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Survey of Advancements in Underwater Wireless Communication Technologies

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Abstract— Analyzing six separate studies, this study examines the current state of underwater wireless communication. Examples of the scope of innovation covered in these case studies include hybrid wired/wireless network architecture designed for energy-efficient 5G networks and wireless communication in underwater and open-air environments. This have identified the most promising and efficient methods for establishing wireless connections underwater based on the analysis of these studies. The design of hybrid fiber-wireless access networks and the use of TENGs have the potential to revolutionize the future of underwater communication. This paper details the methods by which modern technology is advancing underwater wireless communication and finding solutions to the obstacles it confronts, making it an invaluable resource for keeping apprised of the latest developments in this vital area.

Keywords— Underwater Wireless Communication, Triboelectric Nanogenerators (TENGs), 5G Networks, Power Consumption Reduction, Offshore Exploration, Acoustic Communication.

I. INTRODUCTION

In recent years, advancements in underwater wireless communication have enabled a multitude of new applications in disciplines such as environmental monitoring, ocean research, and the offshore economy [1]. This comprehensive overview explores in depth six key studies that have significantly contributed to the development of underwater communication technology and provides a window into the cutting edge of this dynamic field [2]. The importance of this research lies in its ability to offer a comprehensive review of innovative solutions, evaluate their applicability, and assess their potential to address the particular problems of underwater wireless communication [3].

Triboelectric nanogenerators (TENGs) are currently the subject of study as a potential energy source for underwater communication devices [4]. Due to their adaptability in accumulating energy from a variety of mechanical energy sources, TENGs have emerged as a viable option for resolving power issues in underwater environments. The generation of electricity from water waves, sound waves, and water movement is a novel concept that has been thoroughly investigated.

This study has also prioritized the development of theoretical models for long-distance optical communication under water [5]. The focus of these simulations is the difficulty of optical communication at depth, where oceanic turbulence presents a substantial barrier. Temperature, salinity, and other environmental conditions must be taken into account when developing models that accurately reflect the numerous factors influencing the propagation of optical signals over long distances [6]. Underwater and open-air wireless communication case studies have made substantial contributions to the understanding of signal propagation dynamics [7]. The primary conclusion of these studies is that it is essential to comprehend the behavior of wireless communication modules at varying depths. The designers and operators of secure underwater communication networks must account for this depth-dependent communication behavior [8].

To further reduce the energy requirements of 5G systems, a novel hybrid wired/wireless network architecture is proposed [9]. This concept employs fiber-optics, micro cells, and heterogeneous networks to optimize energy efficiency without sacrificing data transmission rates or reducing latency. All of these studies demonstrate that in order to satisfy the energy demands of 5G networks, low-power solutions must be considered. These findings not only enhance the comprehension of wireless communication in the ocean, but also provide novel insights with the potential to pave new ground. These findings highlight the need for additional research and implementation of sustainable energy sources, improved communication networks, and theoretical models that reflect the complexities of underwater communication adequately [10].

This study summarizes the promise and excitement surrounding underwater wireless communication devices. It's a guide for navigating the sea of new technologies that are revolutionizing the ability to investigate the deep sea and keep a watch on what's happening below. These studies contribute significantly to the ongoing research on safe and dependable underwater communication. This study seeks to cast light on the collaborative efforts and discoveries that will pave the way for more efficient and effective underwater wireless communication, thereby facilitating deeper exploration of the ocean's depths and pushing the limits of what is possible in this crucial area.

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II. Proposed Reviews

Zhao et al [11] Using TENGs to produce Maxwell's displacement current for wireless data transmission beneath the surface of the water. Design and construction details for many additional varieties of TENGs are provided as well, including a hybrid resonant TENG (HR-TENG), a voice-activated TENG (V-TENG), a button-type TENG (B-TENG), and a single-layer TENG (S-TENG). Similar to the voice-activated TENG, the HR-TENG can utilize the kinetic energy of water waves to generate electricity. The button-type TENG converts mechanical pressure most efficiently, whereas the S-TENG converts the kinetic energy of moving water. Also included is information on how to construct a vessel using five parallel-connected S-TENG units to generate in-phase AC electricity. The vessel is designed to provide power to a wireless communication module when submerged. Using a Keithley 6514 electrometer, the scientists conducted experiments to measure the signals transmitted by the TENGs and the buoy. On an optical panel were affixed a JBL speaker and an HR-TENG powered by sinusoidal waves from a function generator. The results of the experiments demonstrated that TENGs can harvest mechanical energy from sound waves, water flow, and water motion. In response to a 1 Hz sinusoidal wave with an amplitude of 0.5 cm, the maximal output voltage and current of the HR-TENG were measured to be 1.2 V and 0.2 A, respectively. When exposed to a 1 kHz sound wave at an 80 dB sound pressure level, the greatest voltage and current outputs from the voice-activated TENG were 0.8 V and 0.1 A, respectively. The conclusion of the study proposes the use of TENGs to generate electricity from a wide array of mechanical energy sources as a novel solution for wireless underwater communication. The authors' experiments demonstrate the viability of this strategy, paving the way for future study in this area. The scientists also evaluated the buoy's efficacy as a power module for underwater wireless communication. Using commercial underwater acoustic communicators (Teledyne Benthos ATM-900-4A), a communication link was established between two buoys at a distance of one meter. In other words, the buoy was able to consistently power the underwater acoustic modem, which enabled the transmission of signals between the buoys. As a novel approach to wireless underwater communication, the research proposes using TENGs to generate electricity from a wide variety of mechanical energy sources. Experiments conducted by the authors demonstrate that the approach is effective, paving the way for future research in the field. The results demonstrate that TENGs are capable of generating a significant amount of energy from acoustic and hydrodynamic sources, and that a vessel with five parallel-connected S-TENG units could provide stable electricity for wireless data communications beneath the waves. This research has the potential to significantly alter the course of undersea communication by developing a sustainable and reliable power source. Fig 1 illustrates the modulation and demodulation of current signals for underwater data transfer.

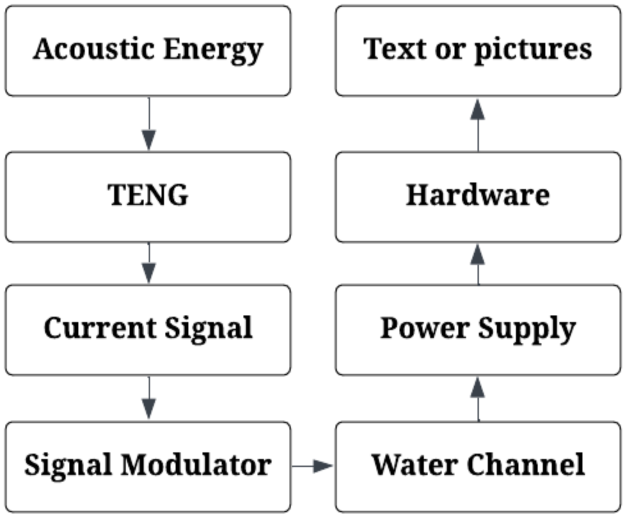

Fig. 1. Modulation and demodulation of current signals for data transmission in water

Vivekananthan. V et al [12] that by developing a sustainable, long-lasting, and reliable triboelectric nanogenerator (SE-TENG) to create an active pressure sensor with zero power consumption. The device is intended to convert mechanical energy into electrical current in order to operate electronics that do not require a lot of power. The SE-TENG was taken through its trials in terms of real-time output analysis, impedance matching, local power density, and dependability. Real-time measurement results confirmed that the SE-TENG device is capable of maintaining a constant electrical output over an extended period of testing. The device was able to withstand mechanical duress without losing electrical output, hence it passed the durability test. The ability of the SE-TENG device to charge capacitors efficiently validated the technology's claims. The cyclic charging and discharging characteristics of a 1 mF capacitor were measured to determine its charging/discharge efficacy. The maximum area power density of the SE-TENG device at a 1 GU load resistance is 17 mW m-2, as determined by instantaneous area power density testing and impedance matching analysis. Throughout the duration of the two-minute measurement, SE-TENG's power output remained constant. The fact that sixty green LEDs wired in series illuminated proved that the device could power low-power circuitry. Among other disadvantages, the efficacy of triboelectric nanogenerators (TENGs) degrades when they come into contact with water. Variations in humidity degrade the stability and efficacy of TENGs due to the decrease in surface charge generation. The problem was fixed by hermetically encapsulating the SE-TENG to prevent

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moisture from interacting with the triboelectric layers. The proposed research in the PDF demonstrates that SE-TENG can effectively power low-power devices. Not only is the device effective at storing electrical energy, but it also has a consistent electrical output and can withstand mechanical pressure. With a maximal area power density of 17 mW m-2 at a resistance of 1 GU, the SE-TENG is a substantial improvement over earlier TENGs.. The device is significantly more water-resistant than previous TENGs. The research proposed in the attached PDF demonstrates a highly dependable, indestructible, and sustainable triboelectric nanogenerator (SE-TENG) that could function as an active pressure sensor with no external power source required. It has been rigorously examined for power density in its immediate surroundings, impedance matching analysis, durability, and energy storage capacity. Based on the results, SE-TENG appears to be a promising energy source for low-power electronics. The device is resistant to mechanical stress, has a constant electrical output, and is able to store energy effectively.

Schirripa Spagnolo, G et al [13] that the proposed study aims to create a theoretical model that faithfully represents underwater long-distance optical communication. Due to the lack of a model for oceanic turbulence, which is defined as variations in the index of refraction caused by changes in temperature and salinity, this remains the greatest barrier to the widespread adoption of an underwater optical communication system. Using a function with two exponentials, the model will account for the attenuation of light caused by variables such as the concentration of dissolved and in-suspension materials in turbid harbor waters to more precisely estimate the power loss for long distance underwater channels. After taking into account the impact of propagation through modest oceanic turbulence, the Monte Carlo method will be used to evaluate the efficacy of the optical communication system. The model will account for the light attenuation caused by planktonic materials, detritus, and mineral components, as well as the concentration of dissolved and suspended items. The PDF contains a table with the attenuation coefficients for various varieties of water. According to Beer's Law, the propagation loss factor (LP) is frequently described in terms of wavelength and distance. This criterion does not account for non-line-of-sight channels, and as the distance increases, the channel losses are affected by multiple scattering, which could lead to confusion if any photons arrive at the receiver via such pathways. The best approximation of power loss for deep water conduits is thus a function with two exponentials. One attenuation loss length exponential is smaller than the diffusion length, while the other is greater. Using Monte Carlo simulations, we will investigate the propagation of a signal over a flat ocean. It is possible to simulate the path of light through water by simulating the photon's behavior as it interacts with its surroundings. This method allows the model to account for the disruption caused by ocean waves on optical communication networks. The Monte Carlo method is not restricted to underwater optical communication; it is an effective instrument for approximating the propagation of light through complex environments. This study's theoretical model is believed to provide an accurate description of underwater long-distance optical communication under realistic conditions. This model has evident oceanographic applications, but it will also aid in the development of underwater optical communication systems for use in offshore oil and gas exploration, underwater surveillance, and other fields. The model's comprehension of performance-influencing factors will aid in enhancing the dependability and effectiveness of existing underwater optical communication systems. In conclusion, the proposed study aims to develop a theoretical model that precisely explains long-distance optical communication in unmodified underwater environments. Using a function with two exponentials, the model will account for the attenuation of light caused by variables such as the concentration of dissolved and in-suspension materials in turbid harbor waters to more precisely estimate the power loss for long distance underwater channels. After taking into account the impact of propagation through modest oceanic turbulence, the Monte Carlo method will be used to evaluate the efficacy of the optical communication system. The proposed work is intended to enhance the dependability and efficacy of optical communication systems used underwater. Fig 2 depicts the Schematic of a typical UOWC link.

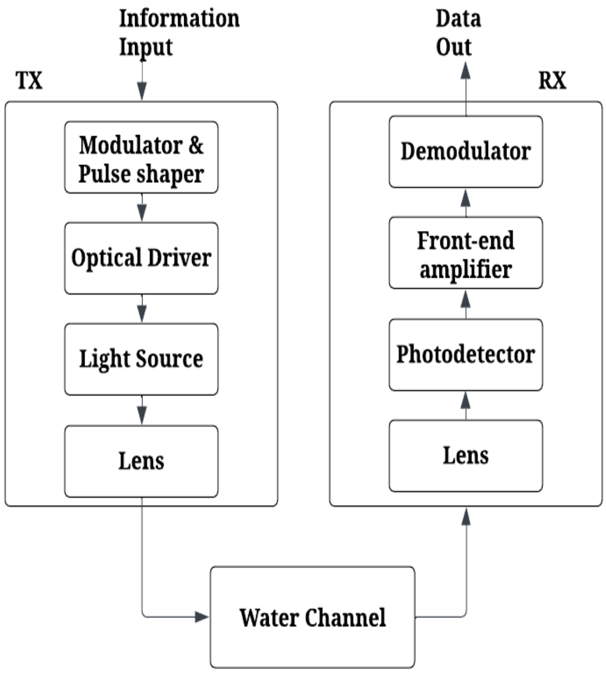

Fig. 2. Schematic of UOWC link

Hiron N et al [14] that appended case study analyzing the use of IEEE 802.15.4-based Xbee Pro S2B for wireless communication in submerged and open-air environments. Finding the optimal depth and distance for wireless communication while submerging the Xbee Pro S2B module in water was the objective of this study. It was discovered that deeper water improves communication, and that a distance of only 20 centimeters is optimal. During testing, the module failed to establish a connection at any depth greater than 20 centimeters, even at 500 centimeters. The Xbee Pro S2B module required more power when submerged in salt water, particularly at depths of less than 20 centimeters. Therefore, the underwater communication device Xbee Pro S2B must have energy management. For this research, one hundred depth measurements were transmitted via XCTU from the local module to the distant module. The error rate increases when transmitting 100 bytes of data if the remote module is submerged deeper. The number of data transmission errors decreased from 2.5 meters to 3 meters depth. The difference in precision is due to the fact that the remote module was transported by the saline stream and brought closer to the surface. This investigation was funded in 2017 by the Siliwangi University Research Innovation Program for Higher Education. The efforts of KEMENRISTEK DIKTI, LPPM-PMP at Siliwangi University, are greatly appreciated by the authors. The results indicated that the IEEE 802.15.4 protocol and the Xbee Pro S2B module performed poorly in the saline environment. Energy management for sensors used in saline environments is a subject worthy of further research. This study has substantial implications for the advancement of underwater wireless communication. The Xbee Pro S2B module is not appropriate for wireless communication at seawater depths exceeding 20 centimeters, according to the findings. Therefore, novel methods of underwater communication must be devised for applications below this depth. Using the Xbee Pro S2B module for measurements in seawater, the study demonstrated the necessity of energy management in greater detail. This finding emphasizes the need for additional research into aquatic environments that require energy-efficient communication systems. This study expands the knowledge of wireless communication in the depths of the ocean. This study confirmed the findings of previous research indicating that communication efficacy increases with increasing water depth. The study confirmed previous findings that high energy costs are a significant barrier to wireless communication when using the Xbee Pro S2B module submerged in seawater. A case study on IEEE 802.15.4-based wireless communication using Xbee Pro S2B for use in submerged and surface environments is presented in the adjacent PDF. It was discovered that deeper water improves communication, and that a distance of only 20 centimeters is optimal. The Xbee Pro S2B module was shown to have a higher power need when used in saline water, particularly at depths of less than 20 cm. Therefore, energy management must be included on the Xbee Pro S2B underwater communication apparatus. The results indicated that the IEEE 802.15.4 protocol and the Xbee Pro S2B module performed poorly in the saline environment. Energy management for sensors used in saline environments is a subject worthy of further research. This research contributes to the comprehension of wireless networking in marine environments and has significant implications for the future development of this field.

Lee. H. K et al [15] that the modeling subsea acoustic channels for Internet of Things applications is the objective of the study. This research seeks to develop an empirical model in order to precisely define critical aspects of underwater communication channels, such as path loss, background noise, and channel capacity. Network architects and optimizers will find their research on underwater IoT networks beneficial. Beginning with thermal noise, shipping noise, wave noise, and ambient noise, the authors discuss the numerous causes of perturbation in the underwater channel. These noise components are represented using colored Gaussian noise with empirical power spectral density (psd) versus frequency. When selecting transmission frequencies for underwater acoustics, frequency dependence of background noise should be considered. Both Parameter I and Parameter II are used to estimate the route loss in the underwater channel. Parameter I cover the range of 22 to 127 meters, while Parameter II covers the range of 127 to 273 meters. Multiplying the distance-dependent route loss exponent by the log-normal shadowing factor yields the overall path loss. The measured channel and the empirical model proposed correspond quite well. The authors then consider the channel capacity of an Internet of Things network submerged in water. They describe the transmission capacity and the process of converting acoustic energy to electrical energy. The channel capacity at a given distance can be expressed by multiplying the channel coefficients by the expected noise psd flatness as a proportion of the signal bandwidth. Additionally, the authors propose throughput, which they define as the product of capacity and bandwidth. The authors demonstrate the accuracy of their model by comparing the predicted underwater channel to the actual channel. The blue 'x's represent the channels that were actually measured, while the red '*'s represents the fictitious data generated by the proposed model. The close similarity between the two data sets provides additional evidence that the proposed model is accurate. In conclusion, the efforts of the authors to simulate underwater acoustic channels for IoT networks significantly advance the understanding of how to optimize the performance of such systems. The proposed empirical model accurately represents the underwater channel's route loss, ambient noise, and channel capacity, making it a valuable instrument for network design and optimization.

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Al-Halafi et al [16] that the objective of this research is to identify methods for wireless networks to reduce their energy consumption without sacrificing performance. The authors propose a hybrid wired/wireless network architecture to reduce the power consumption of 5G networks. The study begins by emphasizing how the rise in prevalence of wireless networks has coincided with a rise in electricity demand. The authors contend that traditional wireless networks must be replaced with fiber-optic technology in order to reduce energy consumption and enhance network performance. Fiber optic front-haul, wireless access network, and wireless backhaul comprise the three fundamental pillars of the proposed concept. Fiber-optic front-haul transports high-speed data from the primary network to the base stations. The base stations are linked to the rest of the network via wireless backhaul. The authors present strategies that can be utilized to save energy. It is suggested that wavelength-division multiplexing (WDM) and passive optical networks (PONs) be used in the fiber-optic front-haul to reduce the burden on the network's power supply. They recommend employing micro cells and heterogeneous networks to enhance wireless access network coverage and capacity while reducing power consumption. Lastly, they suggest employing microwave and millimeter-wave technologies in the wireless backhaul to increase data transfer rate and decrease power consumption. To determine the efficacy of the proposed architecture, the researchers ran a series of simulations and compared the outcomes to those of conventional wireless networks. The simulation results confirmed that the proposed layout can substantially reduce power consumption without compromising data transfer rates or latencies. The research continues by emphasizing the necessity of constructing 5G communication infrastructure with fiber-wireless access networks that are energy-efficient. The authors propose that future research evaluate the feasibility and efficacy of the proposed design. The study concludes with a thorough analysis of the challenges and opportunities implicit in the design of energy-efficient fiber-wireless access networks for 5G communication systems. The authors' proposed architecture and techniques have demonstrated promising results in terms of energy savings and network performance, suggesting that sustainable and environmentally friendly wireless networks may be viable in the future. Fig 3 depicts the digital communications model for the transmitter and the receiver.

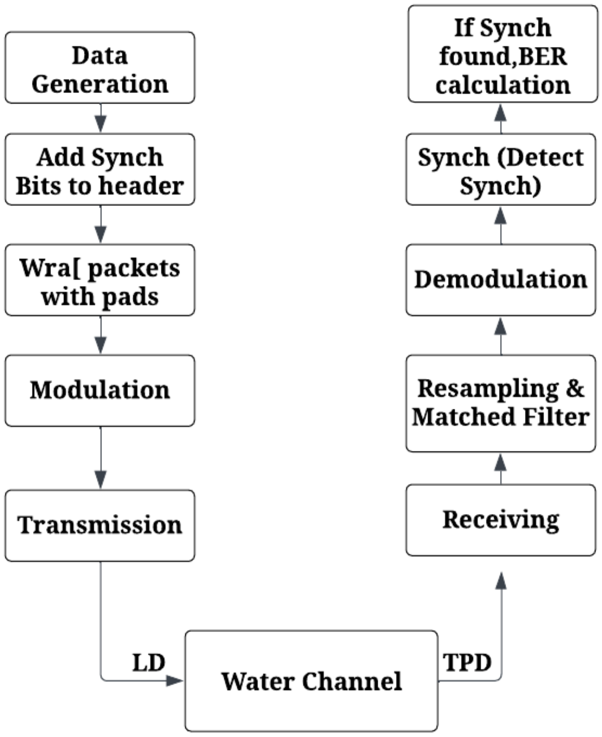

Fig. 3. Digital communications model for the transmitter and the receiver.

III. RESULTS

The method of Zhao et al. [10] focuses on the novel applications of TENGs (triboelectric nanogenerators). This application could utilize mechanical energy sources such as water waves, sound waves, and water flow. The outcomes are encouraging, particularly for the advancement of hydrodynamic and acoustic power generation. Utilizing five parallel-connected, single-layer TENG units enables extremely stable energy production for wireless data transmissions at depth. Vivekananthan et al. [11] demonstrate a long-lasting SE-TENG device that can function as an active pressure sensor. This study demonstrates that the device can withstand significant mechanical stress while producing an electric current reliably for an extended period of time. The SE-TENG device has a resistance of 1 GU and a power density of 17 mW m-2, allowing it to charge capacitors quicker and more efficiently than previous TENG variants. Oceanic turbulence significantly hinders underwater optical communication; Schirripa Spagnolo et al.'s [12] theoretical model seeks to resolve this issue. The study uses a two-exponential model to precisely predict power loss for long-distance underwater pathways by taking into account a number of variables, such as the concentration of dissolved and suspended particulates. This model is a useful instrument for designing and optimizing subsea optical communication networks. In a case study, Hiron et al. [14] evaluate the underwater and outdoor functionality of IEEE 802.15.4-based Xbee Pro S2B modules. At a depth of 20 centimeters, optimal conditions for conversation exist, according to the findings. The inability of the module to maintain communication at depths less than 20 centimeters is also emphasized, as is the need for energy management in underwater communication equipment. The Internet of Things is central to the empirical model devised by Lee et al. [15] for underwater acoustic channels. This study accurately describes essential characteristics of underwater communication channels, such as path loss, background noise, and channel capacity. The findings of this model are invaluable for the planning and construction of undersea networks. Al-Halafi et al. [16] designed a hybrid wired/wireless network architecture to satisfy the expanding demand for 5G networks that are environmentally favorable. The study emphasizes switching to fiber-optic technology to enhance sustainability, network performance, and energy efficiency. Table 1 depicts the comparison of the survey. Fig 4 and Fig 5 depicts the free space path loss model and channel capacity vs SNR.

Table 1: Comparison of the methods in survey

Method	Values
TENGs [11]	Maximal Output Voltage: 1.2 V Maximal Output Current: 0.2A
SE-TENG [12]	Maximal Area Power Density: 17mWm^{-2}
Optical Communication [13]	Accurate estimation of power loss
Xbee Pro S2B [14]	Optimal Depth: 20cm
Subsea Acoustic Channel [15]	Accurate characterization of channels
Hybrid Wired/Wireless Network [16]	Maintenance of data transfer rates

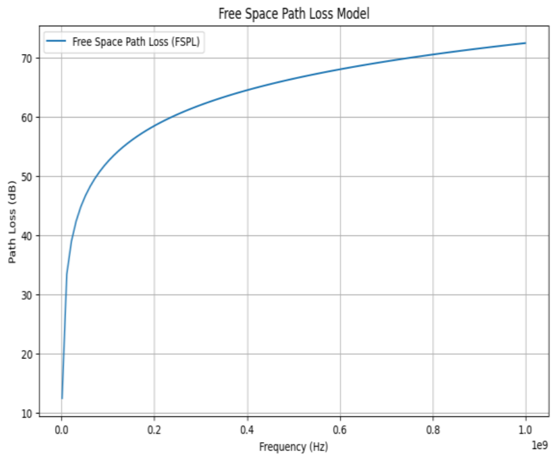

Fig. 4. Free Space Path Loss Model

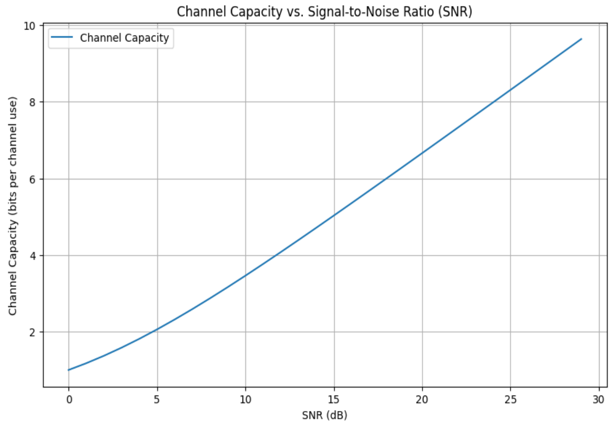

Fig. 5. Channel capacity vs SNR

IV. CONCLUSION

Collectively, the results of these six seminal studies on wireless communication below the waves paint a captivating picture of the numerous ways in which this swiftly developing field is being advanced. The SE-TENG device exemplifies the potential for robust and dependable energy-efficient sensors, and triboelectric nanogenerators (TENGs) have arisen as a viable source of sustainable power generation from water waves and sound waves. Using a theoretical model for long-distance optical communication and an empirical model for subsea acoustic channels facilitates the optimization of communication systems in severe underwater environments. Examples using wireless communication modules and a novel hybrid wired/wireless network architecture are used to investigate the need for low-power and high-performance solutions. The hybrid network architecture is a particularly attractive option for the future of underwater wireless communication because it drastically reduces power consumption without forsaking key performance metrics. In order to propel underwater wireless communication to new heights, it is necessary to develop accurate theoretical models, improve communication networks, and investigate renewable energy sources.

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