Comprehensive Approaches to Enhance Maritime Wireless Networks: A Survey

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Synopsis

In this review paper we explore the advancements and challenges in maritime communication systems. Traditional maritime communication methods, such as high-frequency (HF), very-high-frequency (VHF), and satellite communications, are increasingly insufficient due to their limited bandwidth and high costs. These limitations necessitate the adoption of advanced communication technologies like Mobile Ad Hoc Networks (MANETs), Vehicular Ad Hoc Networks (VANETs), Wireless Mesh Networks (WMNs), and Software-Defined Radios (SDRs). We highlight the potential of cognitive radio technology and cooperative networking to dynamically utilize underutilized frequency bands and enhance network performance through node collaboration. These technologies aim to provide robust, scalable communication solutions adaptable to the challenging maritime environment. Despite advancements, challenges such as network scalability, latency management, data security, and the dynamic nature of maritime environments persist. Here we review recent developments in maritime communication, focusing on the implementation and performance of ad hoc wireless networks, SDRs, and integrated network architectures. The paper emphasizes the importance of adaptive routing protocols, efficient network formation, robust hardware integration, and continuous monitoring. In conclusion, the integration of cognitive and cooperative technologies offers promising solutions for enhancing maritime communication, but ongoing research and development are essential to address remaining challenges and optimize these systems for real-world applications.

Keywords: Marine systems; Wireless networks; Routing protocols; Ship interaction; Ship communication

1. Introduction

The maritime industry, a cornerstone of global trade and security, is undergoing a significant transformation driven by the need for advanced communication technologies. Traditional maritime communication systems, which primarily rely on high-frequency (HF), very-high-frequency (VHF), and satellite communications, are increasingly becoming inadequate to meet the modern demands of high-speed data transmission and real-time applications. HF and VHF systems offer limited bandwidth and low data rates, which are suitable for basic voice communications but fall short in supporting data-intensive operations like video surveillance and comprehensive situational awareness. Although satellite communications can provide broader coverage and higher data rates, their high costs and latency issues make them less viable for routine and widespread use in maritime operations, especially at higher latitudes.

Reliable communication links are essential for navigation, coordination, safety, and emergency response. However, the expansive and often remote nature of maritime domains poses significant challenges to traditional communication methods. Mobile Ad Hoc Networks (MANETs) and their specialized variants, such as Vehicular Ad Hoc Networks (VANETs) and Wireless Mesh Networks (WMNs), and software-defined radios (SDRs) have emerged as promising alternatives, offering dynamic, self-organizing capabilities that can form resilient, high-bandwidth networks without the need for fixed infrastructure. Cognitive radio technology allows for the opportunistic use of underutilized frequency bands, known as white spaces (WS), which can significantly improve the efficiency and cost-effectiveness of maritime communication systems. Cooperative networking, on the other hand, leverages the collaboration between network nodes to enhance overall network performance and reliability. These network technologies aim to provide robust and scalable communication solutions by integrating cognitive and cooperative technologies. Such networks can dynamically adapt to the maritime environment, ensuring seamless communication even in remote, harsh and challenging conditions.

Despite these advancements, significant challenges remain, including network scalability, latency management, data security, and the dynamic nature of maritime environments. Addressing these issues is critical for the successful deployment of next-generation maritime communication systems. This paper provides a comprehensive review of recent developments in maritime communication technologies, focusing on the implementation and performance of ad hoc wireless networks, SDRs, and integrated network architectures. By examining these innovations, we aim to highlight their potential to revolutionize maritime operations and outline the future directions for research and development in this field.

This review aims to synthesize the methodologies, technologies, and innovations presented in these studies, offering a holistic perspective on the advancements in communication protocols and systems. By exploring the

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complementary benefits of these solutions, this paper seeks to provide valuable insights for researchers, engineers, and stakeholders in the maritime and ad hoc networking domains.

In the subsequent sections, we will delve into the methodologies and technologies employed in the reviewed studies, compare their key findings and innovations, and discuss the practical implementations and future directions for research. This comprehensive analysis will guide the development of robust, scalable, and efficient communication systems, ultimately enhancing the connectivity and operational capabilities in maritime and wireless ad hoc networks.

2. Background

The maritime industry has long relied on traditional communication systems, primarily satellite links, for ensuring connectivity over vast oceanic expanses. However, these systems are often plagued by high costs and limited bandwidth, necessitating the exploration of alternative communication frameworks. The advent of cognitive and cooperative communication technologies offers promising solutions to these challenges.

Effective communication systems are essential for the operation and safety of maritime vessels. The maritime industry, which includes commercial shipping, ocean fishery, and naval operations, relies on robust communication links for navigation, coordination, and emergency response. Similarly, ad hoc networks, often used in military, emergency response, and remote sensing applications, require dynamic, decentralized communication solutions due to their lack of fixed infrastructure and mobile node configurations.

Maritime communication systems are integral to ensuring the safety, security, and efficiency of maritime operations. Traditionally, these systems have relied on high-frequency (HF), very-high-frequency (VHF), and satellite communication technologies. HF and VHF systems provide basic communication services but are limited by narrow bandwidth and low data transmission rates, making them insufficient for modern applications that require high-speed data transfer, such as real-time video monitoring and large-scale data exchange. Satellite communication systems, while capable of supporting higher data rates and broader coverage, are often associated with high costs and latency issues, limiting their feasibility for widespread use in routine operations.

The integration of advanced communication technologies in the maritime domain has become increasingly critical due to the growing demand for reliable, high-speed, and secure data exchange across various maritime platforms. This need has driven extensive research into MANETs, VANETs, WMNs, and blockchain-based security enhancements.

Given the increasing frequency and complexity of maritime activities, there is a pressing need for alternative communication technologies that offer higher data rates, lower latency, and cost-effective solutions. This need has driven research into the deployment of wireless ad hoc networks and the utilization of software-defined radios (SDRs) to form robust, flexible, and scalable maritime communication networks

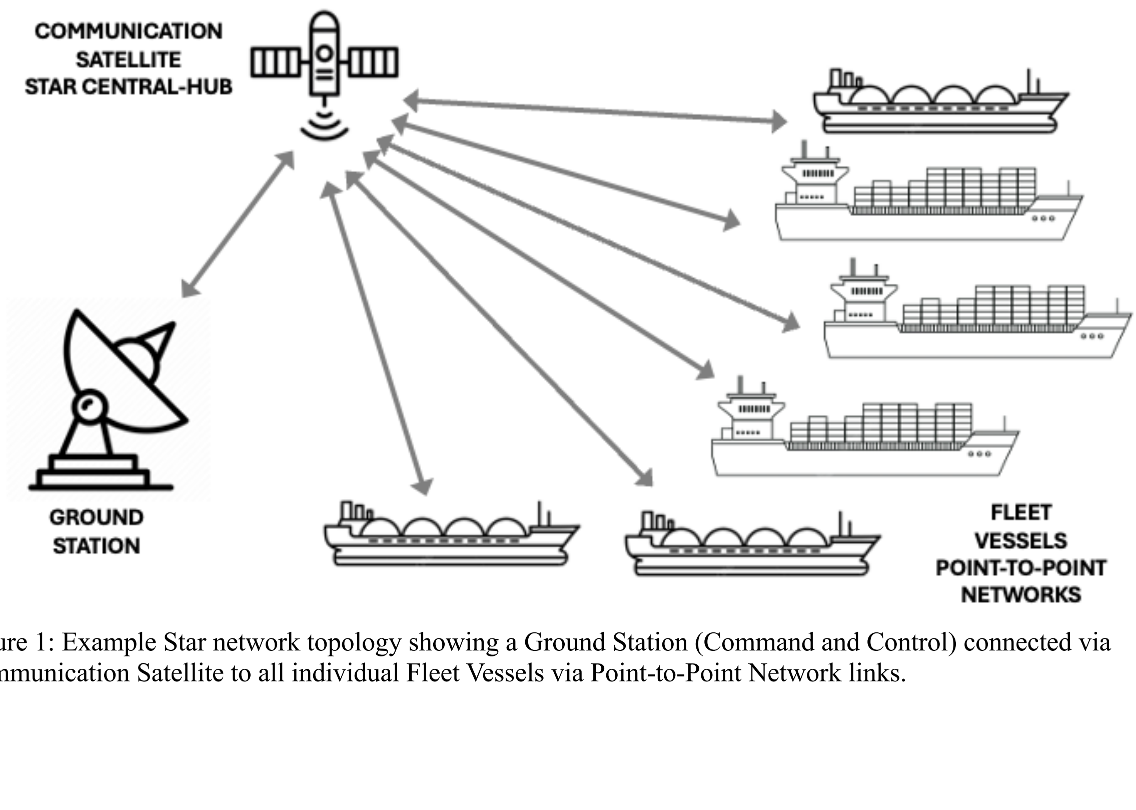

Figure 1: Example Star network topology showing a Ground Station (Command and Control) connected via Communication Satellite to all individual Fleet Vessels via Point-to-Point Network links.

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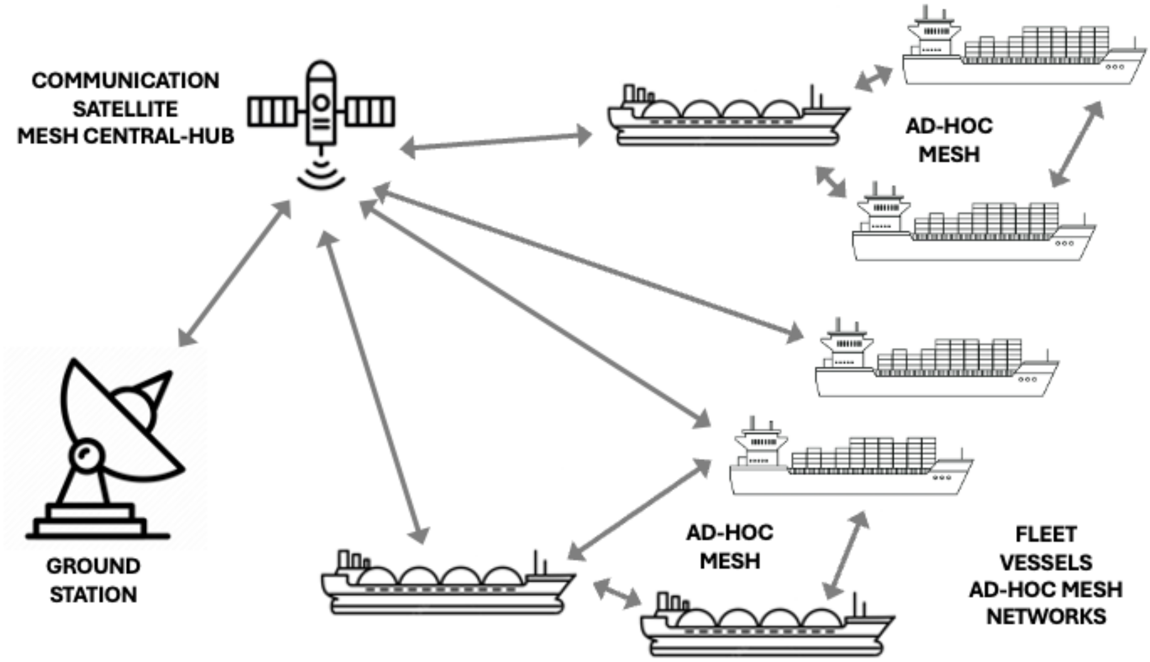

Figure 2: Example Ad-Hoc Mesh Network topology showing a Ground Station (Command and Control) connected via Communication Satellite to Fleet Vessels via Ad-Hoc Mesh Network links, in this topology the Fleet Vessels that do not have connectivity to the satellite use neighbouring vessels to share communications links and exchange valuable information.

3. Literature Review

3.1 Wireless Mesh Networks and Ad Hoc Networks

Akyildiz et al. (2005) provided an extensive survey of WMNs, discussing their architecture, characteristics, applications, and the key factors influencing protocol design. WMNs consist of mesh routers and clients, offering advantages such as low costs, easy maintenance, robustness, and reliable service coverage. The paper highlighted the potential of WMNs to integrate with various networks (e.g., Internet, cellular, IEEE 802.11) and their applicability in numerous areas, including home networking, community networks, and metropolitan area networks. The survey underscored the importance of scalability, Quality of Service (QoS), and security in protocol design, identifying the need for cross-layer designs and the integration of advanced technologies like multiple input/multiple output (MIMO) and cognitive radios to enhance WMN performance.

Boukerche et al. (2011) provided a comprehensive review of routing protocols for ad hoc wireless networks, emphasizing the absence of fixed infrastructure and the need for efficient, dynamic routing solutions. The paper categorized routing protocols into source-initiated (reactive), table-driven (proactive), hybrid, location-aware, multipath, hierarchical, multicast, geographical multicast, and power-aware protocols. A comparative analysis based on metrics such as throughput, packet delivery ratio, control overhead, and energy efficiency revealed that each protocol has specific strengths and weaknesses suited to different applications and network conditions. The study emphasized the need for scalable, energy-efficient, and robust routing solutions to handle high mobility and dynamic topologies in ad hoc networks.

Ad hoc networks, which enable direct communication between devices without the need for fixed infrastructure, are particularly suitable for maritime applications where traditional network setups are impractical. Agrawal et al. (2023) provide an exhaustive review of ad hoc networks, including MANETs, VANETs, WMNs, and wireless sensor networks (WSNs). They discuss various routing protocols such as proactive, reactive, and hybrid protocols, highlighting their impact on network performance in terms of speed, efficiency, and reliability. The study also addresses the unique challenges of ad hoc networks, including node mobility, bandwidth constraints, and error-prone channels, emphasizing the need for robust and efficient routing solutions tailored to dynamic environments like maritime settings.

3.2 Maritime Communication Networks

Ad hoc networks, characterized by their self-forming and self-healing capabilities, have emerged as a promising solution for enhancing maritime communication. These networks can dynamically organize mobile nodes (e.g., ships, buoys) into multi-hop networks, eliminating the need for fixed infrastructure. Various studies have explored the implementation of ad hoc networks in maritime contexts, highlighting their potential to support broadband data transmission over the sea.

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For example, Vann (2010) examined the use of SDRs to create ad hoc meshed networks aimed at improving Maritime Interception Operations (MIO). The study demonstrated the feasibility of using SDRs to create robust, high-bandwidth communication networks capable of supporting voice, video, and data transmissions between Visit, Board, Search, and Seizure (VBSS) teams and command centres.

Laarhuis (2010) introduces MaritimeManet, a mobile ad hoc network specifically designed for maritime environments. Unlike traditional MANETs that rely on omni-directional antennas, MaritimeManet uses multiple directional antennas arranged in a circular pattern to achieve extended transmission ranges. This design enhances signal-to-noise ratios and mitigates the power problem associated with long-distance communication. MaritimeManet supports distributed applications like Sensors in Concert (SinC), which provides continuous and comprehensive maritime surveillance. The system's ability to self-organize and self-heal, coupled with its scalability, makes it a robust solution for various maritime applications.

Bai et al. (2012) investigated the feasibility of integrating various wireless communication technologies to provide efficient and cost-effective communication solutions for mobile users on ocean fishery vessels. Their study focused on analysing existing wireless technologies, understanding their propagation characteristics over the sea, and proposing an integrated wireless networking system. This system combines a MANET, cellular mobile network, and satellite mobile network to leverage the strengths of each. The proposed system architecture and the development of a prototype validated the feasibility and effectiveness of this integrated approach for enhancing communication capabilities in maritime environments.

Maritime environments present unique communication challenges, including signal reflections off the sea surface and fluctuating connectivity due to ship movements. Ejaz et al. (2013) address these challenges with the Maritime Two-State (MTS) routing protocol, specifically designed for maritime multi-hop wireless networks. The MTS protocol operates in two states: beaconing, where ships broadcast routing tables to nearby vessels, and predicting, where ships use historical data to predict future positions and reduce communication overhead. Simulation results indicate that the MTS protocol significantly outperforms existing protocols by reducing periodic updates, bandwidth utilization, jitter, and end-to-end delay, making it a highly effective solution for maritime communication.

WiMAX and LTE technologies have also been explored for enhancing maritime communications. Manoufali et al. (2014) discussed the potential of WiMAX-based maritime wireless mesh networks, which extend terrestrial broadband networks to coastal waters. These networks form multi-hop connections involving shore stations, ships, and other maritime structures. Such systems support high-speed data transmission, essential for applications like maritime safety and surveillance.

Sumić et al. (2015) investigated the optimization of data traffic routes for maritime vessels to address the high costs associated with satellite communication. Their research proposed a hybrid communication approach that integrates satellite and terrestrial links. By utilizing a mathematical model, they demonstrated how switching between satellite links on the high seas and terrestrial links near ports could significantly reduce costs and increase link capacity. The case study in the Netherlands highlighted the practical benefits, showing that the ship could save costs by spending 27.8% of its voyage within terrestrial link range. This approach underscores the potential of integrating terrestrial communication technologies to enhance the cost-efficiency and capacity of maritime data communications.

Xiao et al. (2020) focused on implementing video transmission over maritime ad hoc networks. The study developed video transmission software integrated with maritime broadband wireless ad hoc network systems. Utilizing MANET routers equipped with SDR platforms, the research demonstrated the capability to support multi-hop video transmission. This addresses the critical need for real-time video communication in maritime safety monitoring and accident investigation.

Seferagic et al. (2021) proposed a multimodal network architecture to enhance situational awareness among maritime vessels. The architecture integrates various network interfaces and employs an abstraction layer to manage multimodal communication, traffic, and QoS improvements. This approach ensures seamless and robust communication across different network technologies, supporting the growing demands for high data-rate applications in maritime environments.

In the context of extending network reach and flexibility, Berto et al. (2021) present a novel (long-range) LoRa-based mesh network that operates without traditional gateways. This gateway-free approach is particularly advantageous in maritime and remote applications, where infrastructure is sparse. The network leverages low-cost ESP32 Heltec WiFi LoRa V2 boards equipped with Semtech SX1276 LoRa transceivers, facilitating peer-to-peer communication and multi-hop networking. Their experimental results demonstrate significant improvements in communication efficiency and reliability, showcasing the potential of LoRa technology to support robust and scalable maritime communication systems.

Mishra et al. (2022) evaluated the feasibility of Sea Ad-Hoc Network (SANET) for maritime communications, comparing three routing protocols (Epidemic Routing Protocol, Randomized Rumor Spreading, and Spray and Wait) and three connecting technologies (WiMax, VHF, and Long-Range WiFi). The study demonstrated that SANET could effectively address the limitations of traditional communication systems by providing infrastructure-less, flexible, and cost-effective communication solutions, particularly in regions with poor satellite coverage or during emergencies.

Wang et al. (2023) explored the application of MANETs for improving ship-to-ship communication and interaction. Their research focused on developing a network architecture that adapts dynamically to different navigation scenarios, such as open seas and congested coastal areas. By designing both intercommunication and cluster modes, the study provided a robust framework for managing communication in varying maritime environments.

The intercommunication mode, suitable for open seas with fewer ships, ensures stable and high-quality communication paths necessary for collision avoidance. Conversely, the cluster mode, ideal for congested areas, uses a hierarchical topology to efficiently manage communication among numerous ships.

3.3 Cognitive and Cooperative Technologies

The concept of maritime wireless mesh and ad hoc networks has gained traction as a viable alternative to satellite communication. These networks aim to provide high-speed, cost-effective communication by leveraging cognitive radio technology to exploit underutilized frequency bands, known as white spaces (WS).

In 2012, Zhou and Harada proposed a cognitive maritime wireless mesh/ad hoc network designed to opportunistically utilize available WS in the maritime spectrum. Their work laid the foundation for subsequent research by demonstrating the feasibility of cognitive radios in maritime settings to improve communication efficiency and reduce costs.

Building on the foundational work of Zhou and Harada, Yang et al. (2015) introduced the Cooperative Cognitive Maritime Wireless Mesh/Ad Hoc Networks (CCMWMAN) framework. This framework integrates cognitive and cooperative communication technologies to enhance network performance. The study emphasized the importance of game theory in managing resource allocation among network nodes, proposing a symmetrical system model and a price game based on payoff functions to achieve Nash equilibrium in cooperative communication scenarios.

In a follow-up study in 2016, Yang et al. expanded on their earlier work by developing a bi-level game theory model for resource allocation in cognitive maritime networks. This model addressed the interactions between primary users (PUs) and secondary users (SUs), employing a Stackelberg game to manage resource distribution efficiently. The proposed model demonstrated significant improvements in network throughput and overall system performance, highlighting the potential of game theory in optimizing maritime communication networks.

Peng et al. (2020) proposed an enhanced Ad-hoc On-Demand Distance Vector (AODV) routing protocol, termed AIS-aided AODV (A-AODV), tailored for MANET. This protocol leverages the Automatic Identification System (AIS) to reduce flooding during route discovery by utilizing ship location information. A-AODV maintains a ship-location table to store and use AIS data for efficient routing decisions, significantly lowering routing overhead. Experimental validation on a MANET testbed demonstrated that A-AODV supports multi-hop data transmission with lower routing overhead compared to standard AODV, highlighting the potential of integrating AIS data to improve routing efficiency and network performance in maritime environments.

Accurate classification of maritime vessels is essential for effective maritime surveillance and operational management. Krüger (2018) evaluates several ad hoc classification methods using real-life AIS data, including Decision Tree, Fuzzy Rule, k Nearest Neighbor (kNN), Neural Networks, and Naïve Bayes. The study finds that Decision Tree and Fuzzy Rule classifiers achieve the highest accuracy, providing reliable classification results. This research underscores the importance of robust data-driven methods in enhancing maritime situational awareness and improving operational efficiency in surveillance systems.

3.4 Secure Routing in Decentralized Networks

Neumann et al. (2018) addressed the challenges of secure routing in community mesh networks, which share characteristics with maritime networks due to their decentralized and open nature. They introduced the Securely Entrusted Multi-Topology Routing (SEMTOR) protocol, designed to establish cryptographically secure and individually trusted routing topologies without central management. SEMTOR allows each node to define its trusted nodes, ensuring secure and autonomous routing. The protocol's integration with the BMX7 routing protocol and extensive benchmarking demonstrated its scalability and efficiency in networks with hundreds of nodes. SEMTOR's robustness against various attacks and its ability to maintain secure communication paths in dynamic and diverse network environments highlight its relevance for maritime and other ad hoc applications.

Blockchain technology has emerged as a promising solution to enhance security and efficiency in ad hoc networks. Juarez et al. (2023) propose a dual layer blockchain architecture for VANETs, comprising an event chain and a reputation chain. This architecture employs Bayesian inference to dynamically update the reputation scores of nodes based on their behaviour, effectively identifying and mitigating malicious nodes. The study reports an 86% success rate in countering malicious behaviours through extensive simulations, highlighting the potential of blockchain technology to secure communication networks against various cyber threats in both terrestrial and maritime environments.

4. Practical Implementation

The practical implementation of advanced maritime communication systems involves several key considerations, ranging from the integration of new technologies into existing infrastructures to addressing the unique challenges posed by the maritime environment. The studies reviewed provide a comprehensive foundation for understanding these aspects and offer valuable insights into effective deployment strategies.

4.1 Network Planning, Configuration and Topology Design

Deploying ad hoc networks in maritime environments requires careful planning of network topology to ensure robust and reliable connectivity. Configuring SDRs for maritime operations requires careful planning of network parameters, such as frequency bands, modulation schemes, and power settings. The configuration should optimize coverage and data throughput while minimizing interference. Dynamic configuration capabilities allow SDRs to adapt to changing conditions and optimize performance in real-time, a feature crucial for maritime environments with varying signal propagation characteristics. Key considerations include node placement, transmission range, and network density.

4.2 Adaptive Routing Protocols

Implementing adaptive routing protocols is crucial for maintaining network performance in the dynamic maritime environment. Protocols like Ad-hoc On-Demand Distance Vector (AODV) and Optimized Link State Routing (OLSR) are suitable for dynamic and scalable networks. Protocols like the Maritime Two-State (MTS) routing protocol proposed by Ejaz et al. (2013) should be adapted and tested in real-world conditions to ensure they can handle the frequent topology changes and long transmission distances typical of maritime networks. Boukerche et al. (2011) reviewed various routing protocols suitable for ad hoc and practical protocol selection involves choosing the most suitable routing protocol (e.g., reactive, proactive, hybrid) based on specific application requirements and network conditions. Implementing multi-hop communication extends the network's reach and enhances its resilience. This requires developing efficient routing algorithms that can dynamically manage the network's topology and ensure data packets are delivered reliably across multiple hops.

4.3 Integration of Hardware

The deployment of Software-Defined Radios (SDRs) in maritime environments, as demonstrated by Vann (2010), involves equipping vessels with SDR units capable of forming ad hoc meshed networks. Peng et al. (2020) leveraged AIS data for efficient route discovery in maritime ad hoc networks. For practical implementation, ensure all vessels are equipped with AIS transponders and receivers to provide accurate real-time location data. Implementing data-driven vessel classification systems requires continuous collection and processing of AIS data. Krüger (2018) demonstrates the effectiveness of using real-life AIS data for vessel classification, highlighting the need for robust data preprocessing and feature extraction techniques to ensure accurate classification. These units must be ruggedized to withstand harsh maritime conditions, including exposure to saltwater, humidity, and temperature extremes. The installation process should ensure secure mounting and protection from physical damage while maintaining accessibility for maintenance and upgrades.

4.4 Network Formation

Establishing a MANET involves deploying network nodes on ships, buoys, and shore stations. The study by Xiao et al. (2020) illustrates the importance of a robust network management protocol that can handle the dynamic topology of maritime operations. MANETs should support self-forming and self-healing capabilities to ensure continuous communication links, even when individual nodes move or fail. Akyildiz et al. (2005) highlighted the potential of WMNs for providing robust communication in maritime and terrestrial applications including deployment of mesh routers and clients on vessels and coastal stations to create a multi-hop network, and implementing network management software to oversee mesh topology, optimize routes, and ensure load balancing.

4.5 Machine Learning Models

Deploying machine learning models, such as Decision Trees and Fuzzy Rule classifiers, involves training these models on historical AIS data and continuously updating them with new data to maintain accuracy. Real-time classification systems can be integrated into maritime surveillance platforms to provide operators with timely and accurate vessel identification.

4.6 Quality of Service (QoS) Management

Ensuring Quality of Service (QoS) is essential for applications that require high data rates and low latency, such as video surveillance and real-time monitoring. The multimodal architecture should include mechanisms for prioritizing traffic, managing bandwidth allocation, and minimizing latency. Techniques like traffic shaping and adaptive bandwidth management can help maintain QoS under varying network conditions.

4.7 Security Management

Implement robust security measures to protect data integrity and privacy, including encryption, authentication, and intrusion detection systems. Setting up a blockchain infrastructure involves deploying nodes capable of handling blockchain operations, such as verifying transactions and maintaining the ledger. The dual layer blockchain architecture proposed by Juarez et al. (2023) can be implemented using lightweight blockchain clients to minimize resource consumption while ensuring robust security and trust management. Developing and

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deploying smart contracts on the blockchain can automate various network management tasks, such as reputation scoring and malicious node detection.

4.8 End-User Devices

Deploying video transmission systems requires equipping end-user devices, such as PCs and tablets, with appropriate software and hardware interfaces. These devices should connect seamlessly to MANET routers via Ethernet or wireless connections. User-friendly interfaces are crucial for ease of operation, allowing crew members to initiate and manage video communications with minimal technical expertise. Bai et al. (2012) proposed an integrated system combining MANET, cellular, and satellite networks. The practical network implementation included establishing a MANET among vessels for ship-to-ship communication and integration of this network with cellular gateways (for nearshore communication) and satellite gateways (for deep-sea communication).

4.9 Field Trials

Conducting extensive field trials is vital for validating the performance of the implemented systems. Trials should simulate various maritime scenarios, including open sea, coastal areas, and congested shipping lanes. Performance metrics such as data throughput, latency, packet loss, and network stability should be rigorously tested and analysed. The feedback from these trials can guide further optimizations and refinements.

4.10 Continuous Monitoring and Maintenance

Post-deployment, continuous monitoring of network performance and regular maintenance of hardware are essential to ensure long-term reliability. Implementing remote monitoring tools can help detect issues promptly and facilitate timely interventions. Regular updates to software and firmware can enhance functionality and security, adapting to evolving operational requirements.

In conclusion, the practical implementation of advanced maritime communication systems involves a comprehensive approach that integrates robust hardware, adaptive network configurations, multimodal architectures, and efficient software solutions. By addressing the specific challenges of the maritime environment and conducting thorough testing and validation, these systems can significantly enhance the operational capabilities and safety of maritime operations.

5. Key Performance Indicators

In the maritime domain, reliable and resilient communication networks are essential for ensuring safety, operational efficiency, and coordination between vessels, offshore platforms, and control centres. Network topologies, particularly in wireless environments, must address challenges posed by vast oceanic distances, dynamic node mobility (such as moving ships), and environmental factors like weather and interference. This paper addresses the comparison of traditional network topologies in maritime applications e.g. the wireless point-to-point (or star) topology and the wireless ad-hoc mesh topology, each requiring distinct Key Performance Indicators (KPIs) to measure their effectiveness and ensure optimal performance.

5.1 Wireless Point-to-Point (or Star) Network Topology

In a wireless star topology, all communication is centralized through a hub, which is typically a satellite, shore-based control center, or a dedicated base station on a large vessel. This centralized structure offers simplicity and predictability, but it also presents unique challenges due to the single point of failure at the hub. KPIs in this topology focus on monitoring the central node’s performance and the links between it and the surrounding nodes.

5.1.1 Latency

Measuring the round-trip time (RTT) between vessels or offshore platforms and the central hub is critical, especially when supporting real-time applications like voice, navigation data transfer, or collision avoidance systems. High latency can cause delays in critical decision-making, especially in mission-critical maritime operations.

5.1.2 Throughput

This KPI tracks the rate of successful data transmission between nodes and the central hub. In maritime environments, where data-intensive applications such as remote monitoring, sensor data transmission, and video feeds are common, ensuring adequate throughput is essential. It is vital to assess the hub’s ability to handle concurrent data streams from multiple nodes without becoming a bottleneck.

5.1.3 Packet Loss

Packet loss is particularly significant in maritime communications due to long distances and potential interference from the environment. High packet loss in a star topology can indicate signal degradation, congestion at the central hub, or issues with individual vessel connections. Continuous monitoring of packet loss is essential to maintain service reliability.

5.1.4 Hub Availability

The hub represents a single point of failure in the network. Therefore, ensuring its uptime and reliability is paramount. Any downtime at the hub could result in total communication breakdown, which is particularly detrimental in the maritime domain, where safety and real-time coordination are crucial.

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5.1.5 Signal-to-Noise Ratio (SNR)

In maritime wireless communications, maintaining a strong SNR is essential. Long transmission distances and environmental factors like weather conditions or interference from other maritime communication systems can degrade the signal quality. A low SNR can lead to errors in data transmission, reduced throughput, and increased latency.

5.2 Wireless Ad-Hoc Mesh Network Topology

A wireless ad-hoc mesh network is decentralized, with nodes (vessels or platforms) forming direct connections with each other, allowing for dynamic routing and multiple communication paths. This topology provides greater redundancy and resilience but introduces challenges in network management, as there is no central point controlling the entire network. The KPIs for measuring the performance of a wireless ad-hoc mesh topology differ significantly from those in a star topology.

5.2.1 Hop Count

In a mesh topology, data packets may travel through multiple nodes before reaching their destination. The number of hops directly impacts network performance. Minimizing hop count reduces latency and increases the overall efficiency of the network. A lower hop count is particularly important for real-time communication services, such as voice over IP (VoIP) or emergency alerts.

5.2.2 Link Quality Indicator (LQI)

The LQI measures the quality and strength of links between nodes, which can vary dynamically in a maritime setting due to vessel movement, weather conditions, and distance. Monitoring LQI ensures that data is transmitted over the best possible links, improving the overall network reliability and performance.

5.2.3 Route Diversity

One of the key advantages of a mesh network is the ability to reroute data through multiple paths if one link fails. Route diversity measures the availability of alternative communication paths, providing insight into the network's resilience. High route diversity indicates that the network can withstand failures or disruptions without significant degradation in performance.

5.2.4 Mobility Support and Handoff

Given the highly dynamic nature of the maritime environment, where vessels are constantly moving, tracking the network's ability to support seamless mobility is critical. KPIs such as handoff times and the success rate of handoffs between nodes are crucial for maintaining uninterrupted communication as vessels move in and out of range.

5.2.5 Jitter

Jitter refers to the variation in packet arrival times. In an ad-hoc mesh network, where data may travel through several nodes and over changing paths, jitter can become a significant issue, especially for real-time services like voice and video. Monitoring jitter helps ensure that the network remains stable and that time-sensitive data is delivered reliably.

6. Conclusion

The transformation of maritime communication systems is critical to advancing the operational efficiency, safety, and security of maritime activities. Traditional communication technologies, including HF, VHF, and satellite systems, are increasingly inadequate to meet the modern requirements for high-speed, real-time data transmission essential for contemporary maritime operations. The exploration of wireless ad hoc networks, software-defined radios, and integrated multimodal network architectures presents promising solutions to these challenges.

The collective insights from these studies reveal the necessity of integrating terrestrial communication technologies, secure routing protocols, and AIS data to improve maritime communications. The hybrid approach of using both satellite and terrestrial links can be complemented by secure, decentralized routing mechanisms and efficient route discovery protocols. Future research should focus on further integrating these technologies to develop robust, cost-effective, and high-capacity communication systems for maritime and ad hoc networks. This integrated approach promises to address the unique challenges of these environments, providing reliable and efficient communication solutions for their growing demands.

The reviewed studies provide a wealth of insights and advancements in the field of communication solutions for maritime and ad hoc networks. The unique challenges posed by the vast and dynamic maritime environments, along with the decentralized nature of ad hoc networks, necessitate innovative and robust communication protocols. The key contributions from these studies underscore the importance of integrating diverse technologies and optimizing routing protocols to achieve reliable, cost-effective, and efficient communication.

Despite these advancements, several challenges persist, including network scalability, latency, data security, and the dynamic nature of maritime environments. Addressing these challenges requires ongoing research and development to optimize routing protocols, enhance the robustness of ad hoc networks, and integrate emerging

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technologies such as 5G. Additionally, future research should focus on the practical deployment of these technologies in diverse maritime scenarios, ensuring their reliability and effectiveness in real-world conditions.

The exploration of cognitive and cooperative technologies within maritime wireless mesh/ad hoc networks mark a significant leap forward in the quest to enhance maritime communication. The integration of cognitive radio technologies with mesh networking has the potential to transform the maritime communication landscape, providing high-speed, cost-effective, and reliable connectivity that traditional satellite systems fail to offer.

Despite these advancements, several challenges remain. The dynamic and often harsh maritime environment poses significant obstacles to maintaining stable and reliable communication links. Fluctuating sea states, interference from maritime activities, and regulatory constraints on frequency use are critical issues that future research must address. Furthermore, the integration of emerging technologies, such as machine learning and artificial intelligence, offers promising avenues for optimizing resource allocation and network management.

The integration of advanced communication technologies in maritime operations is essential to meet the growing demand for reliable, high-speed, and secure data exchange. This technical review has examined several key studies that contribute to this evolving field, highlighting significant advancements and identifying areas for future research and development.

In conclusion, the development of cognitive and cooperative maritime wireless mesh/ad hoc networks represent a promising frontier in maritime communication. By leveraging the capabilities of cognitive radio and cooperative networking, these systems offer a path towards more efficient, cost-effective, and reliable maritime communication solutions. Continued research and development in this field are essential to overcoming existing challenges and fully realizing the potential of these innovative technologies. The future of maritime communication is bright, with cognitive and cooperative technologies poised to play a central role in driving this transformation.

7. Challenges

Despite significant advancements, several challenges remain in developing robust maritime communication networks. The dynamic and harsh maritime environment poses unique challenges such as fluctuating sea states and interference from maritime activities. Future research must address these issues by refining cognitive radio technologies and enhancing the resilience of communication protocols.

Moreover, the integration of advanced technologies like machine learning and artificial intelligence could further optimize resource allocation and network management. Ensuring the security and reliability of these networks is also crucial, given the increasing reliance on digital communication for maritime safety and navigation.

The development of cognitive and cooperative maritime wireless mesh/ad hoc networks represent a significant step towards achieving high-speed, cost-effective maritime communication. The integration of game theory into resource allocation strategies offers a promising approach to enhancing network performance and ensuring reliable communication in the dynamic maritime environment.

7.1 Scalability and Network Management

One of the primary challenges in both maritime and ad hoc networks is scalability. As the number of nodes increases, maintaining efficient and reliable communication becomes increasingly complex. Protocols must be designed to handle large-scale networks without compromising performance. Future research should focus on developing scalable routing protocols that can dynamically adjust to network size and topology changes, ensuring consistent performance.

7.2 Security and Trust Management

Security is a critical concern in decentralized networks. Neumann et al. (2018) addressed secure routing through the SEMTOR protocol, but the ever-evolving nature of security threats requires continuous improvement. Ensuring data integrity, preventing unauthorized access, and protecting against various attack vectors remain paramount. Future studies should explore advanced cryptographic techniques, distributed trust management systems, and real-time threat detection mechanisms to enhance network security. Maritime communication systems are vulnerable to various security threats, including spoofing, jamming, and cyber-attacks. The integration of blockchain technology, as explored by Juarez et al. (2023), offers promising solutions for enhancing security, but practical implementations and scalability remain challenges. Ensuring robust security while maintaining system performance is a critical area for further research

7.3 Integration of Emerging Technologies

The integration of emerging technologies such as cognitive radios, machine learning, and blockchain can potentially revolutionize maritime and ad hoc network communications. Cognitive radios can dynamically adjust frequencies to avoid interference, while machine learning algorithms can optimize routing decisions based on real-time data. Blockchain technology could provide a decentralized and secure method for managing trust and authentication. Research should focus on integrating these technologies into existing frameworks to enhance adaptability, efficiency, and security.

7.4 Energy Efficiency

Energy consumption is a critical factor, particularly for nodes in ad hoc networks and maritime vessels operating on limited power supplies. Boukerche et al. (2011) highlighted the importance of power-aware routing protocols. Future research should aim to develop energy-efficient communication protocols that minimize power consumption without sacrificing performance. Techniques such as energy-harvesting, sleep-mode operations, and optimized transmission scheduling can be explored to extend the operational life of network nodes. Energy efficiency is a significant concern for maritime communication systems, particularly for nodes deployed on buoys or autonomous vessels with limited power supplies. Efficient energy management strategies are needed to prolong the operational lifespan of these nodes without compromising communication quality.

7.5 Environmental and Physical Constraints

The highly dynamic nature of maritime environments presents a significant challenge for ad hoc networks. The movement of ships, variable weather conditions, and the vastness of the ocean can cause frequent changes in network topology, making it difficult to maintain stable and reliable communication links. Traditional routing protocols may not be adequate in such conditions, necessitating the development of more adaptive and resilient protocols. Maritime environments present unique physical and environmental challenges, including signal attenuation due to water, interference from weather conditions, and the curvature of the Earth affecting long-range communication. Bai et al. (2012) analyzed over-the-sea radio propagation effects, but further studies are needed to develop robust models that can predict and mitigate these challenges. Experimental validation in diverse maritime conditions is essential to refine these models.

7.6 Cost-Effectiveness

While integrating multiple communication technologies can enhance performance, it also increases complexity and cost. Sumić et al. (2015) and Bai et al. (2012) proposed hybrid approaches to balance cost and efficiency, but the economic feasibility of large-scale deployment remains a concern. Future research should focus on optimizing cost-effectiveness, exploring low-cost hardware solutions, and developing economic models to justify investments in advanced communication infrastructures.

7.7 Interoperability

Ensuring seamless interoperability between different communication technologies and protocols is vital for the success of integrated systems. Akyildiz et al. (2005) discussed the potential of WMNs to integrate with various networks, but practical implementation requires standardization and compatibility. Future work should aim at developing universal standards and protocols that facilitate seamless communication across different platforms and technologies. Maritime communication networks often face limitations in bandwidth and suffer from high latency due to the large distances involved. These constraints can hinder the performance of data-intensive applications and affect real-time communication. Innovative solutions that optimize bandwidth usage and reduce latency are crucial for improving the efficiency of maritime networks. The integration of various communication technologies, such as AIS, LoRa, MANETs, and blockchain, poses interoperability challenges. Ensuring seamless communication and data exchange between different systems and technologies requires standardized protocols and interfaces.

8. Future Directions

The advancement of cognitive and cooperative maritime wireless mesh/ad hoc networks mark a significant progression in maritime communication. However, the implementation and optimization of these technologies face several formidable challenges that require further research and innovative solutions.

8.1 Optimization of Routing Protocols:

Further research is needed to develop and optimize routing protocols tailored to maritime environments. Protocols must be adaptive to the dynamic nature of maritime operations, providing reliable and efficient routing under varying conditions. Studies should focus on reducing overhead, improving route discovery processes, and enhancing fault tolerance.

8.2 Network Scalability and Management:

One of the primary challenges in implementing maritime wireless communication systems is network scalability. As the number of nodes (ships, buoys, etc.) increases, the network must efficiently manage and maintain robust communication links. Ensuring consistent performance across a wide area, especially in dense maritime environments, requires sophisticated network management and optimization strategies. The dynamic nature of maritime operations, with constantly moving nodes, further complicates this task.

8.3 Latency and Data Transmission Rates:

Although significant progress has been made in enhancing data transmission rates, achieving low latency remains a critical challenge. Real-time applications, such as video surveillance and emergency response, demand minimal delays in data transmission. Wireless ad hoc networks and SDRs need to be optimized to reduce latency while maintaining high data rates, ensuring seamless and timely communication across maritime networks.

8.4 Interoperability with Existing Systems:

Integrating new communication technologies with existing maritime systems (HF, VHF, and satellite) is another challenge. Ensuring interoperability and seamless transition between different communication platforms is necessary to provide continuous and reliable communication. This requires standardization efforts and the development of compatible interfaces and protocols.

8.5 Integration of Emerging Technologies:

Exploring the integration of emerging technologies, such as 5G and beyond, with maritime communication systems holds great potential. 5G technology promises ultra-low latency, high data rates, and enhanced connectivity, which can significantly benefit maritime operations. Research should focus on the practical implementation of 5G in maritime contexts, addressing coverage, deployment, and interoperability challenges.

8.6 Spectrum Management and Regulatory Constraints

Efficient utilization of white spaces is central to cognitive maritime networks, but it is accompanied by regulatory challenges. Different countries have varying regulations regarding the use of licensed but unused frequency bands. Harmonizing these regulations to allow seamless cognitive radio operations across international waters remains a critical issue. Additionally, ensuring that secondary users do not interfere with primary users is essential to comply with regulatory requirements and protect vital maritime communication channels. Future studies should focus on developing standardized regulatory frameworks and advanced spectrum sensing technologies to detect and avoid PU transmissions reliably.

8.7 Interference and Coexistence

The coexistence of multiple cognitive and non-cognitive communication systems in the maritime environment can lead to interference, affecting overall network performance. As maritime communication networks grow in complexity and density, managing this interference becomes increasingly challenging. Research into sophisticated interference mitigation techniques and cooperative communication protocols is necessary to ensure harmonious operation of diverse communication systems.

8.8 Development of Robust Security Measures

To address the data security challenges, further study is required to develop advanced encryption techniques, secure communication protocols, and intrusion detection systems specifically designed for maritime networks. Ensuring data integrity and confidentiality while maintaining high performance is a key area for future research. Maritime communication systems must handle sensitive information, including navigation data, surveillance footage, and emergency communications. Ensuring the security and privacy of this data is paramount. Ad hoc networks, due to their decentralized nature, are particularly vulnerable to security breaches. Robust encryption, secure routing protocols, and intrusion detection systems are essential to protect data integrity and prevent unauthorized access.

8.9 Environmental Adaptation Strategies

Developing communication technologies that can adapt to and mitigate the effects of harsh maritime environments is crucial. Research should explore advanced signal processing techniques, adaptive modulation schemes, and robust hardware designs that can operate reliably under challenging conditions. Maritime environments pose unique challenges, including harsh weather conditions, multipath propagation, and interference from physical obstacles such as waves and ships. These factors can significantly impact the performance and reliability of wireless communication systems. Developing resilient communication technologies that can withstand and adapt to these environmental conditions is crucial.

8.10 Large-Scale Field Trials

Conducting large-scale field trials and real-world experiments is essential to validate the performance and reliability of proposed communication technologies. These trials should involve various maritime scenarios, including open sea, coastal areas, and busy shipping lanes, to comprehensively assess the effectiveness of the technologies under different conditions.

In conclusion, while significant advancements have been made in maritime communication technologies, addressing the challenges of scalability, latency, security, environmental adaptation, and interoperability requires ongoing research and development. By focusing on these areas, future studies can further enhance the capabilities of maritime communication systems, ensuring they meet the evolving demands of modern maritime operations.

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