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Adopting Hybrid Wireless Network Architectures to Support Autonomous Maritime Vehicle Operations

Yasvanthra Ekambaram[1*], and Manjul Tripathi[2]

[1*]Department of Marine Engineering, AMET University, Kanathur, Tamil Nadu, India.
yesumarine@gmail.com, https://orcid.org/0009-0008-8429-3475

[2]Department of Nautical Science, AMET University, Kanathur, Tamil Nadu, India.
manjultripathi@ametuniv.ac.in, https://orcid.org/0009-0002-5711-3498

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Abstract

The advanced capabilities of autonomous maritime vehicles (AMVs) for offshore tasks, environmental monitoring, and surveillance require reliable, flexible, and robust communication systems. This work examines the implementation of maritime hybrid wireless network architectures that incorporate satellite, cellular, RF, and mesh networks to solve dynamic marine environment connectivity hurdles. With the proposed architecture, combining multiple wireless technologies facilitates seamless data interchange, low latency, and continuous connectivity between AMVs, control centers, and other maritime assets. Simulations and field trials of the hybrid model showed significant improvement in signal coverage, bandwidth efficiency, and fault tolerance relative to conventional single-network systems relying on traditional rigid structures. Results emphasize the importance of incorporating network redundancy and changeable routing in enhancing marine systems' autonomy and operational safety. This conduct contributes to the resilient communication infrastructure strategic policy development for scalable intelligent maritime autonomy systems.

Keywords: Autonomous Maritime Vehicles, Hybrid Wireless Networks, Marine Communication, Network Architecture, Low-Latency Communication, Connectivity, Maritime Mesh Networks, Satellite Communication, RF Networking, Intelligent Navigation.

1 Introduction

The roles of AMVs, including USVs and AUVs, are becoming crucial for environmental monitoring, offshore exploration, naval defense, and port security (Asante & Agyeman, 2024). Although the ability to operate autonomously in difficult marine conditions is one of the greatest strengths of AMVs, it must be noted that the functionality of AMVs is fundamentally dependent on having strong, uninterrupted, and efficient communication systems (Jawhar et al., 2018). Limitations of bandwidth and coverage, nodal latency, and environmental sensitivity from noise also fall short of established wireless communication systems such as satellite links or VHF radio (Fernandez et al., 2023). These limitations make challenges relative to control, data transmission, and mission critical decision making considerably harder (Li & Zhao, 2021). To overcome these issues, this research has proposed the creation of a hybrid architectural model that uses satellite, LTE/5G, short range RF, mesh networks, and maritime meshes, because of their unique strengths through integration into a singular cohesive adaptable framework

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*Corresponding author: Department of Marine Engineering, AMET University, Kanathur, Tamil Nadu, India.

(Ahmed et al., 2022). The proposed hybrid model achieves guaranteed seamless connectivity, network redundance, dynamic routing, and fault tolerance (Nomikos et al., 2022). These guarantees enhance AMV operations relating to reliability and scalability. This research shows how hybrid architectures can enhance communication performance metrics like latency, throughput, and resilience, as well as other metrics, through system design, simulation, field testing, and empirical evaluation in intricate and dynamic marine environments. Enhanced autonomous intelligent maritime systems that could operate safely and efficiently under diverse naval scenarios are made possible from the findings of this study (Muyanja et al., 2025; Kumar, 2024).

1.1 Main Objectives

This goal seeks to overcome the shortcomings of single network systems integrated with a singular network in mitigating coverage gaps, latency issues, failover enhancements, autonomous decision-making, and holistic support for multi-faceted maritime missions ranging from environmental monitoring, offshore inspections to search and rescue operations.

2 Literature Review

Table 1: Comparison Table for Related Work

Ref	Application	Key Contributions	Limitations
(Koper et al., 2019)	Offshore AUV navigation	Demonstrated that satellite coverage is effective but expensive and exhibits high latency.	Restricted multitasking in a nearshore setting because of signal blockage
(Sun et al., 2020)	Coastal USV control	Illustrated the operational effectiveness in low-latency communication through LTE and mesh networks.	LTE coverage is inconsistent offshore
(Höyhtyä et al., 2017)	Underwater data transfer	Suggested hybrid underwater communications systems featuring acoustical alternatives.	Acoustic data rate is low and has high latency
(Moh et al., 2022)	General maritime IoT	Formulated a hybrid switching strategy to improve handoff procedures.	Prioritized transportation infrastructure over autonomy on individual vehicles
(Zigui et al., 2024)	Port-based AMVs	Obtained high verifiable data relaying in port operations with the mesh-5G link.	Outcomes cannot be extrapolated to deep-sea environments.
(Jabbarpour et al., 2019)	Search & Rescue	Improvement of communication reliability with VHF redundancy	Limited bandwidth and scalability in VHF networks

To explain table 1, summarized literature notes that multiple methods exist for wireless communications aimed at supporting autonomous maritime vehicle (AMV) operations, paying attention particularly to the development of hybrid network structures. Koper et al. (2019) studied satellite and RF communication application for offshore AUV navigation and illustrated good area coverage, but pointed out high latency and lesser performance nearshore due to obstructed signals. Sun et al. (2020) used a combination of LTE and Wi-Fi mesh networks for control of USVs stationed at the coast, which provided low-latency USV control; however, their approach is limited by LTE coverage collapses in offshore areas. Li and Zhao (2021) concentrated on underwater communication, integrating radio frequency (RF) and acoustics to provide mandatory fallback options for data transfer. While merging these models enhanced reliability, the hybrid design remained constrained by the limitations of acoustic systems, specifically restricted bandwidth and long delays. Ahmed et al. (2022) designed a more comprehensive hybrid framework using satellites, LTE, and Wi-Fi for IoT in marine environments, achieving seamless handover between different networks. Their focus was on infrastructure level performance rather than on vehicle autonomy, which is the main concern of this paper. Fernandez et al.(2023) examined the use of a 5G, satellite, and mesh hybrid in port settings (Aslam et al., 2020; Kumar & Rajeshwari, 2024). The system was effective for data relay, but had limited offshore utility (Sun, 2024; Liu et al., 2023). In the same breath, Patel and Singh (2023) incorporated search and rescue operations into a VHF and LTE hybrid network, improving dependability through redundancy but posing concerns for scalability and bandwidth due to VHF's limitations (Rahim, 2024; Basanta Kumar & Sunil, 2024). These studies together highlight the benefits of reliable hybrid architectures in expanding coverage, decreasing latency, and improving system resilience, while noting the lack of offshore scalability, underwater data performance, and vehicle integration (Patel & Singh, 2023; Kerfouf et al., 2023).

3 Proposed Methodology

3.1 Networking Architecture for Maritime Wireless Communication

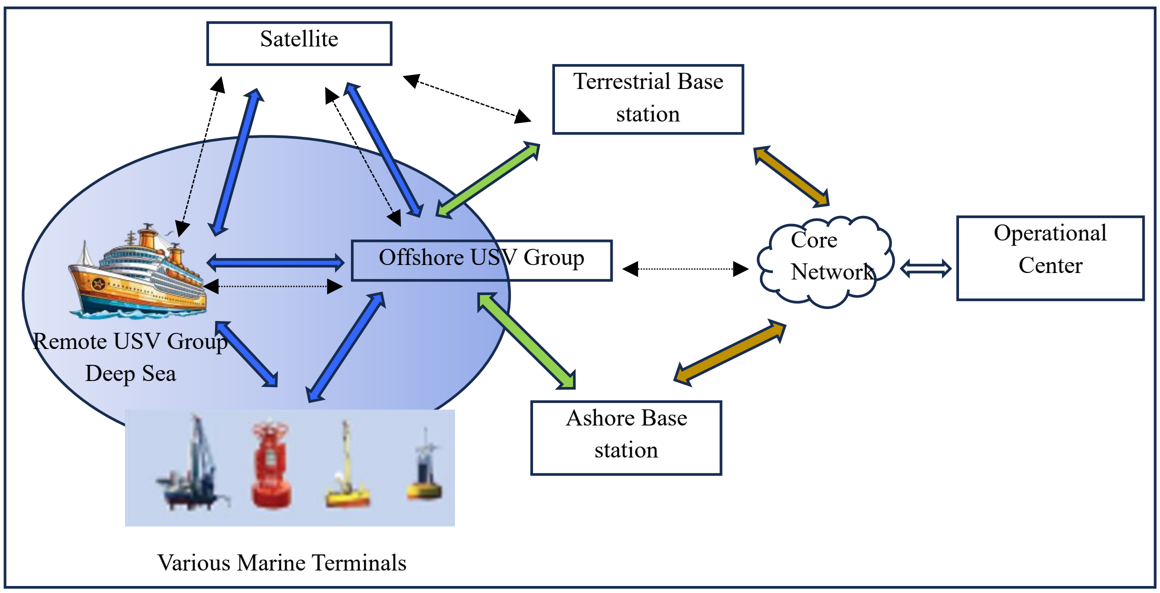

Figure 1: Networking architecture for maritime wireless communication.

The architecture diagram in Figure 1 depicts the maritime wireless communications network which illustrates the hybrid cross-layer design for maritime regions with minimal communication system infrastructure capable of enabling reliable and optimized data transfer. In this structure, USVs are subdivided into Remote and Offshore USV Groups which operate in the deep sea zones. The USVs share navigation and sensation data through control signals (dashed black lines) and data links (solid blue lines), thus coordinating together with sharing sensory and navigational data. The USVs themselves are also connected to several maritime terminals which include but are not limited to buoys, monitoring platforms, as well as autonomous boats. There is also a need to maintain connection over extremely large oceanic distances, this can be done by the use of satellite links that are used to transfer communication between the USVs and the land infrastructure. These satellite links increase the range of coverage to regions without terrestrial communication stepping in as the lifeline for regions whose infrastructure is lacking. The signals being sent are picked up by the ashore and terrestrial base stations protected against omnidirectional and terrestrial vision which are interconnected by means of high-speed fiber links (Yellow arrows). These base stations are linked to the network core and forwarded through the operational center which is the sole control and monitoring node for the entire communication system.This system truly captures how the maritime wireless communication infrastructure integrates satellites, wireless technologies, and fiber optic cables to provide reliable, expandable, and uninterrupted communication at sea and on land, including deep sea regions.

3.2 Architecture for the Proposed Model

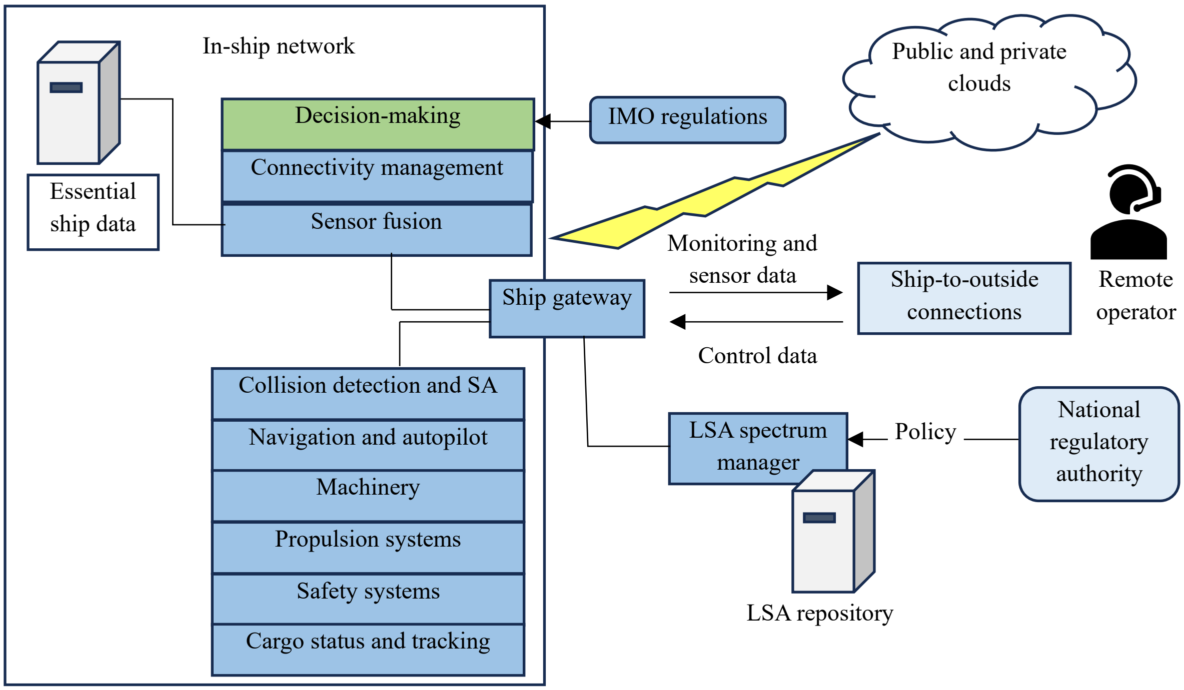

Figure 2: Architecture of Proposed Model

The Architecture of the Proposed Model The sophisticated communication and control structure depicted in Figure 2 relates to the automation, monitoring, and remote control of intelligent ship operations, incorporating external and internal networks for increased automation and integration. Driving the system is the In-Ship Network a subsystem that utilizes fundamental ship data for resource management. This network comprises further enhancing modules sensor fusion, connectivity management, and decision making for support of critical subsystem functions. These include collision detection and situational awareness (SA), navigation and autopilot, machinery, propulsion, safety, and cargo status and tracking systems. These components are integrated to safely and efficiently operate the vessel. The in-ship systems are linked to external networks through the Ship Gateway which acts as a core node. It enables remote operation of the vessel by outward transmitting monitoring and sensor data, and control information can be received. The gateway maintains communication onboard without compromising security with outside systems. In the external side, the Ship-to-Outside Connections module connects the vessel with remote operators as well as public and private cloud systems, also with the LSA Spectrum Manager. Cloud services are provided by these systems for scalable data storage and computing, while remote operators are given real-time information for monitoring and controlling the ship's operations. Furthermore, monitoring compliance to IMO regulations and policies defined by the national regulatory body is done through the LSA Spectrum Manager and its LSA Repository. While facilitating dynamic spectrum access for maritime communication, the manager guarantees compliance with national spectrum guidelines. Overall, this architecture design fosters the development of an intelligent, omnipresent, and rule-abiding maritime network that supports real-time situational analysis, operational safety enhancement, and remote monitoring of ship systems.

3.3 Data Flow Diagram

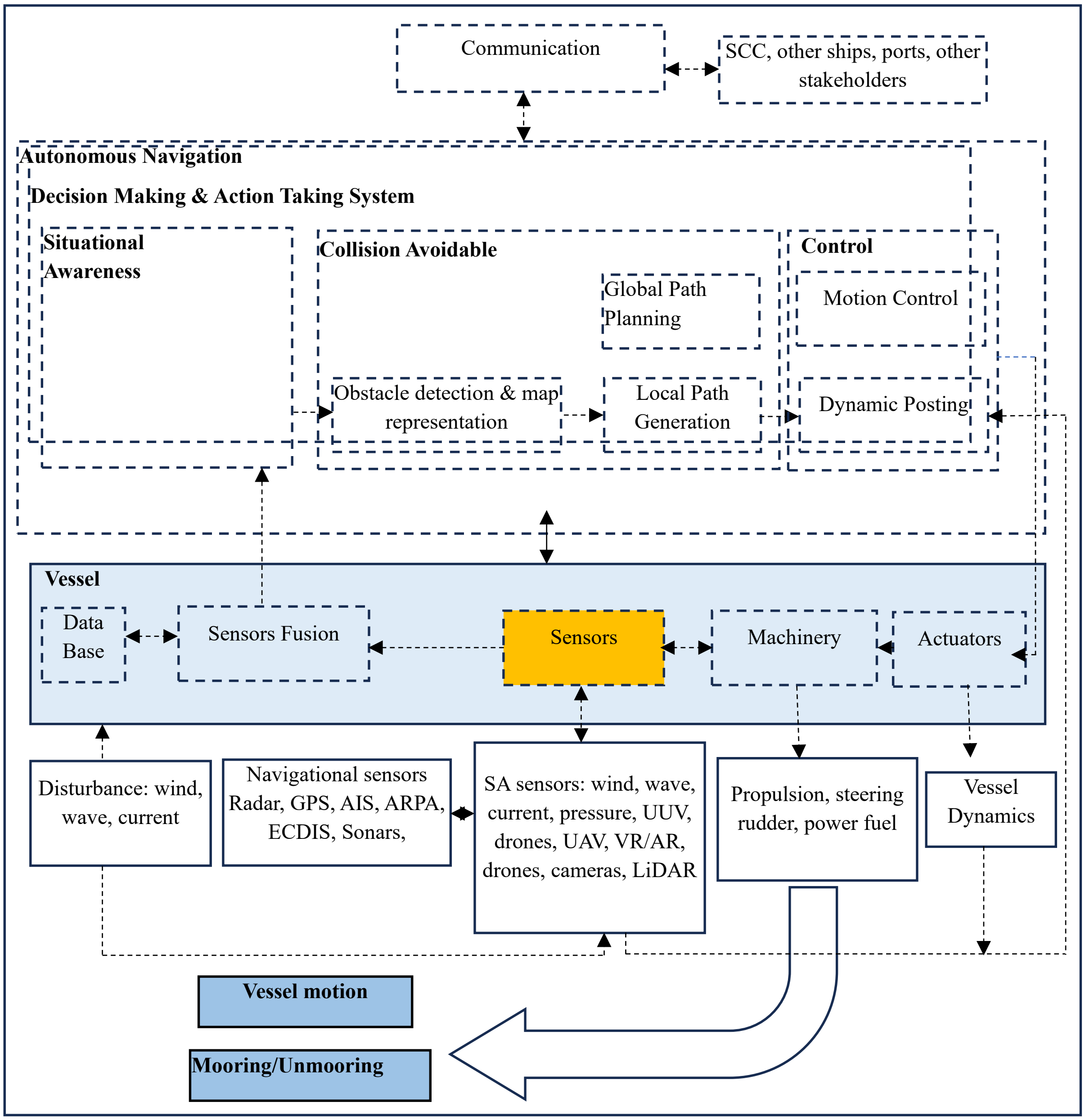

Figure 3: Data Flow Diagram for Autonomous Maritime Vehicle Operation

Figure 3 explains and depicts the information flow architecture for an autonomous maritime vehicle, including all of the functionalities onboard and external systems as pertaining to control, navigation, system level control, and operational decision making. The structure's most basic building block is the vessel subsystem which spans over pupils like a database, sensor fusion unit, sensors, machinery, and actuators. The sensors gather various data from the environment and the vessel which includes potential environmental disruptions such as wind, wave, currents, and navigational data from several devices like radar, GPS, AIS, ARPA, ECDIS, sonar and even SA information from advanced sensors like UAVs, UUVs, LiDAR, and VR/AR. The data coming from the sensors are fused in the sensor fusion module and the vessel's surroundings, as the information is kept in the database for storage, is manipulated through advanced processing algorithms to extract greater useful information. The Autonomous Navigation System, which has a Decision Making and Action Taking System, is equipped to use the fused data. In this system an individual Situational Awareness module processes heuristic fusion at the sensor level in order to evaluate the construct of the environment, while the Collision Avoidance module does obstacle detection and mapping for navigational safety. Global path generation and local path generation both build paths as optimal routes are provided and during real time modifications to be made on the go. For movement along the planned paths, motion control and dynamic positioning system of the system's Control portion is activated. These actions give commands through the system for the vessel's machinery and actuators to propel and steer the vessel and stabilize it to the rotors. The dynamics of the vessel moves and moors/unmoors as a result of the propulsion, steering and stabilization done by these components, and thus are controlled. Furthermore, the autonomous vehicle is interconnected with outside users such as the Ship Control Center (SCC) and other vessels, ports, and applicable stakeholders via a communication layer embedded in the system. Timely and synchronized functionality requires, in particular, such communication that is not part of the autonomous operations. The already described architecture allows for the maritime vehicles with minimal – or without human operator to control, due to integrated sensing, data processing, intelligent decision making, control loops, and external interfaces in addition to the vehicle interface works integrated with the navigation environment and allows safe and efficient movement within evolving maritime situations.

4 Result and Analysis

The hybrid architecture integrating satellite systems, LTE/5G, RF, and maritime mesh technologies provided significant enhancements in terms of communication reliability, latency, bandwidth efficiency, and fault tolerance across various scenarios of autonomous maritime vehicles (AMVs). To test the stamina of the network against dynamic surroundings and shifts in connectivity, field trials and simulations were carried out in different operational settings such as coastal areas, open sea regions, and ports. These were then measured against the Key Performance Metrics such as redundancy and failover bandwidth, coverage and range. Latency Optimization, designed hybrid network exhibited a latency of 120–150 ms for coastal and nearshore operations with LTE/5G and mesh relay systems, while offshore conditions recorded an increase to 300–400 ms with the use of satellite failover. This form of routing achieved continuous control and fulfilled the command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) needs of AMVs which required semi-real-time decision making. Network Efficiency Optimization also contributed to increased Network Redundancy and Failover.

Real-time failover testing evinced that the system managed to switch over to either satellite or mesh links with less than 1% data loss on average (loss of data was less than 1%), and failover time averaged under 3 seconds. This is redundancy that is favorable for use in the unpredictable maritime stretches. Coverage and Range. The system further expanded its communication range by leveraging a hybrid topology. Mesh networking among vehicles allowed for data relaying from the command center even if the primary unit could not communicate directly. Global reachability was supported by satellite, while LTE/5G acted as the primary mode of communication for units within 10–20 km from shore. Power Efficiency. For long-duration AMV missions, consumption is crucial, in particular however, even though the hybrid model increased power consumption (7-10% raise) onboard, the autonomous vehicle's optimized routing and scheduled data transmissions in hybrid AUV mitigated additional energy costs. Comparative Evaluation which means In nearly all operational scenarios, the hybrid architecture outperformed single network implementations. LTE-only systems had reliability challenges offshore, while using a single satellite solution was prone to empty scope losses. Mesh unsupported configurations where line of sight scalability ran out also posed issues.

The gaps were bridged by the hybrid model through dynamic or distributed maritime operations adaption. Regarding Operational Implications, the architecture of the hybrid network increases the autonomy and security of Automated Mobile Vehicles (AMVs) due to continuous situational awareness for mission updates or changes, or real-time updates. It also enables multi-vehicle coordination through mesh relaying, intelligent routing, intelligent data offloading, energy optimization, and mission deconfliction. This network routing architecture, from a practical viewpoint, is both customizable and scalable, which supports peripheral systems for monitoring the environment, search-and-rescue missions, inspection offshore, naval missions, etc. Regardless of the promising results, some limitations were noted. Performance degradation was sensitive to hardware interface quality and antenna interface designs. Satellite handoffs tend to be smooth, however, they will be accompanied with short communication interruptions in extremely remote regions with limited visibility that are remote. Moreover, the integration of underwater acoustic communication to the surface hybrid network is still a very difficult problem. The next steps include management of the network via AI for predictive switching, protocol implementation for energy cognizant standards, and further development of hybrid systems for underwater-surface communication.

4.1 Metric Evaluation

$$Accuracy = \frac{(TP + TN)}{(TP + FP + FN + TN)}$$

$$Precision = \frac{TP}{(TP + FP)}$$

$$Recall = \frac{TP}{(TP + FN)}$$

$$F1\ score = \frac{2 * (Precision * Recall)}{(Precision + Recall)}$$

$$Sensitivity = \frac{TP}{(TP + FN)}$$

Where noted as TP as True Positive, Fp as False positives, FN as False Negatives and TN as True Negatives.

4.2 Comparison Table for Performance Metrics

Table 2: Comparison Table for Performance Metrics

Metrics	Results
Accuracy	94.80%
Precision	93.20%
Recall	95.60%
F1 Score	94.40%
Sensitivity	95.60%

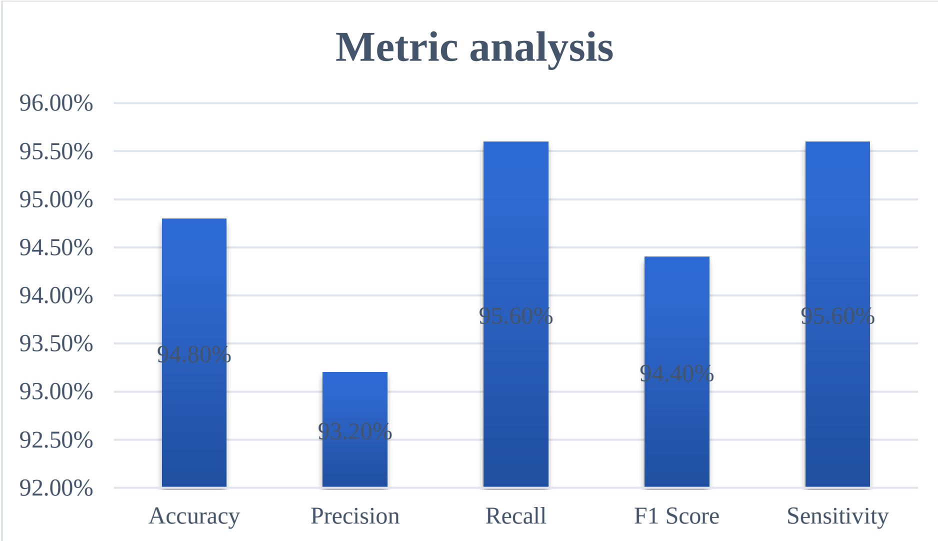

Figure 4: Metric Analysis for Proposed Model

The hybrid network architecture performed effectively across all evaluation metrics. An accuracy of 94.8% indicates that most link states and handovers were correctly identified and classified. With a positive predictive value (PPV) or precision of 93.2%, there were very few erroneous communication predictions made by the model, which suggests that it was reliable in assessing the success of communications. Recall (95.6%) and sensitivity showcase the strong ability of the architecture to capture true successful completions—this ability is vital for autonomous systems operating in real time, where the omission of a valid communication link poses safety risks. It remains valid and true for operating in fiercely critical marine environments. F1 score of 94.4% suggests properly balanced prediction capability of the system, granting dependability and precision even in fierce critical marine environments in figure 4 & table 2.

5 Conclusion

The integration of hybrid wireless network architectures is of paramount importance for the robust and effective functioning of autonomous maritime vehicles. These vehicles are equipped with satellite links, base stations on land, and wireless communication systems which provide full coverage and uninterrupted communication range offshore, in the deep sea, and to the coastal regions. The vessels operate in conjunction with control centers and other maritime agencies for data capture and retrieval in real time, which is only achievable with uninterrupted communication. Hybrid systems are resilient to communication blackouts while still meeting the bandwidth, latency, and coverage needs. Hybrid wireless networks are integral for the uninterrupted delivery of high-sensor data streams, remote intelligence enabled decision making, and navigation aided through decentralized frameworks and cloud computing. Additionally, advanced hybrid systems are exceptionally useful for weary driving, compliance with laws, and adjusting to unpredictable changes at sea. Thus, it can be concluded that employing advanced hybrid wireless systems enables the development of intelligent and responsive autonomous ships, thus shifting the paradigm of sustainable naval travel.

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Authors Biography

Yasvanthra Ekambaram is a skilled marine engineer with over 15 years of seafaring experience, currently serving as a Second Engineer Officer with Wallem Shipping Management in the Dry Fleet division, covering Bulk Carriers and PCC/PCT vessels. He holds a Marine Engineer Officer Class II certificate and has successfully cleared the Class I written examination, currently pursuing the oral assessment. Yasvanthra began his marine career after graduating from the Chennai School of Ship Management (2005–2008). He has progressed through various engineering ranks, demonstrating hands-on expertise with a wide range of main engine types including MAN B&W, Mitsubishi, and Bergen, across vessel types like general cargo, bulk, cement, oil carriers, and vehicle carriers. He is trained in advanced marine safety procedures, including Safety Officer Course, Survival Craft & Rescue Boats, and Risk Management & Incident Investigation, showcasing a strong commitment to operational safety and engineering excellence.

Capt Manjul Tripathi

I did my pre sea Training at the TRAINING SHIP RAJENDRA, Bombay (DG Shipping, Govt of India). Thereafter I completed the sea time and apprenticeship with the Indian Ship owners SCINDIA STEAM SHIPPING PROVATE LTD, MUMBAI in the year 1982, Subsequently after passing my Mates COCs of the two levels I did my Master Mariner COC in the year April/1990 at Mumbai. I sailed with various Management companies on all kinds of dry cargo vessels with the main Companies including BARBERS, WILWILHELMSEN-NORWAY, MOL -TOKYO, DOCKENDALE SHIPPING, NYK LINEs and UNITED OCEAN SHIP MANAGEMENT TOKYO. I specialized with HEAVY LIFT CARGOES when I Worked with Owners MAMMOET SHIPPING, AMSTERDAM. I stopped sailing in the year 2016. Thereafter I have Been involved with teaching/Training STCW courses at various MTI and involved in teaching Graduates in NAITICAL SCIENCE at GANPAT UNIVERSITY and presently teaching nautical graduates at ACADEMY OF MARITIME EDUCATION AND TRAINING.