Optical Signals and Prospects Towards Multimedia in Underwater Wireless and Mobile Communication

Tharuka Govinda Waduge
Electrical and Electronic Engineering
Auckland University of Technology
Auckland, New Zealand
tharuka.waduge@autuni.ac.nz

Adnan Al-Anbuky
Electrical and Electronic Engineering
Auckland University of Technology
Auckland, New Zealand
adnan.anbuky@aut.ac.nz

Kay C. Vopel
Environmental Science
Auckland University of Technology
Auckland, New Zealand
kay.vopel@aut.ac.nz

***Abstract*—Light may be suitable for underwater wireless communication of multimedia data. However, current optical solutions face obstacles due to directionality and wavelength-dependent absorption and scattering. Here, we propose a conceptual design using differential signalling and a concave, multiple-aperture array of photodetectors. This combination could increase the field of view, enhance link adaptability, and introduce redundancies, supporting remote monitoring and data-collection with mobile robots in offshore operations.**

Keywords—underwater optical communication, mobile wireless networks, differential communication, adaptable links, transceiver design.

I. INTRODUCTION

Reaching carbon emissions goals and sustainable food production are complex fields of interest that are being rapidly investigated to meet the future climate and sustainability goals. Transitioning to renewable energy, carbon capture and offshore aquaculture are a few effective approaches among these [1]. Due to the restrictive availability of suitable land and higher efficiencies offshore, there has been a significant shift towards developing these solutions offshore [2], [3]. Offshore windfarms, floating solar farms, aquaculture set-ups, and ocean-based carbon-capture technologies are some examples of these [2]–[4].

Transitioning offshore is a resource-intensive task. Given many of the necessary installations will be below the water surface, the operations require divers and diving equipment for day-to-day monitoring tasks. There is a growing transition to the use of autonomous underwater vehicles (AUV) [5]. However, there are obstacles towards data communication, because with tethered AUVs, there is likelihood of entanglements with structures, limited manoeuvrability, risk of biofouling during long-term deployments, and limitations in performing multi-robot operations due to costs and entanglements with each other [5]–[7]. Wireless alternatives in the form of acoustic, radiofrequency (RF) and magnetic induction (MI) are available, but severe attenuation in water limits the performance from being fast, cost-effective, power efficient and compact [8]–[10].

RF and acoustic systems are limited by the channel bandwidth and latencies, unlike optical methods, which are far superior over moderate distances (<200 m) [9], [11]–[14]. Optical technology is more mature than MI and has demonstrated high data rates in the visual wavelength spectrum, suitable for transmitting pictures, video, and multimedia. This can be achieved with off-the shelf components such as laser diodes (LD) and light emitting diodes (LED) as emitters, whilst using relatively inexpensive photo-transducers for receivers such as avalanche-photodiodes (APD), photodiodes (PD) and phototransistors. Photomultiplier tubes (PMT) are much more sensitive, but are very big and expensive [11].

Nevertheless, due to light being a directional wave, there are many challenges in transmission between a mobile robot and transmitting station. Therefore, diffused-light emitters such as LEDs are preferred [9], [11], [15]. However, the wider beam-spread angles cause rapid degradation of the signal-to-noise ratio (SNR) and increase the bit-error-rate (BER), limiting the transmission distances. Prior research indicates that this can be improved by targeting the various levels of the open systems interconnection model (OSI model) [13] as well as implementing certain diversity technologies [16]. However, several gaps remain in the application of diffused light in underwater optical wireless communication (UOWC) for monitoring tasks.

Here we survey some design considerations how diffused light may be used in underwater wireless communication (UWC) at a low cost in conditions ranging from turbid harbours to clearer offshore waters, as suitable for mobile robotic applications. Differential signalling with a suitable intensity-modulation direct-detection (IM-DD) scheme, and a receiver design that incorporates diversity schemes have been proposed. This could reduce directionality, lower the effects of turbulence [11], and maintain a stable link with a moving device from the starting location of a mission to the finish. Additionally, it may contribute towards effective localisation, useful for mobile robotic missions and sensor networks. Expanding on such a system using surface buoys may be possible to cover a wide area such as a marine farm or renewable energy site.

II. A BRIEF REVIEW OF THE EXISTING UWC METHODS

Radiofrequency waves in the electromagnetic spectrum provide relatively high data rates at low frequencies (30–100 Hz) underwater. They can operate in the MHz region at a range of about 100 m using dipole radiation, but demand a high transmission power [9]. This is because radiofrequency waves (including microwaves) are attenuated by the high conductivity in water as shown in figure 1 [13], [17]. Hence, large, complex antennas and sizeable battery systems are required. Therefore, radiofrequency solutions are more suitable for submarines than untethered AUVs which are built for manoeuvrability. Shallow-water alternatives are available that propagate the radiofrequency signal over the water–air barrier to the receiver, significantly reducing the attenuation in water [18]. However, the problem remains unresolved for water–water links. Thus, radiofrequency solutions remain cumbersome and costly for operation and maintenance.

Alternatively, electromagnetic induction may be used to transmit data between two coils of wire (Tx and Rx

978-1-6654-9927-9/22/$31.00 ©2022 IEEE

respectively) [11], [19]. Magnetic induction can accommodate both analogue and digital modulation schemes, which are sometimes much simpler to process than those used in optical communication [19]. However, the technology is immature and the range of transmission low. Therefore, it is unemployable in a mobile underwater wireless communication system at the current stage.

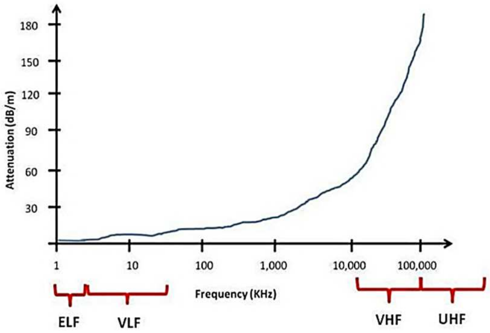

Fig. 1. Attenuation (dB/m) of radiofrequency in the ocean [17].

Sound as a mechanical wave is ideal for wireless data transmission in water—signals generated by an acoustic modem at frequencies in the upper end of the audible spectrum including ultrasound that are spread as vibrations in water to be picked-up by a receiver [13]. This way they can travel around obstacles reducing the effects of blocking and shadowing and are less prone to scattering due to suspended debris. Yet, the speed of transmission is relatively low, at approx. 1500 m/s, and is influenced by the water temperature, pressure, and salinity (or density) [11], [13]. However, acoustical attenuation is much less in comparison to other means and offers the best range reaching several kilometres. Despite this, slower speeds expose the channel to inter-symbol interference (ISI) caused by Doppler effects during AUV motion, water currents in the channel and multipath propagation in shallower waters. Given the data rates are often low, time-division multiple access is commonly used to share the narrow bandwidths; the channel capacities further degrade with increasing range [11]. Lou *et al.* have suggested using multihopping as it could improve throughput and power usage, but it adds to the system cost and complexity [11]. Albeit these drawbacks, acoustic systems are the most mature to date with many robust products available for purchase commercially from manufacturers like EvoLogics™ and Sonardyne™. Unfortunately, the high latencies, high delay spreads, slow speed, low data rates and bandwidths, and vulnerability to doppler spreads make it an unlikely candidate for wireless multimedia transmission in a mobile underwater channel. Therefore, an alternative solution needs to be sought.

Underwater optical wireless communication in contrast use wavelengths in the visual region of the electromagnetic spectrum. It has achieved minimal propagation times, high data rates and bandwidths (over 1 Gbps) at moderate ranges surpassing many other alternatives. For example, Li et al. and Wu et al. have demonstrated links at 16.4 Gbps (10 m range) and 12.4 Gbps (1.7 m range) respectively using lasers, and Lu and Liu have demonstrated a 205 Mbps connection using blue LEDs at 10 m range [20]–[22]. Despite this, light is vulnerable to attenuation due to absorption in water and scattering by suspended particles. The attenuation is wavelength dependent and appears to dip in the blue and green wavelength spectrum. Directionality is another concern, where obstructions in the path such as fish, debris, plant matter or even misalignments can cause link loss or breakage [15]. Considering the multipath propagations may assist recovery, but at the expense of system complication as often the multipath propagations travel greater distances than the point-to-point distance and therefore gets absorbed at the points of impact [9], [13]. To overcome directionality, Pontbriand et al. discuss using omnidirectional transmitters and receivers [23]. They achieve data-rates of up to 5 Mbps at maximum range of 200 m (in clear water), with a further exponential increase with decreasing range. However, their experiment also shows severe attenuation in shallow and turbid waters, producing very low capacities for the range and data-rates. This may be similar to waters with high chlorophyll content, agitated sediments, and natural peaking of bioluminescence in the blue-green spectrum, which are all conditions probable in an aquaculture setting [9]. The effects of back-scattering may be mitigated by differentiating the return signal using a different wavelength [24], but this does not solve the noise from surface light, in shallow water.

The lack of adaptability of UOWCs can be attributed to a lack of research as the attainable channel capacities and efficiencies are suitable for a link transmitting multimedia from a mobile AUV. Lanzagorta presents how LEDs and LDs could be used as high frequency emitters, and various photosensors selected from PDs, APDs and PMTs as receivers. Incorporating various modulation and diversity schemes could further increase the range and channel bandwidths [9], [11], [13], [25]. Given the high channel capacities, compact hardware footprints, cost and availability, and high efficiencies (approx. 30,000 bits/J), optical methods have been identified as the most feasible approach for an adaptable mobile link.

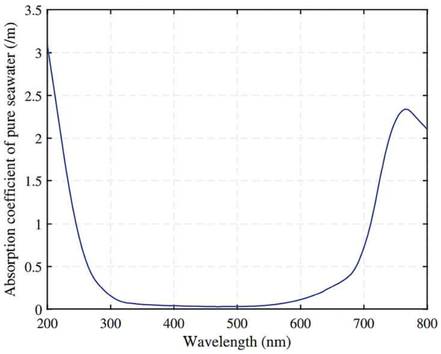

Fig. 2. Absorption coefficient of light waves in sea water [11].

III. THE OPTICAL CHANNEL

To achieve the best UOWC link performance, the intrinsic optical properties (i.e. properties of medium, e.g., absorption, scattering) and apparent optical properties (i.e. properties of device, e.g., beam spread angle) need to be analysed. By the law of conservation of energy:

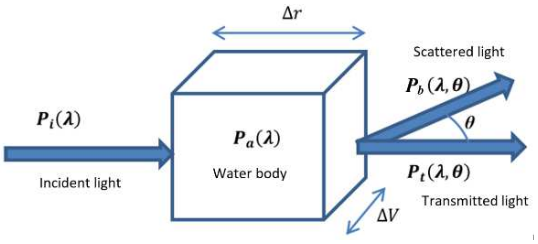

Fig. 3. Inherent optical property geometric model [9], [13].

$$P_i(\lambda) = P_a(\lambda) + P_b(\lambda) + P_t(\lambda) \qquad (1)$$

Where a and b reflect absorption and scattering respectively, and each is wavelength dependent. The effective attenuation (beam extinction coefficient) may be represented as:

$$c(\lambda) = a(\lambda) + b(\lambda) \qquad (2)$$

Both absorption and scattering are further dependent on the composition of the seawater: the water itself (w), the coloured and dissolved organic matter (CDOM), the phytoplankton (phy), and the inorganic particles like metal oxides and clay called detritus (det).

$$a(\lambda) = a_w(\lambda) + a_{CDOM}(\lambda) + a_{phy}(\lambda) + a_{det}(\lambda) \qquad (3)$$

$$b(\lambda) = b_w(\lambda) + b_{phy}(\lambda) + b_{det}(\lambda) \qquad (4)$$

Therefore, it should be inferred that the UOWC behaviour at an offshore site will be highly dependent on the water quality around the structures. However, a distinct variance can be seen in clear, coastal and turbid oceans as seen in table 1 [9].

TABLE I. NOMINAL VALUES OF ABSORPTION AND SCATTERING COEFFICIENTS IN DIFFERENT WATER TYPES [9].

Water Type	a (m^{-1})	b (m^{-1})	c (m^{-1})
Clear ocean	0.114	0.037	0.151
Coastal ocean	0.179	0.220	0.339
Turbid harbor	0.366	1.829	2.195

The propagation loss for a distance z, is given as:

$$L_P(\lambda, z) = e^{-c(\lambda)z} \qquad (5)$$

Based on (5), [26] formulates the channel capacity as:

$$C = B\log_2\left(1+\frac{S^2P_r^2}{\left(\frac{4k_BTB}{R}\right)+2q(i_d+SP_r+SP_a)B}\right) \qquad (6)$$

Where:

C – Optimal capacity
P_a – Received optical power from solar and blackbody radiation
P_r – Optical power from source
k_B – Boltzmann constant
S – Receiver PD sensitivity
R – Feedback resistor
T – Temperature
q – Electronic charge
i_d – Receiver PD dark current
B – Bandwidth

They further show that the capacity increases with increasing input electrical power, power conversion efficiency, diameter of the photodiode, feedback resistor, and receiver photodiode sensitivity. The capacity decreases with increasing transmitter–receiver distance, receiver inclination angle, half-angle transmitter beam width, temperature, receiver photodiode dark current and received solar and blackbody radiation. These factors are imperative in the design considerations of the transmitter and receiver [26].

This helps to justify why higher data rates are achieved at night and why the ideal transmission wavelength spectra change from blue-green light in a clear ocean to a green-yellow spectrum in a turbid harbor, which corroborate with Figures 3 and 4 [26], [27]. However, this model ignores the possibility of multi-scattering, in which case for a more accurate model of that, the authors recommend referring to the radiative transfer equation [28].

IV. DESIGN CONSIDERATIONS

Given the expectations and limitations in the optical channel explained above, a transceiver design is proposed as shown in Figure 5. These intrinsic and apparent optical design considerations have been addressed in the sections following.

A block diagram for the UOWC is given in Figure 6. The designs are mainly focused on the link's physical layer features.

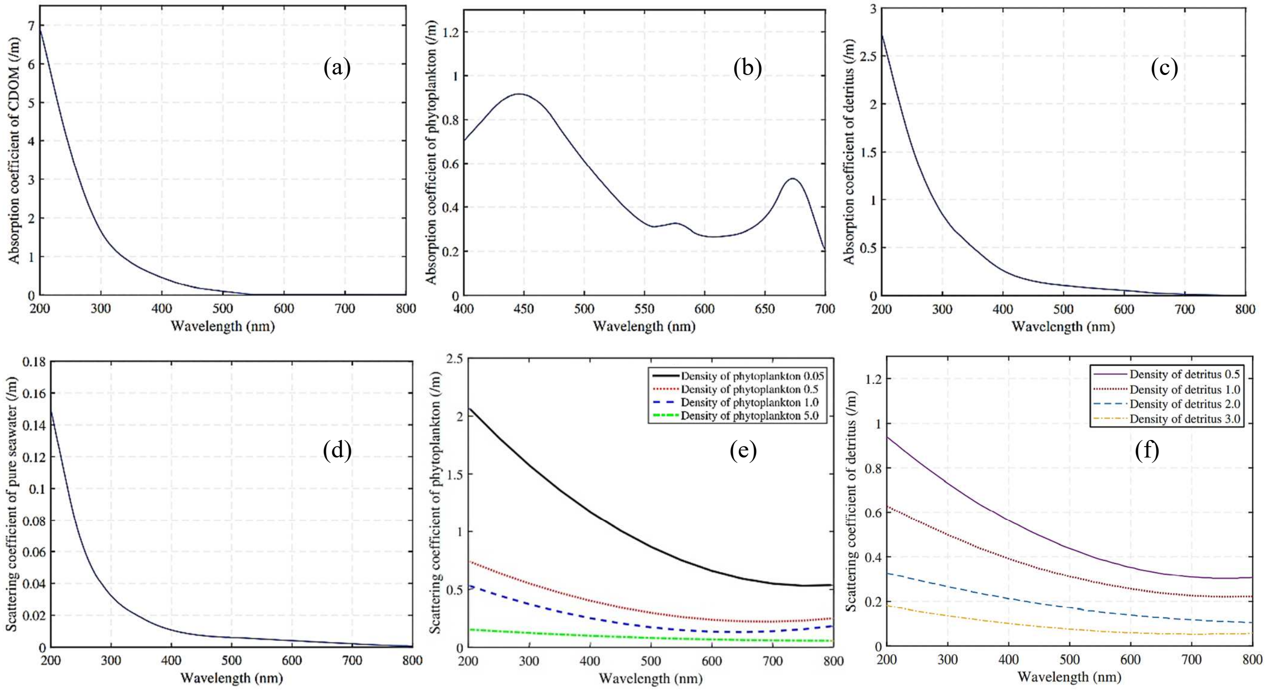

Fig. 4. Absorption coefficient of CDOM (a), absorption coefficient of phytoplankton (b), absorption coefficient of detritus (c), scattering coefficient of pure seawater (d), scattering coefficient of phytoplankton (e), scattering coefficient of detritus (f) [11], [12].

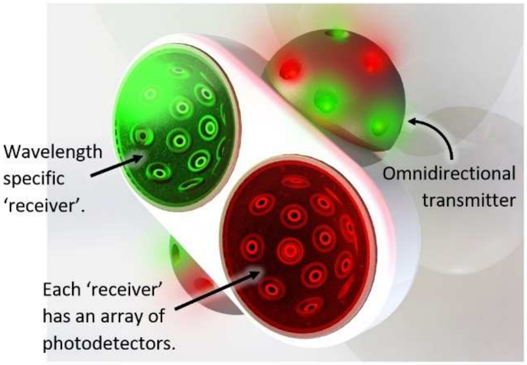

Fig. 5. Concept design for the adaptable, mobile UOWC transceiver.

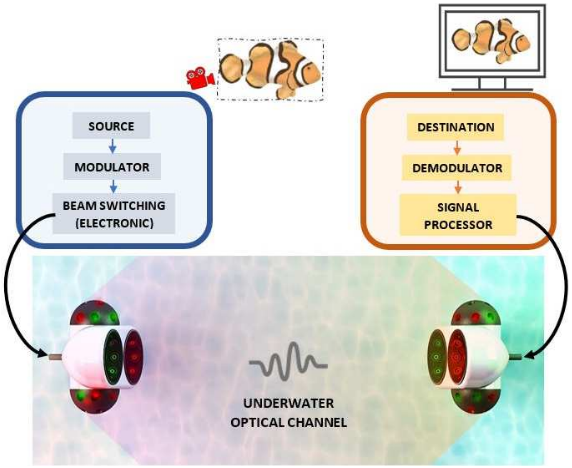

Fig. 6. A simplified block diagram of the proposed UOWC.

A. Link Configurations

An optical link may be identified by the type of transmitter–receiver configuration. Point-to-point line-of-sight are directional links as with a laser. They offer high data-rates and efficiencies but require rigid alignment between only one receiver–transmitter pair. Retroreflection achieves full duplex communication by reflecting a modulated version of the transmitted signal at the receiver. They require less overall power but are affected by background light and demand tight alignment. Non-line-of-sight links depend on background reflections and multipaths to transmit data. They have lesser pointing and tracking requirement but experience the most dispersion, path loss and background noise. In contrast, diffused line-of-sight links use wide beam divergence angles covering greater regions, possible with LEDs. They allow for broadcasting, at the cost of moderate path loss, BER, and limited range [9], [13], [15]. However, since optical links are line-of-sight, the angle of incidence at the receiver plays a significant role in signal recovery. Due to this and the freedom of alignment a diffused line-of-sight link is proposed.

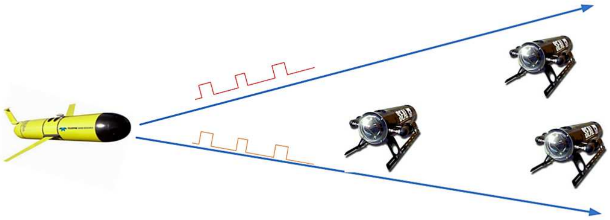

Fig. 7. An illustration of a diffused line-of-sight link [12].

B. Emitter Design

An omnidirectional emitter was proposed as it offers the most outspread illumination region. LEDs will be used as diffused beams and wide beam-spread angles are preferred. They are much safer around marine animals and humans where human-robot cooperate missions are concerned, than lasers. The wide choice of LEDs available in the market is an added advantage. However, LEDs handle significantly lesser bandwidths than lasers, therefore additional diversity schemes need to be employed to improve this.

Red and green LEDs are alternated on two hemispheres as shown in Figure 8 to allow for differential communication. Two wavelengths on the opposite ends of the visual spectrum are chosen to mitigate the effects of absorption and scattering during movement between turbid or chlorophyll-rich and clear waters. Moreover, wider band gaps avoid overlapping of LED emission spectra which will amount to better signal recovery and performance. Beam switching will be employed to illuminate the active link direction, thus improving electrical efficiency, and reducing channel noise. Two hemispheres will be useful to separate between surface-down and seabed-up link functions.

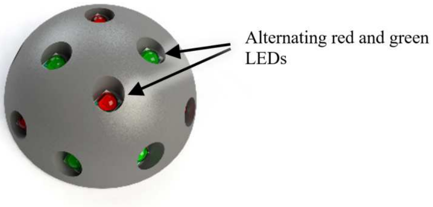

Fig. 8. The hemispherical, omnidirectional emitter design.

C. Diversity

Given diffused beams with LEDs are proposed for transmission, as mentioned earlier, there are bottlenecks by design. However, employing diversity schemes could introduce redundancies that could improve the SNR, reduce ISI, and favour signal recovery. An adapted version of spatial diversity and simplified approach to frequency diversity are proposed for the transducer. Spatial diversity is achieved by an array of photosensors with overlapping and non-overlapping field-of-views (FOV). Frequency diversity is achieved by transmitting a differential signal in two different colours. Time diversity has not been recommended at this stage due to the possibility of saturating the channel. Cooperate diversity will be explored at a later stage, in the form of multihopping to increase the attainable coverage [11].

Diversity combining will be used at the receiver for signal recovery. Given that two receivers of red and green are used, each with a separate array of photosensors, several combining schemes may be needed. Maximum ratio combining or switching combining is proposed for each array where less computation, but quicker adaptation is beneficial during motion. However, selection combining is proposed for each coloured 'receiver', since a continuous assessment of SNR from each would be useful to maintain link adaptability over changing water conditions [11].

Channel fading by turbulence due to rapid density fluctuation of the medium (scintillation) can be mitigated through aperture averaging, where a large receiving aperture may even out fluctuation variance [11]. As a large aperture is impractical in AUVs, a collective of smaller apertures may be to similar effect.

D. *Differential Communication*

Differential optical signalling in terrestrial free-space communication have demonstrated better performance for IM-DD schemes by reducing noise and background effects on the system [29], [30]. It has further mitigated the optimal detection level variations caused by misalignments [29], [30]. In this case it appears appropriate for an adaptable optical wireless system to introduce redundancy in a channel, especially where channel fading is wavelength dependent [9], [13]. This way two complimentary signals, where one wavelength is more immune to scattering and the other immune to absorption, generated simultaneously may reduce ISI and BER. However, more research is necessary. Achieving a differential system for non-coherent modulation approach may be simpler to process and fitting for a mobile link, at the expense of performance than a coherent approach.

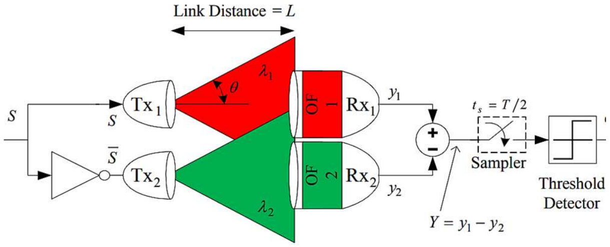

Fig. 9. A simplified bock diagram for differential communication [29].

E. *Receiver Design*

Several design considerations are proposed for the receiver as the most integral part of an UOWC. A transceiver will have two ‘receivers’, one focused on the red beam, and the other on green. Thin-film bandpass filters are proposed for superior performance and the convenience of customising the passbands, over coloured-glass filters which are less transmissive, and passbands are wide. However, it should be noted that thin-film filters are sensitive to the angle of incidence and are prone to shifting the passband spectra [31]. Therefore, special attention is needed in adopting such filters for a mobile system.

An array of photosensors (Fig. 10) is proposed to enhance the diversity of the system. A combination of PIN-photodiodes and avalanche photodiodes will be used for the collective benefit (PIN-PDs are cheaper, less sensitive linear response devices with good noise performance, whilst APDs are expensive, non-linear, more sensitive with high gain, but has bad noise performance) [32], [33]. PMTs were not chosen due to their size, extreme costs, and worse noise performance, unsuitable in a mobile setting. Sticklus *et al.* show how LEDs could be used as photodiodes with inherent bandpass characteristics, but the applicability of such for an UOWC needs more experimentation [34].

Having a higher collective FOV with overlapping regions will mitigate the effects of turbulence and increase reception redundancy. The received signal strength intensities of each can be compared from photosensors for directional information that may later support the beam switching functions, or even localisation. However, a concave shape is proposed for the array as opposed to the flat, domelike, or even orblike arrays available in literature [13]. This will place the collective focal point between the photodetector and source, by which the scattered signal portions could be utilised for recovery also. More research is needed to validate this claim.

Internally, a dark and porous, matte ‘sponge’ or similar material will be layered between the photodiodes to minimise the internal reflections and scattering. Each photodetector will be housed inside a protruding aperture that limits the detectors effective FOV.

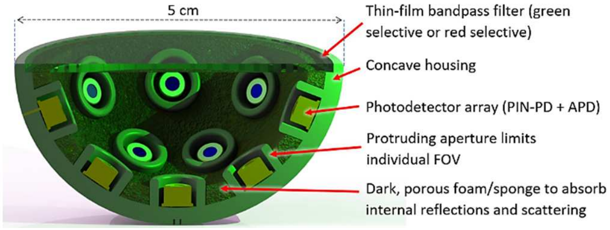

Fig. 10. Wavelength-selective receiver and photodetector array concept.

This receiver design has the FOV intentionally limited to a hemisphere as most AUV-based inspections and monitoring are forward-lit. In which case, the transceiver will be attached to the back of the AUV facing the back, shadowing any stray light from the front of the AUV or reflected from objects being inspected.

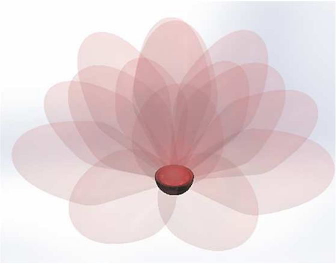

Fig. 11. Hemispherical collective FOV of a receiver (not to scale).

F. *Modulation, Electronics, Simulation and Modelling*

LEDs, unlike lasers are not two-dimensional emitters, and so non-coherent IM-DD techniques such as on-off keying, pulse-position modulation or digital pulse-interval modulation or pulse-width modulation may be useful [15]. Each will have its merits and weaknesses, and therefore needs to be selected based on application and requirement. In terms of the electronics, transimpedance amplifiers and voltage amplifiers are essential in the receiver for current-voltage conversion and signal amplification respectively. Realising the PIN-photodiode and avalanche-photodiode array architectures, and the LED beam-switching circuitry however requires more work and remains a future prospect for the authors.

Several modelling and simulation tools have been simultaneously identified. Rong *et al.* provides many mathematical models for evaluating the channel capacities under different design constraints and environment conditions [26]. These could be emulated in MATLAB to model channel behaviour. In addition, the Monte Carlo simulation has been identified as a great tool to model beam propagation. Leathers *et al.* have provided a comprehensive model for this in MATLAB [35]. To complement these, eye-diagram simulations could assist to evaluate the quality of the transmitted signals. As the receiver and omnidirectional transmitter has many intricate parts that need to be designed precisely, they can be designed using CAD and 3D printed. The main housing will need to be casted to withstand pressure underwater. Using thermoplastics, such as acetal, may be appropriate for this.

V. CONCLUSIONS AND FUTURE WORK

A brief survey has been presented and a conceptual design for a transceiver suitable for high-bandwidth mobile communication, that would increase link adaptability and overcome issues with directionality. A novel approach is discussed using a concave, multiple-aperture array of photodetectors to improve system diversity and implement differential signalling taking into consideration the limitations imposed by the water medium. The considerations have been linked to respective provisions in the most recent available research.

Future work entails mostly around the electronics aspects, such as beam switching, diversity combining, amplification circuits and in the approach to modulation. However, it remains the prerogative of the authors to present numerical data in the subsequent publications such as of the array sensitivities, adaptability, and performance benefits.

REFERENCES

[1] S. Evans et al., “COP26: Key outcomes agreed at the UN climate talks in Glasgow,” Carbon Brief, Nov. 15, 2021. https://www.carbonbrief.org/cop26-key-outcomes-agreed-at-the-un-climate-talks-in-glasgow (accessed Apr. 02, 2022).

[2] C. Costello et al., “The future of food from the sea,” Nature, vol. 588, no. 7836, pp. 95–100, 2020.

[3] P. I. Macreadie et al., “The future of Blue Carbon science,” Nature communications, vol. 10, no. 1, pp. 1–13, 2019.

[4] E. S. Rubin, H. Mantripragada, A. Marks, P. Versteeg, and J. Kitchin, “The outlook for improved carbon capture technology,” Progress in energy and combustion science, vol. 38, no. 5, pp. 630–671, 2012.

[5] D. R. Blidberg, R. M. Turner, and S. G. Chappell, “Autonomous underwater vehicles: Current activities and research opportunities,” Robotics and Autonomous Systems, vol. 7, no. 2–3, pp. 139–150, 1991.

[6] H. H. Wang, S. M. Rock, and M. Lees, “Experiments in automatic retrieval of underwater objects with an AUV,” in “Challenges of Our Changing Global Environment”. Conference Proceedings. OCEANS’95 MTS/IEEE, 1995, vol. 1, pp. 366–373.

[7] G. Meinecke, V. Ratmeyer, and J. Renken, “HYBRID-ROV-Development of a new underwater vehicle for high-risk areas,” in OCEANS’11 MTS/IEEE KONA, 2011, pp. 1–6.

[8] K. M. Awan, P. A. Shah, K. Iqbal, S. Gillani, W. Ahmad, and Y. Nam, “Underwater wireless sensor networks: A review of recent issues and challenges,” Wireless Communications and Mobile Computing, vol. 2019, 2019.

[9] H. Kaushal and G. Kaddoum, “Underwater Optical Wireless Communication,” IEEE Access, vol. 4, pp. 1518–1547, 2016, doi: 10.1109/ACCESS.2016.2552538.

[10] J. Sticklus, P. A. Hoeher, and R. Röttgers, “Optical underwater communication: The potential of using converted green LEDs in coastal waters,” IEEE Journal of Oceanic Engineering, vol. 44, no. 2, pp. 535–547, 2018.

[11] Y. Lou and N. Ahmed, Underwater Communications and Networks. Springer, 2021.

[12] Z. Zeng, S. Fu, H. Zhang, Y. Dong, and J. Cheng, “A survey of underwater optical wireless communications,” IEEE communications surveys & tutorials, vol. 19, no. 1, pp. 204–238, 2016.

[13] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, “Underwater optical wireless communications, networking, and localization: A survey,” Ad Hoc Networks, vol. 94, p. 101935, 2019.

[14] G. Schirripa Spagnolo, L. Cozzella, and F. Leccese, “Underwater optical wireless communications: Overview,” Sensors, vol. 20, no. 8, p. 2261, 2020.

[15] P. A. Hoeher, J. Sticklus, and A. Harlakin, “Underwater Optical Wireless Communications in Swarm Robotics: A Tutorial,” IEEE Communications Surveys & Tutorials, 2021.

[16] K. Anbarasi, C. Hemanth, and R. Sangeetha, “A review on channel models in free space optical communication systems,” Optics & Laser Technology, vol. 97, pp. 161–171, 2017.

[17] M. Lanzagorta, “Underwater communications,” Synthesis lectures on communications, vol. 5, no. 2, pp. 1–129, 2012.

[18] M. Dautta and M. I. Hasan, “Underwater vehicle communication using electromagnetic fields in shallow seas,” in 2017 International Conference on Electrical, Computer and Communication Engineering (ECCE), 2017, pp. 38–43.

[19] Y. Li, S. Wang, C. Jin, Y. Zhang, and T. Jiang, “A survey of underwater magnetic induction communications: Fundamental issues, recent advances, and challenges,” IEEE Communications Surveys & Tutorials, vol. 21, no. 3, pp. 2466–2487, 2019.

[20] C.-Y. Li et al., “16 Gb/s PAM4 UWOC system based on 488-nm LD with light injection and optoelectronic feedback techniques,” Optics Express, vol. 25, no. 10, pp. 11598–11605, 2017.

[21] T.-C. Wu, Y.-C. Chi, H.-Y. Wang, C.-T. Tsai, and G.-R. Lin, “Blue laser diode enables underwater communication at 12.4 Gbps,” Scientific reports, vol. 7, no. 1, pp. 1–10, 2017.

[22] I.-C. Lu and Y.-L. Liu, “205 Mb/s LED-based underwater optical communication employing OFDM modulation,” in 2018 OCEANS-MTS/IEEE Kobe Techno-Oceans (OTO), 2018, pp. 1–4.

[23] C. Pontbriand, N. Farr, J. Ware, J. Preisig, and H. Popenoe, “Diffuse high-bandwidth optical communications,” in OCEANS 2008, 2008, pp. 1–4.

[24] L. J. Johnson, R. J. Green, and M. S. Leeson, “Hybrid underwater optical/acoustic link design,” in 2014 16th International Conference on Transparent Optical Networks (ICTON), 2014, pp. 1–4.

[25] M. V. Jamali, J. A. Salehi, and F. Akhoundi, “Performance Studies of Underwater Wireless Optical Communication Systems With Spatial Diversity: MIMO Scheme,” IEEE Transactions on Communications, vol. 65, no. 3, pp. 1176–1192, 2017, doi: 10.1109/TCOMM.2016.2642943.

[26] Y. Rong, S. Nordholm, and A. Duncan, “On the Capacity of Underwater Optical Wireless Communication Systems,” in 2021 Fifth Underwater Communications and Networking Conference (UComms), pp. 1–4.

[27] M. A. Das, P. Arjun, A. S. Bhaskaran, P. Aravind, T. Aswin, and V. Sadasivan, “Estimation of maximum range for underwater optical communication using PIN and avalanche photodetectors,” in 2019 International Conference on Advances in Computing and Communication Engineering (ICACCE), 2019, pp. 1–6.

[28] S. Arnon, J. Barry, G. Karagiannidis, R. Schober, and M. Uysal, Advanced optical wireless communication systems. Cambridge university press, 2012.

[29] M. M. Abadi, Z. Ghassemlooy, M. R. Bhatnagar, S. Zvanovec, M.-A. Khalighi, and A.-R. Maheri, “Using differential signalling to mitigate pointing errors effect in FSO communication link,” in 2016 IEEE International Conference on Communications Workshops (ICC), 2016, pp. 145–150.

[30] M. M. Abadi, Z. Ghassemlooy, M. R. Bhatnagar, S. Zvanovec, K. Mohammad-Ali, and M. P. Lavery, “Differential signalling in free-space optical communication systems,” Applied Sciences, vol. 8, no. 6, 2018.

[31] J. Sticklus, M. Hieronymi, and P. A. Hoeher, “Effects and constraints of optical filtering on ambient light suppression in LED-based underwater communications,” Sensors, vol. 18, no. 11, p. 3710, 2018.

[32] H. Brundage, “Designing a wireless underwater optical communication system,” PhD Thesis, Massachusetts Institute of Technology, 2010.

[33] E. Friedman and J. L. Miller, Photonics rules of thumb: optics, electro-optics, fiber optics, and lasers. McGraw-Hill, 2004.

[34] J. Sticklus, P. A. Hoeher, and M. Hieronymi, “Experimental characterization of single-color power LEDs used as photodetectors,” Sensors, vol. 20, no. 18, p. 5200, 2020.

[35] R. A. Leathers, T. V. Downes, C. O. Davis, and C. D. Mobley, “Monte Carlo radiative transfer simulations for ocean optics: a practical guide,” Naval Research Lab Washington Dc Applied Optics Branch, 2004.