A simulation into the physical and network layers of optical communication network for the subsea video surveillance of illicit activity.

STEWART, C., FOUGH, N. and PRABHU, R.

2022

A simulation into the physical and network layers of optical communication network for the subsea video surveillance of illicit activity

Craig Stewart, Nazila Fough, Radhakrishna Prabhu
School of Engineering, Robert Gordon University, Aberdeen, UK

ABSTRACT

Criminal activity is increasingly entering the ocean subsurface with acts such as illegal fishing and narco-submarining becoming points of contention. This among other illicit acts taking place in this domain imply a need for surveillance to render these activities apparent. However, subsurface Underwater Sensor Networking which is central to the surveillance is still generations behind terrestrial networking, therefore it is still challenging to monitor for subsurface activities. This is since the current signal transmission standard, acoustic communication, is limited in practical bandwidth and thus channel data-rate, this is, however, caveated with omni-directional propagation and supreme range rendering it reliable but incapable of carrying video or other data intensive sensor information. There is, however, an emerging technology based on optical (visible light) communication that can accommodate surveillance applications with superior data rates and energy savings. This investigation demonstrates how theoretically it is possible to achieve a network of underwater channels capable of sustaining a multimedia feed for monitoring subsurface activity using modern optical communication when in compared to an acoustic network. In addition, a simple topology was investigated that shows how the range limitations of this signaling can be extended by adding floating relay nodes. Through simulations in Network Simulator 3 (NS-3)/Aquasim-NG software it is shown that Visible Light wireless communication in visible light networks have a channel capacity high enough to carry out monitoring in strategic areas, referencing, optical modems that are available in the market. This implies that data-rates of 10 Mb/s are possible for the real-time video surveillance.

Keywords: Optical Communication, Subsea Surveillance, Underwater Wireless Sensor Networks (UWSN), Structures in the Marine Environment

1. INTRODUCTION

Oceans remain a challenging domain to perceive to this day due to the fact a significant proportion of typical sensing signals are attenuated due to the characteristics of this unfavourable environment. Acoustic signaling tends to be the favoured approach for sensing, imaging and communications; however, it suffers from diminishing utilisable bandwidth with distances, prior studies [1] have shown inadequacy for modern applications such as video streaming.

Current research trends towards finding solutions for this problem. One such theory is to replace acoustic connectivity with another communication channel such as Visible Light Communication (VLC) on the physical layer of the network in the blue to green band of wavelengths (400 nm – 500 nm) [2]. The benefits of using a VLC physical layer in Underwater Wireless Sensor Networks (UWSN) are that data-rates are significantly higher than acoustics equivalent at this nascent stage (tens of Mb/s), energy consumption is reduced per bits transmitted which renders it superior to acoustics for densely populated networks discussed in the literature typically. UWSN is an underwater technological paradigm parallel to the concept of Wireless Sensor Networks (WSN), WSN are densely populated networks of sensor nodes transmitting large quantities of data to be used for analysis through cloud-based applications or otherwise. VLC also does not have to contend with the propagation speed derived issues associated with acoustic waves (the speed of sound underwater is around 1500 m/s depending on the physical properties of the water whilst VLC operates at 3×10^8 m/s) [2]. Having implemented a VLC physical layer, the discussion broadens out to incorporate the remaining layers of the system such as the network and data-link layers of the OSI model as these will be affected by this fundamental change. The network layer is responsible for selecting the best method of routing packets containing sensor data source through the network from source to sink and has been considered in this project.

State of the art in this area is diversifying into several areas of research. One area focusses on the VLC network's physical layer primarily, implementing modulation techniques on devices such as laser diodes analysing for data-rate [3], bit error rate and energy efficiency gains as well as other related experiments in Multiple Input Multiple Output (MIMO) systems [4] and modelling etc [5]. There have been investigations into designing nodes and other related UWSN hardware [6]. An emerging area is the implementation of multimodal communication underwater, the trend currently being hybrid VLC/acoustic systems to achieve the best properties of these two modes, alternatives seek to blend two or three of the four modes into a cohesive system [7]. Others focus on the upper network layers developing new data link and network strategies [8].

This report presents the results of a study and simulation into how a UWSN could be realised for carrying sensor data from seabed to surface given a case scenario in the North Sea, where offshore wind farm operations have imposed exclusion areas on what were traditional local fishing grounds through legislation. It will be structured as follows. Section 2 will discuss recent works related to Underwater Wireless Optical Communication (UWOC) when benchmarked to acoustic. Section 3 will discuss the parameters of the case study and simulation. Section 4 will disseminate and discuss the results derived from the simulation and Section 5 will arrive at a conclusion.

2. RELATED WORKS

The academic body has embraced VLC as a progression in the domain of subsea communications, the field has progressed to the point where optical based modems have been developed and experimented with at leading oceanographic organisations. This potential has been recognised beyond academia in recent times, in industry. These devices on the market are typically blue wavelength LED systems, this because a minimum of the absorption coefficient of pure seawater exists in the 400 to 500nm range of wavelengths, this is predominantly blue/cyan. The prevalence of LEDs is due to their diffuse, quasi-omnidirectional beam pattern, this allows for Line-of-Sight (LOS) restrictions, to be mitigated partially. Table 1 presents several LED modems both research and those available in the market.

Table 1: Selected Optical Modems in Market

Model	Maximum Data rate (MB/sec)	Maximum Range (m)	Power Consumption (W)	Beam Pattern
Sonardyne Bluecomm 200 [9]	10	150	10	180°
Hydromea Luma X [10]	10	50	2-17	120°
AquaOptical II [11]	2.28	50	N/A	N/A
WHOI Modem [12]	10,000 15 1	Contact 80 138	6 6 6	N/A N/A N/A

All the modems above other than the AquaOptical II, which is an older academic literature favourite, are broadly similar in operation. The reason why the Woods Hole Oceanographic Institution (WHOI) modem is favoured is because it has a higher recorded data-rate at medium range which renders it superior to the other options and has an abundance of experimental data from which to refer to. The former are industrial products, practical performance being harder to verify beyond the information given in datasheets, WHOI is one of the global leaders in oceanic engineering and research, the device has seen significant field testing and has publications in reknowned journals. Thus, it is a relatively reliable device to implement in a simulation as well as being the best performer at this juncture.

3. CASE STUDY AND SIMULATION

The aim of these simulations is to use NS-3 [13] and AquaSim-NG [14] to develop a UWSN topology that can transmit intensive data such as video by making use of parameters provided in the academic literature according to a surveillance case study. NS-3 is software frequently utilised in network research literature providing a framework to quickly test the performance of novel physical, network and datalink protocols through a series of C++ notebooks. AquaSim-NG is a library for NS-3 that allows for acoustic UWSN to be modelled, it can be adapted to implement VLC. Table 2 shows the constants of the simulations and table 3 shows the variables between the three simulations. The parameters of the simulation were decided according to a case study based on the upscale in offshore wind farm development. In some countries such as the United Kingdom, it is illegal to fish in areas designated for offshore wind farms for conservation and power security purposes. Research shows that many commercially desirable catches congregate around marine structures such as decomissioned oil rigs and wind turbines [15]. A floating wind farm has recently been installed 15 km offshore from Peterhead, UK at water depths of up to 120 m [16]. Peterhead itself being a traditional fishing hub, a potential zone for conflict to arise. A camera, sensor array or imaging sonar could be used to detect if fishing nets or anchors associated with such activity are active in proximity to such an installation, allowing for prompt security measures to take place. The topology chosen was a mesh network to provide redundant paths in case of node failure, this was compared to two single-hop connections. Figure 1 shows how the nodes were placed given this case study. The floating sensor nodes were placed based what would render them accessible to the source node and sink node whilst maintaining the higher data-rate.

The optical modem selected was based upon the WHOI device [12] which represents the current technology available on the market. The video transmission techniques were derived from [17] which demonstrates a successful video transmission using the AquaOptical II modem [11]. The network layer protocol was selected as Depth Based Routing (DBR) [18]. DBR is a famous protocol in the acoustics literature, that routes data with minimal computational complexity by considering depth and parameters such as hop count to reliably and quickly transmit packets through the network. This is key for video based surveillance as in terrestrial systems video is transmitted in a similar manner. For comparison, the same simulation was ran assuming EvoLogics HS series [19] acoustic modems were used instead of the WHOI modems without the relay nodes N0-N4. This is due to the significant range advantage in using acoustic communication. Table 5 shows the parameters used in the equivalent acoustic scenario.

Table 2: Constant Simulation Parameters

Parameters	Depth	Topology	Modem	Data Link Protocol	Network Protcol
Value	120 m	Mesh	WHOI	Broadcast	DBR [18]
Parameters	Packet Size	Compression	Transform	Error Check	Encoding
Value	255 Bytes	M-JPEG	Luby	CRC32	Reed-Solomon

Table 3: Variable Simulation Parameters

Parameters	Range (m)	Data Rate (Mb/s)	Propagation Speed (m/s)	Mobility
Value (WHOI VLC Mesh)	80	15	3×10^8	Static
Value (WHOI VLC Single-Hop)	138	1	3×10^8	Static
Value (Acoustics Single-Hop)	300	0.0625	1500	Static

(a) (b)

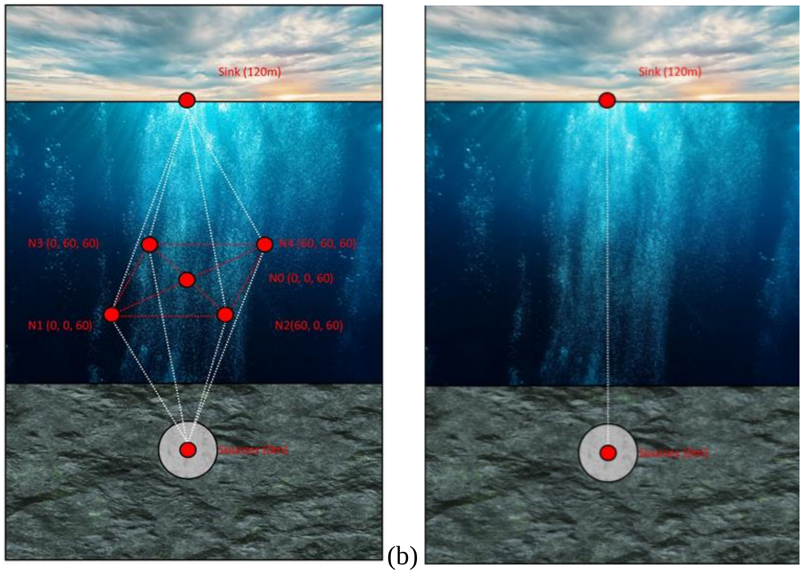

Figure 1: (a) Mesh topology used in multi-hop VLC and (b) Single hop network used for acoustics and VLC

4. RESULTS AND DISCUSSION

These parameters were implemented in NS-3/AquaSim-NG to analyse how the networks performed. To implement the VLC, the code was modified to replicate the parameters of the WHOI VLC modem and channel. The results were then analysed through the trace file and logs produced by the simulation. Tables 4 and 5 show the obtained results from the simulation described. Formulae 1 – 4 are the metrics used to judge performance and isolate potential issues to be resolved. *T (end to end),* given by formula 1, is the time needed to transmit a packet from source to sink. It is key to keep this value low overall when transmitting video, the larger this delays the larger the deviation from a perfect value of 0 seconds delay (ie real time monitoring).

$$T(end\ to\ end) = T(SinkRxEnd) - T(SourceTxStart) \qquad (1)$$

This is calculated using variables *T (SinkRxEnd),* the moment in time when the sink completely receives the packet and *T (SourceTxStart),* the moment where the source begins transmitting the packet. *T (processing delay),* given by formula 2, considers the time delay introduced by the system itself when compared to instantaneous transmission based on the properties of light speed relative to distance, this too ideally should be closer to 0, however, this unachievable as there will always be a level of latency introduced through internal processing through routing, modulation, error checks etc.

$$T(processing\ delay) = T(end\ to\ end) - \frac{Source\ to\ Sink\ Distance}{Speed\ of\ Light\ or\ Sound} \qquad (2)$$

Where speed of light is implemented simply as $3*10^8$ m/s and the speed of sound is given simply as 1500 m/s. This is made up of two time components, the queuing delay which is made up of the serialization/deserialization process in simulated buffers and the nodal processing time which is given as 10 ms in Aquasim-NG by default. *T (node to node packet transmit),* given by formula 3, is the time needed for the source to begin and finish propagating and depends on the data-rate of the link according to the given range. Ideally, this too should be close to 0 for real-time video.

$$T(node\ to\ node\ packet\ transmit) = T(SourceTxStart) - T(SourceTxEnd) \quad (3)$$

T(SourceTxStart) is the moment when transmission of the packet from source begins whereas *T(SourceTxEnd)* is the moment when the final bit of the packet is transmitted from the source. This describes the limitation imposed by the physical layer regarding the rate of data capable of being transmitted in the channel during a period. *T(node-to-node propagation)*, given by formula 4, defines the time delay caused by the finite speed of the carrier signal. This should also be near 0 as possible.

$$T(node\ to\ node\ propagation) = \frac{Distance}{Speed\ of\ Light/Sound} \quad (4)$$

Table 4: VLC Simulation (80 m/138 m range) Results

Parameters	T (end-to-end) (secs)	T (Processing Delay) (secs)	T(Source-N0 Packet) (secs)	T(Source-N0) (secs)
Value (80 m range)	75.33364 ms	75.3294 ms	136 µs	200 ns
Value (138 m range)	39.6404 ms	39.4364 ms	2.04 ms	200 ns

Table 5: Acoustic Simulation (300 m range) Results

Parameters	T (end-to-end) (secs)	T (Processing Delay) (secs)	T(Source-N0 Packet) (secs)	T(Source-N0)
Value (300 m range)	150.136 ms	71.36 ms	32.535 ms	40 ms

Figures 2 and 3 illustrate these results.

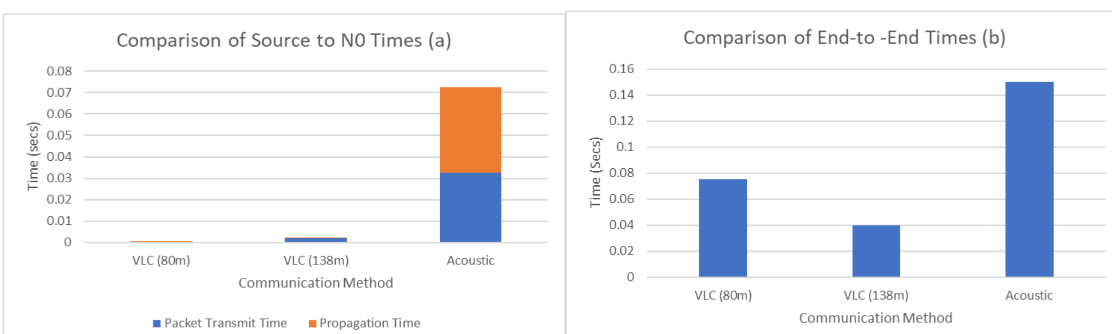

Figure 2: (a) Soure to Node N0 time, (b) Source to sink times between VLC and acoustic modems utilising DBR

Figure 2 (a) show how the implementation of VLC regardless of range and data-rate reduced the time on a single-hop basis significantly towards the ideal time delay of 0 when compared to acoustics demonstrating how simply changing the physical layer technology to VLC results in considerable gains that lend to a network capable of carrying video as the literature suggests. This now approaches what is necessary of a link required for real-time video surveillance in terms of delay. Figure 2(b), shows again, that the mere implementation of VLC from acoustic shows siginificant gains towards zero delay for quality real-time video, however, it sees a siginficant delay introduced in the VLC networks that is neither due to the propagation delay or the choice of routing technique (as these are effectively controlled during the simulation design process). These will be sourced from various other finite-time processes in the node simulated such as from serialisation/deserialisation in the buffer for instance, that are instantiated in NS-3/Aquasim-NG naturally to simulate the workings of an individual node. This creates a delay in the system that steers the end-to-end time from zero. The nature of this problem is due to the low processing capabilities of individual nodes as demanded by finite energy sources such as batteries and the lack of recharging facilities deep underwater. Research is ongoing into how these problems can be eleviated, this has consequences for the quality of real-time surveillance, however, limiting the real-time performance due to this severe bottle-necking processes. Figure 3 shows the proportion of time dedicated to these processing delays.

Acoustics having been used to benchmark this approach, has not been implemented successfully beyond highly experimental, very low frame rate, highly compressed video that would not perform well for surveillance. The research undertaken in this project suggests that using a single hop at longer range would be good for video surveillance as it involves only a single instance of such systematic delays, tending closer to zero delay overall when compared to the multi-hop impementation. There is a caveat to this approach however, the single hop means there are no alternative paths through the system if a fault or interference is to develop. The problem being with VLC is that it is relatively easier to interfere with these networks than acoustics, objects entering the line-of-sight can act as a source of interference, such as schools of fish, floating debris or whales. In addition, the reduced data-rate of 1Mb/s means that compression will need to take place to ensure it can be carried through this channel, this adds computational complexity, more delay, reduces feed quality and consumes more energy. Given that video demands high quality of service, this could be a large issue depending on how critical the information flow is, such dropouts are relatively intolerable in such applications, as surveillance capabilities could be lost arbitrarily and unpredictably, perhaps deliberately.

The mesh network deals with this by offering more paths to the sink so that if a given node is blocked by an object or otherwise there are alternative methods of reaching the surface, this is caveated by the extra time delay but this renders it far more apt for surevillance as it would take considerable effort to disrupt the network and the feed. With careful network design and technological progress this mesh approach will improve considerably as efforts to implement surperior wireless power systems are underway [20], this will allow for improvements to be gained in processing with more energy available for utilisation. In addition, it maintains the datarate of 15 Mb/s, which opens an opportunity to have a high quality video feed or possibly several low quality feeds depending on how the sensors are distributed. The development of suitable laser diode systems undergoing in the literature will see data-rates continue to increase opening more opprotunities for deep sea surveillance technology to take place.

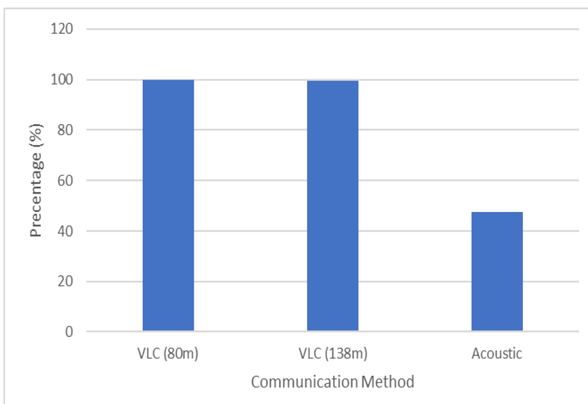

Figure 3: Processing time proportion between topologies

5. CONCLUSION AND FUTURE WORK

This research presents an investigation into how various network technologies utilizing visible light communication in the blue-green bandwidth can be utilised to implement subsea surveillance technology for the monitoring of illicit activity. It presents a novel case study relevant to the development of large-scale wind turbine fields in the UK where it is illegal to fish among wind farms, however, it can be broadened out for many scenarios. The research presents two topologies with physical and network layers engineered for surveillance applications that allow for quick, near-real time connectivity, a fragile single hop network with reduced data-rates and reduced processing delay and a resilient mesh network with high data-rates, higher processing delay. Both were found to improve on standard existing acoustic technology however, both were capped by processing delays inbuilt into other technology within the network. It was identified that this will have to be overcame if the potential is to be realised. Ultimately, it was found that the mesh network would be better for this scenario despite the higher delay from processing as it achieves higher data-rates and is more apt for security applications due to the in-built redundant paths that render the network challenging to interfere with.

6. REFERENCES

[1] C. Stewart, N. Fough and R. Prabhu, "An investigation into routing protocols for real-time sensing of subsurface oil wells," in International Conference on System-Integrated Intelligence, 2023, pp. 689-699.

[2] Kaushal, H. and Kaddoum, G., "Underwater optical wireless communication," IEEE Access, vol. 4, pp. 1518-1547 (2016).

[3] Oubei H. M., Duran J. R. Janjua B, Wang H. Y., Tsai C. T., Chi Y. C., Ng T. K., Kuo H. C., He J. H., Alouini M. S., Lin G.R., 4.8 Gbit/s 16-QAM-OFDM transmission based on compact 450-nm laser for underwater wireless optical communication. Optics express, 23(18):23302-9. (2015)

[4] Ghazy, A. S., Hranilovic, S., and Khalighi, M., "Angular MIMO for underwater wireless optical communications: Link modeling and tracking," IEEE J. Ocean. Eng., vol. 46, (4), pp. 1391-1407, 2021.

[5] Geldard, C. T., Thompson J., and Popoola, W. O., "An overview of underwater optical wireless channel modelling techniques," in 2019 International Symposium on Electronics and Smart Devices (ISESD), 2019, pp. 1-4.

[6] WHOI, Orpheus, June 22, Available from https://www.whoi.edu/what-we-do/explore/underwater-vehicles/auvs/orpheus/

[7] Matera, UNDINA, June 22, Available from https://www.martera.eu/projects/2020/undina

[8] Khan, H., Hassan, S. A., and Jung, H., "On underwater wireless sensor networks routing protocols: A review," IEEE Sensors Journal, vol. 20, (18), pp. 10371-10386, 2020.

[9] BlueComm 200, Sonardyne, Available from https://www.sonardyne.com/products/bluecomm-200-wireless-underwater-link/

[10] Luma X, Hydromea, Available from, https://www.hydromea.com/underwater-wireless-communication

[11] Doniec, M., and Rus, D., "BiDirectional optical communication with AquaOptical II," in - 2010 IEEE International Conference on Communication Systems, pp. 390-394 (2010)

[12] Pontbriand, C., Farr, N., Hansen, J., Kinsey, J. C., Pelletier, L. P., Ware, J., and Fourie, D., "Wireless data harvesting using the AUV sentry and WHOI optical modem," in - OCEANS 2015 - MTS/IEEE Washington, pp. 1-6 (2015).

[13] nsmam, June 22, Available from https://www.isi.edu/nsnam/ns/

[14] Aqua-Sim Next Generation, June 22, Available from https://github.com/rmartin5/aqua-sim-ng

[15] Fujii, T., and Jamieson, A., "Fine-scale monitoring of fish movements and multiple environmental parameters around a decommissioned offshore oil platform: A pilot study in the North Sea," Ocean Eng., vol. 126, pp. 481-487, (2016)

[16] Future Energy Industry Trends, northsearegion.eu, June 22, Available from https://northsearegion.eu/northsee/e-energy/future-energy-industry-trends/

[17] Doniec, M., Anqi, X., and Rus, D., "Robust real-time underwater digital video streaming using optical communication," in - 2013 IEEE International Conference on Robotics and Automation, pp. 5117-5124, (2013)

[18] Yan, H., Shi, Z. J., and Cui, J., "DBR: Depth-based routing for underwater sensor networks," in International Conference on Research in Networking, pp. 72-86 (2008)

[19] HS communication and positioning devices, EvoLogics, June 22, Available from https://evologics.de/acoustic-modem/hs

[20] de Oliveira Filho, J. I., Trichili, A., Ooi, B. S., Alouini, M. S., and Salama, K. N., "Toward Self-Powered Internet of Underwater Things Devices," IEEE Communications Magazine, vol. 58, (1), pp. 68-73 (2020)