Bio-inspired Internet of Fish Towards a Climate Resilient Future

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***Abstract*—This essay reports on the utilization of microwave, optical, and acoustic technology in establishing an underwater interconnected network, internet-of-fish (IoF), to provide comprehensive and real-time information on marine quality for climate monitoring and freshwater preservation. In particular, bio-inspired ocean explorers, capable of traversing different levels of the ocean from shallow to deep waters, are incorporated with communication front-ends to allow inter-explorer communication. Additionally, microwave sensors are discussed as complementary sensing to conventional sensors to provide a more comprehensive and cost-effective characterization of water quality. Moreover, wireless charging mechanisms and mmWave and microwave power beaming are also discussed to provide sustainable and efficient power. Data from these explorers are to be transmitted to nearby hovering unmanned aerial vehicles (UAVs) wherein cross-boundary communication methodology is discussed. With the well-established IoF, a deeper understanding of the earth and its climate is achieved leading to adaptation, mitigation, and prevention of further climate degradation.**

Keywords—bio-inspired, climate change, climate resilience, microwave, mmWave

I. Introduction

As climate uncertainty continues to grow, humanity faces increasing societal changes such as reduction of available fresh water, decline in agricultural production, and evolving threats to human health and safety caused by severe weather events. In particular, recent years an increase in natural calamities have been reported including strongest hurricane and typhoon, unprecedented flooding, and extreme temperatures [1].

To mitigate and adapt to these uncertainties, environmental monitoring has been a useful tool in detecting, forecasting, and assessing the effects of climate change on society. Specifically, an increasing trend in the form of climate resilience is growing wherein environmental monitoring data is being used to reduce the negative impacts brought about by environmental change on human society [2]. Several methods of monitoring the environment are being implemented to date including aerial, land-based, and underwater sensing. Considering the relative cost and impacts between air, water, and land, it is evident that water is the most important type of environment to monitor mainly due to the significance of water in all ecological processes. Moreover, the ocean represents 99% of the habitable volume on Earth which is estimated to house over two million different species. Furthermore, the ocean is considered as a primary lever of climate change due to its ability to sequester carbon [3]. In terms of livelihood and economy, the ocean has been a major contributor to countries' gross domestic product (GDP). Safe water is also a crucial factor in sustaining livelihood; however, water pollution is increasing at an alarming rate which affects both humanity and the earth's ecosystem. As such, monitoring waterbodies such as oceans and rivers are vital for achieving climate resilience.

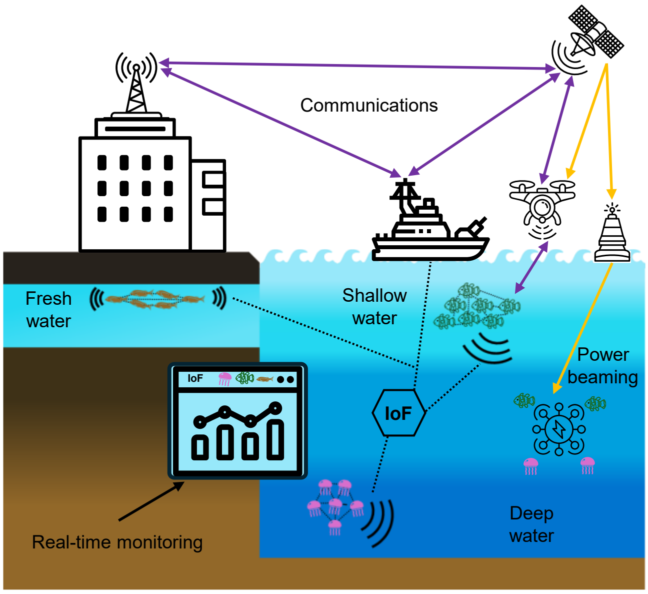

Fig. 1. Block diagram of the proposed real-time multi-level bio-inspired underwater IoF monitoring system which includes deep-water, shallow-water, and freshwater explorers interconnected with ground, aerial, and satellite stations.

Since 1970, satellite monitoring has been the prevailing technology in monitoring the earth's characteristics providing a macro perspective of how the oceans, geography, and weather changes throughout the years [4]. Information from satellite has proved to be useful in providing sea surface temperatures changes, phytoplankton blooms, water turbidity, etc. over relatively long periods of time. However, lossy dielectric property and conductivity of seawater limits the water depth to which satellites can provide useful information. Additionally, it is increasingly complex to achieve both high spectral and spatial resolution required in many water-based monitoring applications.

In this essay, we discuss a comprehensive real-time ocean monitoring system that is capable to identify and assess early climate indicators, water contamination, and marine ecosystem. In particular, we highlight the integrated hybrid microwave technology in providing communication links and detection mechanism of the proposed system creating an underwater network called the internet-of-fish (IoF). At the same time, we explore the advantages brought by utilizing bio-inspired ocean exploration methods which shows cost reduction, better navigation, and massive interconnectivity and sensing. This way, monitoring data is instantaneously transferred leading to real-time assessment and planning as depicted in Fig. 1. The outline of this essay is as follows. Section II discusses the challenges of current underwater sensing techniques, and the potential brought about by using bio-inspired explorers. Section III presents the envisioned IoF wherein the different aspects of the proposed system functions are discussed. The challenges and how microwave technology assists in addressing these are presented in Section IV. Finally,

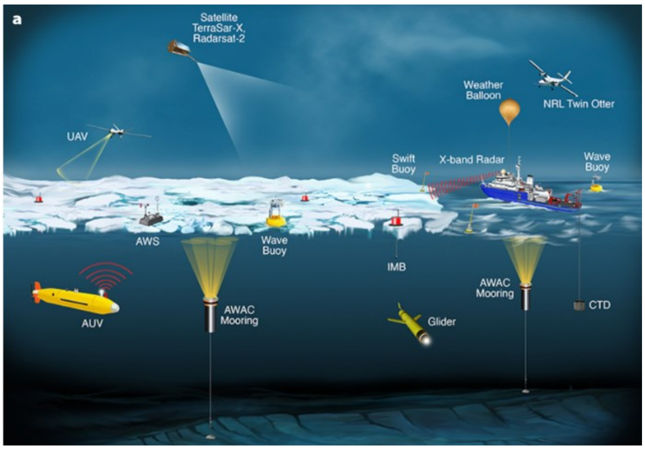

Fig. 2. Existing tools used for characterizing the ocean including satellites, unmanned aerial vehicles (UAVs), weather balloons, buoys, autonomous underwater vehicles (AUVs), and ship-based instrumentation. [5]

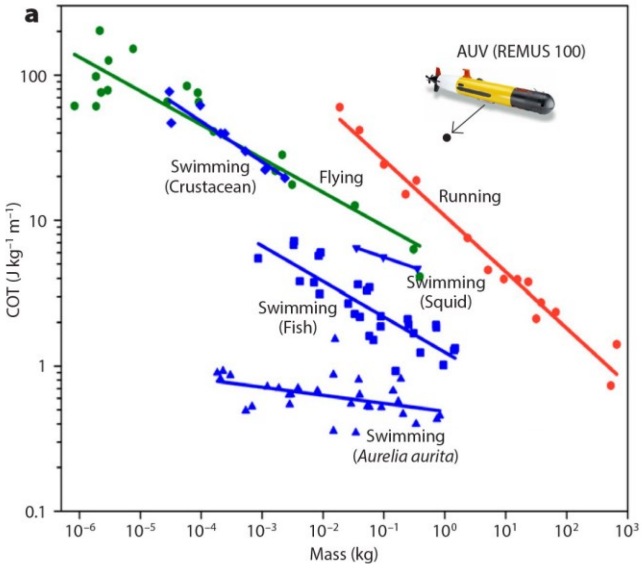

Fig. 3. COT versus mass for a variety of biological organisms. [5]

the potential of this solution in addressing current societal challenges is presented in Section V.

II. Challenges of underwater sensing

Several techniques have been presented in studying underwater characteristics and properties as depicted in Fig. 2. This includes both aerial vehicles such as satellites and weather balloons and marine vehicles such as buoys, surface vessels, and automated underwater vehicles (AUVs). In contrast to the use of existing external monitoring tools, in situ measurements, which measure directly surface and subsea environments, are advantageous. Surface vessels and autonomous surface vehicles (ASVs) have served as the primary tool for ocean science during the past century mapping the seafloor and recording the ocean's salinity and temperature at different depth levels. However, to acquire these measurements, it takes more than 200 ship-years to sample the ocean at a single depth level [6]. At the same time, due to the dynamic nature of water-bodies, the data obtained using this method becomes obsolete once it is completed.

A. Conventional Automated underwater vehicles

In contrast to remotely operated vehicles (ROVs) tethered to ships that require manual operation, AUVs are unmanned underwater robots that are used to independently complete a pre-programmed mission. Since these AUVs are untethered, this allows more data to be collected during its mission while an independent surface vehicle can focus on other tasks and measurements simultaneously. Moreover, AUVs can reach shallower water than ships and deeper waters than human divers and most ROVs can.

AUVs navigate the ocean using various propulsion systems, including propulsor-based mechanisms and buoyancy or wave-driven gliders. Propulsor-based AUVs are typically employed for their greater flexibility and speed, enabling them to cover large areas quickly and perform complex tasks. However, they consume significant power and produce noise, which can disturb marine life. On the other hand, buoyancy and wave-driven gliders are more energy-efficient because they rely on natural forces for propulsion. They also operate with minimal noise, making them less disruptive to the marine environment. Despite their efficiency, these gliders have limited maneuverability, which restricts their ability to perform complex operations. Additionally, their inability to maintain a fixed position can trigger avoidance behaviors in marine organisms, complicating studies of natural behaviors. Furthermore, the extreme and unpredictable conditions of the ocean, with temperatures ranging from -89.2°C to 70°C and pressures from 8.87 m H2O to 10,994 m H2O, make deploying and operating conventional AUVs increasingly complex and expensive.

B. Bio-inspired explorers

To ease the aforementioned challenges, research on bio-inspired sensing and locomotion has taken a growing interest. Over the years, biological organisms have adapted and evolved while facing these challenges which led to its development of advanced locomotion and sensing capabilities. As such, these organisms are ideal candidates for bio-inspired explorers geared towards providing a comprehensive real-time underwater monitoring system.

Bio-inspired engineering has demonstrated significant advances in previous research efforts such as submarine vehicle design [7], wind energy farming [8], and biomedical diagnostics [9]. To better situate the potential of bio-inspired robots, the performance metric of cost of transport (COT), which is the energy expended by an organism per unit mass and per distance traveled, is considered in Fig. 3. The COT can be considered as the inverse of more common efficiency metrics used for vehicles such as fuel economy; hence, a lower COT is desired. As observed, the representative AUV has significantly higher COT compared to bio-inspired equivalents. Hence, by understanding and implementing the dynamics of these organisms, a smack of closely spaced explorers/robots can be deployed within the ocean providing a comprehensive monitoring. At the same time, by leveraging the adaptability of bio-organisms in deeper regions of the water, unprecedented monitoring information can be derived.

III. Internet-of-fish

Utilizing the swarm of bio-inspired explorers outlined in the previous section, several aspects need to be considered to ensure proper operation of the proposed IoF system. These aspects are discussed in detail as follows.

A. Communication

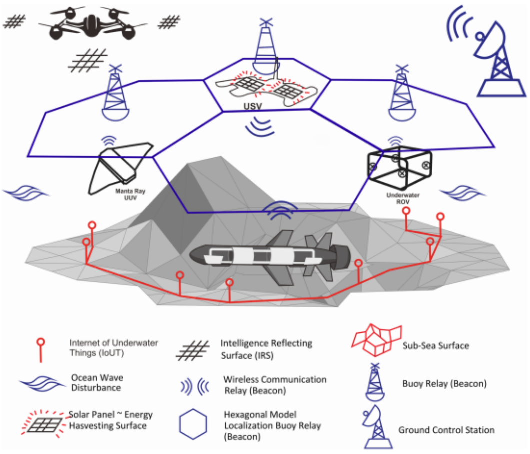

Fig. 4. Joint operation of UAVs, USVs, and AUVs. [10]

Conventionally, data is stored in an AUV and retrieved only after its mission. However, this doesn't provide real-time monitoring information and is dependent on the success of retrieving the AUV. A joint communication network [10], as shown in Fig. 4 wherein underwater, surface, and aerial vehicles are interconnected through different communication links and relays, is considered. At the same time, these vehicles are connected to the ground and satellite station providing a comprehensive data distribution system. To effectively disseminate monitored data instantaneously, the following communication links need to be established: i) underwater link between bio-inspired explorers, ii) cross-boundary interconnectivity between water and air, and iii) air and ground level communication. As such, we discuss the key enabling hybrid integration of microwave, acoustic, and optical technologies in supporting these links as opposed to conventional method of relying on a single technology.

To facilitate underwater communication, electromagnetic waves conventionally used in air and land cannot be directly utilized due to the severe absorption of water limiting its range and data rate. However, bio-inspired explorers present the opportunity of having a swarm of these sensors in close proximity reducing the loss incurred by water absorption. As such, a combination of acoustic (10-15 kHz), optical ($5x10^{14}$ Hz), and microwave (30-300 MHz) communication is envisioned to establish interconnectivity and high data rate transmissions underwater. Optical and microwave technology are to be used to achieve high data rate short-range transmissions (up to 500 m) while acoustic technology, which has been widely used for marine communications, are to be deployed in complement to support communications towards farther distances (km ranges).

Global connectivity envisioned by 6G wireless networks demand a new paradigm shift in interconnecting everything on Earth. However, one of the key challenges is the interface between the sky and the ocean. As such, there has been a growing interest in developing cross-boundary communication technologies that enables direct communication from air to water [11]. Direct water/air cross-boundary communication faces several challenges due to the link between two different transmission media. At the same time, the channel model becomes more complex due to the waves, atmospheric turbulence, and ocean current. Several approaches of enabling cross-boundary connectivity are shown in Fig. 5 such as relay-based indirect communication,

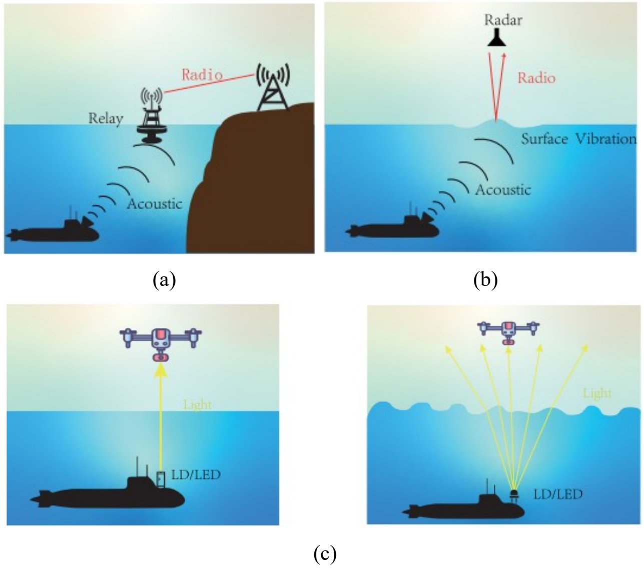

Fig. 5. Illustration of typical scenarios for cross-border communication. (a) Indirect relay-based communication from ship to buoy. (b) Acoustic to radar direct communication. (c) VLC direct communication. Left: line-of-sight optical link and right: diffused line-of-sight optical link. [11]

non-visible light communication (VLC) and VLC communication. In particular, non-VLC communication establishes direct links through microwave vibration measurements when tiny acoustic signals are detected by radar on an unmanned aerial vehicle (UAV) hovering above the water surface. This potential paves the way for establishing cross-boundary communication required by the envisioned real-time monitoring system.

Ground, air, and space communications has been evolving continuously throughout the years from 1G towards the current 5G communication technology. With the advent of 6G communications, it is envisioned that higher data rates, low latency, and higher efficiency would pave the way for a more interconnected future wherein larger data is transferred leading to a plethora of applications and services. One key aspect of 6G would be to enable the potential of incorporating more data gathered from underwater sensing and monitoring. This way, real-time and instantaneous data monitoring is achieved leading to early assessment and response towards climate change.

B. Wireless charging

As with any electronic device/robot, power supply of the bio-inspired explorers is a critical factor in ensuring continuous operation of the device while monitoring the underwater environment. Traditional methods of charging AUVs, include manual retrieval and battery replacement and wired charging of these vehicles using stationary underwater docks. However, these methods tend to be non-sustainable and pose greater risk especially considering manual human intervention. Recently, wireless power transfer has seen a growing interest in addressing energy issues with underwater devices. Particularly, it has shown significant technical advantages such as improved safety, reliability, convenience, and concealment.

With the low-power requirement of the bio-inspired explorers, underwater wireless power transfer comes as an attractive solution in maintaining sustainable and efficient

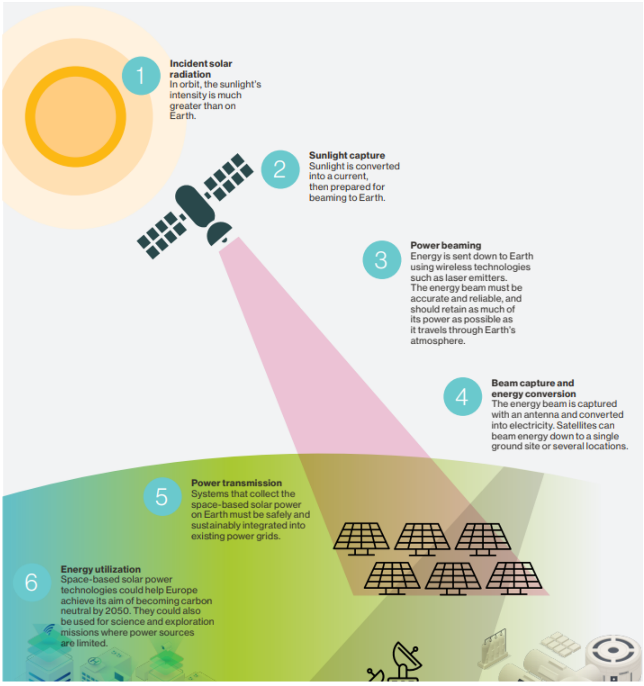

Fig. 6. Conceptual diagram of a power beaming system. [13]

charging of these underwater devices. By placing underwater wireless charging docking stations, these robots can autonomously charge whenever necessary and proceed with its mission.

Traditionally, energy to these underwater docking stations are supplied by ocean energy harvesters or a ground power supply station. Using these methods require huge infrastructure, i.e. – long cables connecting the land to underwater stations, hence, becomes more complex when several of these docks are envisioned. A new innovative approach called power beaming is gaining traction due to the advantages it brings. Power beaming is the efficient point-to-point transfer of electrical energy using a directed electromagnetic beam. An example of a power beaming is depicted in Fig. 6 wherein power from the solar radiation is harvested and beamed to earth through a satellite [13]. Due to its high intensity and long-range transmission, power beaming has the potential to deliver energy to non-easily accessible areas including ocean spaces far from landmass. As a consequence, underwater docking stations are placed in strategic monitoring areas while still obtaining necessary energy source for charging. Furthermore, power beaming can also be utilized to power the UAVs and USVs to be used in conjunction with the bio-inspired explorers for efficient data transfer and communication as discussed in the previous section.

C. *Climate monitoring beneath the waves*

The ocean comprises 71% of the Earth's surface and plays an important role in supporting biological life and regulating the planet's climate. Knowing this, the opportunity offered by the vast marine ecosystem offers a treasure trove of data essential in deciphering the climate status. Identified key metrics include ocean heat content, sea level rise, ocean acidification, salinity, and dissolved oxygen levels. Conventionally, these metrics are measured at the surface level either through satellite, ships, or manual collection and measurement. Although these approaches has proved useful in providing climate assessment for the past years, it remains insufficient.

The introduction of the school of bio-inspired explorers, adds another degree of measurement providing underwater characteristics. In particular, a combination of technology including optical, capacitive, electrochemical, electromagnetic, and ultraviolet are utilized to obtain water properties such as salinity, acidity, dissolved oxygen, and nutrients [14]. For example, these allow detection of abnormal increase in nutrient levels like nitrate, ammonium, and phosphates which are the main causes of algal blooms harmful to marine biodiversity. Additionally, having real-time information of these properties allows mitigation of coral bleaching events which are direct consequence of global warming and climate change.

D. *Freshwater preservation*

Freshwater sources continue to decline with the progressing climate variability. Being one of the most vital resource for various life forms, it is imperative that natural freshwater sources be preserved and maintained. Several microwave-assisted sensors have been developed in assessing water quality and treatment of contaminated water [15]. However, there is no comprehensive monitoring of natural freshwater ways such as rivers. By deploying bio-inspired sensors on these riverways, compact miniaturized water quality sensor is required. One potential solution is through the use of mmWave radars as discussed in [16]. These miniature mmWave radar devices demonstrates water quality estimation capable of detecting low concentrations of substances such as nitrate and salt. Having these devices adapted for underwater bio-inspired sensors would enable real-time monitoring of a river's water quality potentially identifying contaminant sources at an early stage. This way, timely treatment and preservation techniques can be applied to maintain the integrity of our natural fresh water source.

Aside from water quality, similar with oceans, rivers also deal with marine litter which are harmful to its ecosystem. Marine litter which are closely tied with climate change is detected through acoustic and electromagnetic means [17]. Through integration of these sensors, marine cleanup can be organized efficiently addressing both floating and submerged litter. This method is also applicable for ocean based monitoring of seafloor litter.

IV. Role of Microwave Integrated Circuit

To facilitate the successful deployment of the proposed real-time monitoring IoF, communication between nodes becomes an indispensable component of the system. Specifically, microwave integrated circuit (IC) has been the forefront in implementation and realization of over-the-air communications for the past decade. Through the years, it has continuously evolved to provide massive connectivity to a plethora of applications, such as satellite communications, communication links between devices in internet-of-things (IoT) applications, vehicle-to-vehicle communications, wearable electronics, and mobile communications. Due to the advances of semiconductor technology, microwave ICs have become more compact, robust, and efficient leading to its wide adaptation in various communication platforms. However, challenges exist in integrating these ICs in the proposed IoF system.

The proposed IoF requires multiple distinct mobile devices interconnected simultaneously. At the same time, the spectrum is congested and it becomes challenging to allocate specific frequency bands for the system. As such, dynamic spectrum reuse becomes and attractive solution wherein devices are reconfigured to operate at white spaces (unused frequency bands) in the frequency band. To address these challenges, a reconfigurable phase array transceiver is used to cover the mobility factor when the devices move from one place to another and tune the frequency to an unused band. Phased array systems has been demonstrated in [18] capable of providing multiple beams that can be reconfigured to different frequency bands of operation. By having multiple beams, make-before-break handovers is allowed between satellites. This way, we can ensure continuous connectivity and data transfer among devices across different platforms.

Another important aspect to consider for the proposed IoF is the cross-boundary communication between unmanned aerial vehicles (UAVs) and the underwater explorers. To enable this link between water and air requires lightweight and energy efficient communication hardware to facilitate uninterrupted real-time monitoring data transfers. To date, several researches have presented miniaturized UAV payload implementations. In particular, [19] presents a single channel approach to save power while achieving comparable data rate and bandwidth compared to power-hungry phased array systems for UAVs. Another example is presented in [20], which demonstrates a radar detection transceiver in MMIC technology for UAV applications. Radars are one of the key enablers of cross-boundary communication, these mmwave radars are able to detect water surface vibrations effectively establishing sonar to radar communications [21]. Through the use of these radar technologies, links between air and water-based devices can be established.

Communication and detection between underwater explorers is very challenging due to the harsh underwater condition (i.e. temperature and pressure) and the significant deterioration of microwave transmission in water. To resolve microwave links in water, optical communications as a hybrid solution such as microwave photonics [22] becomes attractive. In particular, an electronic-photonic integrated circuit can potentially enable high data-rate transmission and communication in water. Such photonic front-ends has been demonstrated using various technologies while achieving high data rate transmission [23], [24]. The other condition to address is the harsh underwater environment which these ICs must operate in. Fortunately, several works has studied the reliability of ICs in harsh conditions such as space [25]. This proves the reliability of such technology for extraterrestrial environment and its potential towards even harsher conditions. However, it must be noted that pressure and temperature are expected to be very different underwater. Hence, further analysis and investigation is necessary in this aspect albeit its promising potential for applicability towards realization of the proposed system. In terms of mechanical flexibility, it is highly desirable that the ICs to be incorporated within the bio-inspired explorers are mechanically robust. Flexible ICs are increasingly explored through the use of thinner substrates of less than 20um. One example is shown in [26], wherein a receiver is implemented showed good RF performance while being implemented on a mechanically flexible structure. Integrating the mechanically robust structure with photonic integrated circuits while examining its performance within underwater conditions are key research areas in establishing communication of these underwater explorers.

Aside from establishing reliable communication links for the proposed IoF, the charging mechanism is also an important consideration. mmWave and microwave power beaming is an efficient and green technology capable of powering this swarm of devices. Specifically, mmWave power beaming commonly operated at 35 GHz and 95 GHz are to be deployed for small sites and mobile platforms while microwave power beaming operating at 10 GHz are to be utilized for high power and long distance applications. In the proposed IoF, the links from satellite to buoys, ground station, and stationary charging platforms will use microwave power beaming while the links from these buoys/ground stations to mobile UAVs and devices are to be facilitated by mmWave power beaming. Additionally, several integrated rectenna array circuits are increasingly explored for facilitating efficient energy conversion [27] of power beaming applications.

Considering the aforementioned challenges with the proposed IoF, we can leverage the advantages brought about by microwave ICs, such as miniaturization, efficiency, low power consumption, mechanical flexibility, and robustness, in enabling both underwater and over the air connectivity. Hence, establishing a microwave-assisted real-time climate monitoring system.

V. Conclusion

As climate uncertainty continues to threaten human society, we look into the ocean for guidance. The ocean comprises and inhabits majority of ecosystems; however, little is known and studied about it. With the advancement of microwave technology and the advent of 6G, interconnecting these oceans with the rest of the planet becomes plausible. We discuss a real-time underwater monitoring system implementation through the IoF. Specifically, by interweaving swarms of bio-inspired explorers, a new bank of data is obtained containing comprehensive measurement of ocean characteristics. Through the joint communication between these bio-inspired explorers and UAVs, satellites, and ground stations, instantaneous distribution of data is achieved creating the opportunity for early planning and mitigation of climate events. At the same time, the advantages brought about by microwave ICs elevates the potential of realizing such systems. With different technologies coming into play and working cohesively, a comprehensive environmental monitoring data is obtained reducing the negative impacts of climate change towards human society. Thus, establishing a climate resilient future for our planet.

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