (1) that the BL Law only considers attenuation due to absorption and scattering and does not consider any collection of scattered light that contributed to the power received. This is because, in reality, some of the scattered light will be collected by the receiver. As a result, it underestimates the power received in high turbidity water where scattering is significant. Apart from that, the simplicity of the BL Law only applies to collimated beams in LOS links. An effort to create a generic channel model is reported by Doniec et al. where the model includes the light source, detectors, amplifiers and detector circuitry [15]. The weakness of this model is that it is limited to clear water where scattering is not significant.

III. SYSTEM MODEL

A. *Simulation setup*

Monte Carlo simulation is used to model the diffuse underwater channel where the light beam is modelled as the continuous propagation of a large group of photons. A set of probability rules and random variables are used to model the initial beam distributions, path length and scattering angle. For a detailed description of Monte Carlo simulation, we refer readers to [16-17]. Three types of water are considered in this simulation: clear water, coastal water and turbid water. Table 1 shows the absorption *a,* scattering *b,* and attenuation coefficients *c*, of the three types of water.

Here, we considered a short-range diffuse LOS link with a receiver located 15 m away from the transmitter. At the receiver plane, we defined the zone of communication to be a square area of 10 m × 10 m centered at coordinate (0,0) as shown in Fig. 1.The interest in this configuration is mainly to investigate the power received and bandwidth supported over the area defined. To simplify the simulation, we neglected the effect of turbulence, background radiation, and surface waves.

Other simulation parameters were set as following: the wavelength, $\lambda = 514$ nm and the initial beam width = 2 mm. A relatively large receiver aperture of 10 cm was chosen to increase the number of the scattered photons that was collected. The diffuse beam had a full angle divergence of 15°.

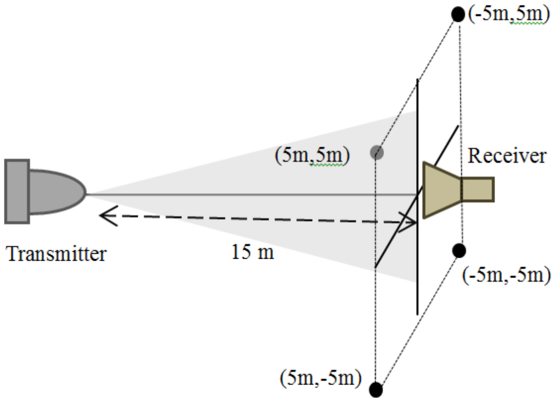

Fig.1 Diffuse LOS links configuration

TABLE 1
OPTICAL PROPERTIES FOR THREE TYPES OF WATER

Water type	a(m^{-1})	b(m^{-1})	c(m^{-1})
Clean water	0.114	0.037	0.151
Coastal water	0.179	0.219	0.398
Turbid water	0.366	1.824	2.19

IV. SIMULATION RESULTS

In this section, the simulation results to evaluate the effect of receiver FOV on the power distribution and frequency response are presented. Fig. 2 shows the cross section view of the power distribution at the receiver plane in clear water, coastal water and turbid water. The *x*-axis is the radial distance centered at (0,0) at the receiver plane. It is clear from Fig.2 that as would be expected the maximum power is received at on-axis locations when the FOV is 180° and drops gradually for off-axis locations. As the receiver is moved 5 m away from the center there is approximately 20 dB, 13 dB and 5 dB of power loss in clear water, coastal water and turbid water respectively. These values of power loss at off-axis locations are still tolerable compared to using a collimated source where more than 50 dB of power is lost in clear water [13].

A. Effect of receiver FOV on the power received

By referring to Fig.2, it can be seen that at the center of the receiver axis, increasing the receiver FOV has no effect to the power received in clear water and little effect to the power received in coastal water. A totally different observation is found for turbid water as there is an increase of almost 15 dB as the FOV is increased from 10° to 180°. An interesting fact can be seen when the FOV is increased beyond 60°, where there is no increase in power in clear water and only a small benefit in coastal and turbid water. This provides some insights concerning the largest angle of arrival that is useful, namely around 30° as 60° FOV is the full angle value. Additionally, it can be deduced that; the light that reaches the on-axis locations for clear and coastal water is dominated by the unscattered light as a smaller FOV of 10° is able to capture most of the light, whereas at on-axis location in turbid water, a larger receiver FOV is needed to capture most of the light signifying that it is dominated by multiple scattered light with large angle of arrivals. For off-axis locations, it is evident that the increase of FOV from 10° to 180° significantly affects the power received in all types of water where approximately 35 dB, 27 dB and 18 dB are gained in clear water, coastal water and turbid water respectively.

From these observations, it is useful to classify these different cases into two operating regimes depending on the extent of multiple scattering [12]. Both on-axis locations in clear and coastal water can be classified as operating in minimal scattering regime as unscattered light dominates whereas on-axis locations in turbid water and all off-axis locations can be classified as operating in multiple scattered regimes.

B. Effect of receiver FOV on the channel bandwidth

The frequency response for the system was considered for 2 locations, namely at the center of the beam (on-axis) and 5 m away from the center (off-axis) locations. The bandwidth supported by the links can be estimated from the 3 dB point. Fig. 3, Fig.4 and Fig.5 depict the frequency response of the diffuse links in clear water, coastal water and turbid water for both on-axis and off-axis locations. For the on-axis scenario in clear water, the frequency plots do not show signs of rapid decrease with frequency as it is dominated by unscattered lights. However, for off-axis locations the channel bandwidth can be estimated to be around 260 MHz to 420 MHz as the FOV is reduced from 180° to 10°. In coastal water, as the FOV is decreased from 180° to 10°, the bandwidth increased from 5 GHz to 10 GHz for on-axis scenario and from 116 MHz to 290 MHz for off-axis scenario. From this observation we can see that FOV has a greater impact on the on-axis bandwidth compared to off-axis bandwidth. For turbid water, it can be seen that the effect of FOV on bandwidth is not so distinguishable for both on-axis and off-axis scenario as there is only slight decrease in bandwidth as the FOV is increased from 10° to 180°. On-axis, the bandwidth decreases from 79 MHz to 56 MHz while off-axis, the bandwidth decreases from 74 MHz to 44 MHz. This analysis shows that in minimal scattering regime, receiver FOV has large influence on the bandwidth performance whereas in multiple scattered regimes, the receiver FOV has little effect to the bandwidth performance.

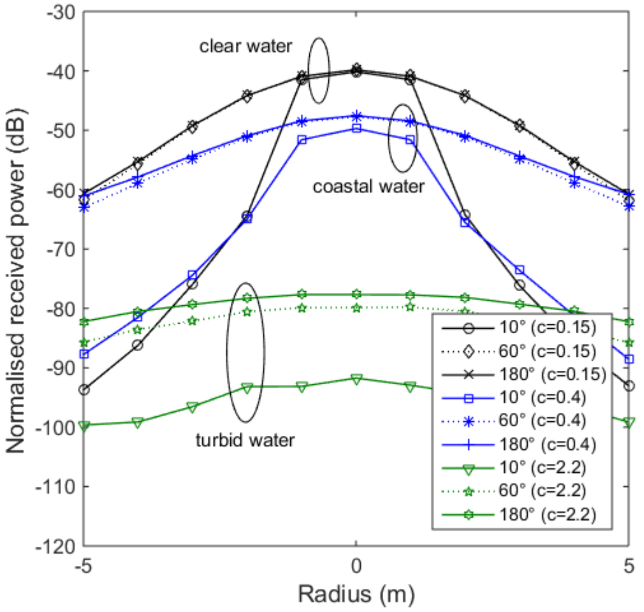

Fig 2. Power distribution in clear water, coastal water and turbid water as a function of various receiver FOVs.

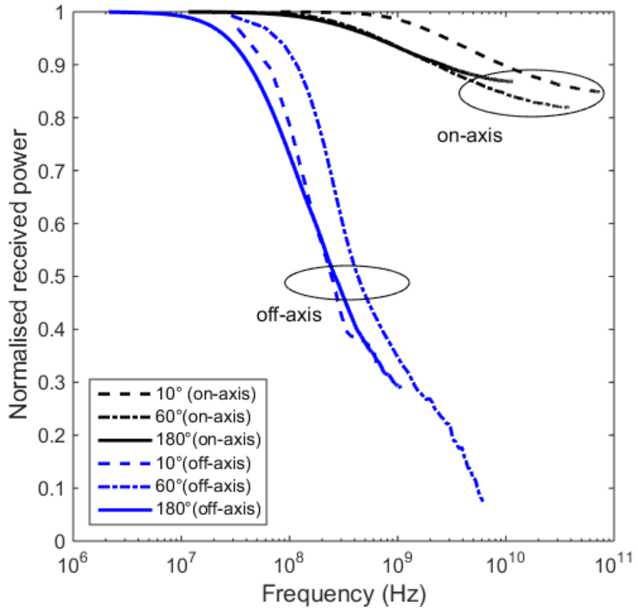

Fig 3. Frequency response in clear water as a function of various receiver FOVs (c=0.15)

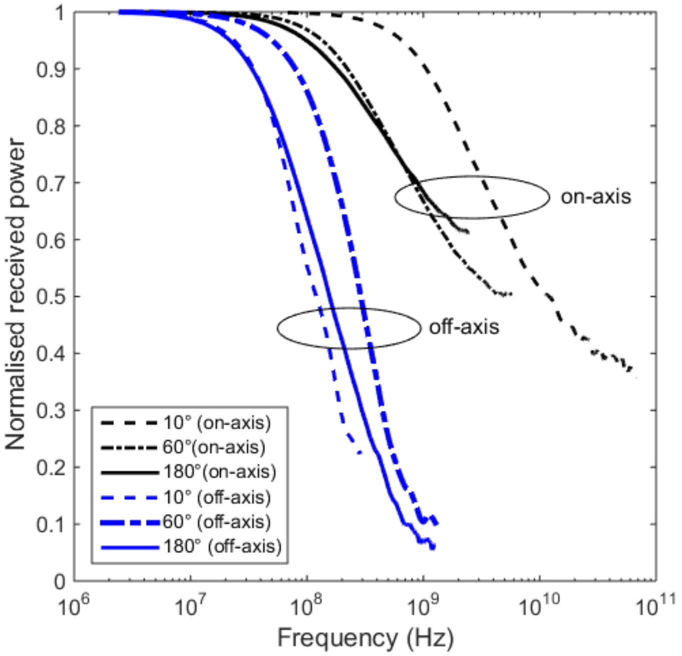

Fig 4. Frequency response in coastal water as a function of various receiver FOVs (c=0.4)

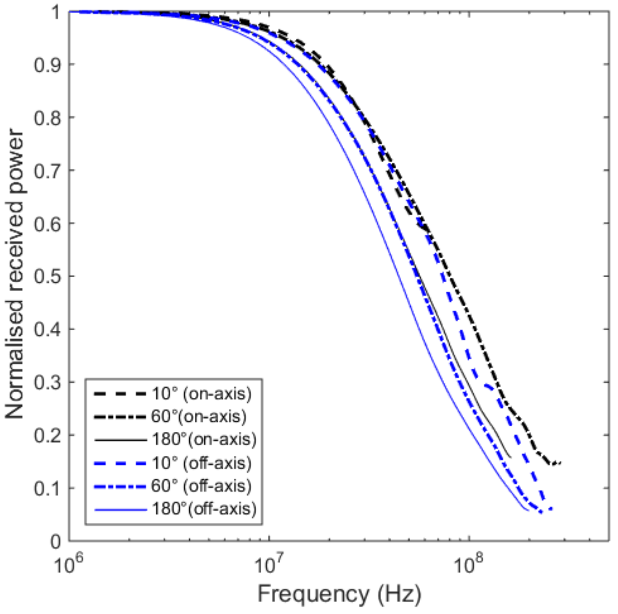

Fig 5. Frequency response in turbid water as a function of various receiver FOVs (c=2.2)

V. CONCLUSION

This paper investigates the power distribution and bandwidth limitations of diffuse links in three types of water. This study utilizes a propagation distance of 15 m using diffuse beams of 15°. However, by analyzing the results obtained, several important conclusions on the behavior of the light can be made. First, it can be said that in minimally scattered region, which is represented by on-axis locations in clear water and coastal water, a smaller FOV can be chosen to optimize the power performance as most of the light has small angle of arrivals. At the same time, a higher bandwidth can be obtained by choosing a smaller FOV. On the other hand, for multiple scattered regions which are represented by the on-axis location in turbid water and all off-axis locations, a larger receiver FOV is needed to maximize the received power. Interestingly, this can be achieved without any significant decrease in bandwidth. It is believed that these findings will be beneficial for system designers in determining the size of receiver FOV in different situation where different scattering behavior is observed.

REFERENCES

[1] L. J. Johnson, F. Jasman, R. J. Green, and M. S. Leeson, "Recent Advances in Underwater Optical Wireless Communication," *Underwater Technology*, vol. 32, no.3, pp. 167-175, 2014.

[2] H. M. Oubei, J. R. Duran, B. Janjua, H.-Y. Wang, C.-T. Tsai, Y.-C. Chi, T. K. Ng, H.-C. Kuo, J.-H. He, and M.-S. Alouini, "4.8 Gbit/s 16-QAM-OFDM transmission based on compact 450-nm laser for underwater wireless optical communication," *Opt Express*, vol. 23, no.18, pp. 23302-23309, 2015.

[3] M. Chitre, S. Shahabudeen, and M. Stojanovic, "Underwater acoustic communications and networking: Recent advances and future challenges," *Marine Technology Society Journal,* vol. 42, no.1, pp. 103-116, 2008.

[4] W. Cox and J. Muth, "Simulating channel losses in an underwater optical communication system," *Journal of the Optical Society of America A*, vol. 31, no.5, pp. 920-934, 2014.

[5] C. Gabriel, M. Khalighi, S. Bourennane, P. Leon, and V. Rigaud, "Monte-Carlo-based channel characterization for underwater optical communication systems," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 5, no. 1, pp. 1-12, 2013.

[6] J. Li, Y. Ma, Q. Q. Zhou, B. Zhou, and H. Y. Wang, "Monte Carlo study on pulse response of underwater optical channel," *Optical Engineering*, vol. 51,no 6, pp.066001-1-066001-5, 2012.

[7] F. Hanson and S. Radic, "High bandwidth underwater optical communication," *Appl Opt*, vol. 47, no. 2, pp. 277-283, 2008.

[8] G. Baiden, Y. Bissiri, and A. Masoti, "Paving the way for a future underwater omni-directional wireless optical communication systems," *Ocean Engineering*, vol. 36, no.9, pp. 633-640, 2009.

[9] C. Pontbriand, N. Farr, J. Ware, J. Preisig, and H. Popenoe, "Diffuse high-bandwidth optical communications," in *OCEANS*, Quebec City, Canada, 15-18 Sept, 2008, pp. 1-4.

[10] C. D. Mobley, "*Light and water: Radiative transfer in natural waters*," vol. 592: Academic Press, San Diego, CA, 1994, p.112.

[11] T. J. Petzold, "Volume scattering functions for selected ocean waters," Scripps Institute of Oceonography, San Diego,CA, Tech. Rep. Oct 1972.

[12] B. Cochenour, L. Mullen, and J. Muth, "Temporal response of the underwater optical channel for high-bandwidth wireless laser communications,"*IEEE Journal of Oceanic Engineering,* vol. 38, no.4, pp. 730-742, 2013.

[13] F. Jasman and R. Green, "Power Distribution and Frequency Response Performance of Underwater Optical Wireless Communications," *20th IEEE Int. Workshop on Computer Aided Modelling and Design of Communication Links and Networks (CAMAD 2015),* Surrey, UK, 2015.

[14] S. Arnon, J. Barry, G. Karagiannidis, R. Schober, and M. Uysal, "Advanced optical wireless communication systems," Cambridge University Press, 2012, p.203.

[15] M. Doniec, M. Angermann, and D. Rus, "An End-to-End Signal Strength Model for Underwater Optical Communications," *IEEE Journal of Oceanic Engineering*, vol. 38, no. 4, pp. 743-757, 2013.

[16] R. A. Leathers, T. V. Downes, C. O. Davis, and C. D. Mobley, "Monte Carlo Radiative Transfer Simulations for Ocean Optics: A Practical Guide," Naval Research Lab., Washington, DC, Tech.Memo. NRL/MR/5660—04-8819, Sept 1, 2004.

[17] W. C. Cox Jr, "Simulation, Modeling, and Design of Underwater Optical Communication Systems," PhD Thesis, Dept. Elect. and Comp. Eng, North Carolina State Univ, 2012.