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Performance and energy modelling for a low energy acoustic network for the underwater Internet of Things.

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Performance and Energy Modelling for a Low Energy Acoustic Network for the Underwater Internet of Things

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***Abstract*— As the Internet of Things (IoT) continues to find new applications, there is academic and industrial interest in expanding these concepts to the oceanic environment where data is traditionally challenging to communicate wirelessly, establishing an Underwater Internet of Things. One of the main challenges is rendering the network energy efficient to avoid regular retrievals for battery recharging processes, which can be expensive. The work proposes using low powered networks with multiple hops to reduce cost by avoiding the need for large transmitters, transformers and high rated components, thus rendering the technology cheaper and more accessible. The investigation found that even at low transmission powers a robust underwater acoustic network can be developed over hundreds of meters distance between hops, capable of carrying small packets of sensor data commonly used in Internet of Things applications. The successful delivery ratio and the signal-to-noise ratio metrics are used to assess the robustness of the network as a function of power. The analysis demonstrated that lower power levels exhibit higher energy efficiency when compared to their counterparts employing higher powers, aligning with the trends observed in commercial products, consuming significantly less energy than current single hop networks potentially allowing for longer life Underwater Wireless Sensor Networks.**

Keywords*— *Acoustic Communication, Underwater Wireless Sensor Networks, Underwater Internet of Things, Marine Monitoring, Power Preservation

I. INTRODUCTION

The IoT paradigm is a pervasive phenomenon in modern society and compelling research topic to a broad range of academics in many disciplines. Allowing for the automated aggregation of data and processes with minimal human intervention, this has clear benefits for scientific and industrial interests, given that natural and artificial processes can be analysed in depth from a remote location over a significant period using an inexpensive densely connected radio frequency sensor network using Bluetooth Low Energy (BLE), LoRa or other appropriate standards. An extension of this is the UIoT (Underwater Internet of Things) which aims to achieve the same in the oceanic environment. However, there are significant challenges to achieve the same effect in the underwater environment, as fast, low energy, radio frequency communication is over long distances akin to the IoT, the equivalent technology in the oceanic environment is enabled through acoustic pressure waves which have significantly higher energy demands and several physical restraints such as the speed of propagation etc. [1] Alternatively, Visible Light Communication (VLC) is increasingly being seen as the viable alternative to fill gaps in acoustic technology specifically high-speed, low-energy transmissions in environments where there is little probability between wireless links of physical obstruction [2]. Although, a step forward in terms of energy savings and increased data rate towards an UIoT, it is an inherently less robust method of communication compared to acoustics. In addition to all these issues, there is minimal standardisation in place between businesses supplying underwater wireless communications equipment meaning that there is no pervasive technology akin to BLE or LoRa in place. What also proves a challenge is accessibility due to the high costs of acoustic modems, these end to transmit at powers of tens of watts which requires components such as transformers and transmitters that can be expensive.

This project aims to research a low energy acoustic wireless sensor network that can achieve reliable coverage and robust transmission for short range, low traffic, and data-rate applications such as long-term environmental measurements of temperature, pressure data etc. In addition, this discussion further expanded to show how the network could be used in a multi-hop context to implement acoustic long-term deep water acoustic networks. The theory regarding this is proven through a series of simulations using MATLAB, this data has been compared to an equivalent single hop network provided by a commercial modem across a body of water 1000m deep.

II. BACKGROUND

Many research work focused on reducing energy consumption through network and data-link layer management, proposing new techniques to manage these layers [3]. Modern general-purpose modems such as those provided by EvoLogics tend to transmit at powers between 8.5W-60W in a range of data rates in the hundreds of kB/sec ranges depending on range and data-rate characteristics [4]. This is a significant amount of energy being consumed per packet that would result in diminished lifespan of the network and frequent battery recharges which tend to be expensive due to the cost of retrieval, equipment, staff and the vessels needed, thus the focus on managing the layers to reduce energy consumption through an extended network in order to increase lifespan. In addition, many are attempting to re-evaluate the physical layer by implementing VLC as the signalling method with the intent to reduce energy consumption and increase data-rate so that applications such as remote image transfer and video streaming can take place. VLC modems such as the Sonardyne Bluecomm 200 that use LEDs tend to transmit at powers around 6W in the MB/sec range, this comes with the caveat however, of less reliable links as they are reliant on Line-of-Sight (LOS) [5]. In addition, lasers are being increasingly analysed for utilising in the same environment for transmitting at higher rates [6], this however, is limited further by limited propagation pattern of lasers meaning that the system needs to be able to track the target through a chaotic environment which is a technical challenge in of itself.

Analytically, none of these technologies would be suitable at surface level for relatively cheap, long term, low power reliable transmission of data packets simultaneously. However, analysis of the results in [7] suggests that there are significant “diminishing returns” that come into effect as power is increased versus Successful Delivery Ratio. This suggests that there are possible energy efficiency gains to be found in an acoustic network by quantifying this process and designing a network with this in mind. Based on this observation, a series of simulations were carried out to characterise this phenomenon and take advantage of this to achieve a network that is as energy efficient as possible, thus, has the longest lifespan theoretically.

III. CHANNEL MODELLING

There are several models available for understanding the likely behaviour in oceanic acoustic channels. [7] provides a step-by-step account of how to derive, from transmission power, centre frequency and distance, the Successful Delivery Ratio (SDR), which represents a measure of how robust the network is at communicating packets. Formula 1 allows for the calculation of the source level according to transmitter power (P) and range (r) [8].

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

Formula 2 is the method used to calculate the transmission loss T_{loss} [9] 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, Thorp’s equation [10].

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

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

Formula 4 shows how to calculate noise level N_{level} for a given frequency [11].

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

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 (γ)) of Bit-phase Shift Keying (BPSK) in a Rayleigh fading channel for the value of SNR produced by formula 6. 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 [7].

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

Once the BER has been obtained for a given communication method, the SDR of a given packet size in bytes can be given by formula 7 where *m* is the size of the packet in bits for either of the architectures.

$$p^{m}_{successful}(\gamma) = [1 - BER(\gamma)]^m \qquad (7)$$

IV. SIMULATION DESIGN

A simulation utilising the above mentioned model equations was developed to explore the relationship between SDR changes and decreasing transmission power, while also examining possible bandwidths and data rates. In addition, calculations were carried out to decide where the point of diminishing returns would lie in this relationship. Understanding this relationship will facilitate the development of an acoustic network with the highest level of resilience in terms of SDR with the longest lifespan. The simulation parameters used are shown in table 1.

Table 1 Data utilised in the simulation.

Parameter	Value
Depth	0m-500m
Packet Size	500 bytes
Acoustic Frequency	0-10kHz
Acoustic Transmission Power	0.1W-1W
Directivity Index	0

In addition to this, the SNR relationship derived can be used determine the available bandwidth for communicating through the network, which is inherently tied to its capacity to communicate data, in this case, the rate of data transfer. This is also an important aspect to consider when discussing energy management, as reduced bit rates mean more time required to transmit a packet, which is inherently tied how much energy in joules is required per packet. Also, a previously suggested, diminishing returns can be analysed to determine at which threshold the network is at its most efficient. One measure is to evaluate the change in output productivity for a given change in input work. In addition, to validate the design, a multi-hop network case study was implemented comparing the performance of the EvoLogics R48 [4] utilised in a single hop to an equivalent multi-hop network based upon the proposed topology. This case study is to bridge a body of water 1000m deep using both topologies, and then, evaluate power consumption. Figure 1 illustrates the single hop network equivalent used for the base comparison. Table 2 shows the relevant parameters of the Evologics R48 acoustic modem.

Table 2 The parameters considered for the EvoLogics R48 modem used in the single hop link.

Parameter	Value
Bitrate	31.2kbit/sec
Packet Size	500 bytes
Transmit Power	60W
Receive Power	0.8W
Operational Range	1000m

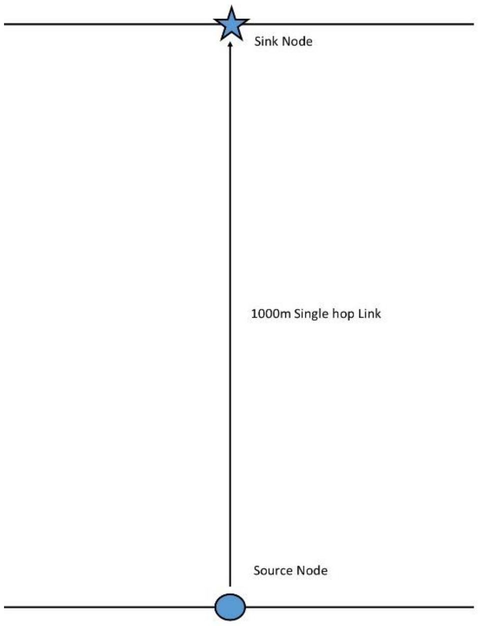

Fig. 1 Single hop equivalent network for a 1000m body of water

V. RESULTS AND DISCUSSION

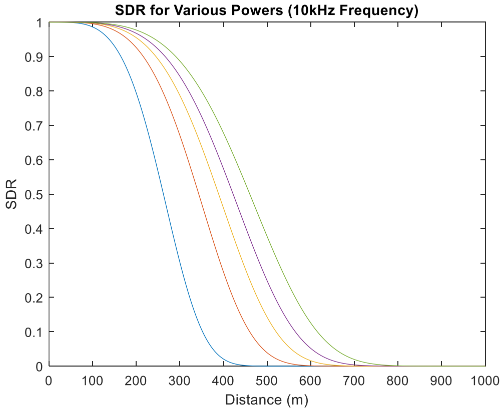

Fig. 2 SDR/Distance Characteristic for a given Input power where blue is 0.1W, orange is 0.3W, yellow is 0.5W, purple is 0.7W and green is 1W.

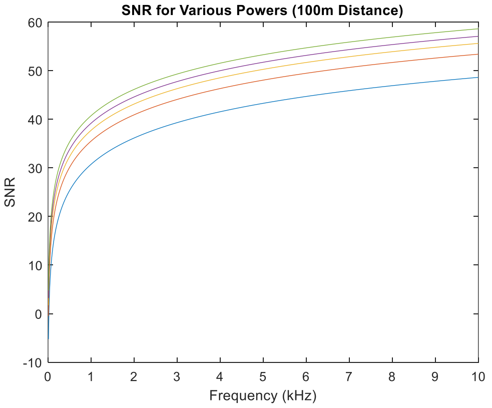

Fig. 3 SNR/Frequency Characteristic for a given Input power where blue is 0.1W, orange is 0.3W, yellow is 0.5W, purple is 0.7W and green is 1W.

Below, the results of the modelling are presented. Figure 2 shows the SDR as a function of power and distance away from source at 10Hz frequency. Whereas figure 3 shows the SNR profile for frequencies at these same transmission powers at a 100m distance. As is typical in communication networks, it can be seen that decreasing the power reduces the range that the node can successfully transmit packets to. What is compelling specifically, in this context however, is that at less than 1W transmission power there is still substanial range achieved by the network. Successful delivery ratio remains above 90% for hundreds of metres. This is compelling as many moderns industry modems transmit at significantly higher powers, several watts, even devices intended for short distances of hundreds of metres. In terms of SNR over the frequency range, there is a significant bandwidth available for utilisation over 30dB for instance, even at 0.1W, which suggests that 500 byte packets can still be transmitted through this channel relatively quickly through this low power channel. Figure 4 shows an analysis of "work done" for selected transmission powers below 1W compared to SDR. This was achieved by integrating under the curve for the corresponding curve. Figure 5 shows the difference between the areas under the curves per change in input power.

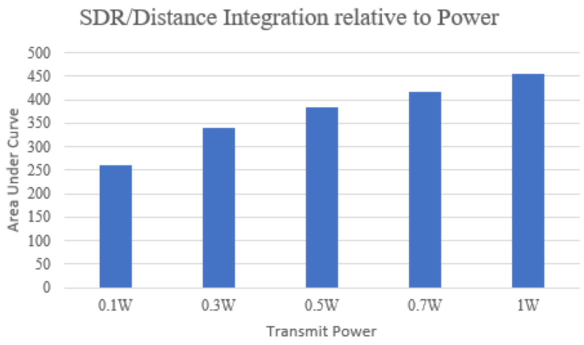

Fig. 4 the result of trapezium integrating the SDR/Distance curve to analyse work done.

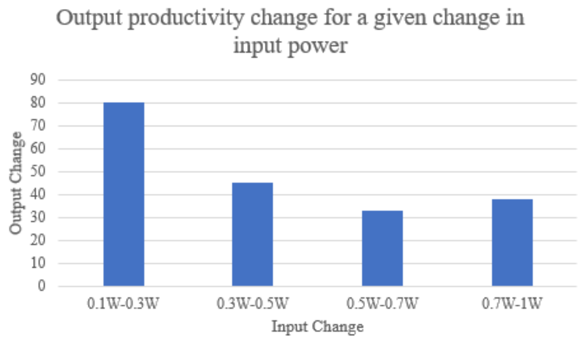

Fig. 5 the difference between the areas under each curve

This shows some compelling data regarding calculating diminishing returns regarding input energy vs output work done. It shows that by increasing energy it does not mean more useful work is done in achieving successful delivery, in fact, it decreases significantly. Between 0.1W and 1W useful work done diminishes by half. This suggests that using a small network with multiple hops is key for increasing lifespan of a network rather than just using a single hop that consumes more energy. Based upon the data in figure 3 and continuing the usage of BPSK as the modulation technique. This means it can be expected that the data rate in this network will be around 20kbit/sec for a hop, given that data rate is equal to bandwidth doubled when using BPSK modulation. Given the transmission power is 0.1W and this bitrate, it can be said that to transmit the 500-byte packet, the energy consumed will be 0.02 joules per packet. Based upon these results parameters were selected that reflect the proposed network table 3 are the parameters of the equivalent multi-hop acoustic network whilst figure 6 illustrates the proposed multi-hop topology.

Table 3 The parameters of the nodes within the proposed multi-hop network

Parameter	Value
Bitrate	20 kbit/sec
Packet Size	500 bytes
Transmit Power	1W
Receive Power	0.8W
Operational Range	200m

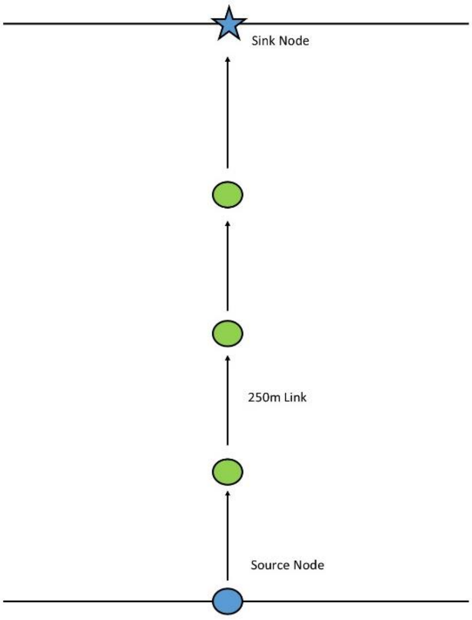

Figure 6 Proposed 4 node hop topology to bridge across a 1000m body of water

Reasoning behind the selection of these parameters is due to analysis of power consumption from the receiving chain. Although the transmission energy has been decreased significantly, there is an assumption that the same energy is required to power the receiver as before, packet reception therefore becomes the dominant energy consumer as it takes 0.8W for this process. Therefore, unless the receiver can be rendered more energy efficient diminishing returns will come into effect where reducing the transmission power becomes proportionately irrelevant as the receiver draws elevated levels of energy relative to the transmission. Table 4 therefore compares the energy consumption across four options, the single hop network, a multi-hop network that uses 5 nodes all using 0.1W of transmission power with 200m between hops, another that uses 4 nodes at 0.5W with 250m between hops and finally, one topology that uses 3 nodes at 1W that uses 333m between hops.

Table 4 Results of the power consumption for a single 500-byte packet in the proposed networks to transmit between source and sink.

Parameter	Value
Single Hop Evolgics R48	7.7J
5 hops, 0.1W, 200m link	0.9J
4 hops, 0.3W, 250m link	0.8J
3 hops, 1W, 333m link	1.08J

As can be seen, the multi-hop has the potential to save significant energy consumption, the overall energy consumption per packet used is around 7-10 times less than the single hop Evologics link although they are all roughly around 1J consumption the four-node network consumes least at 0.8J per packet. Compounding this, the overall network lifetime will be longer theoretically as the energy consumption will be spread across all the nodes in the network rather than just two, as each will be equipped with its own battery. This means that nodes will not be need retrieval as regularly saving money and skilled labour. However, there is potential problems resulting from the single route in the topology as one node failing would result in the whole network failing due to a missing hop. This could be solved by expanding the network so that there are more routes or using an adaptive transmitter that can reach 500m range. In addition, although the network uses standard models regarding noise and propagation within the literature, there needs to be further analysis on spectral basis as to how impulse and environmental sources of noise effects the signal transmission, how much can be engineered around by using digital signal processing.

VI. CONCLUSIONS AND FUTURE WORK

In conclusion, the work shows the potential in using low power acoustic communication in underwater environments to provide a robust, relatively energy efficient network for IoT style applications. Over a range of 100m packets of 500 bytes can be successfully transmitted from source to sink with 100% chance of successfully delivery according to the relevant modelling at less than 1W transmission power. At 200m there is beyond 90% chance of successful transmission of the same packet. Given that a significant portion of the frequency spectrum is above 30dB SNR, there is also a significant bandwidth to be utilised for transmitting data. Quantitative analysis also shows that low power networks are more energy efficient requiring only 20mJ per 500-byte packet. Further lifespan expansion can be found by adapting the packet length to be as efficient as possible. It was also found that this method of ad-hoc networking can effectively and robustly cover a body of water 1000m deep with significant power savings.

Future work will investigate utilizing adaptive power control mechanisms to adjust the transmission power based on the distance between nodes and the desired communication range. We will also attempt to practically implement the network and analyse performance, as well as develop nodes and framework that can use this basis to develop resilient, robust packet transmission in the underwater environment as far as practically possible. It will also be analysed to discover the best method to integrate this into a protocol stack that further renders the network more robust and energy efficient and into a multimodal communication system additionally building on previous works [12-16].

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