Assessing Communications Equipment Performance for Reliable USV Teleoperation and Autonomy

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ABSTRACT

The ability to simulate long-range communication is critical for supporting modeling and simulation of unmanned surface vessels (USVs). Typically, a USV is operating via a virtual tether, and onboard software must reliably determine if the connection to the control station is intact. Frequently, this is done by establishing a control station response timeout which must be long enough to avoid false disconnects but short enough to maintain responsive control. Improving communications equipment simulation fidelity is necessary for increasing realism of USV simulations. In this paper, we revise a testing methodology and present test data that allows calibrating communication model parameters based on measured performance. Specifically, this study evaluates the performance of Persistent Systems' MPU5 radios, a commonly used device in military UxV operations, to establish stable connectivity between a USV and a ground station over extended distances. Unlike conventional bandwidth tests, our primary objective is to characterize radio performance under realistic conditions, focusing on model parameters that assist with determining optimal timeout thresholds to detect connection loss while avoiding unnecessary disruptions. Using a USV and a ground station, both equipped with MPU5 radios, we conducted tests at multiple distance intervals, evaluating network latency, loss of packets and throughput under operational conditions that mirror typical USV usage patterns. Bandwidth performance was analyzed using custom measurement software and iPerf3 with varying packet sizes to assess responsiveness and reliability. Our findings indicate that small control packets (≤100 bytes) maintain negligible loss even at distances beyond 6 miles, while larger packets (≥500 bytes) exhibit growing loss rates and jitter as range increases. These results can be leveraged to develop validated communications equipment simulations and increase realism which allows use of simulation for setting response timeouts, calibrating tethered communication parameters and refinement of robust communication strategies for mission-critical USV operations in maritime environments.

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INTRODUCTION

Unmanned surface vessels (USVs) are increasingly used in defense, environmental monitoring, and maritime logistics, where they may be remotely operated or run autonomously for extended periods and over long distances. Modeling and simulation are commonplace when designing and evaluating the overall performance of such systems and the ability to reliably model wireless communication is essential for improving overall simulation realism and support simulation-based design. As these platforms operate at greater distances and in more complex environments, high fidelity simulation of the communications link between the vessel and the control station is critical to maintaining simulation validity and in turn, usefulness of simulation. For example, maintaining stable communications links becomes a central challenge, particularly when system safety and operator situational awareness depend on timely detection of true link failures without unnecessary interruptions (Costanzi et al., 2020).

A common approach for remotely operated USVs is the use of a “virtual tether,” where continuous communication between the vessel and control station is assumed. To manage connection health, many control systems implement heartbeat-style mechanisms, using periodic packets to verify link status. However, one of the key design challenges in such systems lies in setting appropriate timeout thresholds. If the threshold is too short, transient delays or packet loss may trigger a false disconnect; if too long, actual loss of control may go undetected, delaying failsafe behaviors or responses. A simulation model for a USV that does not explicitly address such issues diminishes the overall value of simulation-based evaluation and design. This often leads system designers to rely on ad-hoc heuristics or lab-based assumptions to set timeout values and packet sizes, in lieu of data-driven models. In maritime environments, where interference from the water surface as well as distance affect network performance, this approach is insufficient. While mobile ad-hoc networking (MANET) solutions have proliferated in maritime robotics, there remains limited empirical data that can be used to develop communications model with enough granularity to model how packet loss, jitter, and throughput vary with range under real-world maritime conditions, metrics directly relevant to heartbeat timeout configuration and overall system reliability. Most prior studies have focused on technology comparisons or have not addressed the operational nuances of small-packet control traffic versus high-bandwidth payloads in long-range scenarios.

This study presents a field-based evaluation of a commercial MANET radio system (Persistent Systems' MPU5) operating over open water at distances up to 7 miles. The MPU5 radios implement a Mobile Ad-hoc Networking protocol and allow the installation of various radio modules operating at different bands. The radios in this study were equipped with radio modules operating in the L-band spectrum (1.37GHz). Our primary objective is to obtain quantitative performance data that will allow development of communications equipment modeling with enough granularity to calibrate heartbeat timeout policies and leverage simulation for experimenting with network performance tradeoffs that USV designers and operators face as a function of range. Our focus extends beyond bandwidth capacity to encompass latency, jitter, and most critically packet loss behavior as a function of packet size and distance. Note that even though the radio supports ad-hoc networking, this test involved 2 radios, one on the shore and one on a sea vessel so the radios were operating in point-to-point mode.

To achieve our objective, we conducted over 160 tests using custom bandwidth measurement software and iPerf3, systematically measuring packet loss, jitter, and throughput for both small control packets and larger data streams across control-relevant packet sizes (ranging from 5 bytes to 1500 bytes) under calm weather conditions. Our results quantify how performance degrades with distance and demonstrate that small packets maintain near-zero loss even at extended ranges, while larger packets are increasingly vulnerable to disruption. These insights directly inform the design of heartbeat mechanisms and timeouts that are both responsive and tolerant to real-world conditions, ultimately providing robust, data-driven communication models that can leverage simulation to assess strategies for USV operations in demanding maritime environments.

RELATED WORK

There has been extensive work on the fundamentals of simulating communications systems (Jeruchin et al., 2000). Using first principles, such techniques can be accurate but complicated and require extensive information on the low-level operational characteristics of modern radio firmware and antenna performance.

Reliable long-range communication is a foundational requirement for autonomous and remotely operated maritime systems, with numerous studies addressing network performance characteristics such as latency, packet loss, and connection stability under dynamic operational conditions. Recent research has emphasized the need to characterize network behavior beyond raw bandwidth, particularly for safety-critical USV operations where loss and delay directly impact mission reliability (Alqurashi et al., 2023).

Mobile ad-hoc networks (MANETs) have emerged as a robust solution for mobile and distributed systems, including maritime robotics. MANET radios such as Persistent Systems' MPU5 are widely adopted in defense and robotics applications due to their mesh networking capability, resilience, and infrastructure independence (Coccolo et al., 2023). Prior work in aerial and ground robotics, such as speed-aware routing in UAV ad-hoc networks (Rosati et al., 2013), highlights the relevance of MANET resilience and mobility for USV scenarios as well.

Heartbeat-based supervision is a standard approach for monitoring connection integrity in teleoperated and autonomous systems and is widely used in robotics and distributed control loops. However, setting timeout thresholds for these heartbeat messages remains largely ad hoc. While adaptive failure detection and dynamic timeout strategies have been proposed, their validation in maritime wireless networks remains limited (Fetzer et al., 2001). Furthermore, latency and packet loss behavior under variable load and distance are often ignored in broader MANET studies (Zhang et al., 2016).

In the maritime domain, several studies have examined the performance of USV communication systems and wireless technologies. Norgren et al. tracked autonomous underwater vehicles using USVs (Norgren et al., 2015), while Ma et al. presented a cooperative UAV-USV communication framework for coordinated operations (Ma et al., 2018). Lv et al. evaluated underwater acoustic communication quality for USVs, noting environmental factors like sea state and wind as major influencers of signal fidelity (Lv et al., 2018). Broader studies often compare the tradeoffs of Wi-Fi, LTE, and SATCOM for marine robotics (Al Mashhadany et al., 2020), while swarm robotics applications in marine environments have demonstrated the importance of decentralized control and local communication for scaling to large numbers of autonomous units (Duarte et al., 2016). Although these systems offer varying coverage and bandwidth capabilities, MANET solutions like MPU5 radios are attractive for maritime robotics due to their extended range, resilience, and infrastructure independence.

Recent contributions stress the importance of field validation and interoperability in maritime systems. Costanzi et al. emphasized the importance of interoperability and field validation in unmanned maritime systems while advocating for realistic testing under operational conditions (Costanzi et al., 2020). Similarly, Pokorny et al. (Pokorny et al., 2021) proposed and have experimentally validated collaborative maritime communication systems using packet-level metrics. These perspectives support our argument that communication performance must be evaluated in terms of probabilistic loss and jitter, rather than peak throughput alone.

Other contributions have tackled network-aware autonomy. Sarda et al. explored station-keeping strategies under wind and current disturbances that requires resilient communication channels (Sarda et al., 2016). Alqurashi et al. (Alqurashi et al., 2023) surveyed enabling technologies for maritime communications, highlighting MANET radios and long-range wireless systems as promising but under-characterized in practice.

Despite these advances, timeout calibration for heartbeat-based connection validation is still largely heuristic, with little empirical guidance for maritime MANET deployments. This study addresses this gap by providing a practical, field-tested dataset that links packet size, distance, and packet loss under real-world USV conditions. By focusing on packet loss, jitter, and bandwidth across operational distances, our results directly inform heartbeat timeout calibration and robust communication design for USVs in maritime environments.

METHODOLOGY

The objective of this study is to evaluate long-range wireless communication performance between a USV and a stationary ground control station using MPU5 radios. Specifically, we aim to characterize network behavior in terms of packet loss probability, bandwidth, and jitter across a range of distances and packet sizes with the ultimate goal of using such data to develop validated communication systems models with enough granularity to allow calibration of heartbeat timeout thresholds, which are essential for safe and responsive teleoperation and autonomous fallback behaviors.

Our approach involved conducting controlled field tests under realistic environmental conditions, using both custom-developed bandwidth testing software and the industry-standard iPerf3 tool. Measurements were taken at multiple fixed GPS waypoints extending up to 7 miles from the ground station.

Experimental Setup

Ground Station: A ground station was established a few feet from a shoreline in the north portion of Norfolk VA. The ground station consisted of a laptop running the USV control application, a network switch, a WR-INT-ANT-SYS-08 L-Band Integrated Sector Antenna, and a portable power bank that provided power for all equipment. The WR-INT-ANT-SYS-08 is a combination of an MPU-5 radio and a highly directional antenna with a gain of 9 dBi. The antenna was located approximately 2 feet away from the shore station to minimize any interference. The center of the antenna was positioned 86.5 inches above the ground and aligned at 0° vertical tilt, facing the USV during all tests, at a site with a topographic elevation of 24 inches above sea level for a total vertical distance between the antenna and water surface of 110.5 inches.

USV and Onboard Equipment: The remote radio was installed on a vessel and connected to an NVIDIA Jetson Nano via ethernet. The remote antenna used was a triple-antenna array with a gain of 5 dBi and mounted so that the base of the antenna was 94.5 inches above the waterline. The radios operated in a direct point-to-point link without intermediary relays or external infrastructure. During testing, the vessel remained stationary.

Radio Configuration: The MPU5 radios used in both ground and onboard stations were configured to the following settings:

- Frequency: 1.372 GHz
- Maximum Bandwidth: Enabled
- Transmit Power: 35.0 dBm (3.2 W)
- Maximum Link Distance: 10 miles
- Channel Density: 3–8 nodes

Environmental Conditions: The weather conditions were mild to ensure that the communication performance results primarily reflect distance and inherent network factors, not extreme environmental disruptions. All tests were conducted under clear line-of-sight (LOS) conditions and calm weather, with winds below 5 knots, air temperatures ranging from 30°C to 35°C, and minimal sea surface activity.

To illustrate the test configuration and validate consistent line-of-sight conditions, Figure 1 shows the layout of the experimental area. The ground station was located near the Ocean View Beach Park in Norfolk, Virginia, and remained stationary throughout all tests. The USV traveled to a series of pre-determined GPS waypoints along a straight maritime path extending up to 7 miles offshore. These waypoints were selected to incrementally increase distance while maintaining direct visibility to the ground antenna, thereby minimizing environmental interference and ensuring optimal antenna alignment.

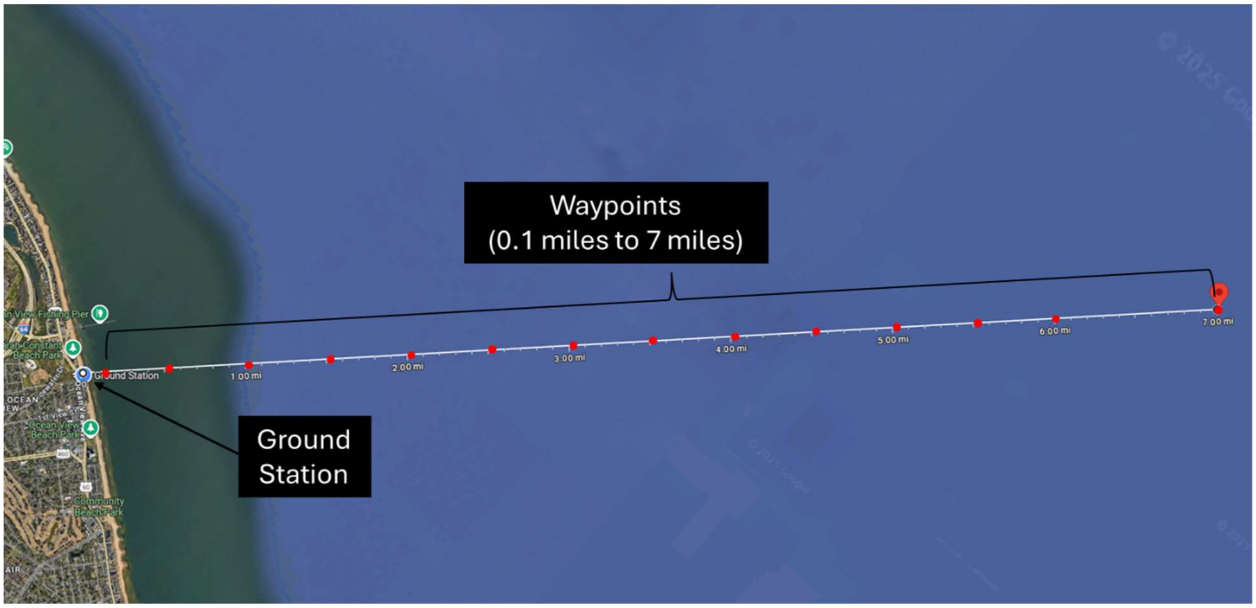

Figure 1. The location of ground stations and measurements waypoints' bird-eye view.

Test Procedure

Two tools were used to make measurements. Our custom bandwidth tool consists of a client running on the remote vessel and a server running on the ground station. A test point is obtained by providing the tool with three parameters, the packet size (in bytes), required bandwidth (in Kbytes/sec) and test duration (in seconds). Once the test begins, the server establishes an internal buffer whose size is equal to the desired packet size, filled with a packet sequence identifies and a known and varying pattern. It then begins transmitting the buffer using UDP at a rate that ensures the desired bandwidth is achieved over the period of one second. It simultaneously monitors for a small response packet by the client and verifies if a packet is successfully delivered by monitoring the sequence identifier on the response packet. It continues this process for the entire test duration. Note that the way this test is setup, sending a buffer can cause multiple UDP packets to be sent by the C++ communications library, as the attached network MTU was 1500 bytes. In addition, the server introduces delays between sending each copy of buffer as opposed to sending all data as fast as possible and then waiting for the 1 second interval to expire.

To evaluate not only peak performance, but also how packet loss and jitter behave as a function of bandwidth load, testing was performed at 14 pre-defined GPS waypoints, with distances ranging from 0.1 to 7.0 miles. During each trial, the USV remained stationary at the target location to ensure consistent LOS to the ground station.

The two complementary tools were used as follows to measure bandwidth performance and packet loss:

Custom Bandwidth Tool: Performance was measured using variable packet sizes with a maximum of 24 KBytes, at data rates of 5, 10, 25, 100, 500, and 1500 KBytes/s for a duration of 20 seconds. The result is the packet loss percentage. This tool was designed to mimic typical USV messaging patterns and control-loop update frequencies.

iPerf3 Testing: To evaluate raw throughput and network behavior under varying loads, we used iPerf3 in UDP mode. At each test distance (0.1–7.0 miles), we first measured the maximum achievable bandwidth using the command:

```
iperf3 -u -c <IP_CLIENT> -b 0 -t 20
```

This generated an uncapped 20-second UDP stream from the client (shore-based control station) to the server (onboard Jetson Nano). Following the initial measurement of maximum throughput, we conducted five additional tests at 90%, 70%, 50%, 30%, and 10% of the measured maximum bandwidth. These tests helped us evaluate communication behavior and packet delivery under more realistic and constrained traffic loads.

At the 7-mile waypoint, the uncapped bandwidth test proved unreliable due to unstable link conditions. The unreliability involved the tool hanging for over 1 minute, or complete loss of connection. To ensure consistent and interpretable results, we used a capped test rate of 2.29 Mbits/s, which reflected the highest stable bandwidth observed at that range. The follow-up tests at 90–10% of this capped value were conducted in the same manner.

At each distance, both tools were executed sequentially, producing 168 total test runs (2 tools × 6 data rates × 14 distances). Collected metrics included:

- Bandwidth/Bitrate (KBytes/s or Mbits/s)
- Packet Loss (%)
- UDP Jitter (ms)

RESULTS

This section presents the key findings from our bandwidth and packet loss measurements using both the custom testing tool and iPerf3, collected across distances ranging from 0.1 to 7.0 miles. In total, 168 test runs were performed across 14 distances and six packet size/bandwidth settings using each tool.

Custom Bandwidth Tool Results

The custom bandwidth tool demonstrated that low-bandwidth control traffic is extremely resilient even at long distances. Across all tested distances (0.1–7 miles), packet loss remained approximately 0.002% for transmission rates between 5 and 100 KB/s. These rates are representative of typical heartbeat, telemetry, and control command streams in USV operations.

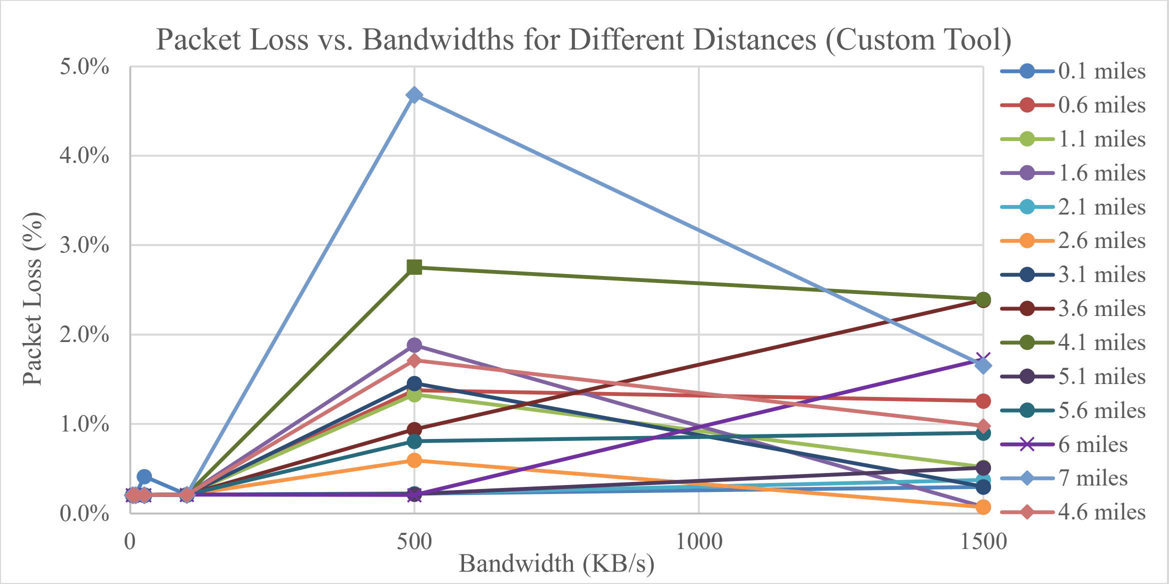

Figure 2. Packet loss percentages measured using the custom bandwidth tool at varying packet sizes (5 KB/s to 1500 KB/s) and distances (0.1 to 7 miles).

As bandwidth increased, some trends emerged. At 500 KB/s, moderate packet loss appeared intermittently. Notably, the spike at 7 miles (approaching 4.7%) corresponded with a large cargo ship momentarily obstructing line-of-sight, illustrating how temporary obstructions, not just distance, can degrade performance. At 1500 KB/s, performance remained largely robust (<1% loss) through the first 3–4 miles but showed increased variation beyond that, with sporadic jumps in loss at greater ranges.

Interestingly, packet loss did not follow a smooth upward curve with either distance or bandwidth. Instead, the loss rate remained remarkably flat at low throughputs and only increased under specific channel stress or obstruction conditions. This is visualized in Figure 2, where nearly horizontal lines for smaller payloads emphasize the consistency and resilience of the MPU5 link under realistic maritime conditions. These results indicate that USV control protocols can safely operate with aggressive timeout and retry settings even over long distances, while high-volume data (e.g., video or dense telemetry) may require adaptive strategies depending on line-of-sight quality.

iPerf3 Throughput Results

To complement the custom bandwidth tool results, we used iPerf3 to assess maximum achievable throughput across the same range of distances. The results, visualized in Figure 3, reflect how MPU5 radio performance gracefully degrades over longer links.

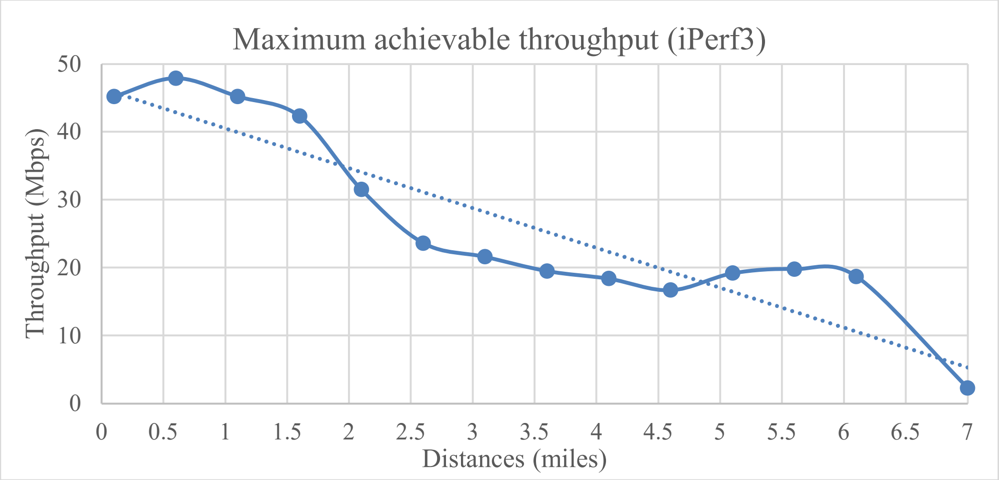

Figure 3. Maximum achievable throughput measured using iPerf3 across distances from 0.1 to 7 miles. The trend line (dotted) highlights the gradual decline in link performance with range, with a sharp drop occurring after 6 miles.

From 0.1 to 1.6 miles, throughput remained strong, fluctuating between 45 and 48 Mbps with zero packet loss and minimal jitter. This indicates full channel efficiency in near-shore operations. At 2 miles, throughput began to decline, dropping to ~31 Mbps, followed by a steady reduction across greater distances. Between 3 and 6 miles, throughput stabilized around 18–22 Mbps, remaining sufficient for telemetry and control traffic. At the 7-mile mark, the connection remained usable only when capped to 2.29 Mbps, with a corresponding packet loss increase (~4.7%), indicating the upper limit for sustained stable communication without rate adaptation.

These results confirm that the MPU5 system reliably supports high-throughput communication up to 6 miles, with graceful degradation rather than abrupt loss of service. Beyond this range, performance remains usable for low-bandwidth tasks but requires careful tuning or fallback protocols.

iPerf3 Jitter and Packet Loss Results

Figure 4 presents the client-reported jitter measurements across all distances for the maximum throughput load. Jitter, a key indicator of network stability and temporal predictability, remained relatively low and consistent through the first 6 miles.

At short ranges, from 0.1 to 2.1 miles, jitter remained under 0.6 ms, with a minimum value of 0.2 ms at 0.6 miles. These values suggest minimal packet delay fluctuation, well within acceptable thresholds for real-time control and telemetry data in USV operations.

Beyond 2.6 miles, jitter began to exhibit a mild upward trend. Most measurements between 2.6 and 6.1 miles ranged from 0.5 to 0.8 ms, still within an acceptable envelope for many maritime teleoperation and autonomy scenarios.

A significant deviation occurred at 7 miles, where jitter spiked to 7.2 ms, which is more than an order of magnitude higher than all other locations. This sharp increase corresponds to the upper limit of the radio system's expected range and aligns with other indicators of degraded link quality observed at this distance.

These results confirm that while overall throughput degrades gradually, jitter remains tightly controlled until the far end of the operational range. Only at 7 miles does jitter exceed thresholds that might impact real-time control or streaming.

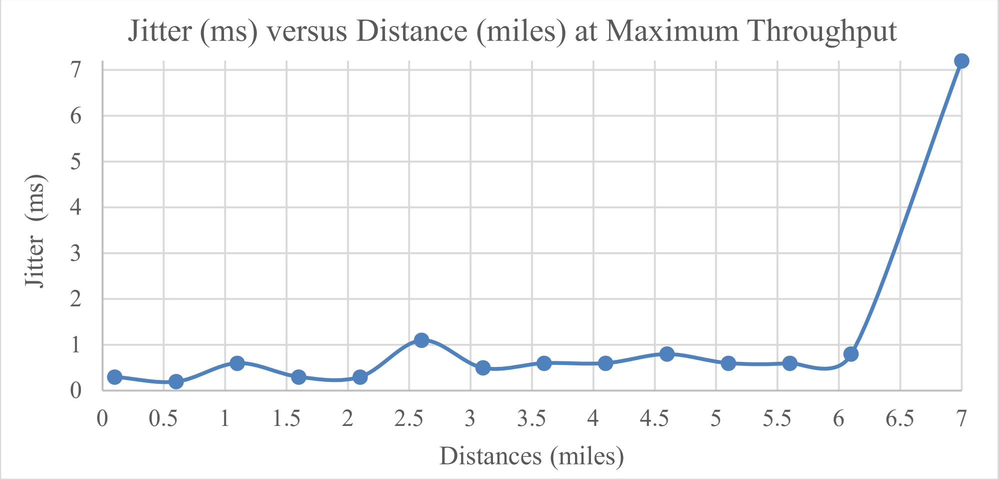

Figure 4. Measured jitter (ms) reported by the client during iPerf3 tests.

Packet loss was evaluated using iPerf3 during maximum throughput tests at each distance (Figure 5). As expected under saturated UDP traffic, the radio link experienced significant packet loss when attempting to transmit beyond its practical capacity. At most distances, loss rates ranged from 92% to 97% under the unconstrained "maximum bandwidth" setting, indicating severe oversubscription of the link. However, these results are not indicative of typical USV communication behavior. When the bandwidth was capped to a sustainable value, particularly at 7 miles, where the link could not support unrestricted throughput, the observed packet loss dropped to 4.6%. This demonstrates that even at the farthest range tested, the MPU5 radios can support stable transmission when operated within reasonable throughput limits.

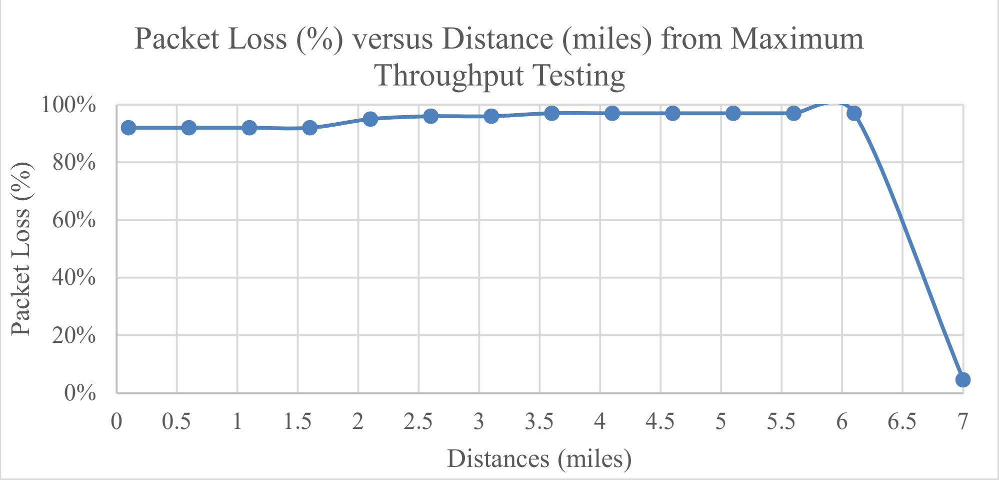

Figure 5. Packet Loss (%) versus Distance (miles) at Maximum Throughput.

At all lower throughput levels (e.g., 90%, 70%, etc.), and in the custom bandwidth tool tests using 5–100 KBytes/s rates, packet loss was consistently negligible (typically <0.002%). These lower-bandwidth levels better represent real-world USV operations, including heartbeat signals, status telemetry, and control commands.

The jitter and packet loss values reported here reflect the most demanding transmission conditions, specifically the maximum throughput at each distance. Lower-bandwidth scenarios (for example, 90%, 70%, and so on) exhibited substantially lower jitter and negligible packet loss but were omitted for clarity. These results are best interpreted as upper-bound stress tests rather than representations of typical USV communication loads.

DISCUSSION

The results presented in this study provide the basis for development of validated communications model which can be used to drastically increase the usefulness of simulations by incorporating accurate communications models. They also demonstrate the viability of using MPU5 radios for long-range USV operations, particularly for applications requiring low to moderate data throughput. Across all test distances, packet loss for low-bandwidth control traffic (5–100 KB/s) remained consistently low, with an average around 0.002%. This indicates strong resilience of small, periodic data streams that typically carry heartbeat, telemetry, and command messages. Even at the maximum tested distance of 7 miles, these low-bandwidth streams experienced minimal degradation, which suggests reliable support for essential control loops and status updates.

At higher data rates, particularly 500 KB/s and 1500 KB/s, packet loss began to increase in a more noticeable manner. For example, loss at 500 KB/s remained under 1% through 1 mile, but increased progressively with distance, reaching nearly 5% at 7 miles. While these data rates exceed the typical requirements for USV control traffic, they provide a useful reference point for stress-testing the system under heavier network loads. These results help define the upper limits of reliable performance and can inform design choices in systems that may incorporate higher-bandwidth applications such as video streaming or batch telemetry uploads. Throughput and jitter results from the iPerf3 tests further corroborate these findings. Maximum achievable throughput decreased gradually from approximately 45 Mbps at short ranges to around 2 Mbps at 7 miles, aligning with expected attenuation over distance. Jitter remained low and stable for all test points up to 6 miles but spiked significantly at 7 miles, suggesting increased transmission instability near the operational range limit. This behavior is important to consider in timing-sensitive applications, where elevated jitter may introduce latency or disrupt synchronization in control loops.

One of the primary motivations for this work was to develop simulation models for communication systems with enough granularity to allow simulation-based design of control station timeout thresholds, which are commonly used in heartbeat mechanisms to detect connection loss. These thresholds are often set heuristically without supporting data, leading to potential misclassification of transient delays as disconnections or, conversely, delayed recognition of true failures. The packet loss data collected in this study, especially under controlled and repeatable conditions, offers the ability to develop validated communications models that can be used for setting timeout parameters. In particular, the consistency of low-loss performance at lower data rates suggests that conservative timeout values can be employed with high confidence in reliable communication.

Beyond the immediate implications for timeout calibration, these results also highlight opportunities for more adaptive network-aware behaviors in USV systems which can only be tested in simulation if adequate models for the communications equipment is utilized. For instance, real-time monitoring of jitter or loss trends could enable dynamic adjustment of communication strategies, such as reducing update frequency or switching to lower-bitrate encodings in degraded conditions. This would allow USVs to maintain functional links under variable signal quality while preserving critical situational awareness and control. In summary, the experimental data supports the suitability of MPU5 radios for both teleoperated and autonomous USV missions operating within several miles of a control station. The methodology and findings not only validate existing practices but also offer a framework for improving reliability and responsiveness in future maritime systems.

CONCLUSION AND FUTURE WORK

This study presented a detailed evaluation of MPU5 radio performance in the context of long-range USV operations. Through a series of structured experiments over distances ranging from 0.1 to 7 miles, we analyzed key communication metrics including throughput, packet loss, and jitter using both a custom bandwidth tool and the iPerf3 utility. The results demonstrate that low-rate periodic traffic, representative of heartbeat and control signals, remains highly reliable even at the farthest test points. Moderate degradation in higher-rate data streams was observed as range increased, but remained within acceptable bounds for most USV use cases, particularly up to 5–6 miles under clear line-of-sight conditions.

These findings provide an empirical basis for improving control system robustness, particularly in setting communication timeout parameters. Rather than relying on heuristics, system designers can leverage the measured packet loss probabilities and jitter characteristics to calibrate thresholds that balance responsiveness and fault tolerance. Additionally, the results suggest that performance monitoring during operation (i.e., especially tracking changes in jitter and throughput) could be used to dynamically adjust update rates or communication strategies, increasing resilience under varying signal conditions.

Future work will focus on expanding the test set to include more complex operational scenarios such as mobile USVs with dynamic trajectories, partial line-of-sight conditions, and the presence of environmental interference or signal obstruction.

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