Field Measurement of Multi-band Maritime 5G Communication in Deep Sea Scenario

Hang Wu, Kun Yang, Jianjun Ding, Jinglong Lin , Li Qin
Department of Information Engineering
Zhejiang Ocean University

ZhouShan, China

emails: {2778312726@qq.com, yangkun@zjou.edu.cn, zou709142266@163.com, linjinglong@zjou.edu.cn, ql_qinli@zjou.edu.cn}

***Abstract*—The burgeoning marine economy necessitates robust 5G communication capabilities. However, offshore 5G coverage is inherently constrained by the limited reach of terrestrial base stations, and systematic empirical data on its performance in such environments remains scarce. To bridge this knowledge gap, this study conducted comprehensive empirical measurements of 5G network performance from April 29-30, 2025, utilizing the "Zhe Yu Ke 2" as a mobile testbed in an offshore region extending up to 69 km from the coast. Systematic measurements were conducted on critical performance metrics, including end-to-end latency, uplink/downlink transmission rates, Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), and Signal-to-Interference-plus-Noise Ratio (SINR), across the 700/850/1800/2100 MHz frequency bands. The empirical results indicate that while 5G can provide fundamental communication services within 69 kilometers offshore, its performance significantly degrades with increasing distance. Notably, the 700 MHz band demonstrated superior capabilities for extended coverage and maintaining more consistent data rates. This study provides crucial empirical evidence for the strategic planning and optimized deployment of marine 5G networks, facilitating critical applications,such as offshore wind power monitoring and smart shipping.**

Keywords-Marine 5G; Long-range Communication; Frequency Band Performance; Data Analysis; Signal Quality.

I. INTRODUCTION

The rapid development of the marine economy places higher demands on communication systems. 5G technology, with its advantages such as high bandwidth, low latency, and massive connectivity, is considered a key enabler for digital transformation in the marine sector [1]. However, in vast marine scenarios, particularly in far-sea areas far from land-based base stations, current 5G faces severe challenges, such as insufficient network coverage and fluctuating signal quality [2]. It is particularly noteworthy that systematic field measurement data is extremely scarce in far-sea areas tens of kilometers away from the coastline, making objective performance evaluation difficult.

Recent studies have explored maritime 5G from theoretical and simulation perspectives. For instance, Saini et al. [4] assessed path loss at air–sea interfaces, providing theoretical insights into long-range signal propagation. Gao et al. [6] modeled electromagnetic wave propagation over rough sea surfaces using parabolic equations, while Lindenbergs et al. [7] investigated multi-hop 5G architectures for maritime connectivity. Despite these efforts, most existing works rely on simulations or near-shore trials, lacking comprehensive empirical data from true far-sea environments. In particular, there is a lack of field measurements evaluating multi-band (e.g., 700/850/1800/2100 MHz) 5G performance beyond 50 km offshore, and limited understanding of how key indicators—such as latency, throughput, RSRP, RSRQ, and SINR—evolve jointly under real oceanic conditions.

This gap leads to a clear “wish list” for maritime 5G research: (1) conducting systematic field tests in deep-sea scenarios (>50 km); (2) quantifying the trade-offs between coverage and data rate across different frequency bands; and (3) generating practical, data-driven guidance for offshore base station deployment and spectrum planning.

To fill this gap and provide reliable evidence, this study conducted comprehensive field measurements up to 120 km offshore near Zhoushan, China, using the research vessel Zhe Yu Ke 2 as a mobile testbed. We systematically evaluated 5G performance across multiple frequency bands (700/850/1800/2100 MHz), collecting end-to-end latency, uplink/downlink rates, RSRP, RSRQ, and SINR under real marine conditions. The results reveal the degradation patterns of 5G signals over long distances and highlight the superior coverage capability of the 700 MHz band.

These field measurement data provide important data support and a decision-making basis for the optimized design and technology selection of future maritime 5G networks, as well as their promotion in various marine application scenarios, such as offshore wind monitoring and smart shipping [3]. They also serve as a technical benchmark for communication system deployment in coastal and near-sea regions.

Despite the comprehensive nature of our field measurements, this study has several limitations that should be acknowledged. The measurements were conducted over a short period under relatively calm sea states and favorable weather conditions, which may not fully capture the performance degradation caused by severe weather, strong tides, or atmospheric ducting phenomena. Furthermore, the results are based on a single network operator and a specific maritime route, and performance may vary with different network configurations or in other geographical locations. These limitations highlight valuable avenues for future research.

The remainder of this paper is organized as follows. Section II details the experimental setup, including the test environment, the measurement platform, and the data collection procedures. Section III presents and analyzes the empirical results, focusing on key performance indicators such as latency, network speed, and signal quality across different frequency bands. Finally, Section IV concludes the paper by summarizing the key findings, discussing their implications, and outlining directions for future work.

II. TEST SCENARIO

This section details the experimental methodology, describing the geographical test environment, the hardware setup, and the data collection procedures.

A. Test Environment

The tests were conducted from April 29 to April 30, 2025, in the waters near Zhoushan City, with the navigation route as shown in Figure 1.

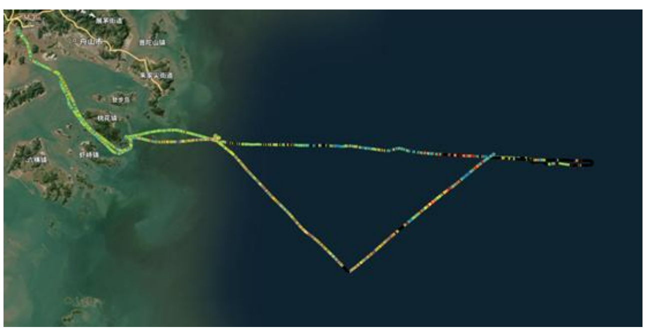

Figure 1. Route Map

The furthest point of the test route extended approximately 69 kilometers offshore, covering the transition zone from coastal to far-sea areas. During the testing period, the marine and meteorological conditions were generally stable. On Tuesday, April 29, 2025, the temperature in the test area ranged from 15°C to 24°C, with the weather transitioning from overcast to partly cloudy, a southeast wind at level 3, and excellent air quality (AQI 32). Overall, the meteorological conditions were suitable for offshore operations. On Wednesday, April 30, the temperature ranged from 18°C to 24°C, the weather changed from overcast to light rain, and the wind strength increased to a southerly wind at level 5. The sea conditions became slightly rougher, which could have had some impact on certain communication indicators and signal propagation. The 5G network operator relied upon for the tests was China Mobile.

B. Experimental Setup

To evaluate the performance of 5G communication systems in far-sea environments, we conducted field measurements over a coastal-to-offshore range of 0–120 km. The experimental platform was based on a self-developed 5G terminal integrating an n78 band (3.5 GHz) 5G module, a high-gain directional antenna, and an embedded data acquisition system, capable of stable long-term operation in complex marine electromagnetic conditions.

During the test, the research vessel sailed at a constant speed along a predefined route for data collection. Key performance metrics were periodically measured with tailored sampling frequencies according to their dynamic characteristics, balancing measurement accuracy and system load.

TABLE I. MEASUREMENT PARAMETER TABLE

Measurement Parameter	**Measurement Configuration**	
	Sampling frequency	***Collection toll***
Latency	Every 5 seconds	Vim Ping
GPS Positio	Every 5 seconds	GPS module
Downlink/Uplink Throughput	Every 5 minutes	Speedtest
RSRP、RSRQ、SINR	Every 30 seconds	5G terminal backend web interface

All data were locally recorded with timestamps for subsequent spatiotemporal alignment and statistical analysis. The terminal antenna was kept stable during testing to minimize directional signal attenuation. All experiments were conducted under favorable weather conditions and calm sea states (wind force < 4) to avoid additional interference from harsh environments.

III. TEST RESULTS AND ANALYSIS

This section presents a detailed analysis of the collected field data, evaluating the maritime 5G network performance through key metrics including latency, throughput, and signal quality indicators.

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A. *Latency Performance Analysis*

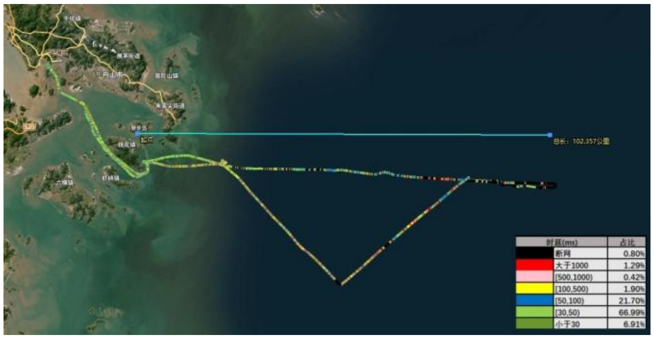

Figure 2. Latency vs. Offshore Distance

Analysis of Figure 2 reveals that as the vessel gradually moves away from the shore-based base station, the end-to-end communication latency of the 5G network in the maritime environment generally shows an upward trend. In waters closer to the shore, due to the shorter physical distance between the terminal equipment and the base station, the communication link is relatively stable, and network latency remains at a low level. However, as the vessel moves further away from land and gradually enters far-sea areas, latency exhibits a step-by-step increase. Particularly after crossing a specific distance threshold (e.g., 70 km or 100 km), network latency increases significantly, showing a notable phenomenon of edge performance degradation. This phenomenon fully demonstrates the direct impact of distance on the quality of maritime wireless communication links.

A comprehensive analysis of the causes of the aforementioned network performance degradation can be summarized into several aspects: Firstly, as the wireless signal transmission path lengthens, the path loss experienced by the signal during transmission continuously increases, leading to a weakening of the received signal strength [4]. Secondly, due to increased distance, the link quality continuously deteriorates, forcing the system to initiate more retransmission mechanisms to ensure data integrity, thereby further extending the total latency. Thirdly, the base station's ability to serve long-distance users decreases due to its scheduling strategy, limiting the quality of service for edge users. Furthermore, at certain specific maritime coordinates, the study also observed anomalous fluctuations or sudden increases in communication latency. Such phenomena may be jointly induced by multiple factors, such as automatic switching of communication bands, changes in ship attitude during navigation, or the presence of local electromagnetic interference sources [5].

B. *Network Speed Performance Analysis*

The fundamental reason for the overall decline in speed primarily stems from the complex physical environment faced during maritime radio wave propagation. Firstly, after the vessel departs from shore, the signal propagation path significantly lengthens, and path loss rapidly accumulates, thereby weakening the signal strength at the receiver. Especially when the communication link extends beyond the line-of-sight boundary, the attenuation of direct signals sharply increases due to the Earth's curvature. Secondly, because the sea surface is relatively flat, it is prone to strong specular reflection effects, leading to severe multipath propagation problems. This phenomenon can cause frequency selective fading, interfering with certain frequency bands in the channel and leading to a reduction in the usable modulation and coding levels, fundamentally limiting the terminal equipment's data throughput capacity.

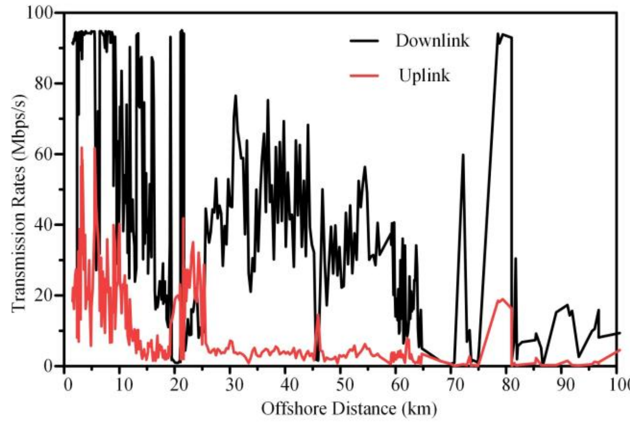

Figure 3. Link Rate vs. Distance Graph

In addition to channel propagation characteristics, the network resource allocation mechanism itself also significantly impacts speed performance. Typically, mobile communication systems allocate more transmission resources in the downlink direction, and base stations possess higher transmit power. In contrast, terminal equipment's transmit capability, antenna gain, and anti-interference performance are often insufficient on the uplink. Therefore, in long-distance communication scenarios facing extended signal paths and increased interference factors, the uplink is more susceptible to impact, exhibiting instability or even an inability to maintain connection. Furthermore, from Figure 3, certain anomalous fluctuation characteristics can also be observed. For example, at approximately 22 km and 60 km, the downlink speed momentarily increased to abnormally high values. This sudden change may be related to the vessel temporarily entering a high signal coverage area (e.g., a new base station sector or the coverage range of a repeater station), or it could be related to the system scheduling momentarily releasing high bandwidth resources. Relatively, the frequent drop of uplink speed to zero is more likely due to limitations in terminal communication capability, which may be caused by severe deterioration of channel quality, unstable ship antenna attitude due to fluctuations, or local interference sources leading to communication link failure.

This systematically outlines the typical performance characteristics of the current maritime 5G communication environment: "excellent communication quality in near-shore areas, significant fluctuations in mid-range, sharp decline in speed in far-sea areas, and the uplink link being more susceptible to damage." The above trends and their anomalous phenomena not only reveal the real challenges faced by maritime communication coverage but also profoundly reflect the complex and dynamic coupling relationship between wireless propagation conditions, network scheduling strategies, and terminal technical capabilities, providing important empirical reference for future maritime 5G network optimization, coverage strategy formulation, and technological iteration.

C. *Signal Quality Indicator Analysis*

SINR has a decisive impact on wireless network data transmission capability, directly related to throughput, bit error rate, and the supported modulation and coding levels. For instance, in LTE or 5G networks, if the SINR value reaches above 20 dB, the system can typically employ higher-order modulation schemes, such as 64QAM or even 256QAM, thereby significantly improving data transmission rates. However, SINR is comprehensively influenced by multiple factors, including severe multipath propagation in marine environments, interference from neighboring base stations, and background noise in the device's environment. SINR is not only an important basic parameter for wireless network performance evaluation but is also widely applied in key technical aspects, such as system capacity design, dynamic interference control, network optimization, and real-time quality monitoring.

Figure 4 shows the dynamic evolution of maritime communication signals in complex environments.

Firstly, the gradual attenuation of RSRP (from -90 dBm to -112 dBm) conforms to the free-space path loss model. Particularly in open sea areas without land reflection support, signal propagation is exacerbated by the dual effects of atmospheric scattering and sea surface absorption. It is worth noting that signal recovery in the V-shaped return path might be related to brief line-of-sight optimization or the Doppler effect caused by route adjustments, which suggests the potential role of dynamic antenna directivity in signal maintenance.

The significant decline in RSRQ (from -10 dB to -20 dB) indicates a rapid increase in interference components. This could stem from coherent multipath interference caused by sea surface reflection, as well as electromagnetic interference from other vessels or aircraft. Combined with the SINR data (dropping from 5-10 dB to <0 dB), it can be inferred that there is higher non-thermal noise or adjacent channel interference in far-sea areas, possibly due to ionospheric reflection in the marine environment or the superposition effect of distant base station signals. Mathematically, the deterioration of SINR is significantly amplified by increasing distance.

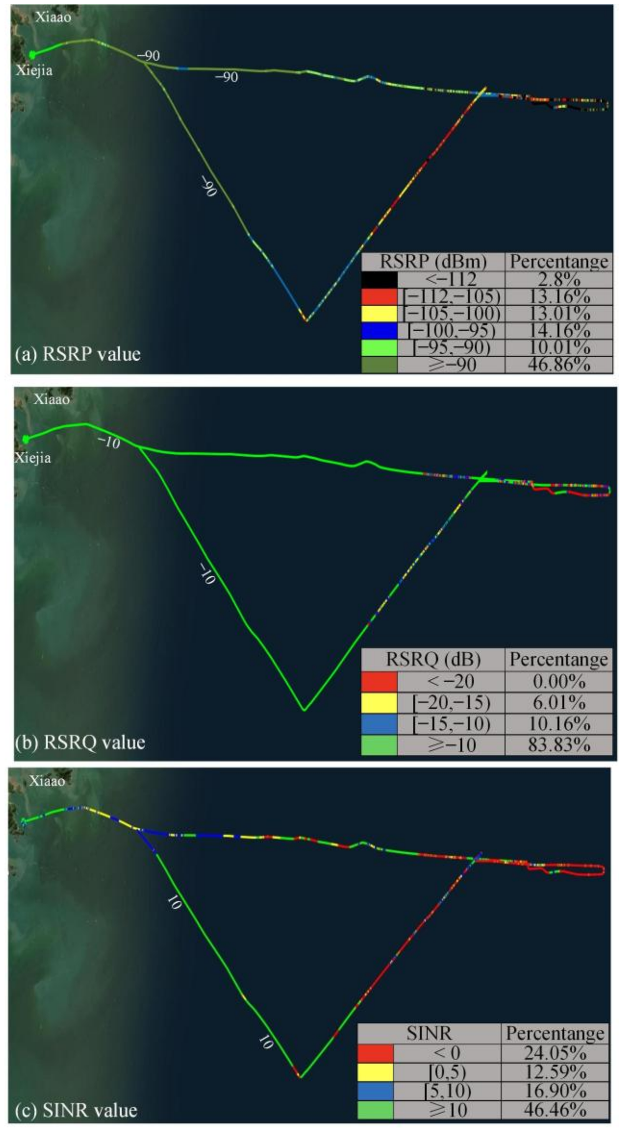

Figure 4. RSRP, PSRQ, and SINR Summary Chart

Based on this analysis, it can be predicted from the above analysis that if we continue into deeper waters, signal quality will further deteriorate unless targeted technical interventions are introduced. Improvement directions include: first, deploying adaptive relay networks based on buoys or Unmanned Aerial Vehicle (UAV) to shorten signal propagation distance and improve RSRP; second, adopting Multiple-Input Multiple-Output (MIMO) technology combined with beamforming to optimize RSRQ and SINR; third, developing machine learning-based adaptive modulation and coding schemes to dynamically adjust transmission parameters to cope with interference. In the future, these hypotheses can be further verified and communication strategies optimized through simulations combining marine environmental data with signal models.

D. Analysis of Communication Bands and Network Speed

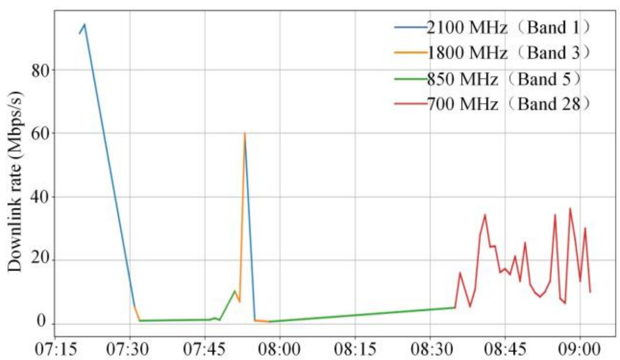

Figure 5. Relationship between Frequency Band and Network Speed

In the initial stage of communication, figure 5 shows that the two higher frequency bands, 2100 MHz (Band 1) and 1800 MHz (Band 3), exhibited excellent downlink data transmission rates. Specifically, the downlink rate of the 2100 MHz band once exceeded 90 Mbps, and the 1800 MHz band also briefly reached a peak of 60 Mbps. This phenomenon indicates that in near-shore areas close to land-based base stations, higher frequency bands, by virtue of their larger channel bandwidth and higher spectrum utilization efficiency, can provide strong data throughput capability to meet high-speed data transmission demands. However, as the vessel sailed further away from land-based base stations, the attenuation speed of the aforementioned high-frequency signals significantly accelerated, eventually leading to connection interruptions and a plummeting data transmission rate to near zero. Thereafter, maritime communication primarily relied on the two lower frequency bands, 850 MHz (Band 5) and 700 MHz (Band 28), for maintenance. Although the overall data transmission rate provided by these two low-frequency bands was only between 10–30 Mbps, their connection stability was significantly enhanced, providing a basic guarantee capability for far-sea communication.

In the maritime wireless communication environment, the propagation characteristics of electromagnetic waves are significantly affected by frequency: the higher the frequency, the faster the signal attenuates during propagation, and the poorer its penetration and diffraction capabilities [6]. Therefore, although the 2100 MHz and 1800 MHz bands have the advantage of providing high data transmission rates, their coverage range is greatly limited, maintaining high performance only in areas close to base stations or under good line-of-sight propagation conditions. In contrast, low-frequency bands (especially 700 MHz and 850 MHz), due to their longer electromagnetic wavelengths and stronger diffraction capabilities, can achieve longer communication distances and stronger anti-interference capabilities in an unobstructed but complex propagation medium like the sea surface, becoming typical main frequency bands for long-distance coverage [7]. It is particularly worth mentioning that Band 28 has gradually become one of the internationally recognized core resources for far-sea wide-area communication, playing a key role in far-sea communication coverage.

From the test data graph, it can be observed that during the 07:30–08:00 time period, the frequency bands used by the communication system frequently switched, and data transmission rates also fluctuated significantly, even experiencing "blank periods" of communication interruption. This phenomenon may be due to the user terminal equipment's inability to quickly and effectively complete frequency band switching in a complex multi-band environment, or due to improper handling of frequency band coverage boundaries on the network side. Simultaneously, since the current system has not enabled frequency band carrier aggregation technology, various frequency bands operate relatively independently in actual communication, leading to fragmented overall network performance. That is, while low-frequency bands can provide basic connection guarantees, they cannot support high-throughput service demands. Overall, the stability and consistency of current maritime communication links still face significant challenges, which is unfavorable for the continuous conduct of critical services, such as real-time transmission of high-definition video and precise remote control of remote equipment.

To address the above issues, it is recommended that maritime communication systems be optimized simultaneously in terms of frequency band strategy and terminal capabilities. In near-shore areas, priority can be given to using 2100/1800 MHz high-frequency bands to enhance initial link quality. When entering far-sea, intelligent switching to Band 28/5 should occur to maintain basic connectivity. Simultaneously, the deployment of Carrier Aggregation should be promoted, especially multi-band aggregation schemes involving low-frequency + mid-frequency (e.g., Band 28+5+3), to balance speed and coverage. Additionally, consideration can be given to deploying high-gain directional antennas or mobile base station facilities, such as relay buoys to extend the effective service radius of high-frequency bands [8]. Terminal equipment should also support features like MIMO, band aggregation, and fast switching to maintain stable communication capabilities under dynamic sea conditions and complex propagation conditions, thereby providing a network guarantee basis for future maritime intelligent operations.

IV. CONCLUSION AND FUTURE WORK

This study presents a comprehensive field measurement of 5G network performance in a deep-sea maritime environment, revealing key patterns in latency, throughput, and signal quality over distances up to 120 km offshore. The results show that end-to-end latency increases with distance, while network performance exhibits significant edge degradation in far-sea areas. Specifically, downlink rates can reach 90–100 Mbps within 2–10 km from the coast but drop rapidly to below 10 Mbps—or even zero—beyond 40–60 km. Uplink performance remains consistently weak, with frequent disconnections observed in distant zones. Signal quality indicators—including RSRP, RSRQ, and SINR—gradually deteriorate with distance, and SINR typically falls below 0 dB beyond 70 km, severely compromising link stability.

Frequency band analysis further highlights a critical trade-off between coverage and capacity: high-frequency bands (e.g., 1800 MHz and 2100 MHz) deliver high data rates near shore but suffer rapid signal decay; in contrast, low-frequency bands (e.g., 700 MHz and 850 MHz) maintain stable connectivity over long distances, demonstrating superior propagation characteristics for maritime coverage.

These empirical findings provide valuable insights into the evolution of maritime 5G links across rate, latency, and signal quality dimensions. They offer practical guidance for communication operators in optimizing base station deployment, frequency planning, and resource scheduling to enhance offshore coverage. Moreover, the identified performance bottlenecks inform the design of reliable communication strategies for intelligent maritime applications—such as unmanned vessel control, ocean monitoring, and smart shipping—where stable and low-latency connectivity is essential. The results also support the development of advanced terminal technologies, including multi-band aggregation, beamforming, and intelligent handover mechanisms, laying a foundation for future 6G and space-air-ground integrated networks.

When compared to Low Earth Orbit (LEO) satellite systems (e.g., Starlink, OneWeb), terrestrial 5G offers distinct advantages in near-sea scenarios (<70 km). First, 5G achieves lower latency, with measured average RTT under 40 ms, outperforming LEO systems (typically 25–80 ms) due to shorter propagation paths and fewer relays. Second, 5G leverages existing infrastructure, resulting in significantly lower deployment and operational costs, whereas LEO terminals are expensive (often >USD 500) and require recurring subscription fees—prohibitive for large-scale near-shore sensor networks. Third, 5G provides higher and more stable throughput (up to hundreds of Mbps) with QoS support, while LEO links are prone to interruptions and rate fluctuations caused by weather, sea clutter, and terminal orientation.

Nonetheless, 5G's coverage is inherently limited by line-of-sight propagation and Earth's curvature, making it unsuitable for open-ocean use. Therefore, we advocate a complementary architecture: using 5G as the primary, cost-effective, and low-latency solution in near-sea regions, and seamlessly transitioning to LEO satellites in far-sea or global coverage scenarios—forming a hybrid "Near-sea 5G + Far-sea Satellite" integrated communication system.

This study has some limitations. Measurements were conducted under relatively calm sea states and favorable weather conditions, without fully capturing the impact of severe weather or tidal dynamics. Some performance fluctuations may also stem from operator-specific network policies, requiring further investigation. Future work will extend testing across diverse marine conditions, explore heterogeneous networks (e.g., 5G + satellite + UAV relays), and incorporate machine learning for adaptive link optimization. Additionally, we plan to integrate Quality of Experience (QoE) assessment to better align technical performance with application-level requirements, ultimately enabling robust and intelligent maritime communication ecosystems.

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