

An Integrated Satellite and Underwater IoT Framework for Real-Time Oceanic Disaster Monitoring and Resilient Communication

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Abstract

Ocean-based environmental disasters such as tsunamis and underwater earthquakes pose significant risks to human life, coastal infrastructure, and regional stability. However, traditional communication networks often collapse during such events, leading to delayed alerts and uncoordinated response efforts. This study presents an integrated framework that combines underwater Internet of Things (IoT) systems with satellite communication technologies to enable real-time oceanic disaster monitoring and reliable emergency communication. The system connects underwater sensor networks to low Earth orbit (LEO) satellite constellations, allowing for continuous data transmission and early detection of marine hazards. By removing dependency on terrestrial infrastructure, this framework ensures timely alerts and uninterrupted communication in affected areas. The proposed approach promotes a scalable, infrastructure-independent model for oceanic disaster preparedness and response.

Keywords: Satellite communication, underwater IoT, oceanic disaster monitoring, tsunami detection, remote sensing, LEO satellites, resilient communication, real-time alert systems

INTRODUCTION

The increasing frequency and intensity of oceanic disasters, such as tsunamis, underwater earthquakes, and coastal flooding, have underscored the urgent need for faster, more reliable monitoring and communication systems. Traditional infrastructure-based networks often fail under such conditions, delaying early warnings and disrupting disaster response efforts. To address these challenges, this research proposes a framework that integrates underwater IoT systems with satellite communication

technologies, offering a scalable and infrastructure-independent approach to real-time disaster detection and communication.

Role of Satellite Communication in Disaster Management

Satellites provide a robust means of communication, particularly in scenarios where terrestrial infrastructure is damaged or completely inaccessible.

Low Earth Orbit (LEO) satellites can offer wide-area coverage and low-latency connectivity, which is critical for transmitting disaster alerts, sensor data, and coordination messages. Their ability to function independently of ground networks makes them invaluable during natural disasters (Figure 1).

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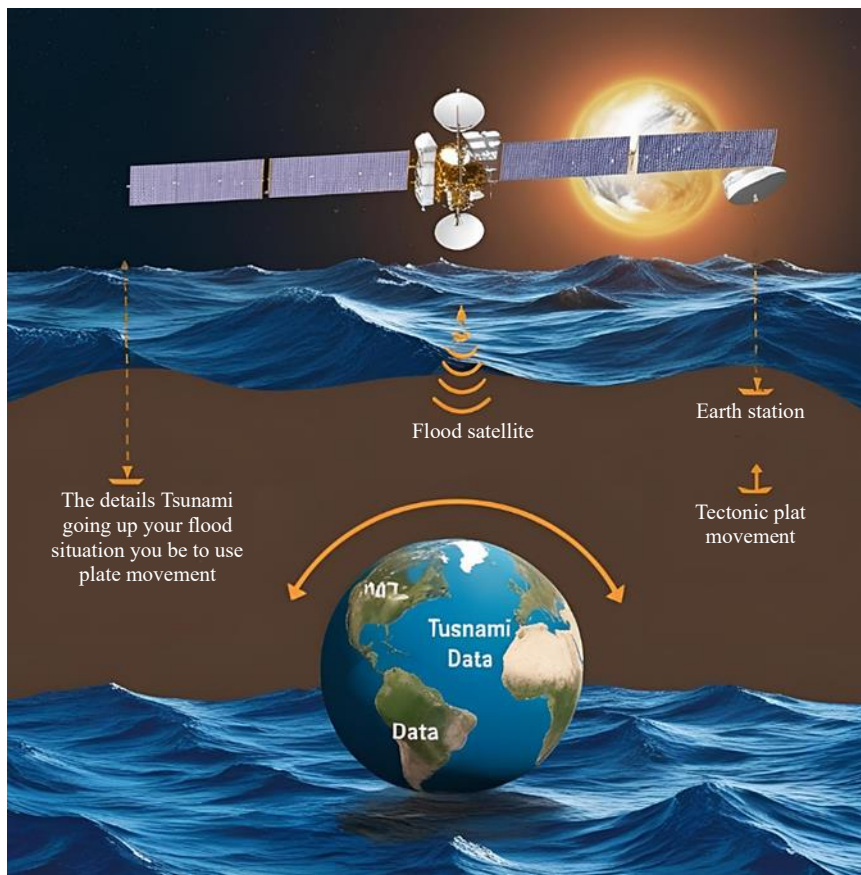


Figure 1. Satellite communication system in disaster management.

Underwater IoT and Remote Sensing Technologies

Underwater IoT involves sensor nodes deployed in oceanic environments to collect data such as pressure, seismic activity, and temperature. These nodes use acoustic, optical, or RF communication to transmit data to surface buoys, which then relay it to satellites. The collected data enables early detection of underwater disturbances that may evolve into larger natural disasters. Remote sensing technologies further support this system by providing continuous environmental monitoring, enhancing the accuracy and speed of detection (Figure 2).

LITERATURE REVIEW

Oceanic disasters, such as tsunamis and underwater earthquakes, represent significant challenges for both local populations and global disaster management systems. In recent years, advancements in satellite communication and underwater IoT technologies have paved the way for more effective real-time monitoring and response systems. This section reviews key research in these areas and highlights the gaps that the proposed framework aims to address.

Satellite Communication in Disaster Management

Satellite communication has long been recognized as a critical tool in disaster management. As opposed to terrestrial networks, satellite systems are less susceptible to damage from disasters like earthquakes, tsunamis, and storms, making them invaluable in emergency situations [1]. LEO satellites, in particular, offer low-latency communication, which is essential for transmitting real-time alerts and data [2]. However, despite the clear advantages, many satellite systems still face challenges related to network congestion, high costs, and limited bandwidth, which can delay critical communications during peak demand [3]. Recent advancements aim to address these issues by incorporating dynamic bandwidth management and high-throughput satellite constellations, yet solutions to these challenges are still evolving [4].

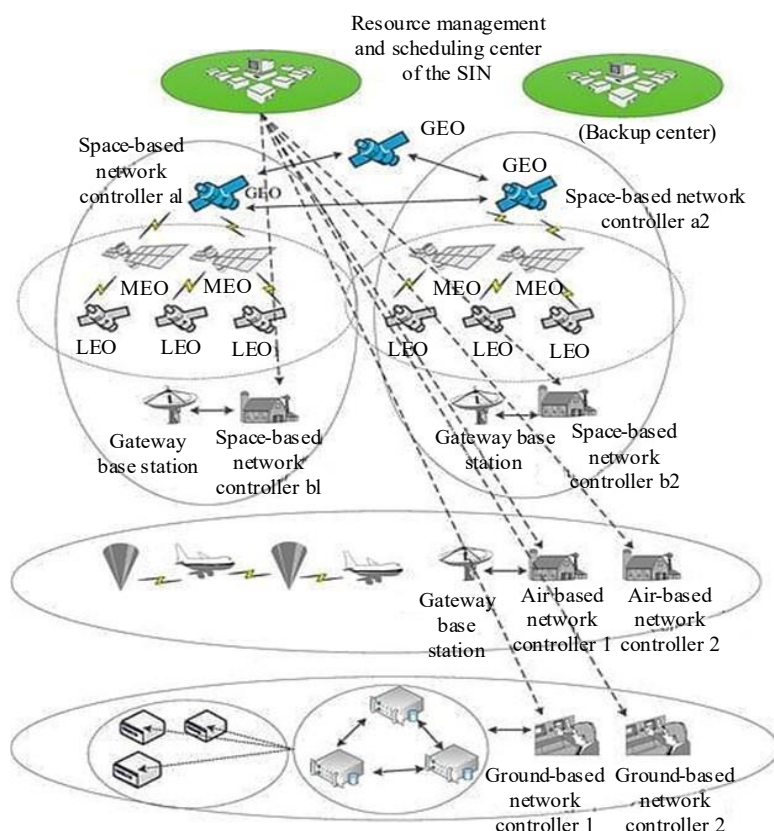


Figure 2. Role of Underwater IoT and Remote Sensing Technologies.

Underwater IoT and Remote Sensing Technologies

Underwater IoT systems have emerged as a key component in monitoring oceanic conditions and detecting potential hazards. These systems use sensors deployed on the ocean floor or integrated into buoys to monitor seismic activity, pressure changes, and other environmental indicators that could signal a disaster such as a tsunami or underwater earthquake [5]. By integrating remote sensing technologies, these systems provide critical data that can be used to forecast oceanic events in real time, offering early warnings to nearby coastal regions [6]. However, one of the primary challenges faced by these systems is ensuring reliable data transmission from underwater sensors to the surface, as well as maintaining the long-term stability of these sensors in harsh oceanic conditions [3].

Limitations and Gaps in Existing Literature

While significant progress has been made in the areas of satellite communication and underwater IoT, there are still several gaps that hinder the full realization of a comprehensive, real-time oceanic disaster monitoring system. First, existing systems often rely on fixed bandwidth allocations, which can result in delays and congestion during high-demand periods [4]. Second, the integration of underwater sensors with satellite constellations is often constrained by cost and maintenance challenges, particularly in deep-sea environments [7]. Finally, real-time decision-making tools that combine environmental data from various sensors with disaster response protocols remain underdeveloped, leaving gaps in the ability to prioritize and coordinate responses effectively.

PROPOSED SYSTEM

System Overview

The proposed system integrates underwater IoT networks with satellite communication to provide a robust solution for oceanic disaster monitoring and response (Figure 3). It uses underwater sensors, surface buoys, and low Earth orbit (LEO) satellites to enable real-time detection and communication, ensuring continuous data transmission even when traditional terrestrial infrastructure fails.

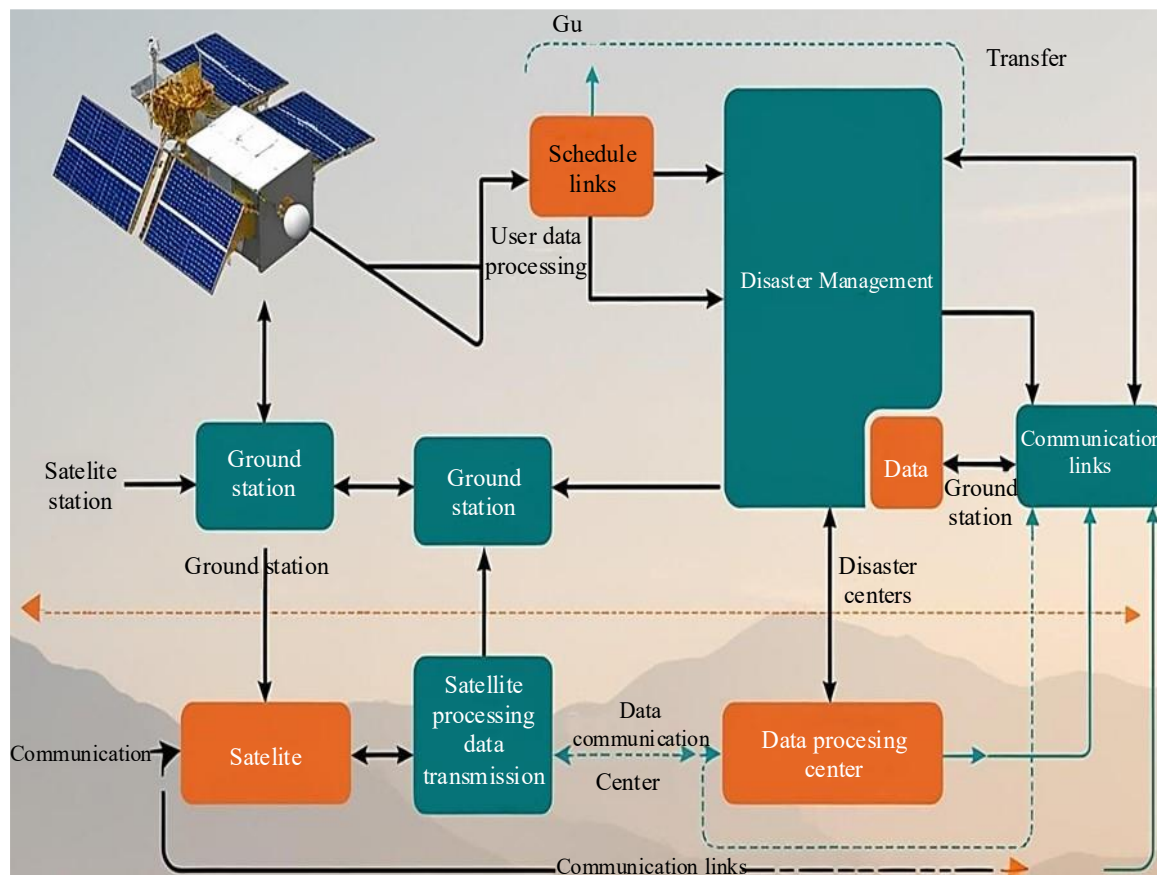


Figure 3. Workflow of the proposed system.

The system consists of three key components: underwater IoT sensors, surface buoys, and satellite communication networks.

System Benefits

The proposed system offers several key advantages. Resilience is one of its most significant strengths, as the system remains operational even when local infrastructure is destroyed by oceanic disasters. The use of satellites ensures that communication is maintained, providing continuous data flow for disaster management. Additionally, the system is highly scalable, making it adaptable for different geographical regions and capable of handling varying levels of data traffic as more sensors and buoys are deployed [8, 9]. Lastly, the system is cost-efficient. Although the initial deployment may involve higher costs for sensors and buoys, the long-term maintenance costs are relatively low compared to traditional communication infrastructure. The ability to leverage satellite networks eliminates the need for extensive ground-based communication systems, making the solution both effective and sustainable.

SIMULATED CASE STUDY: TSUNAMI DISASTER RESPONSE

To evaluate the effectiveness of the proposed system, a simulated case study is presented based on the 2011 Tōhoku tsunami disaster. This disaster serves as a fitting example due to the scale and complexity of the event, as well as the communication challenges faced during the emergency response.

Scenario Overview

The Tōhoku earthquake, which struck off the coast of Japan in March 2011, triggered a massive tsunami that led to widespread devastation. During the event, communication infrastructure was severely impacted, hindering timely responses from disaster management teams. Had the proposed system been in place, it could have played a crucial role in providing early warnings and facilitating continuous communication between affected regions and emergency response teams [3].

System Application in the Tōhoku Scenario

In this scenario, underwater IoT sensors would be deployed along the seafloor off the coast of Japan to monitor seismic activity and oceanographic conditions. As the earthquake occurs, these sensors would detect rapid shifts in pressure and seismic waves indicative of a potential tsunami. The data would then be transmitted via acoustic communication to surface buoys that are strategically positioned to act as data relays.

These surface buoys would aggregate the data from multiple sensors and send it to LEO satellites. The satellite network, in turn, would relay the data to ground stations, which could transmit alerts to local authorities and disaster management teams. The system's low-latency communication would ensure that tsunami warnings are issued quickly, allowing for faster evacuations and the mobilization of resources [5, 9].

Outcomes in the Simulated Case Study

If the proposed system had been operational during the Tōhoku disaster, several outcomes could have been significantly improved:

1. *Faster Early Warning Alerts:* Real-time detection and transmission of seismic data from underwater sensors would enable early warning systems to trigger tsunami alerts much earlier than traditional methods. This would have provided coastal communities with more time to evacuate, potentially saving lives.
2. *Enhanced Communication:* Even if terrestrial communication networks were compromised, the satellite-based system would ensure that disaster management teams remained in constant contact with each other and with local authorities. This would have improved coordination for relief efforts and resource deployment [7, 10].
3. *Data-Driven Decision Making:* The system would have provided continuous data on the ocean's condition, offering valuable insights into the tsunami's progression and impact. This would have allowed for more informed decision-making regarding evacuation routes and resource allocation.

Challenges and Limitations

While the system offers many benefits, there are also challenges that must be addressed. For example, sensor calibration and maintenance in deep-sea environments are critical for ensuring data accuracy. Additionally, the cost of deploying and maintaining such a system, especially over large oceanic regions, remains a consideration. The long-term sustainability of the system would depend on government support and international collaboration for continued funding and upkeep.

DISCUSSION

The proposed system, which combines underwater IoT networks with satellite communication, offers a revolutionary approach to oceanic disaster monitoring and response. By addressing the limitations of traditional communication networks and offering real-time, resilient communication, the system holds significant potential for enhancing disaster management in coastal and oceanic regions.

Key Insights from the Proposed System

One of the most promising aspects of the system is its ability to provide continuous, real-time monitoring in oceanic environments, even when traditional communication infrastructure is compromised. This is particularly important in areas prone to tsunamis, underwater earthquakes, or other ocean-based natural disasters, where swift response times are crucial. By using underwater IoT sensors to detect seismic activity and other indicators of potential disasters, the system can provide early warnings that give communities and authorities more time to prepare and respond effectively [3, 7].

The satellite-based communication ensures that the system remains operational even in the absence of ground-based infrastructure, which is often destroyed in the wake of large-scale disasters. This offers an inherent advantage over conventional communication networks, which typically fail under the strain

of a major disaster. Moreover, the use of low Earth orbit (LEO) satellites ensures low-latency, reliable communication for transmitting critical data to ground stations for immediate action.

System Benefits and Challenges

The system's benefits are clear: resilience, scalability, and cost-effectiveness stand out as its most significant advantages. However, as with any complex technology, there are challenges that need to be addressed. Deployment and maintenance of underwater sensors and surface buoys in harsh oceanic environments can be costly and technically demanding. These sensors need to be regularly calibrated and serviced to ensure accurate readings, and the infrastructure required to support satellite communication may involve significant upfront investments [5, 6].

While the system's scalability is an advantage, the expansion of such a network would require international collaboration and coordinated efforts among governments and agencies, especially in the case of large-scale oceanic regions. The long-term sustainability of the system is also an important factor to consider, as regular maintenance and updates to the satellite and sensor networks would be necessary to maintain optimal performance.

Impact on Disaster Response and Management

The ability to provide timely data-driven insights into oceanic conditions during a disaster is invaluable. In the simulated case study based on the Tōhoku tsunami, for example, the proposed system could have dramatically improved the effectiveness of early warnings and coordinated disaster response. By ensuring that emergency responders and local authorities have access to continuous data from the ocean floor, the system could have reduced response times, saved lives, and minimized the destruction caused by the disaster [6].

Moreover, this system enhances decision-making during crises. Real-time access to oceanic data would allow disaster response teams to make more informed decisions about evacuation routes, resource deployment, and the prioritization of relief efforts. This ability to adapt quickly and accurately to changing disaster scenarios can be the difference between success and failure in disaster management.

Future Directions

While the current system presents a promising solution, several areas can be explored to enhance its capabilities further. Integration with other disaster monitoring systems, such as weather or seismic prediction models, could provide a more comprehensive response to disasters. Additionally, advancements in sensor technology, machine learning algorithms for predictive modelling, and satellite communication could improve the overall efficiency and accuracy of the system [2].

In the future, the global expansion of such systems, especially in high-risk coastal and island regions, could lead to widespread adoption of this model, ultimately improving global disaster preparedness and response capabilities.

CONCLUSION

This study proposed an innovative system that combines underwater IoT networks with satellite communication to enhance the monitoring and response to oceanic disasters. By addressing the limitations of traditional communication systems, the proposed solution offers a reliable, resilient, and real-time framework for detecting and mitigating the impacts of disasters such as tsunamis and underwater earthquakes.

The system's key components: underwater IoT sensors, surface buoys, and satellite communication, ensure that critical data flows seamlessly from the ocean floor to disaster response teams, even when terrestrial infrastructure is compromised. This robust communication infrastructure can play a pivotal role in improving early warning systems, enhancing disaster response efforts, and ultimately saving lives by providing timely and accurate information.

The simulated case study based on the 2011 Tōhoku tsunami disaster demonstrated the practical applicability of the system, highlighting how real-time data transmission from underwater sensors to satellites could have expedited disaster alerts and resource allocation. While the system presents significant advantages, such as resilience and scalability, there are challenges related to the deployment and maintenance of underwater sensors and satellite networks. These challenges underscore the need for collaborative international efforts to ensure the sustainability and long-term effectiveness of such a system.

In conclusion, the proposed system represents a step forward in disaster management by providing a data-driven, reliable solution for oceanic disaster monitoring and response. With continued advancements in sensor technology, satellite communication, and data analytics, this system could significantly enhance global disaster preparedness and response, helping to protect vulnerable communities from the devastating effects of oceanic disasters.

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