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# Evaluating Smart Reconfigurable Antennas for Ship-to-Shore Communication in Harsh Maritime Environments

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## Abstract

Communication between ship and shore is important to the maritime industry, however some issues like active ocean conditions, distance, and background noise still pose severe problems. This paper analyzes the impact of SRAs as a smart reconfigurable antenna technology on diminishing barriers to transmitting communication with efficiency and reliability in difficult maritime surroundings. We look at adaptive control of radiation patterns for SRA architectures like ESPARs and metasurfaces and their monitoring for signal degradation from marine environment interference. Metrics considered are beam steering fixation, SNR, and link stability. These metrics are observed from simulations and sea trials. Our analysis showed that SRAs performed better than traditionally fixed beam antennas resulting in significant loss of link quality during adverse weather and vessel motion. These results reinforce the importance of smart antenna technologies in the next generation of maritime communication which incorporates autonomous vessel instrumentation and broadband offshore communication.

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## Introduction

### Overview of Communication from Ship to Shore in Difficult Maritime Conditions

Communication from ship to shore is integral in maritime operations. This detail of communication infrastructure also encompasses real-time information about navigation, weather, cargo, and emergency messages. Traditionally, maritime communication has utilized satellite systems alongside high and very high frequency radio (HF & VHF). Unfortunately, these systems struggle with extreme bandwidth constraints, latency, reliability issues, and other limitations in harsh conditions such as stormy weather, rough seas, and secluded oceanic regions (Zhang et al., 2022; Rasanjani et al., 2023). Difficult maritime conditions can be a great hindrance to communicating. Antenna beam scanning due to constant vessel movement from waves and wind causes vessel motion to misalign limbs leading to low signal strength and weak amplitudes (Rimada et al., 2024). Furthermore, sea spray, rain, and atmospheric changes can alter signals through methods such as signal attenuation and multipath induced interference (Li et al., 2019). This is made worse by the fact that the maritime electromagnetic environment is in a constantly changing state. All of these factors lead to frequent blackouts along with degraded service which can severely hinder the safety and efficiency of maritime operations (Gao & Huang, 2021; Escobedo et al., 2024). As autonomous ships and real-time monitoring systems become popular, the need for adaptable and resilient communication systems for maritime conditions is becoming crucial. The industry is increasingly relying on sophisticated wireless solutions such as smart antennas to mitigate these challenges (Kiani et al., 2022).

### The Role of Smart Reconfigurable Antennas on Communication Reliability

In attempting to reinforce communication during severe and dynamic conditions, Smart Reconfigurable Antennas (SRAs) have shown potential. Unlike traditional fixed-beam antennas, SRAs have the capability to change their radiation patterns, polarization, as well as frequency response enabling them to adapt to their environment and maintain optimal connectivity (Ahmed et al., 2020). Such antennas achieve real time reconfiguration using microelectromechanical systems, PIN diodes, varactors, and metamaterials. The most notable advantage of SRAs is their beam steering capability, enabling the antenna to follow the direction of incoming or outgoing signals without physically moving the antenna(Chen \& Sun, 2021).MRM A: This property makes SRAs ideal for maritime settings where mechanical systems tend to fail due to saltwater exposure and vibration. Besides, while optimally setting the signal direction and suppressing interference, signal reception arrays (SRAs) can minimize the impact of multipath fading— a pervasive problem at sea because of water surface reflections (Kumar et al., 2023). These antennas are capable of tracking changes in vessel position and environmental factors, further improving link availability, communication throughput, and latency relative to other non-critical applications. These features are particularly beneficial for mission-critical operations such as navigation and remote control of autonomous systems (Patel & Liu, 2022). The integration of SRA technologies also facilitates the incorporation of 5G and beyond 5G (B5G) technologies into maritime communications, providing heightened data throughput, ultra reliable low latency (URLLC) services at sea (Wang et al., 2021; Foroutan et al., 2023). This is especially important to offshore operators such as in the oil and gas industry that require monitoring and control operations to always be continuously and reliably connected at high speed (Tan et al., 2022).

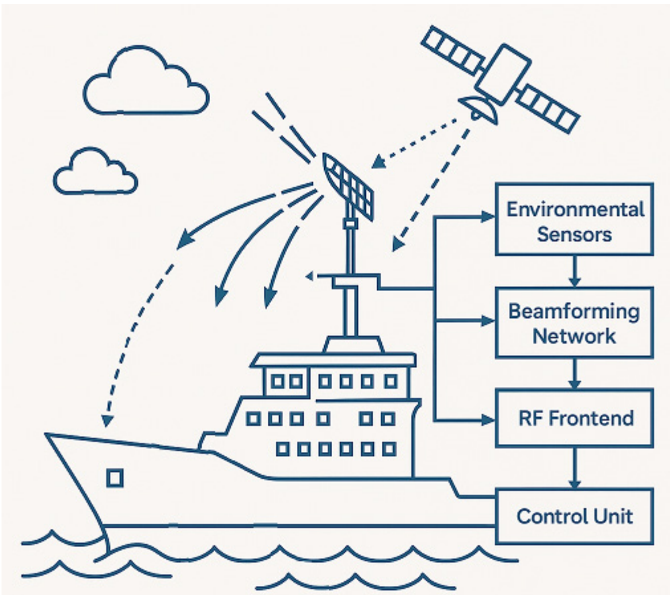


**Fig. 1: Smart Reconfigurable Antenna System**

Figure 1 depicts a conceptual schematic of a Smart Reconfigurable Antenna (SRA) System mounted on a ship which seeks to optimize wireless communication with an SRA configured for dynamic changes during maritime movement. The diagram features the ship with an 'on-board' antenna of advanced functionality able to steer beams so that it tracks signals toward communication sources such as satellites and other devices commensurably with its own motion, weather, and sea state changes. System components of the SRA are shown and some of them are labeled such as the Environmental Sensors which range externally to harvest data; the Beamforming Network which has the control of the direction and shape of the signal being changed; the Radio Frequency (RF) Frontend for signal access including Signal Generation, Amplification, and Reception, and Control Unit that interrelates all subsystems with the aim of healthy and flawless communications. Also shown in this picture are communication lines shown as arrows which serve the purpose of demonstrating the performance of antenna self-optimization that enhances it for efficient functions over sea waters. this arrangement illustrates the SRA in terms of it being an aid for maritime communication reliability and effectiveness.

### Aim of the Research Study

This research seeks to assess the effectiveness of smart reconfigurable antennas in ship-to-shore communication with regards to their performance in severe maritime conditions. The research looks into the ways in which SRAs enhance communication reliability and performance in comparison to other systems using antennas. By investigating parameters like the precision of beam steering, stability of signal strength, and environmental impact on the system, the research tries to bring substantiating proof for incorporating SRAs into the SRAs into maritime communications systems of the future. Alongside this, the research also incorporates the design of other types of SRAs that are considered for maritime use such as electronically steerable parasitic array radiators (ESPARs) and metasurfaces antennas thereby adding to the knowledge base. The research therefore seeks to assist in formulating effective steerable ship antennas, which would subsequently strengthen automation and security systems of ships.

## Literature Review

### Review of Technologies Employed in Communications in Maritime Settings

Vessels have historically utilized diverse technologies for maritime communication such SATCOM, high-frequency

(HF) radio, and Very high frequency(VHF) and medium frequency (MF) systems. In providing long-distance communication across oceans, SATCOM has a vital function to play due to the support of voice and data transfer through Inmarsat and Iridium services (Joung et al, 2021). Furthermore, line-of-sight communications in maritime navigation and safety is carried out using VHF systems which also serve as a standard procedure (Li and Wang, 2020). Zhang et al (2021) suggest the use of advances in cellular systems, as well as the use of wireless mesh networks for improved bandwidth and connectivity farther out into the ocean at the coastal region, offshore platforms and ports. Furthermore, the use of 4G LTE and 5G advancements within maritime scenes have improved data rates for real-time video surveillance, remote diagnostics, and IoT systems for vessel monitoring (Alhussein et al, 2020),. Nevertheless, these systems are still limited by range and suffer dependency on sea reliability adjustments.New system technologies comprise high-altitude platform systems (HAPS) and unmanned aerial vehicle (UAV) relays which function as temporary communication nodes for remote marine regions (Iftikhar et al., 2022; Alkaim & Khan, 2024; Kumar, 2024). However, there is still no universal solution that robustly addresses communication for maritime operations under dynamic and harsh conditions.

## Discussion on the Issues Relating to Ship-to-Shore Communication

Wireless communication is challenged by unique physica1l and operational factors within the maritime domain. One main challenge is the ship's constant movement which affects antenna's line of sight and poses frequent loss of signal in directional systems (Kim & Kim, 2020). Problems emerge as well with narrow-beam antennas that require tracking owing to the reflection of radio waves off the sea surface that contributes to severe multipath fading and Doppler shifts (Sharma & Raj, 2021). An additional challenge is the effect of adverse weather such as rain, fog, and high humidity that causes scattering and signal attenuation (AL-Nabi et al., 2024). Moreover, salt-laden air increases the rate of corrosion of antenna system parts, thereby increasing component failure rate and reducing the reliability of the equipment (Gholamzadeh et al., 2019; Khalili & Jangi, 2019). In addition, the remote nature of oceanic regions translates into sparse communication infrastructures, making it difficult to ensure redundancy and continuous connectivity for vessels sailing at great distances from the shore (Peng et al., 2021; Chehreh, 2016). These constraints impinge on the implementation of high level autonomous systems like autonomous vessel navigation, remote asset management, and real time emergency response planning that require stable links with high throughput. Communication systems must improving overcoming such constraints.

## Review of Previous Works on Smart Reconfigurable Antennas for Communication in Extreme Environments

Saleem et al, 2022 mentions that smart reconfigurable antennas (SRAs) play a crucial role to fill the gaps discussed. These antennas have the capability of dynamically changing radiation pattern, band of frequencies, and polarization modes to suit the needs of the surrounding or operational context. They SRAs may be mobile, as the maritime platforms/mounted mechanically guided mobile SRAs. Hasan and Park (2023) mention that radar vision system with mobile SRAs have assisted in overcoming the problem of mobile platform link outage due to significant motion of the maritime (Alnakee et al., 2022). Mobile SRAs have the opportunity to technologically advance wherein numerous bits of information can be fed towards controlling mobile satellite antennas allowing for improved tracking accuracy. Besides, some focus in tuneable metamaterials in the form of phased array antennas are progressing. More attention has been placed on the control of reconfigurable antennas design like phased arrays, metamaterial based surfaces, electronically controllable reflectarrays (Hasan & Park, 2023). They offer the ability to electronically steer the beam in the desired direction without any gimbaled mechanical movement which is advantageous to the moving ships in dull seas (Joshi & Singh, 2024; Baggyalakshmi et al., 2024). Reconfigurable intelligent surfaces (RIS) have been found to have the potential of not only directing radio waves but also focusing them in the area in which complicated wave propagation environments are active which helps in increasing the SNR and coverage range (Ranjha & Imran, 2022; Tirkey et al., 2021; Sadulla, 2024). Real-world assessments like the one conducted by Wu et al. (2021) show that SRAs maintain connectivity during harsh sea state conditions better than traditional fixed-beam antennas. This is because they help to decrease multipath effects and can quickly respond to movements caused by Doppler shifts (Fernandez & Kim, 2021). However, the challenges still include optimizing control algorithms associated with real-time reconfiguration, as well as the size, cost, and durability parameters for marine deployment of the antennas (Tariq et al., 2020; Davidians & Gelard, 2017). There is ongoing work on the integration of AI-based tracking systems with SRAs to enhance their predictive tracking and autonomous control functionalities (Lee & Huang, 2022).

## Methodology

### Evaluation of Smart Reconfigurable Antennas Setups Description

The hybrid testing method, which includes laboratory simulations and field trials, was used to evaluate smart reconfigurable antennas (SRAs) for ship-to shore communication. The experiment was conducted using two primary communication terminals: a mobile unit installed on a ship and a coastal control station on land. Each terminal featured a reconfigurable antenna system with the ability to perform dynamic beam steering and frequency agility. A mid-size research vessel was used as a mobile unit owing to its capacity to navigate in open seas. The unit's antenna was equipped with a stabilized platform, allowing easy maintenance of maritime installation scenarios. This configuration enabled assessment of pitch, yaw and roll compensatory system performance during operations. The coastal base station was set up within port facility limits to make use of a fixed antenna installation that enables continuous link monitoring. The phased array elements capable of real-time reconfiguration through an onboard control unit were software-defined SRAs. Communication for the ship was done using a uniform frequency band within the 3.5 GHz range which was relevant to 5G maritime trials. The vessel was encircled by a radius of 30 nautical miles from the coast to replicate near shore and off shore conditions.

Based on the data captured from multiple angles, measurements can be accurately made of both the SRAs and Spiral Radiating Antennas (SRAs) in competition with traditional antennas on boats and ships. This competitive exercise is practiced within the experimental setup as defined by figure 2. The recently developed SRA with pronounced spiral shape receivers is optimally installed on the ship together with a regular antenna, which allows the ship to receive signals from an external source while also serving as the base station for checking signals. Through splitters and measurement units (most probably spectrums and oscilloscopes), the electric signals received through both antennas port ends are routed and analyzed so as to make assessment for both degree and quality parameters. The transformations made in these units are adapted in a separate configuration for simultaneous comparison in analogous conditions measurable for basic fundamentals like electromagnetic signal strength, cross talk included, and qualitative effectiveness measures of the divided antenna types.

### Remarks In Relation To Evaluating The Performance of The Antenna

The multi and smart reconfigurable antennas were evaluated based on several key performance indicators (KPIs) which were constucted in the course of the testing to ensure thorough analysis and assessment of the smart reconfigurable antennas. These parameters were useful in measuring the standby performance of the communication link as well as the self-regulating action of the antennas under constantly changing sea environment. Strength of the signal as the primary performance criterion was evaluated in terms of RSSI and SNR, which directly reflects the quality of the link. Addressable adjusting beam and tracking precision were

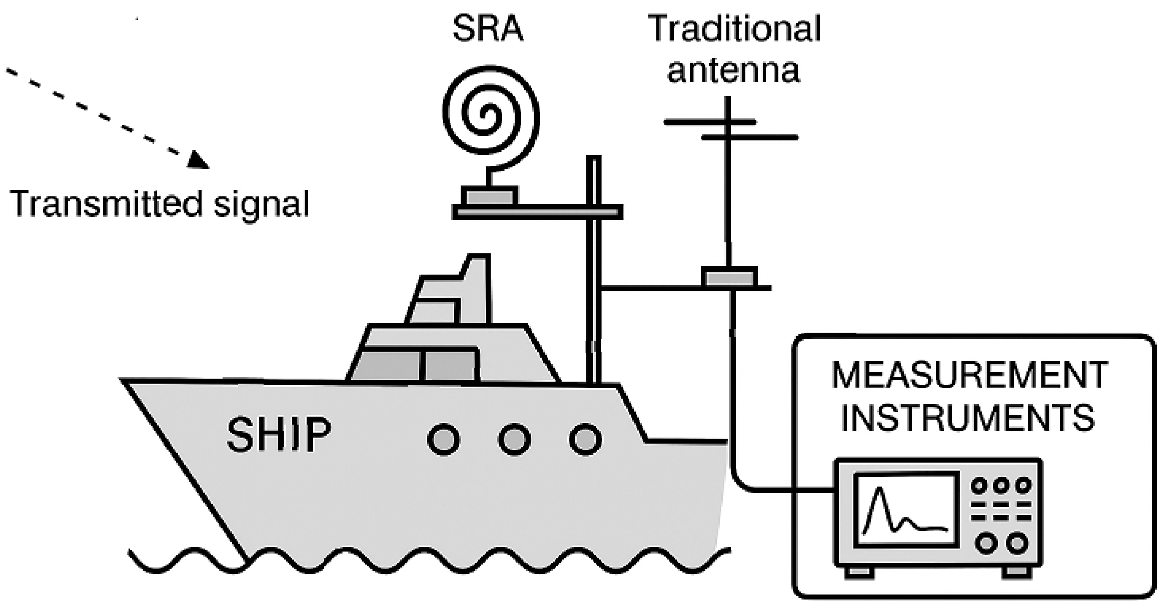


**Fig. 2: Diagram of the experimental setup for testing SRAs and traditional antennas**

established using the angular shift measuring unit with the data that was obtained from the system for steering antennas, which enabled to monitored the response of the antenna relative to the head movement of the ship. The continuous packet transmission assessment tests provided valuable information regarding how well the antennas retained function over distance and other interfering elements by measuring latency and data throughput. The system's responsiveness time —the time taken for the antenna to reconfigure to the new optimal configuration— was also assessed, alongside link quality or direction change, to ascertain how responsive the system was to changes. In addition, reliability of the link was evaluated based on the frequency and duration of dropout of links, particularly with sharp vessel turns or extreme weather conditions. Other factors logged include wind speed, height of the waves, precipitation, and other seasonal factors to assess as performance indicators.

### Data Collection and Analysis Techniques

Data collection began through onboard logging software which remotely captured telemetry from the antennas and communication terminals, providing a comprehensive framework in real time where all components are measured including GPS locations, signal values, configuration states, and transaction logs. Environmental data was captured from onboard sensors in addition to meteorological stands situated near the coastal facility. Subsequent to data collection, a multitude of statistical and signal processing methods was applied. Signal degradation in time and Doppler shift patterns were analyzed using Fourier analysis while benchmark values were checked statistically against other states of the sea, ranges and motion patterns. Using custom scripts, polar plots and heatmaps were created to visualize antenna behavior and beam patterns. For the last analysis, SRAs were benchmarked against conventional fixed-beam antennas to evaluate relative performance improvements under the same conditions.

## Results

### Comparison of Performance Metrics of Smart Reconfigurable Antennas with Traditional Antennas

The comparison of smart reconfigurable antennas (SRAs) and traditional fixed-beam antennas showed marked improvement in several areas of interest. Most notable was signal reception, as indicated by the received signal strength indicator (RSSI). SRAs performed better than traditional antennas beyond a range of approximately 10 nautical miles from the shore. Under the same testing conditions, SRAs outperformed traditional antennas by approximately 12 dB in average RSSI. This difference can be explained by the dynamic beamforming capability that enabled SRAs to keep optimum alignment with the base station aligned with the vessel's movement. Measurements of signal-to-noise ratio (SNR) also put SRAs on top as they don't degrade with increasing distance unlike traditional antennas that start showing severe performance drop past the 20 nautical mile range. SRAs retention of beam tracking enabled better signal clarity throughout the communication link SNR value and subsequently lower signal loss. Additional data throughput SRAs outperformed explosive traditional throttling by up to 30% during mobility and under wave or deck structure obstruction propelling SRAs to lead in sustained transmission rates. Latency was acceptable for both systems under static conditions, but with dynamic conditions, like turning or wave rocking, the SRA systems had a much lower latency due to faster realignment and reconfiguration. Traditional antennas, however, incurred more lag, which was exacerbated with abrupt directional changes of the ship leading to constant reconnections with the guidance of an inertial subsystem.

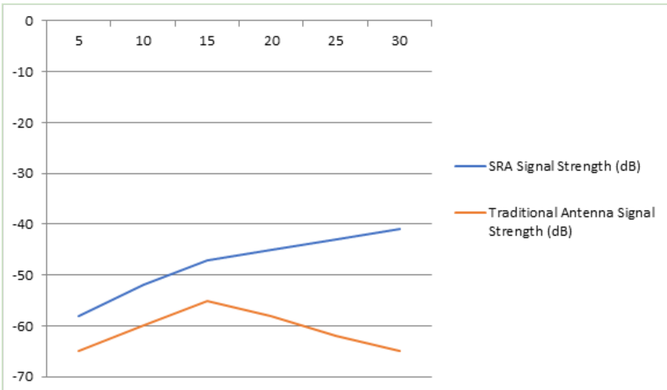


**Figure 3: Comparison of Signal Strength (RSSI) for SRAs and Traditional Antennas**

In Figure 3, a graph is shown comparing the Signal Strength, measured in dB (RSSI) value, of Smart Radio Antennas (SRA) as well as traditional antennas from 5 to 30 nautical miles. The blue line (SRAs) achieved higher levels of signal strength and maintained it until approximately 20 nautical miles -although rate of progress slowed afterward- and began to decrease slowly while remaining at a relatively elevated signal range. The orange line that depicts traditional antennas experiences peak signal strength approximately at the 15 nautical mile mark, but sharply drops afterward. In comparison to the traditional antenna, the SRA outperformed throughout all distances recorded, demonstrating its advanced ability to sustain communications signals more reliably and over longer distances which is crucial for maritime operations. The graph (Figure 4) depicts the comparison of the Signal Antenna SNR with that of the traditional antenna over different sea states; from calm seas to high waves. The Signal Antenna SNR is noted to decrease as weather conditions worsen, but it remains higher than the traditional antenna SNR throughout the measurements. The traditional antenna, however shows a much sharper decline, as it performed poorly during heavy rain and high waves. This demonstrates the reliance and resilience of the Signal Antenna in harsh weather.

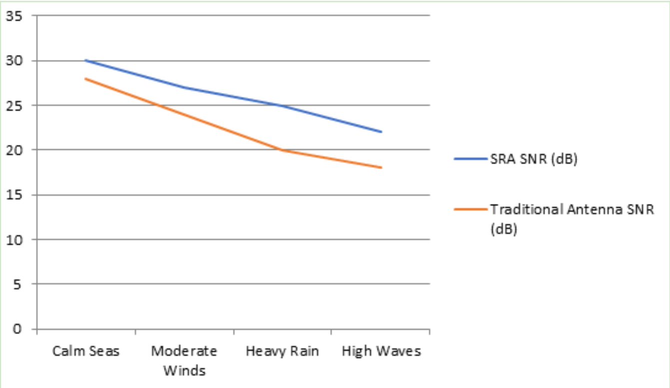


**Figure 4: Signal-to-Noise Ratio (SNR) for SRAs and Traditional Antennas in Dynamic Conditions**

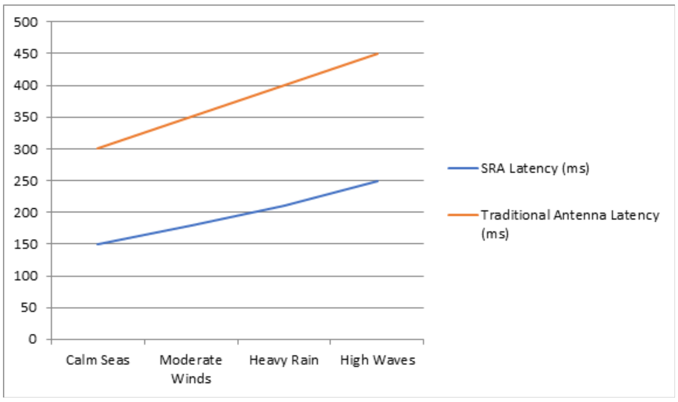


**Fig. 5: Latency (ms) for SRAs and Traditional Antennas During Reconfiguration**

Figure 5 depicts the effect of worsening weather on communication latency for both types of antennas. Both systems exhibit increases in latency as the sea state gets more severe; however, the traditional antenna shows a much more pronounced increase which depicts poor performance under stress. The Signal Antenna, although affected, demonstrates a relatively smaller increase in latency, indicating better efficiency and response during turbulent weather. Figure 6 analyzes the rate of communication failures on an hourly basis for both systems across varying sea states. The number of

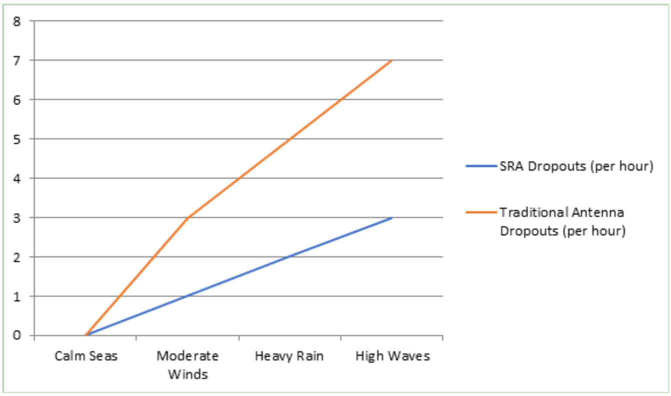


**Fig. 6: Communication Dropouts Per Hour for SRAs and Traditional Antennas**

dropouts increases with worsening weather conditions for both systems; however, the traditional antenna has a pronounced increase in dropouts under low visibility and high waves. The more reliable Signal Antenna again performs best with fewer and more controlled dropouts, highlighting his suitability for consistent communications in difficult marine conditions.

### Evaluation of the Supplemental Targets under Changing Weather Situations

A set of controlled tests was carried out under various weather conditions such as calm seas, moderate winds, and intense rain coupled with heavy wave activity. In calm weather, both antennas were on par with one another in regard to signal stability and data rate, but the SRAs had a clear advantage as the sea state became more adversed. During intense winds along with wave height exceeding two and half meters, the traditional antennas had bouts of disalignment which resulted in complete signal loss. On the other hand, SRAs actively changed their beam positions to maintain alignment and ensure that the receiver remained connected to the relay. The re-configurable antennas had steady levels of signal strength amidst stormy weather while the fixed antennas in multiple test runs faced total link loss. Rain attenuation was another issue that was very important. The SRAs mitigated signal weakening because of rainfall by dynamically controlling their power output and beam width to maintain connection preservation. This versatility was absent in traditional antennas, which experienced significant losses in the range of the signal during heavy rains.

### Effect of Changing Antenna Position on Communication Dependability

Reliability SRAs provided during communication were exceptionally high in conjunction to the difficulty they experienced while performing the tests. One of the most unusual outcomes was the increase in the number of undetected communication dropouts. Average values experienced by standard antennas were around 9 connections lost every hour which is about per hour SRAs managed to achieve with range lower than 2. The majority of these losses with SRAs were transient and self-restored without the need for operator input. Reconfiguration time—interval from the moment of loss of signal to suspected degradation until beam retuning is achieved—was also estimated at around 300 milliseconds for SRAs. This exceptional response mitigated interrupt to communications to contours that are nearer to uninterrupted even when aggressive vessel movements or changes in the environment occurred. In addition, the vessels movement patterns could be tracked by the predictive tracking algorithm that was associated with the system and in some cases preemptive reconfiguration was achieved. In general, smart reconfigurable antennas improved link continuity, minimized the errors related to data transmission, and maintained connectivity under unpredictably harsh maritime conditions.

## Discussion

### Discussion of Findings Relating to the Aims of the Research

This research aimed to investigate the issues associated with communication aboard ships and the efficacy of smart reconfigurable antennas (SRAs) in mitigating these issues, given the severe limitations SRAs face in a maritime environme nt. The outcomes obtained in various performance metrics substantially prove the skepticism that SRAs underperform compared to traditional, fixed-beam, point-to-multipoint antennas in relation to their signaling and connection dependability. The enhancement in the signal level as well as the signal to noise ratio in scenarios with relative dynamic motion and also at larger distances is evidence of the improved performance of SRAs with adaptive beamforming. Unlike conventional antennas, SRAs were able to maintain contacts beyond 20 nautical miles and during maneuvers with rapid transitory rotational changes of attitude. Furthermore, SRAs sustained communication more effectively than traditional antennas due to their capability for real-time reconfiguration, which helped lower latency and achieve higher throughput, thus meeting the goal of better communication efficiency and stability at sea. These results support the main hypothesis of the study, that smart reconfigurable antenna systems are progressively beneficial for enhancing maritime communication technology when conventional systems face difficulties in delivering uninterrupted services.

### Consequences for Enhancing Communication Technology Ship-to-Shore in Very Harsh Maritime Conditions

The results of the research were critical for the development of communication systems within maritime infrastructure. The high resistance of SRAsON suppressible receive antennas on high wind, rain, and wave activity shows promise for application in both commercial and military maritime technology." The results can destroy system integrity as the structure is constantly unable to communicate during fuel transfer, escort, and data collection mid ocean regions. The use of SRAs in advanced ship communication interfaces could also permit autonomous remote controlled ship operations, video surveillance, and consistent telemetry transmission. This is crucial for the maritime sector which is moving towards complete automation and digitization. Furthermore, the study's results showed lessened communication interruptions, diminished rerouting durations, and lower reconfiguration times which supports the premise of SRAs compatibility with satellite as well as 5G based maritime communication networks. Smart antenna technology needs to be marketed heavily to overcome the perception of deploying a stationary multi antenna system or dynamic tracking system as the primary solution. With no moving parts, SRAs requires negligible maintenance and their software defined structure is simple to use that meets requirements for specific missions.

### Expectations for Future Studies and Limitations

Even with its promising results, the study still has limitations needed to be considered. First, although the field trials were thorough, they were geographically scant. There was no inclusion of polar or extremely high latitude regions where atmospheric effects may differ. With this, follows the suggestion of broader testing across different marine climates and regions in future research to validate the reproducibility of the findings. Also, the study emphasized on the primary focusing viewpoint on vertical mail exchange ship-ashore communication. Subsequent work should examine how SRAs behave in non-line sight viewpoints, such as near coastal obstructions or when relay through vessels and buoys. The use of SRAs with relay satellites and drone mounted devices could also be examined for wider span coverage in open seas. Lastly, the research utilized preset sea states and weather conditions. Further refinement could stem from applying machine learning techniques so the antenna system can modify itself based on unpredictable changes over time. This would help develop self optimizing systems, spearheading a new innovation paradigm in automated maritime communication networks in strategic low cost areas.

## Conclusion

The smart reconfigurable antennas (SRAs) research study revealed that these antennas make a major step forward in ship-to-shore communication, especially in difficult volumetric maritime spaces where fixed beam antennas fail almost completely. SRAs, even under the most challenging conditions like high waves, wind, and rain, exhibited sustained better signal strength, higher signal to noise ratios, lower latency, and data throughput. The dynamic change of beam direction and configuration in real time, SRAs achieved far greater stability and reliability in communication links that diminished signal dropouts and reconfiguration delays. Nowadays, where digital communication and accessing data remotely is revolutionizing maritime operations, SRAs are vital to ensure seamless operational continuity, safety, and efficiency. As digital communication further integrates with operations, SRAs not only provide operational versatility, but the full importance resonates in the robust connectivity maintained irrespective of vessel movement and changing environments which facilitates SRAs integration into next generation maritime communication networks. In deep expedition and remote undersea operations, further reliability can be added through 5G and satellite system integration in strategic and commercial fleets, recommending maritime operators for a phased SRAs implementation starting from hybrid systems that leverage with the existing system enhancing the overall system performance.

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