NetSim®

Accelerate Network R & D

UWAN

Underwater Acoustic Networks

A Network Simulation & Emulation Software

By

TETCOS LLP

The information contained in this document represents the current view of TETCOS LLP on the issues discussed as of the date of publication. Because TETCOS LLP must respond to changing market conditions, it should not be interpreted to be a commitment on the part of TETCOS LLP, and TETCOS LLP cannot guarantee the accuracy of any information presented after the date of publication.

This manual is for informational purposes only.

The publisher has taken care in the preparation of this document but makes no expressed or implied warranty of any kind and assumes no responsibility for errors or omissions. No liability is assumed for incidental or consequential damages in connection with or arising out of the use of the information contained herein.

Warning! DO NOT COPY

Copyright in the whole and every part of this manual belongs to TETCOS LLP and may not be used, sold, transferred, copied or reproduced in whole or in part in any manner or in any media to any person, without the prior written consent of TETCOS LLP. If you use this manual you do so at your own risk and on the understanding that TETCOS LLP shall not be liable for any loss or damage of any kind.

TETCOS LLP may have patents, patent applications, trademarks, copyrights, or other intellectual property rights covering subject matter in this document. Except as expressly provided in any written license agreement from TETCOS LLP, the furnishing of this document does not give you any license to these patents, trademarks, copyrights, or other intellectual property. Unless otherwise noted, the example companies, organizations, products, domain names, e-mail addresses, logos, people, places, and events depicted herein are fictitious, and no association with any real company, organization, product, domain name, email address, logo, person, place, or event is intended or should be inferred.

Rev 15.0, Mar 2026, TETCOS LLP. All rights reserved.

All trademarks are property of their respective owner.

Contact us at

TETCOS LLP

214, 39th A Cross, 7th Main, 5th Block Jayanagar,

Bangalore - 560 041, Karnataka, INDIA.

Phone: +91 80 26630624

E-Mail: sales@tetcos.com

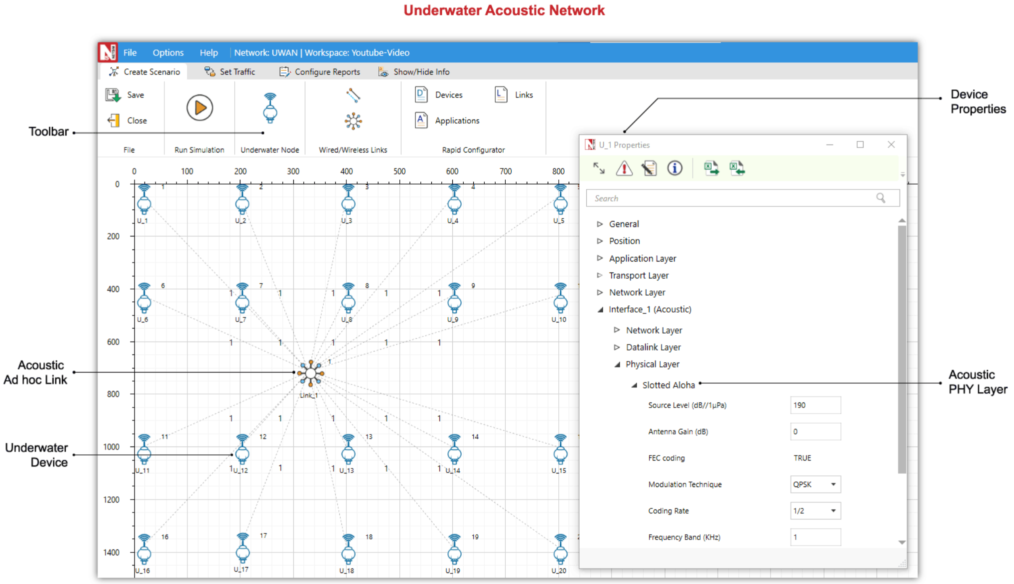
Visit: www.tetcos.com

Contents

1 Introduction

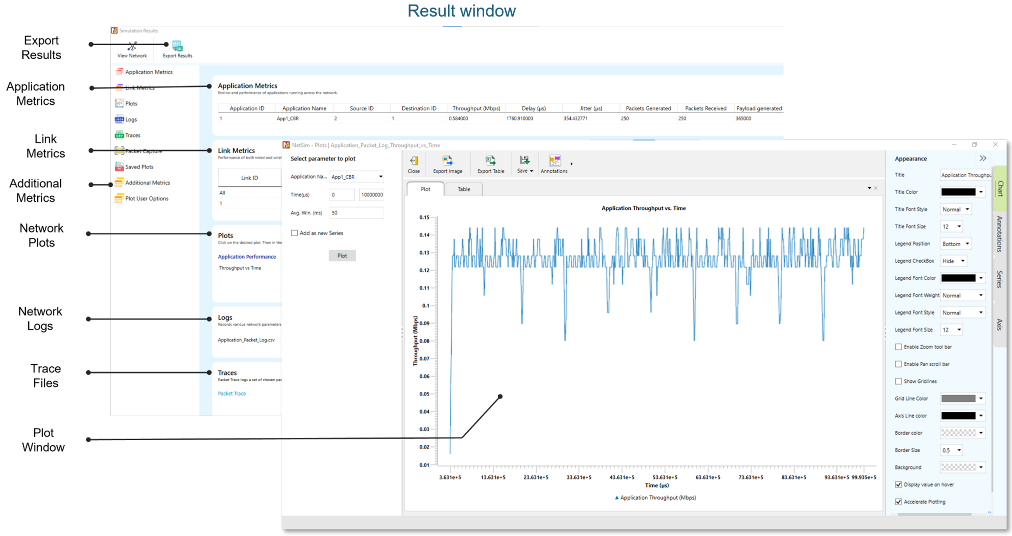
Water covers 71% of the Earth. Underwater communication is essential for a wide assortment of applications covering defence, environmental monitoring, commercial exploration, and scientific discovery. Severe attenuation in water limits the range of electromagnetic, optical and magnetic induction-based communications to just a few meters, leaving acoustic communications as the de facto means for wireless data transfer across tens of kilometers.

NetSim's UWAN library enables users to design, simulate and analyze performance of underwater networks that use acoustic communication.



Source Level (dB//1µPa) 190
Antenna Gain (dB) 0
FEC coding TRUE
Modulation Technique QPSK
Coding Rate 1/2
Frequency Band (KHz) 1

Figure 1-1: *Underwater Acoustic Network in NetSim GUI showing the network setup, device properties, and acoustic PHY layer configuration.*



Application Metrics

Application ID	Application Name	Source ID	Destination ID	Throughput (Mbps)	Delay (µs)	Jitter (µs)	Packets Generated	Packets Received	Payload generated
1	App1_CBR	2	1	0.584000	1760.910000	354.432771	250	250	365000

Link Metrics

Link ID
All
1

Application Na... App1_CBR
Time(µs) 0 10000000
Avg. Win. (ms) 50
☐ Add as new Series

Title Application Throughput
Title Font Style Normal
Title Font Size 12
Legend Position Bottom
Legend CheckBox Hide
Legend Font Weight Normal
Legend Font Style Normal
Legend Font Size 12
☐ Enable Zoom tool bar
☐ Enable Pan scroll bar
☐ Show Gridlines
Border Size 0.5
☑ Display value on hover
☑ Accelerate Plotting

Figure 1-2: *NetSim Design Window and the Result dashboard and Plot window shown in NetSim after completion of simulation.*

NetSim UWAN simulations are full stack with all 5 layers of the TCP/IP stack being supported as explained below:

- L5, Application: Users can model various kinds of applications as explained in section 3.4. This library supports a new (and default) underwater sensor application - with small packet sizes (order of 10s of Bytes), and large inter-packet arrival times (orders of seconds) - that parallels typical underwater applications.
- L4, Transport: UDP Protocol is supported. TCP is not provided as an option since it is not used in UWAN applications, due to the very low communication bit rates and the high propagation delays.
- L3, Network: Static routing is supported.
- L2, Data Link: Slotted-aloha protocol is supported.
- L1, Physical: Specialized underwater acoustic PHY model and the Thorp propagation model, are supported. Omni directional antennas are assumed.

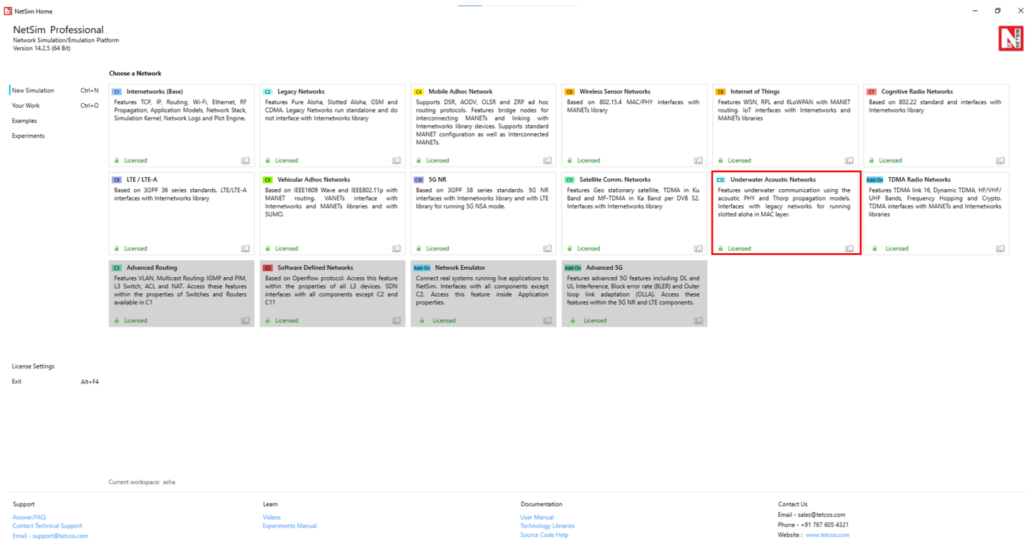
UWAN is architected to interface with NetSim component 2 (Legacy networks) which provides L2 functionality and component 3 (Advanced switching and routing) which provides the L3 static routing functionality.

The UWAN library is available as Component 12 and is currently available only in NetSim Standard and NetSim Pro versions. Protocol source C code is open to users; it is modular and customizable to help researchers to design and test their own UWAN protocols.

2 Simulation GUI

2.1 Create Scenario

Open NetSim and click New Simulation > Underwater Acoustic Networks as shown in Figure 2-1.



C1 Internetworks (Base)
Features TCP, IP, Routing, Wi-Fi, Ethernet, RF Propagation, Application Models, Network Stack, Simulation Kernel, Network Logs and Plot Engine.
Licensed

C2 Legacy Networks
Features Pure Aloha, Slotted Aloha, GSM and CDMA. Legacy Networks run standalone and do not interface with Internetworks library
Licensed

C4 Mobile Adhoc Network
Supports DSR, AODV, OLSR and ZRP ad hoc routing protocols. Features bridge nodes for interconnecting MANETs and linking with Internetworks library devices. Supports standard MANET configuration as well as Interconnected MANETs.
Licensed

C6 Wireless Sensor Networks
Based on 802.15.4 MAC/PHY interfaces with MANETs library
Licensed

C6 Internet of Things
Features WSN, RPL and 6LoWPAN with MANET routing. IoT interfaces with Internetworks and MANETs libraries
Licensed

C7 Cognitive Radio Networks
Based on 802.22 standard and interfaces with Internetworks library
Licensed

C8 LTE / LTE-A
Based on 3GPP 36 series standards. LTE/LTE-A interfaces with Internetworks library
Licensed

C9 Vehicular Adhoc Networks
Based on IEEE1609 Wave and IEEE802.11p with MANET routing. VANETs interface with Internetworks and MANETs libraries and with SUMO.
Licensed

C10 5G NR
Based on 3GPP 38 series standards. 5G NR interfaces with Internetworks library and with LTE library for running 5G NSA mode.
Licensed

C11 Satellite Comm. Networks
Features Geo stationary satellite, TDMA in Ku Band and MF-TDMA in Ka Band per DVB S2. Interfaces with Internetworks library
Licensed

C12 Underwater Acoustic Networks
Features underwater communication using the acoustic PHY and Thorp propagation models. Interfaces with legacy networks for running slotted aloha in MAC layer.
Licensed

Add-On TDMA Radio Networks
Features TDMA link 16, Dynamic TDMA, HF/VHF/UHF Bands, Frequency Hopping and Crypto. TDMA interfaces with MANETs and Internetworks libraries
Licensed

C3 Advanced Routing
Features VLAN, Multicast Routing: IGMP and PIM, L3 Switch, ACL and NAT. Access these features within the properties of Switches and Routers available in C1
Licensed

C5 Software Defined Networks
Based on Openflow protocol. Access this feature within the properties of all L3 devices. SDN interfaces with all components except C2 and C11
Licensed

Add-On Network Emulator
Connect real systems running live applications to NetSim. Interfaces with all components except C2. Access this feature inside Application properties.
Licensed

Add-On Advanced 5G
Features advanced 5G features including DL and UL Interference, Block error rate (BLER) and Outer loop link adaptation (OLLA). Access these features within the 5G NR and LTE components.
Licensed

Current workspace: asha

Support
Answer/FAQ
Contact Technical Support
Email - support@tetcos.com

Learn
Videos
Experiments Manual

Documentation
User Manual
Technology Libraries
Source Code Help

Contact Us
Email - sales@tetcos.com
Phone - +91 767 605 4321
Website : www.tetcos.com

Figure 2-1: *NetSim Home Screen*

2.2 Devices specific to NetSim UWAN Library

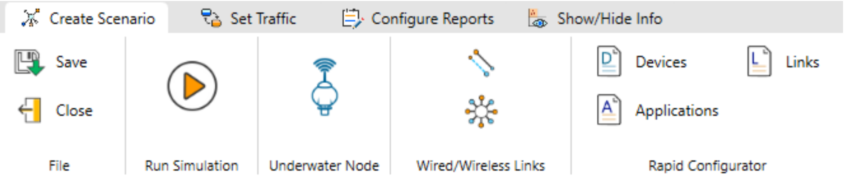


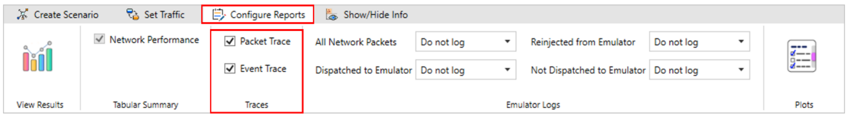
Figure 2-2: *The Devices present in the ribbon of NetSim GUI*

2.3 Placement of devices on the grid environment

Add an Underwater Device - Click on the Underwater Device icon on the toolbar and place the device in the grid.

2.4 Enable Packet Trace, Event Trace (Optional)

Check Packet Trace / Event Trace option from the Configure Reports tab. To get detailed help, please refer to sections 8.4 and 8.5 in User Manual.

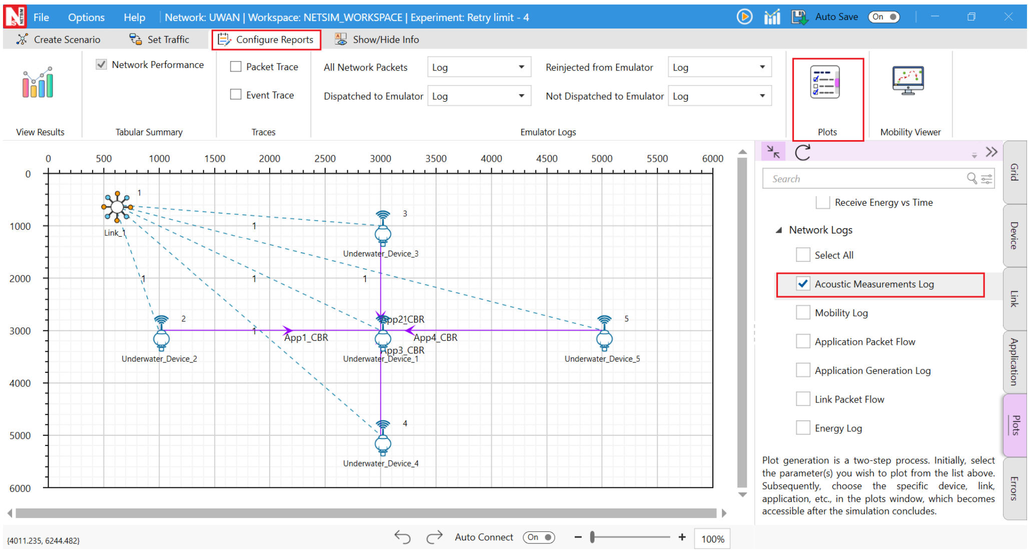


☑ Network Performance
☑ Packet Trace
☑ Event Trace
All Network Packets: Do not log
Dispatched to Emulator: Do not log
Reinjected from Emulator: Do not log
Not Dispatched to Emulator: Do not log

Figure 2-3: *Enable Packet Trace, Event Trace & Plots options on top ribbon.*

2.5 Enable protocol specific logs and plots

NetSim provides protocol-specific logs for UWAN libraries, which users can enable before running a simulation. These can be enabled by clicking on configure reports in top ribbon > clicking on plots > choosing as desired and running the simulation.



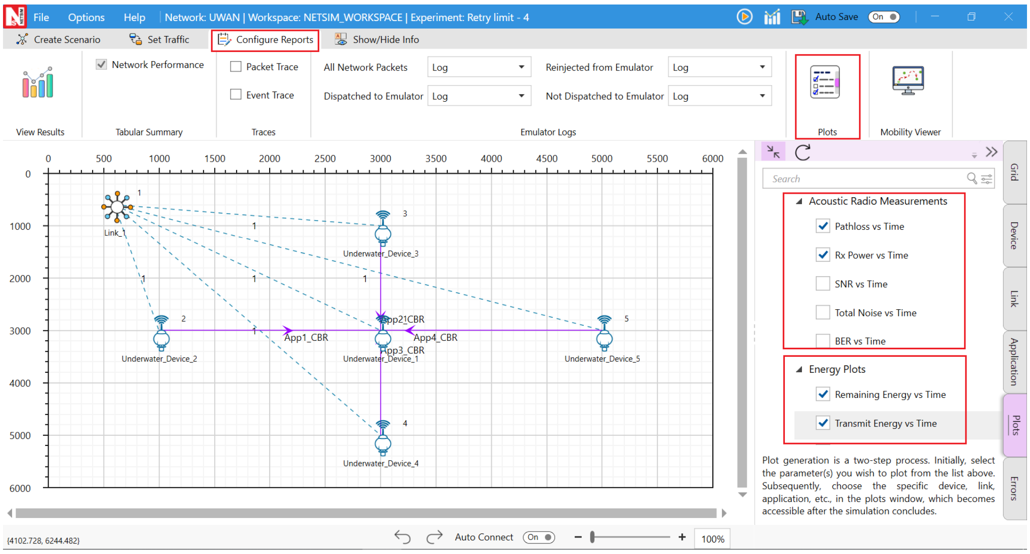
☑ Network Performance
☐ Packet Trace
☐ Event Trace
All Network Packets: Log
Dispatched to Emulator: Log
Reinjected from Emulator: Log
Not Dispatched to Emulator: Log

☐ Receive Energy vs Time
Network Logs
☐ Select All
☑ Acoustic Measurements Log
☐ Mobility Log
☐ Application Packet Flow
☐ Application Generation Log
☐ Link Packet Flow
☐ Energy Log

Plot generation is a two-step process. Initially, select the parameter(s) you wish to plot from the list above. Subsequently, choose the specific device, link, application, etc., in the plots window, which becomes accessible after the simulation concludes.

Figure 2-4: *Enabling Acoustic Measurements log*

Similarly, users can enable the plots for Acoustic Measurements and energy.



Acoustic Radio Measurements
- ☑ Pathloss vs Time
- ☑ Rx Power vs Time
- ☐ SNR vs Time
- ☐ Total Noise vs Time
- ☐ BER vs Time

Energy Plots
- ☑ Remaining Energy vs Time
- ☑ Transmit Energy vs Time

Plot generation is a two-step process. Initially, select the parameter(s) you wish to plot from the list above. Subsequently, choose the specific device, link, application, etc., in the plots window, which becomes accessible after the simulation concludes.

Figure 2-5: *Enabling the plots for UWAN*

2.6 GUI Configuration Parameters

The UWAN parameters can be accessed by right clicking on an Underwater device > selecting Open properties as new window > Interface (Acoustic) Properties → Physical Layers.

Table 2-1: *UWAN Config Properties*

UWAN Properties

Interface (Acoustic) – Physical Layer

Parameter	**Type**	**Range**	**Description**
Source Level	Local	170–225 dB// 1 μPa, Default: 190 dB// 1 μPa	It is the signal level of the transmitter. NetSim GUI takes source level, SL, as the input, with units dB// 1 μPa. In seawater, 1 W of radiated acoustic power creates a sound field of intensity 170.8 dB// 1 μPa, 1m away from the source. For converting from electrical transmit power, in Watts (W), to SL in dB// 1 μPa, the following equation can be used: $SL = 10\log_{10}((\xi \times P_{tx}^{el})[W]) + 170.8$
Antenna Gain (dBi)	Local	-1000 to 1000 dBi	A relative measure of an antenna's ability to direct or concentrate radio frequency energy in a particular direction or pattern. The measurement is typically measured in dBi.
Forward error correction coding (FEC)	Fixed	TRUE	FEC is used for controlling Error-Correcting code, in data over unreliable or noisy communication channels. This is always set to true and the SNR BER calculations factor in FEC.
Modulation	Local	QPSK, BPSK, FSK, 16QAM, 64QAM, 256QAM	Modulation is the process of varying one waveform in relation to another waveform. It is used to transfer data over an analog channel.
Coding Rate	Local	1/2, 2/3, 3/4, 5/6	It states what portion of the total amount of information is useful (non-redundant). This code rate is typically a fractional number.
Frequency	Local	0.01–1000 kHz	The center frequency in the transmission bandwidth
Data rate (kbps)	Local	0–255 kbps	It is the number of kilo-bits that are conveyed or processed per second
Receiver Sensitivity (dB)	Local	-120 – 0 dBm, Default: -85 dBm	It is the lowest power level at which the receiver can detect the acoustic signal and demodulate data. The interference threshold is equal to the receive sensitivity as explained in 3.1.8
Bandwidth (Hz)	Local	0–1000 Hz	Bandwidth is the range of frequencies occupied by acoustic signals.

3 Model Features

3.1 Acoustic PHY

Underwater acoustic channels are generally recognized as one of the most difficult communication media in use today. The worst properties of radio channels - poor link quality, and high latency - are combined in the acoustic channel. Acoustic propagation is best supported at low frequencies and is characterized by two major factors: attenuation that increases with signal frequency, and the low speed of sound ($\approx$1500 m/s).

3.1.1 Speed of sound

The propagation delay model is complex due to the dependency of the speed of sound on the depth of the water. The speed of sound in water, in meters per second, is given by the formula [1].

$$\begin{aligned} c_{sound} &= 1449.05 + 45.7t - 5.21 \times t^2 + 0.23 \times t^3 \\ &\quad + \left(1.333 - 0.126t + 0.009 \times t^2\right)(S - 35) + 16.3 \times z + 0.18 \times z^2 \end{aligned} \tag{1}$$

Where t is one-tenth of the temperature of the water in degrees Celsius, z is the average depth in km of the temperature zone and S is the salinity of the water in parts per thousand.

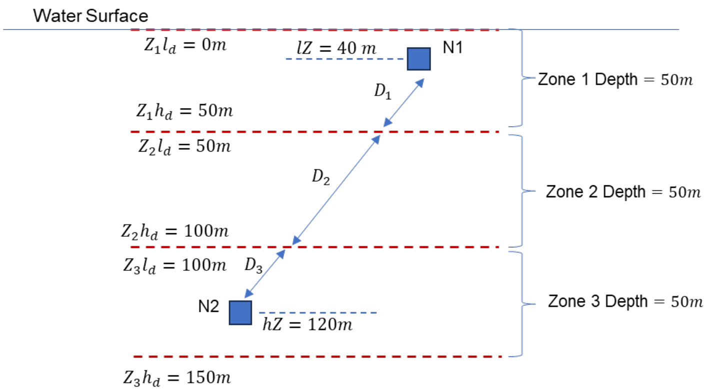


Figure 3-1: *An illustration of temperature zones in NetSim where sensor N1 is in zone 1 and sensor N2 is in zone 3.*

In the figure, l_d denotes the starting depth and h_d denotes the ending depth of each zone. The zone count (three in this case) and the depth of each zone can be set in NetSim. The average depth in Zone 1 is $\frac{Z_1 l_d + Z_1 h_d}{2} = \frac{0+50}{2} = 25m$, in Zone 2 is $\frac{Z_2 l_d + Z_2 h_d}{2} = \frac{50+100}{2} = 75m$, and in zone 3 is $\frac{Z_3 l_d + Z_3 h_d}{2} = \frac{100+150}{2} = 125m$. The propagation delay is computed separately as

$$\Delta_{tot} = \Delta_1 + \Delta_2 + \Delta_3 = \frac{D_1}{C_{sound}^{zone1}} + \frac{D_2}{C_{sound}^{zone2}} + \frac{D_3}{C_{sound}^{zone3}} \tag{2}$$

3.1.2 Transmit power and Source Level

An acoustic signal propagates as a pressure wave, whose power is measured in Pascals (commonly, in dB relative to a micro-Pascal). NetSim GUI takes source level, SL, as the input, with units $dB//1\mu Pa$. We may think of $dB//1\mu Pa$ in acoustics as playing the role of dBm in RF. When referring to the Tx/Rx (acoustic) power it is customary to specify the acoustic intensity value in decibel (dB) relative to the intensity due to 1 micro-pascal (μPa) root mean square (RMS) pressure. In seawater, 1 W of radiated acoustic power creates a sound field of intensity 170.8 $dB//1\mu Pa$, 1m away from the source. For converting from electrical transmit power, P_{tx}^{el} in Watts (W), to SL in $dB//1\mu Pa$, the following equation can be used

$$SL = 10\log_{10}((\xi \times P_{tx}^{el})[W]) + 170.8 \tag{3}$$

where ξ is transducer efficiency. The 170.8 dB accounts for the conversion between $dB//1\mu Pa$ and W. Given below in Table 3-1 are the properties of six commercial and research underwater modems. SL is computed assuming $\xi = 1$.

Table 3-1: *Commercial underwater modems and their specifications*

Underwater modem	P_{tx}^{el} (W)	SL (dB)	BW (kHz)	Rate (kbps)
EvoLogics S2CR 18/34 WiSE	35	186.2407	26	13.90
WHOI Micromodem	48	187.6124	25	5
Teledyne Benthos ATM9XX	20	183.8103	24.50	15.36
LinkQuest UWM4000	7	179.251	17	8.50
Aquatech AQUAModem 1000	20	183.8103	9.75	2
DSPComm AquaComm Marlin	1.8	173.3527	23	0.48

3.1.3 Transmission Losses: Thorp Propagation model

A distinguishing property of acoustic channels is the fact that path loss depends on the signal frequency. This dependence is a consequence of absorption (i.e., transfer of acoustic energy into heat). The simplest model for acoustic attenuation in water is

$$A\,(d, f) = d^k \alpha(f)^d \tag{4}$$

Where α: absorption coefficient factor, depends on the sound frequency f, d: Distance, and k: the spreading coefficient defined by geometry. The spreading factor, k, describes the geometry of propagation and is typically $1 \leq \alpha \leq 2$, e.g., $k = 1$, and $k = 2$ correspond to cylindrical and spherical spreading, respectively. $k = 1.5$ is often considered a practical setting. A cylindrical spreading corresponds to cases in which the transmission distance l is much larger than the depth of the ocean. In this case, the ocean bottom and the interface between the ocean and the air act as boundaries for the spreading of acoustic waves. On the other hand, spherical spreading is considered when the transmission distance is smaller than the depth of the ocean. This type of spreading provides a similar k as the free-space approximation for radio wireless communications.

A common empirical formula used for absorption $\alpha\,(f)$ is Thorp's formula, which for f in kHz is given by

$$10\log_{10}(\alpha\,(f)) = \begin{cases} 0.11 \times \dfrac{f^2}{1+f^2} + 44 \times \dfrac{f^2}{4100+f^2} + 2.75 \times 10^{-4} \times f^2 + 0.003 & f \geq 0.4 \\ 0.002 + 0.11 \times \dfrac{f^2}{1+f^2} + 0.011 \times f^2 & f < 0.4 \end{cases} \tag{5}$$

This output is in dB/km. Combining absorption effects and spreading loss, the total attenuation is as follows:

$$10\log A\left(d,f\right) = k\times 10\log(d_m) + d_{km}\times 10\log\alpha(f) \tag{6}$$

Here d_m is the distance in meters, $d_{km} = \frac{d_m}{1000}$, and f is in kHz. The Thorp model outputs the attenuation in dB.

3.1.4 Noise

The calculation for the ambient noise in the underwater environment is divided into the major factors contributing to the total: turbulence, shipping, wind, and thermal. The following formulae give the noise power $[dB]$ of the four components

$$10\log N_t\left(f\right) = 17 - 30\log(f) \tag{7}$$

$$10\log N_s\left(f\right) = 40 + 20\times(s-0.5) + 26\log f - 60\times\log(f+0.03) \tag{8}$$

$$10\log N_w\left(f\right) = 50 + 7.5\times\sqrt{w} + 20\log f - 40\log\left(f+0.4\right) \tag{9}$$

$$10\log N_{th}(f) = -15 + 20\log f \tag{10}$$

Where f is frequency in kHz, s is the shipping factor and w is the wind-speed in m/s. The default value for s is 0.5 and for w is 0.

Turbulence noise influences only the very low frequency region, $f < 10Hz$. Noise caused by distant shipping is dominant in the frequency region $10Hz - 100Hz$, and it is modeled through the shipping activity factor s, whose value ranges between 0 and 1 for low and high activity, respectively. Surface motion, caused by wind-driven waves (w is the wind speed in m/s) is the major factor contributing to the noise in the frequency region $100Hz - 100kHz$ (which is the operating region of most acoustic systems). Finally, thermal noise becomes dominant for $f > 100$ kHz.

The total noise in linear scale is given as

$$N_{total}^{linear} = N_t^{linear} + N_s^{linear} + N_w^{linear} + N_{th}^{linear} \tag{11}$$

and the total noise in dB domain is $N_{dB}^{total}[dB] = 10\log_{10}(N_{total}^{linear})$

3.1.5 Passive Sonar equation

NetSim uses the passive sonar equation to compute the SNR at the receiver. The passive sonar equation is written as

$$SNR = SL - TL - (NL - DI) \tag{12}$$

Where SL is the source level, TL is the transmission losses, NL is the noise level and DI is receiver directivity index. NetSim assumes $DI = 0$, and upon appropriate substitutions the equation turns out as

$$SNR\ [dB] = SL - 10\log_{10}(A\left(d,f\right))\ [dB] - N_{dB}^{total}\ [dB] \tag{13}$$

On the RHS of the equation, the second term is TL and the final term is the NL.

3.1.6 MCS, Bit error rate (BER) and Packet error rate

Unlike 802.11 or 5G protocols, there are no standards specifying the modulation and coding scheme (MCS) for different received signal powers. Hence MCS is a user settable input parameter. Bit-error-rate (BER) is computed from the received signal to noise ratio (SNR) and the modulation and coding scheme (MCS) set by the user. NetSim assumes that the noise variance is Gaussian and computes BER using theoretical formulas for each modulation scheme. The energy per bit to noise spectral density ratio (E_b/N_0) is first derived from the SNR, adjusted for the ratio of data rate to bandwidth:

$$\frac{E_b}{N_0} = SNR_{linear} \times \frac{\text{Data Rate}}{\text{Bandwidth}} \tag{14}$$

Packet error rate (PER) is then calculated from BER based on packet length as follows:

$$PER = 1 - (1 - BER)^{L_{bits}} \tag{15}$$

where L_{bits} is the total packet length in bits.

Users who wish to use their own (custom) SNR-BER tables can modify the UWAN_Calculate_BER function in UWAN.c file under the UWAN project.

3.1.7 Data Rate

The data rate is set through a GUI parameter; it is not computed by NetSim during simulation. In NetSim, the modulation and coding scheme (MCS) is set by the user in the GUI. This MCS setting does not affect the data rate; it only impacts BER calculations. More information on MCS is provided in section 3.1.6. The implicit assumption is that the user sets the right combination of data rate and MCS.

3.1.8 Collisions, Interference and Packet Capture

Per conventional definition, collisions occur when there is simultaneous packet transmission, and these collided packets are assumed failed or lost. In this characterization, when there is simultaneous packet transmission, collisions are assumed to occur whatever the spatial separation (distance) between nodes and whatever the nodes' transmit powers. Clearly this is an approximation aimed at simplification. In case of simultaneous packet transmissions, it is possible that one (or more) signals have sufficient strength to be decoded by the receiver. Therefore, packets involved a collision can sometimes be successfully received. This phenomenon is known as Packet Capture.

NetSim approximately models Packet Capture considering interference threshold (I_{th}) rather than SINR. To elaborate, we start by denoting Underwater device as UWD and let UWD_{tx} be transmitting a packet to UWD_{rx}, while UWD_I^n be n other $UWDs$ that are transmitting at the same time. These are marked with subscript I since these transmissions would interfere with the UWD_{tx} to UWD_{rx} transmission. NetSim computes the total received power at UWD_{rx} from all simultaneously transmitting $UWDs$, including UWD_{tx}. The interference power is then obtained by subtracting the desired signal power (from UWD_{tx}) from the total received power. That is, the interference is $\Sigma_{j=1}^{n} P_r^j$ where P_r^j is the received power of interfering UWD_I^j at UWD_{rx}, excluding the power of the desired signal. This interference power is compared against an interference threshold I_{th} which is equal to the receive sensitivity (set to $-85dB$ by default in NetSim). If the interference power is greater than the interference threshold, then the packet being transmitted from UWD_{tx} to UWD_{rx} is marked as collided. Should the interference power be less than $-85dB$, the packet being transmitted from UWD_{tx} to UWD_{rx} is successfully received at UWD_{rx}.

An exact SINR based packet capture model (rather than the approximate interference threshold-based packet capture model) is under development.

3.2 MAC Layer

NetSim currently only supports slotted Aloha in the MAC layer.

The reason for not supporting a contention-based protocol is: the basic principle of carrier sensing multiple access — that a node should transmit only if it hears no ongoing transmissions — is compromised in an acoustic channel where the packets propagate slowly, and the fact that none are overheard does not mean that some are not present in the channel.

3.2.1 Slotted Aloha

NetSim UWAN stack runs slotted Aloha (s-Aloha) in the MAC layer. s-Aloha is decentralized medium access control protocol that does not perform carrier sensing. Data transmission by devices is synchronized to timeslots. All devices are assumed to be perfectly synchronized to one another and to the timeslots.

In NetSim's s-Aloha implementation, the transmitter sends the next packet only after the current packet has either been received or errored. The knowledge of a packets successful or erroneous reception (due to collision or channel error) is known by the receiver only after it receives the complete packet. In case of unicast applications, the total time taken for the reception of a packet after the transmission commences is equal to the transmission time T_{tx} plus the propagation delay Δ. It is assumed in NetSim, that the transmitter knows packet status at the exact time that the receiver knows the packet status. Hence the transmitter gets to know if a packet is successful or errored only $(T_{tx} + \Delta)$ seconds after commencing transmission. If the packet is errored the transmitter will retransmit (depending on the retry count set by the user in the UI) the packet; if the packet is successful, the transmitter will send the next packet.

3.2.2 Slot Length

Due to the long propagation delays user should take care to set the slot size in the GUI. This is a global parameter applicable to all UWAN devices. As a starting step, estimate the transmission time, T_{tx} which would be

$$T_{tx}\,(\mu s) = \frac{(L_{pkt} + OH) \times 8}{PHY\,Rate} \tag{16}$$

where L_{pkt} is the application layer packet size, OH is the overheads of all layers which is equal to 28B, and $PHY\,Rate$ is the data rate set in the PHY layer. Next, the propagation delay, Δ is computed as $\Delta = \frac{d}{c_{sound}}$, where d is the distance between the transmitter and the receiver. Thus, the ideal slot length should be

$$L_{slot} = \frac{(L_{pkt} + OH) \times 8}{PHY\,Rate} + \frac{d}{C_{sound}} \tag{17}$$

Example: Let us consider the default values of $L_{pkt} = 14B$ and $PHY\,Rate = 20\ Kbps$ which leads to $T_{tx} = 16{,}800\ \mu s$. Then using $t = \frac{25}{10} = 2.5$, $z = 50$, and $S = 35$ - where t is one-tenth of the temperature of the water in degrees Celsius, z is the depth in meters and S is the salinity of the water - we get (per earlier section 3.1) $c_{sound} = 2799.33\ m/s$. When the transmitter receiver distance is $d = 2km$, the propagation delay, $\Delta = \frac{2\times10^3}{2799.33} = 714{,}456.4\ \mu s$. Substituting all these, we see that the ideal slot length (when $d = 2km$) would be

$$L_{slot} = T_{tx} + \Delta = 16{,}800 + 714{,}456.4 = 731{,}256.4\ \mu s = 0.73\ s \tag{18}$$

Considering a slot length of 731,256.4 μs, we see if one packet exactly fits one slot then the predicted saturation throughput would be

$$\theta_{sat} = \frac{(L_{pkt} \times 8)}{L_{slot}} = \frac{(14 \times 8)}{731256.4 \times 10^{-6}} = 153\ bps \tag{19}$$

NOTE:

- If different Tx-Rx pairs are at different distances, then users should set the slot length based on the largest Tx-Rx distance i.e., based on the largest propagation delay.
- NetSim limitation of not modeling link-level (reverse) ACKs can be overcome by adding additional time in the slot length to account for ACK transmissions. This work around, however, does not account for ACK failures.

3.2.3 Retry count and Back-off

An important MAC layer parameter is Retry Count. This is a user-configurable parameter. A transmitter running s-Aloha retries when packets received (at the receiver) are in error. Recall here the NetSim assumption that the transmitter knows the packet status at the receiver.

The maximum number of times the transmitter retries is equal to Retry Count. Once this limit is hit the transmitter drops the packet. For example, if the Retry Count is 3, and if a packet fails in 1st transmission and in the 1st, 2nd and 3rd retransmission, then that packet is dropped by the transmitter.

The transmitter backs-off before each retry. The back off time (in slots) is a random number chosen from $[0, CW - 1]$ where CW is the contention window and is equal to 2^n, where n is the current value of the Retry Count. Unlike the 802.11 protocols, in s-Aloha, the transmitter does not back off before the 1st transmission.

The description above pertains to the behavior of unicast packets. For broadcast applications, the procedure varies as follows:

- Prior to the first transmission, the transmitter implements a back-off. The duration of this back-off is randomized, selected from a range of 0 to 7 slots.
- Broadcast packets do not undergo re-transmissions.

3.3 IP Addressing, Routing, Queuing and Buffers

Addressing for UWAN devices is IP based. The IP addresses are automatically set by NetSim.

3.3.1 Multi hop communication

The fact that the acoustic bandwidth depends on the distance has important implications for the design of underwater networks. Specifically, it makes a strong case for multihopping, since dividing the total distance between a source and destination into multiple hops enables transmission at a higher bit rate over each (shorter) hop.

NetSim currently supports static routing for multi-hop communication. Ad hoc routing is not yet available. While, no routing configuration is required for single hop communication, static routing needs to be configured for multi-hop communication. Static routing configuration is explained in the Internetworks technology library manual, Section: Configuring Static Routing in NetSim.

3.3.2 Queuing and Buffers

Queuing in UWAN devices is on a first-in-first-out (FIFO) basis. For example, if a UWAN device is acting as both a source of traffic and a relay, then source traffic and relay traffic would arrive at the device's (MAC) buffer. The traffic would be queued and served per FIFO working. UWAN devices in NetSim have infinite (MAC) buffers.

3.4 Underwater Applications (Network Traffic Generation)

Users can model various kinds of applications (that generate network traffic). These include CBR, File transfer, Video etc. Typical examples of transfers from one underwater device to another include (i) transferring a file (ii) transmitting very low bit rate video (iii) generating a constant-bitrate (CBR) application for theoretical performance studies etc. Details of the different application models are provided in Section 6 of the NetSim user manual.

3.5 Acoustic Measurements Log

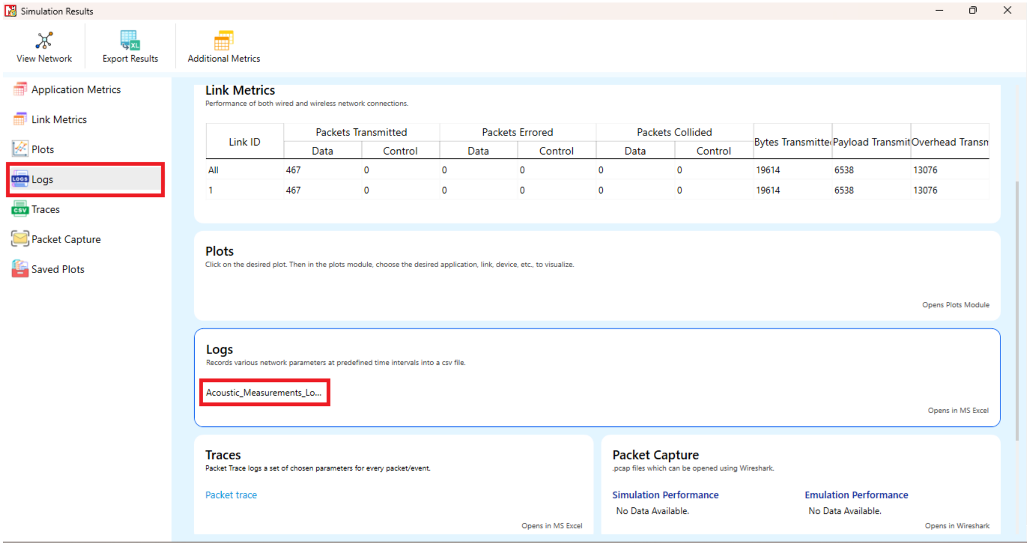
NetSim Acoustic Measurements Log csv file records pathloss, distance, transmitted power, received power, total noise, SNR, BER etc. This log can be used to understand the effects of the acoustic propagation model and the impact of varying channel conditions.

This log file can be enabled from the Configure report tabs > Plots > Acoustic measurements log as explained in section 2.5.

The Acoustic Measurements Log.csv file will contain the following information:

- Time in milliseconds
- Transmitter Name
- Receiver Name
- Distance between transmitter and receiver in meters.
- Transmitter Power in dB/μPa
- Pathloss in dB/μPa
- Total Noise in dB/μPa
- SNR in dB
- Receiver Power in dB/μPa
- BER

The log file can be accessed from the Simulations Results Window by clicking Logs option in the left pane.



Link Metrics

Performance of both wired and wireless network connections.

Link ID	Packets Transmitted		Packets Errored		Packets Collided		Bytes Transmitte	Payload Transmit	Overhead Transn
	Data	Control	Data	Control	Data	Control			
All	467	0	0	0	0	0	19614	6538	13076
1	467	0	0	0	0	0	19614	6538	13076

Plots

Click on the desired plot. Then in the plots module, choose the desired application, link, device, etc., to visualize.

Logs

Records various network parameters at predefined time intervals into a csv file.

Acoustic_Measurements_Lo...

Traces

Packet Trace logs a set of chosen parameters for every packet/event.

Packet trace

Packet Capture

.pcap files which can be opened using Wireshark.

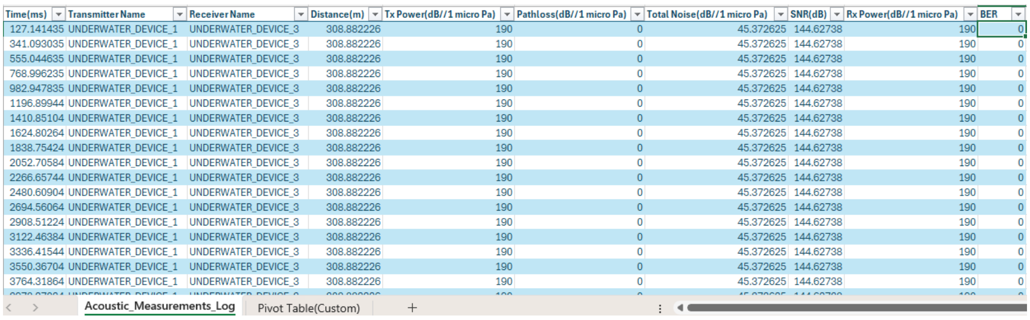
Simulation Performance

No Data Available.

Emulation Performance

No Data Available.

Figure 3-2: *Acoustic Measurements Log.csv file highlighted in the Results window.*



Time(ms)	Transmitter Name	Receiver Name	Distance(m)	Tx Power(dB//1 micro Pa)	Pathloss(dB//1 micro Pa)	Total Noise(dB//1 micro Pa)	SNR(dB)	Rx Power(dB//1 micro Pa)	BER
127.141435	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
341.093035	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
555.044635	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
768.996235	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
982.947835	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
1196.89944	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
1410.85104	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
1624.80264	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
1838.75424	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
2052.70584	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
2266.65744	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
2480.60904	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
2694.56064	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
2908.51224	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
3122.46384	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
3336.41544	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
3550.36704	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0
3764.31864	UNDERWATER_DEVICE_1	UNDERWATER_DEVICE_3	308.882226	190	0	45.372625	144.62738	190	0

Figure 3-3: *Acoustic Measurements Log.csv file*

3.6 Energy Model in UWAN

In UWAN, nodes consume different amounts of energy in each of their modes of operation, namely, sending/transmitting mode, receiving mode, and idle mode.

Transmitting mode: In this mode, nodes consume energy to transfer packets.

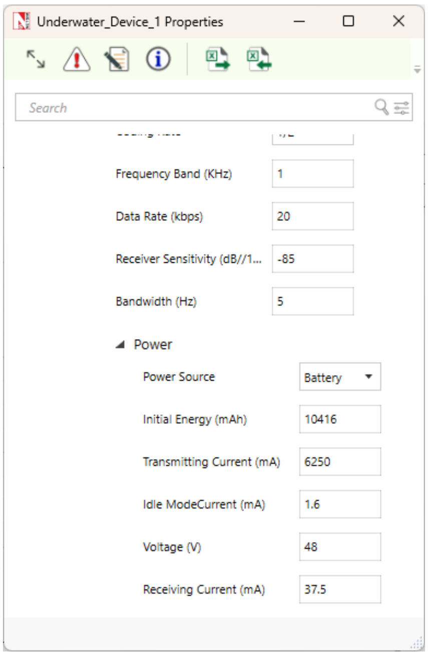
Receiving mode: In this mode, nodes consume energy to receive packets.

Idle mode: In this mode, a node neither transmits nor receives data packets. This is typically a low energy mode.

In NetSim, default energy model settings are as follows.

- Initial Energy (mJ): 10416
- Transmitting current (mA): 6250
- Receiving current (mA): 37.5
- Idle mode current (mA): 1.6
- Voltage (V): 48

The power model is disabled by default. It can be enabled in physical layer of an underwater device. Right click on underwater device properties > Interface 1(Acoustic) > Physical layer



Frequency Band (KHz): 1
Data Rate (kbps): 20
Receiver Sensitivity (dB//1...: -85
Bandwidth (Hz): 5

Power
Power Source: Battery
Initial Energy (mAh): 10416
Transmitting Current (mA): 6250
Idle ModeCurrent (mA): 1.6
Voltage (V): 48
Receiving Current (mA): 37.5

Figure 3-4: *Power model in UWAN.*

3.6.1 Energy Calculation

The energy calculations for each packet in each mode are given below. This data is logged in NetSim's energy log file.

$$\text{Transmitting Energy (mJ)} = \frac{V \times I_{mode} \times (t_{current} - t_{switch})}{10^3} \tag{20}$$

$$\text{Receiving Energy (mJ)} = \frac{V \times I_{mode} \times (t_{current} - t_{switch})}{10^3} \tag{21}$$

$$\text{Idle Energy (mJ)} = \frac{V \times I_{mode} \times (t_{current} - t_{switch})}{10^3} \tag{22}$$

where V is Voltage (V), I_{mode} is ModeCurrent (mA), $t_{current}$ is CurrentTime (ms), and t_{switch} is ModeSwitchTime (ms).

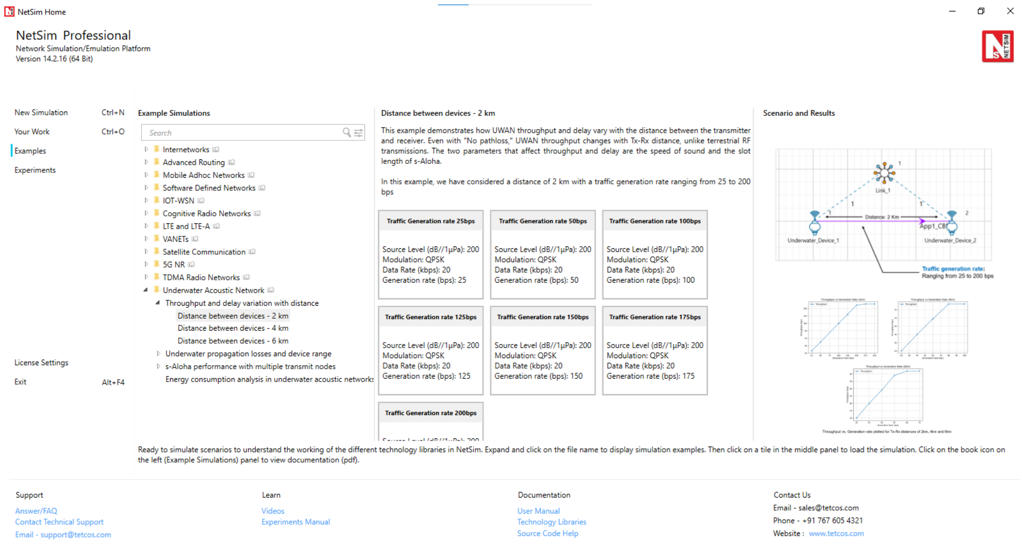
$$\begin{aligned}\text{Consumption Energy (mJ)} = \ & \text{Transmitting Energy (mJ)} \\ & + \text{Receiving Energy (mJ)} + \text{Idle Energy (mJ)}\end{aligned} \tag{23}$$

where current time minus mode-switch-time is the time for which the node is in a particular mode.

4 Featured Examples

4.1 Throughput and delay variation with distance

Open NetSim and Select Examples → Underwater Acoustic Network → Throughput and delay variation with distance and then click on the tile in the middle panel to load the example as Figure 4-1.



Distance between devices - 2 km

This example demonstrates how UWAN throughput and delay vary with the distance between the transmitter and receiver. Even with "No pathloss," UWAN throughput changes with Tx-Rx distance, unlike terrestrial RF transmissions. The two parameters that affect throughput and delay are the speed of sound and the slot length of s-Aloha.

In this example, we have considered a distance of 2 km with a traffic generation rate ranging from 25 to 200 bps

Traffic Generation rate 25bps

Source Level (dB//1μPa): 200
Modulation: QPSK
Data Rate (kbps): 20
Generation rate (bps): 25

Traffic Generation rate 50bps

Source Level (dB//1μPa): 200
Modulation: QPSK
Data Rate (kbps): 20
Generation rate (bps): 50

Traffic Generation rate 100bps

Source Level (dB//1μPa): 200
Modulation: QPSK
Data Rate (kbps): 20
Generation rate (bps): 100

Traffic Generation rate 125bps

Source Level (dB//1μPa): 200
Modulation: QPSK
Data Rate (kbps): 20
Generation rate (bps): 125

Traffic Generation rate 150bps

Source Level (dB//1μPa): 200
Modulation: QPSK
Data Rate (kbps): 20
Generation rate (bps): 150

Traffic Generation rate 175bps

Source Level (dB//1μPa): 200
Modulation: QPSK
Data Rate (kbps): 20
Generation rate (bps): 175

Traffic Generation rate 200bps

Ready to simulate scenarios to understand the working of the different technology libraries in NetSim. Expand and click on the file name to display simulation examples. Then click on a tile in the middle panel to load the simulation. Click on the book icon on the left (Example Simulations) panel to view documentation (pdf).

Contact Us
Email - sales@tetcos.com
Phone - +91 767 605 4321
Website : www.tetcos.com

Figure 4-1: *List of scenarios for the example of Throughput and delay variation with distance*

In this example, we understand how UWAN throughput and delay varies as the distance between 1 transmitter and 1 receiver is varied. Even with no pathloss the throughput in UWAN varies with Tx-Rx distance which is not the case in terrestrial RF based transmissions. The two parameters that affect throughput and delay are the speed of sound and the slot length of s-Aloha. The speed of sound in water is given by the formula

$$c_{sound} = 1449.05 + 45.7t - 5.21 \times t^2 + 0.23 \times t^3 \\ + \left(1.333 - 0.126t + 0.009 \times t^2\right)(S - 35) + 16.3 \times z + 0.18 \times z^2 \quad (24)$$

where t is one-tenth of the temperature of the water in degrees Celsius, z is the depth in km and S is the salinity of the water in ppt. Then using $t = \frac{25}{10} = 2.5$, $z = 50$, and $S = 35$ - where t is one-tenth of the temperature of the water in degrees Celsius, z is the depth in meters and S is the salinity of the water - we get $c_{sound} = 2799.33\ m/s$. When the transmitter receiver distance is $d = 2km$, the propagation delay, $\Delta = \frac{2\times10^3}{2799.33} = 714{,}456.4\ \mu s$

Next, as explained in section 3.2.2, we consider ideal slot lengths for different transmitter receiver distances. In the case when $d_{Rx}^{Tx} = 2\ km$ the slot length turns out as

$$L_{Slot} = T_{tx} + \Delta = 16{,}800 + 714{,}456.4 = 731{,}256.4\ \mu s = 0.73 \quad (25)$$

Table 4-4 shows the ideal slot length settings for $d_{Rx}^{Tx} = 4\ km$ and $d_{Rx}^{Tx} = 6\ km$.

Network setup:

- The following network diagram illustrates what the NetSim UI displays when you open the example configuration file.

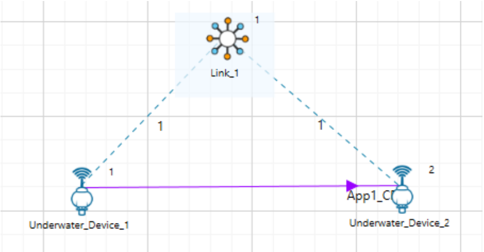


Figure 4-2: *Network Scenario. Two underwater devices connected via an acoustic ad hoc link*

- In case #1, distance between the underwater devices is set to be 2km. In case #2 the distance is 4km, while in case #3 it is set to 6 km
- Click on link, expand the property panel on the right and set the Channel characteristics as No pathloss.
- Device Configuration:

Table 4-1: *Device properties set for this example*

Device > Interface (ACOUSTIC) > Datalink Layer	
Slot Length (μs)	731257 for 2 km
Device > Interface (ACOUSTIC) > Physical Layer	
Source Level ()	200
Modulation	QPSK
Data Rate (kbps)	20

Application Configuration:

We run simulations for different traffic generation rates. The generation rate depends on the inter arrival time – a GUI input in NetSim – in the following way

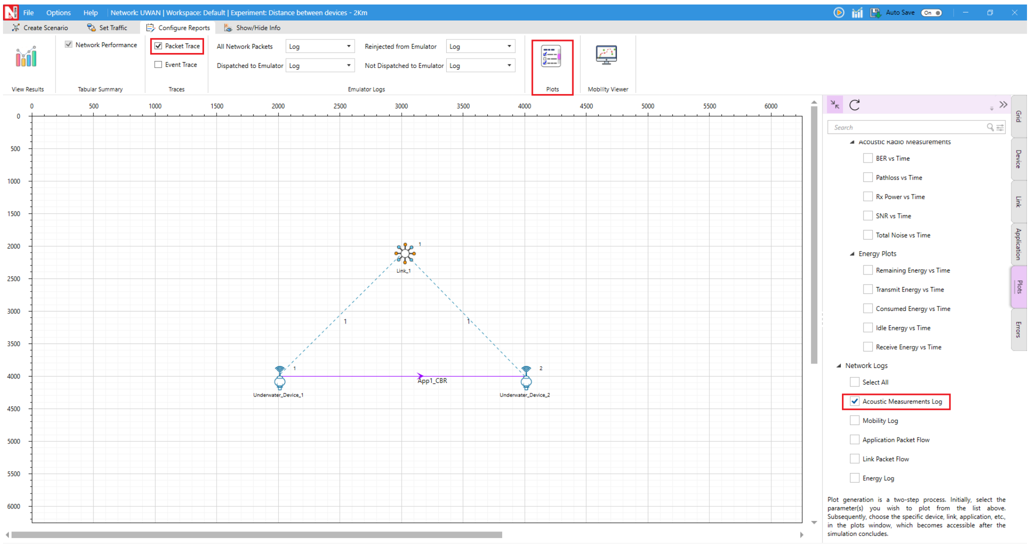
$$\text{Generation Rate (Mbps)} = \frac{\text{Packet Size (Bytes)} \times 8}{\text{Interarrival Time } (\mu\text{s})} \tag{26}$$

Table 4-2: *Application properties for the different samples in each case studied in this example*

Application Properties	
Application Method	App1 CBR
Source ID	1
Destination ID	2
Packet Size (Bytes)	14

	Inter arrival Time (μs)	Generation rate (bps)
Case-1		
	4480000	25
	2240000	50
	1120000	100
	896000	125
	746666.6666	150
	640000	175
	560000	200
Case-2		
	5600000	20
	2800000	40
	1866666.6666	60
	1400000	80
	1120000	100
Case-3		
	5600000	20
	3733333.333	30
	2800000	40
	2240000	50
	1866666.6666	60
	1600000	70

- Enable packet trace and Acoustic Measurements Log under Configure report tab as shown below



Network: UWAN | Workspace: Default | Experiment: Distance between devices - 2Km

☑ Network Performance

☑ Packet Trace

☐ Event Trace

All Network Packets: Log

Dispatched to Emulator: Log

Reinjected from Emulator: Log

Not Dispatched to Emulator: Log

☐ BER vs Time

☐ Pathloss vs Time

☐ Rx Power vs Time

☐ SNR vs Time

☐ Total Noise vs Time

☐ Remaining Energy vs Time

☐ Transmit Energy vs Time

☐ Consumed Energy vs Time

☐ Idle Energy vs Time

☐ Receive Energy vs Time

☐ Select All

☑ Acoustic Measurements Log

☐ Mobility Log

☐ Application Packet Flow

☐ Link Packet Flow

☐ Energy Log

Plot generation is a two-step process. Initially, select the parameter(s) you wish to plot from the list above. Subsequently, choose the specific device, link, application, etc., in the plots window, which becomes accessible after the simulation concludes.

Figure 4-3: *Enabling the Acoustic Measurements Log*

- Run the Simulation for 100 sec.

Theoretical Predictions

The predicted propagation delay when the speed of sound $c_{sound} = 2799.33\ m/s$ is

Table 4-3: *Theoretically predicted propagation delay for different Tx-Rx distances*

Distance between devices	Propagation delay (μs)
2km	714456.4
4km	1428912.7
6km	2143369.1

Transmission delay and Saturation Throughput

Considering a slot length of 731,257 μs, we see that one packet exactly fits one slot and hence the predicted saturation throughput would be

$$\theta_{sat}^{2km} = \frac{(L_{pkt} \times 8)}{L_{slot}} = \frac{(14 \times 8)}{731256.4 \times 10^{-6}} = 153\ bps \tag{27}$$

Proceeding similarly for 4 km and 6 km, the predictions for saturation throughput are

Table 4-4: *Ideal slot lengths and theoretically predicted saturation throughputs (θ_{sat}) for different Tx-Rx distances.*

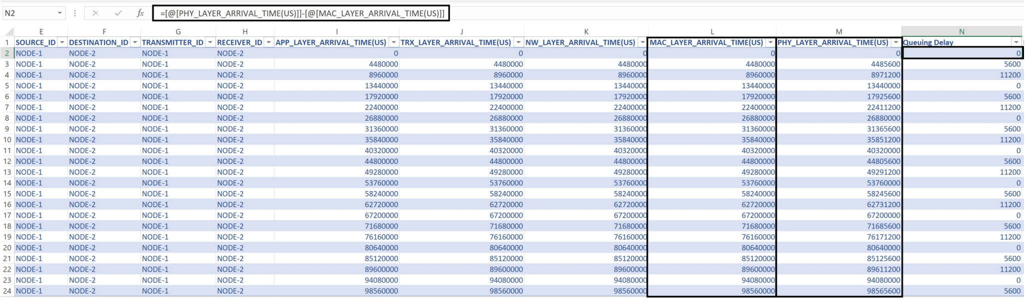
Distance between devices	Slot Length (μs)	Saturation Throughput (bps)
2 km	731257	153
4 km	1445713	77
6 km	2160170	52

Simulation results

We calculate queuing delay, transmission delay, and propagation delay from the packet trace. The steps are:

- Open Packet Trace file using the Packet Trace option available in the Simulation Results window under traces.
- The difference between the PHY LAYER ARRIVAL TIME(US) and the MAC LAYER ARRIVAL TIME(US) will give us the delay of a packet. (Refer Figure 4-4)

$$\text{Queuing Delay } (\mu s) = \text{PHYSICAL LAYER ARRIVAL TIME}(\mu s) - \text{MAC LAYER ARRIVAL TIME } (\mu s) \quad (28)$$



N2

=[@[PHY_LAYER_ARRIVAL_TIME(US)]]-[@[MAC_LAYER_ARRIVAL_TIME(US)]]

	E	F	G	H	I	J	K	L	M	N
1	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIVAL_TIME(US)	MAC_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_ARRIVAL_TIME(US)	Queuing Delay
2	NODE-1	NODE-2	NODE-1	NODE-2	0	0	0	0	0	0
3	NODE-1	NODE-2	NODE-1	NODE-2	4480000	4480000	4480000	4480000	4485600	5600
4	NODE-1	NODE-2	NODE-1	NODE-2	8960000	8960000	8960000	8960000	8971200	11200
5	NODE-1	NODE-2	NODE-1	NODE-2	13440000	13440000	13440000	13440000	13440000	0
6	NODE-1	NODE-2	NODE-1	NODE-2	17920000	17920000	17920000	17920000	17925600	5600
7	NODE-1	NODE-2	NODE-1	NODE-2	22400000	22400000	22400000	22400000	22411200	11200
8	NODE-1	NODE-2	NODE-1	NODE-2	26880000	26880000	26880000	26880000	26880000	0
9	NODE-1	NODE-2	NODE-1	NODE-2	31360000	31360000	31360000	31360000	31365600	5600
10	NODE-1	NODE-2	NODE-1	NODE-2	35840000	35840000	35840000	35840000	35851200	11200
11	NODE-1	NODE-2	NODE-1	NODE-2	40320000	40320000	40320000	40320000	40320000	0
12	NODE-1	NODE-2	NODE-1	NODE-2	44800000	44800000	44800000	44800000	44805600	5600
13	NODE-1	NODE-2	NODE-1	NODE-2	49280000	49280000	49280000	49280000	49291200	11200
14	NODE-1	NODE-2	NODE-1	NODE-2	53760000	53760000	53760000	53760000	53760000	0
15	NODE-1	NODE-2	NODE-1	NODE-2	58240000	58240000	58240000	58240000	58245600	5600
16	NODE-1	NODE-2	NODE-1	NODE-2	62720000	62720000	62720000	62720000	62731200	11200
17	NODE-1	NODE-2	NODE-1	NODE-2	67200000	67200000	67200000	67200000	67200000	0
18	NODE-1	NODE-2	NODE-1	NODE-2	71680000	71680000	71680000	71680000	71685600	5600
19	NODE-1	NODE-2	NODE-1	NODE-2	76160000	76160000	76160000	76160000	76171200	11200
20	NODE-1	NODE-2	NODE-1	NODE-2	80640000	80640000	80640000	80640000	80640000	0
21	NODE-1	NODE-2	NODE-1	NODE-2	85120000	85120000	85120000	85120000	85125600	5600
22	NODE-1	NODE-2	NODE-1	NODE-2	89600000	89600000	89600000	89600000	89611200	11200
23	NODE-1	NODE-2	NODE-1	NODE-2	94080000	94080000	94080000	94080000	94080000	0
24	NODE-1	NODE-2	NODE-1	NODE-2	98560000	98560000	98560000	98560000	98565600	5600

Figure 4-4: *Screen shot of NetSim trace showing the Queuing Delay column*

- Now, calculate the mean queuing delay by taking the average of the queueing delays of all the packets. This is nothing but the column average. (Refer Figure 4-4)
- Similarly, users can get the Mean Transmission Delay and Mean Propagation Delay from the packet trace using the formulas

$$\text{Transmission Delay } (\mu s) = \text{PHY LAYER START TIME}(\mu s) - \text{PHY LAYER ARRIVAL TIME}(\mu s) \quad (29)$$

$$\text{Propagation Delay } (\mu s) = \text{PHY LAYER END TIME}(\mu s) - \text{PHY LAYER START TIME}(\mu s) \quad (30)$$

Table 4-5: *Tabulated results (throughput and delays) for 3 different Tx-Rx distances.*

Case	**Gen. Rate (bps)**	**Thru-put (bps)**	**Delay (μs)**	**Mean Prop. Delay (μs)**	**Mean Tx Delay (μs)**	**Mean Queue Delay (μs)**
Case #1: Distance between underwater devices is 2km						
	25	26	1113144.78	714456.35	16800	381888.43
	50	50	1111731.73	714456.35	16800	380475.37
	100	100	1094568.64	714456.35	16800	363312.29
	125	124	1091089.64	714456.35	16800	359833.28
	150	149	1116252.45	714456.35	16800	384996.10
	175	152	6891103.855	714456.35	16800	6159847.5
	200	152	12291103.8	714456.35	16800	11559847.5
Case #2: Distance between underwater devices is 4km						
	20	20	2036146.04	1428912.7	16800	590433.33

Case	**Gen. Rate (bps)**	**Thru-put (bps)**	**Delay (μs)**	**Mean Prop. Delay (μs)**	**Mean Tx Delay (μs)**	**Mean Queue Delay (μs)**
	40	40	2081859.04	1428912.7	16800	636146.33
	60	59	2148454.18	1428912.7	16800	702741.47
	80	77	2999954.70	1428912.7	16800	1554242
	100	77	12519954.7	1428912.7	16800	11074242
Case #3: Distance between underwater devices is 6km						
	20	20	3163994.06	2143369.06	16800	1003825
	30	30	3230739.43	2143369.06	16800	1070570.37
	40	39	3194853.63	2143369.06	16800	1034684.57
	50	49	3340415.65	2143369.06	16800	1180246.5
	60	52	8763994.06	2143369.06	16800	6603825
	70	52	14763994.0	2143369.06	16800	12603825

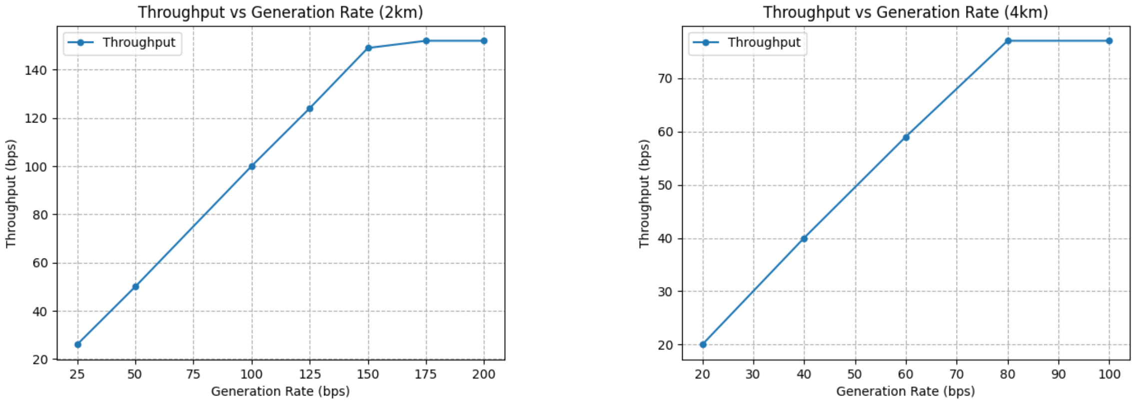


Figure 4-5: *Throughput vs. Generation Rate for Tx-Rx distances of 2km (left) and 4km (right).*

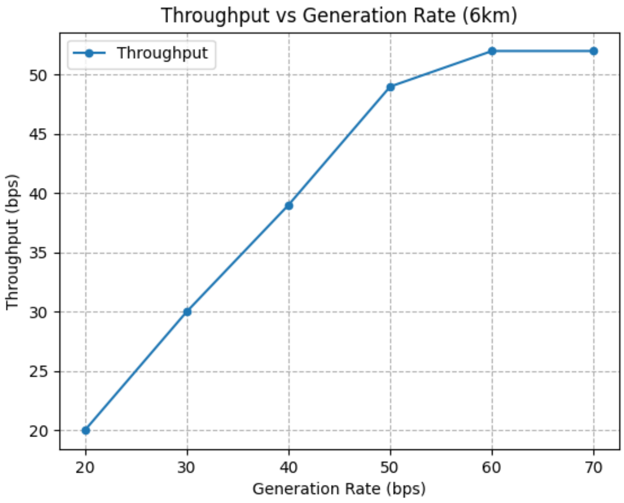


Figure 4-6: *Throughput vs. Generation rate plotted for Tx-Rx distances of 2km, 4km and 6km based on earlier tables.*

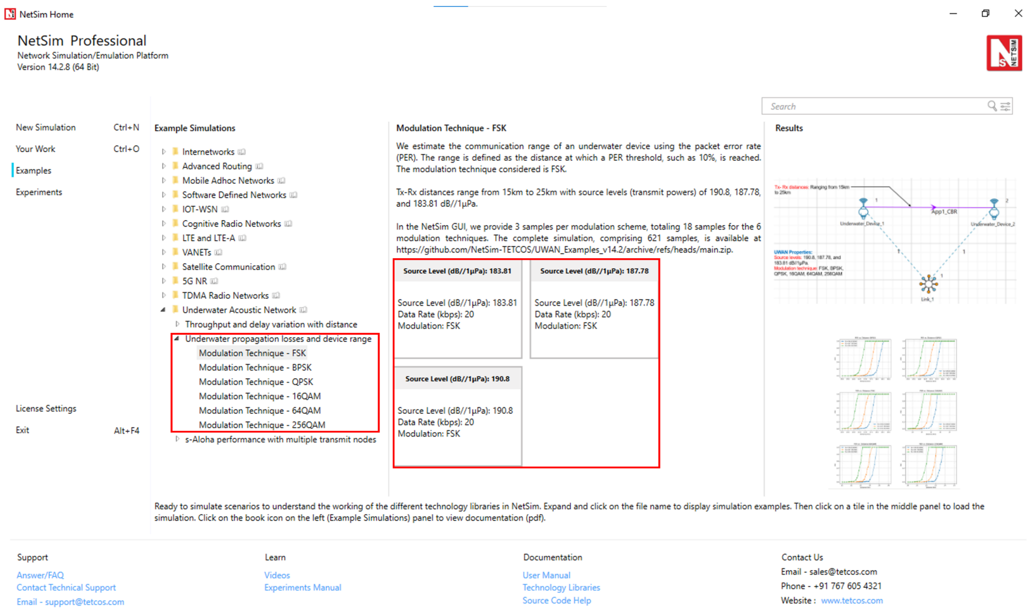
From Table 4-5, we see that the propagation delays from simulation match predictions in Table 4-3. Then we observe that saturation throughput (the Y axis value once the curve flattens) matches prediction.

Table 4-6: *NetSim UWAN Simulation results vs. theoretical prediction of saturation throughput, for different Tx-Rx distances.*

Distance between devices	Saturation Throughput Predicted (bps)	Saturation Throughput Simulatio
2 km	153	152
4 km	77	77
6 km	52	52

4.2 Underwater propagation losses and device range

Open NetSim and Select Examples → Underwater Acoustic Network → Underwater propagation losses and device range and then click on the tile in the middle panel to load the example as Figure 4-7.



Modulation Technique - FSK

We estimate the communication range of an underwater device using the packet error rate (PER). The range is defined as the distance at which a PER threshold, such as 10%, is reached. The modulation technique considered is FSK.

Tx-Rx distances range from 15km to 25km with source levels (transmit powers) of 190.8, 187.78, and 183.81 dB//1µPa.

In the NetSim GUI, we provide 3 samples per modulation scheme, totaling 18 samples for the 6 modulation techniques. The complete simulation, comprising 621 samples, is available at https://github.com/NetSim-TETCOS/UWAN_Examples_v14.2/archive/refs/heads/main.zip.

Source Level (dB//1µPa): 183.81

Source Level (dB//1µPa): 183.81
Data Rate (kbps): 20
Modulation: FSK

Source Level (dB//1µPa): 187.78

Source Level (dB//1µPa): 187.78
Data Rate (kbps): 20
Modulation: FSK

Source Level (dB//1µPa): 190.8

Source Level (dB//1µPa): 190.8
Data Rate (kbps): 20
Modulation: FSK

Tx- Rx distances: Ranging from 15km to 25km

UWAN Properties:
Source levels: 190.8, 187.78, and 183.81 dB//1µPa
Modulation technique: FSK, BPSK, QPSK, 16QAM, 64QAM, 256QAM

Ready to simulate scenarios to understand the working of the different technology libraries in NetSim. Expand and click on the file name to display simulation examples. Then click on a tile in the middle panel to load the simulation. Click on the book icon on the left (Example Simulations) panel to view documentation (pdf).

Email - sales@tetcos.com
Phone - +91 767 605 4321
Website : www.tetcos.com

Figure 4-7: *List of scenarios for the example of Underwater propagation losses and device range.*

In this example, we understand the Thorp propagation model, the sources of underwater noise, the passive sonar equation and how device range can be estimated based on received SNR. Refer to section 3.1 for the underlying theory on signal level, transmission losses, and the passive sonar equation.

In the NetSim GUI, we provide 3 samples per modulation scheme, totaling 18 samples for the 6 modulation techniques. The complete set of configuration files (scenario, settings and other related files) comprising of 621 samples, is available at `https://github.com/NetSim-TETCOS/UWAN_Examples_v14.4/archive/refs/heads/main.zip`.

Click on the link given and download UWAN Experiments

1. Extract the zip folder. The extracted project folder consists of Underwater propagation losses and device range example files.
2. How to import the workspace is explained in section 4.9.2 in NetSim User Manual.

Network setup

- The following network diagram illustrates what the NetSim UI displays when you open the example configuration file.

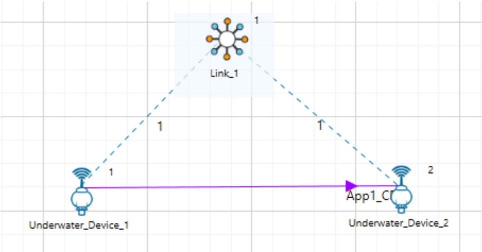


Figure 4-8: *Network Scenario*

- Click on link, expand the right-side property panel and set the Channel characteristics as Pathloss Only.
- Click on Underwater Device 1, expand the right-side property panel change the following parameters,

Table 4-7: *Device Properties*

Device Properties > Physical Layer	
Source Level ()	190.8, 187.78, 183.81
Data Rate (kbps)	20
Modulation Technique	QPSK, BPSK, FSK, 16QAM, 64QAM, 256QAM

- Configure a CBR Application from Source ID as 1 and Destination ID as 2 from set traffic window present in the ribbon at the top with Default Properties.
- Enable packet trace and Acoustic Measurements Log under Configure report tab as shown in Figure 4-3.
- Run the Simulation for 1000 sec.

Analytical computations

In the Thorp model, the dB/km attenuation is given by

$$10\log_{10}(\alpha\,(f)) = \begin{cases} 0.11 \times \dfrac{f^2}{1+f^2} + 44 \times \dfrac{f^2}{4100+f^2} + 2.75 \times 10^{-4} \times f^2 + 0.003 & f \geq 0.4 \text{ kHz} \\ 0.002 + 0.11 \times \dfrac{f^2}{1+f^2} + 0.011 \times f^2 & f < 0.4 \text{ kHz} \end{cases} \tag{31}$$

For this example, substituting $f = 20$, we get $10\log_{10}(\alpha\,(f)) = 4.133\ dB/km$, we see that the total pathloss is

$$10\log A\,(d,f) = k \times 10\log(d_m) + d_{km} \times 10\log\alpha(f) \tag{32}$$

Using input parameters K (spread coefficient) $= 2, f = 20\ kHz$ and distance between the source and destination, $d = 18\ km$, and we get the total transmission loss, TL, as

$$TL = 10\log A\,(d,f) = 159.51\ dB \tag{33}$$

Next, we turn to noise level NL. The turbulence, shipping, wind, and thermal, noise level in dB is given by

$$10\log N_t\,(f) = 17 - 30\log(f) \tag{34}$$

$$10\log N_s\,(f) = 40 + 20 \times (s - 0.5) + 26\log f - 60 \times \log(f + 0.03) \tag{35}$$

$$10\log N_w\,(f) = 50 + 7.5 \times \sqrt{w} + 20\log f - 40\log\,(f + 0.4) \tag{36}$$

$$10\log N_{th}(f) = -15 + 20\log f \tag{37}$$

Substituting $f = 20\ kHz$, shipping factor $s = 0.5$, surface windspeed $w = 0\ m/s$, we get $N_t = -22.03\ dB$, $N_s = -4.27\ dB$, $N_w = 23.63\ dB$, and $N_{th} = 11.02\ dB$. As explained in section 3.1.4 we see that wind noise has the most impact. After adding these noises in the linear scale and then converting back to dB, Total noise, $N^{dB}_{Total} = 23.87$. From the passive sonar equation

$$SNR = SL - TL - (NL - DI) \tag{38}$$

Substituting we get

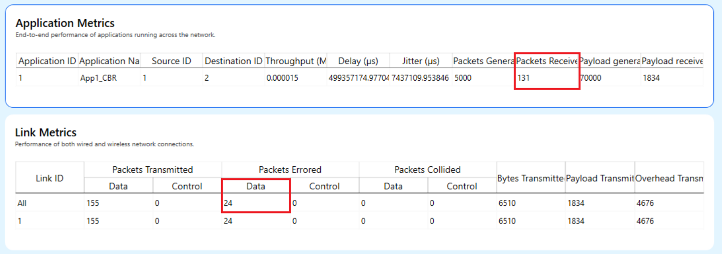
$$SNR = 190.80 - 159.51 - (23.87 - 0) = 1.41\ dB \tag{39}$$

Results: Packet Error Rate vs Distance

For the above SNR, we plot PER vs. distance for different modulation schemes given default packet size of 14B.

$$PER = \frac{\text{No. of errored packets}}{(\text{No. of errored packets} + \text{No. of received packets})} \tag{40}$$

No. of errored packets can be obtained from link metrics and No. of received packets can be obtained from application metrics of the results dashboard as shown in the image below.



Application Metrics

End-to-end performance of applications running across the network.

Application ID	Application Na	Source ID	Destination ID	Throughput (M	Delay (µs)	Jitter (µs)	Packets Genera	Packets Receive	Payload genera	Payload receive
1	App1_CBR	1	2	0.000015	499357174.97704	7437109.953846	5000	131	70000	1834

Link Metrics

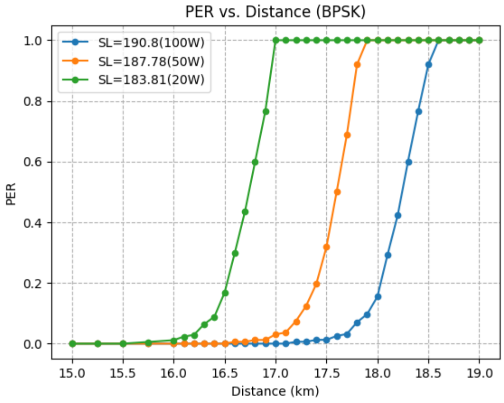
Performance of both wired and wireless network connections.

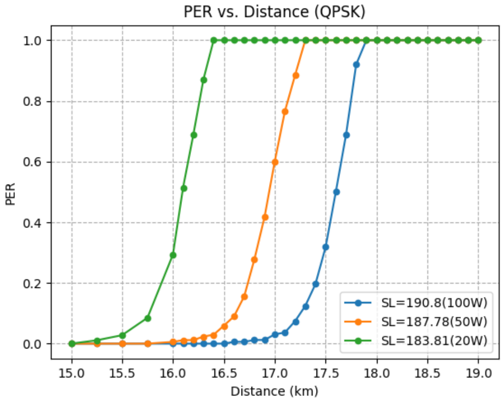
Link ID	Packets Transmitted		Packets Errored		Packets Collided		Bytes Transmitte	Payload Transmit	Overhead Transn
	Data	Control	Data	Control	Data	Control			
All	155	0	24	0	0	0	6510	1834	4676
1	155	0	24	0	0	0	6510	1834	4676

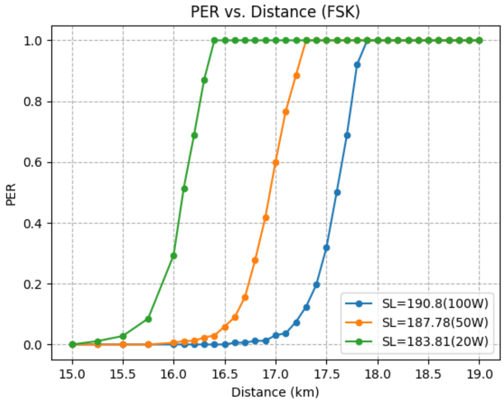
Figure 4-9: *Result Dashboard window.*

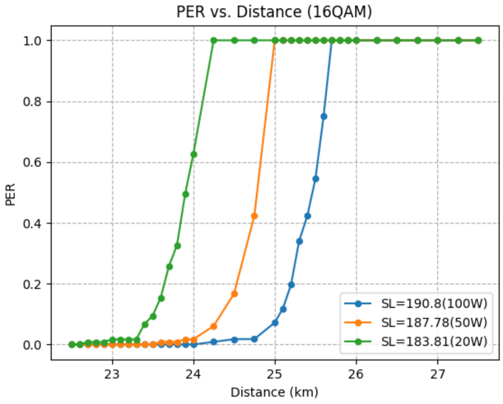
Table 4-8: *PER values for different modulations and distances.*

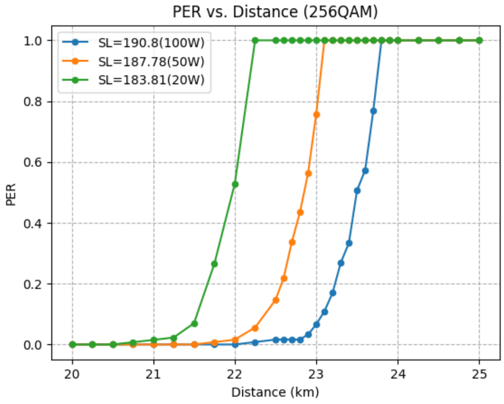
Distance (m)	Source Level (dB/μPa)	Modulation	Pkts Received	Pkts Errored	PER
18000	183.81	FSK	0	19	1
18000	183.81	BPSK	0	19	1
18000	183.81	QPSK	0	19	1
18000	187.78	FSK	0	19	1
18000	187.78	BPSK	0	19	1
18000	187.78	QPSK	0	19	1
18000	190.8	FSK	0	19	1
18000	190.8	BPSK	131	24	0.154839
18000	190.8	QPSK	0	19	1
23000	183.81	16QAM	119	2	0.016529
23000	183.81	64QAM	32	41	0.561644
23000	183.81	256QAM	0	13	1
23000	187.78	16QAM	121	0	0
23000	187.78	64QAM	119	2	0.016529
23000	187.78	256QAM	7	22	0.758621
23000	190.8	16QAM	121	0	0
23000	190.8	64QAM	121	0	0
23000	190.8	256QAM	113	8	0.066116

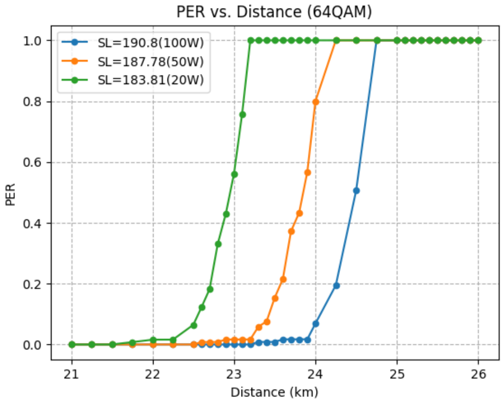








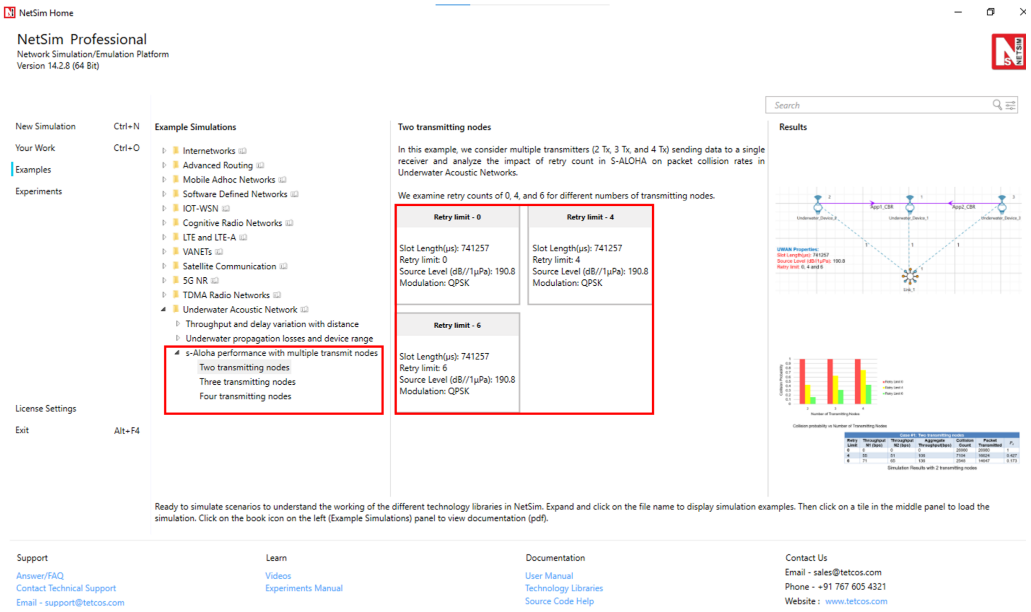




Generally, range is defined as the Tx-Rx distance at which the PER is 10%. From these plots we can determine a device's range. In summary, we see how the device range is dependent on Source Level, Noise, MCS and packet size.

4.3 s-Aloha performance with multiple transmit nodes

Open NetSim and Select Examples → Underwater Acoustic Network → s-Aloha performance with multiple transmit nodes and then click on the tile in the middle panel to load the example as Figure 4-10.



Two transmitting nodes

In this example, we consider multiple transmitters (2 Tx, 3 Tx, and 4 Tx) sending data to a single receiver and analyze the impact of retry count in S-ALOHA on packet collision rates in Underwater Acoustic Networks.

We examine retry counts of 0, 4, and 6 for different numbers of transmitting nodes.

Retry limit - 0

Slot Length(μs): 741257
Retry limit: 0
Source Level (dB//1μPa): 190.8
Modulation: QPSK

Retry limit - 4

Slot Length(μs): 741257
Retry limit: 4
Source Level (dB//1μPa): 190.8
Modulation: QPSK

Retry limit - 6

Slot Length(μs): 741257
Retry limit: 6
Source Level (dB//1μPa): 190.8
Modulation: QPSK

Ready to simulate scenarios to understand the working of the different technology libraries in NetSim. Expand and click on the file name to display simulation examples. Then click on a tile in the middle panel to load the simulation. Click on the book icon on the left (Example Simulations) panel to view documentation (pdf).

Email - support@tetcos.com

Email - sales@tetcos.com
Phone - +91 767 605 4321
Website : www.tetcos.com

Figure 4-10: *List of scenarios for the example of s-Aloha performance with multiple transmit nodes.*

Network setup

We consider three scenarios as shown in the figure below, with 2, 3 and 4 transmitting nodes.

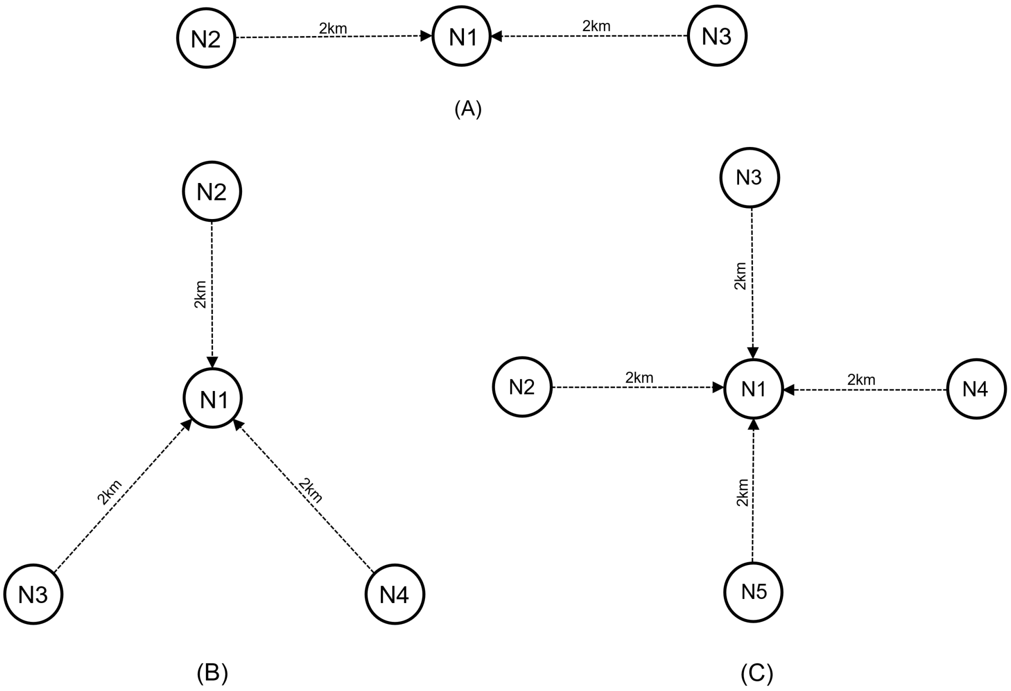


Figure 4-11: *Simulation scenarios with 2 transmitting nodes in (A), 3 transmitting nodes in (B) and 4 transmitting nodes in (C). In all cases there is a single receiver.*

Properties

Then we set the UWAN device properties as shown below

Table 4-9: *UWAN Device Properties*

Device Properties	
Device > Interface (ACOUSTIC) > Datalink Layer	
Retry Limit	0, 4, 6
Slot Length (μs)	741257
Device > Interface (ACOUSTIC) > Physical Layer	
Source Level ()	190.8
Modulation	QPSK
Data Rate (kbps)	20

- Here, we set the Slot Time as 741257 μs, which is the ideal value of 731257 μs plus a guard interval of 10,000 μs
- Configure a CBR Application from the source nodes (2, 3, 4 and 5 per the cases) to the destination (Node 1) with a packet size of 14 bytes and Inter arrival time as 560000 μs from set traffic window present in the ribbon at the top.
- Enable packet trace and Acoustic Measurements Log under Configure report tab as shown in Figure 4-3.
- Run the Simulation for 10000 sec.

Results

We observe throughputs from network metrics and packets transmitted and packets collided from the Link Metrics. We compute collision probability as $P_c = \frac{\text{Collision Count}}{\text{Packet Transmitted}}$ and tabulate the results in the different cases.

Table 4-10: *Simulation Results with 2 transmitting nodes*

Case #1: Two transmitting nodes						
Retry Limit	**Thru. N1 (bps)**	**Thru. N2 (bps)**	**Agg. Thru. (bps)**	**Collision Count**	**Pkt Tx**	P_c
0	0	0	0	26980	26980	1
4	51	55	106	7104	16624	0.427
6	65	71	136	2548	14647	0.173

Table 4-11: *Simulation Results with 3 transmitting nodes*

Case #2: Three transmitting nodes							
Retry Limit	**Thru. N1 (bps)**	**Thru. N2 (bps)**	**Thru. N3 (bps)**	**Agg. Thru. (bps)**	**Collision Count**	**Pkt Tx**	P_c
0	0	0	0	0	40470	40470	1
4	26	26	27	79	12234	19348	0.632
6	43	41	37	121	4969	15726	0.316

Table 4-12: *Simulation Results with 4 transmitting nodes*

				Case #3: Four transmitting nodes	
Retry Limit	**Throughput N1 (bps)**	**Throughput N2 (bps)**	**Throughput N3 (bps)**	**Throughput N4 (bps)**	**Aggrega**
0	0	0	0	0	
4	15	15	14	16	
6	28	27	26	26	

We carry out simulations with different settings of Retry Count. The final results are plotted below. When Retry count is set to zero, all packets collide even when just two nodes are transmitting. With retry count set to 0, the node attempts a packet transmission. If it fails, there is no retry and the packet is dropped. Recall, that in s-Aloha the transmitter does not back off before the first transmission attempt for a packet. With backlogged queues, the two transmitting nodes keep attempting at each slot. This leads to continuous collisions.

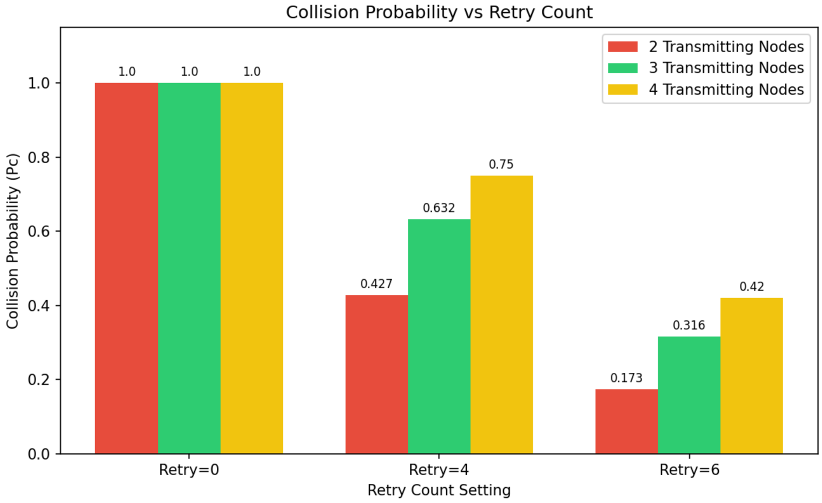


Figure 4-12: *Collision probability vs. number of transmitting nodes for different retry count settings.*

When the retry count is set to 4 (or 6) a transmitting node back off per the exponential backoff algorithm, before every retransmission. The back off algorithm is explained in section 3.2.3. Hence there is an element of randomness in packet transmissions at each slot. Nodes may or may not transmit. The probability of transmission at a particular slot reduces as the Retry Count is increased. Hence, we see lower collision probabilities for Retry count of 6.

4.4 Energy consumption analysis in underwater acoustic networks under varying traffic loads

4.4.1 Introduction

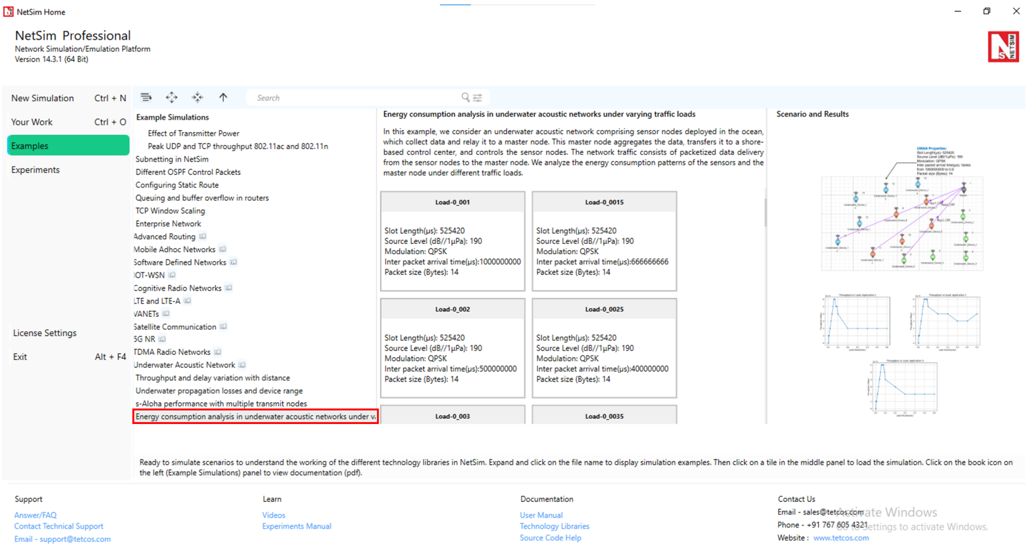
Efficient energy usage is important for underwater devices because the underwater environment imposes constraints on recharging options. Optimizing energy consumption is essential to ensure the longevity of the network.

Consider a practical underwater acoustic network comprising sensor nodes deployed in the ocean, which collect data and relay it to a master node. This master node aggregates the data, transfers it to a shore-based control center, and controls the sensor nodes. The network traffic consists of packetized data delivery from the sensor nodes to the master node.

In our project, we model such a network in NetSim. The setup includes master and sensor nodes distributed across 16 underwater devices, organized into three clusters (A, B, and C). Each cluster contains sensor nodes responsible for data collection and transmission, with the master node managing data aggregation. The scenario is based on [9].

We analyse the energy consumption patterns of the sensors and the master node under different traffic loads.

Open NetSim and Select Examples → Underwater Acoustic Network → Energy consumption analysis in underwater acoustic networks under varying traffic loads and then click on the tile in the middle panel to load the example as shown in figure.



Energy consumption analysis in underwater acoustic networks under varying traffic loads

In this example, we consider an underwater acoustic network comprising sensor nodes deployed in the ocean, which collect data and relay it to a master node. This master node aggregates the data, transfers it to a shore-based control center, and controls the sensor nodes. The network traffic consists of packetized data delivery from the sensor nodes to the master node. We analyze the energy consumption patterns of the sensors and the master node under different traffic loads.

Load-0_001

Slot Length(µs): 525420
Source Level (dB//1µPa): 190
Modulation: QPSK
Inter packet arrival time(µs):1000000000
Packet size (Bytes): 14

Load-0_0015

Slot Length(µs): 525420
Source Level (dB//1µPa): 190
Modulation: QPSK
Inter packet arrival time(µs):666666666
Packet size (Bytes): 14

Load-0_002

Slot Length(µs): 525420
Source Level (dB//1µPa): 190
Modulation: QPSK
Inter packet arrival time(µs):500000000
Packet size (Bytes): 14

Load-0_0025

Slot Length(µs): 525420
Source Level (dB//1µPa): 190
Modulation: QPSK
Inter packet arrival time(µs):400000000
Packet size (Bytes): 14

Load-0_003

Load-0_0035

Ready to simulate scenarios to understand the working of the different technology libraries in NetSim. Expand and click on the file name to display simulation examples. Then click on a tile in the middle panel to load the simulation. Click on the book icon on the left (Example Simulations) panel to view documentation (pdf).

Figure 4-13: *List of scenarios for the example of Energy consumption analysis in underwater acoustic networks*

4.4.2 Network setup

The scenario comprises of 16 underwater devices, organized into three clusters (A, B, and C) and a master node.

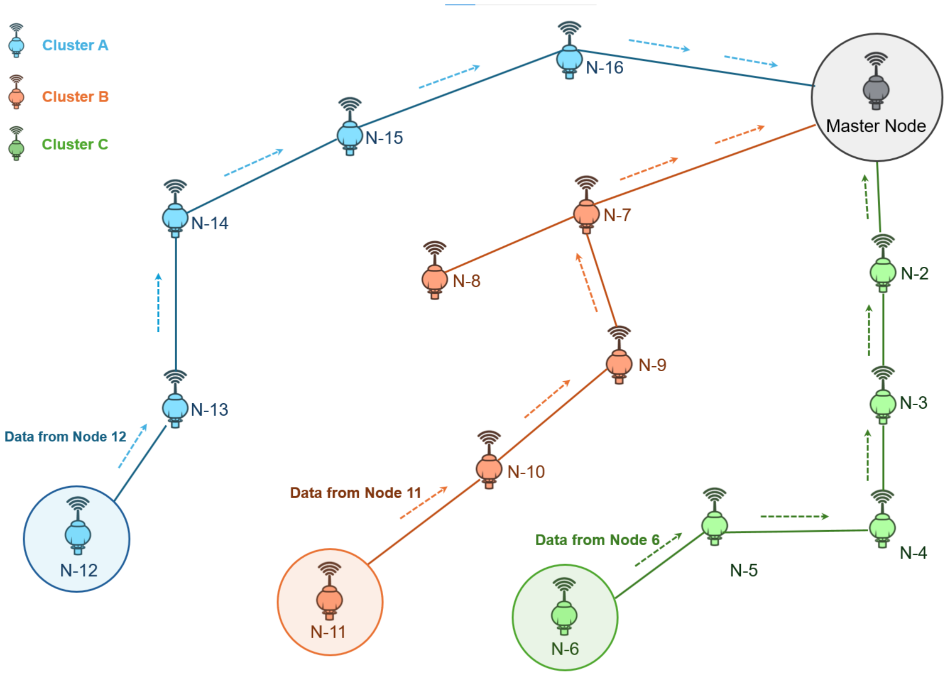


Figure 4-14: *Scenario representing 3 different clusters and master node and data transmission from each cluster to the master node.*

Cluster A: Underwater nodes 12, 13, 14, 15, 16.

Cluster B: Underwater nodes 11, 10, 9, 8, 7.

Cluster C: Underwater nodes 6, 5, 4, 3, 2.

Master Node: Node 1, responsible for collecting data from all the clusters.

The network is configured with static routing to ensure data transfer from sensor nodes to the master node. We assume an ideal channel with no pathloss.

Device Configuration

Table 4-13: *Device properties set for this example*

Device Properties	
Mac Layer	
Protocol	Slotted Aloha
Slot Length(μs)	525420
Phy Layer	
Source Level (dB//1μPa)	190
Modulation	QPSK
Data Rate (kbps)	20
Power	
Power source	Battery
Initial energy (mAH)	10416
Transmitting current (mA)	6250
Idle mode current (mA)	1.6
Voltage (v)	48
Receiving current (mA)	37.5

In our project, we use a data rate of 20 Kbps, whereas at the time of publication of reference [9], the modems supported data rates of 10s to 100s of bits per second. Consequently, the network in the current NetSim simulation can support a much higher traffic load. Therefore, while we expect different numerical results when comparing the outcomes, we anticipate observing similar trends to those reported in [9].

Slot Length Calculation This is a global parameter applicable to all UWAN devices. As a starting step, estimate the transmission time T_{tx}, which would be

$$T_{tx}\,(\mu s) = \frac{(L_{pkt} + OH) \times 8}{PHY\,Rate} \tag{41}$$

where L_{pkt} is the application layer packet size, OH is the overheads of all layers which is equal to 28B, and $PHY\,Rate$ is the data rate set in the PHY layer. Next, the propagation delay, Δ is computed as $\Delta = \frac{d}{c_{sound}}$, where d is the distance between the transmitter and the receiver. Thus, the ideal slot length should be

$$L_{slot} = \frac{(L_{pkt} + OH) \times 8}{PHY\,Rate} + \frac{d}{C_{sound}} \tag{42}$$

In our scenario $L_{pkt} = 14B$ and $PHY\,Rate = 20\ Kbps$ which leads to $T_{tx} = 16{,}800\ \mu s$. Then using $t = \frac{25}{10} = 2.5$, $z = 50$, and $S = 35$ - where t is one-tenth of the temperature of the water in degrees Celsius, z is the depth in meters and S is the salinity of the water - we get $c_{sound} = 2799.33\ m/s$.

When the transmitter receiver distance is $d = 1423.79\ m$, the propagation delay,

$$\Delta = \frac{1423.79}{2799.33} = 508618.13\ \mu s. \tag{43}$$

Substituting all these, we see that the ideal slot length (when $d = 1423.79$) would be

$$L_{slot} = T_{tx} + \Delta = 16{,}800 + 508618.13 = 525420\ \mu s \tag{44}$$

NOTE: The slot length is set based on the largest Tx-Rx distance i.e., from node 2 to Master node 1

Application Configuration

- Create a three CBR Application from the source nodes (12, 11, 6) to the Destination (Node 1) with a packet size of 14 bytes each and we will vary the inter arrival according to the load

Table 4-14: *Application properties for different loads*

Load (Pkt/sec)	Inter Arrival time	Load (Pkt/sec)	Inter Arrival time
0.001	1000000000	0.0095	105263157
0.0015	666666666	0.01	100000000
0.002	500000000	0.02	50000000
0.0025	400000000	0.03	33333333
0.003	333333333	0.04	25000000
0.0035	285714285	0.05	20000000
0.004	250000000	0.06	16666666
0.0045	222222222	0.07	14285714
0.005	200000000	0.08	12500000
0.0055	181818181	0.09	11111111
0.006	166666666	0.1	10000000

Load (Pkt/sec)	Inter Arrival time	Load (Pkt/sec)	Inter Arrival time
0.0065	153846153	0.2	5000000
0.007	142857142	0.3	3333333
0.0075	133333333	0.4	2500000
0.008	125000000	0.5	2000000
0.0085	117647058	0.6	1666666
0.009	111111111		

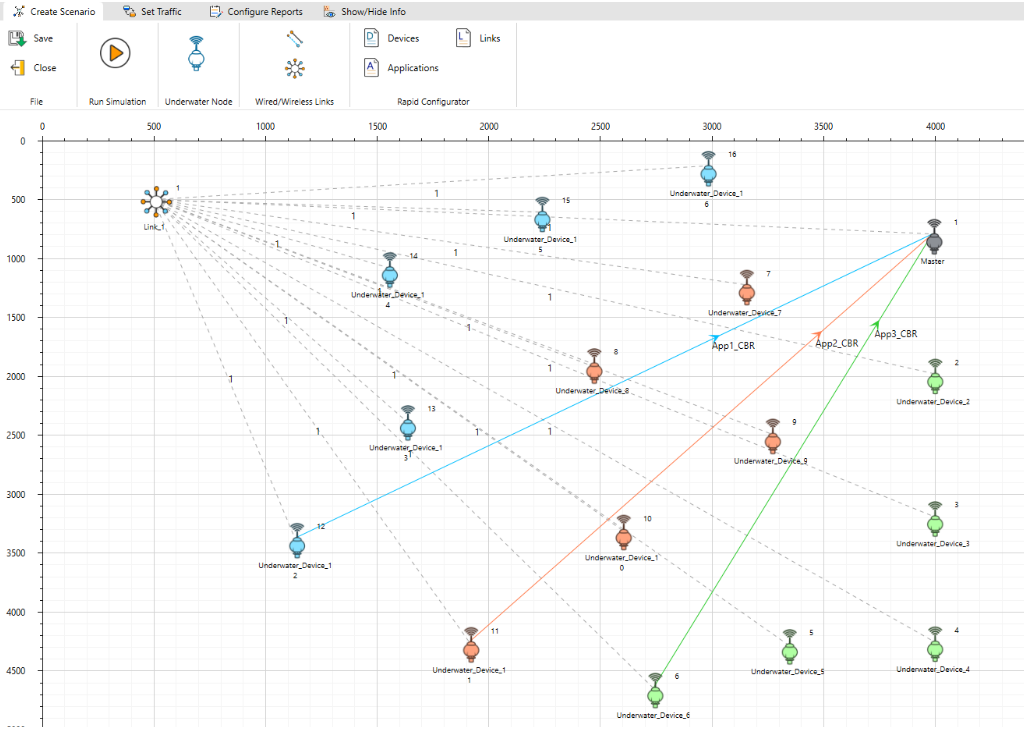
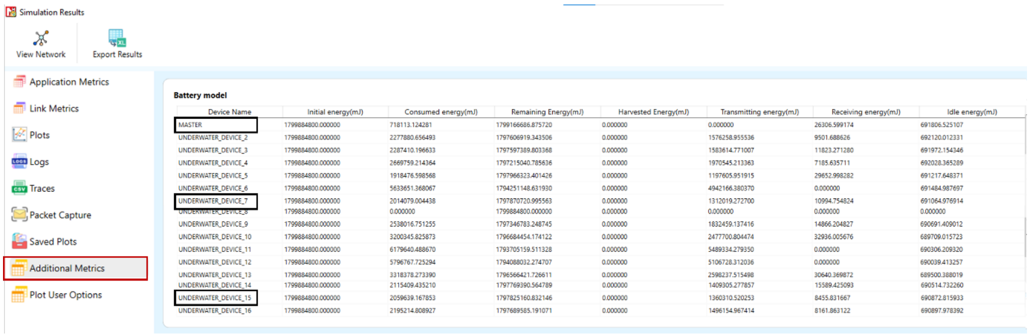


Figure 4-15: *The network consists of 16 underwater devices connected via an acoustic link. Three applications are configured to send data from underwater sensors to the master node using static routes: App1 from Node 12 to Master Node 1 and App3 from Node 6 to Master Node 1.*

4.4.3 Simulation results

Post simulation, click on the additional metrics in the simulation results window and scroll down for battery model metrics as shown below.



Battery model

Device Name	Initial energy(mJ)	Consumed energy(mJ)	Remaining Energy(mJ)	Harvested Energy(mJ)	Transmitting energy(mJ)	Receiving energy(mJ)	Idle energy(mJ)
MASTER	1799884800.000000	718113.124281	1799166686.875720	0.000000	0.000000	26306.599174	691806.525107
UNDERWATER_DEVICE_2	1799884800.000000	2277880.656493	1797606919.343506	0.000000	1576258.955536	9501.688626	692120.012331
UNDERWATER_DEVICE_3	1799884800.000000	2287410.196633	1797597389.803368	0.000000	1583614.771007	11823.271280	691972.154346
UNDERWATER_DEVICE_4	1799884800.000000	2669759.214364	1797215040.785636	0.000000	1970545.213363	7185.635711	692028.365289
UNDERWATER_DEVICE_5	1799884800.000000	1918476.598568	1797966323.401426	0.000000	1197605.951915	29652.998282	691217.648371
UNDERWATER_DEVICE_6	1799884800.000000	5633651.368067	1794251148.631930	0.000000	4942166.380370	0.000000	691484.987697
UNDERWATER_DEVICE_7	1799884800.000000	2014079.004438	1797870720.995563	0.000000	1312019.272700	10994.754824	691064.976914
UNDERWATER_DEVICE_8	1799884800.000000	0.000000	1799884800.000000	0.000000	0.000000	0.000000	0.000000
UNDERWATER_DEVICE_9	1799884800.000000	2538016.751255	1797346783.248745	0.000000	1832459.137416	14866.204827	690691.409012
UNDERWATER_DEVICE_10	1799884800.000000	3200345.825873	1796684454.174122	0.000000	2477700.804474	32936.005676	689709.015723
UNDERWATER_DEVICE_11	1799884800.000000	6179640.488670	1793705159.511328	0.000000	5489334.279350	0.000000	690306.209320
UNDERWATER_DEVICE_12	1799884800.000000	5796767.725294	1794088032.274707	0.000000	5106728.312036	0.000000	690039.413257
UNDERWATER_DEVICE_13	1799884800.000000	3318378.273390	1796566421.726611	0.000000	2598237.515498	30640.369872	689500.388019
UNDERWATER_DEVICE_14	1799884800.000000	2115409.435210	1797769390.564789	0.000000	1409305.277857	15589.425093	690514.732260
UNDERWATER_DEVICE_15	1799884800.000000	2059639.167853	1797825160.832146	0.000000	1360310.520253	8455.831667	690872.815933
UNDERWATER_DEVICE_16	1799884800.000000	2195214.808927	1797689585.191071	0.000000	1496154.967414	8161.863122	690897.978392

Figure 4-16: *Battery model metrics*

The transmitting energy, receiving energy, idle energy, and total consumed energy for the Master node, Layer1 Node 7, and Layer2 Node 15 are tabulated in individual tables for different loads.

Table 4-15: *Tabulated results for Master node*

Load (Pkt/sec)	Transmit Energy (mJ)	Receive Energy (mJ)	Idle Energy (mJ)	Total Consumed Energy (mJ)
0.001	0	26307	691807	718113
0.0015	0	40796	716045	756841
0.002	0	55483	728281	783764
0.0025	0	68962	735374	804336
0.003	0	85278	739642	824919
0.0035	0	98271	742889	841159
0.004	0	111749	744856	856605
0.0045	0	125491	746883	872373
0.005	0	140663	748698	889361
0.0055	0	153426	748517	901943
0.006	0	169059	749059	918118
0.0065	0	182570	749340	931910
0.007	0	198170	750409	948580
0.0075	0	211879	749936	961815
0.008	0	223927	751157	975083
0.0085	0	235974	750280	986253
0.009	0	249913	750492	1000405
0.0095	0	266096	750124	1016220
0.01	0	281333	749353	1030686
0.02	0	575793	740784	1316577
0.03	0	854663	731155	1585818
0.04	0	1202139	715724	1917863
0.05	0	1619240	698524	2317764
0.06	0	2258239	670898	2929137
0.07	0	3088371	636044	3724415
0.08	0	3558266	616165	4174430
0.09	0	3645710	612425	4258136
0.1	0	3724541	608901	4333442
0.2	0	3488490	619132	4107622
0.3	0	3471500	619817	4091317
0.4	0	3377058	622000	3999057
0.5	0	3479548	619362	4098910
0.6	0	3542675	616830	4159505

Table 4-16: *Tabulated results for Layer 1, Node 7*

Load (Pkt/sec)	Transmit Energy (mJ)	Receive Energy (mJ)	Idle Energy (mJ)	Total Consumed Energy (mJ)
0.001	1312019	10995	691065	2014079
0.0015	1908392	15224	716275	2639890
0.002	2504764	20298	729141	3254203

Load (Pkt/sec)	**Transmit Energy (mJ)**	**Receive Energy (mJ)**	**Idle Energy (mJ)**	**Total Consumed Energy (mJ)**
0.0025	3339685	24527	735728	4099940
0.003	4174607	30447	740628	4945682
0.0035	4770979	35522	743810	5550311
0.004	5605901	42288	745971	6394159
0.0045	6202273	46516	748664	6997454
0.005	7037194	50745	749118	7837057
0.0055	7752841	54974	750409	8558223
0.006	8349214	60048	751573	9160835
0.0065	9064860	65969	751702	9882531
0.007	9780507	74426	752167	10607100
0.0075	10496154	78655	752933	11327742
0.008	11092527	89650	754046	11936222
0.0085	11688899	93878	753350	12536127
0.009	12285271	98953	753788	13138012
0.0095	12881644	103182	753777	13738603
0.01	13478016	107410	753323	14338750
0.02	27790954	219049	748891	28758894
0.03	42700264	317612	741797	43759672
0.04	59517965	434000	732687	60684652
0.05	76335667	584479	723131	77643277
0.06	108062678	712383	708987	109484048
0.07	147542531	1025897	686074	149254502
0.08	170443231	1274352	669363	172386946
0.09	201454596	1458335	653378	203566309
0.1	204078634	1622671	645366	206346672
0.2	236521293	2101952	617747	239240991
0.3	243319938	1984392	620982	245925312
0.4	229841922	1961101	625426	232428449
0.5	211473652	1905802	631998	214011452
0.6	255128111	2118476	612071	257858659

Table 4-17: *Tabulated results for Layer 2, Node 15*

Load (Pkt/sec)	**Transmit Energy (mJ)**	**Receive Energy (mJ)**	**Idle Energy (mJ)**	**Total Consumed Energy (mJ)**
0.001	1360311	8456	690873	2059639
0.0015	1943301	14093	716389	2673783
0.002	2526291	17475	728847	3272613
0.0025	3303611	20858	736534	4061003
0.003	3789436	24240	741228	4554905
0.0035	4469592	27059	744525	5241176
0.004	4955417	29877	746823	5732117
0.0045	5441242	34387	748685	6224314
0.005	6121397	37206	751498	6910101
0.0055	6898718	40024	751542	7690284

Load (Pkt/sec)	Transmit Energy (mJ)	Receive Energy (mJ)	Idle Energy (mJ)	Total Consumed Energy (mJ)
0.006	7481708	43970	751749	8277427
0.0065	8161863	48480	752431	8962775
0.007	8647688	51862	753131	9452682
0.0075	9133513	55245	753387	9942145
0.008	9910834	58063	754561	10723458
0.0085	10493824	60882	754372	11309078
0.009	10979649	64828	754200	11798678
0.0095	11562639	68210	754552	12385402
0.01	12048465	71593	754728	12874785
0.02	23513939	145440	752394	24411774
0.03	35076578	212523	747783	36036884
0.04	48874014	303846	741121	49918981
0.05	58292600	395733	734991	59423323
0.06	77508797	546810	724029	78779637
0.07	106500128	751442	707997	107959567
0.08	123932855	968475	688867	125590197
0.09	144988766	1032739	686546	146708050
0.1	158314046	1169160	676869	160160075
0.2	129284179	1241880	681804	131207862
0.3	136798000	1231169	679611	138708780
0.4	140626797	1258228	678243	142563269
0.5	167477286	1303889	669477	169450652
0.6	141795989	1167468	681776	143645234

4.4.4 Throughput and Packet collision count

The values for throughput of three applications and packets collided are listed below for different loads:

Table 4-18: *Tabulated results for throughput and packets collided.*

Load (Pkt/sec)	Throughput-1 (Mbps)	Throughput-2 (Mbps)	Throughput-3 (Mbps)	Packets Collided
0.001	0	0	0	154
0.0015	0	0	0	233
0.002	0	0	0	306
0.0025	0	0	0	374
0.003	0	0	0	439
0.0035	0	0	0	511
0.004	0	0	0	578
0.0045	0.000001	0.000001	0.000001	642
0.005	0.000001	0.000001	0.000001	719
0.0055	0.000001	0.000001	0.000001	782
0.006	0.000001	0.000001	0.000001	843
0.0065	0.000001	0.000001	0.000001	913
0.007	0.000001	0.000001	0.000001	980
0.0075	0.000001	0.000001	0.000001	1052
0.008	0.000001	0.000001	0.000001	1125

Load (Pkt/sec)	Throughput-1 (Mbps)	Throughput-2 (Mbps)	Throughput-3 (Mbps)	Packets Collided
0.0085	0.000001	0.000001	0.000001	1194
0.009	0.000001	0.000001	0.000001	1261
0.0095	0.000001	0.000001	0.000001	1331
0.01	0.000001	0.000001	0.000001	1396
0.02	0.000002	0.000002	0.000002	2805
0.03	0.000003	0.000003	0.000003	4167
0.04	0.000004	0.000004	0.000004	5747
0.05	0.000005	0.000005	0.000005	7542
0.06	0.000006	0.000006	0.000006	10088
0.07	0.000006	0.000006	0.000006	14228
0.08	0.000005	0.000006	0.000006	18428
0.09	0.000005	0.000006	0.000005	21346
0.1	0.000004	0.000005	0.000004	24555
0.2	0.000002	0.000004	0.000003	27718
0.3	0.000002	0.000004	0.000002	27771
0.4	0.000002	0.000003	0.000002	28000
0.5	0.000002	0.000003	0.000002	28074
0.6	0.000002	0.000004	0.000002	28143

Packets Collision Count

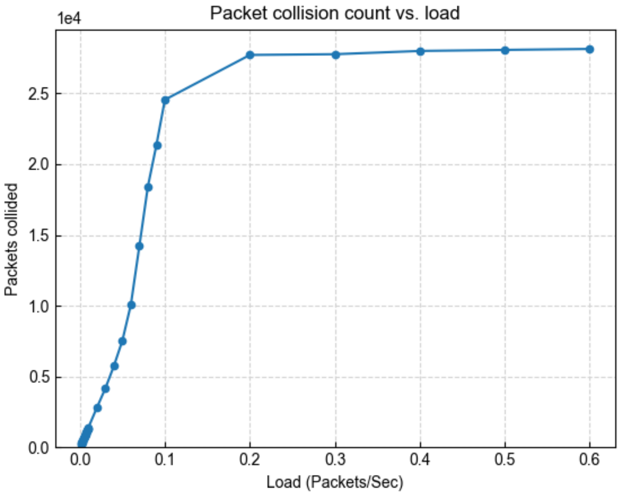
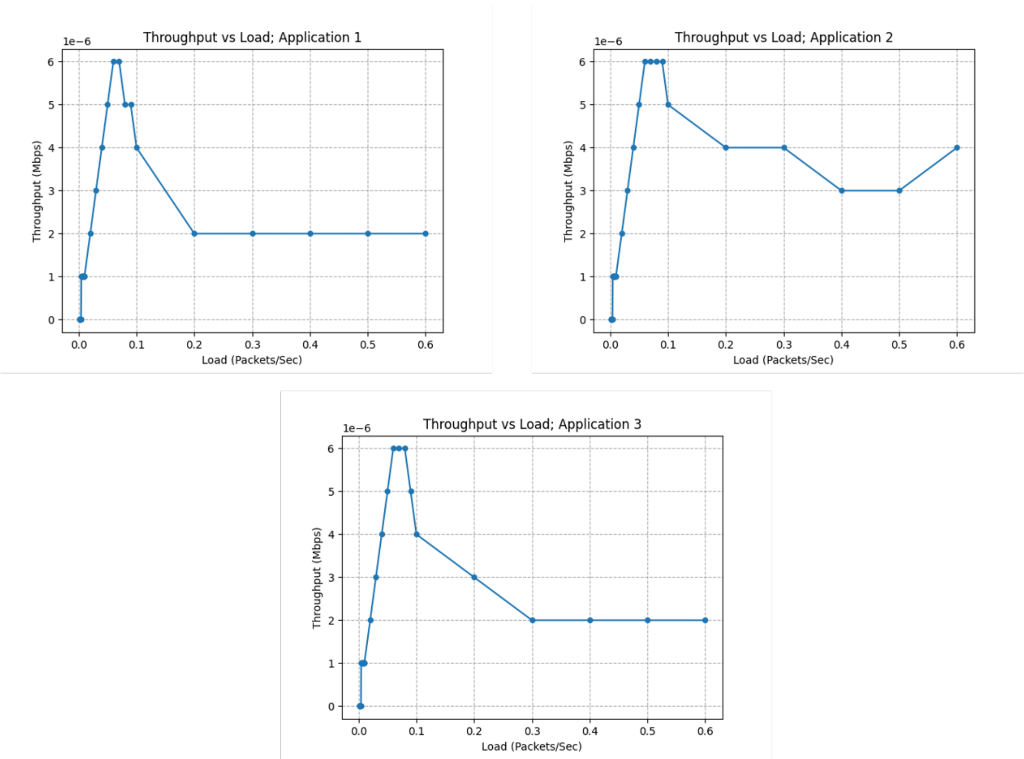


Figure 4-17: *We observe the variation in collision count vs load, for this 16-node network running slotted aloha in the MAC layer.*

As the load increases, the number of collisions rises sharply until it reaches a plateau. At low loads, the probability of collision is relatively low, and most packets are successfully transmitted. However, as the load increases, the probability of two or more packets being transmitted in the same time slot rises exponentially, leading to a rapid increase in collisions.

NetSim slotted Aloha implementation uses the exponential backoff algorithm when collisions occur. As collisions become frequent at high loads, nodes spend more time in backoff, effectively reducing their transmission attempts and stabilizing the collision rate.

Throughput


Throughput vs Load; Application 1

Throughput vs Load; Application 2

Throughput vs Load; Application 3

Figure 4-18: *Throughput plots for all three applications.*

The throughput behaviour can be explained by considering both the collision plot and the throughput graphs:

- Initial increase: At low loads, throughput increases as more packets are successfully transmitted with relatively few collisions.
- Peak throughput: The throughput reaches a maximum at an optimal load point (around 0.05–0.07 packets/sec). This represents the best balance between channel utilization and collision avoidance.
- Sharp decline: As load increases beyond the optimal point, we see a sharp rise in collisions (from the collision plot). This leads to a rapid drop in throughput because:
  - More transmission attempts result in collisions rather than successful transmissions.
  - Colliding packets waste channel capacity without contributing to throughput.
  - The exponential backoff algorithm causes nodes to wait longer before retransmitting, reducing overall transmission attempts.
- Gradual stabilization: The collision plot shows a plateau at higher loads, but throughput continues to decrease slightly or stabilize at a lower level. This occurs because:
  - The network is saturated with collisions.
  - Most transmission attempts fail due to collisions.
  - The backoff algorithm limits new transmission attempts.
  - The actual number of successful transmissions becomes a small fraction of the total load.
- Differences between applications:
  - Applications 1 and 3 use routes with 4 hops and show similar throughput patterns. They experience more throughput degradation at high loads as compared to application 2 due to longer paths.
  - Application 2 uses a route with only 3 hops and sees better throughput, at higher loads. This is because of the shorter path length, which reduces the overall collision probability because each additional hop increases the likelihood of collisions and packet loss.

- The throughput differences among applications stem from cross layer interactions of routing path lengths and the slotted Aloha MAC layer's behaviour under varying loads.

Master Node 1 Energy Consumption See Figure 4-19

- The transmission energy from the master node will be zero because no transmission is occurring from the master node.
- As the load increases, the number of collisions initially rises rapidly but flattens out. Although the number of successfully received packets decreases, the node continues to receive collided packets. In the NetSim energy model, note that energy is expended in receiving these collided packets. However, once received, the node cannot decode the packets that have undergone collisions.
- The idle energy remains significant throughout all loads, though it slightly decreases at higher loads. This is because more energy is being consumed in receiving packets, leaving less time for the node to be idle.

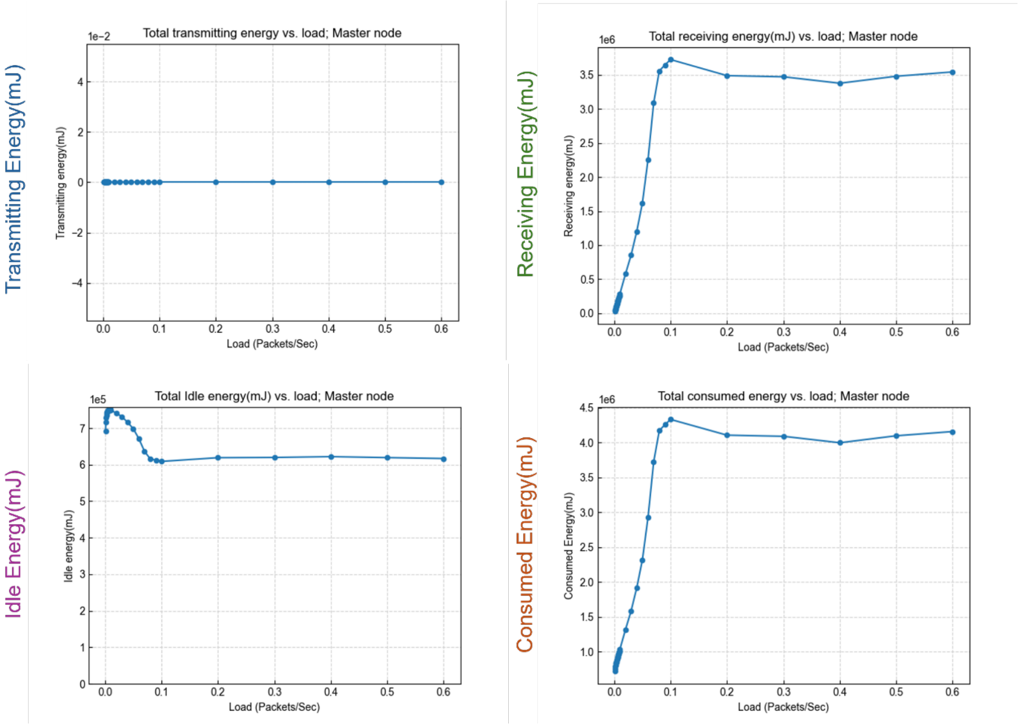


Figure 4-19: *Energy Consumption Plots for the Master Node.*

- The total consumed energy initially increases with network load, primarily due to the rise in receiving energy, and then flattens out.

Layer-1 Device – Node 7, Energy Consumption See Figure 4-20

- The transmitting energy for Layer 1 Node 7 increases significantly with the network load as it relays packets of Application 2 to the master node.
- The receiving energy also increases with load. This reflects its role in receiving packets that it must then forward to the master node.
- The idle energy remains relatively stable but shows a slight decrease at higher loads. This is due to the node spending more energy on transmission and reception rather than staying idle, at higher loads.

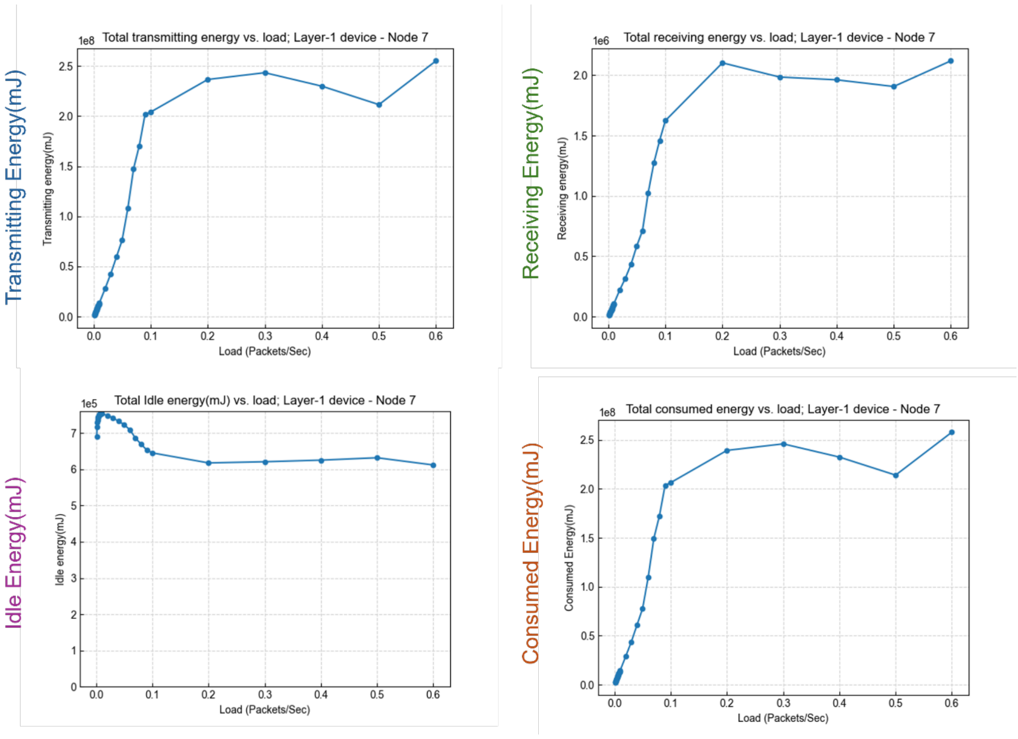


Figure 4-20: *Energy Consumption Plots for the Layer1 Node 7*

- The total consumed energy increases with the network load, driven by the substantial rise in both transmitting and receiving energies.
- These plots reflect Node 7's active role in relaying traffic from outer layers to the master node.

Layer-2 Device – Node 15 Energy Consumption See Figure 4-21

- The curves depicted in the four panels in Figure 4-21 closely resemble those in Figure 4-20 with the only distinction being slightly lower values. This difference arises because: Node 15 serves as a relay for Application 1, while Node 7 relays for Application 2. Application 1 sees lower throughput compared to Application 2 due to its longer path (4 hops versus 3 hops). Consequently, Node 15 relays fewer packets than Node 7, resulting in reduced transmit and receive energy consumption. This, in turn, leads to lower total energy consumption for Node 15.

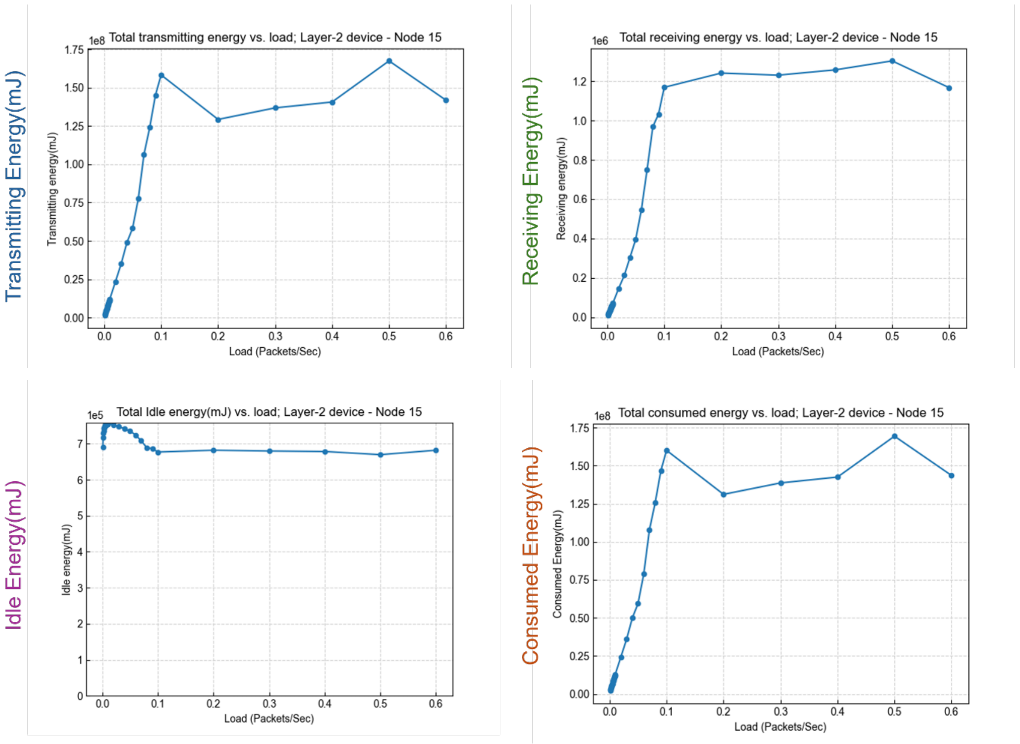


Figure 4-21: *Energy consumption plot for a Layer-2 device, Node 15*

5 Limitations

- Users cannot model buoy nodes, behaving as network sink(s) to collect data which can then be transmitted, via Radio Frequency (RF), to a nearby boat, or satellite
- Link layer ACKs are not modeled in s-Aloha
- There is no Guard time between slots in s-Aloha
- Doppler shift on account of transmitter and/or receiver motion is not accounted
- UWAN cannot connect to an "external" network; it operates stand alone.
- All devices are assumed to be time synchronized.
- Models for simulating multipath fading are not currently available.

6 References

[1] A. B. Coppens, “Simple equations for the speed of sound in Neptunian waters,” 1981.

[2] H. U. Yidliz, V. C. Gungor and B. Talvi, “Packet Size Optimization for Lifetime Maximization in Underwater Acoustic Sensor Networks,” IEEE Transactions on Industrial Informatics, 2019.

[3] M. Stojanovic and J. Preisig, “Underwater Acoustic Communication Channels: Propagation Models and Statistical Characterization,” IEEE Communications Magazine, 2009.

[4] D. E. Lucani, M. Medard and M. Stojanovic, “Capacity Scaling Laws for Underwater Networks,” 2012.

[5] M. Stojanovic, “On the Relationship Between Capacity and Distance in an Underwater Acoustic Communication Channel,” in WUWNet, 2006.

[6] J. L. J. M. J. a. L. P. S. Sendra, “Underwater Acoustic Modems,” Sensors journal, vol. 16, p. 11, 2016.

[7] [Online]. Available: `https://www.l3harris.com/sites/default/files/2020-09/ims-maritime-datasheet-GPM%20300.pdf`.

[8] R. J. Urick, “Principles of Underwater Sound, Peninsula Publishing,” 1983.

[9] M. S. a. J. G. P. E. M. Sozer, “Design and Simulation of an Underwater Acoustic Local Area Network”.