Use of Gaussian Beam Divergence to Compensate for Misalignment of Underwater Optical Wireless Communication Links

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Abstract: The vast majority of underwater wireless optical communications (UWOC) links use collimated blue/green laser beams to deliver high speed data links over distances ranging from a few metres to tens of metres. However, such links are extremely susceptible to misalignment of the transmitter and receiver. Although UWOC links are well studied in the literature, previously considered techniques for mitigating such misalignment have been relatively complicated and expensive. Here, we consider the possibility of: 1) simply increasing the divergence of the transmitted Gaussian beam in order to reduce the sensitivity of the link to misalignment and 2) increasing the field of view (FOV) and aperture of the receiver in order to compensate for the resulting broadening of the angle-of-arrival distribution. Here, we consider the performance of such UWOC links over a typical range of distances using transmitters and receivers with a range of divergence, and FOV and aperture size, respectively. Using Monte Carlo simulations, we demonstrate the tradeoff between the transmitter divergence and receiver size in terms of angle-of-arrival (AOA), path loss and channel bandwidth. The results show that this simple approach can effectively mitigate link misalignment over a range of deployment scenarios without significantly compromising link performance.

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1. Introduction

Underwater wireless optical communication (UWOC) is a recently emerged technology which uses the optical carriers to transmit data in the marine environment. UWOC technology has appealed attraction in recent years in discovering and resolving issues related to the waters in the earth surface with ocean exploration systems. Ocean data sampling, marine archaeology, investigation and environmental monitoring of mineral stores, oil fields, oceanic flows and fish tracing, communication between submarines and with the off-shore, ships and divers for search, rescue and navigation process are some potential applications of UWOC systems.

Optical carriers have some tremendous features which make them attractive in recent applications compared to the previously acoustic and radio frequency (RF) carriers. While a link range up to several tens of kilometres can be achieved with a kbps data rate with acoustic communications underwater and a few metres with RF at the frequency range of 30-300 Hz in salty conductive water [1], using UWOC a high data rate i.e., up to 1 Gbps over a transmission range of tens of metres with a low link delay can be achieved. These features support the transmission of a large volume of real time data. A summary of the transmission distance, power and data rates for UWOC systems can be found in [2]. The low cost and relative simple implementation features of optical systems make them highly desirable in large scale underwater sensor networks [3].

However, in UWOC systems the propagating optical beam encounters absorption and multiple scattering phenomena particularly in sea waters. Absorption is the irreversible loss of light intensity, which depends on the wavelength λ and is defined by the spectral absorption coefficient $a(\lambda)$, whereas scattering refers to the deflection of light from its original path and is represented by the spectral scattering coefficient $b(\lambda)$ [4]. Scattering results in both attenuation and dispersion of the transmitted signal, thus resulting in reduced signal to noise ratio (SNR) and increased the bit error rates (BER) due to the dispersion induced inter-symbol-interference (ISI). The latter is more actuate at higher data rates and when using laser beams in turbid waters [5, 6]. Therefore, investigation of light propagation in the water and considering the effects of both scattering and absorption is important within the context of UWOC.

The effect of multiple scattering in UWOC from different aspects has been reported in the literature. An UWOC simulation model for AUVs was proposed in [7]. A Monte Carlo study on time dispersion of UWOC systems was considered in [4]. UWOC channel impulse response was modelled with a closed form expression of the double gamma function [6]. The effect of random sea surface created by wind and a numerical based BER analysis for a downlink UWOC systems was considered in [8]. [9] described a high-sensitivity experimental method for measuring the frequency response of the underwater optical channel. In [10] the impulse response of a MIMO UWOC link was considered. A complete simulation framework for undersea laser communications and networking was described in [5]. The outage performance for vertical buoy-based UWOC with pointing errors was studied in [3]. [11] studied the transmission property of red laser light in water. [12] obtained a closed form expression of angle of arrival (AOA) for collimated laser beams. Papers considering the effect of turbulence in underwater channel modelling are not considered here, since it is not the focus of this paper.

Misalignment of UWOC systems have been studied in previous researches. [13] investigated the performance of link alignment for UWOC systems for a collimated laser source and presented the relationship of transmit power, link range and receiver offset distance with a closed-form expression. Again in [14] the effect of elevation angle and FOV of detector for a collimated transmitter beam on link misalignment was considered. It was shown in [15] that the larger divergence angle and elevation angle of a diffused point source, the more decrement of received intensity will occur.

In UOWC systems employing a narrow divergence optical source the mode of transmission is mostly based on point-to-point LOS configuration, which require highly accurate link alignment for the collimated Gaussian laser beam [16]. The link alignment and its maintenance also becomes a major issue when considering turbulence, random movement of the sea surface, wind, and underwater vehicles movements, which could led to link un-availability. In additions multiple scattering will lead to pulse broadening, thus leading to much reduced SNR and higher BER when using a small area photodetector. In this scenarios there are a number of situations including link alignment and active tracking, multi-array photodetectors, and a wide area detector. Alternatively, it is worthwhile to investigate transmitters with beam divergence, thus making tracking and alignment less challenging tasks. In this paper, we will propose that divergent beams can mitigate link misalignment both in turbid and clear waters. To the best of our knowledge this is the first time that this investigation is being reported.

However, increasing beam divergence may cause performance degradation in point-to-point link. In this paper we are interested to see how multiple scattering phenomena impresses the choice of transmitter divergence in design of UWOC systems. Therefore, we will propose the channel performance in turbid waters for a variety of transmitter divergence from different aspects of angular spreading, power loss and time dispersion which has not been studied before.

The widely used optical beam is the lowest order TEM00 Gaussian mode, which is the output of the single mode lasers and needs to be investigated thoroughly through theoretical and simulation studies before experimental setups. The focus is on the divergence effect of Gaussian beam which is converged to the limitation cases of plane and spherical beams.

In addition, the impact of the aperture and FOV of detector is investigated to improve the performance of the system with divergent beam in point to point link.

The rest of the paper is organized as follows. In Section II, we introduce the system model adopted in UWOC link. In Section III, the simulation results will be presented and discussed. Finally, the paper will be concluded in section IV.

2. System Model

We consider a SISO LOS communication link, which is composed of transmitter, channel and receiver. The exit aperture of transmitter lies in the xy plane and z coordinate is the direction of propagation. It is assumed that there is no reflection from water and air surface. Only forward scattering is taken into account and any back reflected photons towards the transmitter is not considered.

In order to trace photons along the path in the water, Monte Carlo method is used. Photons are supposed to propagate within the water in the straight line unless a scattering event occurs and photons direction changes. In each scattering event, three random variables should be selected, path length l, polar angle θ and azimuthal angle φ to track the photons. l is the distance between two interactions and (θ, φ) determines the scattering direction in each interaction of photon with particles. More details about Monte Carlo method can be found in [17, 18].

2.1. Transmitter

To model transmitter in Monte Carlo simulation, the initial position of each photon and the initial output angle from transmitter should be determined. For a Gaussian beam, the probability density function (PDF) of the radial position of each photon is given by [17, 19]:

$$p(r) = \frac{e^{(-r^2/b^2)}}{b^2} \times 2r. \tag{1}$$

Consequently, the cumulative distribution function (CDF) and the radial position r are given by

$$P(r) = 1 - e^{-r^2/b^2} \ . \tag{2}$$

$$r = b\sqrt{-\ln\left(1-\zeta\right)} \ . \tag{3}$$

where $b = w_0/\sqrt{2}$ and w_0 is the beam waist of the Gaussian beam and ζ is a uniformly selected random number between 0 and 1. Output polar angle from transmitter θ is obtained according to [18] and azimuthal angle φ is chosen randomly in the interval $[0, 2\pi]$. Therefore, the directions of photon through the channel along the *x*, *y* and *z* coordinates are given by

$$(u_x, u_y, u_z) = (\sin\theta\cos\varphi\,, \sin\theta\sin\varphi,\ \cos\theta)\ , \tag{4}$$

where u_x, u_y and u_z are directional cosines.

In modelling a plane wave, one option would be to consider that all photons originate from the same point of (0, 0, 0). However, to reflect a real scenario, here we have assumed that photons are randomly spread out within a small circular area which is the same as the initial cross section of the Gaussian beam. The PDF of the radial position of each photon can be obtained from [19]:

$$p(r) = \frac{2\pi r}{\pi a^2} \tag{5}$$

where $r = a\sqrt{\zeta}$, ζ is a uniformly selected random number in the interval of [0, 1] and a is the radius of the initial plane. The directions of photon through the channel are given as

$$(u_x, u_y, u_z) = (0,0,1) \tag{6}$$

To model spherical beam, we have assumed a forward hemisphere which is produced by an optical isotropic point source [17]. The normalization condition of the source function $I(\theta, \varphi)$ is defined as:

$$\int_0^{2\pi} \int_0^{\pi/2} I(\theta, \varphi) \sin\theta d\theta d\varphi = 1 \tag{7}$$

Since $I(\theta, \varphi)$ is independent of φ , after simplification we have

$$I = \frac{1}{2\pi} \tag{8}$$

The PDF and CDF of polar angle θ are defined as

$$p(\theta) = 2\pi I(\theta) \sin\theta \tag{9}$$

$$P(\theta) = \int_0^{\theta} 2\pi I sin\theta d\theta \tag{10}$$

Then the direction along *z* coordinate will be obtained as (12)

$$\cos\theta \quad = 1 - \zeta \tag{11}$$

2.2. Channel

Calculating path length l and azimuthal angle φ in each step of photon propagation is a straightforward task. However, it is more challenging to obtain polar angle from its CDF in a way that method of calculating the polar angle significantly influences the speed of simulation. One way to choose polar angle is through the measured scattering phase function (SPF) of Petzold's data [20] and then numerically calculates the polar angle in each step of propagation and each channel realization according to [18] which is a time consuming method. To perform the simulation much faster, polar angle can be obtained directly from an analytical SPF formula. To this aim, we used Henyey-Greenstein (HG) scattering phase function although it cannot predict small forward scattering angles according to measured Petzold's data [20]

$$p_{HG}(\theta,\varphi) = \frac{1-g^2}{4\pi\,(1+g^2-2g\cos\theta)^{3/2}} \tag{12}$$

Then scattering angle can be obtained in terms of the random number q according to [17]:

$$\mu_s = \frac{1}{2g}\left[1+g^2-\left(\frac{1-g^2}{1+g-2gq}\right)^2\right], g \neq 0 \tag{13}$$

Where $\theta = \cos^{-1}\mu_s$ and g is the average cosine of θ. The parameters used in the simulation are presented in Table 1. The absorption and scattering coefficients, the albedo $w_0(\lambda)$ and g is selected from [20].

Table 1 Simulation Parameters

Parameters	Value
$c$lear water ($a(\lambda)$, $b(\lambda)$, $c(\lambda)$, $w_0(\lambda)$)	(0.114,0.037,0.151,0.247)
$harbour$ water ($a(\lambda)$, $b(\lambda)$, $c(\lambda)$, $w_0(\lambda)$)	(0.366, 1.824, 2.19, 0.8329)
g	0.924
Number of Photons	5×10^7
Wavelength	520 nm
Source beam width	1 mm

3. Results

This section consists of four parts. Link misalignment will be presented in the first section and the channel performance according to AOA, loss and bandwidth investigation will be presented in second, third and fourth sections respectively. The transmitter half divergence angle varies from 0 rad in plane beam to pi/2 rad in spherical beam.

3.1. Misalignment Investigation

The influence of transmitter beam divergence on link misalignment is shown after 50 metre of clear water and 5 metre of harbour water respectively in Fig. 1 and Fig. 2. In both Figures the received optical beam is presented along the x axis at the receiver plane. As it is clear from both Figures, more divergent beams extent in a wider beam width along the x axis. However, the trends of beams are more similar in the harbour water than the clear water. Fig. 1 and Fig. 2 suggest that for a particular receiver sensitivity, how much receiver offset distance each transmitter can tolerate.

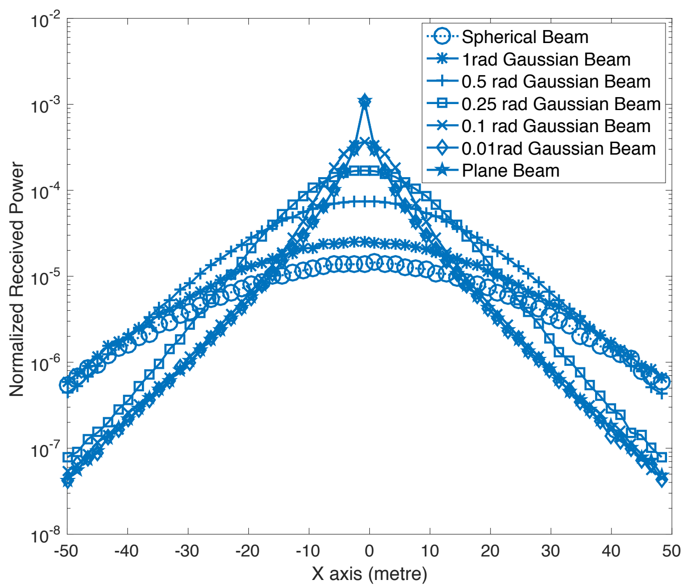

Fig. 1. *Received optical beam at receiver plane along x axis after 50 metre of clear water*

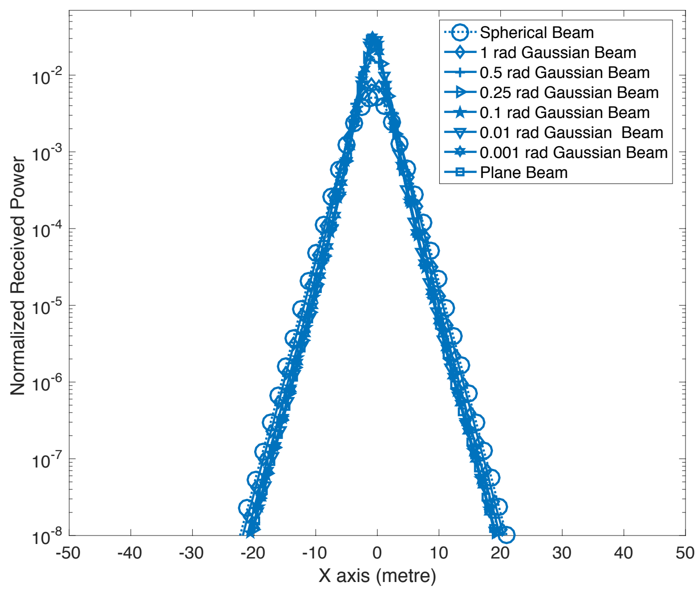

Fig. 2. *Received optical beam at receiver plane along x axis after 5 metre of harbour water*

3.2. AOA Investigation

This part consists of two scenarios. In the first scenario, the AOA is investigated for different transmitted beam divergence with the same detector at the two link lengths of 5 and 8 metres. However, the effect of beam divergence on AOA of UWOC systems has not been addressed in prior works and deserves a full study. AOA is the distribution of received photons angles at the receiver plane and it has been studied in wireless communication application and channel modelling [21, 22] but it has not addressed in prior works of UWOC thoroughly despite of its substantial role in performance analyses. The wider the AOA distribution, the larger FOV will be needed at the detector.

In our model, AOA in polar direction in the receiver plane is calculated by

$$\theta = \cos^{-1} u_z. \quad (14)$$

Fig. 3 and Fig. 4 show AOA for different beams and for 5 metres and 8 metres link distance respectively. A detector with 180 degree FOV and aperture diametre of 0.8 metres is chosen so that we can investigate even the widest case of spherical beam. As it is clear from Fig. 3 and Fig. 4, more collimated beams have similar behaviour to plane beam and more divergent beams are similar to spherical beam. In

Fig. 3, more divergent beams have the peak value around 10 degrees while more collimated beams have the peak value around 5 degrees. This shows that more divergent beams will experience more angular spreading. In other words, more divergent beams experience a wider angular spreading than less divergent beams for the same power loss. This observation is true for Fig. 4. As the link distance increases, angular spreading is even more and the peak values are shifted approximately 5 degrees toward higher degrees.

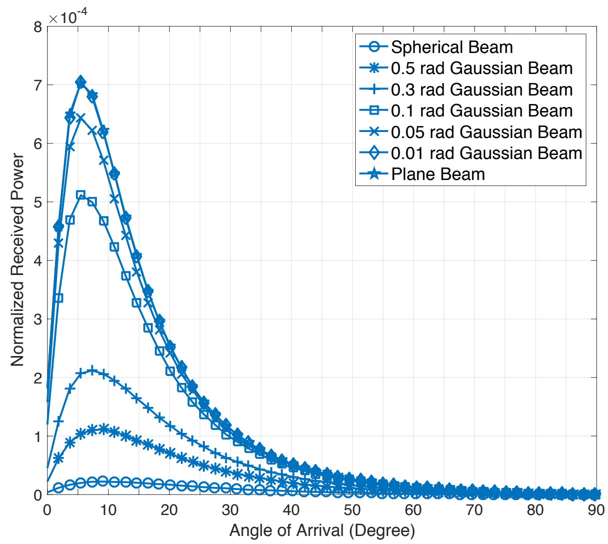

Fig. 3. *AOA after 5 metres of harbour water*

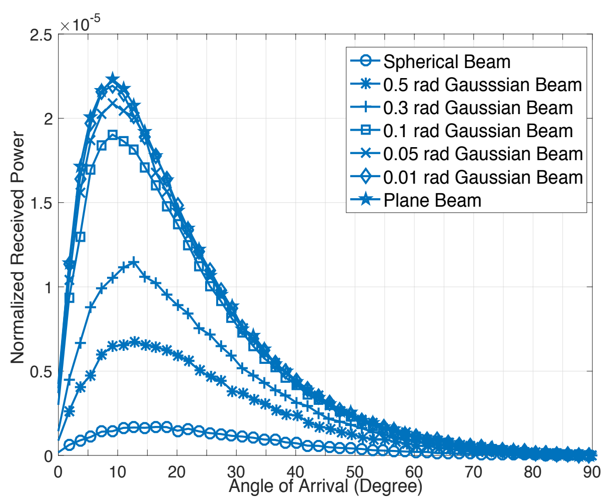

Fig. 4. *AOA after 8 metres of harbour water*

In the second scenario, the effect of detector's aperture will be presented for a 5 metre link in harbour water. FOV is 180 degrees. Fig. 5 and Fig. 6 show AOA for different receiver aperture sizes and for transmitter divergence angle of 0.001 and 0.5 rad respectively. As it is obvious on Fig. 5, the peaks of the AOA are shifted toward bigger angles with the increase of aperture diametre. This means that more angular spreading can be captured with wider aperture. According to Fig. 6, for 0.5 rad beam, the peaks of all diagrams intend to be the same and near 10 degree. The reason is that in this case, more spreading occurs and diagrams for different apertures are almost the same except in the amount of power loss.

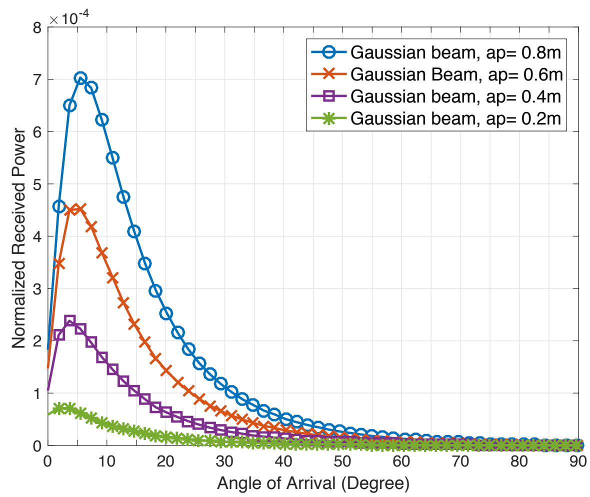

Fig. 5. *AOA in harbour water for 0.001 rad divergence beam*

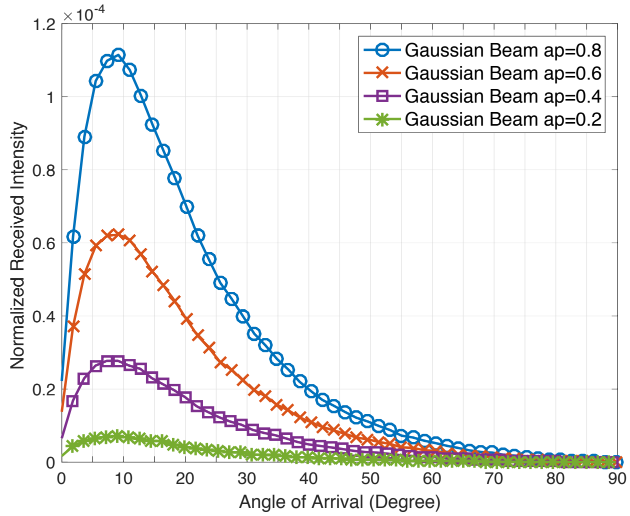

Fig. 6. *AOA in harbour water for 0.5 rad divergence beam*

3.3 Loss Investigation

In this part, the path loss for various transmitter beam divergence is studied. In the meantime, the effect of FOV and aperture diametre is considered in the model. Proper transmitter beam divergence depends on the active area and FOV of the receiver and matching should be done precisely to avoid coupling losses. More power will be captured in cost of wider receiver, so one should find a tradeoff between the transmitter and receiver for the desired performance.

Fig. 7 and Fig. 8 show the received optical power for different receivers in 5 and 8 metres link distances respectively. As a general trend for all receivers, the loss increases by increasing the transmitted beam divergence angle and the wider aperture with a wider FOV can capture more power. The received power decreases rapidly for lower divergence angles in comparison of the higher angles. Fig. 8 is the received power for 8 metres link. It can be seen that the slops of the traces have decreased compared to Fig. 7 due to the increasement of scattering.

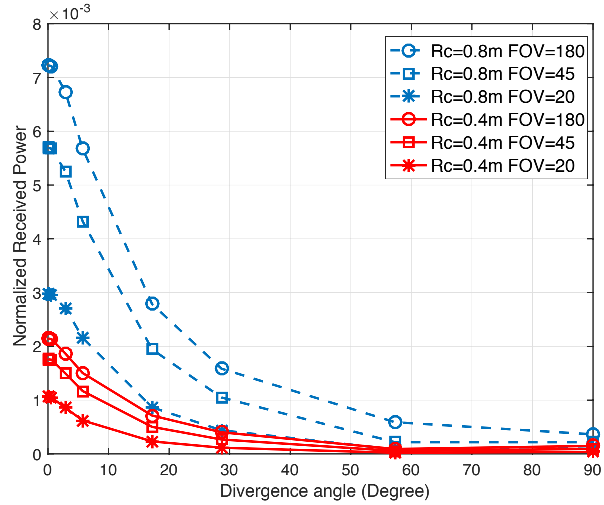

Fig. 7. *Normalized received power after 5m harbour water*

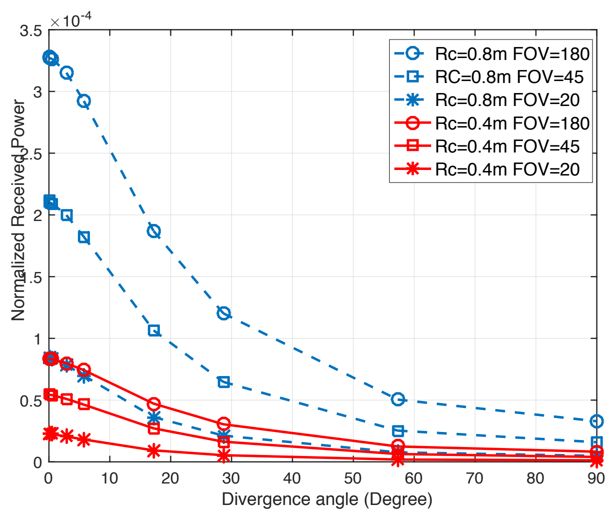

Fig. 8. *Normalized received power after 8m harbour water*

3.4 Bandwidth Investigation

To investigate the bandwidth, the impulse response of the channel for different transmitters and receivers is studied. Firstly, the impact of transmitter in the induced temporal dispersion of 8 metre channel is presented in Fig. 9. The aperture is chosen to have a diametre of 0.8 metre and 180 degree FOV. To obtain the impulse response through Monte Carlo simulation, sampling frequency was selected 7.5 GHz according to the maximum delay observed among the received photons.

According to Fig. 9, more divergent beams will experience more temporal dispersion and the normalized received power is more extensive in time. Fig. 10 shows the corresponding frequency response for the same parametres. The frequency response slopes of more divergent beams are higher and they experience more bandwidth drop.

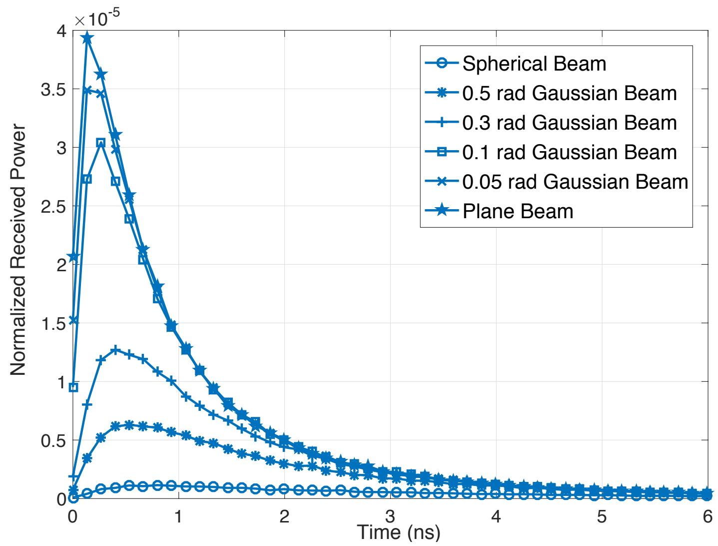

Fig. 9. *Impulse response after 8m harbour water*

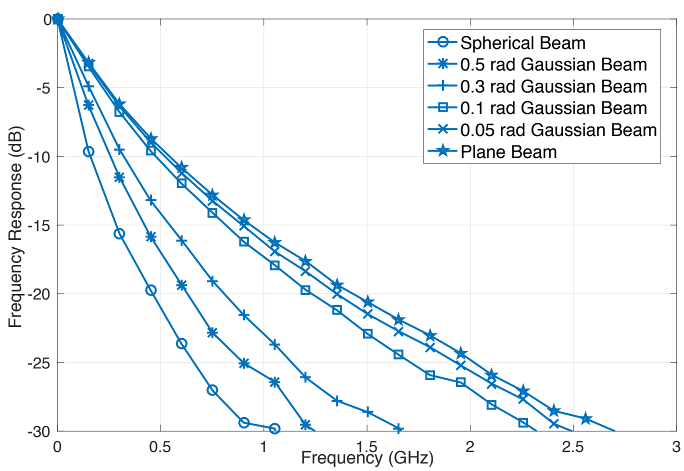

Fig. 10. *Frequency response after 8m harbour water*

The 3 dB bandwidth of the channel is presented for 5 and 8 metre links in Fig. 11 and Fig. 12 respectively. As it is clear from Fig. 11 and Fig. 12, the bandwidth decreases highly by increasing the divergence angle and also it depends highly on the FOV. By increasing FOV from 20 to 180 degrees, bandwidth decreased highly since more time dispersion is captured with wider FOV. The slopes of the diagrams decrease when divergence angle increases. In addition, the effect of aperture on channel bandwidth is negligible for high divergence angles and for longer link length.

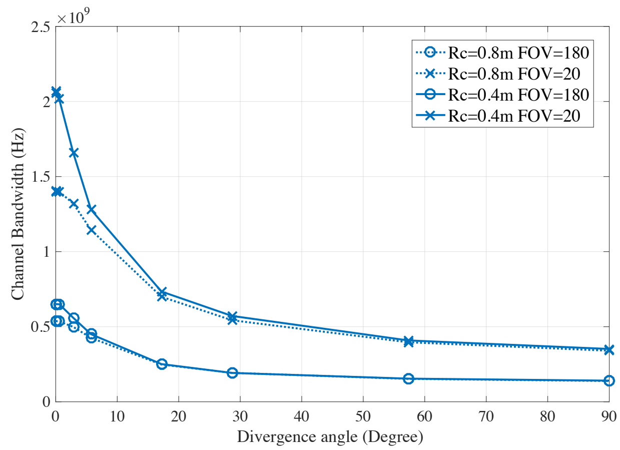

Fig. 11. *3 dB bandwidth after 5 m harbour water*

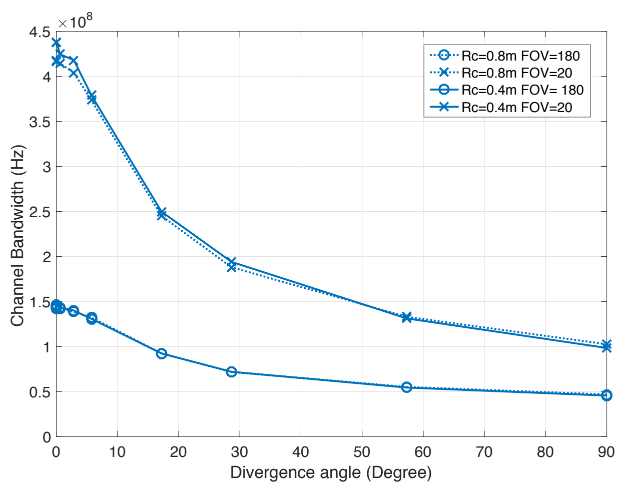

Fig. 12. *3db bandwidth after 8m harbour water*

4 Conclusion

Laser-based UWOC links are extremely susceptible to misalignment of the transmitter and receiver. Here, we have considered the possibility of simply increasing the divergence of the transmitted Gaussian beam in order to reduce the sensitivity of the link to misalignment. Simulation results suggest that increasing the transmitter beam divergence can mitigate the link misalignment in both clear and harbor water. The performance of UWOC link using various transmitter beam divergences and receivers was studied. The results show that wider detectors improve the performance of systems with divergent transmitter beam.

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