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Underwater Optical Communication Module: An Extension to the ns-3 Network Simulator

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***Abstract*—In the last decade, the field of wireless optical communication has gathered immense interest due to its adoption in growing bandwidth-hungry underwater applications. The expensive and non-standardized on-field research measurements call for a reliable simulation tool that allows researchers to realistically design and assess the performance of Underwater Optical Communication (UOC) systems before conducting actual underwater experiments. In this paper, we present a UOC module as an extension to the network simulator ns-3. The module can study the impact of different water conditions on underwater optical networks from the physical layer to the network layer. The proposed UOC module realizes physical layer models of the UOC channels where the added noise and interference effects are modeled as Additive White Gaussian Noise (AWGN). Results show the capability of our module to facilitate large underwater optical network design and optimization. Since ns-3 is an open-source software, the module has the flexibility and reusability to be further developed by the worldwide research community.**

***Index Terms*—Underwater Optical Communication, Channel Models, Network Simulator, ns-3.**

I. Introduction

Wireless optical signals have become the new alternative to radio frequency and acoustics due to their massive bandwidth, availability, efficiency, and security in underwater data communication. One of the common applications of UOC is in short-range communication between an underwater sensor node and a data mule. In data mulling, an Autonomous Underwater Vehicle (AUV) hovers around a predefined trajectory to locate sensor nodes and collect data from them [1]. With high wireless optical data rates, the sensor node can offload the data to an AUV with shorter delays and lesser end-to-end energy consumption. With the rapid increase in research related to the design and development of underwater optical networks, a software-based tool for evaluating their performance is in high demand. In this aspect, network simulators play an important role in objectively evaluating the performance of such networks. Simulators specifically designed for underwater networks include SUNSET [2], Aqua-Sim [3], Aqua-Sim Next Generation [4], and Underwater Acoustic Network (UAN) framework for ns-3 [5]. Additionally, some other network simulators currently available, i.e., OMNET++, ns-2, ns-3, OPNET, MATLAB, and NetSim have the models to design and evaluate the performance of large wired and wireless networks. However, none of them is capable of simulating a UOC network. Therefore, the need for a highly accurate and scalable network simulator for analyzing different network conditions, and applications of underwater optical networks is critical.

To the best of our knowledge, there is no state-of-the-art network simulator available for the design and testing of underwater optical wireless networks apart from DESERT [6] which is built on ns-2. However, developments related to ns-2 nearly stopped more than a decade ago after the advent of ns-3. This motivated us to develop a UOC module for ns-3 capable of efficiently simulating characteristics such as optical channel attenuation and packet collisions in underwater wireless communication systems. ns-3 is an open-source, discrete event network simulator developed in C/C++ and Python that is actively being developed and maintained. It provides application programming interfaces (APIs) that allow different types of wired and wireless networks to connect with the network entities and respective applications. Following are some key facts about ns-3 that led us to create the UOC module in ns-3.

1) Since 2016, the number of researchers, users, and developers using ns-3 has significantly increased with an active online community [7].
2) ns-3 has the essential libraries that help developers create new modules and integrate them with the ns-3 core.
3) It provides the flexibility to design networks and devices close to the real networks in terms of performance and functionality, making the evaluation of such networks reliable. Also, it has a diverse range of radio access technologies and communication protocols.
4) Object Oriented Programming (OOP) as the main programming language simplifies the task of connecting and organizing different system components in a hierarchical system model. Moreover, a user-friendly compiler interface, debugging, and visualization tools extensively help in coding and debugging.

In this work, we design a new open-access module, the "UOC module" as an extension to the ns-3 core libraries. We aim to study the performance of the physical layer as well as discuss its impact on the network layer for underwater optical networks. The main features of the UOC module are as follows:

1) The module implements a UOC channel model, propagation loss model, signal-to-noise ratio (SNR) model, error model, and transmitter and receiver NetDevice

models to emulate distinct characteristics of an underwater optical system.
2) The module can evaluate the performance of a point-to-point (p2p) UOC system through SNR, bit error rate (BER), and packet error rate (PER) models for On-Off Keying (OOK) modulation.
3) The module can simulate UOC in different water types such as pure sea, coastal ocean, clean ocean, and turbid harbor. The purpose is to demonstrate the impact of different water conditions such as turbidity, attenuation, and temperatures on the received optical signal.

The rest of the paper is organized as follows: In section II, we describe the theoretical model of a UOC channel. Section III presents the main features of UOC module design in ns-3. Section IV provides details of the implemented scenario followed by a discussion on the simulation results to evaluate the performance of UOC module. In section V, we conclude our work.

II. Theoretical Model of a UOC channel

The design of a UOC channel is an extension of the traditional free-space visible light communication design. However, the magnitude of scattering and absorption in underwater applications is many times greater than in free space. A UOC channel can be modeled as an AWGN channel [8]:

$$y\left(t\right) = x\left(t\right) * h\left(t\right) + n\left(t\right). \tag{1}$$

where $x\left(t\right)$ is the instantaneous optical signal emitted from an optical transmitter with the transmitting power P_o (Watts) and has traveled through the channel with an impulse response $h\left(t\right)$ and $n\left(t\right)$ represents the AWGN. AWGN is generally used to represent channels whose only source of impairment added to the channel is a wideband noise with a Gaussian distribution and uniform spectral density over the frequency band. Although the AWGN model does not count for the fading, dispersion, and multiple scattering which are all particularly present in the underwater channel, the AWGN model is used to design a simple and flexible mathematical model to determine the underlying behavior of a UOC channel.

A. Light Propagation Underwater

The total attenuation of the light beam underwater is measured with the attenuation coefficient c_o as:

$$P = P_o e^{-c_o d}, \tag{2}$$

where P is the light power collected at the receiver that is d distance away from the transmitter, P_o is the transmitter emitted light power and c_o is the attenuation coefficient:

$$c_o\left(\lambda\right) = a\left(\lambda\right) + b\left(\lambda\right), \tag{3}$$

While propagating through the water, absorption $a\left(\lambda\right)$ causes the light beam to lose its energy; however, scattering $b\left(\lambda\right)$ changes the direction of the light beam. Absorption and attenuation are dependent on the wavelength of light λ, whereas scattering depends on the turbidity of water as well as the light wavelength. Other effects such as dispersion, turbulence, and inter symbol interference (ISI) caused due to multi-scattering of the light beam should also be considered. Albeit these elements influence the propagation of light underwater, they are hard to be represented accurately. Given the variation of water quality and its widely changing optical properties, the underwater environment is hard to be modeled. In propagation studies, ocean water types are generally differentiated based on their attenuation coefficient [9]. A simple yet appropriate generalization is to use the light beam attenuation coefficient c_o to model the effect of turbidity on light propagation underwater. Also, the existing literature can provide useful data for attenuation coefficient attained from in-situ underwater exploration and even from satellite remote sensing [9]–[11].

Considering a line-of-sight (LOS) link configuration between an optical transmitter and receiver, the total optical power for a single light source propagated to the receiver is derived using Eq. 2 and is given as:

$$P = \frac{2P_o A_r \cos\beta}{\pi d^2\left(1-\cos\theta\right) + 2A_t} \cdot e^{-c_o d}. \tag{4}$$

It combines the attenuation coefficient c_o, transmitter and receiver geometric parameters, including beam divergence angle θ, area of the light source and photodiode A_t, and A_r respectively, and receiver's inclination with respect to the light beam β.

B. Optical Noise and Channel Characteristics

Like all other terrestrial communication channels, UOC is also affected by noise. The additive noise modeled in our channel includes the external and internal sources [12]. They are (1) dark current noise, (2) shot noise, and (3) thermal noise.

*1) **Dark Current Noise**:* The source of the dark current is at the receiver (photodiode). It is caused due to reverse leakage current. It is defined as:

$$i_{DC} = \sqrt{2qI_D B}\cdot \tag{5}$$

where q is the electronic charge, I_D is the dark current of the receiver (Ampere), and B is the system's bandwidth (Hertz).

*2) **Shot Noise**:* The noise is produced by the incident light itself and is represented as:

$$i_{SH} = \sqrt{2qI_L B}\cdot \tag{6}$$

where $I_L = S \cdot P$ is the light current produced by the incident light (Ampere), S is the sensitivity of the receiver (Ampere/watts), and P is the received power (Watts).

*3) **Thermal Noise**:* It is also known as the Johnson noise and is associated with the shunt resistance R (Ohm).

$$i_{TH} = \sqrt{\frac{4KTB}{R}}\cdot \tag{7}$$

where T is the temperature of the environment (Kelvin), and K is the Boltzmann constant.

The total noise added to the system is the sum of all the noises $i_{noise} = i_{DC} + i_{SH} + i_{TH}$. The respective channel capacity and SNR are given by Eq. 8 and 9.

$$C = B \cdot \log_2\left(1 + SNR\right). \tag{8}$$

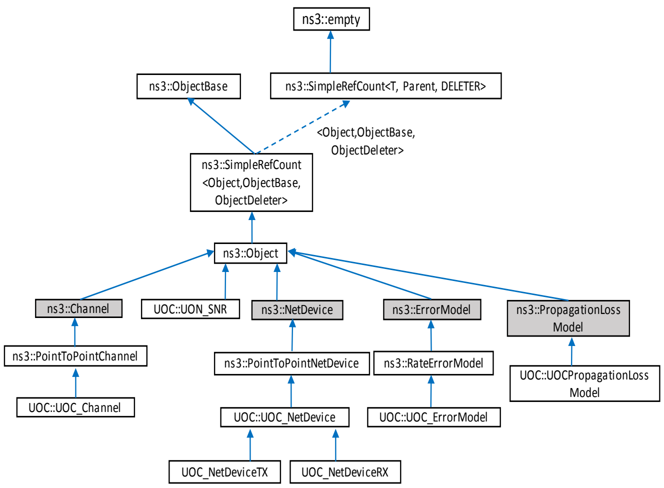


Fig. 1: Class inheritance diagram for the UOC Channel, NetDevice, Error, SNR, and Propagation Loss Models.

$$SNR = \frac{i_L^2}{i_{noise}^2}, \tag{9}$$

The SNR of a common Si PIN photodiode is given as:

$$SNR = \frac{(P \cdot S)^2}{2q(I_D + I_L)B + \frac{4KTB}{R}}. \tag{10}$$

Note this noise model does not include background noise generated from the solar irradiance and blackbody radiation. We assume our system for deep-sea explorations and nighttime procedures.

III. The UOC Module

The UOC module is built for simulating underwater optical networks using ns-3. The main idea is to provide a communication channel between nodes, which enables wireless optical communication underwater and is able to follow specific communication protocols within a network domain. For this purpose, a very similar channel exists in ns-3 which is known as the ns-3 PointToPoint channel. Similar to a wired p2p connection in which two devices are connected directly to one another, an underwater optical network also contains devices connected through a dedicated wireless optical channel. Due to this similarity, the main classes of our module are inherited from the existing ns3::PointToPoint class. The class inheritance diagram in Figure 1, further elaborates the relation between classes. A few new classes are also introduced but the main focus was to reuse the existing ns-3 methods. Our module adheres to the ns-3 format and naming conventions and is written in C++. Further details about module integration to ns-3 core and its use can be found at *https://github.com/RabiaTuni/UOC-module-for-ns-3.git*.

A. UOC Helpers

Helpers are created in our module to simplify the design and upgrading of large and complex UOC networks. Our helper directory comprises of two helper classes, i.e., UOC Channel and UOC Device helper. The UOC Channel helper manages tasks related to underwater optical communication channel creation. It contains appropriate methods for installing the channel, attaching the transmitter and receiver net devices, and setting channel parameters, such as wavelength. Using this helper, specific attributes of the propagation loss model such as propagation delay and SNR are also controlled. The UOC channel helper connects the underwater optical channel to two UOC net devices; however, the UOC Device helper handles this connection. It enables developers to change the transmitter and receiver attributes at runtime. The most common attributes are data rate, bias voltage, Field-of-View (FoV), photodetector area, refractive index, angle of incidence, and modulation scheme. It also manages transmitter and receiver positions, and generation and transmission of an optical signal between the UOC nodes.

B. UOC Models

The UOC model directory comprises the optical communication models and methods which are necessary for accurate simulation.

1) UOC Channel Model: The UOC channel class depicts an instance of the underwater optical channel and encompasses the required optical characteristics. We have extended the ns-3 p2p channel by introducing the UOC propagation loss model. The principle is to design a channel model that acts as an optical wireless communication channel between two nodes but also keeps track of the signal corrupting factors that are reflected through the channel SNR. Every time a packet is transmitted across this channel, the SNR model calculates the signal corruption; thus providing an on-the-go corruption computation model. This enables the module to reflect the channel's frequent variations at run time. The main parameters of the UOC channel model are propagation loss and delay, the distance between optical transmitters and receivers, received power, and SNR. The propagation loss is a pointer that points to the desired propagation loss model. Whereas, delay defines the transmission delay of the channel.

2) UOC Propagation Loss Model: The propagation loss model takes the transmitted optical power and the distance between the transmitter and receiver devices, photodetector area, transmitter beam divergence a.k.a. semiangle, transmitter size, and attenuation coefficient to calculate the received power as defined in Eq. 4. Other methods of this class include setting the transmitted and received power and getting the distance between communicating nodes.

3) UOC SNR Model: The UOC SNR model is an ns-3 object that computes the channel's SNR based on the calculated optical received power given in Eq. 4. Total noise variance and average received optical power signal are the private members of this class. The sensitivity of the receiver, electronic charge, Boltzmann constant, dark current of the receiver, photodiode shunt resistance, and system bandwidth are defined as static constants. Shot noise variance and thermal noise variance are calculated on the go and are added to total noise variance which is used in calculating the SNR along with the received optical power signal.

4) UOC Transmitter NetDevice: The UOC transmitter net device class represents a typical optical signal transmitter in a UOC network. It is inherited from the UOC NetDevice class which is derived from the ns3::NetDevice class; therefore, it contains the typical attributes of a net device along with device coordinates needed in a UOC network. The private members of this class are maximum transmitter optical power, instantaneous optical power, transmitter beam divergence, and bias power. The UOC module implements the Intensity Modulation/Direct Detection (IM/DD) method which represents an optical signal by following the variations in the instantaneous power. Finally, the received optical signal is directly converted to an electrical signal at the receiver. The optical transmitter has a maximum instantaneous transmit power in watts. However, at any time instance t, it produces an instantaneous optical power $y(t)$ in watts, restricted by $0 \leq y(t) \leq Tp_{max}$.

5) UOC Receiver NetDevice: The UOC receiver net device class represents a typical optical signal receiver in a UOC network. Similar to the transmitter net device it is derived from the ns3::NetDevice class; thus, inherits all the attributes of a typical ns-3 net device along with the receiver coordinates needed in a UOC network. Keeping in mind the elements of an actual optical receiver, e.g., a pin photodiode, we have added FoV, photodetector area, refractive index, angle of incidence, received optical power, and receiver error model as private members of the class. These members have associated setter and getter methods and are used to simulate a specific type of receiver. The instantaneous values of the received signal power are calculated through the propagation loss model during signal transmission through the UOC channel. The UOC error model then determines the error rate of the transmission using the received optical power.

6) UOC Error Model: The module in its current form has a simple error model inherited from the ns-3 RateError model. We have studied our channel's behavior under On-Off-Keying (OOK) modulation. Our error model gets the calculated SNR from the SNR model and modulation type to calculate the BER as defined in the following equation:

$$BER_{OOK} = \frac{1}{2} erfc\left[\frac{\sqrt{SNR}}{2}\right]. \tag{11}$$

To use this definition of BER, we have assumed that the UOC channel is subject to AWGN given in Eq. 1. The *erfc* is the complementary error function defined as

$$erfc(n) = \frac{2}{\sqrt{\pi}} \int_{n}^{\infty} \exp\left[-t^2\right] dt. \tag{12}$$

It is implemented using ns-3's built-in function *erfc* with std library. The model also calculates the PER of an *m* bits long packet to verify the receiver sensitivity using the BER information as defined by [13]:

$$PER = 1 - (1 - BER)^m. \tag{13}$$

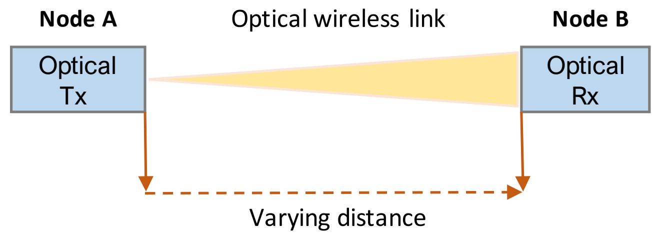


Fig. 2: Simulated scenario

IV. Performance Evaluation

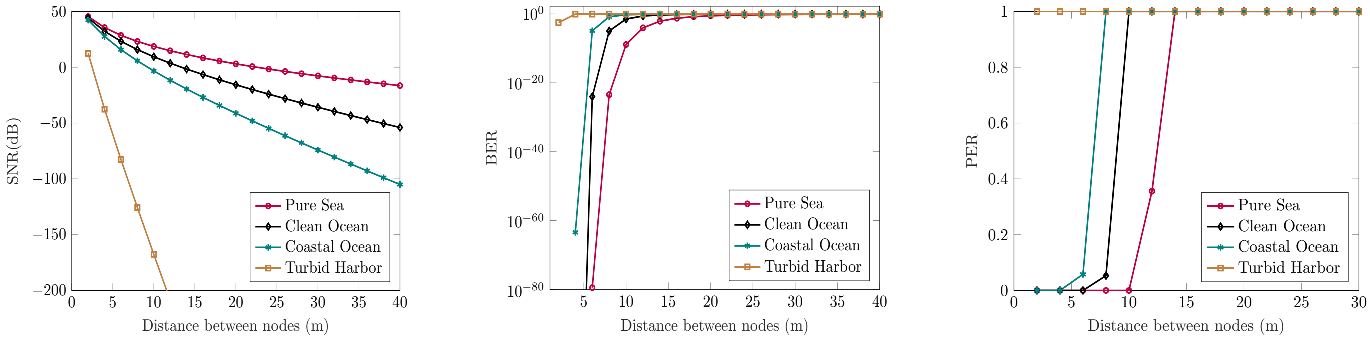
To evaluate the performance of our module, we simulate a p2p underwater optical system. In this configuration, we consider two nodes as shown in Figure 2, where node A represents an optical transmitter, e.g., a light emitting diode (LED), and node B represents an optical receiver such as a photodiode. The UOC transmitter NetDevice class is used to create the optical source by assigning transmitter parameters to node A and the UOC receiver NetDevice class is used for creating the optical receiver by employing receiver parameters at node B. The UOC channel is attached to nodes A and B for connecting them. Internet Protocol version 4 (IPv4) is used to assign IP addresses to both nodes and ns-3 static routing is implemented for directing the data packets in one direction from source to receiver. Table I provides the values for simulation parameters used in this experiment.

TABLE I: Optical Parameters: Notations and Values [14]

Parameter	Notation	Value
Max. transmission power	P_o	100 W
System Bandwidth	B	100 kHz
Transmitter Area	A_t	10 mm^2
Receiver Area	A_r	1.1 mm^2
Transmitter beam divergence	θ	0.5 rad
Attenuation Coefficient	c_o	0.043 m^{-1}
Receiver sensitivity	S	0.26 A/W
Electronic charge	q	1.6×10^{-19} C
Boltzmann Constant	K	1.38×10^{-23} J/K
Receiver's Dark current	I_D	1 nA
Shunt resistance	R	1.43×10^{9} Ω
Water Temperature	T	286^o K

A. Simulation Results

In this section, we discuss the performance of our simulator in terms of SNR, BER, and PER. In the simulated environment, the transmitter and receiver are aligned parallel to each other, and the distance between Node A and Node B is varied from 2 to 40 meters. The results are obtained for four different water types, i.e., pure sea, clear ocean, coastal ocean, and turbid harbor. A total of 1×10^5 bytes were sent from transmitter to receiver in one simulation, where each packet contains 1024 bytes of payload using a UDP connection.



(a) (b) (c)

Fig. 3: Simulator (a) SNR, (b) BER, and (c) PER using OOK modulation for varying distance between transmitter and receiver.

The results for the SNR, BER, and PER versus varying distances for OOK modulation are shown in Figures 3a, 3b, and 3c respectively. The results in Figure 3a show that the SNR is nearly the same at shorter distances for all water types except for turbid harbor water. This is intuitive since harbor water has the highest level of absorption and scattering components that deteriorate the received signal strength. As the distance increases, the received optical power decreases, resulting in lower SNR values. The BER is derived using Eq. 11 and is a function of the channel's SNR. As the channel SNR drops, the BER also increases and remains 10^{-2} after 15 m (See Figure 3b). Since the packet corruption occurs according to the BER, a similar trend is observed in Figure 3c, where the PER drops after 6 m for the coastal ocean, 8 m for the clean ocean, and after 14 m for pure sea water type.

V. Conclusion

In this paper, we present an ns-3-based module that can be used to study standalone underwater optical systems as well as extended for hybrid optical-acoustic networks. The motivation behind this research was the unavailability of network simulators that can help to study large and complex underwater optical communication systems. Our module is validated by deriving the SNR, BER, and PER against the varying distance between two p2p nodes connected through the UOC channel. Results indicate good agreement with the theoretical phenomena of wireless optical communication limited by short transmission range and higher attenuation at longer distances due to absorption and scattering effects of the underwater channel. In our future work, we plan to extend the module by adding a packet rejection mechanism based on PER and improve the BER performance through error correction methods. We also plan to study the characteristics of large underwater optical networks incorporating new combinations of UOC physical channels and modulation schemes using the developed UOC module.

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