Project: IEEE 802.11bb Task Group

Submission Title: IEEE 802.11bb Reference Channel Models for Underwater Environments

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Abstract: This contribution proposes LiFi reference channel models for underwater environments.

Purpose: To introduce reference channel models for the evaluation of different PHY proposals.

IEEE 802.11bb
Reference Channel Models for Underwater Environments

Outline

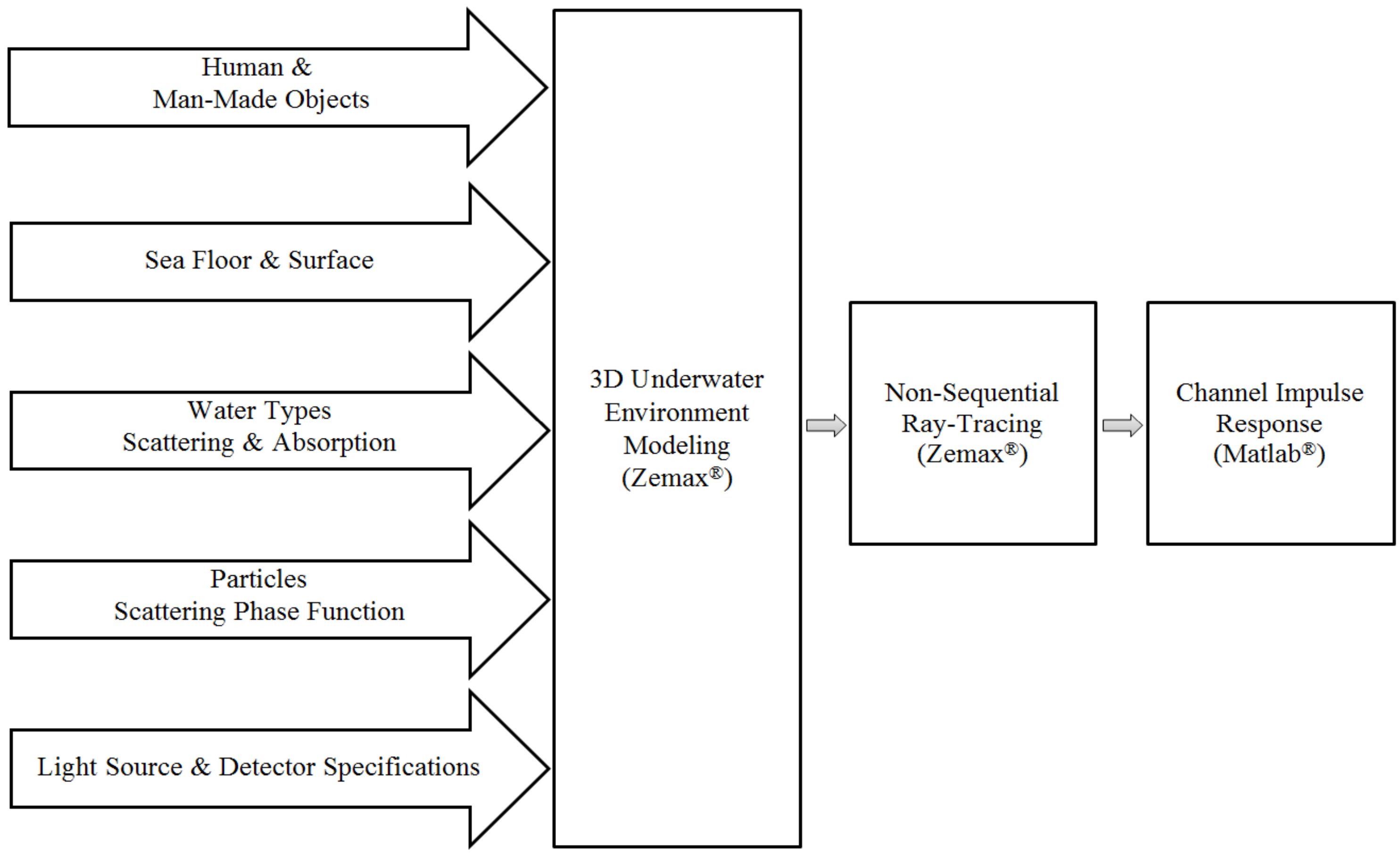
- Introduction
  - Channel Modeling Approaches in the Literatures
  - Overview of Channel Modeling Methodology
  - Sea Surface and Sea Bottom Modeling
  - Optical Characterization of Water and Particles
  - Scattering Phase Function
- Underwater Scenario under Consideration: Empty Sea
  - Channel Impulse Responses (CIRs)
  - Effective Channel Responses
  - Channel Characteristics
- Conclusions

Channel Modeling Approaches in the Literatures

- **Radiative Transfer Equation (RTE)** [1, Chapter 9] can be employed to fully characterize underwater light propagation. However, RTE involves integro-differential equation which does not yield a general analytical solution.
- **Monte Carlo Ray Tracing** [2-4] can be used to generate channel impulse response for a given underwater environment.
- As a basic tool, the **Beer-Lambert formula** [5] can be used to calculate underwater path loss. It assumes line-of-sight (LOS) transmission and ignores the possibility of receiving scattered photons.

[1] S. Arnon, J. Barry, G. Karagiannidis, R. Schober, and M. Uysal, ***Advanced optical wireless communication systems***, Cambridge, U. K.: Cambridge Univ. Press, 2012.
[2] C. Gabriel, M. A. Khalighi, S. Bourennane, P. Leon, and V. Rigaud, "**Monte-Carlo-based channel characterization for underwater optical communication systems**," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 5, no. 1, pp. 1-12, 2013.
[3] V. Guerra, C. Quintana, J. Rufo, J. Rabadan, and R. Perez-Jimenez, "**Parallelization of a Monte Carlo ray tracing algorithm for channel modelling in underwater wireless optical communications**," *Procedia Technology*, vol. 7, pp. 11-19, 2013.
[4] S. Tang, Y. Dong, and X. Zhang, "**Impulse response modeling for underwater wireless optical communication links**," *IEEE Trans. Commun.*, vol. 62, no. 1, pp. 226-234, 2014.
[5] C. D. Mobley, B. Gentili, H. R. Gordon, Z. Jin, G. W. Kattawar, A. Morel, P. Reinersman, K. Stamnes, and R. H. Stavn, "**Comparison of numerical models for computing underwater light fields**," *Appl. Opt.*, vol. 32, no. 36, pp. 7484-7504, 1993.

Overview of Channel Modeling Methodology[6]



[6] F. Miramirkhani, and M. Uysal "**Visible light communication channel modeling for underwater environments with blocking and shadowing**," *IEEE Access*, vol. 6, no. 1, pp. 1082-1090, 2018.

Sea Surface and Sea Bottom Modeling

- We assume mud for the sea bottom and consider purely diffuse reflections.
- To characterize the reflection and refraction of transmitted rays from the sea surface, we use Fresnel equations given by

$$R_s = \left| \frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t} \right|^2 \qquad R_p = \left| \frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i} \right|^2$$

Optical Characterization of Water and Particles

- Absorption, Scattering and Extinction Coefficients
  - Gordon & Morel Model [7]

$$a(\lambda)=\left[a_w(\lambda)+0.06a_c^{*\,'}(\lambda)C_c^{\,0.65}\right]\left[1+0.2\exp\left(-0.014(\lambda-440)\right)\right]$$

$$b(\lambda)=\left(\frac{550}{\lambda}\right)0.30C_c^{\,0.62}$$

  - Haltrin & Kattawar Model [8]

$$a(\lambda)=a_w(\lambda)+a_f^0\exp\left(-k_f\lambda\right)C_f+a_h^0\exp\left(-k_h\lambda\right)C_h+a_c^0(\lambda,z)\left(C_c/C_c^0\right)^{0.602}$$

$$C_f=1.74098C_c\exp\left(0.12327\left(C_c/C_c^0\right)\right)\qquad C_h=0.19334C_c\exp\left(0.12343\left(C_c/C_c^0\right)\right)$$

$$b(\lambda)=b_w(\lambda)+b_s^0(\lambda)C_s+b_l^0(\lambda)C_l$$

$$C_s=0.01739C_c\exp\left(0.11631\left(C_c/C_c^0\right)\right)\qquad C_l=0.76284C_c\exp\left(0.03092\left(C_c/C_c^0\right)\right)$$

$$b_w(\lambda)=0.005826(400/\lambda)^{4.322}\qquad b_s^0(\lambda)=1.1513(400/\lambda)^{1.7}$$

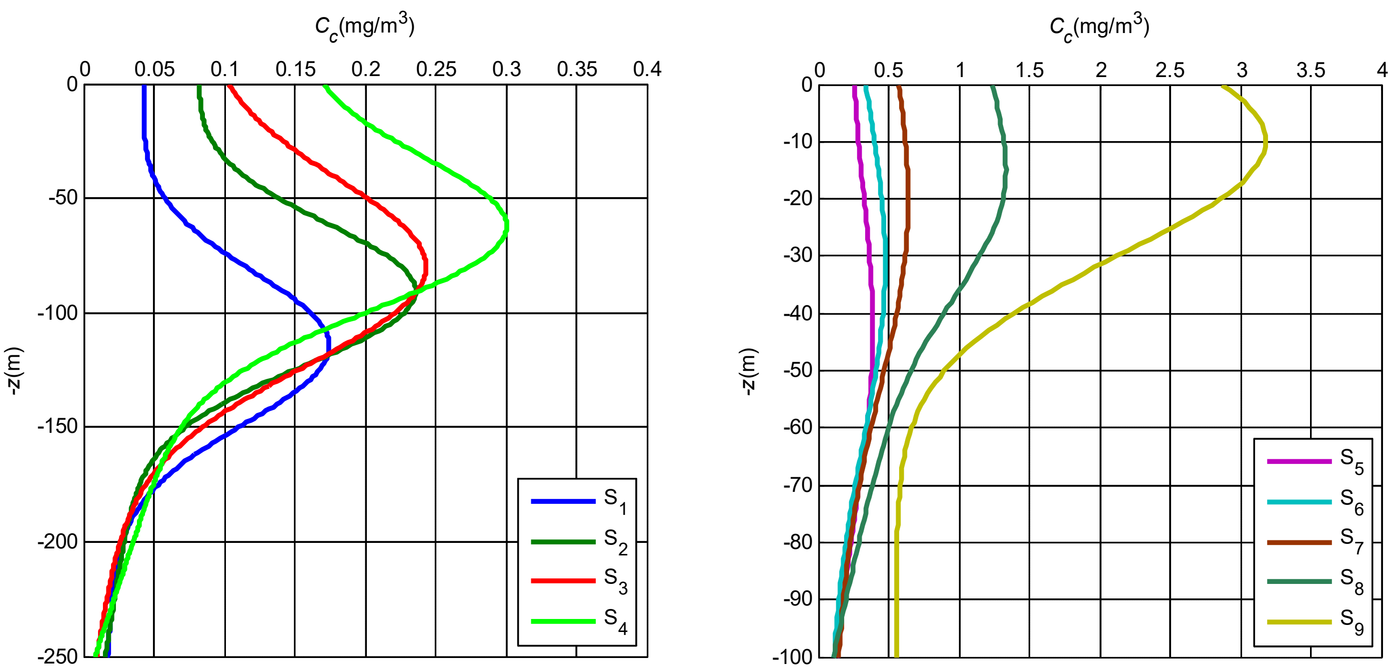
$$b_l^0(\lambda)=0.3411005826(400/\lambda)^{0.3}$$

[7] C. D. Mobley, ***Light and Water: Radiative transfer in natural waters***, Academic Press, June 1994.
[8] V. I. Haltrin, "**Chlorophyll-based model of seawater optical properties**," *Appl. Opt.*, vol. 38, no. 33, pp. 6826-6832, 1999.

Optical Characterization of Water and Particles

- Chlorophyll Concentration Depth Profiles [9]

$$C_c(z) = B_0 + Sz + \frac{h}{\sigma\sqrt{2\pi}} \exp\left[\frac{-(z - z_{\max})^2}{2\sigma^2}\right] \text{ where } \sigma = \frac{h}{\sqrt{2\pi}\left[C_{chl}(z_{\max}) - B_0 - Sz_{\max}\right]}$$



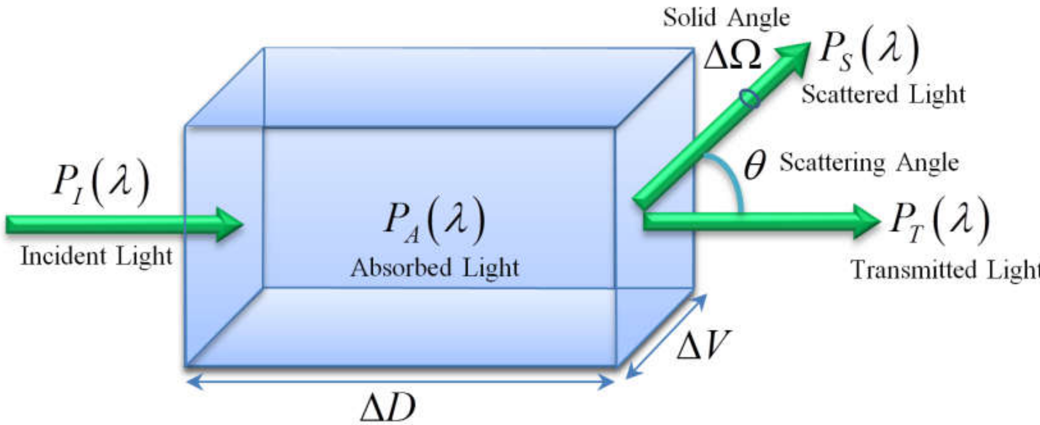
[9] L. J. Johnson, R. J. Green, and M. S. Leeson, "**Underwater optical wireless communications: depth dependent variations in attenuation**," *Appl. Opt.*, vol. 52, no. 33, pp. 7867-7873, 2013.

Scattering Phase Function

- Scattering Phase Function
  - Mie Scattering
  - One-Term Henyey-Greenstein
  - Two-Term Henyey-Greenstein

$$\beta(\theta,\lambda) = \lim_{\Delta D \to 0} \lim_{\Delta\Omega \to 0} \frac{P_S(\theta,\lambda)}{\Delta D \Delta\Omega} \qquad b(\lambda) = \int \beta(\theta,\lambda) d\Omega = 2\pi \int_0^{\pi} \beta(\theta,\lambda)\sin(\theta) d\theta$$

$$\tilde{\beta}(\theta,\lambda) = \frac{\beta(\theta,\lambda)}{b(\lambda)}$$



Channel Impulse Response (CIR)

- Based on Monte Carlo Ray Tracing.
- Sobol sampling is used for speeding up ray tracing.
- The Zemax® non-sequential ray-tracing tool generates an output file, which includes all the data about rays such as the detected power and path lengths for each ray.
- The data from Zemax® output file is imported to MATLAB® and using these information, the multipath CIR is expressed as

$$h(t) = \sum_{i=1}^{N_r} P_i \delta(t - \tau_i)$$

P_i = the power of the i^{th} ray
τ_i = the propagation time of the i^{th} ray
$\delta(t)$ = the Dirac delta function
N_r = the number of rays received at the detector

Effect of LED Response

- In addition to the multipath propagation environment, the low-pass characteristics of the LED sources should be further taken into account in channel modelling.

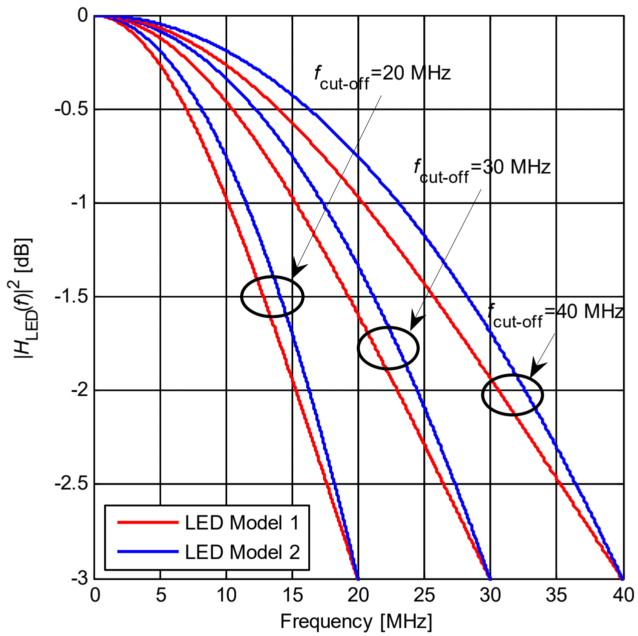
LED Model 1 [10]

$$H_{\text{LED}}(f) = \frac{1}{1 + j\dfrac{f}{f_{\text{cut-off}}}}$$

LED Model 2 [11]

$$H_{\text{LED}}(f) = e^{-\ln\left(\sqrt{2}\right)\left(\dfrac{f}{f_{\text{cut-off}}}\right)^2}$$

$f_{\text{cut-off}}$: 3 dB cut-off frequency of the LED

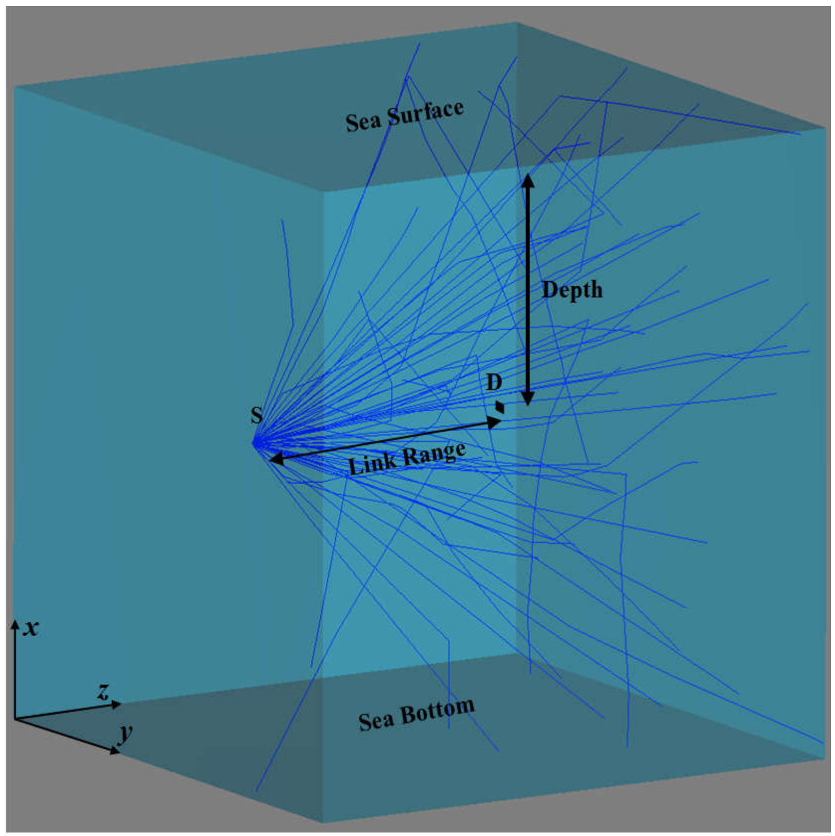


[10] L. Grobe, and K. D. Langer, "**Block-based PAM with frequency domain equalization in visible light communications**," In *IEEE Globecom Workshops (GC Wkshps)*, pp. 1070-1075, 2013.

[11] M. Wolf, S. A. Cheema, M. Haardt, and L. Grobe, "**On the performance of block transmission schemes in optical channels with a Gaussian profile**," *In 16th International Conference on Transparent Optical Networks (ICTON)*, pp. 1-8, 2014.

Simulation Scenario: Empty Sea

- We consider the scenario illustrated in figure below where the transmitter-receiver pair is placed at a depth of 45 m with 20 m distance apart in empty coastal water.

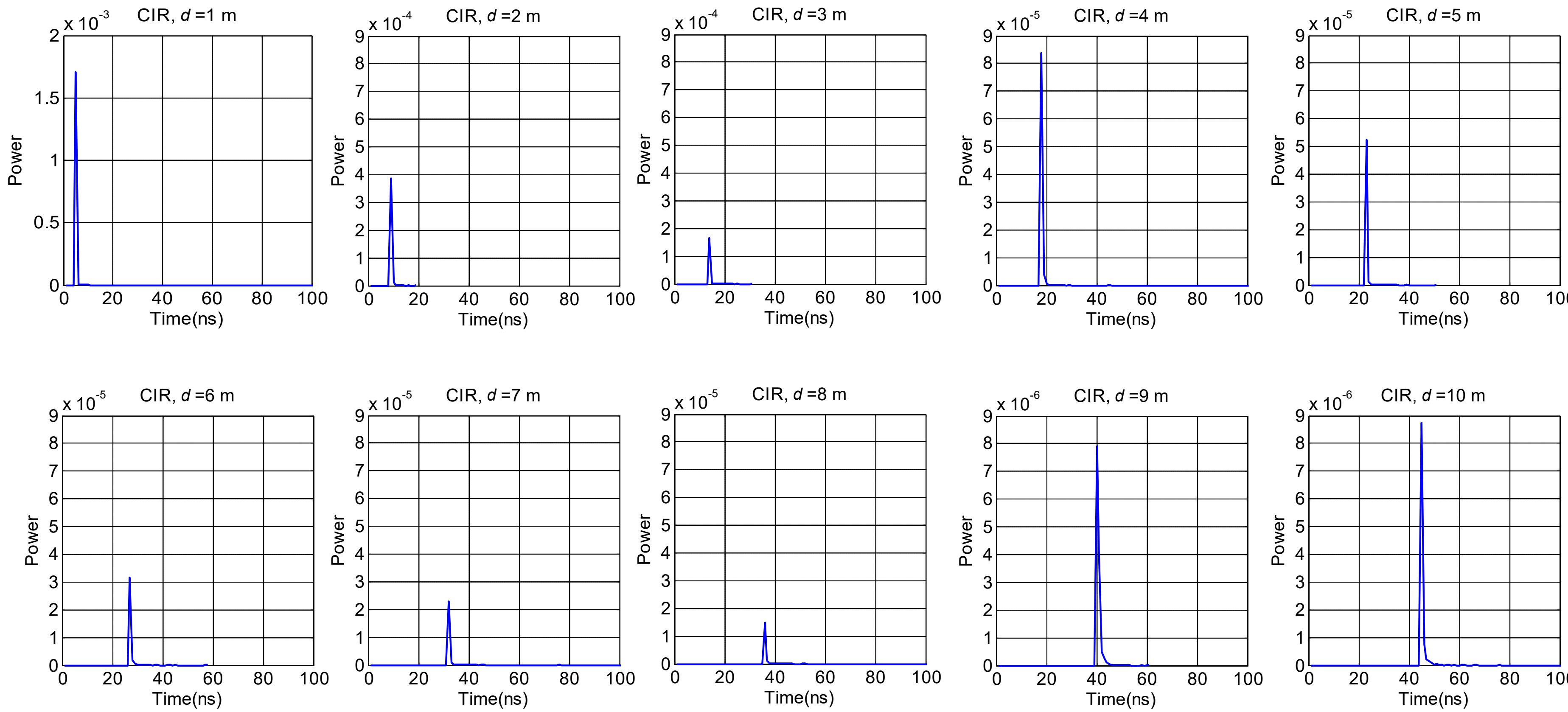


Simulation Parameters

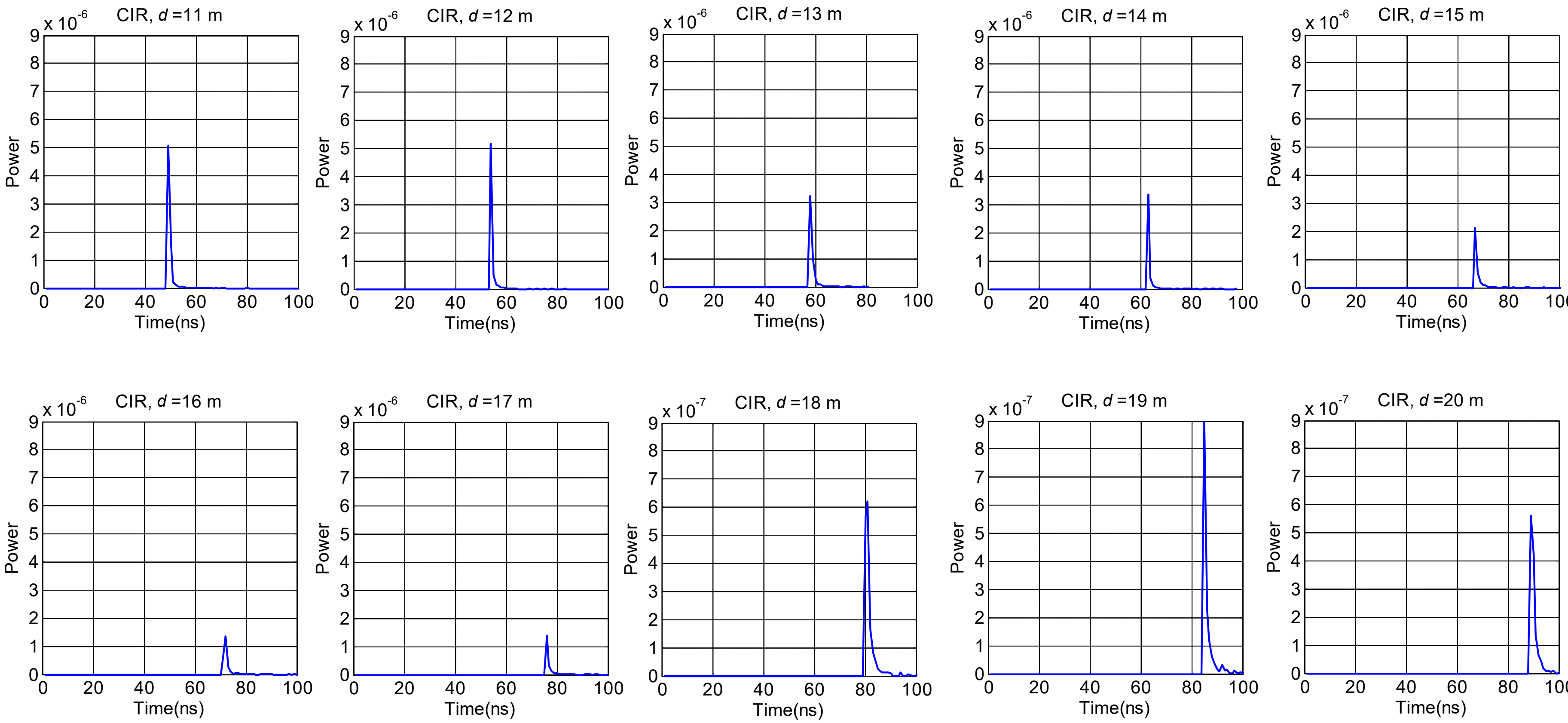
Transmitter specifications	Power: 1 Watt LED brand: Super Blue Cree® XR-E [12] Viewing angle: 60º [12]
Receiver specifications	Aperture diameter: 5 cm [13] Field of view: 180º [13]
Link Range (m)	20
Depth (m)	45
Water type	Coastal- S_8 group (C_c: 0.8~2.2 mg/m^3) [9]
Absorption, scattering and extinction coefficients (m^{-1})	0.0508, 0.2116, 0.2624
Scattering phase function	OTHG
Mean cosine of scattering angles	0.9470

[12] B. Tian, F. Zhang, and X. Tan, "**Design and development of an LED-based optical communication system for autonomous underwater robots**," In *IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics (AIM)*, pp. 1558-1563, 2013.
[13] C. Gabriel, M. A. Khalighi, S. Bourennane, P. Léon, and V. Rigaud, "**Channel modeling for underwater optical communication**," in *Proc. IEEE Global Communication Conf. (GLOBECOME'11)*, pp. 833-837, Dec. 2011.

CIR Results

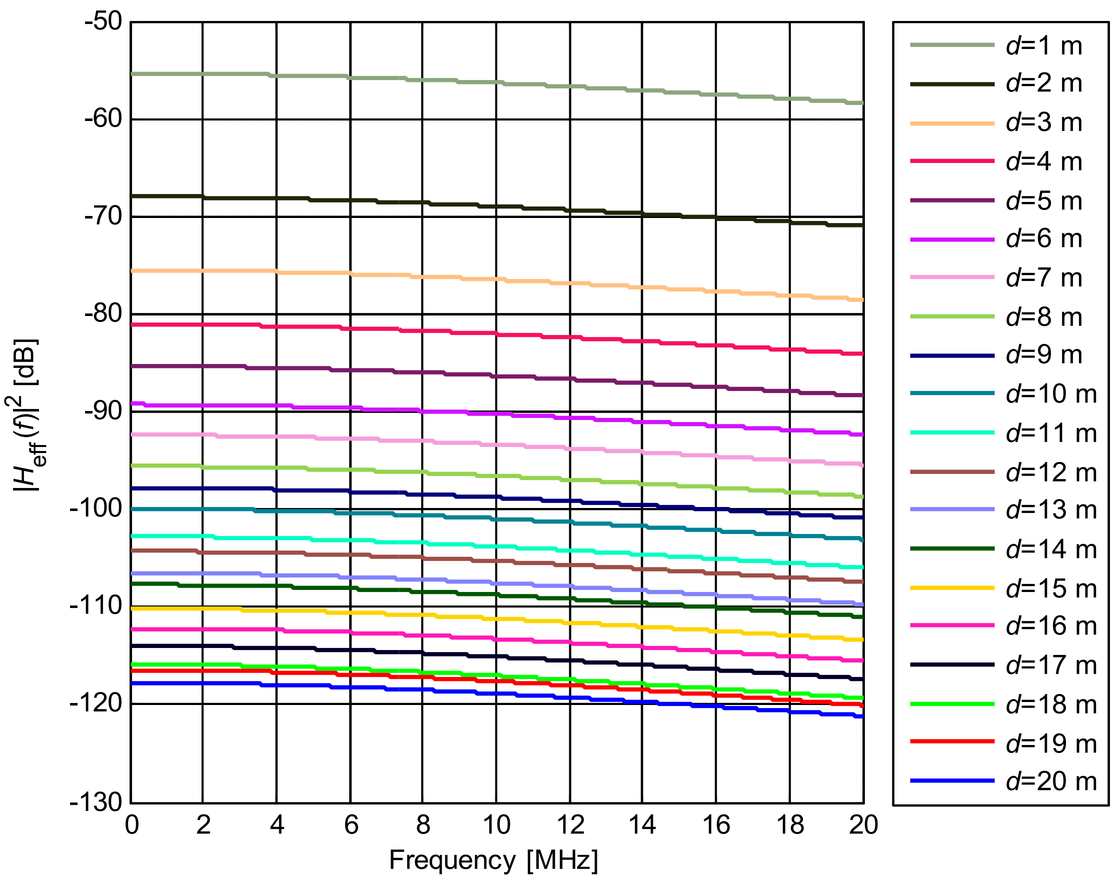

CIR, d =1 m
x 10^-3
2
1.5
1
0.5
0
Power
0 20 40 60 80 100
Time(ns)
CIR, d =2 m
x 10^-4
CIR, d =3 m
x 10^-4
CIR, d =4 m
x 10^-5
CIR, d =5 m
x 10^-5
CIR, d =6 m
x 10^-5
CIR, d =7 m
x 10^-5
CIR, d =8 m
x 10^-5
CIR, d =9 m
x 10^-6
CIR, d =10 m
x 10^-6
0 1 2 3 4 5 6 7 8 9

CIR Results


CIR, d =11 m
CIR, d =12 m
CIR, d =13 m
CIR, d =14 m
CIR, d =15 m
CIR, d =16 m
CIR, d =17 m
CIR, d =18 m
CIR, d =19 m
CIR, d =20 m
x 10^-6
x 10^-7
Power
Time(ns)

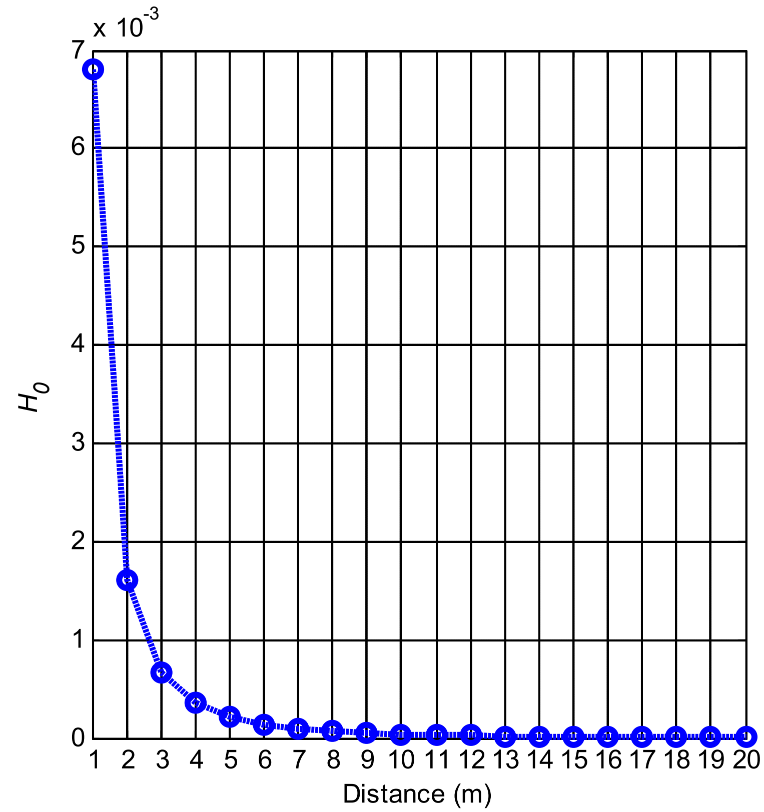
Effective Channel Responses

- For the effective channel responses, the "LED Model 1" with cut-off frequency of 20 MHz is considered.



Channel Characteristics

d (m)	τ_{RMS} (ns)	H_0
1	7.95	6.80×10^{-3}
2	7.95	1.60×10^{-3}
3	7.95	6.70×10^{-4}
4	7.97	3.53×10^{-4}
5	7.97	2.16×10^{-4}
6	7.98	1.37×10^{-4}
7	7.99	9.60×10^{-5}
8	7.99	6.64×10^{-5}
9	8.04	5.15×10^{-5}
10	8.08	4.01×10^{-5}
11	8.26	2.89×10^{-5}
12	8.08	2.43×10^{-5}
13	8.11	1.88×10^{-5}
14	8.34	1.64×10^{-5}
15	8.62	1.24×10^{-5}
16	8.32	9.82×10^{-6}
17	8.53	7.97×10^{-6}
18	8.84	6.42×10^{-6}
19	8.97	6.02×10^{-6}
20	9.54	5.19×10^{-6}



Conclusions

- This contribution proposes LiFi reference channel models for underwater environments to assist the IEEE 802.11bb.

Acknowledgement

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