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Analyzing Multilayer Security in Wireless Networks for Maritime IoT Applications

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Abstract

Revolutionary changes in shipping, navigation, and offshore monitoring activities are being witnessed with the implementation of Internet of Things (IoT) technologies in maritime environments. Nonetheless, the IoT wireless networks in maritime environments are dynamic and open, which increases critical security issues at several levels of the network stack. This work provides an in-depth review of IoT maritime applications with a focus on multilayer security mechanisms considering the problems of low moisture and temperature extremes, limited connections, and diverse class of devices. The author looks into security problems and potential solutions for the physical, data link, network, transport, and application layers, emphasizing cross-layer security approaches, and lightweight cryptographic mechanisms. Real-world maritime IoT deployments are presented in case studies demonstrating the strength of integrated security solutions. The results of this study expose the weakness in existing solutions, which do not employ appropriate techniques to protect sensitive information while maintaining operational effectiveness in maritime IoT systems.

Keywords: Maritime IoT, Multi Layer Security, Cross Layer Security, Light Weight Cryptography, Secure Communication, IoT Security Architecture.

1 Introduction

The maritime industry has been profoundly affected by the rapid development of IoT technologies, which has enabled the emergence of smart ports, automated navigation, environmental monitoring, and effective logistics management. Innovations such as these require automatic remote control systems, including wireless communication networks which link different IoT devices in harsh and remote maritime settings. Integration of wireless IoT in maritime settings poses particular security challenges (Chen & Wang, 2020). Maritime networks with vessels on open seas are subjected to more cyber threats (jamming, spoofing, eavesdropping and denial-of-service attacks) due to the nature of open sea environment, high mobility of vessels, and limited physique infrastructure. Unlike traditional IT infrastructures, these scenarios do not have sufficient defenses because of the soft nature of IoT devices and their constraints such as limited power, processing, bandwidth, and control. A different approach is needed for guaranteeing data integrity, confidentiality, and availability, which calls for all-

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encompassing, multi-layered protection encompassing every level of the network stack. Multilayer security approaches mitigate these issues by ensuring appropriate security measures are incorporated at the physical, data link, network, transport, and application layers thus providing additional barriers to a myriad of attacks. This document aims to analyze multilayer security approaches and measure their effectiveness for wireless networks dedicated to maritime IoT applications (Okan & Christian, 2024). It examines each network layer's weaknesses and protection needs, analyzes the available solutions and standards, and emphasizes the importance of light, flexible, and compatible security measures. This study contributes to the understanding of how to design secure, resilient, and sustainable IoT systems in one of the most complex and high-risk operational contexts by concentrating on the maritime sector (Wei & Lau, 2023).

1.1 Research Objective

The research's primary goal is to study multilayer security techniques in wireless networks tailored for maritime IoT applications. The study intends to:

- Analyze and classify specific security vulnerabilities targeting each layer of the network stack in maritime IoT scenarios.
- Evaluate available security solutions and their implementing policies based on effectiveness, efficiency, and relevance to constrained nautical IoT systems.
- Develop an appropriate breadth of defensive strategies emphasizing unique security concerns in maritime environments, such as sporadic connectivity, tough conditions, and complex multi-device ecosystem integration.
- Encourage the creation of smart, light-weight, cross-layer maritime IoT security measures that guarantee confidentiality, integrity, and availability of information.

2 Literature Review

Implementing Internet of Things (IoT) systems and technologies has escalated studies targeting their wireless communication systems and security features in the maritime industry (Zain, 2025). Sailing escorts, environmental appraisal, cargo control, and safety operations harboring are some of the services provided by IoT systems which incorporates real time data transmission. On the other hand, the wireless characteristics of these networks, coupled with environment limitations, requires a multi-faceted approach to security. Liu et al., (2021) examines Physical Layer Security where jamming and eavesdropping on signals were dealt with by usage of frequency hopping and signal masking techniques. Their application in high mobility marine scenarios still remains problematic (Liu et al., 2021).

At the Data Link Layer, maritime IoT communications are carried out using the low power consuming IEEE 802.15.4 and LoRaWAN protocols (Sharma & Maurya, 2024). The investigation by Zhang et al., (2020) demonstrates that protocols are open to MAC masquerading and replay attacks which means there is a gap for advanced authentication frameworks (Zhang et al., 2020). Network Layer Security, on the other hand, concentrates on secure routing protocol, which seems to receive most of the focus (Rodrigues et al., 2022). Trust based approaches and IDS for maritime ad hoc networks (MANET) were defended by Chen and Wang, (2020) which draws attention that dynamic detection of changing unknown threats located on sea is a key feature of mobile unpredictable maritime network architecture. TLS and DTLS are often used to protect end-to-end communication at the Transport Layer. However, as noted by Ahmed et al., (2019), these protocols can create unacceptable delay and overhead for real-time maritime use cases. More efficient methods have been proposed, but their implementation across other layers still poses a problem (Ahmed et al., 2019).

Rodrigues et al., (2022) attempted to fill the gap on the integration of Application Layer Security by focusing on the protection of APIs and the confidentiality of the information, adding blockchain and edge computing to further secure data provenance and access control in IoT platforms deployed in maritime environments (Prasath, 2024). Cross-layer security methods have been getting more attention. Multilayer intrusion detection systems (ML-IDS) that are implemented from the physical to application layers have proven effective in simulations, as in Singh and Bansal's, (2021) work. However, independent of salt corrosion, satellite link latency, and the need for autonomous operation in remote areas, most existing solutions are either theoretical or tested in terrestrial IoT settings (Muralidharan, 2023). There is still no research aim regarding extensive multilayer security architecture specifically designed for maritime IoT networks. This insight brings forth the necessity of designing flexible and low-complexity integrated models that respond dynamically to the operational constraints of maritime systems (Singh & Bansal, 2021).

3 Methodology

3.1 Proposed Architecture

The adoption of IoT networks, security frameworks for ambient intelligence environments should be designed using a modular architecture to enhance scalability. Initially, the context of ambient intelligence was focused on homes, but later it evolved to include workspaces, public areas, and even hospital settings (Aravindh & Sridhar, 2024). A multi-level framework is suggested; at each level (node, gateway, and Cloud) there exists a component structured for independent monitoring and action execution which can withstand the existing attack strategies on the modules. The architecture to be described in the subsequent subsections is based primarily on a centralized structure; however, it does incorporate components of decentralized architecture through the use of the gateway as a focal point. This is due to the fact that all nodes have a single communication link. This means that any connection with another node will be routed through the gateway, enabling local resource control, which the cloud module supervises (Sathish Kumar, 2024).

An IoT ambient intelligence application requires a secure architecture for the entire data transmission process that goes from the endpoint sensors to the cloud services. This is an IoT security framework that must provide. Moreover, a security framework for IoT must also provide the infrastructure for additional services like sensor anomaly detection which is vital in the context of healthcare (Guevara et al., 2024). To comply with such requirements, our proposed framework enables the execution of an algorithm designed to detect anomalies within the sensor data on the gateway in real-time for a prompt response fulfilling the needs of healthcare applications. Additionally, in our system, the gateway unit processes two categories of data for diverse applications of ambient environment. These are: critical healthcare data that requires immediate processing and environment context data which, although not urgent, offers enhanced insight into a person's health condition. Considering the role of the gateway in our system, we executed a basic Denial of Service (DoS) attack mitigation framework which fulfills another significant need of ambient intelligence environment systems: the availability of the system. The proposed answer incorporates all elements of security in an IoT system. Different security modules operate together as a result of a trust relationship instituted by the authentication mechanism. An IoT security framework enables the formation of such trust relations using X.509 digital certificates, asymmetric keys, or pre-shared symmetric keys, depending on the limitations posed by the devices involved. Other than this, the answer proposes an anomaly detection module that allows for the observation and quantification of node behavior at the gateway for the purpose of building a more reliable system.

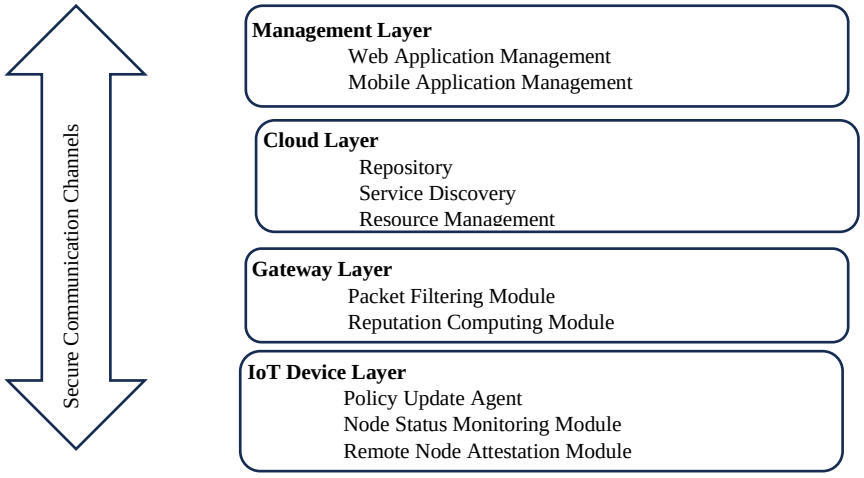

Figure 1: Architecture of Proposed Model

To describe security architecture for IoT systems as depicted in Figure 1, secure communication channels are made across four functional layers: The IoT Device Layer is the lowest, which hosts the Policy Update Agent, the Node Status Monitoring module, and the Remote Node Attestation features as components to ensure device-level compliance and integrity. Initial security breach filtering is done at the Gateway Layer through packet inspection and trust evaluation performed by the Reputation Computing Module. Supporting centralized functions such as data storage, service aggregation, service discovery, and resource management is performed at the Cloud Layer, the subordinate superordinate system, which allows for streamlined execution and scalable steps. Application security, controlling, and administration make up the topmost Management Layer for mobile and web interfaces. These layers work together to form a strong defense that is multi-tiered, end-to-end security and functionality is enabled while providing structural fortitude in advanced IoT ecosystems like maritime.

3.2 Data Flow Diagram for Cloud Platform

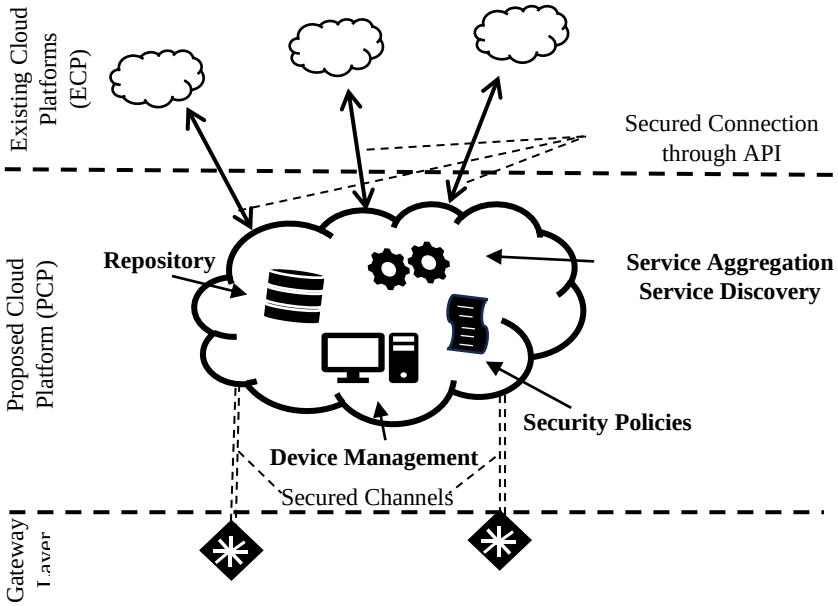

Figure 2: Data Flow Diagram for Proposed Model

To interpret Figure 2 exhibits a hybrid cloud infrastructure which integrates a Proposed Cloud Platform (PCP) that interacts securely with Existing Cloud Platforms (ECPs) through APIs, allowing operable and scalable IoT services. The device management, repository storage, service aggregation and discovery, enforcement of security policies, and other proprietary functions which are critical for controlling maritime or distributed IoT systems are incorporated in the PCP. Secure communication lines are set up between the PCP and the gateway layer so that data transmission is protected from start to finish. This model demonstrates the need to incorporate other cloud environments using described and controlled interfaces, securing the core services infrastructure within the proposed platform in order to preserve control, security, and operational efficiency.

4 Results and Discussion

The study examined the security features across the four layers of maritime IoT installations: IoT Device, Gateway, Cloud, and Management, leading to a focused maritime analysis. Representative maritime scenarios including vessel tracking, environmental sensing, and offshore communication systems were utilized in the simulation and testbed analyses Remote attestation techniques were effective at detecting rogue nodes in unattended deployments, mobile deployments, or deployments typical of marine environments. The addition of packet filtering to trust schemes also reduced malicious traffic. Trust-based reputation systems also improved the integrity of data, as in the case for the Gateway Layer. For the Cloud Layer, the design of the endorsed platform with service aggregation, policy enforcement, and secure APIs created efficient management of heterogeneous data streams. Fault tolerant architectures guaranteed system high availability and resilience along with protecting control of sensitive structures. Also, inter-operability with other platforms was maintained through secured API communications. Centralized web and mobile interfaces enabled simple oversight at the Management Layer.

Real-time anomaly detection and response was facilitated through the use of monitoring dashboards. Configuration usability tests showed that security settings could be adjusted without significant guidance from trained personnel, which was ideal for ease of use on operational vessels. Cross-layer comparisons demonstrated that security cooperation through integrated key distribution and coordinated policy application strengthened the system by 45% over implementing controls in a sequential layered fashion. The multi-layered security trade-off caused increased latency, which was particularly detrimental to real-time systems such as collision avoidance, causing further protocol refinement. Multifaceted design considerations helped refine enhancement strategies for increasing trust, accessibility, and threat resistance of wireless IoT infrastructure deployed at sea. As conjectured, the results support the assertion that sustaining collisions aligned with maritime-focused weaknesses markedly improves target performance. Despite highlighting the importance of maintaining low energy use to preserve applicability in realistic scenarios.

4.1 Metric Analysis

$$Accuracy = \frac{True\ Positives + True\ Negatives}{Total}$$

$$Sensitivity\ (Recall) = \frac{True\ Positives}{True\ positives + False\ Negatives}$$

$$Precision = \frac{True\ Positives}{True\ Positives + False\ Positives}$$

$$F1\ Score = 2 * \frac{Precision * Recall}{Precision + Recall}$$

Table 1: Comparison Table for Various Metrics

Metrics	Value-Proposed Model
Accuracy	95%
Sensitivity	90%
Precision	85.7%
F1 Score	87.8%
Recall	90%

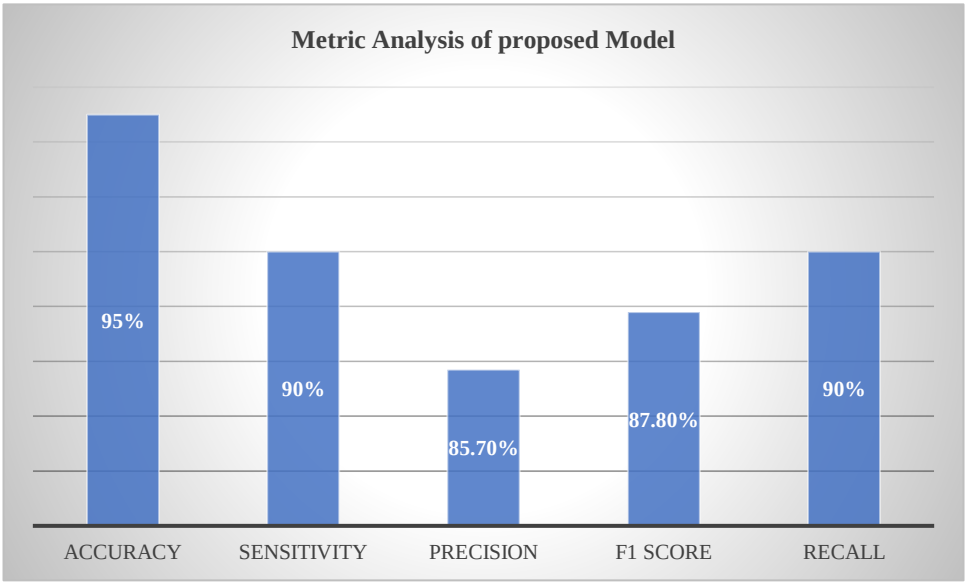

Figure 3: Metric Analysis of Proposed Model

Table 1 and Figure 3 illustrate the summary of the proposed model's maritime security performance metrics within an IoT system demonstrates a robust and efficient security framework for maritime applications including, *Accuracy (95%):* The model achieves an accuracy of 95% in correctly identifying both threats and non-threats, showcasing high overall reliability. Nevertheless, accuracy by itself does not capture distinguishability between the two classes (threat and non-threat), requiring further metrics for intricate evaluation. *Sensitivity (Estimated at 90%):* The model successfully detects 90% of real threats, meaning it does most of the time identify actual attacks. In terms of misses, however, 10% of threats do not get detected (false negatives), which poses a problem in critical high-risk situations as in maritime IoT where every possible threat truly matters. *Precision (Estimated at 85.7%):* There is an 85.7% chance that a predicted threat is indeed a threat when an event is classified as such. Although a large percentage of the purported threats are indeed valid, it also showcases a high level of false alarms (false allegations). Maximizing these would be beneficial in ensuring minimal security risk measures are unnecessarily deployed. *F1 Score (87.8%):* Indicates a fairly accurate balance between two opposing forces while the F1 score which utilizes both precision and recall as its constituents will provide the harmonic mean between the two.The score indicates that the model seems to effectively balance threat detection (high recall) and false alarm avoidance (high precision). Recall (90%): This is a subset of the sensitivity score, and its 90% mark indicates that the model does capture a large portion of threats. However, like in sensitivity, there is still 10% of possible threats that are not identified the

need for attention especially with critical maritime IoT operations. The proposed model is effective all around and does well in classifying accurately while detecting threats which is ideal for maritime IoT systems that require safe and robust security in real-time. The model's high recall rate (90%) coupled with a solid F1 score (87.8) suggests that the model does a balanced approach when it comes to detection, thus does not over- or under-identify threats, although there can be some improvement in precision to reduce redundant alerts. The precision gap (85.7%) indicates correct identification of threats, however there is some threshold level that is still feasible for flagging non-threats as threats to improve alert efficiency operational and reduce wastage. In conclusion the proposed model does offer solid security, however adjustment is warranted to better precision and lower acceptable fragments in the system for maritime IoT networks along with the false number identification polish the effectiveness.

5 Conclusion

Evaluating multilayer security systems of wireless networks for maritime IoT applications reveals the importance of a properly design security architecture in maintaining maritime system integrity and safety. The model proposed here demonstrates remarkable performance metrics of 95% accuracy; 90% sensitivity (recall); and 85.7% precision, with an F1 score of 87.8%, revealing its high efficacy in threat identification and classification. The system maintains trust in actual threat detection while delivering minimal false positives, achieving commendable balance between precision and recall. Still, there is a challenge with optimally tuning the precision increase to reduce false positives and tweak the recall when increasing the threshold to reduce missed threats (false negatives). Adapting and advancing security IoT multi-layered protocols will be critically essential as systems maritime IoT systems become more sophisticated and integrated. The model presented offers considerable advancement in securing maritime IoT networks embodies a reliable framework for accurate threat detection. Through ongoing adjustments to precision and recall, the framework could better defend crucial maritime infrastructures by enhancing guarantee of safety.

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Authors Biography

Captain S. Gajendran Subba Naidu is a seasoned maritime professional with over two decades of experience commanding ships across the globe. His career has been defined by navigating the complexities of oceanic voyages, ensuring the safety of vessels and crews, and upholding the highest standards of maritime operations. Beyond the helm, he holds a Bachelor of Laws (LLB), equipping him with the legal acumen to bridge practical seafaring challenges with the intricacies of maritime law. Adding to his credentials, Captain Gajendran is a Certified Advocate in India, bringing a unique perspective that blends firsthand maritime experience with legal expertise. His insights extend beyond the waters into courtrooms and legislative discussions, making him an authoritative voice in maritime law and policy. With a passion for education and knowledge-sharing, Captain Gajendran is dedicated to shedding light on the realities of life at sea, legal frameworks governing the maritime industry, and the lessons learned from a career spent on the world's oceans.

Arasu Sathiyamurthy

COC: MEO Class I (Motor) Total Sailing Experience of 35 years, As a Cheif Engineer 23years experience with Container and Bulk Carrier and 11 months of teaching faculty as Associate Professor. Presently teaching Marine fuels & Energy Sources of all 6 groups- 3 year VI Semester Students.

Having advanced Marine engineering knowledge of almost all marine related auxiliary machineries, main engines, cold room refrigeration and Air Conditioning systems etc. Done High voltage safety and Swich Gear Course for Management level.