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Multimodal, software defined networking for subsea sensing and monitoring.

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Multimodal, Software Defined Networking for Subsea Sensing and Monitoring

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***Abstract*—The prevalence of oceanic industry and ocean borne interests has given rise to the concept of the Underwater Internet of Things as a vector for automation and data analytics in an environment hostile to anthropomorphic activity. Through the Internet of Underwater Things, it is theorised that sensors along the ocean floor or otherwise can be densely connected to the internet through wireless acoustic or optical links. However, both technologies have significant disadvantages that prevent either becoming a dominant technology. This project proposes a wireless software defined multimodal network infrastructure, that is proven using channel modelling and power analysis calculations, to be capable of robustly transmitting sensor data from source to sink by managing each technology according to its optimal environment. It was found that it is achievable to populate an opto-acoustic network in such a way that Successful Delivery Ratio becomes 90%-100% in clear water whilst achieving a 17% saving in overall energy consumption in a network mounted on a pipeline at 200 m depth when compared to a stand-alone equivalent acoustic network.**

Keywords— Acoustics, Underwater Internet of Things, Visible Light Communication, Software Defined Networks

I. INTRODUCTION

The field of the Underwater Internet of Things (UIoT) has emerged as an area of great interest within both academia and industry. Representing an extension of the Internet of Things (IoT), the overarching objective of UIoT is to enable efficient and reliable measurement of data through a saline, oceanic channel wirelessly, without the need for long tethers and armoured cables. Underwater wireless nodes can collect and communicate various types of data, whether for monitoring oil and gas pipelines in industry or monitoring underwater conditions driven by biological or natural processes in the sea for academic or other purposes. However, there are considerable challenges to delivering on this idea currently, these stem from the nature of the saline channel and the signalling methods commonly used. The primary technique utilized for communication through the oceanic or coastal channel is to employ acoustics to transmit data. This method can transmit data for significant distances, spanning kilometres, and is relatively reliable. However, it has its limitations; the primary issues with this method are its slow propagation, low utilisable bandwidth, and significant power demands, resulting in a fading channel. As a result, its ability to handle significant volumes of traffic, such as image/video and data, is restricted. The emerging solution to bandwidth restraints imposed using acoustics are to utilise Visible Light Communication (VLC) links centred around the 450-500nm wavelength that corresponds with blue/green spectra [1]. The bandwidth at this wavelength is magnitudes larger than acoustics, potentially carrying significant volumes of data within its range tolerances depending on the turbidity and noise level in the water. Otherwise, the utilization of Visible Light Communication (VLC) can result in significant energy savings and low propagation times, enabling near-real-time communication across networks with longer lifespans. However, this method is significantly limited by its range and is restricted to Line-of-Sight (LOS) links. To address these challenges, this project proposes a pragmatic, opto-acoustic multimodal, Software Defined Network (SDN) capable of transmitting data packets containing temperature or pressure reliably from source to surface. This paper presents the findings of simulations conducted using MATLAB and NS-3/Aquasim-NG, examining range, power, and topology related to this concept.

II. BACKGROUND

Multimodal communication [2], edge computing [3], and Software Defined Networks (SDN) [4] are increasingly being discussed within both terrestrial and underwater networks as potential solutions to various challenges, in order to meet the demands of future data-intensive applications. Light-based communication is being increasingly considered as a supplement to the existing infrastructure, as the operating bandwidth for both terrestrial and underwater networks is significantly higher for light-based communication over their counterparts, albeit at the expense of a reliable link. As such, a solution would be to consider novel hybrid networks using light and acoustic to provide this increased bandwidth. Table 1 presents the characteristics of each signaling method [1].

Table 1 VLC and acoustic signal parameters [1]

Characteristic	**VLC**	**Acoustics**
Bandwidth	<150Mhz	<100kHz
Line-of-Sight	Yes	No
Data rate	<Gb/s	Kb/s
Latency	Low	High
Range	<150m	<10km
Transmission Power	Watts	Tens of Watts
Speed	2.255 x 10^8m/s	1500m/s

For the UIoT, the intent is to use blue-green laser diodes or LEDs to communicate the data through the aquatic channel corresponding with the local attenuation minima in that medium given the presence of material produced by various biological processes which ranges between 450-500nm (blue/green) to oceanic water and 520-570nm (green/yellow) for coastal waters according to the level of scattering and absorption that takes place [1]. Blue/green LED driven modems have proven data rates into the tens of MB as seen in commercial and early academic projects, these also have the benefit of having a propagation spread that is hemispherical allowing certain LOS restriction to be relaxed that laser diode driven modems succumb to, laser diodes currently being evaluated and studied for future use in high data rate aquatic channels. There is significant academic speculation that this could provide for the UIoT in near future networks when combined with relatively reliable, long-range acoustic networks. Work is progressively being undertaken into the evaluation and implementation of these networks and possible architectures therein. Examples of this work are CAPTAIN [5] and MURAO [6], investigations into how communication can be achieved through these links in clustered Underwater Wireless Sensor Networks (UWSN) and between individual nodes and submersibles respectively.

SDN technology represents an abstraction of a physical network that allows for it to be controlled by a software decision making according to the parameters of the network, this allows for the network behaviour to become significantly more fluid than a typical network. Given the unpredictability of the oceanic network regarding currents, detritus, marine life, and oceanic noise that can affect overall performance this layer of control will allow for more nuanced, resilient network communication to take place. Edge computing is another paradigm being discussed regarding UIoT, where routing decisions can take place at the "edge" of the network closer to where the data source or sink within the network [7], this also allows for more nuanced decision making regarding how packets are transmitted considering the demands of the data, the environment, and the network itself on-site through sensing.

III. NETWORK DESIGN

The basis for this project is to provide an adaptable, reliable energy efficient architecture that is relatively pragmatic and simple for industry and academia to implement across a variety of UIoT scenarios. To meet this end, the proposition will be to utilise a static 3D mesh network that utilises two different types of nodes, hybrid opto-acoustic nodes used for the source and sink as well as single mode VLC nodes. The number of hybrid nodes are minimal as it is known that acoustics tend to be reliable and capable of long-range communication, therefore the number of acoustic equipped nodes in this network are lower to represent the fact that they can cover larger areas. If designed properly an acoustic packet can be send straight from source to sink at the expense of the increased power consumption that comes with that, therefore the only nodes that strictly need acoustic capabilities are the sink and source. These nodes will also be equipped with optical modems to enable the use of relay nodes, which have been strategically placed in between the source and sink, thereby extending the range of the VLC network to enable communication across the vast distances that it spans [8].

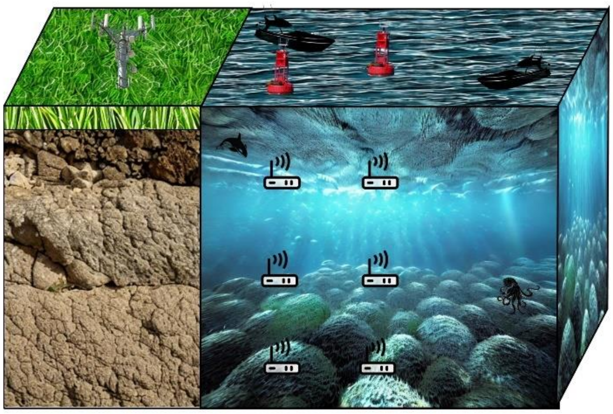

Figure 1 The proposed multimodal software defined topology with hybrid nodes placed on the surface and the seafloor and the floating relay nodes placed in the body of water between

The reason why we can specifically elect to have fewer acoustic nodes and retain a reliable network hinge on using robust routing techniques to ensure that the VLC links can be effectively transmitted through the network that deal with mitigating factors. To reduce the impact of LOS restrictions and prevent the need for the installation of beam steering systems, LED communications will be utilized between the hops to expand the coverage area. The static 3D mesh network between these two points will feature anchored VLC modem nodes, and the software-defined nature of the network will prioritize the optimization of these links, as they can handle more data, reduce propagation delay, and consume less energy. This will allow for greater flexibility in terms of the capabilities of the network if managed effectively. The acoustic link shall serve only as a backup in the event of blocked LOS or for localization if a node is dislodged from its anchor, thus primarily enhancing the network's reliability. Figure 1 present an illustration of the proposed architecture. There exist various routing techniques for acoustic communications, such as Depth Based Routing (DBR) [9], Vector Based Forwarding [10], and Hop to Hop Vector Based Forwarding (HH-VBF) [11,12]. Nevertheless, vulnerabilities persist within the wireless VLC network concerning the routing of information across the VLC aquatic channels. These vulnerabilities may arise from interference, potentially caused by detritus and aquatic life. Therefore, it is proposed, that a routing technique is utilised that manages the transmission reliably from sink to source. One such technique is Vector Based Void Avoidance (VBVA) [13] which is the extended version of VBF. This routing method that is designed for UWSN that addresses the emergences of "voids" (areas where the transmitted signal cannot cross) using several novel algorithms specifically backpressure, void detection and vector shifting. This allows for areas of poor connectivity to be determined within the network and for the packet to be routed around this area towards the surface. Thus, it deals the impacts that these events can have in the VLC aspect of the network. The added benefit however, of these networks are that since it is "software-defined" in nature, this schema could be changed accordingly. Due to this, it is a good candidate technology for routing packets through unpredictable networks with fragile links and thus good for monitoring the pipelines. Figure 2 shows the algorithm flowchart for deciding how to transmit the packet.

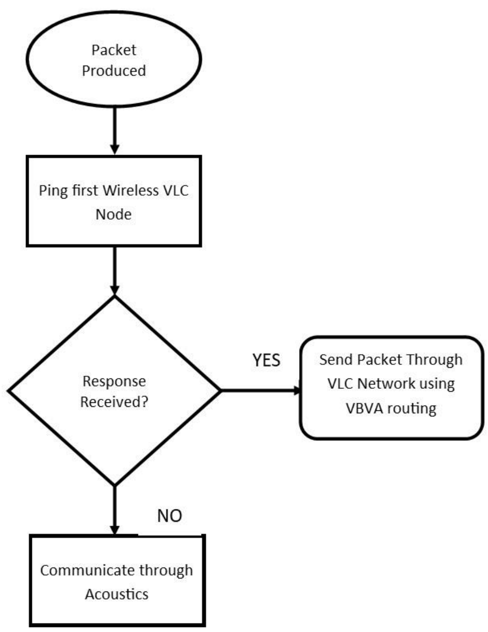

Figure 2 An algorithm diagram of how the SDN decides on whether to use optics or acoustics.

To judge whether the first node on the network is connectible and if the local channel is clear for transmission, a "ping" packet is sent out to the nearest connectible VLC node, this serves the purpose of detecting whether the water is turbid, there is the presence of excessive interfering light in the channel and if it is immediately contactable by the node. If these criteria are fulfilled, then the first node will respond to the source with its own acknowledgment and the data packet can therefore begin to be transmitted.

IV. SIMULATION DESIGN

Several challenges needed to be addressed to assess the reliability, power efficiency, and transmission capacity of the network. Considering these requirements, a set of simulations was devised and conducted to examine the network's feasibility across MATLAB platforms and NS-3/Aquasim-NG. A series of MATLAB simulations were carried to solve the transmission power/ relative range/Successful Delivery Ratio (SDR) problem in both optical and acoustic networks. This relationship describes how the SDR of the packets compare to the transmission power and the distance that the receiver lies from the transmitter. For the acoustic network this was carried out using [14] as reference for the calculations. Formula 1 allows for the calculation of the source level according to transmitter power (P) and range (r).

$$S_{level} = 10[\log(P) - \log(4\pi r^2) - \log(0.67 * 10^{-18}) \qquad (1)$$

Formula 2 is the method used to calculate the transmission loss T_{loss} for a given distance from the transmission source where d is range/distance, $\alpha(f)$ is the attenuation coefficient for a given frequency which is given by formula 3 [14].

$$T_{loss} = 20\log(d) + \alpha(f) * (d * 10^{-3}) \qquad (2)$$

$$a(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75 * 10^{-4}f^2 + 0.003 \qquad (3)$$

Formula 4 shows how to calculate noise level N_{level} for a given frequency.

$$N_{level} = 50 - 18\log(\mathrm{f}) \qquad (4)$$

Formula 5 shows how to calculate the Signal-to-Noise Ratio (SNR or γ) using the values that were calculated in formulae 1,2 and 4.

$$\gamma = S_{level} - T_{loss} - N_{level} \qquad (5)$$

Formula 6 shows the Bit Error Rate ($BER_a(\gamma)$) of Bit-phase Shift Keying (BPSK) in a Rayleigh fading channel for the value of SNR produced by formula 5. This fading channel model is an established method of modelling the multipath effect in both shallow and deep-water acoustic channels, whereas BPSK is a modulation technique commonly utilised in UWSN [15,16].

$$BER_a(\gamma) = \frac{1}{2}\left(1 - \sqrt{\frac{10^{\frac{\gamma}{10}}}{1+10^{\frac{\gamma}{10}}}}\right) \qquad (6)$$

In order to simulate the wireless VLC channel, the BER is calculated for a clear water acoustic channel assuming LOS links. The power level of the signal reaching the receiver, denoted as P_R Los, is determined using formula 7 [17].

$$P_{R\,LOS} = P_T \eta_T \eta_R L_{pr}\left(\lambda, \frac{d}{\cos\theta}\right)\frac{A_{Rec}\cos\theta}{2\pi d^2(1-\cos\theta_0)} \tag{7}$$

Where P_T is the transmission power, η_T and η_R are optical efficiencies of the transceiver and receiver respectively, $L_{pr,}$ the propagation loss factor as a function of wavelength, λ, and distance z is given by formula 8.

$$L_{pr}\ (\lambda, z) = exp(-c(\lambda)z \tag{8}$$

Perpendicular distance, d, between the transmitter and receiver plane, θ is the angle between the perpendicular to receiver plane and the transmitter receiver trajectory. A_{Rec} is the receiver aperture area and θ_0 is the laser beam divergence angle. The accepted stochastic model for coherent photon arrival in photon counters is the Poisson distribution, where the photon arrival rate during the gated receiver slot, T, is given by formula 9 [17]. This is relevant as in the analogue domain as the photon is the fundamental particle of light and therefore probability of arrival at the transmitter is inherently tied to the BER.

$$r_S = \frac{1}{T}\left(\frac{P_R}{R_D}\right)\frac{\eta_D}{h_v} \tag{9}$$

Where R_D is the data rate, η_D is the detector counting efficiency, P_R is the output from formula 7, h is Planck's constant and v is the frequency of the photon. Formula 10 shows the method utilised to determine the bit error ratio of the VLC channel, $BER_{O,}$ where $r_1 = r_d + r_{bg} + r_{s,}$ $r_2 = r_d + r_{bg,}$ r_d is the background calculating rate and r_{bg} is the background counting rate and the complementary error function *"erfc"* is given by formula 11.

$$BER_O = \frac{1}{2}\,erfc\{\frac{r_1T - r_0T}{\sqrt{2}(\sqrt{r_1T}+\sqrt{r_0T})}\} \tag{10}$$

$$erfc(\psi) = \frac{2}{\sqrt{\pi}}\int_{\psi}^{\infty}\exp(-\gamma)\,d\gamma \tag{11}$$

Once the BER has been obtained for both communication methods, the SDR of a given packet size in bytes can be given by formula 12 where m is the size of the packet in bits for either of the architectures.

$$p^m_{successful}(\gamma) = [1 - BER(\gamma)]^m \tag{12}$$

To calculate the energy consumed by the network in transmitting and receiving packets, E_T, based on the simulation parameters in this scenario, knowing the power consumed in watts of the transmitters and receivers, the size of the packets and the data rate we can use the formula 13, where N is the number of nodes in the route,

$$E_T = \sum_0^{N-1}(P_T + P_R)\frac{m}{R_D}\ [13]$$

A scenario based upon a practical use for this network was developed which would act as a platform to carry out analysis regarding performance. The aim was to calculate the best network parameters that would allow for a data packet of 500 bytes to be transmitted from a source node attached to a pipeline 200m below a body of clear water, with an increased channel capacity reliably and efficiently. Given these parameters, MATLAB and then NS-3/Aquasim-NG were utilised to carry out the relevant power, distance and SDR analysis to calculate where to position the hybrid sink and source nodes as well as the VLC relay nodes in this body of water. The following parameters in table 2 were utilised to produce results from the calculations discussed.

Table 2 The simulation parameters

Parameter	Value
Depth	200m
Packet Size	500 bytes
Acoustic Frequency	120kHz
Acoustic Transmission Power	8.5W
Acoustic Receiver Power	0.8W
Acoustic Data rate	62.5kB/s
Optical Extinction Rate	0.151
Optical Efficiencies of Transmitter and Receiver	0.9
Pulse Duration	1ns
Transmitter Inclination Angle	0 °
Beam Divergence	68°
Detector Counting Efficiency	16%
Dark Counting Rate	1MHz
Background Counting Rate	1MHz
Receiver Aperture Area	0.01m^2
Optical Data rate	1MB/s
Optical Transmission Power	20W
Optical Receiver Power	10W

V. RESULTS AND DISCUSSION

Based on the given parameter values, two series of SDR data were produced, one that would help decide how to place the acoustic nodes for maximum reliability and another that helps to analyse where to place the VLC relay nodes between the source and the sink nodes, given that it is known than the optical nodes have problems with a short range that requires multiple hops to extend coverage in this network. Figure 3 and 4 shows plots of the relationship between range and SDR for acoustics with a transmission power of 8.5W and VLC at 20W respectively.

Figure 3 suggests that for this scenario the idea of only requiring the two acoustic nodes in the network is acceptable. Given that the depth is 200m in this scenario an SDR of 100% is easily achieved at this range with the 8.5W of transmission power utilised by modern "high-speed" acoustic routers. This means that all packets will be transmitted without error if there is no competition for network resources between source nodes, this can be managed simply by managing the time multiplexing and scheduling of the network in order to ensure that the sources do not divulge their data at once. Figure 4 shows the same for VLC at 20W of transmission power, the propagation pattern for this is effectively driven by beam extinction as the roll off is sharply down to 0% chance of success beyond 60m for this data rate and transmission power. However, this figure suggests that up until 60m there is a significant chance of the packets being accepted if the channels are not obstructed and the water remains clear, reaching an SDR of 100% for anything below 55m.

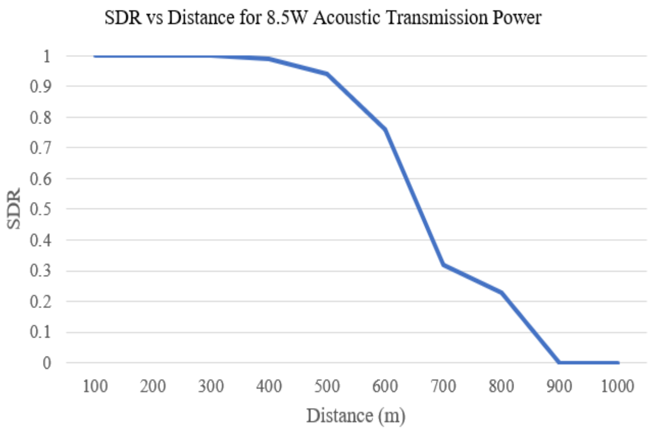

Figure 3 SDR vs Distance for an 8.5W Acoustic Transmission link

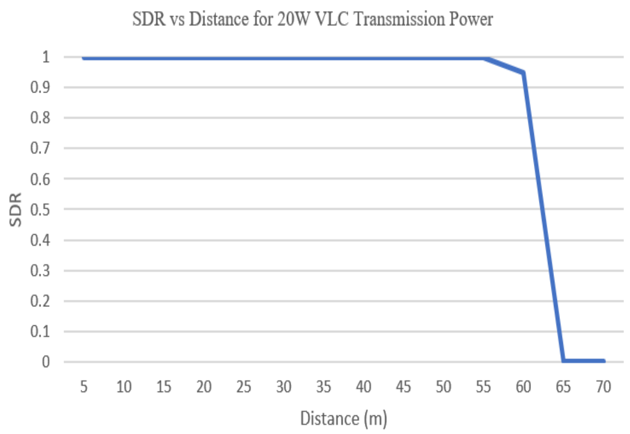

Figure 4 SDR vs Distance for a 20W VLC transmission link

This confirms that for this network, at 200m depth, there will need to be several relay nodes between sink and source less than 60m apart. Therefore, in this scenario at least three layers of relay nodes will be needed. Therefore, to maintain that high level and avoid accumulating error of sequential hops, the distance between possible hops will be lower than 55m, at this point it should ensure 100% successful delivery from end-to-end in clear water.

In terms of power consumption, the calculations showed the results in figure 5. Figure 5 shows that for a single transmission of this 500-byte packet, acoustic communication will cost 6x times as much to transmit than communicating through VLC. Knowing that there are at least five nodes in the VLC relay network and therefore, at least four hops we can summate these values accordingly to compare how much energy is being consumed by the network. This results in figure 6.

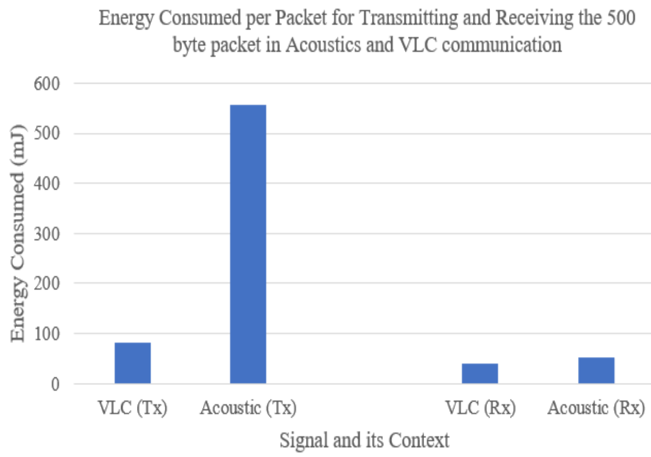

Figure 5 Energy consumed for 500-byte packet using the parameters given in table 1

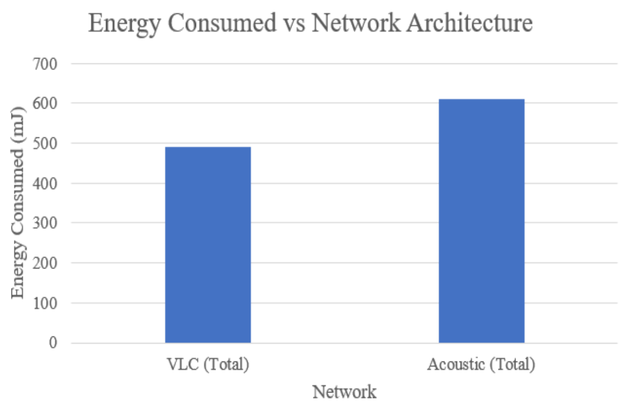

Figure 6 Total energy consumed over the whole network considering transmission and reception.

Figure 6 shows that despite the extra hops added, energy savings were gained from using the VLC architecture overall compared to the acoustic network, consuming roughly 19% less in terms of total energy consumption. Also, of relevance to consider is that that this total energy will be distributed over the four nodes so that in the respect, the overall lifespan of the network will be expanded considerably through implementation of the VLC network in tandem with the acoustic architecture, this shall decrease the frequency of recharges. These results highlight the need to manage the number of hops in the VLC network, as it is directly proportional to the total energy consumed by the network. Compellingly, this also shows that if energy efficiency is to be valued, that in an VLC underwater network it is also key manage the links in such away that the number of packets being received are minimal, as this process costs considerable energy.

With these results in mind. Figure 7 shows the topology simulated NS-3/Aquasim-NG to confirm that network indeed achieves end-to-end connectivity using the routing technique VBVA for the VLC links and the source to sink acoustic connection. It was found that this topology can effectively connect source to sink in both acoustics and VLC as well as provide redundant paths that can be used when nodes are blocked or isolated from other nodes in the network.

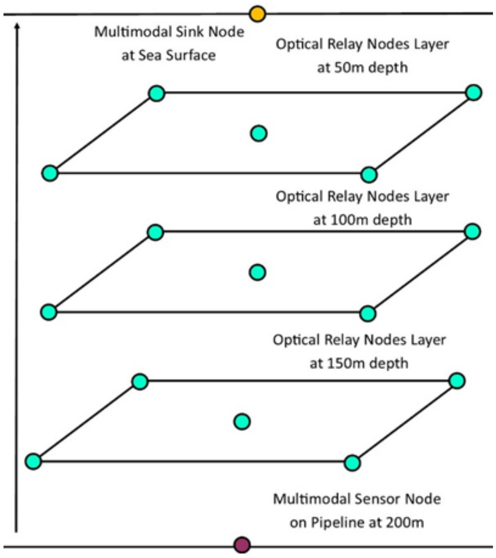

Figure 7 the proposed topology post confirmation of power and range through MATLAB calculation

VI. Conclusion

In conclusion, this paper proposes a multimodal, software defined network architecture for UIoT that can achieve successfully raises that possible data rate, communicate reliably and achieve energy savings by utilising a novel hybrid wireless opto-acoustic communication architecture that switches communication mode from VLC to acoustic depending on the environmental parameters that effect reliable VLC communication. With guidance from MATLAB simulations, this architecture was implemented to analyse the SDR, power consumption and thus, ideal placement of the nodes in order to maximise SDR whilst increasing data rate and reducing energy consumption. It was confirmed in NS-3/Aquasim-NG that successful end-to-end connectivity was achieved.

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