**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.

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Reference Channel Models for Underwater Environments
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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.

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Overview of Channel Modeling Methodology[6]

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

\[
R_s = \left| \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} \right|^2 \quad R_p = \left| \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} \right|^2
\]
Optical Characterization of Water and Particles

- Absorption, Scattering and Extinction Coefficients
  - Gordon & Morel Model [7]
    \[
    a(\lambda) = a_w(\lambda) + 0.06a_c^*(\lambda)C_c^{0.65}[1 + 0.2 \exp(-0.014(\lambda - 440))] \\
    b(\lambda) = \left(\frac{550}{\lambda}\right)0.30C_c^{0.62}
    \]
  - Haltrin & Kattawar Model [8]
    \[
    a(\lambda) = a_w(\lambda) + a_f^0 \exp(-k_f\lambda)C_f + a_h^0 \exp(-k_h\lambda)C_h + a_c^0(\lambda,z)\left(C_c/C_c^0\right)^{0.602} \\
    C_f = 1.74098C_c \exp\left(0.12327\left(C_c/C_c^0\right)\right) \\
    C_h = 0.19334C_c \exp\left(0.12343\left(C_c/C_c^0\right)\right) \\
    b(\lambda) = b_w(\lambda) + b_s^0(\lambda)C_s + b_l^0(\lambda)C_l \\
    C_s = 0.01739C_c \exp\left(0.11631\left(C_c/C_c^0\right)\right) \\
    C_l = 0.76284C_c \exp\left(0.03092\left(C_c/C_c^0\right)\right) \\
    b_w(\lambda) = 0.005826(400/\lambda)^{4.322} \\
    b_s^0(\lambda) = 1.1513(400/\lambda)^{1.7} \\
    b_l^0(\lambda) = 0.3411005826(400/\lambda)^{0.3}
    \]

Optical Characterization of Water and Particles

- Chlorophyll Concentration Depth Profiles [9]

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

where \( \sigma = \frac{h}{\sqrt{2\pi} \left[ C_{\text{chl}}(z_{\text{max}}) - B_0 - Sz_{\text{max}} \right]} \)

Scattering Phase Function

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

\[
\beta(\theta, \lambda) = \lim_{\Delta D \to 0} \lim_{\Delta \Omega \to 0} \frac{P_s(\theta, \lambda)}{\Delta D \Delta \Omega} \quad b(\lambda) = \int \beta(\theta, \lambda) d\Omega = 2\pi \int_0^\pi \beta(\theta, \lambda) \sin(\theta) d\theta
\]

\[
\tilde{\beta}(\theta, \lambda) = \frac{\beta(\theta, \lambda)}{b(\lambda)}
\]
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
- \( \tau_i \) = 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]**

\[
H_{LED}(f) = \frac{1}{1 + j \frac{f}{f_{cut-off}}}
\]

**LED Model 2 [11]**

\[
H_{LED}(f) = e^{-\ln(\sqrt{2}) \left( \frac{f}{f_{cut-off}} \right)^2}
\]

\(f_{cut-off}\): 3 dB cut-off frequency of the LED


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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- S₈ group (Cₖ: 0.8~2.2 mg/m³) [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                           |


CIR Results

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CIR Results

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Effective Channel Responses

For the effective channel responses, the “LED Model 1” with cut-off frequency of 20 MHz is considered.
## Channel Characteristics

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<th>$\tau_{RMS}$ (ns)</th>
<th>$H_0$</th>
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Conclusions

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

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