Underwater Channel and Energy Models

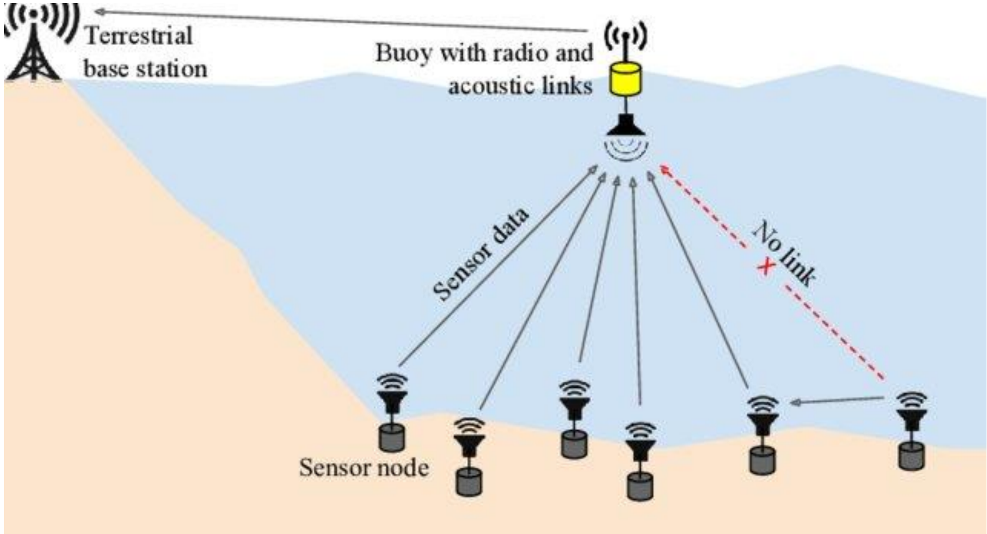
Huseyin Ugur Yildiz

Outline

1) Underwater Sensor Networks
2) Attenuation
3) Concept of Decibel
4) Popular Underwater Modems
5) A Simple Energy Model
6) A Simple Network Flow Programming Model for Lifetime Maximization
7) Ambient Noise
8) Passive Sonar Equation
9) Sound Intensity
10) SNR and Source Level
11) SNR vs Bit Error Rate
12) Two-Way Handshake
13) Timing Analysis
14) Energy and Delay Cost Models
15) A Middle-Level Network Flow Programming Model for Lifetime Maximization

Underwater Wireless Sensor Networks

- Underwater Wireless Sensor Networks (UWSNs): numerous battery limited nodes + single (multiple) sink node(s).
- Use cases: pollution monitoring, tactical surveillance, assisted navigating, *etc.*
- UWSNs generally use acoustic waves for communications.



Source: Morozs, N., Mitchell, P., & Zakharov, Y. (2018, August). Unsynchronized dual-hop scheduling for practical data gathering in underwater sensor networks. In *2018 Fourth Underwater Communications and Networking Conference (UComms)* (pp. 1-5). IEEE.

Attenuation [1]

- Attenuation (linear scale): $\boxed{A(l,f) = l^k \times \alpha(f)^{l \times 10^{-3}}}$

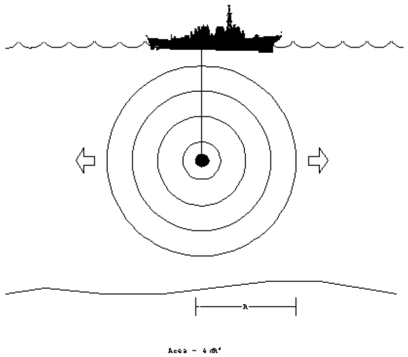
Distance between the transmitter and the receiver in m.

- Attenuation (dB): $\boxed{10\log_{10} A(l,f) = 10k\log_{10} l + l \times 10^{-3} \times 10\log_{10}\alpha(f)}$

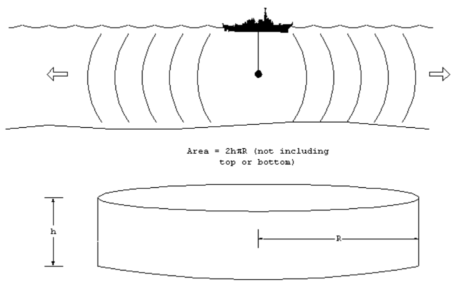
- k: Spreading factor

$k = 2$	Spherical spreading
$k = 1.5$	Practical spreading
$k = 1$	Cylindrical spreading

Spherical spreading



Cylindrical spreading

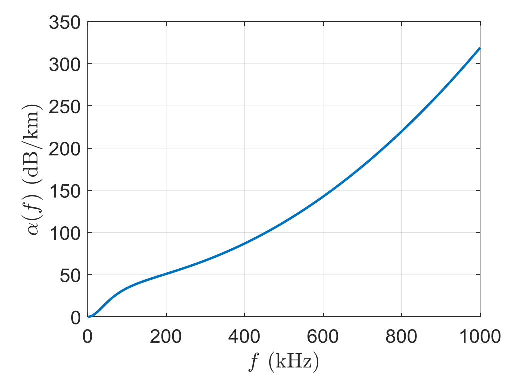


- f: Underwater modem's carrier frequency (kHz)
- $\alpha(f)$: Absorption coefficient (dB/km)

Ref: https://fas.org/man/dod-101/navy/docs/es310/SNR_PROP/snr_prop.htm

$$\boxed{10\log_{10}\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 + 0.003}$$

Thorp's Empirical Formula



Concept of Decibel

- dB: decibel, W: Watts (Power), mW: milliWatts
- dBW: decibel-Watt
- dBm: decibel-milliwatts

$$\boxed{1\ W = 1000\ mW}$$

- dBW ↔ W

$$\boxed{\begin{aligned} P\ [dBW] &= 10\log_{10}(P\ [W]) \\ P\ [W] &= 10^{\left(\frac{P\ [dBW]}{10}\right)} \end{aligned}}$$

- dBm ↔ mW

$$\boxed{\begin{aligned} P\ [dBm] &= 10\log_{10}(P\ [mW]) \\ P\ [mW] &= 10^{\left(\frac{P\ [dBm]}{10}\right)} \end{aligned}}$$

- dBm ↔ dBW

$$P\ [dBm] = 10\log_{10}\left(P\ [W]10^3\right) = \underbrace{10\log_{10}(P\ [W])}_{P[dBW]} + \underbrace{10\log_{10}\left(10^3\right)}_{30}$$

$$P\ [dBm] = P\ [dBW] + 30$$

Ref: https://www.rapidtables.com/electric/dBW.html

$$\bar{P} \rightarrow dBW\ (or\ dBm)$$
$$P \rightarrow W\ (or\ mW)$$

We prefer to use «overbars» to represent a power quantity in dB

dBm to Watt, mW, dBW conversion table

Power (dBm)	Power (dBW)	Power (watt)	Power (mW)
-100 dBm	-130 dBW	0.1 pW	0.0000000001 mW
-90 dBm	-120 dBW	1 pW	0.000000001 mW
-80 dBm	-110 dBW	10 pW	0.00000001 mW
-70 dBm	-100 dBW	100 pW	0.0000001 mW
-60 dBm	-90 dBW	1 nW	0.000001 mW
-50 dBm	-80 dBW	10 nW	0.00001 mW
-40 dBm	-70 dBW	100 nW	0.0001 mW
-30 dBm	-60 dBW	1 μW	0.001 mW
-20 dBm	-50 dBW	10 μW	0.01 mW
-10 dBm	-40 dBW	100 μW	0.1 mW
-1 dBm	-31 dBW	794 μW	0.794 mW
0 dBm	-30 dBW	1.000 mW	1.000 mW
1 dBm	-29 dBW	1.259 mW	1.259 mW
10 dBm	-20 dBW	10 mW	10 mW
20 dBm	-10 dBW	100 mW	100 mW
30 dBm	0 dBW	1 W	1000 mW
40 dBm	10 dBW	10 W	10000 mW
50 dBm	20 dBW	100 W	100000 mW
60 dBm	30 dBW	1 kW	1000000 mW
70 dBm	40 dBW	10 kW	10000000 mW
80 dBm	50 dBW	100 kW	100000000 mW
90 dBm	60 dBW	1 MW	1000000000 mW
100 dBm	70 dBW	10 MW	10000000000 mW

Popular Underwater Modems [2]

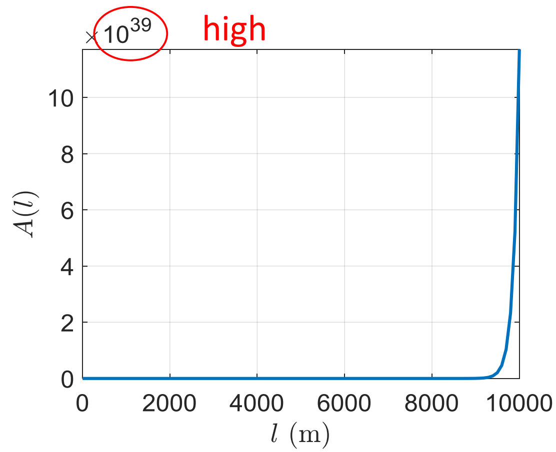
Underwater Acoustic Modem	Modulation	Carrier Frequency	Bandwidth	Data rate	TX Power consumption	RX Power consumption	Idle Power consumption	Max. distance
DEVICES DEVELOPED BY RESEARCH GROUPS								
[5]	FSK	320 Hz and 10 kHz	1 kHz	96 bps and 2400 bps	12 mW	24 mW	3 μW	100 m
[19]	n/a	n/a	n/a	1-10 Mbps	n/a	n/a	n/a	100 m
[25]	FSK	35 kHz	6 kHz	200 bps	750 mW		35 mW	350 m
[27]	KSK	85 kHz	n/a	1 kbps	108 mW	24 mW	8.1 μW	240 m
[28]	n/a	9-14 kHz	75 kHz	1.2 kbps	n/a	n/a	n/a	2000 m
[21]	BPSK	80 kHz	n/a	80 kbps	n/a	n/a	n/a	50 m
[30]	FSK	30 kHz	n/a	300 bps	n/a	n/a	n/a	400 m
[32]	FSK	9 kHz	n/a	1900 bps	n/a	n/a	n/a	200 m
COMMERCIAL DEVICES								
Aquatec AQUAModem 1000 [36]	n/a	9.75 kHz	4.5 kHz	2000 bps	20 W	0.6 W	1 mW	5000 m
DSPComm AquaComm Marlin [37]	n/a	23 kHz	14 kHz	480 bps	1.8 W	0.252 W	1.8 mW	1000 m
DSPComm AquaComm Mako [38]	n/a	23 kHz	14 kHz	240 bps	1.8 W	0.252 W	1.8 mW	100 m
DSPComm AquaComm Orca [37]	n/a	14 kHz	100 kHz	0.007 bps	0.252 W	1.8 W	25.2 mW	3000 m
Desert Star Systems SAM-1[38]	n/a	37.5 kHz	9 kHz	154 bps	32 W	0.168 W	n/a	1000 m
EvoLogics S2CR 48/78USBL [39]	n/a	48-78 kHz	30 kHz	31200 bps	18 W	1.1 W	2.5 mW	1000 m
EvoLogics S2CR 40/80 USBL [39]	n/a	38-64 kHz	26 kHz	27700 bps	40 W	1.1 W	2.5 mW	1000 m
EvoLogics S2CR 18/34wise [39]	n/a	18-34 kHz	16 kHz	13900 bps	35 W	1.3 W	2.5 mW	3500 m
EvoLogics S2CR 12/24 USBL [39]	n/a	13-24 kHz	11 kHz	9200 bps	15 W	1.1 W	2.5 mW	6000 m
EvoLogics S2CR 7/17 USBL [39]	n/a	7-17 kHz	10 kHz	6900 bps	40 W	1.1 W	2.5 mW	8000 m
LinkQuest UWM1000 [40]	n/a	35695 kHz	17.85 kHz	17800 bps	1 W	0.75 W	8 mW	3500 m
LinkQuest UWM2000 [40]	n/a	35695 kHz	17.85 kHz	17800 bps	2 W	0.8 W	8 mW	1500 m
LinkQuest UWM2000H [40]	n/a	35695 kHz	17.85 kHz	17800 bps	2 W	0.8 W	8 mW	1500 m
LinkQuest UWM2200 [40]	n/a	71.4 kHz	35.7 kHz	35700 bps	6 W	1 W	12 mW	1000 m
LinkQuest UWM3000 [40]	n/a	10 kHz	5 kHz	5000 bps	12 W	0.8 W	8 mW	3000 m
LinkQuest UWM3000H [40]	n/a	10 kHz	5 kHz	5000 bps	12 W	0.8 W	8 mW	3000 m
LinkQuest UWM4000 [40]	n/a	17 kHz	8.5 kHz	8500 bps	7 W	0.8 W	8 mW	4000 m
LinkQuest UWM10000 [40]	n/a	10 kHz	5 kHz	5000 bps	40 W	0.8 W	9 mW	1000 m
Teledyne Benthos Atm9xx [41]	PSK	11.5 kHz 18.5 kHz 24.5 kHz	5 kHz	15360 bps	20 W	0.768 W	16.8 mW	6000 m
Teledyne Benthos Atm9xx [41]	MFSK	11.5 kHz 18.5 kHz 24.5 kHz	5 kHz	2400 bps	20 W	0.768 W	16.8 mW	6000 m
Teledyne Benthos Atm88x [41]	PSK	11.5 kHz 18.5 kHz	5 kHz	15360 bps	84 W	0.756 W	16.8 mW	6000 m
Teledyne Benthos Atm88x [41]	FSK	11.5 kHz 18.5 kHz	5 kHz	2400 bps	84 W	0.756 W	16.8 mW	6000 m
TriTech MicronModem [42]	n/a	22 kHz	4 kHz	40 bps	7.92 W	0.72 W	n/a	500 m
uComm Underwater Acoustic Modem [43]	n/a	26 kHz	n/a	9000 bps	40 W	60 mW	3 mW	3000 m
AM-OFDM-S [44]	OFDM	21-27 kHz	n/a	1600 bps	5-20 W	0.7W	0.13 mW	4000 m
MATS 3 G 12 KHZ [45]	n/a	10-15 kHz	n/a	Up to 7400 bps	75 W	0.6 W	40 mW	15 Km
GPM 3000 Acoustic Modem [46]	DSSS	n/a	n/a	Up to 1200b•s	300W	1.8 W	0.08 W	25 Km

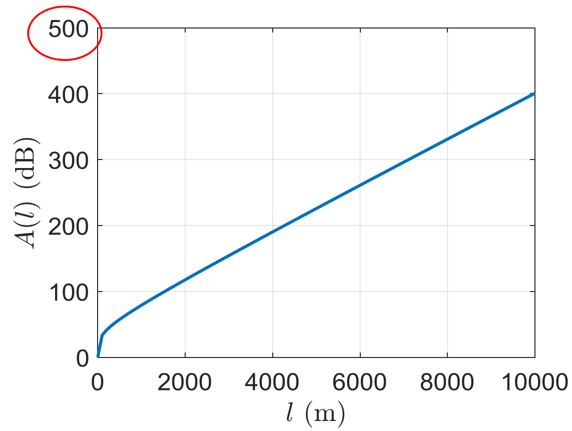
https://evologics.de/

Source: Sendra, S., Lloret, J., Jimenez, J. M., & Parra, L. (2015). Underwater acoustic modems. *IEEE Sensors Journal*, *16*(11), 4063-4071.

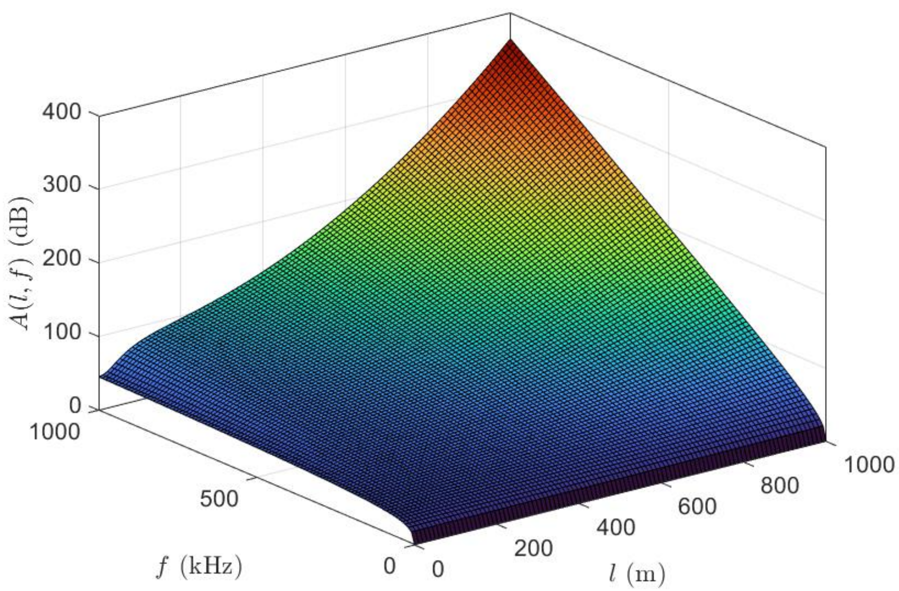
https://www.link-quest.com/

Attenuation (Cont'd) [1]





Fixed Parameters:
$k = 1.5, f = 100\ kHz$



Observations:

- As l (or f) increases $A(l, f)$ increases.
- Increment in l dominates the increment in f.

A Simple Energy Model [3, 4]

$$\overline{\alpha(f)} = 10\log_{10}\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75\times10^{-4}f^2 + 0.003$$ Absorption coeff.

$$\alpha(f) = 10^{(\overline{\alpha(f)}/10)}$$ dB to W conversion

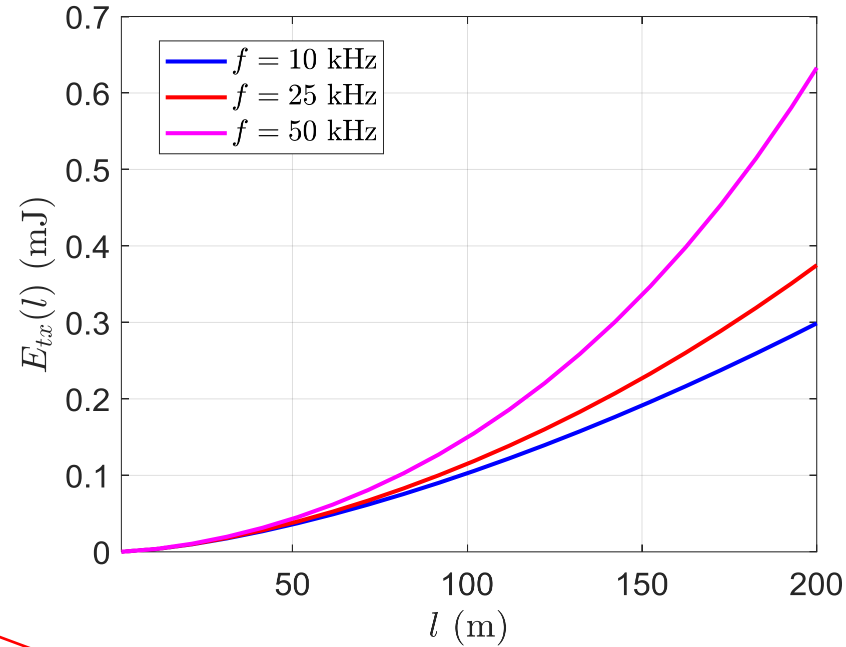
m

$$A(l,f) = l^k \times \alpha(f)^{l\times10^{-3}}$$ Attenuation

$$E_{tx}(l) = A(l,f)P_0$$ Transmission energy consumption per bit

$$E_{rx} = P_r$$ Reception energy consumption per bit

P_0	Power required at the input to the receiver (J/bit)	10^{-7}
P_r	Reception Constant (J/bit)	0.2×10^{-7}



5 times greater

- Simple to implement but unrealistic!

A Simple Network Flow Programming Model for Lifetime Maximization

Maximize t

subject to:

$$\sum_{j \in \mathcal{V}} g_{ij} - \sum_{j \in \mathcal{W}} g_{ji} = \begin{cases} s_i \times t, & \forall i \in \mathcal{W} \\ -\sum_{j \in W} s_j \times t, & i = 1 \end{cases}$$

Flow Balance

$$g_{ij} \geq 0, \ \forall (i,j) \in \mathcal{A}$$

Bounds

$$g_{ii} = 0, \ \forall i \in \mathcal{W}$$

Loop elimination

$$\sum_{j \in \mathcal{V}} g_{1j} = 0$$

Sink node cannot generate data

$$g_{ij} = 0 \text{ if } d_{ij} > d_{\max}, \ \forall (i,j) \in \mathcal{A}$$

Communication range constraint

$$\sum_{j \in \mathcal{V}} E_{tx}(d_{ij}) \times g_{ij} + E_{rx} \sum_{j \in \mathcal{W}} g_{ji} = \varepsilon_i, \ \forall i \in \mathcal{W}$$

Energy balance constraint

$$\varepsilon_i \leq \varepsilon_{\text{bat}}, \ \forall i \in \mathcal{W}$$

Battery constraint

Underwater Energy Model

Ambient Noise [1]

- The ambient noise in the ocean can be modeled using four sources: turbulence, shipping, winds, and thermal noise.

Turbulence $10 \log N_t(f) = 17 - 30 \log f$

Shipping $10 \log N_s(f) = 40 + 20(s - 0.5) + 26 \log f - 60 \log(f + 0.03)$

Winds $10 \log N_w(f) = 50 + 7.5 w^{1/2} + 20 \log f - 40 \log(f + 0.4)$

Thermal $\underbrace{10 \log N_{th}(f)}_{dB\ re\ 1\ \mu Pa \text{ (or simply } dB)} = -15 + 20 \log f$

$0 \leq s \leq 1$: Shipping activity

$w = 10$ m/s: wind speed

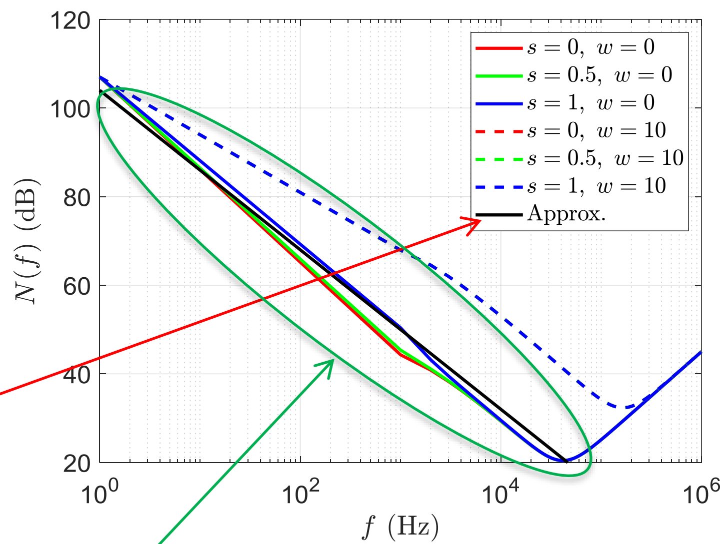
reference pressure for underwater sound.

- Ambient Noise (linear):

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f)$$

- Ambient Noise (dB): $\overline{N(f)} = 10 \log_{10} N(f)$

- Approximation to the Ambient Noise:
- $\overline{N(f)} \approx 50 - 18 \log_{10} f$ (in dB where f in kHz)



Have a good performance when $w = 0$ and $f < 50$ kHz

Passive Sonar Equation [5-8]

- Remark: $\log_{10}\left(\frac{a}{b}\right) = \log_{10} a - \log_{10} b$

Signal-to-Noise Ratio

- Passive Sonar Equation (dB) [5]:

$$\overline{SNR} = \overline{SL} - \overline{A(l,f)} - \overline{N(f)}$$

❓ ✔ ✔

- Passive Sonar Equation (linear) [6]:

$$SNR = \frac{SL}{A(l,f)N(f)}$$

Signal Power

Noise Power

- Attenuation (dB):

$$\begin{aligned}
\overline{A(l,f)} &= 10\log_{10}\big(A(l,f)\big) \\
&= 10\log_{10}\left(l^k \times \alpha(f)^{l\times 10^{-3}}\right) \\
&= 10k\log_{10} l + l \times 10^{-3} \underbrace{\times \log_{10}\alpha(f)}_{\overline{\alpha(f)}} \\
&\boxed{= 10k\log_{10} l + l \times 10^{-3} \times \overline{\alpha(f)}}
\end{aligned}$$

- Source Level – Signal Power (dB) [7]:
- *Known as acoustic transmission power*

$$\overline{SL} = 10\log_{10} SL$$

$$\boxed{\overline{SL} = 10\log_{10}\left(\frac{I_t}{I_0}\right)}$$

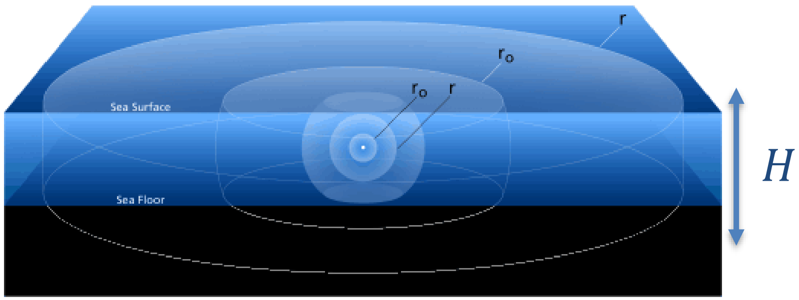
Sound Intensity (W/m²)

Reference Sound Intensity (W/m²)

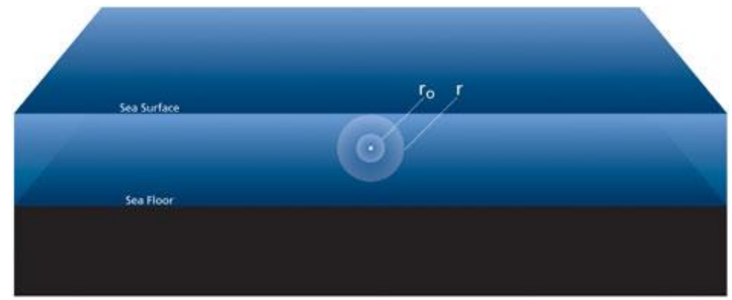
[8] $I_0 = 0.67 \times 10^{-18}$ (W/m²)

Sound Intensity [7,8]

Ref: https://dosits.org/science/advanced-topics/cylindrical-vs-spherical-spreading/



Cylindrical spreading in shallow water acoustic networks ($H < 150\ m$).



Spherical spreading in deep water acoustic networks ($150\ \mathrm{m} < H < 1000\ m$).

- Intensity: power per unit area carried by a wave (W/m²).

$$I_t = \frac{P}{A} = \frac{P_{tx}}{2\pi r H} = \frac{P_{tx}}{2\pi \times (1m) \times (H\ m)}$$

W

m²

$$I_t = \frac{P}{A} = \frac{P_{tx}}{4\pi r^2} = \frac{P_{tx}}{4\pi \times (1m)^2}$$

W

H: depth of the water (m)

P_{tx}: electrical transmission power (W)

Spherical

$$\boxed{\overline{SL} = 10\log_{10}\left(\frac{I_t}{I_0}\right) = 10\log_{10}\left(\frac{P_{tx}}{4\pi(0.67 \times 10^{-18})}\right)}$$

- Acoustic Transmission Power (dB): Cylindrical

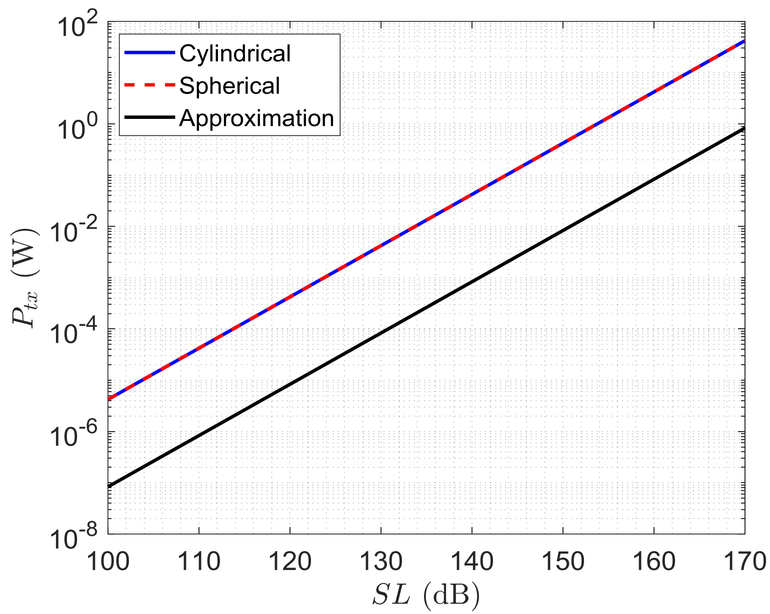
$$\boxed{\overline{SL} = 10\log_{10}\left(\frac{I_t}{I_0}\right) = 10\log_{10}\left(\frac{P_{tx}}{2\pi H(0.67 \times 10^{-18})}\right)}$$

$$\boxed{P_{tx} = 2\pi H I_0 10^{0.1\overline{SL}}}$$ Cylindrical

$$\boxed{P_{tx} = 4\pi I_0 10^{0.1\overline{SL}}}$$ Spherical

SNR and Source Level

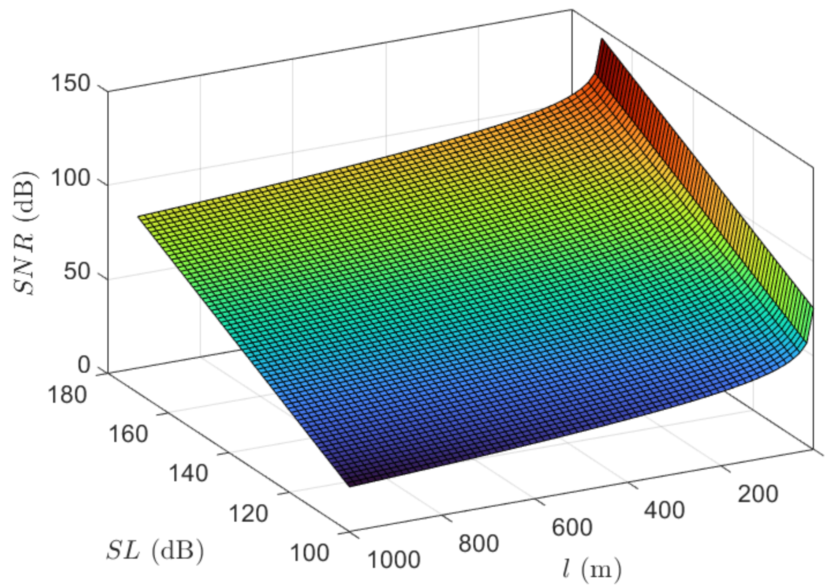
- Acoustic Transmission Power vs. Electrical Transmission Power ($H = 100\ m$)



- Approximation [9]:

$$\boxed{\overline{SL} = 170.8 + 10 \log_{10} P_{tx}}$$

- SNR vs $\overline{SL}$ and l ($f = 25\ kHz, k = 1.5$)



$$\overline{SNR} = \overline{SL} - \overline{A(l,f)} - \overline{N(f)}$$

$$= \overline{SL} - 10k \log_{10} l + l \times 10^{-3} \times \overline{\alpha(f)}$$
$$-(50 - 18\ \log_{10} f)$$

SNR vs Bit Error Rate

- If SNR is known, calculating Bit Error Rate (BER) is easy.
- BER: the percentage of bits that have errors relative to the total number of bits received in a transmission.
- Calculation of BER depends on the modulation technique that is used.

As an example, assume this transmitted bit sequence:

0 1 1 0 0 0 1 0 1 1

and the following received bit sequence:

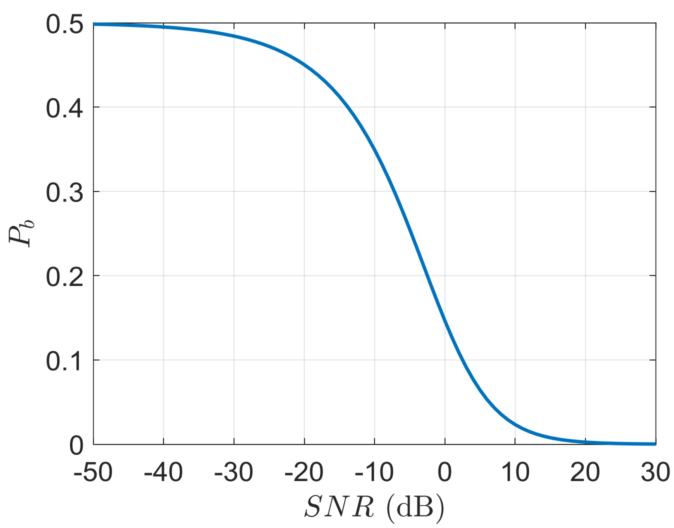
0 0 1 0 1 0 1 0 0 1,

The number of bit errors (the underlined bits) is, in this case, 3. The BER is 3 incorrect bits divided by 10 transferred bits, resulting in a BER of 0.3 or 30%.

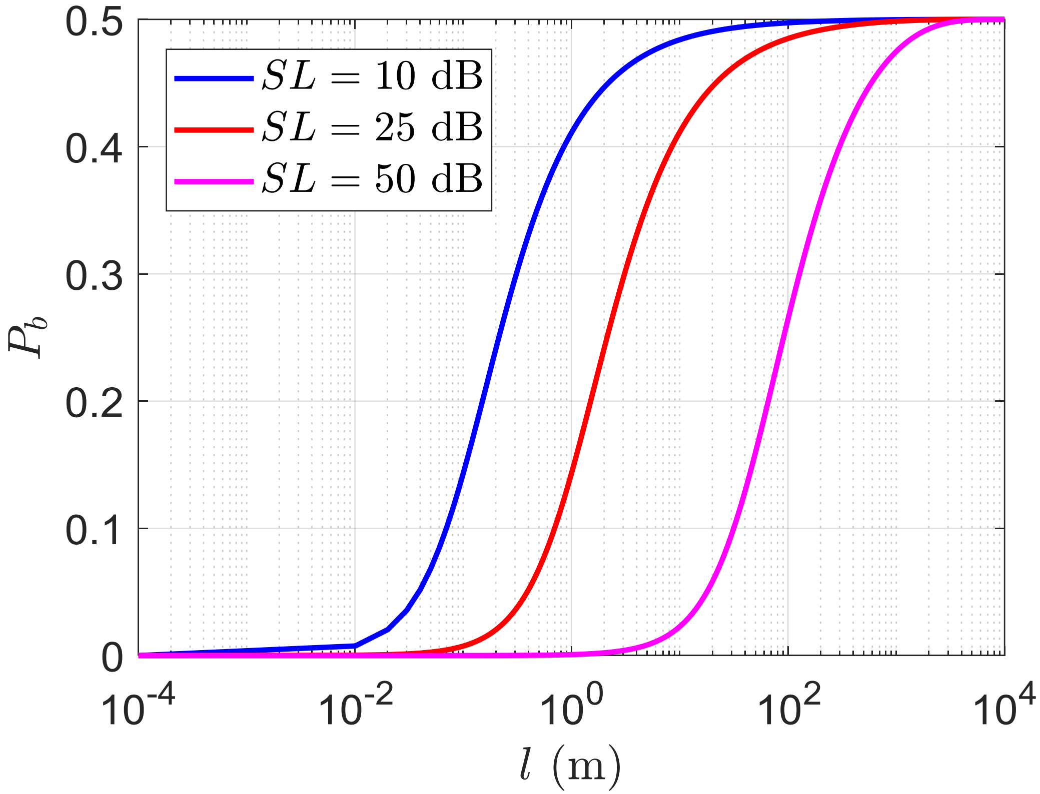
- Reasons for the bit errors: channel noise, interference, distortion, bit synchronization problems, attenuation, wireless multipath fading, etc.

- BER (P_b) for BPSK modulation with Rayleigh fading [5]:

$$\boxed{P_b = 0.5 - 0.5\sqrt{\frac{10^{0.1\overline{SNR}}}{1 + 10^{0.1\overline{SNR}}}}}$$



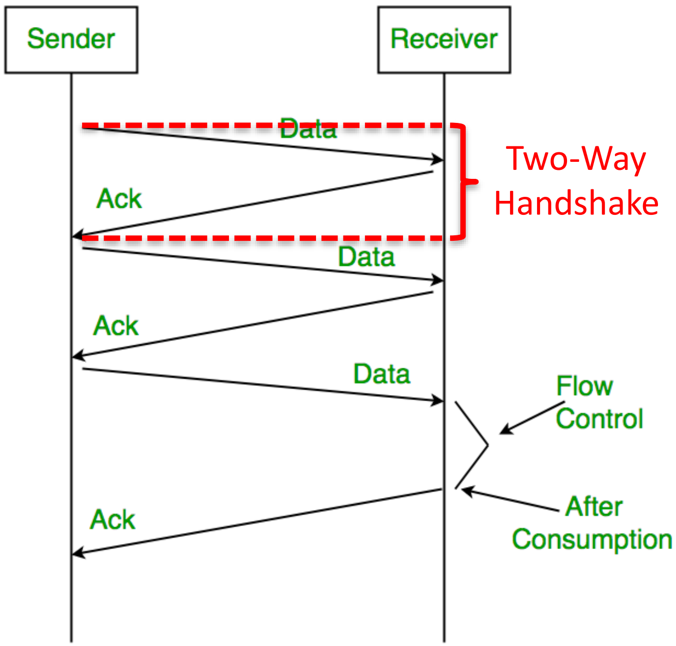
SNR vs Bit Error Rate



- P_b vs l $(f = 25\ kHz, k = 1.5)$

Two-Way Handshake

- Stop-and-Wait Automatic Repeat Request (ARQ): It ensures that information is not lost due to dropped packets and that packets are received in the correct order.

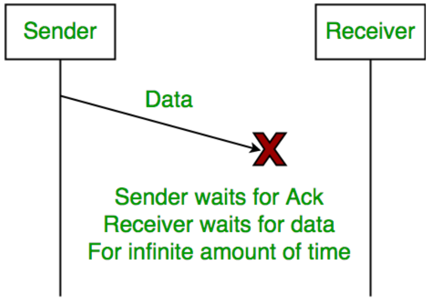


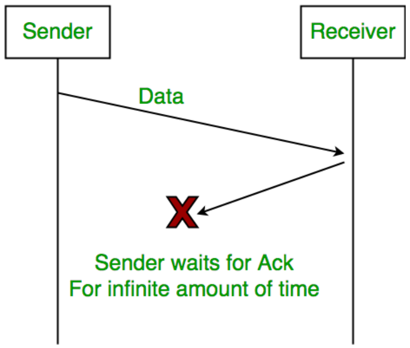
Stop-and-Wait ARQ - Timing Diagram

Ref: https://www.geeksforgeeks.org/stop-and-wait-arq/

- Data packet length: L_D bits
- ACK (Acknowledgment) packet length: L_A bits
- Typically, $L_D \gg L_A$.
- Two-Way Handshake: Both Data and ACK packets needed to be successfully transmitted.

Problems:

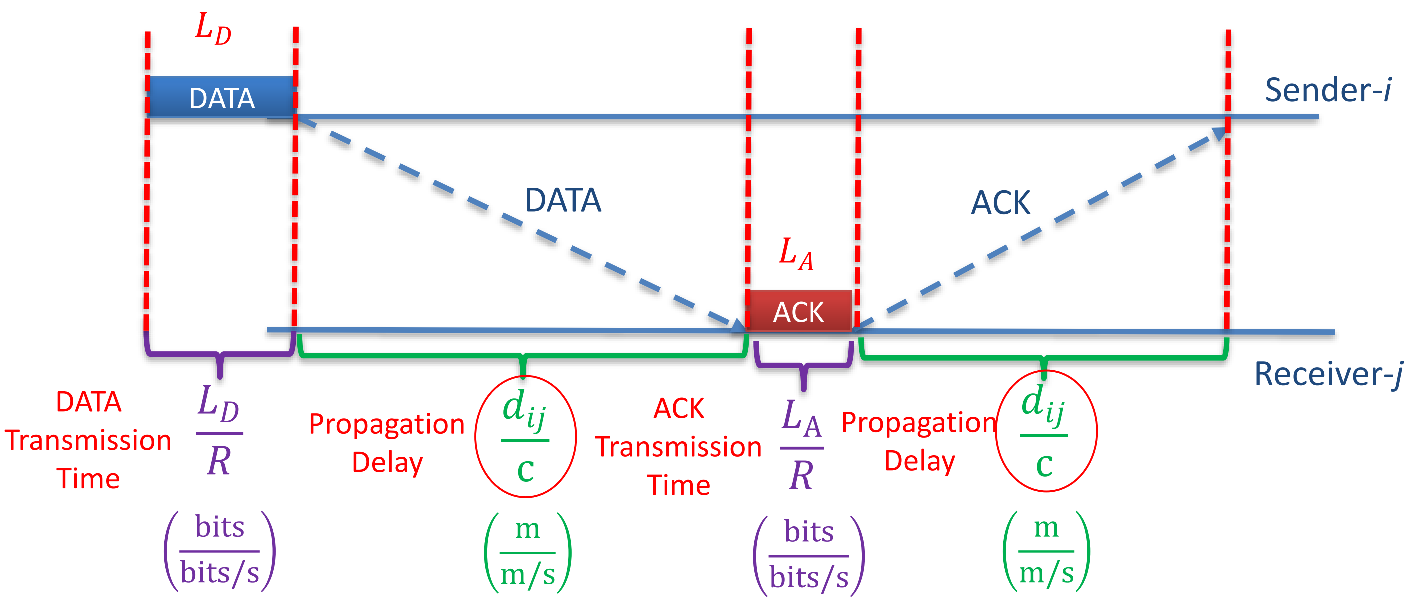




- $p_D^s = P(\text{Data packet is successfully received})$
- $p_A^s = P(\text{ACK packet is successfully received})$
- $p_D^s = (1 - P_b)^{L_D}$
- $p_A^s = (1 - P_b)^{L_A}$

Timing Analysis

- If the two-way handshake is unsuccessful, then packets needed to be retransmitted.
- Hence, the two-way handshake must be repeated until it successfully occurs.
- X: the number of handshake attempts until the handshake is successful.
- $X \sim Geo(p)$ where $p = p_D^s \times p_A^s$ is the probability that the handshake is successful.
- Since X is a geometric random variable, $\mathrm{E}[X] = \frac{1}{p} = \frac{1}{p_D^s \times p_A^s}$, which is the average number of transmissions required to have a successful handshake.



In underwater, propagation delay dominates the transmission times as d_{ij} increases.

$$\boxed{\frac{d_{ij}}{c} \gg \frac{L_D}{R} \text{ (or } \frac{L_A}{R}\text{)}}$$

It is important to minimize the propagation delay for the routing.

- R: data rate of the underwater modem (bits/s), c: speed of sound in water (~1500 m/s)

Energy and Delay Costs [10]

- Average energy consumption for a successful handshake:

$$E_{tx} = \Big(\underbrace{\frac{L_D}{R}P_{tx}}_{\text{DATA packet transmission energy cost}} + \underbrace{\frac{L_A}{R}P_{rx}}_{\text{ACK packet reception energy cost}}\Big) \times \underbrace{\frac{1}{p_D^s \times p_A^s}}_{\text{Scaling Factor (for retransmissions)}}$$

Reception Power

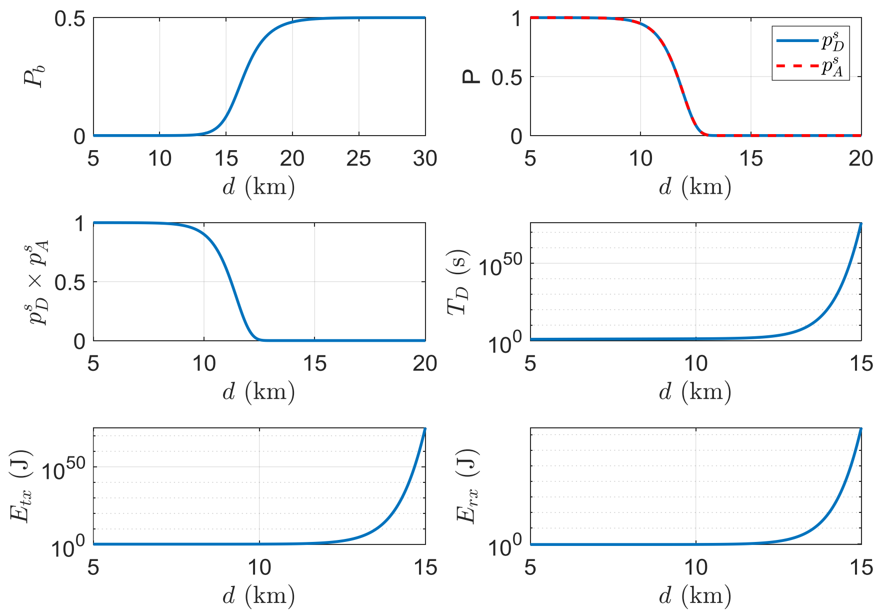
$$\boxed{\text{Energy} = \text{Power} \times \text{Time}}$$

$$E_{rx} = \Big(\underbrace{\frac{L_D}{R}P_{rx}}_{\text{DATA packet reception energy cost}} + \underbrace{\frac{L_A}{R}P_{tx}}_{\text{ACK packet transmission energy cost}}\Big) \times \underbrace{\frac{1}{p_D^s \times p_A^s}}_{\text{Scaling Factor (for retransmissions)}}$$

- Average delay experienced over link-*(i,j)*:

$$T_{ij}^D = \left(\frac{L_D}{R} + \frac{L_A}{R} + 2\frac{d_{ij}}{c}\right) \times \frac{1}{p_D^s \times p_A^s}$$

- $P_{tx} = 8\,W$, $P_{rx} = 1\,W$, $L_D = 1024\,bits$, $L_A = 64\,bits$, $R = 5000\,bits/s$, $H = 1\,km$, $k = 1.5$, $f = 25\,kHz$, $c = 1500\,m/s$



Severe Channel Conditions

A Middle-Level Network Flow Programming Model for Lifetime Maximization

$$\max N_R \times T_R$$

$$\sum_j f_{ij} - \sum_j f_{ji} = \begin{cases} s_i \times N_R, \forall i \neq 1 \\ -\left(\sum_j s_j\right) \times N_R, if\ i = 1 \end{cases}$$

$$\boxed{\sum_j f_{ij} T_{ij}^D + \sum_j f_{ji} T_{ji}^D \leq N_R \times T_R, \forall i}$$

$$\sum_j f_{ij} E_{tx} + \sum_j f_{ji} E_{rx} \leq E_{bat}, \forall i \neq 1$$

$$f_{ij} \geq 0, \forall i, j$$

Total delay experienced cannot be greater than the network lifetime.

- Decision Variables:
  - f_{ij}: the number of packets transmitted from node-*i* to node-*j*.
- Free Variable:
  - N_R: network lifetime (the number of rounds).
- Parameters:
  - T_R: round duration (in seconds),
  - s_i: number of packets generated by node-*i* per round.
  - E_{bat}: initial battery energy of nodes,
  - E_{tx} and E_{rx}: TX and RX average energy costs,
  - T_{ij}^D: average delay observed over link-*(i,j)*.

- Good model which accounts the bit errors and considers the large propagation delay.

References

[1] Stojanovic, M. (2007). On the relationship between capacity and distance in an underwater acoustic communication channel. *ACM SIGMOBILE Mobile Computing and Communications Review*, *11*(4), 34-43.

[2] Sendra, S., Lloret, J., Jimenez, J. M., & Parra, L. (2015). Underwater acoustic modems. *IEEE Sensors Journal*, *16*(11), 4063-4071.

[3] Ozmen, A., Yildiz, H. U., & Tavli, B. (2020, November). Impact of Minimizing the Eavesdropping Risks on Lifetime of Underwater Acoustic Sensor Networks. In 2020 28th Telecommunications Forum (TELFOR) (pp. 1-4). IEEE.

[4] Khan, M. A., Javaid, N., Majid, A., Imran, M., & Alnuem, M. (2016, March). Dual sink efficient balanced energy technique for underwater acoustic sensor networks. In 2016 30th International Conference on Advanced Information Networking and Applications Workshops (WAINA) (pp. 551-556). IEEE.

[5] Khan, J. U., & Cho, H. S. (2014, April). A data gathering protocol using AUV in underwater sensor networks. In OCEANS 2014-TAIPEI (pp. 1-6). IEEE.

[6] Jornet, J. M., Stojanovic, M., & Zorzi, M. (2010). On joint frequency and power allocation in a cross-layer protocol for underwater acoustic networks. IEEE Journal of Oceanic engineering, 35(4), 936-947.

[7] Domingo, M. C. (2008). Overview of channel models for underwater wireless communication networks. Physical Communication, 1(3), 163-182.

[8] Felemban, M., & Felemban, E. (2013, July). Energy-delay tradeoffs for underwater acoustic sensor networks. In 2013 First International Black Sea Conference on Communications and Networking (BlackSeaCom) (pp. 45-49). IEEE.

[9] Mhemed, R., Comeau, F., Phillips, W., & Aslam, N. (2021). Void Avoidance Opportunistic Routing Protocol for Underwater Wireless Sensor Networks. Sensors, 21(6), 1942.

[10] Yildiz, H. U. (2019, November). Utilization of Multi-Sink Architectures for Lifetime Maximization in Underwater Sensor Networks. In 2019 2nd IEEE Middle East and North Africa COMMunications Conference (MENACOMM) (pp. 1-5). IEEE.

- http://www.fao.org/3/x5818e/x5818e05.htm
- https://dosits.org/
- http://oalib.hlsresearch.com/AcousticsToolbox/

Thank you
Questions?