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Article

SEAWAVES: A Hybrid Mobile and SMS Communication Framework for Intelligent Maritime Safety Monitoring in Remote Coastal Communities

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Abstract: This study presents a hybrid SMS and mobile network communication framework for maritime safety monitoring in low-connectivity coastal areas through the implementation of the SEAWAVES (Sea-condition Emergency Alert and Warning Apparatus for Vessel Safety) technology. The proposed framework integrates Android sensor technologies, hybrid communication mechanisms, local offline storage built-in to the smartphone, cloud-based monitoring, and automated alert dissemination for small watercraft operations. The system utilizes built-in Android sensors including accelerometer, gyroscope, magnetometer, and GPS/GPRS modules to acquire and compute real-time vessel parameters such as pitch, roll, heading, speed, and geographical location. Results showed that the proposed framework achieved an overall accuracy of 98.78%, with communication success rates of 96% for mobile data transmission and 98% for SMS fallback communication. The framework demonstrated reliable operational continuity under low-connectivity areas, providing a scalable and low-cost intelligent maritime monitoring systems at sea and coastal areas.

Keywords: Maritime Safety Monitoring, Hybrid Communication Framework, Android mobile sensor, Intelligent Transport Systems, Low-Connectivity Coastal Areas

1. Introduction

Maritime transportation remains one of the primary concerns in economic activity, tourism, fisheries, and island communities in an archipelagic nation such as the Philippines. Based on the Philippines geographic formation composed of more than 7,000 islands, coastal and island communities depend heavily on island vessels for transportation, livelihood, emergency response, and tourism operations [1]. Small vessels or watercrafts such as fishing boats, motorized bancas, and recreational crafts continue to serve as essential transportation systems in many coastal areas. Despite its importance and significance, most small watercraft operate without real-time monitoring systems, automated warning mechanisms, or even modern maritime communication technologies, making them highly vulnerable to rough sea conditions and hazards, and communication failures [2].

The Philippine government and different agency mandated to monitor watercrafts or ships has continuously promoted the modernization of maritime safety systems through the Maritime Transport Science and Technology Roadmap, which identifies intelligent transport systems (ITS), vessel monitoring technologies, and maritime communication infrastructures as strategic priorities for improving marine transportation safety and operational efficiency [3]. The Republic Act No. 9295, an act on the Domestic Shipping Development Act of 2004 and Republic Act No. 9993, an act establishing the Philippines Coast Guard (PCG) emphasize the importance of vessel safety, maritime monitoring, and enforcement of navigation regulations within Philippine waters [4-5]. The PCG and Local Government Units (LGUs) also continue to strengthen safety monitoring and inspection operations for small crafts and recreational vessels operating in coastal communities in each regions [2].

The current maritime communication systems such as the Automatic Identification System (AIS), satellite communication systems, and VHF/UHF radio technologies have significantly improved navigation and vessel monitoring for commercial ships and large-scale maritime operations. But these technologies are often expensive, resources and infrastructure dependent, and impractical for implementation and use in small-scale watercraft operating in coastal communities and island communities [6]. Existing maritime monitoring systems also heavily depend on stable internet connectivity and satellite communication lines, and dedicated communication infrastructures, which are often unavailable in geographically isolated and low-connectivity coastal environments and most of the island communities [7]. These setbacks limit the effectiveness of real-time vessel monitoring, emergency communication, and maritime operation awareness, especially during adverse weather conditions and operations [8-9].

Current developments in mobile sensing technologies and Internet of Things (IoT) based systems gives an opportunity for the development of low-cost maritime monitoring solutions. Android smartphones now have built-in sensors such as accelerometers, gyroscopes, magnetometers, and Global Positioning System (GPS) modules capable of collecting real-time motion, orientation, and navigation data with high accuracy [10]. Mobile sensing technologies have been successful in utilization in transportation monitoring, environmental sensing, and mobility analytics because of their portability, accessibility, and computational capabilities [11]. These developments allow Android smartphones to function as low-cost onboard data acquisition devices for maritime monitoring applications.

Studies have experimented the use of wireless sensor networks, cloud-based systems, and cellular communication technologies for maritime safety and vessel tracking applications. Recent studies had investigated energy-efficient and communication-optimized wireless sensor network architectures to improve monitoring reliability and transmission efficiency in distributed systems [12]. The work of Xu [7] investigated mobile communication systems for maritime connectivity, another paper [13] discussed low-power, with wide-area communication technologies appropriate for IoT-based monitoring systems. Another group of researchers proposed wireless network architectures [14-16] for maritime hazard condition monitoring and observation applications. Despite these developments, most existing systems still depend on nonstop internet connectivity and dedicated hardware infrastructures, limiting their usage for small-scale coastal operators, island and fishing communities.

Unlike in the previous SEAWAVES (Sea-condition Emergency Alert and Warning Apparatus for Vessel Safety) studies that focused on vessel tracking and monitoring systems, this work proposes and validates a hybrid communication framework combining mobile broadband, SMS fallback communication, and local built-in storage mechanisms for uninterrupted maritime safety monitoring in low-connectivity coastal areas. This study proposes a hybrid SMS and mobile network communication framework for maritime safety monitoring in low-connectivity coastal areas using the enhanced SAEWAVES technology. SEAWAVES technology is a mobile data acquisition system and cloud-based maritime monitoring platform that transforms Android smartphones into onboard data acquisition and communication devices for small watercraft operations. The system utilizes built-in Android sensors including accelerometer, gyroscope, magnetometer, and GPS/GPRS modules to compute vessel parameters such as pitch, roll, heading, speed, and geographic location in real time [17-18].

2. Materials and Methodology

This study adopted a developmental and systems engineering research approach in the design, implementation, and evaluation of the proposed Hybrid SMS and Mobile Network Communication Framework for Maritime Safety Monitoring in Low-Connectivity Coastal Areas. The work is focused on the development of a maritime monitoring architecture framework capable of supporting real-time vessel monitoring, hybrid communication transmission, and automated alert communication for small watercraft operations. The SEAWAVES technology was utilized as the primary platform for implementing the proposed framework.

The development process followed the Feature Driven Development (FDD) methodology to support iterative system development, feature integration, testing, and deployment.

2.1 *System Architecture*

The SEAWAVES technology architecture was designed to provide a low-cost maritime monitoring framework capable of operating in geographically isolated and low-connectivity coastal environments. The architecture integrates Android built-in sensor technologies, hybrid communication mechanisms, cloud-based monitoring services, and real-time alert dissemination to support intelligent maritime safety operations for small watercraft. The overall architecture is composed of five major components: (1) the watercraft data acquisition layer, (2) hybrid communication layer using the primary and secondary communication line, (3) data access network layer, the broadband or mobile data link, SMS gateway, and local storage mechanism, (4) cloud processing layer, which is the cloud-based monitoring system, and the (5) user deployment layer which is a dashboard monitoring interface. The complete operational workflow and interaction among these components are illustrated in the Fig 1, the hybrid communication workflow diagram and the system architecture diagram.

2.1.1 Watercraft data acquisition layer

The first component of the architecture is the watercraft data acquisition layer, which SEAWAVES mobile application functions as the onboard data acquisition and monitoring device installed on an Android smartphone placed inside the watercraft. The system uses built-in Android sensors including accelerometer, gyroscope, magnetometer, and GPS/GPRS modules to continuously collect navigational and motion-related information from the vessel. These Android built-in sensors are responsible for acquiring and computing real-time parameters such as pitch angle, roll angle, heading direction, vessel speed, latitude, longitude, and timestamp information. The application also executes preliminary processing, sensor calibration, parameter computation, and alert threshold evaluation before transmitting information to the cloud-based monitoring system.

2.1.2 Hybrid Communication Layer

The second component is the hybrid communication layer, serves as the central communication framework of the proposed system. The SEAWAVES technology architecture implements two communication lines: mobile data transmission as the primary communication channel and Short Message Service (SMS) communication as the secondary or alternative transmission mechanism. The system evaluates the accessibility and quality of the mobile communication network every one minutes interval. When mobile internet connectivity is available and stable, sensor data packets are transmitted directly to the cloud-based server through GPRS, LTE, or mobile broadband communication. The implementation of an efficient communication and transmission framework is important in maintaining effective continuous communication in low-connectivity area, particularly in AIoT-based monitoring systems [19]. The merging of IoT-enabled sensing devices and cloud computing platforms has shown to enhance communication reliability, scalability, and data availability in mobile communication systems operating under low-connectivity areas [20]. And when connectivity becomes intermittent, the framework automatically switches to SMS-based transmission to ensure non-stop delivery of critical monitoring information and alerts. This hybrid communication approach improves communication in low-connectivity areas.

The framework implements a local storage mechanism within the mobile application. During low-connectivity or no connection, sensor data are temporarily stored within the device's local storage using queue-based storage and retransmission protocol upon detection of signal. The locally stored information remains in the mobile device while awaiting the connection of either the primary mobile data connection or the secondary SMS communication channel. Once communication becomes available, the stored data packets are automatically retransmitted to the cloud-based server layer. This way prevents data loss, maintains voyage history integrity, and ensures non-stop maritime monitoring even in low-connectivity coastal, and island communities.

2.1.3 Data Access Network Layer

The third layer consist of an SMS gateway, which serves as the in-between communication service responsible for receiving and forwarding SMS-based transmissions from deployed SEAWAVES devices in the areas. The SMS gateway converts received SMS packets into structured digital information that can be processed by the cloud server and integrated into the monitoring system database. This component lets the system to maintain its monitoring function even in environments where internet communication is unavailable but cellular SMS infrastructure is available.

2.1.4 Cloud-based processing layer

The transmitted sensor and monitoring data are processed within the Cloud-based Monitoring System, which functions as the centralized processing and storage infrastructure of the SEAWAVES platform. The utilization of cloud computing provides central data management, scalable processing capabilities, and seamless integration with IoT-enabled mobile computing platforms, making it suitable for real-time monitoring applications in geographically dispersed areas [20]. The cloud server is responsible for data reception, validation, storage, alert processing, voyage logging, historical data management, and system analytics. The server also hosts the alert evaluation engine that analyses vessel movement parameters and determines corresponding alert levels based on predefined safety thresholds. The cloud infrastructure supports synchronization of transmitted data from multiple deployed watercrafts and enables centralized monitoring and decision-making operations.

2.1.5 User deployment layer

The final component of the architecture is the Dashboard Monitoring System, which provides a web-based graphical monitoring interface accessible to maritime authorities, local government units, disaster risk reduction offices, port management agencies, and vessel operators. The dashboard displays real-time vessel positions, motion parameters, voyage logs, alert notifications, and historical navigation records. The monitoring interface also visualizes vessel conditions using a multi-level color-coded alert system composed of blue, yellow, orange, and red alert classifications. This dashboard enables maritime stakeholders to monitor vessel operations, identify abnormal vessel movement, and respond to potential maritime safety risks in real time.

2.2 *Alert Generation Algorithm*

The system incorporates a threshold-based alert detection algorithm designed to identify abnormal vessel movement and potential navigation risks. The algorithm continuously evaluates pitch angle, roll angle, and vessel orientation against predefined safety thresholds configured within the monitoring system.

The system classifies vessel conditions into four alert levels, this one additional condition set from prior paper [15]:

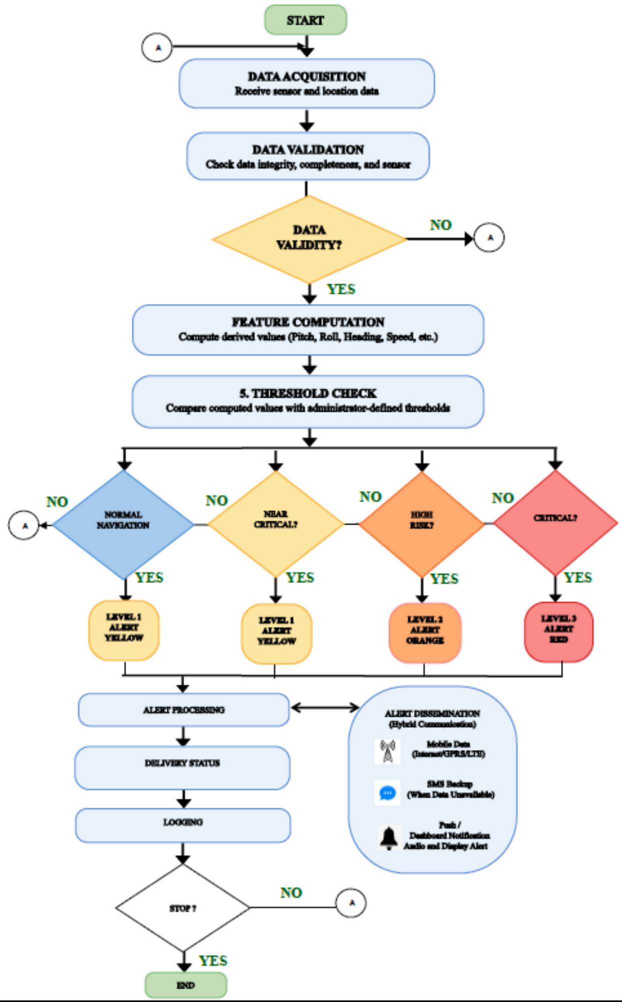
- Blue, normal operating condition;
- Yellow, warning condition threshold reached 20% before the critical level;
- Orange, high-risk condition threshold reached 10% before the critical level; and
- Red, critical vessel condition threshold reached.

When the built-in Android sensor readings exceed thresholds, the application automatically produces display alert and audio alert in the application and transmits notifications to the cloud-based server, monitoring dashboard and vessel operator through mobile data or SMS communication channels.

The SEAWAVES mobile application continuously collect sensor data, and computes for the pitch, roll, heading, speed, and geographical location from the watercraft. The system checks for the validity, of the incoming data to ensure completeness, correctness, and sensor availability, invalid data are flagged and logged.

Validated data and processed to compute for the parameters for normal navigation, alert levels such as yellow, orange and red for alert evaluation. Computed parameters are compared to the threshold for each parameter. Alert decision are determined by the system, for the normal, within the safe navigation condition. Level 1, yellow alert, is 20% before the critical level is reached, and continues to have alert until such time that another level is reached. Level 2, orange alert, is 10% before the critical level is reached, and continues to have alert until such time that another level is reached. Level 3, red alert, when critical level is reached, and continues to have alert until such time that another level is reached.

When condition is met, the appropriate alert is generated, stored, and prepared for transmission. Alert transmission is sent via the mobile channel data or SMS as fallback, which ensures delivery even in low-connectivity areas. For the delivery status, this is being monitored by the system and switches channel if needed. For logging, all alerts and actions are logged for traceability and analytics. The stop navigation function allows the system to terminate the navigation process and continuously iterate until the stop button is activated.



2.3. *System Deployment and Evaluation*

Field testing and deployment activities were conducted in selected coastal and maritime environments in Western Visayas and Surigao del Sur. Actual vessel deployments were performed using small watercraft operating within coastal and inter-island routes. Testing activities included:

- sensor accuracy evaluation;
- communication transmission reliability testing and SMS fallback validation;
- alert generation testing;

Performance metrics evaluated during testing included transmission success rate, sensor accuracy, communication latency, and alert response time. Deployment activities demonstrated that the proposed framework was capable of maintaining reliable maritime monitoring and alert transmission even in low-connectivity coastal and island communities.

To evaluate the operational performance and reliability of the proposed hybrid communication framework, field deployment and testing activities were conducted in actual maritime environments. The SEAWAVES technology was deployed across 10 small watercrafts operating within selected coastal and inter-island routes in Surigao del Sur, Philippines. The deployment covered a total of 30 test voyages conducted over a period of 3 days, 1 day during the rainy season with 3 smallcraft and 2 days during the summer season with 10 smallcrafts, allowing the system to be assessed under varying sea conditions, navigation patterns, and communication environments operating on an average of 3 hours during the deployment.

Based on the deployment period in a 5-minute interval, the SEAWAVES mobile application continuously acquired vessel motion and navigation data including pitch, roll, heading, speed, latitude, and longitude. A total of 1100-1200 transmitted data packets were generated and transmitted through either the primary mobile data communication channel, startup packets, retransmission, alert transmission, and the SMS fallback communication transmission. The transmitted data were received, processed, and stored within the cloud-based monitoring platform for subsequent analysis and validation.

3. Results and Analysis

3.1 *Sensor Accuracy Evaluation*

The performance of the built-in Android sensors was evaluated during field deployment and testing activities. The system uses built-in android sensors such as accelerometer, gyroscope, magnetometer, and GPS/GPRS sensors to compute and acquire vessel motion and navigational information.

The results showed that the mobile application achieved high monitoring accuracy across all evaluated parameters. Table 1 presents the average sensor and computed parameter accuracy obtained during actual maritime deployment activities.

Table 1. Sensor, and Computed Parameter Accuracy Evaluation of the SEAWAVES Monitoring System

Android Sensor, Computed Parameter	**Average Accuracy (%)**
Timer	98
Heading Direction	100
Pitch Angle	99
Roll Angle	99
Gyroscope	99
Accelerometer	99
Magnetometer	97
Latitude	99
Longitude	99
Average	**98.78**

The attained results indicate that Android smartphone-based mobile application can provide reliable vessel motion and navigation measurements for maritime monitoring applications. The accelerometer and gyroscope sensors consistently detected vessel movement and orientation changes with high precision, while the GPS/GPRS modules provided accurate positional information throughout navigation activities. These findings support previous studies demonstrating the applicability of smartphone sensors for transportation monitoring and mobile systems [8-9].

3.2 *Communication Transmission Reliability*

The hybrid communication framework was evaluated in terms of transmission reliability under varying network conditions. The framework utilized mobile broadband communication as the primary transmission channel and SMS communication as the fallback communication mechanism. The proposed hybrid communication framework demonstrates similarities with recent energy-efficient wireless sensor network architectures designed to improve communication reliability and transmission performance in intelligent monitoring systems [20].

The results as seen in Table 2, established that the proposed framework maintained reliable communication performance even in low-connectivity coastal environments. During stable network conditions, mobile data transmission provided non-stop real-time synchronization between the mobile application and the cloud-based monitoring platform. During intermittent connectivity interruptions, the framework automatically switched to SMS-based communication while temporarily storing unsent sensor data within the local storage in the smartphone. Once connectivity became available, queued data packets were automatically retransmitted to the cloud monitoring system.

The hybrid communication mechanism significantly improved communication resiliency compared with conventional internet-dependent monitoring systems. The SMS fallback development enabled the system to continue transmitting critical maritime alerts even in areas with low-connectivity issues.

Table 2. Communication Transmission Performance

Communication Parameter	Rate
Average Mobile Data Transmission Success Rate	96%
SMS Transmission Success Rate	98%
Average Transmission Delay	seconds

3.3 Alert Generation and Maritime Safety Monitoring

The alert generation algorithm effectively detected vessel movement and generated corresponding maritime safety alerts during deployment and testing activities. The system continuously computes for the pitch angle, roll angle, heading direction, and track vessel motion conditions against thresholds.

During testing and deployment states, the system successfully generated alerts as seen in Table 3, whenever vessel movement parameters are over safety thresholds. The generated alerts were transmitted through either mobile internet communication or SMS fallback transmission depending on network availability. Alerts were also displayed in real time within the cloud monitoring dashboard using a color-coded system and audio alert can be heard from the mobile application.

Table 3. Alert Generation Performance

Alert Level	Trigger Condition	Rate (%)
Blue	Normal operation	99
Yellow	20% before threshold of critical level	99
Orange	10% before threshold	99
Red	Critical threshold reached	99

3.4 Analysis of the Proposed Framework

The results demonstrate that the proposed hybrid communication framework provides a low-cost and scalable maritime monitoring solution for small watercraft operating in low-connectivity areas. Different from conventional maritime monitoring systems that depend entirely on internet communication infrastructures and satellite communications, the proposed framework implements a hybrid communication framework to maintain operational continuity during network interruptions.

The use of Android built-in sensors in smartphones as onboard data acquisition systems also effectively minimizes deployment costs compared with traditional maritime instrumentation systems such as AIS and dedicated vessel monitoring equipment. The framework also demonstrates the practicality of implementing mobile applications, cloud-based monitoring systems, and intelligent communication fallback framework for maritime safety applications.

The successful deployment of the hybrid framework in actual coastal and island communities indicates its usefulness and effectivity for maritime safety operations, coastal disaster preparedness, intelligent transport systems, and community-based maritime monitoring initiatives in geographically isolated maritime regions. The deployment generated a total monitoring duration of 69 navigation hours and covered approximately 400 kilometers of maritime travel routes.

Table 3. Comparative Evaluation of the Enhanced SAEWAVES Technology Against Existing Maritime Monitoring Systems

Feature	AIS	VHF Radio	SEAWAVES Framework
Real-time tracking	/	X	/
SMS fallback	/	X	/
Low-cost deployment	X	/	/
Smartphone-based	X	/	/
Cloud Monitoring	Partial	X	/
Local Offline Storage	X	X	/

4. Conclusions

This study presented the implementation of a Hybrid SMS and Mobile Network Communication Framework for Maritime Safety Monitoring in Low-Connectivity Coastal Areas through the deployment of the SEAWAVES technology. The framework effectively implemented an android smartphone-based mobile application, hybrid communication transmission, local offline storage, cloud-based monitoring system, and automated maritime alert transmission to support intelligent maritime safety operations for small watercraft. Results of the field deployment and testing demonstrated that the built-in android sensors, achieved an effective monitoring performance with an overall average accuracy of 98.78% rating in acquiring and computing vessel parameters such as pitch, roll, heading, speed, and geographic position. These findings confirm the fitness of Android smartphones to function as low-cost instrumentation and mobile data acquisition systems for watercraft.

The hybrid communication architecture also established an improvement in communication under low-connectivity coastal and island communities. By using mobile broadband communication with SMS fallback transmission and local storage mechanisms, the framework maintained operating non-stop even during low-connectivity issues. The automatic communication switching and effectively minimized data loss while ensuring non-stop transmission of vessel monitoring information and alerts. The alert generation algorithm effectively identifies from normal to critical vessel alerts and this categorized vessel status into blue, yellow, orange, and red alert levels.

The study effectively adds to the development in intelligent maritime transport systems by demonstrating the practical application of mobile sensing technologies, cloud-based monitoring systems, and hybrid communication frameworks for maritime safety and disaster applications. Future work may focus on integrating data analytics, machine learning-based sea-condition prediction, and large-scale deployment across multiple maritime transport corridors and coastal regions in the Philippines.

Conflicts of interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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