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Review

Underwater Communication Systems and Their Impact on Aquatic Life—A Survey

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Abstract: Approximately 75% of the Earth's surface is covered by water, and 78% of the global animal kingdom resides in marine environments. Furthermore, algae and microalgae in marine ecosystems contribute up to 75% of the planet's oxygen supply, underscoring the critical need for conservation efforts. This review systematically evaluates the impact of underwater communication systems on aquatic ecosystems, focusing on both wired and wireless technologies. It highlights the applications of these systems in Internet of Underwater Things (IoUT), Underwater Wireless Sensor Networks (UWSNs), remote sensing, bathymetry, and tsunami warning systems, as well as their role in reducing the ecological footprint of human activities in aquatic environments. The main contributions of this work include: a benchmark of various underwater communication systems, comparing their advantages and limitations; an in-depth analysis of the adverse effects of anthropogenic emissions associated with communication systems on marine life; and a discussion of the potential for underwater communication technologies, such as remote sensing and passive monitoring, to aid in the preservation of biodiversity and the protection of fragile ecosystems.

Keywords: noise pollution; underwater wireless communication (UWC); modulation; protocol; UWSNs; underwater visible light communication (UVLC)

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1. Introduction

Marine, riverine, and lacustrine environments and other natural water formations are scenes of industrial complexity [1–4]. Underwater communication systems find applications in extreme environment communications [5] as applied in Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicless (ROVs) [6,7], IoUT systems, and docking in the offshore industry [8]. Ships, heavy machinery, and a multiplicity of technologies are found performing distinct economic, scientific, and communication activities [1–3] for civilian and military applications, such as oil and gas exploration, fishery, transportation, distributed tactical surveillance, scientific surveys, environmental monitoring, climate data collection, disaster prevention, assisted navigation, and mine detection [2,9] to name a few. Moreover, the subsea environment is highly complex; for instance, the UK relies on the surrounding seabed for 99% of its gas production, supported by a 14,000 km subsea pipeline network, with around 100 oil platforms and 180 gas platforms operating in dangerous and inhospitable conditions [10].

Underwater industrial activities are economically and strategically vital to humans [4]. The application of deep-water positioning systems enables the precise location of AUVs [8]. In addition, underwater technologies contribute to the preservation and protection of aquatic lifeforms [11,12]. They are applied to environmental monitoring systems to equip expert biologists in the underwater domain, such as ichthyologists, with vital data and information to make informed decisions concerning environmental measures to preserve and protect the aquatic biodiversity and its ecosystems [11–13].

Over 900 underwater species and families of living organisms communicate via acoustic expressions and cues [1,3,14–16] in the range from 10 Hz to over 100 kHz [14–16], which includes mammals, fishes, and invertebrates [1,3,14–17]. In addition to acoustics, other signal types are used by aquatic organisms [3,18,19]. Species like plankton use optical communication in the form of bioluminescence [18]. Furthermore, an African freshwater fish group called mormyridae uses both acoustic and electrical signals in social interactions and for spacial orientation [19]. Anthropic emissions in aquatic environments cause negative footprints, which pose a serious threat to their inhabitants [1,3]; for example, fish and invertebrates have been reported to exhibit Deoxyribonucleic Acid (DNA) damage and reduced egg production due to noise pollution [1]. The vitality of communication for both humans and living organisms in the underwater medium is evidenced in this article, which endorses a symbiotic co-existence between humans and nature. A balanced co-existence is mutually beneficial for the survival of both parties [20].

The main contributions of this article are (i) benchmarking various wired and wireless underwater communication systems and comparing their advantages and disadvantages; (ii) highlighting and discussing the negative impacts of anthropogenic emissions from communication systems on aquatic lifeforms; and (iii) demonstrating the importance of underwater communication technologies, such as remote sensing and passive monitoring, in preserving biodiversity and ecosystems. The structure of the article is as follows: Section 2 covers the underwater ecosystems and biodiversity; the types of underwater communication are discussed in Section 3; the applications of sensor network modalities in Section 4 cover the sensors network modalities and applications; and the conclusions and future directions are discussed in Section 5.

2. Underwater Ecosystems and Biodiversity

To understand the composition and dynamics of the Earth's biosphere, a census of the Earth's biomass is crucial [9]. About 75% of the Earth's surface is covered with water, comprising oceans, rivers, canals, and seas [21]; Bar-On et al. [9] reported 71% of Earth's surface being covered in water. Earth's total biomass is approximately 550 Gigatons of Carbon (Gt C) (Gt Cis a unit of mass that is equal to one billion metric tons, or 1012 kg) [9]. While plants are primarily terrestrial, animals are mainly marine (aquatic), and bacteria and archaea are predominantly located in deep subsurface environments [9]. On the terrestrial surface, the biomass of the vegetal kingdom comprises close to 450 Gt C, and in the marine environment, the animal biomass accounts for nearly 2 Gt C, while the biomasses of bacteria and archaea in deep subsurface environments add 70 Gt C and 7 Gt C, respectively [9,22]. Table 1 summarises the distribution of the Earth's biomass on land, in water, and in subsurface environments. It shows that vegetation dominates the Earth's biomass, contributing to it nearly 80%.

The total marine biomass is estimated at 6 Gt C, of which less than 1 Gt C is vegetation in the form of green algae and seagrass [9]. The marine environment is predominantly inhabited by microscopic organisms, such as bacteria and protists, which collectively make up approximately 70% of the total marine biomass. The remaining 30% is primarily composed of larger organisms, including arthropods and fish [9]. The deep subsurface biosphere, comprising predominantly bacteria and archaea, accounts for approximately 15% of Earth's total biomass [9]. These microorganisms exhibit slow growth rates and long turnover times, spanning from months to millennia [9]. Although there is a marked discrepancy in biomass between terrestrial and marine ecosystems, their primary productivity remains relatively equivalent [9]. In other words, while the majority of plant biomass is found on land, most animal biomass is concentrated in the oceans [9]. Ritchie et al. [22] agreed with Bar-On et al. [9], stating that the majority of life, 86%, exists on land, primarily due to terrestrial plant life, especially trees. Ritchie et al. [22] emphasised that though oceans cover over 70% of Earth's surface, they contain only 1% of its biomass, and yet they dominate the animal kingdom, housing 78% of all animal life [22]. Bar-On et al. advised caution in interpreting the values in Table 1, considering the uncertainty imparted by limited sampling for deep ocean and soil environments.

Marine ecosystems are home to a vast diversity of life, including over 170,000 known invertebrate species and 20,000 fish species [1]. Weilgart [1] reported that all fish species studied to date, as well as a growing number of invertebrates, possess the ability to detect and respond to sound and vibrations [1]. The underwater world is a vibrant and complex ecosystem—replete with rich animal biodiversity, intricate eco-systems, and fascinating environmental dynamics [1,3,9]. Looby et al. conducted a comprehensive review of the peer-reviewed and grey literature from 1874 to 2020, identifying 1185 fish species that have been studied for sound production.

Table 1. Summary of estimated total biomass for abundant taxonomic groups [9,22].

Taxon	Mass (Gt C)	Uncertainty (-Fold)
Plants	450	1.2
Bacteria	70	10
Fungi	12	3
Archaea	7	13
Protists	4	4
Animal	2	5
Viruses	0.2	20
TOTAL	550	1.7

For the assessment of biodiversity indication in an aquatic environment, sounds emitted by various organisms in the area are recorded along with natural ecological events [3,23,24]. However, increasing anthropogenic noise pollution in some coral reefs modifies these habitats, causing difficulties in estimating biodiversity and damaging the ecosystems [3,23,24]. Lin et al. [23] discovered that biological sound dynamics varied across depth gradients in Sesoko Island's coral reefs. Shallow reefs were dominated by crustacean and fish sounds, while upper-mesophotic reefs exhibited diverse fish choruses and transient sounds [23]. Lin et al. [23] showed that sound analysis reveals coral reef health and organism behaviour in high detail, and continuous monitoring provides insights into habitat quality, biodiversity, human impact, and their interactions. Lin et al. [23] also discovered that noise emissions from ships profoundly hindered the soundscapes from the upper-mesophotic reefs, which constituted an unseen threat to aquatic organisms in the low-light habitat. Lin et al. [23] established that international cooperation on underwater soundscapes is expected to create a knowledge-based platform to assess coral reef resilience.

Human activities are a potential source of one or several forms of pressure that affect ecological receptors [25]. Table 2 provides a general description of various sources of negative footprints and the underwater lifeforms affected by them. The quantification of sound footprints necessitates the capture of acoustic pressure profiles and the associated particle velocity fields. [26]. Pressure profiles and velocity fields enable the precise quantification of disturbance impacts in the underwater environment. Specifically, they allow for the calculation of (i) noise power in decibels (dB), (ii) causal particle movements in meters per second (m/s), and (iii) sound-generated pressure in micropascals (µPa) [26]. These measurements provide a comprehensive understanding of the potential effects of human activities on marine ecosystems [26]. A French marine company (RTsys), for example, has devised autonomous systems for passive acoustics detection solutions for coastal area, fresh water, and offshore applications [26]. Such systems enable not only the measurement of noise pollution footprints caused by heavy machinery, such as hovercraft and ships, but also capacitate the detection of marine organisms and marine ecosystem characteristics in real time using the RTsys recorder connected to a hydrophone [26]. The study with this system concluded that hovercraft operation in the North Caspian Region can impact sensitive marine life such as fishes and invertebrates. The noise density emission from ships is determined by type, considering the motor size and propeller types [27].

Table 2. The impact of underwater communication on aquatic life [1,26,28].

Impact	Description	Affected Organisms
Noise Pollution	Generated by machinery, vessels, and communication systems.	Marine mammals, fish, invertebrates
Habitat Disruption	Caused by construction, installation, and operation of underwater infrastructure.	Benthic organisms, coral reefs
Chemical Pollution	From materials used in underwater equipment and operations.	Various marine species
Electromagnetic Interference	Disrupts marine organisms' sensory systems.	Fish, invertebrates
Climate Change	Indirectly impacts marine ecosystems through ocean warming and acidification.	Diverse marine species

The United Nations (UN) adopted the Law of the Sea in 1958 in the Geneva Conventions (GC) [29]. The GC are a series of four treaties, namely, (1) the Convention on the Territorial Sea and the Contiguous Zone, which defines the territorial sea and the contiguous zone and outlines the rights of coastal states within these areas; (2) the Convention on the High Seas, which codifies the rules of international law relating to the high seas, including freedom of navigation, fishing, conservation of marine areas, and scientific research; (3) the Convention on the Continental Shelf, which defines the rights of coastal states over the continental shelf, including the right to exploit its natural resources; and (4) the Convention on Fishing and Conservation of the Living Resources of the High Seas, which establishes rules for the conservation and management of fish stocks on the high seas [29]. The conference aimed to establish international norms for the use and conservation of marine areas, including freedom of navigation, fishing, conservation of marine areas, and scientific research [29]. In 2015, the UN established seventeen Sustainable Development Goals (SDGs). These goals aim to address global challenges such as poverty, inequality, climate change, and environmental degradation [30]. Sustainable Development Goal 14 (SDG 14) is known as Life Below Water, which focuses on conserving and sustainably using the oceans, seas, and marine resources. It aims to protect marine ecosystems, reduce pollution, and promote sustainable fishing practices [30]. SDG 14 is in alignment with the 1982 United Nations Convention on the Law of the Sea (UNCLOS).

The Natural Resources Defense Council (NRDC), a US-based non-profit international environmental advocacy group, estimated that between 80% and 90% of products and commodities transportation is carried out by ships on ocean waters, significantly contributing to noise pollution [31]. Besides machine noises, technological noise emissions are equally regulated, such as acoustic signal power, modulation schemes, and acoustic frequency bands [32]. For example, spread spectrum modulation reduced signal power density per unit of bandwidth [33], and bioacoustics studies have proven animal discomfort and bio-intrusion reduction provided by this method [34]. Underwater simulations performed using the spread spectrum resulted in transmission rates of 45 bs at −18 dB Signal-to-Noise-Ratio (SNR) and 140 bs at −12 dB SNR [34]. Furthermore, the frequency ranges used for communication and active Sound Navigation and Ranging (SONAR) detection systems in some cases match those of certain marine species, causing confusion, disorientation, false alarms, and panic [1]. Ocean Care, a marine life advocacy organisation, added that underwater noise pollution is "deafening, dangerous, and deadly to marine life" [35].

The oceans are increasingly becoming crowded with scores of colossal, transformative, and innovative industries [34], namely long-standing offshore oil and gas, offshore wind farms, aquaculture fish farms, marine mineralogy, and underwater research and exploration. These industries utilise various types of technologies in marine environments, such as heavy machinery, powerful motors and underwater vehicles, and the installation of underwater power plants and piping systems, which are sources of vibrations, sounds, and frequencies of various sorts [1,28,34]. As described in [28], the main sources of noise emissions in the oceans are anthropogenic in origin. Various technologies pollute the waters with harmful noise and chemicals, altering the marine ecosystems with disturbances and other micro-climate changes that ultimately cause disorientation, hearing loss, confusion, bodily malformation, developmental dysfunction, diminished egg production and growth rates, DNA damage, and deaths to the marine life [1,3,28,34].

Both fish and invertebrates use sound to meet distinct existential needs, such as navigation, mating, communication, predator avoidance, and socialising [1,3]. Although not all fish emit active sound [3], all fish species studied to date have been found to possess the ability to hear sound [1], and invertebrates also demonstrated the ability to detect sound and vibrations and respond to acoustic cues [1,3]. Even large mammals such as sharks and whales are impacted by the industrial landscapes, provoking caution and behavioural changes [1,36]. Looby et al. [3] confirmed the use of sound by the majority of fish and invertebrates for their vital life functions, as also reported in [1,2]. Whether plankton, nekton, or benthos, sound governs the ways of life for most aquatic lifeforms [1,3,37]. On the other hand, noise pollution adversely impacts their DNA and consequently their development, mortality rate, and egg production rate [1]. In a case study, blast pressure measurement indicated a significant correlation between frequency emissions and the injuries inflicted on particularly two fish species, the rainbow trout and the juvenile Chinook salmon [37].

The World Health Organization (2011) identifies anthropogenic noise as a significant global pollutant [1]. Weilgart's [1] study incorporated a diverse range of noise sources, such as ship and boat traffic, seismic airguns, pile driving, aquaculture activities, low-frequency sound playback, pure tones, frequency sweeps, and white noise. The author studies the effect of noise pollution on 36 species of invertebrates and and 66 species of fish [1]. It was concluded that the damaging effects of acoustic pollution on aquatic life are numerous [1,3]. Due to noise pollution, in some species growth rates have decreased, physical development has been delayed, and body malformation has been observed [1,3]. In addition, the number of egg and immature mortality increased [1]. For example, Zooplankton, a marine heterotrophic animal, experienced soaring mortality rates when subjected to noise [1]. Due to noise, colossal internal abrasion and cell disruption to statocysts and neurons are some of the various physiological impacts, which are the causes of disorientation, hearing loss, and death [1].

Moreover, the oceans are also home to algae and microalgae or microphytes—minuscule organisms, 2–10 µm in size, which are invisible to the naked eye and of paramount importance for biodiesel production [38–40]. These tiny marine lifeforms, such as Chlorella and Spirulina, make popular food supplements [41]. Algae are responsible for the production of 75% of the earth's supply of oxygen [40–42]. Endangering such vital creatures will heavily impact life on Earth as a whole, speeding up climate change and global warming as these microalgae also absorb CO_2 to create biomass [40,42].

Due to the negative impacts of anthropogenic acoustic, optical, and Electromagnetic (EM) wave proliferation provoked by marine industries on marine lifeforms, ocean observers such as Ocean Networks Canada (ONC), the International Quiet Ocean Experiment (IQOE), and international agreements such as UNCLOS have adopted laws and standards aimed at preserving and protecting marine biodiversity and ecosystems [32,43]. Besides ships and machinery used in oceanic environments, acoustic signals originating from active SONAR detection systems pose a grave danger to marine life, causing migrations and confusion and inflicting pain and ultimately death and extinction [1,31].

The high seas constitute the Earth's largest ecosystem [20]. If permitted, deep-sea mining is estimated to cause irreversible damage to marine ecosystems and to humans, leading to permanent biodiversity loss [20]. Based onthe anticipated noise profile regarding deep-sea mining, as outlined in [44], the major contributors to deep-sea noise pollution, if such mining activities were permitted in the future, would include exploration and research vessels, surface-based acoustic exploration, production vessels, monitoring vessels, offtake vessels, supply vessels, ROVs, AUVs, deep-towed acoustic exploration, seafloor mining tools (collectors and cutters), riser systems, booster pumps, and subsea lift pumps and buffer stations.

The laws and standards pertaining to ocean noise pollution aim at reducing noise footprints [25,29,30]. By understanding the impacts of noise on marine life, the United Nations, the United States, and Europe have written legislation to restrict noise pollution in the oceans by defining and recommending acoustic frequency bands, endorsing the use of other wireless communications with low to zero environmental footprint [25,30]. North American and European private and governmental institutions, such as the National Oceanic and Atmospheric Administration (NOAA) and the European Maritime Safety Agency (EMSA), study the consequences of underwater noise pollution on marine lifeforms and lay out recommendations and regulations for the protection and preservation of aquatic life [1,29,30]. Due to the sensitivity of the oceans, environmental licensing procedures are put in place with precautions and new industries are required to declare their damaging footprints and provide mitigation initiatives [25,29,30]. To fully comprehend the potential effects of underwater technologies on aquatic life, a thorough understanding of the physical principles, operational characteristics, and deployment strategies of different underwater communication systems is crucial, as follows.

3. Types of Underwater Communication Systems

An underwater communication system can be wired, wireless [45,46], or a combination of the two, depending on the applications and system requirements. To illustrate, Hybrid Remotely Operated Vehicles (HROVs) are operated both with tethered cables or wirelessly [47]. HROVs are vehicles used for underwater operations such as monitoring, exploration, and surveillance for scientific, military, recreational, and commercial purposes. Underwater Wired Communication (UWiC) is feasible via coaxial cables [48,49], fibre-optic cables [50], and hybrid systems [51]. UWiC via coaxial cables is feasible using electrical conductors like copper and aluminium [48,52]. Subsea cables are properly insulated with coatings designed to prevent corrosion from salinity and water ingress [53–56].

In Singh et al. [46], three Underwater Wireless Communication (UWC) systems are identified, namely optical, EM, and acoustic. In contrast, Busacca et al. [5] identified four UWC technologies, specifically radio frequency (RF), Magnetic Induction (MI), Underwater Wireless Optical Communication (UWOC), and Underwater Acoustic Communication (UWAC). Each of these communication modalities have trade-offs, and therefore the implementation of these technologies is determined by factors such as costs, throughput capabilities, transmission ranges, latency (latency is the time it takes for a signal to travel a physical distance), and the device's longevity in aquatic conditions [5,46].

While UWiC systems are sizeable and difficult to scale out (see Figure 1), wireless technology is highly scalable and versatile [57]. Light is part of the EM spectrum and is highly malleable; it can be transmitted through fibre-optic cables or wirelessly by propagating it or sending it directly through water, as used in underwater Light Detection and Ranging (LiDAR) and UWOC systems [46,50]. In contrast, acoustic and RF waves are uniquely used as wireless communication methods due to their ability to travel through water [58]. Acoustics is a preferred UWC system for long-distance communication underwater because sound waves travel well in the water medium [17,59], while RF waves are used for shorter distances due to their limited range but faster data transmission in certain underwater conditions [60–62].

Figure 1. An example of underwater communication cable [63].

3.1. Underwater Wired Communication

Ocean waters host numerous intercontinental fiber-optic and electrical cable projects driven by international collaborations [64,65]. The subsea industry integrates complex, large-scale subsea equipment and machinery [64]. In addition to simple coaxial and fiber-optic cables, subsea hydraulic control systems utilise massive umbilical cords and extensible pipes that contain both electrical and optical cables [66–68]. Subsea cables are complex and can have a diameter of up to 320 millimeters (12.6 inches) [54].

UWiC provides a fast and secure connection [5,54]. However, its implementation presents several challenges that must be carefully considered [54], as shown in Figure 1. The logistical complexities, capital expenditures, and operational overhead associated with deploying and maintaining large-scale infrastructure in the marine environment are substantial [5,10,45,60–62,69,70]. Table 3 refers to the types of underwater communication systems and their strengths and weaknesses. Subsea materials include submarine cables and dry-mate and wet-mate connectors [45]. The deployment of subsea cables on ROVs or sea rovers [55] requires trained ship operators [45], making the process time-consuming and labour-intensive. To reduce operational costs and address deployment constraints, innovative system design is essential, opening an opportunity for UWC systems as vital alternatives [5,69,71]. UWC networks are indispensable tools for exploring the remote and poorly understood regions of the deep ocean, which are a major focus of scientific research and academic interest [71]. Table 4 lists the types, application, and costs of subsea connectors. Table 5 specifies the features of UWiC for coaxial and optical cables and admixtures of both.

Table 3. Types of underwater communication systems and their strengths and weaknesses.

Types of Systems (λ)	Signal	Pros	Cons	Range
UWiC (1300–1600 nm) [54]	Electrical, Optical	Reliable, high data rates (optical), secure	Expensive to install, limited range (optical), susceptible to physical damage	As far as cable length
UWOC (380–750 nm) [72]	Optical	High bandwidth, low latency, energy-efficient	Short range, susceptible to absorption and scattering	10 to 100 m in UWSNs application
UWRF (1–10 mm) [60], (1 mm–10 km) [73]	Electromagnetic (RF)	Moderate bandwidth, long range, versatile	High power consumption, large antenna, susceptible to attenuation in saltwater	Up to 100 m between 30 Hz and 300 Hz
UWAC (15 mm–1.5 m) [74]	Acoustic	Long range, low attenuation	Low bandwidth, high latency, susceptible to noise pollution	Up to 100 km in submarines
Hybrid UWAC-UWOC	Acoustic and optical	Combines advantages of both	Complex implementation	Refer to UWAC and UWOC
UEFC (30–3000 m) [75]	Electric field	Potential for high data rates, inspired by natural communication	Limited range due to attenuation	Approx. 8 m
UVLC (430–550 nm) [76]	Visible light (blue/green)	High data rate, low latency, high security, no electromagnetic interference, potential for high-resolution imaging	Limited by water turbidity and distance	Up to 500 m in pure seawater

Table 4. Subsea connectors: types, applications, and costs [54].

Type	Application	Cost (Approximate)
Submersible Pump Connector	Oil and gas production, water supply	USD 10,000 to USD 50,000
ROV Connector	ROVs	USD 5000 to USD 20,000
Subsea Power Cable Connector	Offshore wind farms, subsea power grids	USD 50,000 to USD 200,000
Subsea Fibre-Optic Connector	Telecommunications, data centres, oceanographic research	USD 100 to USD 500
Subsea Optical Power Connector	Subsea power systems, underwater sensors	USD 500 to USD 2000
Subsea Hybrid Power and Data Connector	Subsea systems requiring both power and data transmission	USD 10,000 to USD 50,000

Underwater cables are designed based on a well-established formula that defines the characteristics necessary to endure harsh underwater conditions, including pressure, temperature, corrosion, tension, lift force, hydrodynamic forces, and water ingress [49,54,55]. Material treatment, quality, and insulation (e.g., polyurethane) technologies vary significantly [54,55]. Additionally, underwater cables are expected to be inextensible in both length and diameter due to the effects of the Poisson ratio [54,55].

Table 5. Underwater wired communication systems [45,54,55,69].

Types of Cables	Communication Range	Data Rate	Advantages	Disadvantages
Coaxial	Short to medium distances (up to a few kilometres)	Moderate data rates (up to several Mbps)	Reliable, cost-effective	Susceptible to corrosion and mechanical damage
Optical Fibre	Long distances (tens to hundreds of kilometres)	High data rates (Gbps)	Low attenuation, high bandwidth	Sensitive to bending and tension
Hybrid	Long distances	High data rates	Combined power and data transmission	Complex design and installation
EMI	Short distances (a few meters)	Low data rates	Robust against corrosion and mechanical damage	Limited range, susceptible to interference

To further demonstrate the cost and specialised material requirements involved in UWiC communications, types of connectors are introduced. Several types of connectors exist, varying in application and cost, as summarised in Table 3. The connector's mating location is determined by the type of underwater connector in use. For example, dry-mate connectors, shown in Figure 2, are designed for surface connections; they are assembled outside of the water [77]. In contrast, wet-mate electrical connectors, in Figure 3, are designed to be mated and unmated in wet environments, unlike traditional cables that rely on a watertight seal, which can be susceptible to water ingress [63].

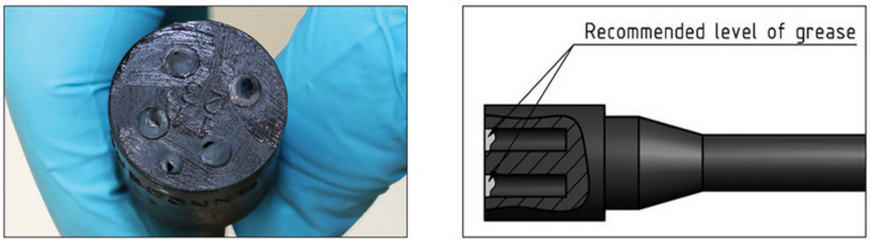

Figure 2. Dry-mate connector [63].

There are several variants of wet-mate cables [63]. Rubber-moulded wet-mate connectors utilise a locking sleeve and neoprene or polyurethane over-moulding to create a watertight seal between a female connector end and a glass-reinforced epoxy bulkhead connector [63]. Rigid shell wet-mate connectors, on the other hand, are moulded into a rigid body, providing greater stability, strength, and lockability. The water-locking mechanism involves screwing the two connector halves together and sealing the junction with an O-ring [63]. The water-locking is normally performed underwater, and adequate connector treatment is necessary to ensure proper sealing against water ingress [63]. Connectors must be greased with Molykote 44 Medium before each mating. Adhering to proper procedures using standard greasing products for the application of grease ensures quality mating and secure connectivity, preventing water ingress.

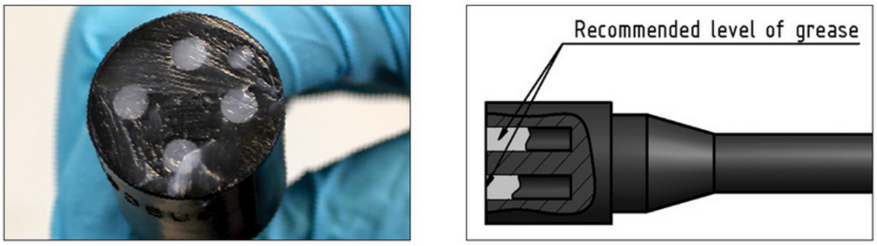

Figure 3. Wet-mate connector [63].

In the oil industry, umbilical cables are widely used for subsea power and control systems, specifically designed to endure the harsh conditions of the sea [49]. These subsea power and control systems are installed on the seabed, with umbilical cords connecting subsea equipment to surface facilities, providing fast, reliable, and robust underwater cabled communication [49]. Like airborne systems, underwater cables are widely used for various purposes, including communications, power transmission, and distribution to islands, oilfield platforms, and underwater infrastructure [78]. However, unlike airborne cables, underwater cables require more specific design considerations for protection and shape to withstand the marine environment, including factors such as pressure, temperature, ocean currents, salinity, and water ingress [55].

3.2. Underwater Wireless Communication

Sajmath et al. and Zeng et al. [45,79] defined UWC as the process of transmitting data wirelessly through an unguided underwater medium. Despite the existence of underwater wireless technologies for several decades, these systems still struggle to achieve high data rates over long distances [5,80]. Optical, RF, and acoustic waves are the common forms of wireless communication employed in water, collectively referred to as UWC systems. The EM spectrum encompasses all EM radiation, ranging from extremely Low Frequency (LF) in the radio band to extremely High Frequency (HF) in the gamma-ray region [72]. Figure 4 illustrates the different regions of the EM spectrum.

Figure 4. The EM Spectrum [72].

Stojanovic [81] reported that the first UWAC system was an underwater telephone developed in the United States in 1945. Stojanovic [81] stated that the UWAC system, operating in the 8–11 kHz frequency band, used single-sideband suppressed carrier (a carrier wave is a periodic wave (usually sinusoidal) that carries information. This information is superimposed onto the carrier wave through a process called modulation. The frequency of this carrier wave is known as the carrier frequency) modulation to communicate with submarines over several kilometers. With the advent of Very Large Scale Integration (VLSI) technology and programmable Digital Signal Processing (DSP)s, UWAC systems have experienced rapid growth and diversification [81]. Initially primarily used for military purposes, UWAC systems are now finding applications in various commercial sectors [5,45,81]. For instance, they are being employed in environmental monitoring, such as pollution detection, and in the offshore oil industry [5,45,81]. Historically, UWAC has been the dominant UWC system due to its comparatively low attenuation and long range, despite its lower bandwidth and higher latency [5,45,81]. Low-latency systems are desired since high volumes of information or data can easily be transferred across nodes (sources and destinations).

Acoustics is the scientific study of sound, which includes its generation, manipulation, propagation, perception, and effects [82]. Unlike EM waves (such as RF and optics), which are transverse [83], acoustic waves are longitudinal [84]. The difference in how these two types of waves travel through a medium significantly impacts their propagation range and attenuation characteristics [58,60]. Acoustic communication stands out in terms of range, mainly due to its resiliency to the physical properties of water, imparted by compression and rarefaction [84].

Although water is highly conducive to propagation of acoustic waves, allowing communication over several kilometers [21,62], current acoustic communication systems suffer from low bandwidth (typically ranging from 5 to 10 Kbps) [21,62]. UWAC systems also face higher latency compared to UWOC and RF technologies and are susceptible to fading and time-varying multipath interference [21,60–62]. In contrast, UWOC is affected by dispersion caused by turbidity, which reduces both transmission distance and reliability [5]. Busacca et al. [5] reported that in USWN implementations, many underwater nodes are battery-powered and must operate for extended periods, adding to the need to devise energy-efficient communication strategies to prolong the operational lifetime of systems.

UWOC is both cost-effective and energy-efficient [61]. Light is known for its dominance in bandwidth and low latency [79,85]. With the increasing demand for higher bandwidth and transmission speeds, optical wireless communication is gaining attention as a viable alternative [68,79]. UWOC, utilising laser beams and other EM wave groups, is widely implemented as a wireless communication system in underwater environments, demonstrating success across various domains [85]. When communication occurs over short distances and requires high data rates, optical communication is a highly recommended option [45,68]. The light wavelength ranges from 380 to 750 nm, corresponding to a frequency range of 400 to 790 THz [72]. Since bandwidth is directly proportional to frequency, this high-frequency range allows significant bandwidth and low latency [45]. Although light is a EM wave and susceptible to absorption (absorption happens when a wave loses energy as it transmits into a material. This can happen in a medium or at a boundary between two materials) [86], its frequency band makes it suitable for UWC [45]. UWOC provides high bandwidth in the range of Mbps to Gbps, high reliability over short distances, a minimal environmental footprint, and low latency [45,61,85]. Over short distances (approximately tens of metres), optical communication can complement more advanced acoustic connections. In addition, optical communication enables the transmission of images and videos, real-time streaming, and high-performance sensor networks. However, due to extreme degradation caused by absorption, dispersion, and turbulence, UWOC is only suitable for short-range applications [45,86]. A UWC system, although cheaper, either has limited signal propagation range or travelling distance, such as the UWOC, or low bandwidth, such as the UWAC [60–62,80].

Underwater RF communication is characterised by the application of the EM frequency band between 3 KHz and 300 GHz [73]. However, some sources define RF to be between 30 kHz and 300 GHz [73]. The International Radio Regulations body defines RF between 9 kHz and 3000 GHz as suitable for wireless communication [77]. Furthermore, Pompili et al. [60] refer to RF as low as 30 Hz. RF signals travel most effectively through salty water at LF, specifically between 30 Hz and 300 Hz, but require large antennae for efficient transmission [60] due to high wavelength, since wavelength is inversely proportional to frequency. At the frequency range 30–300 Hz, Busacca et al. [5] reported a transmission distance of 100 m. Vasilescu et al. [7] and Kalpana et al. [8] have described RF as impractical for underwater applications due to significant attenuation, favouring acoustic waves for signal transmission. Palmeiro et al. reported [10] that despite being part of the electromagnetic spectrum, lower-frequency RF waves experience less attenuation in water. This is because the absorption coefficient of water is inversely proportional to frequency [10].

Challenges in underwater signal propagation include signal reflection and refraction at the ocean surface and floor, which lead to multipath propagation [5,6]. Multipath propagation causes signal pulses to scatter and spread out, reducing data rates and increasing the error rate [6]. The broad EM spectrum is divided into smaller frequency bands, such as RF, microwave, visible light (optics), infrared, ultraviolet, X-rays, gamma rays, and others [72]. The application of each band depends on factors like system design, usage, and environmental conditions [5]. For instance, while both visible light and RF bands belong to the EM spectrum, they behave differently in UWC systems due to their varied responses to water properties and conditions, leading to variations in data rates and transmission range capabilities [5,9].

The high permittivity (approximately 80) and high electrical conductivity of water are significant factors that contribute to the attenuation of EM signals [10]. The conduction effect causes a loss primarily due to the electrical field component in the EM field [10]. The implementation of EM waves is restricted to ranges on the order of tens of metres [45,85]. However, the behaviour of EM wave propagation varies depending on the frequency band within the EM spectrum [10]. The RF range is located at the lower end of the EM spectrum, which has a lower frequency than light and, consequently, a lower bandwidth [45]. As a result, RF is considered intermediate in terms of data rate [45]. Table 6 lists the underwater EM spectrum, signal attenuation and applications. As listed in Table 6, some of the EM frequency ranges have specific applications, while other segments of the spectrum have no current use.

Table 6. Underwater electromagnetic spectrum and signal attenuation [58,87].

Frequency Range	Wavelength (m)	Attenuation	Applications
Extremely Low Frequency (ELF)	10^3–10^6	Low	Submarine communication, geophysical exploration
Very Low Frequency (VLF)	10^2–10^5	Low	Submarine communication, navigation
Low Frequency (LF)	10–10^4	Moderate	Submarine communication, navigation
Medium Frequency (MF)	1–10^3	High	Underwater communication (limited range)
High Frequency (HF)	10^{-1}–10^2	Very High	Short-range underwater communication
Very High Frequency (VHF)	10^{-2}–10^{-1}	Extremely High	Limited use due to high attenuation
Ultra High Frequency (UHF)	10^{-3}–10^{-2}	Extremely High	Essentially unusable underwater

In regard to its physical properties, saltwater is electrically conductive [88]. Liquid saltwater is an electrolyte primarily composed of sodium and chlorine, making it a good electrical conductor [88]. The conductivity of saltwater imposes limitations on UWC using EM waves, resulting in attenuation [61,85,88]. Based on the four Maxwell–Heaviside equations, EM waves possess both magnetic and electrical fields [58]. These fields interact with the electrical and magnetic fields in water, leading to destructive interactions in the form of signal absorption [85,88]. Optical and RF communications offer greater bandwidth and lower latency compared to UWAC [7,62]. Light, like other high-frequency EM waves, is quickly attenuated underwater due to factors such as absorption, scattering (scattering is a change in the direction of motion of a particle because of a collision with another particle), fading, clustering, and fluctuating environmental conditions (e.g., perturbation, low visibility, and conductive ocean currents) [79,85,86]. Time jitters (time jitter refers to the variation in the arrival time of data bits or symbols in a digital system. It is a common phenomenon in communication systems, particularly those that transmit data over long distances or through noisy channels), chromatic dispersion (chromatic dispersion in optics refers to the phenomenon where different wavelengths of light travel at different speeds through a medium. This causes white light to be separated into its constituent colours, similar to what happens in a rainbow), water quality, and turbulence all impact wireless optical links, as highlighted in [85], which examines the probability of link fade (link fade is the reduction in signal strength or quality during transmission due to interference, absorption, scattering, and environmental conditions affecting the communication medium) associated with the propagation of chirped longitudinal Gaussian pulses used as information carriers. Although UWC has been successfully demonstrated in freshwater using EM waves, in most cases it required close sensor proximity to achieve high bandwidth [25]. Ref. [61] states that even though UWOC enables longer propagation ranges than underwater HF RF communication, long-distance communication underwater continues to rely on UWAC systems.

The types of water, salt or fresh, vary in concentration, density, chemistry, and geology [61]. These factors contribute to differences in absorption and scattering coefficients, as well as attenuation [61,88]. Time jitter affects the estimated arrival time at the receiver, negatively affecting signal synchronisation. Furthermore, turbidity of the water exacerbates the adverse effects of scintillation [85]. Turbulence can stretch or compress the signal wavelength from transmission to reception [85]. As a result, monochromatic transmission systems are deemed impractical in underwater environments characterised by turbulence, particularly in seawater [85]. Table 7 lists the typical attenuation coefficients for different types of water.

Table 7. Typical attenuation coefficients for different water types [61,76,89].

Water Types	Absorption (m^{-1})	Scattering (m^{-1})
Pure Sea Water	0.053	0.003
Clear Ocean	0.114	0.037
Coastal Ocean	0.179	0.219
Turbid Harbor	0.295	1.875

Both the absorption and scattering coefficients are indicators of signal attenuation: a reduction in signal power in the medium. While absorption refers to the signal energy being absorbed by the molecules in the medium, scattering refers to the spread of the signal across the medium due to reflection and refraction. In addition to the inherent properties of water, the absorption of light in underwater channels is also influenced by the frequency band range, as different wavelengths are absorbed in varying rates [18]. For example, the photons in the light signal can be absorbed by water molecules and converted into thermal energy, causing heat [90]. In contrast, scattering refers to the deviation of photons from their original path, reducing the signal strength along the desired trajectory [90]. Moreover, the absorption coefficient is lowest for wavelengths in the blue and violet spectrum, making this the optimal optical band for underwater communication [18]. Light attenuation is particularly low between wavelengths of 300 nm and 650 nm, further supporting the suitability of this range for optical communication [61]. To overcome the limitations of UWOC, techniques such as innovative encoding schemes, modulation, and detailed channel analysis have been developed [79]. Although optical waves are less affected by attenuation, they are more vulnerable to scattering [60].

Considering the broad range of the RF band, its performance is influenced by factors such as the frequency sub-band, required bandwidth, and propagation range requirements [10]. The adaptability of RF frequencies allows greater communication flexibility [10]. Underwater radio communication can achieve bandwidths of up to 100 Mbps over short distances [45], resulting in low latency [10]. Furthermore, RF signals are highly tolerant to turbulence, water depth variations, bubbles, marine fouling, and water turbidity, providing reliability for underwater communication [10,45]. However, Busacca et al. stated that between the frequency range of 30 Hz and 300 Hz, both RF and MI are heavily impacted by absorption in such a way that transmission distance is limited to nearly 100 m [5]. Despite the high energy consumption associated with bulky RF transceivers [45], several advantages are offered by RF technologies. RF signals can traverse various media, including air, water, ice, and solid objects and do not require a direct line of sight [10]. Thus, RF can navigate around obstacles, ensuring communication links even when direct visibility is obstructed [10]. Unlike sound waves, an RF signal is not affected by multipath interference, which enhances its reliability [10]. However, ref. [18] notes that RF does not propagate well in underwater environments, particularly in saltwater. Additionally, refs. [5,10,18,60] agreed that RF requires high power consumption. In contrast, UWOC is reported to be a low-energy consumer with extremely high security standards [85]. Despite the challenges in RF technologies, Palmeiro et al. [10] highlighted the successful implementation of underwater radio systems by Wireless Fibre System (WFS) Technologies in 2007, with further developments between 2008 and 2011 in various regions around the world, demonstrating notable progress. Collaborative efforts by companies such as WFS Technologies, Fugro Subsea Technologies, and Viper Subsea Ltd have led to the creation of reliable underwater radio communication systems, overcoming many of the common barriers associated with underwater communication [10]. These radio communication systems enable remote connectivity and management of subsea equipment [10].

Sound travels 4.5 times faster in water than in air [17,59], which contributes to the longer historical application of underwater acoustic communication (UWAC) compared to underwater optical communication (UWOC). For instance, the transmission between nodes and the buoyant gateways in a USWN system UWAC is used due to its long-range transmission capability despite its low bandwidth and high latency [5,21]. The communication advantage is primarily attributed to the extended propagation range and low attenuation associated with UWAC [61].

UWAC, also known as hydroacoustics, is an established system used in both military and civilian applications, including sensor networks, gaining traction since the 1980s using the same single-sideband terrestrial radio approach [91]. For example, the a US military underwater communication system that consists of a control station, a remote control station, a receiver-transmitter, as well as low- and high-frequency transducers (AN/WQC-2A) system is a set of sonar communication that submarine crews use to maintain communication over several nautical miles [91]. The Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas also employs the AN/WQC-2A system to coordinate submarine operations, which include testing, exercises, and “torpedo firing evolutions” [91]. In the 1980s, the US Navy funded the Baggeroer and Catipovic projects at the Massachusetts Institute of Technology (MIT) to advance underwater digital communication and acoustic telemetry [91].

SONAR can be categorised into two main types: passive and active [11,12,28,92,93]. Passive sonar, also known as passive acoustics, involves the direct recording of acoustic signals produced by various sources in air, water, or other media [11,12,28,93]. Passive SONAR, also known as passive acoustics, involves detecting targets by listening to their acoustic emissions without actively transmitting signals [2]. The non-intrusive method is widely employed to detect target signals [5,21] while minimising the impact on marine life, as it does not introduce additional acoustic emissions into the environment [1,3].

Essentially, passive SONAR has a low acoustic footprint [3]. Target signals originate directly from sources such as fish, marine mammals, and other organisms. Training and classification of passive target signals for effective detection of sound sources have become standard practices among researchers and commercial ventures [2,5]. Two forms of passive acoustic monitoring SONAR detection are recognised: the direct approach employs purely algorithmic methods, processing the detected signal of interest using techniques such as signal processing and filtering and comparative analysis of previous data while implementing adaptive and predictive approaches [5]. The second method involves more sophisticated data processing algorithms, such as Machine Learning (ML) and Deep Learning (DL) while also employing adaptive and predictive approaches [5]. Both ML and DL are subsets of Artificial Intelligence (AI). Although often used interchangeably, they have distinct characteristics and applications. ML is a broad discipline that leverages a diverse array of algorithms and techniques to empower computers to learn patterns from data and generate predictions or decisions autonomously [2,5]. DL is a subset of ML that uses artificial neural networks with multiple layers to learn complex patterns from large amounts of data [28].

In the context of underwater communication, sound sources are classified as natural and artificial or anthropogenic [2,28]. Natural sources include fish, marine mammals, and crabs (underwater living organisms, as a whole) [1–3,28], while artificial sources refer to sounds from ships, machinery, and human communication systems [1,2,28]. Sound waves are longitudinal, meaning that the vibrations of the medium occur parallel to the direction of the wave, resulting in regions of compression and rarefaction within the medium, and this process generates pressure that negatively impacts the morph-physiology of fish and invertebrates [1,3]. There are two methods of SONAR detection in use today: active and passive [93]. Passive sonar refers to the sensing and collection of acoustic signals emitted by entities or sources in the marine environment, such as ships, fish, and other sea creatures [2,62,93]. The detection of target objects, such as marine lifeforms and other underwater events using monitoring systems is essential to understand the aquatic environments and their characteristics. UWAC is an established field [91] that employs advanced technologies today. Its applications vary depending on objectives and areas of interest, including military and civilian communications, biological research, underwater resource detection, and bathymetry, among others [62,91]. Consequently, communication interferences between UWAC and sonar detection systems have been reported [94].

In contrast, active sonar involves the emission of a sound wave by an observer, which then detects the echo of the emitted signal to identify the target that reflected the signal sent from the observer’s device [28,93]. Active SONAR, or active acoustics, works similarly to LiDAR and Radio Detection and Ranging (RADAR), but uses sound waves instead of light or radio waves, involving transmitting sound waves into the water column and analysing the echoes that return [28]. The active acoustics method enables precise mapping of sea floors, scanning underwater landscapes, and detecting objects and lifeforms [28,92]. To improve the accuracy of detecting and interpreting reflected signals, ML and DL techniques have become increasingly important [2,28,92,93]. By training these models with extensive data, systems can more effectively differentiate between target signals and environmental noise, leading to more reliable detection [2,28,92,93]. However, since active detection relies on sending a signal and receiving its reflection, errors can occur when the marine environment generates signals similar to those of the target [92]. This overlap makes distinguishing between them challenging, even with matched filters, potentially reducing detection accuracy [92].

The Doppler effect is another factor that can compromise the integrity of the radiated signal from a target [62,94]. The effect occurs when the distance between the sound source and the observer changes, resulting in a shift in frequency as perceived by the observer [62,94]. In underwater environments, the Doppler effect is commonly encountered due to the presence of numerous moving sound-emitting sources. Zhang et al. [94] describe two methods for correcting the Doppler effect: one method involves extracting Doppler coefficients by estimating the frequency change of a clockwise impulse signal using a notch filter [94], while the other method estimates the chirp rate change of a Linear Frequency-Modulated (LFM) signal using the Fractional Fourier Transform (FRFT) [94]. By correcting the Doppler effect, signals of interest can be accurately identified, thereby reducing detection errors.

UEFC is a novel method for underwater communication systems that utilises Electric Field (EF) radiation [75]. This approach is inspired by the natural communication methods of some species of fish, such as the African Mormyridae and the South American Gymnotiformes [19], which possess electroreceptor organs and generate electric organ discharges (EOD) [75]. Some electric fish species use weak EF for both communication and navigation. By mimicking this principle, researchers are developing systems that transmit data through EF in the water [75] known as UEFC. A software-based simulation by Esemann et al. [75] demonstrated a transmission link of 2 megabits per second over several meters using digital modulation in the 2 MHz frequency range. The proposed communication method aims to address the low range associated with attenuation, which is particularly relevant when large amounts of data are required, as seen in optical communication [75]. Lu et al. [95] reported a communication distance of 3.8 m using Binary Frequency Shift Keying (2FSK) modulation in the implementation of UEFC. When spread spectrum modulation was implemented, the transmission distance rose up to 8 m at a 1.2 Kbps data transmission rate [95]. However, when Binary Amplitude Shift Keying (2ASK) modulation was used, the transmission range was only 2.4 m [95]. Continuous research on UEFC is ongoing.

With current advances in AI, various ML classification methods are now widely used to extract valuable information through the application of SONAR [2,96]. Malfante et al. [2] covered several studies that have successfully implemented various ML models to classify bioacoustic signal types, achieving a classification accuracy of 96.9% using Support Vector Machine (SVM) and random forest [2]. The results demonstrate the feasibility of underwater acoustic classification for monitoring and surveillance purposes [2]. In [2], bioacoustics were classified based on fish behavioural sound types, such as impulsion, drums, roars, and quacks, referred to as positive classes. Negative classes were designated as Background and Unknown [2]. In [28], the study included both anthropogenic and bioacoustic signals, comprising 102 sounds. The two studies in sound types confirm that ML models do effectively classify underwater bioacoustic signals. In addition, other AI models have been successfully employed to automatically classify sound sources [97]. With more advanced methods, like Spiking Neural Network (SNN) inspired by brain and auditory systems, AI is gaining momentum for processing sounds emitted by marine life [97]. Before the adoption of ML and DL techniques for signal processing, traditional methods dominated the field. These methods, which include DSP and filtering techniques, are still used for identifying sound sources [98]. For instance, ref. [98] used DSP to recognise broadband hydroacoustic signals, with the signal being digitised via a microcontroller at 70 kHz with 12-bit resolution. By averaging the signal power in a sliding window and comparing it to a dynamic threshold, detection was achieved.

3.3. Applied Underwater Modulation Schemes

For the transmission of wireless signals, a technique known as modulation is widely implemented, which consists in wrapping the signal of interest around a carrier signal [99]. Furthermore, the modulated carrier (signal of interest plus carrier) is radiated through the medium from the transmitter to the receiver. The implementation of UWSNs employs various modulation techniques, with the choice of a specific type depending on the application requirements [100]. Common modulation methods used in underwater environments include Frequency-Shift Keying (FSK), Phase-Shift Keying (PSK), Orthogonal Frequency-Division Multiplexing (OFDM), spread spectrum techniques, pulse-based modulations, chirps, Coded Orthogonal Frequency-Division Multiple Access (COFDM), on-off keying, pulse position modulation, pulse width modulation, and digital pulse interval modulation.

Indriyanto et al. [101] demonstrated the use of FSK modulation on a 40 kHz acoustic modem with ultrasonic frequency, where a microcontroller, amplifier, and transducer were used to implement a UWSNs. The proposed system achieved a transmission rate of 1200 bps for sending a "hello world" message from the transmitter to the receiver. However, FSK supports only low data rates, making it unsuitable for AUVs, as well as audio and video streaming applications [101]. Indriyanto et al. [101] tested their proposed system in a pool, transmitting the signal between two transducers which illustrate all system components. At distances between 100 cm and 130 cm, the resulting Bit Error Rate (BER) was 0%, but at 150 cm and 170 cm, the BER increased to 6.2% and 35%, respectively [101]. These results highlight significant limitations on transmission distance between nodes, as the BER rises with increasing distance and BER measures the quality of a digital communication channel. It is a crucial indicator for assessing the performance of various systems, including telecommunications, wireless networks, and data storage. A lower BER indicates fewer errors in transmitted data. By monitoring BER, engineers and researchers can optimise system performance and ensure reliable data transmission.

Hamagami et al. [102] conducted a test-tank experiment using UVLC with PSK; based on the results, Hamagami et al. [102] proposed the use of UVLC drones employing PSK. Their approach utilised fast-blinking Light-Emmiting Diodes (LEDs) at the transmitter, with the pattern detected by the receiver's Complementary Metal–Oxide–Semiconductor (CMOS) image sensor using the rolling-shutter effect and subsequently demodulated [102]. Rolling shutter is a type of image sensor that captures a frame line by line, rather than all at once. Hamagami et al. [102] stated that the rolling-shutter effect is employed for baseband transmission, while PSK enables passband transmission [102]. Their experiments demonstrated superior PSK performance over On-Off Keying (OOK) modulation, especially when the carrier frequency exceeds the Noise Frequency (fn) [102]. In tests where the fn was 0, both BERs of PSK and OOK remained 0; however, as fn increased between 5 Hz and 1000 Hz, OOK exhibited significant BER, while PSK maintained a BER of 0, confirming its superior performance [102]. At a carrier frequency of 4.5 kHz and fn between 0 and 5 kHz, the transmission rate was 300 bps over a distance of 400 mm between transmitter and receiver [102]. Ali et al. [71] concurs that UVLC is a potential futuristic optical candidate for systems requiring high rate and low latency. However, short distance transmission, severe attenuation, and susceptibility to water turbulence are some drawbacks of Visible Light Communication (VLC) [71,102]. Furthermore, application of UVLC in 5G IoUT technologies produced promising results—up to a 1 Gbps data transmission rate [71]. Due to the absence of interference, compared to RF, in places where RF is less implemented such as in medical fields, oil rigs and gas plants, nuclear power plants (NPPs), underwater communication, and further numerous applications, UVLC succeeds [71]. In addition, Wang et al. [76] conducted tests with UVLC systems and the results showed a transmission distance of 440 m at a data rate of 50 Mbps with the average power of 100 W. However, the authors demonstrated the potential for reaching a distance of up to 500 m in pure sea water [76].

The underwater channel is in constant and unforeseeable transitions due to turbulence, changing temperature, pressure, density, turbidity, salinity, etc. Channel instability imposes limitations on communication reliability, signal integrity, and transmission quality [5,103]. Stationary modulation solutions are increasingly replaced by dynamic ones to address underwater channel variability and unpredictability [5,103]. Busacca et al. [5] introduced three approaches to mitigate channel changes: model-based, algorithm-based, and ML approaches. Both algorithm-based and ML approaches show larger generation features because they do not require characterisation of the channels. However, ML models require large datasets of Channel State Information (CSI). Adaptive Modulation (AM) using OFDM for underwater communication has been shown to improve resiliency, as reported in [5,103]. Busacca et al. [5] reported three AM approaches, namely Adaptive Modulation and Coding (AMC), Adaptive Resource Allocation (ARA), and Adaptive Transmission and Coding (ATC). These AM methods optimise resource utilisation and power efficiency and reduce transmission errors. AMC is an AM technique used in wireless communication systems to dynamically adjust the modulation scheme and coding rate to optimise performance based on the current channel conditions [5]. AMC allows for efficient and reliable data transmission, especially in wireless environments that are prone to fading and interference. ARA is an AM technique used to optimise resource utilisation in dynamic systems [5]. It involves dynamically adjusting the allocation of resources like CPU, memory, bandwidth, or power, based on real-time system conditions and performance requirements [5]. In UWSNs, ARA involves adjusting transmission power, modulation schemes, and channel allocation to optimise network performance. ATC is an AM method that adjusts the transmission scheme to the current channel conditions, allowing more efficient transmission over time-varying channels [5]. ATC offers several benefits: it (i) performs channel estimation, (ii) adjusts the transmission scheme based on the channel characteristics, (iii) adjusts to compensate for changing channel conditions, such as fading during stable or unstable channel periods, (iv) increases average throughput by taking advantage of favourable channel conditions, (v) reduces the required transmit power, and (vi) reduces the average probability of bit error [5].

In addition to adaptive techniques, Busacca et al. [5] also introduced predictive techniques to enhance the performance of UWAC systems, which are extensible to other UWC systems. Predictive techniques are proactive approaches that aim to predict the future state of communication channel conditions using historical observations, allowing better planning and resource allocation [5]. By anticipating future channel conditions, predictive modulation schemes can help avoid the need for retransmissions, thereby saving energy and extending the operational lifetime of underwater nodes [5].

ML-based models are increasingly implemented. Busacca et al. [5] reported ML-based adaptive and predictive techniques such as supervised, unsupervised and reinforcement learning. Models trained on labelled dataset are termed supervised learning, such as decision tree, linear regression, Data-Driven Sparse Learning (DDSL), SVM, Neural Networks (NNs) [5]. Unsupervised learning is an ML technique where algorithms learn patterns from unlabelled data without explicit guidance [5]. Unlike supervised learning, which requires labelled data to train a model, unsupervised learning algorithms discover hidden structures and relationships within the data itself [5]. Linear regression is a statistical method used to model the relationship between a dependent variable and one or more independent variables. Decision trees are tree-like models used to classify or predict outcomes. While decision trees make decisions based on a series of rules, linear regression assumes a linear relationship between the variables and aims to find the best-fitting line. DDSL focuses on finding sparse solutions to complex problems. It involves learning a model with a small number of non-zero parameters, leading to more interpretable and efficient models. SVMs are a powerful algorithm used for classification and regression tasks. They work by finding the optimal hyperplane that separates data points into different classes. NNss are inspired by the human brain and are composed of interconnected nodes called neurons. They are used for a wide range of tasks, including image recognition, natural language processing, and speech recognition.

OFDM is a popular modulation scheme used in 4th Generation (4G) technology due to its robustness against Inter-Symbol Interference (ISI) and its high spectral efficiency. These qualities make OFDM a suitable candidate for UWOC. Lian et al. [61] have explored various OFDM-based techniques for UWOC, including (i) Direct Current Biased Optical Orthogonal Frequency-Division Multiplexing (DCO-OFDM) that excels in high bit rate transmission scenarios; (ii) Asymmetrically-Clipped Optical Orthogonal Frequency-Division Multiplexing (ACO-OFDM) offers a balance between performance and complexity; and (iii) Unipolar Orthogonal Frequency-Division Multiplexing (U-OFDM), which provides longer transmission range with lower power consumption. Another promising modulation technique for UWOC is Single-Carrier Frequency Division Multiple Access (SC-FDMA), which offers a lower peak-to-average power ratio [61]. By understanding the strengths and limitations of these modulation techniques, researchers can design efficient and reliable UWOC systems.

Spread spectra are widely used modulation schemes both for civilian and military applications [34]. They are used as a mitigation technique to reduce acoustic source emissions that affect marine lifeforms by spreading the signal energy over a wide bandwidth; the spread spectrum operates at low SNR, reaching ranges greater than 10 km [34]. Bioacoustics studies have proven animal discomfort and bio-intrusion reduction provided by this method [34]. The simulations they performed resulted in transmission rates of 45 bps at -18 dB SNR and 140 bps at -12 dB SNR [34]. The white noise-like features, near-orthogonal band-limited Pseudo-Noise (PN) codes provided by M-ary Orthogonal Code Keying (M-OCK) and Binary Phase Shift Keying (BPSK) modulations of the spread spectrum have been demonstrated to possess a diminished impact on marine life compared to transmission that has tonal, chirp, or burst characteristics [34]. The spread spectrum approach also effectively overcomes the Doppler effect because it is equipped with an enhanced error correction mechanism, multipath ISI correction, while performing frame synchronisation, and it is able to combine multipath signals [34].

The spread spectrum method consists of spreading the signal over a large frequency band, resulting in increased resistance to natural interference, noise, and jamming or obstruction [104]. By lowering the signal per-Hz density due to the large bandwidth, the spread spectrum method prevents signal detection while limiting power influx density. Through the spread spectrum method, various signals can be combined over the same band, giving rise to multiple-access communications [104]. The variability of the underwater channel causes a shift in the frequency profile of the target signal across the underwater channel. The effect is known as the Doppler effect, which can cause ISI to make the signal hard to demodulate, leading to degradation of the quality of the received signal. That is why mitigation techniques to overcome the Doppler effect are crucial to enable a quality communication system. In addition to the spread spectrum, methods such as AMC, synchronisation, channel encoding, and time-frequency synchronisation are used to mitigate the Doppler effect [5,81].

Sherlock et al. [34] reported a resemblance between FSK and the M-OCK modulation based on bandwidth spreading and message duration. Identical to OFDM, COFDM implements orthogonal code in its modulation and is used as a digital multi-carrier modulation scheme, wherein Forward Error Correction (FEC) is applied before signal transmission [105]. The goal for applying FEC is to overcome errors during transmission [106]. Several other types of modulation are applied to underwater communications, such as Fully Generalised Spatial Modulation (FGSM) [107], Multiple-Input Multiple-Output/Orthogonal Frequency Division Multiplexing (MIMO-OFDM) [108], and Amplitude Shift Keying-Orthogonal

Frequency Division Multiplexing (ASK-OFDM) [109]. ASK-OFDM is a modulation scheme that combines Amplitude Shift Keying (ASK) and OFDM. ASK-OFDM utilises ASK modulation on each subcarrier of an OFDM system. This allows for efficient use of bandwidth and improved spectral efficiency, and it is useful in scenarios with limited bandwidth and noise interference, such as the underwater channel.

MIMO-OFDM as a modulation scheme has several benefits, namely (i) high data rate by exploiting spatial diversity and frequency diversity [108], (ii) improved reliability by offering more robustness to interference and fading [108], and (iii) with better spectral efficiency, it can efficiently utilise the available spectrum [108]. MIMO-OFDM find applications in modern wireless communication systems, such as Wireless Fidelity (Wi-Fi) (both 802.11n [110] and 802.11ac standards [110]), cellular networks (4G and 5th Generation (5G) cellular technologies) and wireless broadband (Worldwide Interoperability for Microwave Access (WiMAX) and Advanced Long-Term Evolution - Advanced (LTE-Advanced)). Quiao et al. [108] reported that although MIMO-OFDM has been used for over two decades in air-based wireless communication, it is a novelty in UWAC that necessitates improvements. Nevertheless, basic MIMO-OFDM systems can employ null and pilot carriers for Doppler and channel estimation in the underwater domain [108].

There are several challenges for implementing workable modulation schemes. Water enables variable propagation speed due to factors such as temperature, salinity, and pressure, which complicate accurate timing and synchronisation [5,21,81]. Propagation speed impacts the efficiency of communication protocols, especially those relying on quick feedback mechanisms [5,21]. Acoustic signals are rapidly absorbed by water molecules and scattered into multipaths by particles in the water [45,74,81]. Both scattering and absorption limit the effective communication range. Higher frequencies attenuate more rapidly than lower frequencies, influencing the choice of modulation schemes [34,61]. In the case of multipath propagation, signals reach the receiver via multiple paths, which can lead to ISI, distortion, and increased delay spread. When it comes to ISI, it can degrade the quality of received signals, making it difficult to recover the original data [5,81]. Another challenge is the Doppler shift, or Doppler effect, which is a phenomenon observed where frequency shift occurs [5,34,81,94]. The relative motion between the transmitter and receiver causes a Doppler shift in the received signal frequency. The Doppler effect can impact the performance of coherent modulation schemes. In reference to noise, whether thermal from electronic systems such as underwater acoustic transceivers or ambient noise from marine life, shipping traffic, and ocean currents, it interferes with signal reception [5,21,81].

3.4. Underwater Wireless Communication Protocols

To account for the variability in underwater channels, robust communication protocols are implemented to ensure communication link stability [60]. A well-designed protocol must provide robustness, efficiency, and low latency [60]. Robustness enables signalling techniques aimed at resiliency to high bit error rates and multipath events to maintain communication links [5,60,108]. Efficiency refers to the optimal utilisation of limited resources and low latency refers to timely signalling, which are critical for data transmission coordination [60].

Various types of protocols are currently used in underwater communication systems. Pompili et al. [60] reported the following classes of protocols: Medium Access Control (MAC), routing, transport, and cross-layer networking protocols. MAC protocols make efficient use of available bandwidth; Aloha-based MAC protocols improve collision avoidance. These features make them suitable for underwater acoustic sensor networks [60]. Two Aloha-based MAC protocols are discussed in [60]: Aloha with Carrier Sense (CS) (Aloha-CS) and Aloha with Advanced Notification (AN) (Aloha-AN). Underwater Medium Access

Control (UW) (UW-MAC) is a distributed single-carrier solution utilising Code-Division Multiple Access (CDMA) to enable multiple access to limited underwater bandwidth, keeping low complexity of resource-limited transceivers.

In [60], three categories of routing protocols are identified for general applications, namely proactive, reactive, and geographical, to meet specific resiliency needs. Examples of proactive routing protocols are Destination-Sequenced Distance Vector (DSDV), and Optimised Link State Routing Protocol (OLSR), which are unsuitable for underwater applications due to unscalability [60]. As for reactive routing, Ad-hoc On-demand Distance Vector (AODV), and Dynamic Source Routing (DSR) are listed; however, these are advised against due to high latency [60]. The geographical routing approach, namely Greedy Face-Greedy (GFG), and Partial-Topology Knowledge Forwarding (PTKF), is scalable and requires limited signalling [60]. Both GFG and PTKF protocols work by node geographical coordinates to establish forwarding decisions and are suitable for large-scale underwater network applications due to reduced energy consumption, reduced delay, and throughput optimisation features [60].

With regards to transport-layer protocols, they are relied on for the provision of reliable data transport, flow and congestion control, and end-to-end communication management across the nodal networks [60]. Furthermore, ref. [60] states that Transmission Control Protocol (TCP) is not a suitable protocol applicable to the underwater environment due to its requirement to have an accurate estimate of the Round Trip Time (RTT), recommending new designs that offer adaptation, control, and reliability. TCP is one of the core protocols of the Internet Protocol Suite (TCP/IP). TCP responsible for providing reliable, ordered, and error-checked delivery of data streams between applications running on different hosts. On the other hand, RTT is a crucial metric in TCP communication. RTT measures the time taken for a packet to travel from the sender to the receiver and back. RTT measurements include the transmission time, propagation delay, and processing time at both ends. To mitigate the RTT limitations of the TCP, Su et al. [111] introduced the Optimal Re-transmission Timeout (RTO) Interval stop-and-wait Transmission (ORIT) protocol. The ORIT protocol incorporates a reduced RTO, shorter than the RTT to increase transport efficiency [111]. The ORIT's interval stop-and-wait transmission mechanism is designed to ensure re-transmission is stabilised based on preceding transmission results to increase data delivery assurance in a narrow acoustic channel [111]. The main design objective of the ORIT protocol is to maximise the goodput, the ratio between delivered data per unit of time, tackling the long propagation delay and narrow channel bandwidth constraints [111]. Furthermore, cross-layer protocol design is referenced as a way to improve performance in wireless networks, particularly in rough conditions similar to the underwater medium [60]. Pompili et al. [60] make reference to a modular cross-layer communication solution for underwater multimedia applications that merges MAC, routing, and physical functionalities.

Pompili et al. [60] reported various challenges for implementing protocols in underwater wireless communications, as follows: (i) severely impaired acoustic channel—the underwater acoustic channel is affected by time-varying multipath and fading, which complicates reliable communication [5,60,94,108]; (ii) limited bandwidth—the available acoustic bandwidth is highly dependent on transmission distance, with only a few kHz available at long distances due to high environmental noise and medium absorption [5,60,61,111]; (iii) high propagation delays—the propagation delay in underwater environments is significantly higher than in terrestrial channels, which can lead to increased latency in communication [60,62]; (iv) high BER—underwater communication can experience high bit error rates and temporary losses of connectivity, often referred to as shadow zones [60,101,102]; (v) device failures—underwater devices are prone to failures due to fouling and corrosion, which can affect their operational reliability [60]; (vi) energy constraints—batteries used in underwater devices are energy-constrained and cannot be easily recharged, limiting the operational time of these devices [5,60]; (vii) localisation challenges—accurate localisation of nodes is difficult due to the lack of Global Positioning System (GPS) functionality underwater, necessitating alternative localisation schemes [5,21,60]; and (viii) mobility issues—the mobility of nodes can lead to outdated information, decreasing the packet delivery ratio as mobility increases [5,60,108]. These challenges require the development of specialized communication protocols that can effectively address the unique conditions of underwater environments.

4. USWN Applications

The USWN, a UWC technology, is a network of autonomous sensor nodes [5,21,60]. It combines smart sensing, intelligence computing, and communication capabilities, enabling underwater scientific and commercial explorations, coastline protection, pollution monitoring, water-based disaster prevention, and water-based recreational activities [21]. Considering that numerous resources lie underwater, UWSNs make it possible the explorations of underwater environments that were recently inaccessible [21,60]. Several applications are found for UWSNs besides in mineralogy [21,60]. USWN technologies are implemented in the monitoring of marine, riverine, and lacustrine lifeforms, as well as the conditions of these environments [21,60]. Sensing turbidity, temperature, density, pressure, water currents and quality, conductivity, pollutants, object tracking, ecosystem modelling, and species classification are some of the key functions made possible by UWSNs [21,60]. In a USWN, a set of nodes transfer their data to buoyant nodes known as gateways that relay the data to the nearest remote station, a coastal monitoring and control station [21].

In UWSNs, sensor nodes are classified as static or stationary and mobile [5,21,60]. Table 8 lists the types of UWSNs and their applications and constraints. A combination of the two classes can be implemented in the same sensor network fulfilling distinct requirements, such as transferring various events of interest [21,60]. Vasilescu et al. [7] applied a sensor network comprised of node-to-node high-speed optical communication with the aim of monitoring corals and reefs. The experimentation has been conducted in pools, rivers, and oceans [7]. They incorporated acoustic protocols into the TinyOS stack to broadcast the network. The nodal points are equipped with various types of sensors to capture pressure, temperature videos, and images [5,7,21]. The mobility of the mobile nodes is used for locating and hovering over static nodes for "data muling" and other maintenance tasks such as recovery, deployment, and relocation [7].

Table 8. Sensor networks modalities and applications [21,98].

Sensor Network Type	Applications	Challenges
Static Sensor Networks	Monitoring water quality, turbidity, temperature, density, pressure, currents, pollutants, and ecosystems.	Power consumption, deployment, maintenance
Mobile Sensor Networks	Object tracking, species classification, data muling, recovery, deployment, and relocation.	Power consumption, mobility limitations
Hybrid Sensor Networks (Static and Mobile)	Combines the advantages of both types.	Power consumption, coordination

Various USWN architectures are implemented, namely One-Dimensional (1D), Two-Dimensional (2D), Three-Dimensional (3D), and Four-Dimensional (4D) [21]. These four architectures reflect the way data are conveyed from underwater sensing to reception at the remote station [21]. The 1D-USWN architecture is characterized by a star topology, and transmission of data from a stand-alone sensor node to a remote node is accomplished in a single hop [21]. An example of a 1D-USWN is the application of AUVs which dive underwater, sense and retrieve data, and relay to the remote station [21]. The deployment of 1D-UWSNs is autonomous and each node is a stand-alone network itself, tasked to sense, process, and transmit data to the remote station [21]. The 1D-UWSN architecture can be as simple as a floting buoy capable of sensing underwater properties and can use UWOC, UWAC, or RF communication systems [21].

The 2D-USWN architecture features a cluster of nodes, including one which is the anchor node or cluster head, which is responsible for gathering the data or information from every sensor node in the cluster and sending them to the buoyant gateway node. In the 2D-USWN, the sensing nodes gather data and send them to the cluster head horizontally (first dimension), and the cluster head, which acts as a data hub, sends the data to the buoyant node vertically (second dimension) [21]. In the 2D-USWN architecture, the transfer of data between the cluster node and the buoyant node is preferably implemented using an acoustic signal due to its long-range capability and communication can be established across sensing nodes via RF, UWOC, and UWAC systems, depending on performance requirements [21]. In 2D-USWN architectures, applicable topologies can be mesh, star, or ring [21]. In 3D-USWN network architecture, the deployment of sensors is in the form of clusters anchored at varying depths [21]. This fact adds dimensions to inter-node communication [21].

Felemban et al. [21] reported that there are three communication scenarios for the 3D-USWN architecture: "(i) inter-cluster communication of nodes at different depths, (ii) intra-cluster (sensor-anchor node) communication, and (iii) anchor-buoyant node communication" [21]. In any of the three scenarios, either UWAC, RF or UWOC communication links can be deployed [21]. Finally, the 4D-USWN architecture is fundamentally like the 3D-UWSNs with the addition of a mobile USWN node such as an AUV, an ROV, a ship, or a submarine [21]. The mobile node collects data from various anchor nodes using RF or acoustic communication depending on the distance of separation between the anchor nodes and the mobile node [21]. Long distance of separation requires acoustic transmission, while shorter range RF can be launched [21].

Felemban et al. [21] expanded on the applications of UWSNs in different underwater domains, such as ocean monitoring, aquatic environment tracking, resources detection, deep sea surveillance, and mine detection and avoidance. With regards to monitoring, Felemban et al. [21] detailed specific projects where UWSNs are successfully implemented in water quality analysis, habitat and marine life monitoring, applications in fish farms, coral reefs, underwater exploration, natural resource detection, marine cable and pipeline detection and monitoring, disaster monitoring and prevention, and flood alert systems. In addition, Felemban et al. [21] also delved into military applications where cameras, imaging sonars, and metal detectors are integrated with AUVs to locate mines and to secure ports, submarines, and other assets of interest.

Felemban et al. [21] concluded that despite the continued progress in USWN technologies, several challenges still remain unsolved, namely the unpredictable underwater environments, requirements for intricate USWN designs and challenging deployments and the difficulties in scaling existing solutions, power efficiency, and repair operations [21]; these observations are shared by Pompili et al. [60] and Busacca et al. [5]. Small-scale networks or single-hop solutions are still prevalent, and this scenario demands more innovative and scalable solutions to meet the implementation needs. Unreliable information due to continuous changes in water currents also poses a great challenge [21]. New protocol designs applicable to underwater media constitute an opportunity for new and innovative ideas [5,21,60]. Underwater communication seeks improvement in data rates, cost reduction, and devising solutions that prolong physical equipment lifetime [21]. Underwater conditions such as algal deposits on camera lenses and salt accumulation on hardware cause rapid degradation of USWN equipment [5,21,60].

Underwater media require dedicated protocols to ensure data transmission integrity and reduced BER. In other words, the underwater signal transmission still copes with the variability of the underwater channel and the physical properties of water. Although adaptation and prediction mechanisms have proven benefits and improved performance, they come with trade-offs, such as hardware power consumption, computation power requirements, and delay due to increased computation [5,21,60]. Although the application of ML and DL has shown robustness and reliability for signal transmission, the cost of implementation increases due to the need for specialised hardware and experts in ML and DL for the implementation of channel-aware edge cognitive devices.

The underwater world is vast and always more can be reported. More can be reported on protocols for underwater communication, and new models applicable to and efficient for underwater communication are needed; modulation schemes that reduce BER and guarantee reliable data transmission are continuously under investigation;. Novel underwater communication modalities will continue to emerge that reduce power and improve both hardware and communication resiliency. The following section summarises the impact of technologies on the underwater environment, both the positive applications and the negative footprints, recommending ways in which we should deal with nature for symbiotic co-existence.

5. Conclusions and Future Directions

Aquatic ecosystems are delicate and shelter 78% of animal life on Earth [9,22]. This fact alone demands greater intervention by governmental bodies to safeguard the diversity of the global animal kingdom in marine, riverine, and lacustrine waters. The Marine Conservation Institute (MCI), an ocean advocate, estimated that less than 3% of the oceans is effectively protected [20]; the organisation advocates for 30% of the oceans to be protected to guarantee the protection of marine biodiversity and secure ocean resiliency [20]. Ecosystems are sensitive to harmful human activities, such as noise pollution, vibrations, and disturbances caused by underwater industries, technologies, and infrastructure [1,3,20]. An anthropogenic activity inevitably brings water movements that alter the pressures, temperatures, and water quality of organic habitats. The changes result in migrations of fishes, mammals, invertebrates, and other life forms. Unfortunately, animal biomass with limited mobility tends to sustain the damage at a cost of DNA damage, reproduction reduction, and finally their demise and probably extinction [1]. Awareness of the impact of human interference in the seas, oceans, rivers, lakes, and other water formations enables the instrumentation of rigorous laws and regulations that aim at preserving ecosystems and the organisms therein [1,20]. Table 9 gives an overview of the impacts of human activities on underwater domains, and mitigation strategies are also presented. Significant efforts have been made to protect aquatic lifeforms and their habitats [32]. Although the laws, regulations, and recommendations have been written, compliance has not been verified as written. Increasing marine activities, for example, leads to rapid increases in environmental footprints despite the tentative efforts aimed at reversing them [1]. Tighter inspections are observed to be needed and harsher sanctions are required.

Overall, pertaining to the impact of technologies on underwater ecosystems, it is a double-edged sword. While noise pollution caused by acoustic, optical, and EM technologies have been confirmed to cause irreparable damage to aquatic organisms [1,3], technologies can aid in the mitigative efforts to not only monitor underwater environments but to help solve natural changes that may impact the waters and their inhabitants. The reduction in noise pollution through technological improvements requires changing modulation schemes to reduce signal spectral density [26,33] and frequency bands for acoustic, optical, and EM technologies. In relation to optical communication, it has been concluded that infrared light does not interfere with fishes, contrary to other optical ranges which have been shown to scare fish away or to attract them, altering as a result the habitat. Infrared is then recommended for use in optical communication, even though this optical range implies relatively higher absorption in underwater environments compared to blue to violet light.

Table 9. A summary of the key impacts of human activities on aquatic ecosystems and potential mitigation strategies. The specific impacts and appropriate mitigation measures may vary depending on the location, type of activity, and ecosystem characteristics [1,3,26,28].

Human Activity	Impact on Aquatic Ecosystems	Mitigation Strategies
Noise pollution (from underwater industries, technologies, and infrastructure)	Disrupts communication, navigation, and reproduction of aquatic organisms; can lead to DNA damage, reduced reproduction, and extinction.	Reduce noise pollution through technological improvements (e.g., changing modulation schemes, and frequency bands); implement stricter regulations and enforcement.
Vibrations (from underwater industries, technologies, and infrastructure)	Can disrupt aquatic organisms' behaviour and physiology.	Minimise vibrations through technological advancements and regulations.
Disturbances (from underwater industries, technologies, and infrastructures)	Can alter water movements, pressures, temperatures, and water quality, leading to habitat degradation and species displacement.	Implement environmental impact assessments and mitigation measures before undertaking new projects.
Overfishing	Depletes fish populations and disrupts marine ecosystems.	Implement sustainable fishing practices, establish marine protected areas, and enforce fishing regulations.
Pollution (from industrial and agricultural runoff, plastic waste)	Contaminates water, harms aquatic organisms, and degrades ecosystems.	Reduce pollution at the source, implement wastewater treatment, and promote sustainable practices.
Climate change	Raises sea levels, alters ocean temperatures, and acidifies oceans, affecting marine biodiversity and ecosystems.	Reduce greenhouse gas emissions, promote renewable energy, and adapt to climate change impacts.

Furthermore, underwater communication is essential for scientific exploration and the livelihoods of countless industries and individuals. Despite the negative impacts imparted by anthropogenic activities in aquatic environments, technologies are aiding in monitoring the oceans with the implementation of IoUT, robust sensor networks, and AUVs [2,112]. Bio-inspired monitoring systems such as Smart Plankton enable the creation of robust node-to-node communications that improve monitoring system designs [112]. IoUT systems equipped with ML computation facilitate the acquisition of valuable information on the marine world [96], such as water currents, water composition (salinity levels), the quantity of marine life, temperatures, pressures, oxygen levels, noise pollution levels, and other footprint levels with reduced power and emissions footprints.

The UN's SDGs are long-term commitments targeted for 2030 [30]. As the deadline approaches, law agencies are hoping to tighten their law-enforcement strategies. Protectionist groups such as the ONC have recommended several restrictive measures and standards to regulate acoustic and non-acoustic noise in oceanic environments with the sole purpose of protecting the marine environment [104]. Spread spectrum and time reversal are just some of several LPD (low probability of detection) methods employed with the objective to minimise signal power spectral density [104]; these methods minimize underwater lifeforms' exposure to signal emissions.

By implementing networks of sensors and robust intelligent systems using ML or DL models [2,5,28,96] for acoustic target detection, underwater ecosystems can be reliably monitored. Experts can then take informed decisions to mitigate marine environmental concerns. Noda et al. [28] and Malfante et al. [2] reported a 94% and 96.9% classification accuracy of four species of dolphins using K-Nearest Neighbors (KNN) and SVM classifiers. These results demonstrate the feasibility of using these technologies for monitoring aquatic life.

Finally, three major challenges remain: minimizing the environmental impact of underwater communication technologies (UWOC, EM and UWAC) and heavy machinery, improving the accuracy of anthropogenic emissions measurements, and enforcing regulations more strictly for the protection of underwater biodiversity and aquatic ecosystems.

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