Exploring Unmanned Aerial Vehicles Communication in Maritime Environments: Challenges and Perspectives

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Abstract: With the continuous advancement of embedded technologies and the growing demand for remote and autonomous operations, Unmanned Aerial Vehicles (UAVs) have been increasingly employed in a variety of maritime applications, including platform inspections, cargo transport, search and rescue missions, environmental monitoring, and open-sea surveillance. However, maintaining reliable, high-performance communication between UAVs and control stations remains one of the main operational challenges, primarily due to the lack of fixed infrastructure, the long distance from shore, and adverse and highly variable environmental conditions. This work presents an exploratory literature review, categorizing the key factors that influence communication performance: latency, data transfer rate, frequency bands (VHF, L, C, Ku, Ka), and phenomena such as signal refraction and multipath propagation over the sea. The limitations of traditional maritime communication systems, such as VHF and L-band, and their impacts when adapted to aerial missions are analyzed in detail. Emerging technologies, including Low Earth Orbit (LEO) satellite constellations, High-Altitude Platform Stations (HAPS), and hybrid architectures that integrate aerial, maritime, and satellite links, show strong potential to expand coverage and reduce latency in challenging oceanic environments. In addition, prospects for sixth-generation (6G) networks are discussed, highlighting their potential to enable ultra-responsive control, enhanced link resilience, and massive data transmissions in remote areas. Selecting the most suitable communication architecture must account for mission type, data volume, and operational context. Despite recent advances, significant gaps remain, underscoring the need for continued research and innovation to develop resilient, mission-tailored communication architectures for UAVs operating in maritime domains.

Keywords: Unmanned Aerial Vehicles; Maritime Communication; Satellite Communication Systems; Maritime Environments;

1. Introduction

With the advancement of embedded technologies and the growing demand for autonomous solutions, Unmanned Aerial Vehicles (UAVs) have expanded their applications beyond terrestrial environments, reaching challenging maritime scenarios [1][2]. In open-sea operations, UAVs are increasingly employed for equipment transport, platform inspection, navigation support, search and rescue, monitoring, and surveillance of remote areas, establishing themselves as strategic tools [3][4].

However, the effectiveness of these operations relies heavily on communication reliability, particularly in missions requiring real-time data transmission, such as high-resolution video streaming and advanced telemetry [4][5]. While terrestrial networks (4G, 5G) can deliver high speeds and low latency in coastal areas, the maritime environment lacks fixed infrastructure, leading to a dependence on technologies such as VHF radio, microwave links, and satellite communications [2]. Moreover, environmental factors including climate variability, atmospheric attenuation, and sea-surface reflection affect signal propagation, making it difficult to maintain stable links [1][6].

Given these challenges and the limited maturity of UAV applications in open-sea operations, this work examines the technical constraints imposed by the maritime environment, with a focus on communication systems. It presents existing solutions and discusses potential approaches to enhance reliability and performance in maritime UAV operations, particularly in those requiring real-time connectivity.

2. Methodology

This study adopts a qualitative, exploratory approach based on a technical literature review conducted using the IEEE Xplore, Scopus, and Google Scholar databases. Initially, the search focused on articles published within the last 10 years, with an emphasis on the application of UAVs in maritime and offshore operations. The search strategy followed a Boolean logic approach, using combinations such as: "UAV AND maritime communication AND satellite links" OR "UAV AND offshore communication" NOT "terrestrial".

Priority was given to publications directly addressing communication between UAVs and their ground control stations, considering technologies such as VHF/UHF radio links and satellite communications. During the analysis, it was observed that a significant portion of the publications focused on scenarios beyond the original scope, such as UAV-to-UAV mesh networks, mobile buoys powered by UAVs, and other forms of hybrid architectures. Although these did not strictly meet the initial selection criteria, some of these works were incorporated for providing relevant insights, including coastal applications, adapted naval technologies, and recent innovations in the field. The inclusion of these studies aimed to support the comparison between typical challenges of maritime communication and those encountered when adapting these solutions to UAVs operating in the same environment.

Data analysis was conducted through thematic categorization, grouping the main technical challenges and communication strategies identified in the literature. This approach enabled a reflection on current technological gaps and the identification of potential pathways for developing solutions better aligned with the demands of the maritime context.

3. Literature Review

This section analyzes the limitations and challenges of communication technologies employed in maritime environments, as well as their adaptation to UAV operations. The analysis covers: (3.1) latency, which is essential for real-time control; (3.2) data transfer rate, a key factor for video streaming, telemetry, and sensor data transmission; (3.3) frequency bands (VHF, L, C, Ku, and Ka) and their suitability for maritime use; (3.4) environmental conditions, such as signal refraction and multipath propagation; and (3.5) the current landscape of applications, highlighting limitations and gaps in long-range and open-sea missions.

3.1. Latency

Latency is one of the most critical factors in long-range maritime operations, where communication must ensure that command transmission and data reception, such as images, videos, or telemetry, occur with minimal delay [2].

In high-criticality missions, even small delays can compromise UAV control and, in extreme cases, lead to aircraft loss [7][8]. In operations such as search and rescue or real-time inspections, the literature recommends values close to 10 ms at the 99.9th percentile in controlled LTE environments [7][8][9]. Outside areas covered by terrestrial networks, performance degrades significantly. GEO satellites typically present 550–700 ms RTT [10], whereas LEO constellations can reduce this to 20–50 ms [10][4][6]. Emerging technologies such as High-Altitude Platform Stations (HAPS) [11] can achieve latencies below 10 ms, and hybrid architectures in which UAVs act as relay nodes combined with LEO satellite backhaul are emerging as promising solutions to mitigate critical delays in open-sea operations [12][16].

3.2. Data Transfer Rate

The data transfer rate is a determining factor for advanced UAV applications in maritime environments, such as high-definition video streaming, high-frequency telemetry, and integration with high-sampling-rate sensors [4][13]. While vessels typically require only voice or text communications, UAVs demand significantly higher throughput. Long-range and low-power technologies such as Long Range (LoRa) and Long Range Wide Area Network (LoRaWAN) provide good coverage for intermittent data but, with typical throughput below 50 kbps, are unsuitable for continuous video transmission [13][4]. In coastal regions, 4th Generation (4G) and 5th Generation (5G) networks can exceed 100 Mbps with latencies below 20 ms, provided there is nearby coverage [14][15].

Within the horizon of emerging technologies, communication architectures oriented toward 6th Generation (6G) are integrating Artificial Intelligence (AI) and Machine Learning (ML) capabilities to optimize dynamic link selection, predictive routing, and adaptive spectrum allocation in maritime operations [16]. Techniques such as Massive Multiple-Input Multiple-Output (Massive MIMO), Federated Learning, and Over-the-Air Computation (AirComp) show potential to enhance the resilience and efficiency of UAV communications even under energy and line-of-sight constraints [16][17].

3.3. Frequency Bands

The frequency band used in communication systems is a determining factor for transmission performance, as it directly influences range, data rate, and latency in UAV–maritime communications [4][18]. In general, lower frequencies provide greater range at lower data rates, while higher frequencies allow higher throughput but with limited range and increased susceptibility to interference and obstacles [18][19].

3.3.1. Very High Frequency (VHF)

Covering 30–300 MHz, with predominant maritime use between 156–174 MHz, VHF is widely employed for voice communications between vessels and coastal stations, and between 118–137 MHz in aviation [4][9][19]. It is characterized by equipment simplicity, line-of-sight reliability, and resistance to atmospheric interference. However, its limited bandwidth makes it unsuitable for high-rate data or video transmissions, restricting its use to commands and simple messages [4][19].

3.3.2. L-Band Communication

Operating between 1–2 GHz, the L-Band is used in mobile services, aeronautical communications, GPS, and satellite telephony [20]. It features low attenuation in rain and fog, good signal penetration, and global coverage through LEO satellites. However, its limited bandwidth restricts its application for large data volumes [20].

3.3.3. C-Band Communication

Operating from 4–8 GHz, the C-Band is stable and weather-resistant, widely used in satellite television broadcasting and fixed-platform communications, including Very Small Aperture Terminal (VSAT) systems [21][22]. The C Band offers good signal stability and lower susceptibility to rain attenuation compared to higher frequency ranges such as Ku or Ka bands. This makes it suitable for robust communications in open-sea environments, where adverse weather conditions are frequent [22].

3.3.4. Ku-Band Communication

Operating in the 12–18 GHz range, the Ku Band stands out for its higher bandwidth, enabling the transmission of larger volumes of data. It is widely used in satellite internet services and high-definition digital broadcasting, including on ships and commercial aircraft [22]. However, it is more susceptible to rain fade. Studies indicate that such effects can be mitigated through techniques such as adaptive modulation and link redundancy, although these measures may increase latency and operational costs [18][23].

3.3.5. Ka-Band Communication

Operating between 26.5–40 GHz, the Ka-Band offers higher speeds than the previous bands and is adopted by modern constellations such as OneWeb and Starlink [24][25]. It requires highly directional antennas and sophisticated tracking systems, increasing cost, power consumption, and complexity, especially on mobile platforms [25][26].

3.4. Environmental Conditions

The maritime environment imposes additional challenges on UAV communications, not only due to the absence of terrestrial infrastructure but also because of physical and atmospheric phenomena that degrade signal quality [14][18][19]. Conditions such as storms, fog, high humidity, and abrupt temperature variations increase attenuation and reduce link stability [18].

In addition, the sea surface promotes multipath fading caused by the reflection of electromagnetic waves, resulting in delay spread, phase distortions, and packet loss [18][19]. These effects are more critical at higher frequencies and are amplified by the altitude and speed dynamics of UAVs. Strategies such as antenna diversity, adaptive modulation, and error correction coding are recommended to mitigate these impacts [13][16].

3.5. Applications Overview: UAV Operational Scenario

The deployment of UAVs in open-sea environments remains relatively uncommon, with operations predominantly concentrated in coastal areas or near offshore platforms equipped with supporting infrastructure [4][6][14]. In these regions, the most frequent applications include environmental monitoring, offshore structure inspection, navigation assistance, search and rescue, border surveillance, and light cargo delivery [2][4].

Despite gradual expansion, long-endurance missions and fully autonomous operations in open-sea contexts are largely confined to military or experimental domains. This limitation is primarily attributed to challenges in connectivity, energy autonomy, and link resilience [4][6].

The principal technical challenges identified in the literature include: (i) the absence of fixed communication infrastructure, (ii) severe bandwidth limitations for real-time data transmission, (iii) susceptibility to link failures caused by adverse environmental conditions, and (iv) the complexity of integration with existing naval systems [2][5].

4. Results and Discussion

Literature indicates that no single communication solution guarantees robust connectivity for UAVs in maritime environments, as each scenario presents distinct constraints related to range, data demand, energy availability, and environmental conditions.

As discussed in Section 3.1 [7][8][9], latency is a limiting factor for time-sensitive missions, particularly in search and rescue operations and real-time inspections. Section 3.2 [4][13][14][15], highlights that data rate directly constrains continuous video streaming and the integration of complex sensors. Regarding frequency bands (Section 3.3) [9][19][20], lower bands such as VHF and L offer robustness under adverse conditions and long-range coverage, but lack sufficient throughput for high-demand applications. In contrast, Ku and Ka-bands support high data rates and multiple video streams, although they are more susceptible to atmospheric attenuation and require high-precision tracking systems, which increase cost and complexity, especially in small UAV platforms. Section 3.4 further emphasizes that multipath fading, delay spread, and rain attenuation can significantly degrade link quality, particularly at higher frequencies [18][19][22].

In practical applications, selecting an appropriate communication architecture involves balancing range, robustness, and throughput capacity. For instance, low-latency critical missions, such as search and rescue or real-time offshore inspections, can benefit from LEO satellite links (e.g., Starlink, OneWeb), which offer data rates between 50 and 200 Mbps with latencies below 50 milliseconds. However, these systems require precise tracking mechanisms and a reliable power source. Periodic data collection missions, including environmental and meteorological monitoring, may utilize GEO satellites or VHF/UHF bands, which provide lower data rates but are sufficient for intermittent transmissions, ensuring wide coverage and reduced power consumption. Coastal operations can leverage LTE/5G networks, achieving data rates above 100 Mbps and latencies below 20 milliseconds, although these depend on proximity to terrestrial infrastructure. For open-ocean scenarios, hybrid architectures, such as combinations of LEO satellites with HAPS, or integration with Unmanned Surface Vehicles and buoy-based repeaters, can extend coverage while maintaining moderate latency and high throughput.

Hybrid integration stands out as the most promising approach. Recent solutions incorporate UAVs as relay nodes, HAPS platforms, and multi-hop links, forming collaborative surface–air–satellite networks. These architectures offer a balance between performance and cost, while adapting to diverse mission profiles. Future integration with 6G networks may enable terabit-per-second data rates and sub-millisecond latencies, supporting ultra-responsive control and multiple simultaneous high-definition video streams, even in remote regions.

Beyond raw transmission capacity, link resilience is essential. As noted in Section 3.4, environmental phenomena can cause abrupt channel degradation. Therefore, robust architectures must incorporate channel redundancy, failover protocols, and fallback operational modes. The application of AI and ML, already proposed in 6G frameworks, could facilitate automatic switching between radio frequency (RF), Free-Space Optics (FSO), and satellite links, as well as predictive routing to avoid congestion and low-coverage areas.

Nevertheless, significant gaps remain in the literature. Most studies emphasize technical performance, with limited consideration of economic and logistical feasibility, particularly regarding the implementation of hybrid architectures in small and medium UAV platforms. There is also a lack of comprehensive research on integration with existing naval systems and the development of unified communication protocols that ensure full interoperability among aerial, maritime, and space-based assets.

In summary, the future of UAV connectivity in maritime environments will be shaped by the convergence of multiple technologies, supported by intelligent network management. Progress depends not only on advancing communication links, but critically on the ability to integrate heterogeneous systems adaptively, ensuring coverage, performance, and reliability under extreme conditions.

5. Conclusion

The analysis conducted demonstrates that, while the deployment of UAVs in maritime scenarios is technically feasible and holds significant potential, communication remains one of the primary bottlenecks for large-scale adoption. Optimal communication architecture must be treated as a core element of system design rather than an isolated decision.

The findings indicate that most technologies traditionally employed in the maritime sector, although robust, are unsuitable for continuous high-rate data missions. The architectures reviewed present viable alternatives to mitigate these limitations, yet still face challenges such as atmospheric attenuation, tracking complexity, and bandwidth constraints within specific frequency bands.

Emerging developments point toward intelligent hybrid architectures that combine satellite, radio, and HAPS links, supported by adaptive protocols and AI-driven coordination. Technologies such as Massive MIMO, dynamic beamforming, and integration with 6G networks have the potential to significantly transform airborne communication, extending coverage while reducing latency. Economic feasibility, maintenance logistics, and regulatory compliance will be decisive for transitioning these solutions from prototypes to operational deployment.

Given the existing technological gap, UAV connectivity in open-sea environments emerges not only as a promising research frontier but also as a strategic enabler for more reliable, responsive, and adaptive aero-maritime operations. This evolution is expected to directly impact safety, operational efficiency, and the expansion of autonomous capabilities within the maritime domain.

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